Grantham Institute

Report GR7

November 2014

A Systematic Review of Current Technology and Cost for Industrial Carbon Capture

Project Team: Duncan Leeson[1], Jamie Fairclough[1], Camille Petit[1], and Paul Fennell[1*]

[1]Department of Chemical Engineering, Imperial College London, London, SW7 2AZ, UK

*p.fennell@imperial.ac.uk

Table of Contents

Executive Summary

This systematic review was carried out in order to provide an accurate overview of the current research into carbon capture, as applied to industrial facilities. Industrial emissions of carbon dioxide in the UK account for 19% of total emissions (110 Mt per year out of a total of 570 Mt). Four industrial sectors have been investigated in this report; the iron and steel industry, the cement industry, petroleum refineries and chemical plants, and the pulp and paper industry, which account for the majority of industrial emissions.

Four major academic databases were searched using a system of carefully chosen and refined keywords to return just over 500 papers. These were screened, to determine whether they were relevant to the study and provided useful information, by studying their abstracts; those that were included in the searches but not relevant to industrial carbon capture and storage were removed, leaving a total of 250 papers. These remaining papers were each read and individually categorised through use of a structured questionnaire to determine their relative importance, with each then being classified as high, medium or low priority depending on how much useful information they contained. Other parameters that were noted were the geographical distribution of the literature, the primary areas of focus of the papers and which industry the paper described. All costs found (and quoted here) were escalated to 2013 $.

The iron and steel industry is responsible for the two largest industrial point source emitters in the UK (non-power related), which are steelworks in Scunthorpe and Port Talbot. The potential for capture of exhaust CO2 from this sector is limited by the emission sources; there are numerous emission point sources on a steelworks, meaning multiple sources might have to be combined in order to capture a large proportion of emissions, increasing the cost. Within the literature, the highest reported emissions that could be captured from a single unit was 55% by using post combustion capture on the blast furnace off-gas. The costs for capture on iron and steel plants varied slightly, with post-combustion amine capture costing an average of $67 per tonne of CO_2 captured, with mineral carbonisation another option, but with a low capture potential (8-20% of emissions) and large discrepancies in anticipated costs ($10-115 per tonne).

The refineries and chemical manufacturing sector is the largest by emissions, responsible for a third of global industrial emissions, with ten of the fifteen largest industrial sites by emission in the UK. Similarly to steelworks, a major challenge is that emissions from a refinery are distributed between a large number of smaller point sources, so capture of a

very high proportion of total emissions is difficult. Emissions reductions of around 50% can be achieved through use of a combined stack and post combustion capture at an average cost of $77 per tonne, though capturing CO_2 from the gasifier by post-combustion capture can be done at a cost of $42 per tonne (with a smaller emissions reduction potential). The use of a nickel-based chemical looping system was found to have a cost of either $44 or $58 per tonne when applied to a refinery boiler, dependent on replacement rate, while the use of oxyfuel combustion has also been proposed for furnaces and boilers at a cost of $65 per tonne.

The pulp and paper industry exhibited little supporting research data for carbon capture and storage, though there were a number of papers concerning site-specific information. Only two estimated costs were found for carbon capture as applied within the industry, perhaps due to most mills being situated away from other industry, meaning pipeline lengths would be longer and not being able to take advantage of industrial clustering. Amine capture of boiler flue gases could be effected with a very low reported cost of $15 per tonne, and would be able to capture 62% of emissions from the plant. However, a competing system of black liquor gasification and subsequent solvent capture from a Kraft mill would be able to capture 90% of emissions, though at a cost of $35 per tonne.

The cement industry has potential to capture large proportions of emissions. The use of post-combustion amine scrubbing, could capture 60% of emissions at a high cost of $108 per tonne. By contrast, using an oxy-combustion system and calcium looping can give much lower capture costs, falling as low as $34 per tonne. In addition, the use of calcium looping capture on other industrial or power plants can be combined with the production of cement through the CaO purge stream, giving large clustering incentives.

Introduction

1.1 Background

Evidence for the existence of anthropogenic climate change is growing by the year (IPCC, 2013), such that preventing the increase of temperature and limiting the ever-growing effect of climate change is one of the most pressing issues for policy makers worldwide. It has become increasingly evident that current levels of emissions of carbon dioxide are unsustainably high, and a variety of different methods are being considered to reduce these emissions.

The total reduction required from current emissions is a subject with conflicting recommendations from different international bodies. These emission reduction targets encompass all emissions so, in addition to emissions from industrial sources, there are also emissions from the power sector and transportation. The most notable international agreement is the Kyoto protocol, signed in December 1997, which set legally binding emissions reductions targets for developed countries (UNFCCC, 1997). Targeting developed countries was part of the Protocol's principle of "common but differentiated responsibilities," in order to not stifle growth of developing nations. The Annex 1 countries (developed nations) were required to reduce their emissions to 5% below 1990 levels by 2012, and the clean development mechanism was set up to promote low-carbon development of nations not included in Annex 1 (developing nations.) However, while cuts of this level are a good start towards reducing the overall global emissions, more drastic deep cuts must be made, with the Intergovernmental Panel on Climate Change (IPCC) recommending emissions reductions of 50-85% by 2050, based on 1990 levels, in order to avoid catastrophic warming (IPCC, 2014). In addition, the emissions must reach a maximum level no later than 2020 in order to mitigate the most serious effects of climate change. The European Commission has set targets of reducing emissions by 80-95% by 2050, with the industrial sector expected to reduce emissions by 34-40% by 2030 and by 83-87% by 2050 (European Commission, 2011). The white paper on energy in 2003 set out target reductions of 60% on 2003 levels by 2050 for the UK in order to comply with the EU and domestic targets on reduction of CO_2 emissions (HM Government, 2003).

1.1.1 Industrial Sector Emissions

In order to make the necessary emissions cuts to achieve the ambitious targets set by the IPCC and the European Commission, there must be savings made across all sectors that emit greenhouse gases. Industry is just one such sector, and worldwide accounts for 27% of emissions of carbon dioxide (World Resources Institute, 2011).

As can be seen in Figure 1, a total of 31,260 Mt of carbon dioxide are emitted into the atmosphere annually from anthropogenic sources, with 8,388 Mt per year coming from the industrial sector. UK emissions of greenhouse gases (as defined by the Kyoto protocol) were 569.9 $MtCO_2$ equivalent in 2013 (Department for Energy and Climate Change, 2013). Of this, only 19% of emissions (110 Mt per year) are from industrial sources, with 30% of emissions coming from energy generation at power plants. As such, measures to reduce emissions from industrial sectors have a large potential to make significant steps towards the targets mentioned above. The largest single sector is energy production, especially when energy demand for different industrial sectors is taken into account. As such, much current research and debate is focused on the energy industry, and while true that it offers the greatest scope for emissions reduction due to its size, industrial emissions are also of sufficient magnitude that they cannot be ignored.

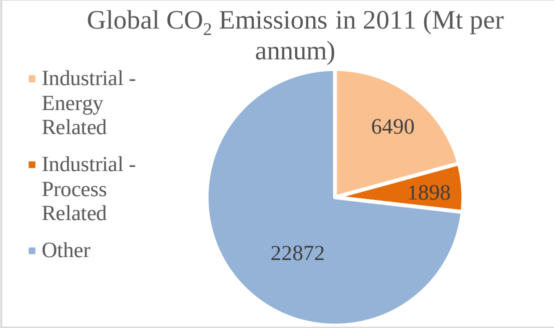

Figure 1 - Contribution of industrial processes to global CO_2 emissions (World Resources Institute, 2011)

Due to the vastly different nature of the processes carried out by different industries, it is necessary to determine the relative magnitudes of the different industries to define their emission reduction potentials. For the purpose of this report, five major industries have been considered; these are the iron and steel industry, the cement industry, chemical manufacturing, petroleum refining and the pulp and paper industry. The first four of these were chosen due to their magnitude; together, they make up a total of 61% of industrial emissions, meaning that initiatives to greatly reduce the emissions from these sources would have a large impact on the total volume of industrial emissions. The fifth industry chosen, pulp and paper, was chosen due to its high potential to cut emissions, due to almost the entire

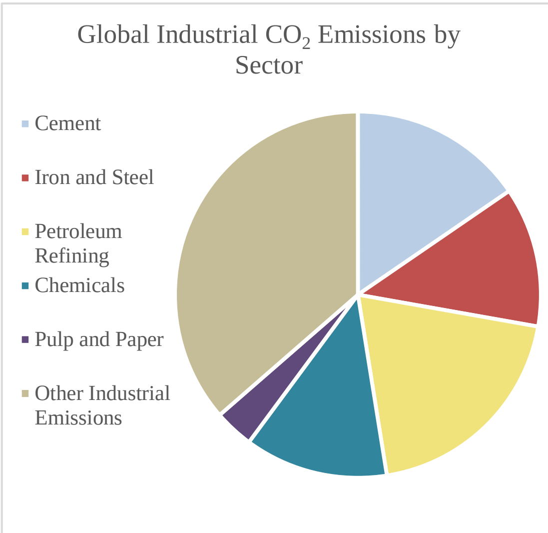

Figure 2 - Global Industrial Emissions by Sector

industry operating the same process. The relative contributions made globally by different industries towards the total industrial emissions can be seen in Figure 2, and detailed in Table 1.

Table 1 - Emissions of Different Industrial Sectors

Industrial Sector	CO_2 Emissions (Mt per annum)	% of Total Industrial CO_2 Emissions
Refineries	1,678	20
Cement	1,258	15
Chemicals	1,090	13
Iron and Steel	1,007	12
Pulp and Paper	252	3
Other Emissions	3,104	37

From these figures, it is clear that another major challenge facing the decarbonisation of industry is the diversity of the emissions sources. The different processes make a common solution almost impossible, so the different industries need to be considered in a bespoke manner. Another potential challenge facing the decarbonisation of these industries is that a significant proportion of the associated emissions are ‘locked-in’, in that the emissions cannot be reduced unless the core process behind the sector is changed. One example of this is the calcination reaction in the cement industry (whereby CO_2 is driven off from limestone rock to produce the main precursor of cement), which accounts for 60% of that industry’s emissions and produces carbon dioxide as a by-product of the useful clinker.

1.1.2 CCS on Industry

To be able to discuss carbon capture’s potential for industrial systems, a thorough investigation of the nature of the industrial plants is necessary to determine where CCS could be applied to capture the greatest quantity of emissions. One of the major differences between industrial plants and power stations is the multitude of sources of the carbon dioxide; on power plants, there is usually only one large source of carbon dioxide, in the boiler. However, on industrial plants, there are many more, smaller sources, some of which may be more amenable to capture than others. Because of this, CCS technologies must be applied carefully to maximise the emissions avoided, while keeping the costs of constructing and operating such systems low.

General information on the different methods of carbon capture that could be applied to industrial plants can be found in the review paper entitled “Carbon Capture and Storage Update” (Boot-Handford et al., 2014). Different technologies are discussed, along with the advantages and disadvantages of each are discussed, alongside potential applications for the technology. While not specifically aimed at industrial CCS, it provides a comprehensive overview of the current progress of the CCS technologies discussed in this review.

1.1.3 Nature of Industrial Emissions

Table 2 – Number of large CO_2 point sources (>0.1 Mt per year) worldwide (IPCC, 2005)

Industrial Process	Number of Plants	Total CO_2 Emissions (Mt per annum)	Average Emissions per plant (Mt per source per annum)
Cement			
Combined Production	1175	932	0.79
Refineries	638	798	1.25
Iron and Steel			
Integrated Steel Mills	180	630	3.50
Other processes	89	16	0.17
Petrochemical industry			
Ethylene	240	258	1.08
Ammonia	194	213	0.55
Ethylene Oxide	17	3	0.15
Pulp and Paper	94	183.3	1.95

To be able to identify how to apply CCS to different industrial sources, it is first important to consider the relative sizes and number of sources that exist within typical plants for each industry. A full breakdown of these large emission sources is found in Table 2 above, where all stationary sources emitting more than 0.1 Mt per year of carbon dioxide are listed. For the purpose of this report, five main sectors of interest were identified; cement, iron and steel, chemical manufacturing and refining, the pulp and paper industry and the food and drink industry. However, no relevant information was found for the food and drink industry, so it has been omitted from the report.

Within the UK, 15 of the 50 highest emitting point sources are industrial plants, with the remainder being power stations, highlighting the importance of reducing emissions from these sectors (British Geological Survey, 2006). The largest two industrial emitters are Scunthorpe and Port Talbot steelworks, which are ranked 8^{th} and 9^{th} respectively with emissions of 7.3 and 7.2 Mt per annum of CO_2. Ten of the 15 industrial sites in the top 50 were refineries or chemical manufacturing facilities, though the three largest industrial emitters are steelworks.

1.2 Aims and Objectives

The primary objective of this review is to give an overview of the current state of carbon capture and storage in the industrial sector based on current literature, using an impartial search process of literature from a variety of sources.

The three principal aims of the investigation in order to achieve the objective are stated below:

- To systematically search for and gather a sufficient amount of literature to give a balanced and informed view of progress in and barriers to industrial carbon capture around the world.
- To summarize the reviewed literature and present a comprehensive analysis of current industrial CCS, with particular attention to the available technologies, their costs and any applicable legislation.
- To identify whether there are any areas of literature that are absent from publications or have a lack of consensus on technological benefit or cost of implementation.

These three objectives were achieved by way of a systematic literature review, followed by the processing of information identified in the gathered and summarised literature. It was necessary to consider the various carbon capture technologies available, the nature of each of the four targeted industries and the applicability of each of the technologies to generic cases for each of the industries. The proposed costs of each feasible technology for each industry were also to be investigated and quantifiably detailed as far as possible from the literature available. However it was recognised that in some cases there would be little or no data on the costs of implementing different capture methods for specific industries.

1.3 Tabulated Results of Systematic Review of Literature

Table 3 – List and source of papers screened and reviewed

Sector/Theme	Number of papers screened				Number of papers reviewed				Number of high priority papers found
	EBSCO	Science Direct	Web of Science	RSC	EBSCO	Science Direct	Web of Science	RSC	
Cement	2	41	3	12	2	25	3	7	12
Chemicals manufacturing	26	23	1	0	20	6	1	0	10
Minerals Processing	4	35	6	0	2	14	4	0	8
Refineries	26	23	4	0	16	7	2	0	4
Policy	9	89	1	0	8	35	1	0	15
Pulp and paper	1	30	0	0	1	17	0	0	5
Iron & Steel & Smelting	0	138	45	0	0	55	20	0	17
Food & Drink	0	5	17	0	0	0	4	0	0
Sub-Totals	**68**	**384**	**77**	**12**	**49**	**159**	**35**	**7**	**71**
Total				**541**				**250**	**71**

1.4 Work Plan

1.4.1 Key Tasks and Breakdowns

Define project scope: This required formulating a set of clear, well-defined aims of the project, and to establish the eventual scope. Subsequently, the key databases to which the search terms would be applied were identified based on the relevance of their literature content to the project requirements.

Literature Search: The literature search utilises an iterative process of defining search terms, running these searches in the selected databases, recording the number and quality of the hits returned for each, refining the search terms and repeating the process until a manageable number of apparently relevant papers were returned from the searches. This was applied to each area that was to be investigated.

Literature Review: Reviewing the literature was to be carried out in two key stages. Firstly, the abstracts of all the literature returned from the refined searches were screened and assessed according to strict criteria discussed in the methodology section, and papers deemed irrelevant discarded. The progressed relevant papers were then to be read fully and reviewed by questionnaire.

Summarise Literature: Short summaries were written on each progressed paper to extract all information regarding the paper's content concerning industrial CCS technology, costs and policy. This data was then to be processed to synthesise a view of the current state of affairs of industrial carbon capture.

2 Methodology

As detailed in the work plan, after the project scope was defined a complete literature search and systematic review of the literature was undertaken, which resulted in a total of 250 papers being thoroughly reviewed. The systematic search and review process methodology, and risks to the systematic process, were identified and are examined below.

Figure 3 below summarizes the methodology for the first part of the review, which involved searching for and gathering relevant papers.

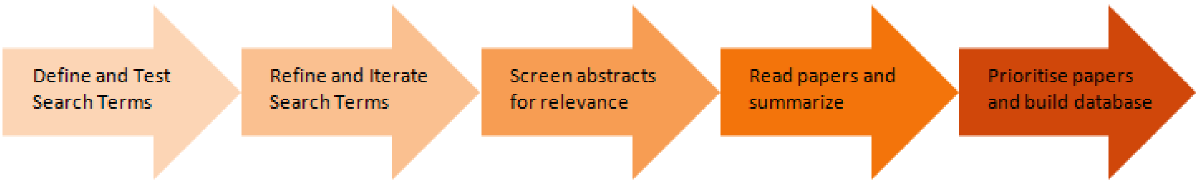

Figure 3: Key steps in collection and review of papers

2.1 Systematic Review Process- Searching, Collection and Initial Screening

An initial list of search terms was drawn together, as listed in Appendix 1. The search terms were then entered into the four databases- Science Direct, EBSCO, Web of Science and Royal Society of Chemistry- returning 14,337 papers.

As both the quantity and relevance of the results from each database varied greatly, a refining step was then taken in order to improve the results of each. Thus the terms were now adapted and further structured (see Appendix 1) to obtain as high a proportion of relevant information as possible. This refining step was an iterative process, and the search terms were developed until a manageable number of papers were attained for each term. This step precipitated 541 papers after duplicates (papers that had appeared under multiple searches) were removed.

The abstracts of these 541 papers were then read, and papers which were deemed as being not relevant to this review were removed from further consideration. In order to ensure consistency, and further to mitigate against the possibility of potentially useful papers being mistakenly discarded, the definition of 'not relevant' was thoroughly discussed and qualified. A relevant paper was agreed, in Boolean logic, to:

'Appear from the abstract to contain information on the technology, economics or legislation around carbon capture in industry'

OR

'Appear from the abstract to contain indirect information relating to technology, economics or legislation around carbon capture in industry'

OR

'Appear from the abstract to contain supporting or otherwise relevant information that might reasonably be used to provide background or contextualising information on carbon capture in industry'

If any ambiguity remained on a given paper's relevance after reading the abstract, the paper was not discarded but progressed for further consideration. 291 papers were discarded based on their abstracts, progressing 250 papers for further consideration at the next stage. Figure 4 shows how the initial 14,337 papers were twice cut down a final 250 papers by first refining search terms, followed by abstract screening.

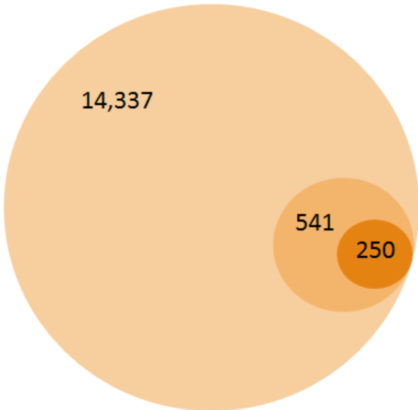

Figure 4 - Narrowing scope of literature for full review

2.2 Secondary Screening and Summary of Papers

The final stage involved three actions to be taken on each of the 250 final papers. Firstly, every paper was read fully, with costing information, policy and technological content summarized for each. A common comparison method was then applied in the form of a questionnaire for each paper which, along with the authors and journal titles, aimed to summarize the key attributes of the paper. These included the location of the papers' publication, their technical content and date of publication. See Appendix 2 for the full set of questions and Appendix 5 for summaries of the final 250 papers.

This reading and summarizing was a considerable task in its undertaking, and was necessarily divided between the authors. The risk that arose from such a splitting of the workload was that an inconsistent approach could be taken. This risk was identified early, and steps were taken to mitigate against it. These are detailed in the risk analysis section below.

Based on this questionnaire and the summaries written on each paper, priority ratings of either 'high', 'medium' or 'low' were assigned to each, according the criteria defined in Table 4 below.

Table 4: Tabulated definitions for assigning priority ratings to reviewed papers

Priority Rating	Required criteria
High	'The paper contains relevant and up-to-date qualitative information on the technology or legislation, or quantitative cost data for carbon capture technology applied to industry'
Medium	'The paper contains supporting or otherwise relevant information that might reasonably be used to provide background or contextualising information on carbon capture in industry'
Low	'The paper does not include information that meets either of the above criteria'

This process allowed the construction of a database in which all 250 relevant papers resulting from the systematic search could be easily accessed and searched for particular information. Appropriate steps were taken to mitigate the risks from inconsistent reviewing which are summarised in Appendix 3.

2.3 Capital Cost Escalator Model

In order to compare historically quoted capital costs on an equal basis, an escalator model was produced. To convert all quoted costs to USD in December 2013, the historical costs were firstly converted into USD using exchange rates averaged for the year of publication of the paper quoting the historical cost. Daily exchange rates at market close were obtained from the International Monetary Fund (IMF, 2013), and averaged for the year. After the costs had been converted to USD of the day, they were escalated to USD 2013 costs via multiplication by the Chemical Engineering Plant Cost Index (CEPCI) (CEPCI, 2011; CheResources, 2012). This escalation allowed cost data derived and published in the past ten years to be compared, although it must be noted that this method is imperfect, and could perhaps be refined by splitting the cost escalator for capital and operational expenditure.

3 Results of Systematic Review

Three general observations were made on this literature:

- Europe contributed more papers, of a higher degree of relevance to this study than any other global region
- While a slightly larger number of papers briefly mentioned the economics of industrial CCS, very few papers focused on this area as compared to technology or policy
- The majority of industry-focused papers were generalist and applied across all industries. In terms of industry-specific literature, the iron and steel and cement industries were by far the best served of the industries considered in this investigation

These three findings were quantified and are discussed further below.

Firstly, the geographical distribution of the literature, in terms of the regions in which it was published, was considered and is shown below in Figure 5. The area of each pie chart is proportional to the number of papers published by the region, while the sectors represent the number of high, medium and low priority papers found from each region.

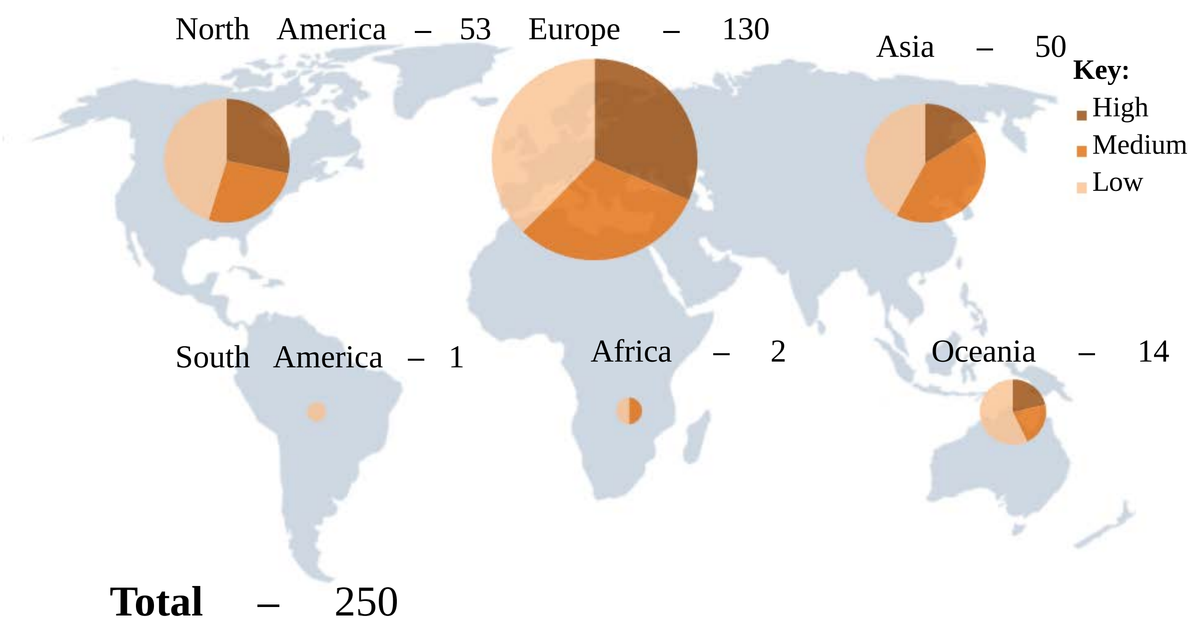

Figure 5 - Geographical location of origin of literature reviewed

Figure 5 shows above all that a large proportion- slightly over half- of all gathered papers were published in Europe. Further to this, it can be seen that not only was Europe the largest contributor to the final 250 papers in terms of the absolute number of papers published by the region, but roughly one third of the European papers reviewed were subsequently assigned a ‘High’ priority rating. This was the highest proportion of high priority papers achieved by any region, suggesting that Europe not only produced the most literature on the subject, but also literature of most relevance to this investigation. The UK produced much of this research, with the 33 UK-written papers bettered only by the USA with 40 as output of a single country; however, the UK’s research was generally found to be more specific to this review, with 39% of the research marked high priority compared to only 30% from the USA.

This could be a result of several factors. Low-carbon energy in Europe is relatively advanced, particularly with regard to academic research, compared to other continents. As part of a carbon emissions mitigation strategy, research into CCS is a natural next-step for institutions specialising in renewable and clean energy. The EU ETS (European Commission on Climate Change, 2013) is an example of how this research has led to tangible policy results, and such progress has given further conviction to academics focusing on emissions reductions that their research is highly valued. Another example of Europe at the forefront of the subject can be seen in Norway’s four large-scale integrated CCS projects (Global CCS Institute, 2013).

Asia’s literature was contributed in the most part by China. Much of this literature focused on the decarbonisation of the Chinese economy with a view to combating pollution, the future of the coal industry in China and the infrastructural requirements for large-scale CO_2 transport and storage. Due largely to this, a lower proportion of the Chinese (and hence Asian) literature was found to be of low or medium relevance to this investigation. Much of the literature contributed by the United States and Canada also tended to focus on potential sequestration sites and pipeline or other transport requirements, which again had the effect of diluting relevant content of the literature published there.

Figure 6 shows how the literature that did focus on industrial CCS distributed itself between the industries. The area of each circle is proportional to the number of papers found relevant to each sector.

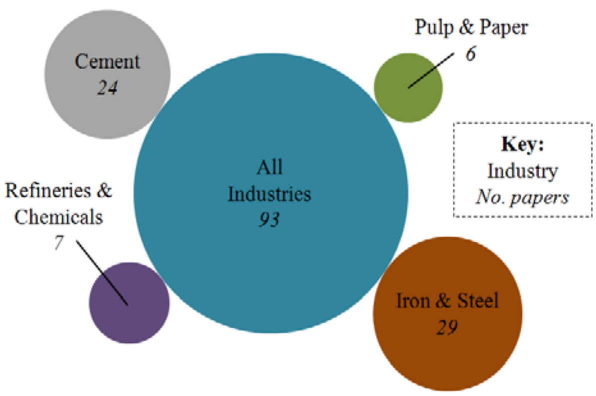

Figure 6 - Relative abundance of industry-specific literature

The first, and most clearly illustrated, observation that can be made on Figure 6 is that, of the 159 papers relating specifically to industry, a majority (58%) were non-industry specific. While a small minority of these looked at each industry in turn, most were general papers that could be applied to any one of the four sectors, for example a technical investigation of a particular carbon capture technology. Much of the literature on industrial CCS is non sector-specific, largely owing to the general absence of progress on integrating CCS technology into any single industry at a significant scale. Of the papers that were single sector specific, 44% studied CCS in the iron and steel sector and 36% considered the cement industry.

While perhaps not immediately obvious, reasons for this uneven focus of the literature can be identified to be a function of industry size and ease of CCS technology application. The cement industry is the second largest industrial emitter of CO_2, closely behind petroleum refining & chemicals manufacture. Its emissions are from the precalciner- approximately 60%- and the kiln- approximately 40%-(Barker et al., 2009), hence the emphasis on CCS.

Despite accounting for 33% of all industrial emissions (van Straelen et al., 2010), there were only seven papers found examining CCS in the refineries and chemical sector. Due to the many point sources of CO_2 from refineries and chemical plants, application of CCS to this sector can be both expensive and technically complex, and the possible realisation of this difficulty is reflected in the lack of literature on the sector. The Iron and Steel industry is also a large polluter, with much pressure on the industry to become ‘greener’ (Obereke & McDaniels, 2012) and the furnaces and boilers account for a large proportion of their emissions. These are often numerous emission locations on any given plant. However, due to the large emissions contributions of the industry, and the resulting pressure from governments and communities to reduce these, a relatively large amount of academic research has been carried out on CCS in this sector.

The pulp and paper industry (PPI) accounts for a relatively small proportion of CO_2 release, at only 4% of industrial emissions (World Resources Institute, 2011). It may be initially surprising therefore, that as many as 9% of the sector-specific papers investigated CCS in this industry. This can be explained by considering that 73% of PPI emissions are from integrated plants using the Kraft process (Jönsson et al., 2012). Thus, once a suitable technological approach was identified, it could be easily rolled-out across the industry. Another aspect of simplicity in the pulp and paper industry is that the single greatest source of emissions in each plant is the boiler, allowing for capture from this single point source to have a great effect on any one plant’s emissions (McGrail et al., 2012).

The distribution of the areas of focus of the literature, between CCS technology, its economics and carbon capture policy was then investigated, and the results shown below in Figure 7, with primary foci in Figure 8.

It is clear from this pie-chart that technology is by far the greatest focus of the literature that was reviewed, with 61% of papers considering technology before policy or costs. Given that CCS is still very much in the research and development phase, this is probably to be expected as both academics and policymakers take interest in the feasibility of new and emerging technological options. 36% of papers focussed on policy. Many of these papers reviewed such measures as the EU ETS, and the proposed Australian carbon tax, while the rest were concerned with legislative recommendations and caveats. Economics and costs were the primary focus of just 3% of the papers reviewed, despite having been explicitly searched for in the databases (see Appendix 1). This clearly displayed the lack of economic data on carbon capture applied to industry that was available to review. However, when all area of focus of the literature were investigated a different result was found, as shown in Figure 7. This shows that while only 3% of papers focussed primarily on the economics of industrial CCS, 13% of the papers included some costing information, albeit more often than not as an area of secondary investigation.

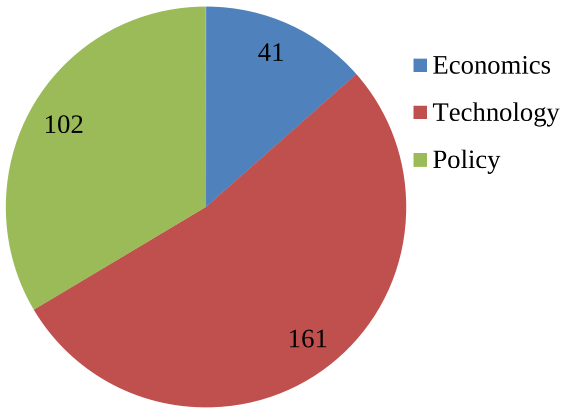

Figure 8 – All areas of research focus of literature

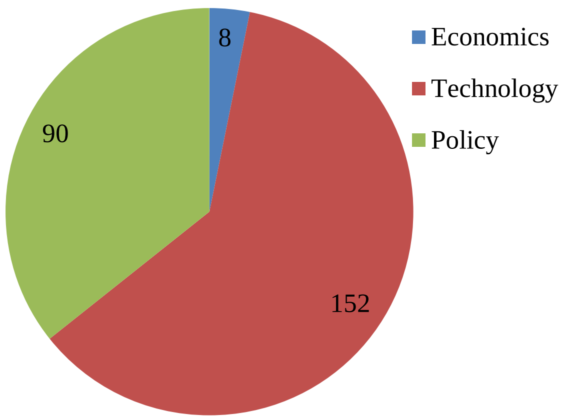

Figure 7 - Areas of primary focus of the literature

4 Industrial Sectors

4.1 The Iron & Steel Industry

The iron & steel industry accounts for 12% of industrial carbon dioxide emissions, and around 3.2% of all anthropogenic emissions (World Resources Institute, 2009). The main body of emissions comes from large integrated steel mills, with 180 such plants existing worldwide (IPCC, 2005). Many more small plants exist, of the 'mini-mill' variety. The biggest potential for emissions reduction is therefore in integrated steel mills, due to the large point sources that exist there for capture. It is these large sources that will be the main focus of the iron and steel emissions reduction section of the report. The steel plants are located disproportionately in developed countries, though large production also occurs in China, India and Turkey. China is the world's largest producer, producing 695 Mt in the year 2011, more than six times the production of Japan, which produced the second most (World Steel Association, 2013). Steel production rates have increased since a drop that coincided with the global financial crisis in 2008-9, and have risen every year since then, with the growth rate tailing off at a rate of increase of about 4%, according to the world steel association. Because of this, implementation of CCS on the steel industry is necessary to bring about a large reduction in industrial emissions, especially due to the projected increase in capacity in the coming years.

In the European Union, a consortium called Ultra Low CO_2 Steelmaking (ULCOS) has been formed of 48 European businesses from 15 countries within Europe. This group is actively pushing for a deep cut in emissions from the steel industry, with an eventual aim of over 50% emissions reduction from today's best available steelmaking routes (ULCOS, 2013). This consortium undertakes research into how current emissions reduction and mitigation technologies such as carbon capture can be applied to the steel industry, and also undertakes research into the development of new technologies for reducing the emissions associated with steelmaking, such as the research into the top gas recycling blast furnace (Birat et al., 2003) (Xu and Cang, 2013).

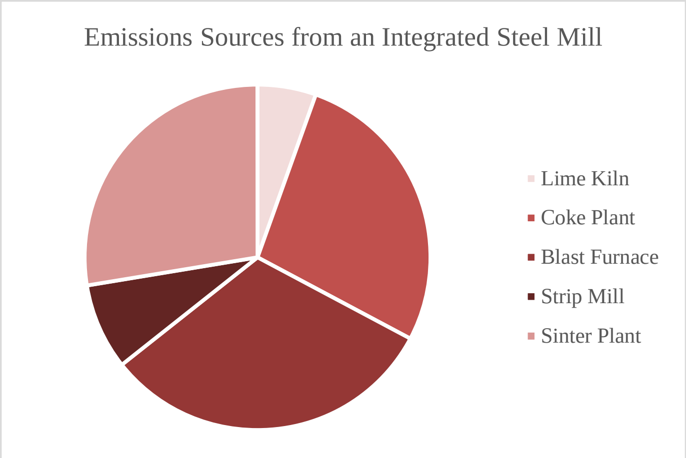

Figure 9 – Direct emissions sources from an integrated steel mill (Birat et al., 2003)

One major problem associated with implementing carbon capture on integrated steel mills is the number of different point sources, as shown in Figure 9. The largest single point source is the blast furnace, where 32% of the emissions can be captured from. The other large sources are the coke plant and the sinter plant, which each account for 27% of the overall emissions, as can be seen in Figure 10. Because of the much larger size of these integrated steel mills and their much larger average emissions than mini-mills (3.5 Mt per year average for an integrated steel mill, 0.17 Mt per year on average for a mini-mill), these are the main focus of the capture costs and technologies. Because of the three larger point sources, multiple carbon capture plants would be needed per large mill in order to save a large amount of emissions.

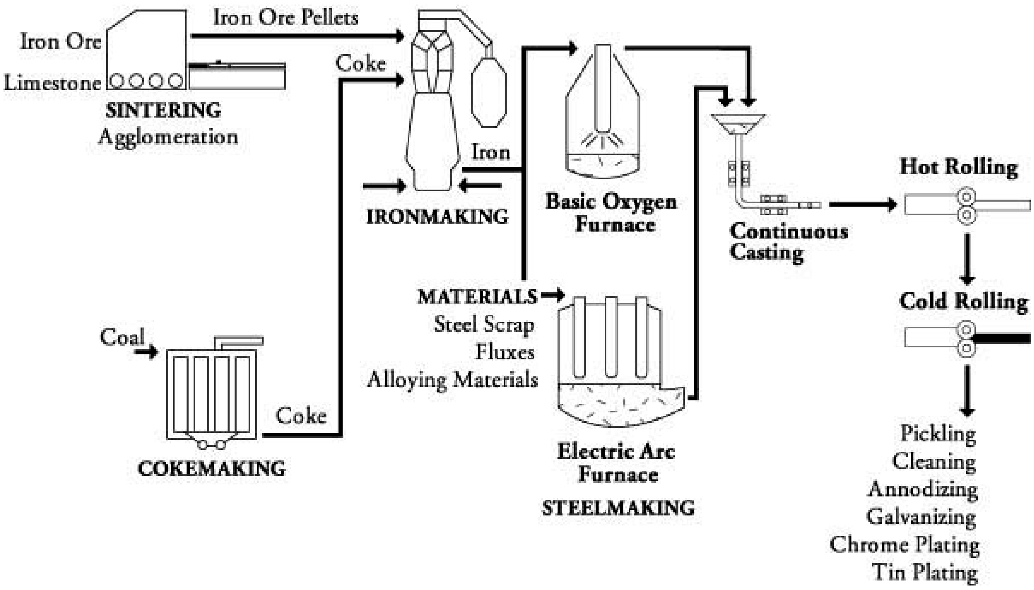

Figure 100 - Flow diagram of an integrated steel mill (http://www.ec.gc.ca)

The most suitable location on the plant is the blast furnace, which is where the majority of the research is focussed. Carbon capture from the sources on a standard integrated steel mill can be effected in a number of ways. Post combustion amine capture of blast furnace emissions is possible and able to capture the emissions at a cost of $60-116 (Arasto et al., 2013a). For some plants, this may amount to over 50% of emissions, if there is a joint stack from multiple process points, with a potential for amine capture to mitigate 50-75% of emissions in a case study looking at an integrated steel plant in Raahe, Finland (Arasto et al., 2013b), at which post combustion can be applied at a cost of $93 per tonne of carbon dioxide avoided (Tsupari et al., 2013). If a Selexol solvent is used for capture from the blast furnace, the carbon dioxide can be captured through a shift reactor at costs of $24-27 per tonne avoided (Gielen, 2003). Use of an MEA solvent was found to be able to capture carbon dioxide from the flue of a blast furnace of an integrated steel mill at $72 per tonne, while capture from a coke oven cost $79 per tonne avoided (Wiley et al., 2011). Use of a top gas recycling blast furnace, as discussed further in Section 4.5, is also an option to reduce emissions, though there are no costs for this in literature as it has only be tested on a small scale (ULCOS, 2008).

The use of a novel Sorbent Enhanced Gas Water Shift (SEWGS) reaction could potentially capture 85% of emissions from a steel plant, though a low technology readiness level means that this cannot be implemented in the near future (Gazzani et al., 2013). Carbonation of steel slag, a waste product of the steelmaking process, in a fixed bed reactor has the potential to capture some of the carbon dioxide in the flue stream (Said et al., 2013) at a cost of $115/$CO_2$ avoided (Huijgen et al., 2007), but no method of capturing large quantities of CO_2 has been devised as yet. A different study found that a smaller volume of CO_2, just 8% of the industry's emissions per year, could be captured by using steel slag at a low cost of just $10 per tonne avoided, but the small scale of this process makes it unfeasible (Stolaroff et al., 2005).

However, there are large objections from some areas of the iron and steel industry to some of the policies being used; the European Union's emission trading scheme faced significant resistance from European iron and steel makers, claiming that the financial penalties imposed by the scheme would lead to a loss of competitivity (Okereke & McDaniels, 2012).

Table 5 – Summary of cost data from literature for iron & steel industry

Title	Year	Author	Technology	Emission Reduction (%)	Cost ($/tCO$_2$)
Using CaO- and MgO-rich industrial waste streams for carbon sequestration	2005	Stolaroff et al.	Usage of steel slag for carbonation	8%	10
CO_2 removal in the iron and steel industry	2003	Gielen	Shift Reactor and Selexol solvent on blast furnace	30%	24-27
Assessment of Opportunities for CO_2 Capture at Iron and Steel Mills: An Australian Perspective	2011	Wiley et al.	Post combustion capture with MEA of blast furnace flue gas	55%	72
Assessment of Opportunities for CO_2 Capture at Iron and Steel Mills: An Australian Perspective	2011	Wiley et al.	Post combustion capture with MEA of coke oven	20%	79
Costs and Potential of Carbon Capture and Storage at an Integrated Steel Mill	2013	Arasto et al.	30% MEA Post Combustion capture from blast furnace	50%	59.60-116.30
Post-combustion capture of CO_2 at an integrated steel mill – Part II: Economic feasibility	2013	Tsupari et al.	Post combustion capture of blast furnace emissions	50%	93
Cost evaluation of CO_2 sequestration by aqueous mineral carbonation	2007	Huijgen	Use of steel slag for mineral carbonation of CO_2 from blast furnace	20%	115

4.2 Refineries and Chemical Manufacture

The petroleum refining industry, when combined with the chemical industry, is the largest industrial sector, accounting for some 33% of industrial emissions, therefore 8.9% of all anthropogenic emissions (World Resources Institute, 2009). The two industries were combined due to a paucity of information about either of them and the relatively similar nature of their processes. The largest sources of emissions are furnaces and boilers, as shown in Figure 11, which account for 65% of total emissions from refineries and chemical manufacturing sites (van Straelen et al., 2010). Therefore the most appropriate place for any carbon capture technologies is to apply the technology to the boilers, which could potentially capture up to 65% of the emissions, and the next greatest area of capture would be a catalytic cracker or gasifier, or equivalent plant item, which accounts for 16% of emissions. A typical process flow diagram for a refinery is shown in Figure 12. The refining sector will expand in the future as demand carries on increasing, with 7.2 million barrels per day increase of capacity compared to today by 2016 (OPEC, 2012), compared with current production of 87.2 million barrels per day for 2009 (True and Koottungal, 2009). The chemicals industry is experiencing a similar growth, mainly in Asia, and as such implementing emissions reduction measures is important to make large reductions in industrial emissions.

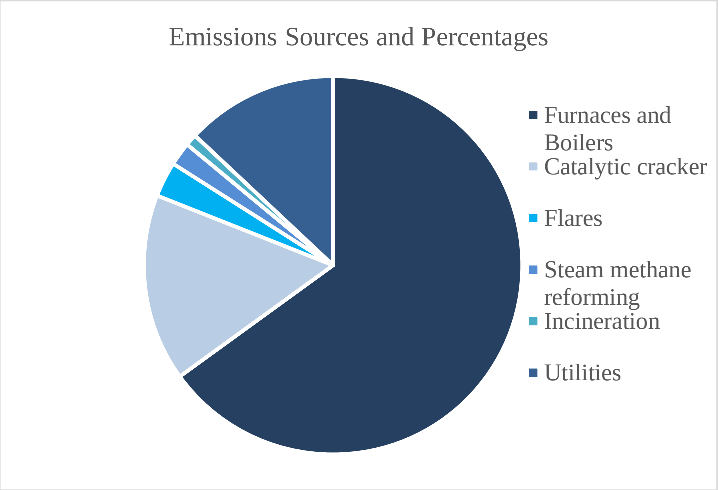

Figure 11 – Emissions sources in refineries (Kuramochi et al., 2012)

Post combustion capture, when applied to the gasifier or to a combined stack, yielded a price of carbon dioxide emissions avoided of $41 and $123 respectively (van Straelen et al., 2010). However, some discrepancy was found between that figure for the combined stack and others found in literature, with some studies showing price bands for post combustion capture of about $70 per tonne avoided after standardisation with regards to currency data, with calculated costs of $69, $69 and $85 per tonne of carbon dioxide avoided respectively (Farla et al., 1995) (Melien, 2005) (Ho et al., 2011). The application of oxy-combustion to boilers or furnaces on plant was also considered, however it is unknown what the capture potential of this is per source as refinery configurations differ, whereas a combined stack from all furnaces and boilers acts as a large source for post combustion capture more easily. This use of oxy-combustion was found to have an operational cost of capture of $65 per tonne of carbon dioxide avoided (Melien et al., 2005). Use of a chemical looping system on boilers can capture emissions at costs of $44-58 per tonne (Melien and Roijen, 2009), though the Nickel catalyst used here would likely no longer be used due to safety issues.

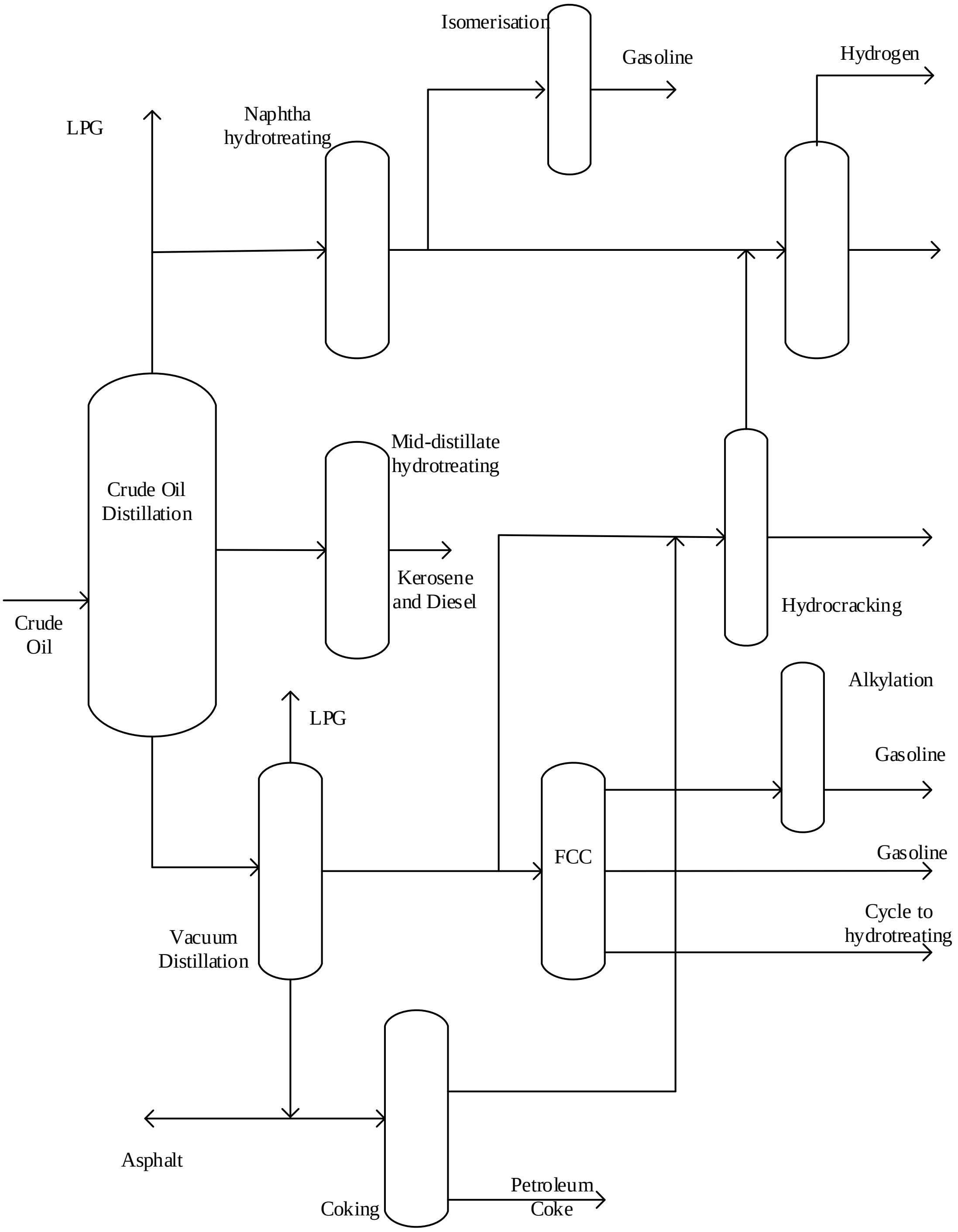

Figure 12 – Process flow diagram of a refinery

Table 6 – Summary of cost data from literature for petroleum refineries and chemical industry

Title	Year	Author	Technology	Emission Reduction (%)	Cost ($/tCO$_2$)
CO_2 capture for refineries, a practical approach	2010	van Straelen et al.	Post combustion capture of carbon dioxide from gasifier	15%	41
Economics, in Carbon Capture for Storage in Deep Geologic Formations	2009	Melien and Roijen	Chemical Looping on Refinery Boiler (Low/High replacement rate)	Unknown	44/58
Vol 1 Chapter 3: Economic and Cost Analysis for CO_2 Capture Costs in the Capture Project Scenarios	2005	Melien	Oxyfuel combustion for boilers/furnaces	Unknown	65
Carbon dioxide recovery from industrial processes	1995	Farla et al.	Post Combustion capture from combined stack	50%	69
Vol 1 Chapter 3: Economic and Cost Analysis for CO_2 Capture Costs in the Capture Project Scenarios	2005	Melien	Amine Scrubbing of flue gases from stack	50%	69
Comparison of MEA capture cost for low CO_2 emissions sources in Australia	2011	Ho et al.	MEA capture of combined stack	50%	86
CO_2 capture for refineries, a practical approach	2010	van Straelen et al.	Post combustion capture of carbon dioxide from combined stack	50%	123

4.3 Pulp and Paper

The pulp and paper industry (PPI) contributes 252 tonnes of CO_2 per year to global emissions (World Resources Institute, 2011) - equivalent to 2% (Brown et al., 2012) of the total industrial emissions. Due to the nature of their feedstock, pulp and paper mills are often situated close to densely forested areas, and so at a distance from other heavy industry. Two main technologies are in common use; mechanical mills and integrated Kraft mills. It is almost exclusively integrated Kraft mills which have on-site emissions greater than 0.5 $MtCO_2$/yr. Kraft mills in Europe for example, account for 73% of European PPI emissions and thus the Kraft PPI plants hold the largest potential for capture of CO_2 (Jönsson & Berntsson, 2012). Due to a lack of quantitative literature on costing, only two proposed costs for carbon capture as applied to the PPI were found in the literature.

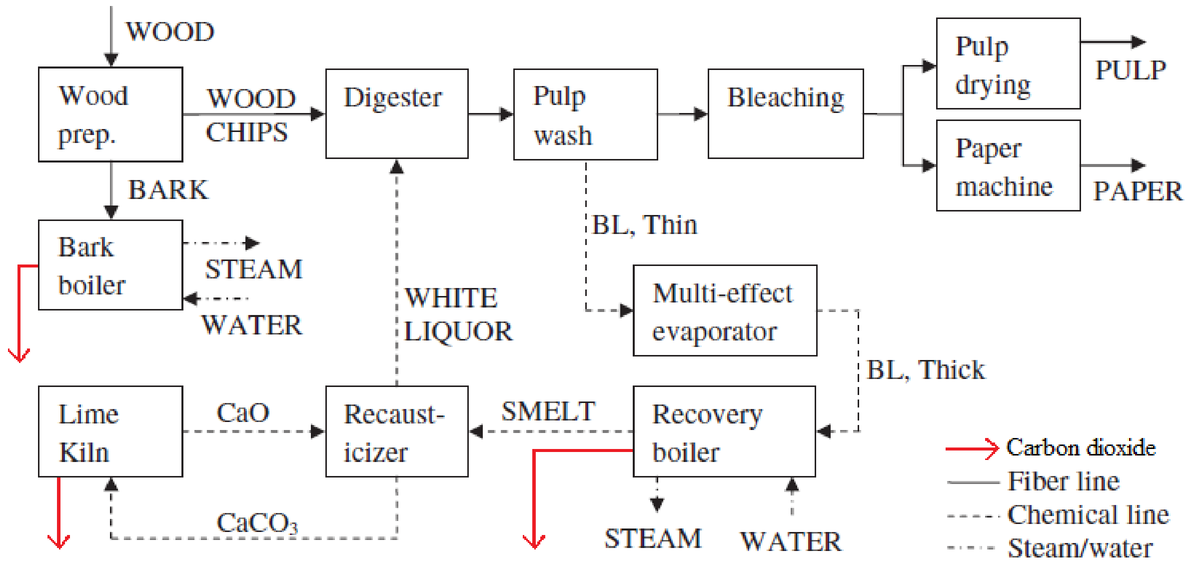

Figure 13: Flowchart of Kraft process (Adapted from Mesfun et al., 2013)

Figure 13 shows the basic Kraft process: Woodchips are prepared by stripping the wood feedstock of bark. The bark is combusted in a boiler, releasing CO_2. The woodchips are then fed into the digester with white liquor which, under high pressure and temperature, breaks down lignin and hemicellulose into fragments which are dissolved in the white liquor to form black liquor. This black liquor is then washed out of the mixture, concentrated in the evaporator and combusted in the recovery boiler, releasing carbon that had been stored in the wood. Carbon is also released from the lime kiln (as shown in Figure 13), both from the calcination reaction and also from the fuel oil used to heat the kiln (Mesfun et al., 2013)

Although plant operations vary considerably (McGrail et al., 2012, Mesfun et al., 2013, Möllerston et al., 2003) the largest emission source in an integrated Kraft pulp and paper plant tends to be the recovery boiler in which the black liquor is combusted, releasing biogenic CO_2 that had been stored in the wood in the form of hemicellulose and lignin resins.

The literature made particular reference to the potential of black-liquor gasification (Möllerston et al., 2004; Pettersson & Harvey, 2011) as a rapidly developing technology that could significantly improve the efficiency of integrated Kraft plants, while also considerably assisting implementation of carbon capture technology. The costed model of Möllerston et al. evaluated the economic potential of such technology.

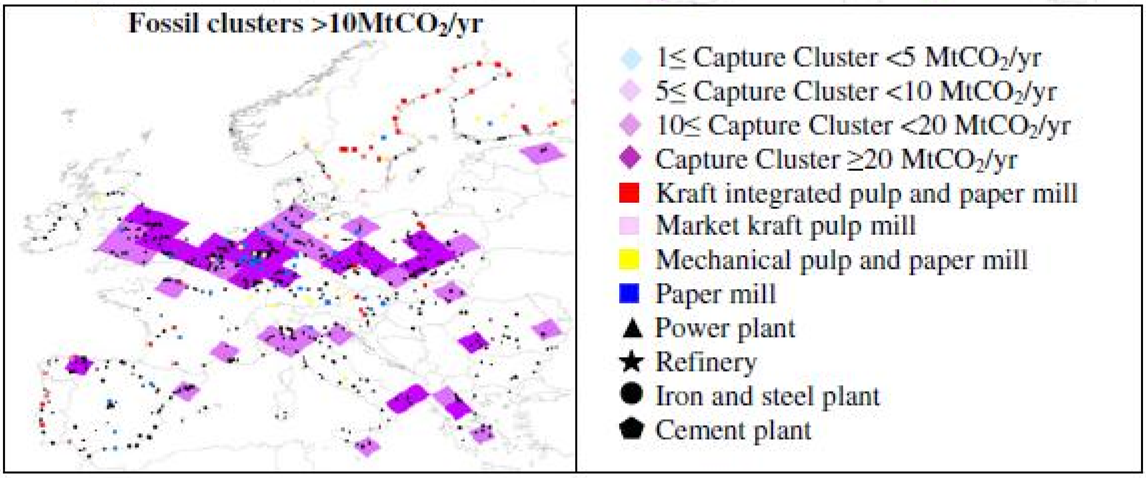

Figure 14: European example of geographical location of PPI at distance from other heavy industry (Source: Jönsson & Berntsson, 2012)

The PPI sector faces one particular challenge in implementing large-scale CCS infrastructure technology. The location of PPI plants (shown by the red markers in Figure 14) was found in the literature to be at considerable distance to other large emitters, meaning that clustering initiatives and shared pipelines would be less economical for the PPI compared to other industries.

Figure 14 shows how the majority of the European Kraft mills are not included in natural geographical 'clusters' of high emissions. Indeed, a study of carbon infrastructure in Northern Europe did not include any integration of Scandinavian PPI into its plan (Kjärstad et al., 2011) This integration challenge could inhibit efforts to promote CCS in the industry, or as in some cases in the literature (McGrail et al., 2012) this could lead to greater independence and initiation of smaller, more localised sequestration projects.

Finding the same infrastructure integration problem as discussed above, the two sources of costing data for PPI CCS found in the literature both assumed that a dedicated, single pipeline would need to be constructed from the plant to a suitable storage site.

Although no references were found in the literature that indicated CCS had been physically applied to any Kraft mill, an investigation by McGrail et al. conducted a feasibility and costing study into CCS applied to a pulp and paper mill in the US. The authors investigated the inclusion of a post-combustion amine capture unit onto the primary recovery boiler. The unit utilised energy from the biomass-fuelled generator (powered by bark and hog-fuel) which could sell excess energy back to the grid if the value of carbon credits was not attractive. Their cost findings are listed below, along with those of Möllerston et al., (2004) who found a cost based on black liquor gasification followed by amine capture using a Selexol solvent.

The two cost findings from the literature are stated below. It is interesting to note that the more recent investigation of McGrail et al. found a lower cost of carbon capture, though on a smaller proportion of emissions.

Table 7: Cost data for CCS in the pulp and paper industry

Paper	Year	Author	Technology	Emissions Reduction (%)	Cost ($/t$CO_2$)
Overcoming business model uncertainty in a carbon capture and sequestration project: Case study at the Boise White Paper Mill	2012	McGrail et al.	Amine capture of boiler flue gas	62%	15[a]
Potential and cost-effectiveness of CO_2 reductions through energy measures in Swedish pulp and paper mills	2004	Möllerston et al.	Black liquor gasification followed by selexol (solvent) capture	90%	34.46[b]

[a] The cost of \$15/tCO_2 was found for 0.5 Mt/year (62% of total CO_2 production) in a new well 11km from the mill site.
[b] CO_2 production rate of 20kgs^{-1} and transport cost of \$9/tCO_2 (or \$11.60 in 2013 USD) was assumed for pipeline transport of less than 100km and subsequent storage.

4.4 Cement

The global cement industry was found from the literature to emit 1,306 $MtCO_2$ per year (World Resource Institute, 2009), which converted to an equivalent carbon emission of 0.81 tCO_2 per tonne of cement produced (Rodriguez et al., 2009). These emissions totalled to 5% of carbon emissions from all anthropogenic sources (Lassare, 2007).

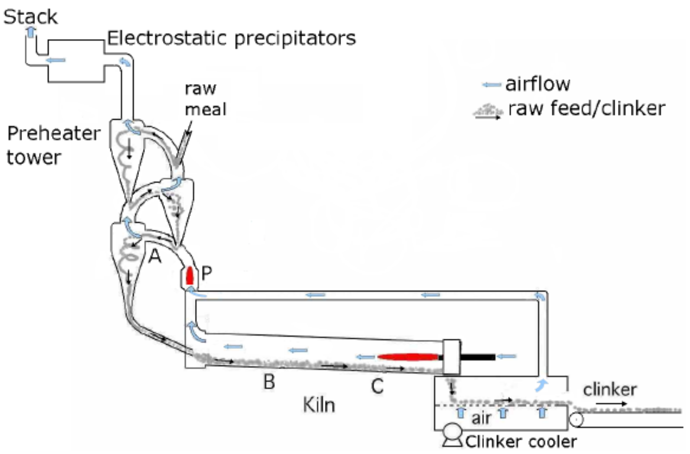

Figure 15 - Schematic of clinker production (Source: http://www.understanding-cement.com)

Figure 15 shows a schematic diagram of the production process for clinker- the process precursor to cement. As shown in the figure, raw 'meal' (usually ground limestone) is fed into the preheater and precalciner centrifuge units. As it is mixed with the hot flue gas from the kiln, the lime starts to calcine. This calcination reaction releases CO_2 which is carried to the stack by the upwards draught created in the centrifuge preheaters. 95% of the total CO_2 which is liberated from the limestone raw material is liberated in the preheaters (Barker et al. 2009). The calcined feed then enters the kiln, and is converted at high temperature to clinker. These clinkers are cooled and carried to milling processes downstream.

Cement plant emissions therefore can be attributed to two main sources: CO_2 liberated from the feedstock by the calcination reaction and CO_2 released through fossil fuel combustion for kiln heating. The general consensus found in the literature was that 60% of cement production emissions stemmed from the calcination (and hence cannot be lowered without lowering production) and the remaining 40% were attributable to heat generation for the kiln (Barker et al., 2009; Dean et al., 2011a). These two large point sources of CO_2 lend themselves well to the implementation of carbon capture technology on cement plants.

Due to the potentially disastrous physical and financial consequences of altering the chemical nature of the cement product, the cement industry was found by Fennell et al., 2012 to be naturally cautious in their approach to incorporating new technology that might in any way affect the clinker composition.

Calcium-looping technology for the cement industry was found from the literature to be being investigated in Monterrey, Mexico by CEMEX (Fennell et al., 2012). Vatopoulus & Evangelos (2012) found that for an equivalent capture efficiency of 85%, calcium looping capture was more energetically efficient than the amine solvent MEA, showing great promise for the technology's potential future applicability to the cement industry. Calcium looping on another industrial plant or a power plant could be linked to a cement plant, with the purged CaO from the looping reactor system able to be used in cement manufacture (Romeo et al, 2011) (Rodriguez et al, 2012).

Oxy-combustion utilises higher oxygen concentrations in the cement kiln to save energy that would otherwise be required to heat up nitrogen, allowing for the kiln capacity to increase as the flue-gas volume decreases. However, the practical limit of this capacity increase was found to be 23-50% (Vatopoulus & Evangelos, 2012) due to a limit on the oxygen concentration of 30-35% by volume in the kiln, to prevent damage to the kiln and formation of NO_x compounds at high temperatures.

Cost data was found to be more readily available for the cement industry than for others such as pulp & paper, and is presented in Table 8.

Table 8: Cost data for CCS in the cement industry

Paper	Year	Author	Technology	Emissions Reduction (%)	Cost ($/t$CO_2$)
Reduction of greenhouse gas emissions by integration of Cement Plants, Power Plants and CO_2 Capture Systems	2011	Romeo et al.	Oxy-combustion with calcium looping	94%	16.85
CO_2 Capture from Cement Plants Using Oxyfired Precalcination and/or Calcium Looping	2012	Rodriguez et al.	Oxy-combustion with calcium looping	84%	22.24
Comparative assessment of CO_2 capture technologies for carbon-intensive industrial processes.	2010	Kuramochi et al.	Oxy-combustion with calcium looping	60%	35
CO_2 Capture and Storage: A Key Carbon Abatement Option	2008	IEA	Oxyfuel Combustion	60%	59.46
CO_2 Capture in the Cement Industry	2009	Barker et al.	Oxy-combustion with calcium looping	52%	62
Capture of CO_2 from a Cement Plant – Technical Possibilities and Economic Estimates.	2006	Hegerland et al.	Post-combustion amine scrubbing	60%	66
Comparative assessment of CO_2 capture technologies for carbon-intensive industrial processes	2010	Kuramochi et al.	Post-combustion amine scrubbing	60%	89
CO_2 Capture in the Cement Industry	2009	Barker et al.	Post-combustion amine scrubbing	77%	170

4.5 Industry Specific Capture Technologies

There also exist specific technologies that have been developed to capture carbon dioxide that are specific to one industry or one specific unit on an industrial plant.

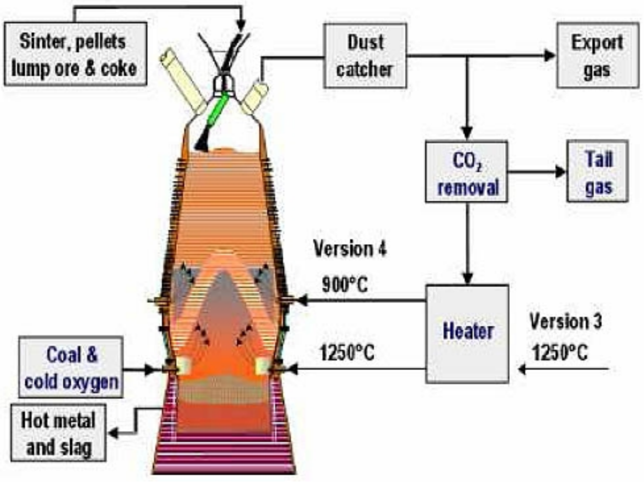

Figure 16 - Top gas recycling blast furnace (http://cdn.globalccsinstitute.com)

One example of this is the use of a top gas recycling blast furnace (Xu and Cang, 2013) for the iron & steel industry, as shown in Figure 16. The technology has been developed by ULCOS (Ultra-Low CO_2 Steelmaking), a consortium of 48 EU companies that operate a joint research network into decarbonisation of the steel industry. The top gas recycling blast furnace operates by capturing the top gas off a furnace, which then passes through a post combustion capture unit. The remaining gas is then recycled into the base of the furnace (Birat et al., 2003). The furnace operates in oxygen instead of with air, and this, combined with the recycling of hot gas, means that even without the carbon capture, this process is more energy efficient, and the cost savings of this can help offset the cost of the post combustion capture. This has such large potential as the technology is fairly well established, can be easily and cheaply retrofitted, and a pilot project in Luleå on a large scale laboratory furnace has proved successful (ULCOS, 2008).

5 Summary of Costs from Literature

In order to best review the costs provided by the literature, the cost data found for each of the four major industries was gathered and presented as below in Figure 17. The individual costs found for each sector in the literature were averaged, and inputted into the figure below. See Appendix 4 for the tabulated costs.

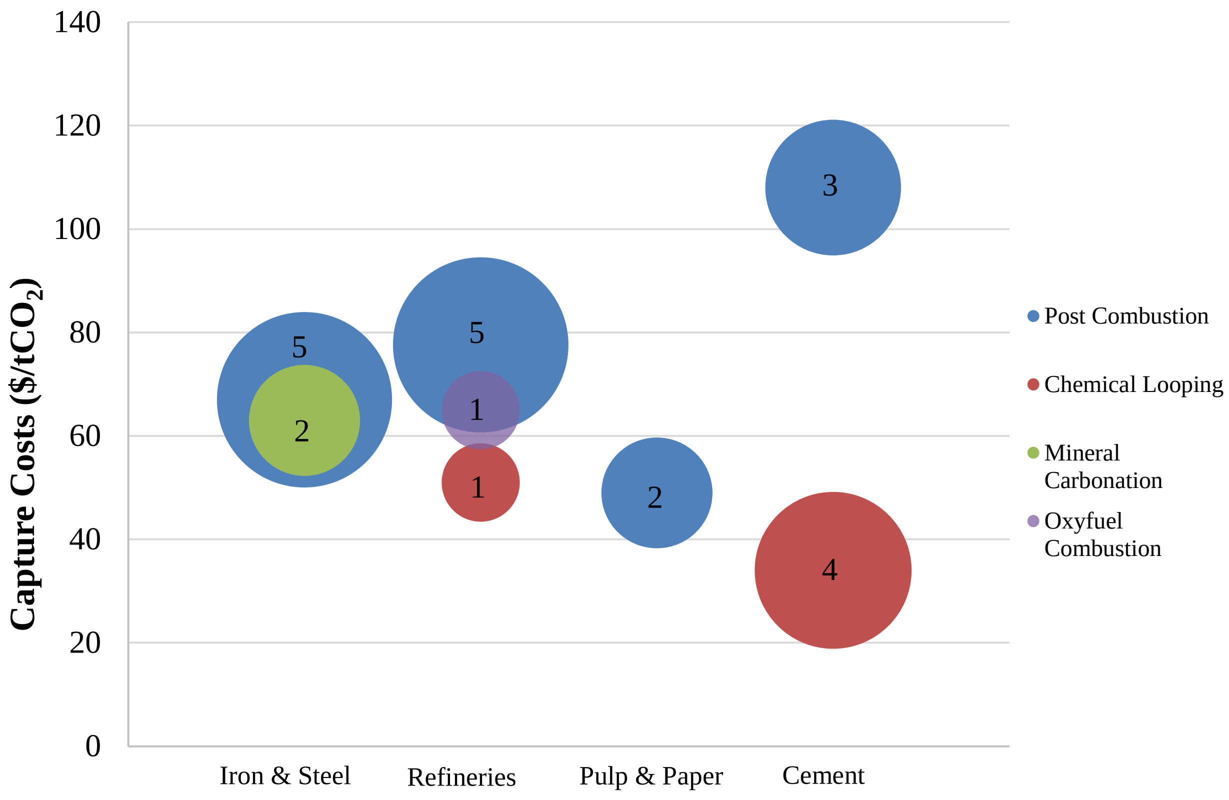

Figure 17: Bubble-chart showing average technology costs per industry from the literature

It is interesting to note that costs for carbon capture in the iron & steel and refineries sectors are very similar for post combustion capture, falling between $60 and $80 per tonne of CO_2 avoided. Economic data for both of these sectors was also relatively abundant, allowing for reasonably valid costs of technology to be found post combustion technology applied to the pulp and paper industry was found to be relatively inexpensive. Only two sources of cost data for CCS applied to the pulp and paper industry were found in the literature (McGrail et al., 2012; Möllerston et al., 2004), but these seemed to show that relatively low-cost, post combustion capture could be applied to the boiler. The most striking economic comparison of technologies was found in amine scrubbing technology compared to calcium looping technology in the cement industry. This was found by both sources that compared the two technologies (Barker et al., 2009; Kuramochi et al., 2010) and found calcium looping technology to be the most cost effective, with post combustion capture being about three times as expensive. It is important to note that the figure above and the costs given here do not take into account the quantity of emissions that can be captured at this cost. Recent comparative work by Ozcan has demonstrated that the differences between oxyfired kiln operation and calcium looping post-combustion CO_2 capture are small in terms of the cost, but that both are significantly better than amine scrubbing (Ozcan, 2014).

6 Conclusions

This systematic review was carried out with the aims of gathering, summarizing and analysing sufficient literature on the technologies, costs and policies on industrial carbon capture in order to give an informed and balanced view on the sector. With binding targets for a deep cut in emissions across all sectors of 60% by 2050 (HM Government, 2003), it is important that all sectors devise ways in which they can meet these emissions reduction targets. The industrial sector, which emits 110 Mt of carbon dioxide per year out of the total of 570 Mt in the UK, is responsible for almost a fifth of all emissions (DECC, 2013). The only technology that will allow these targets to be met, without necessitating a complete overhaul of industrial processes, is carbon capture and storage. Although mostly focused on the power generation industry, there is a significant quantity of research into the implementation of carbon capture onto industrial processes. By considering four major industrial sectors, namely the iron and steel industry, the cement industry, the pulp and paper industry and the refining and chemicals industry, this report covers sectors that account for a majority of industrial emissions. For the purpose of this report, only large industrial plants (defined as emitting over 0.1 $MtCO_2$ per annum) were considered due to the economics of implementing CCS onto small plants being unfavourable, considering the small potential for emissions mitigation.

The systematic search process initially yielded 14,337 results from four different databases, which were reduced to 541 by systematic refining of the search terms. The abstracts of these papers were screened for relevance, and 250 papers were carried forward for further review. These 250 papers were fully read and reviewed, with 71 of these designated with a ‘high’ priority rating. Throughout the review process, several other papers were added by the authors to enhance the quality of the reviewed literature. It was found that Europe contributed 130 of these papers, of which 40 were ‘high’ priority, showing a high output of quality carbon capture-focussed literature from the region. Of the four sectors investigated, cement and iron & steel were the best researched, accounting for 24 and 29 industry-specific papers respectively. Pulp & paper and the refineries industries were found to have far less specific literature on carbon capture available, and of the 250 papers reviewed a total of only 13 papers focussed on these industries.

The current characteristics of representative plants were found from the literature for the four sectors of interest, with discussions on the feasibility of applying CCS to each of the industries, identifying the main obstacles that must be overcome to be able to offer significant reduction in emissions. Due to the large number of point sources, a large reduction in emissions from iron and steel plants, and refineries and chemical plants, is difficult and expensive. On account of having fewer CO_2 rich streams, capture from cement plants and pulp and paper mills would allow a greater proportion of emissions to be captured with reduced process complexity when compared to the other industries.

A quantitative comparison of costs was undertaken on application of the key carbon capture technologies to the four industry sectors, and found conclusively that post-combustion amine scrubbing was the best-researched, the literature returning evidence of its application in all sectors. However, it was also found to be the most expensive technology for each sector, with costs (appropriately adjusted and averaged) ranging from \$49/tCO_2 in the pulp and paper industry to \$108/tCO_2 in the cement industry. Calcium looping was observed to be a promising technology, with the cost findings of literature sources pricing the technology at only \$48/tCO_2 in the cement sector. There is potential for it to be used in an integrated system, where CO_2 can be captured from an industrial plant, with purged CaO used in the cement manufacturing process. A nickel based chemical looping system was proposed for refineries (Melien and Roijen, 2009). No conclusive economic findings could be drawn on mineral carbonation, with two literature references for mineral carbonation in iron & steel ranging from \$10/tCO_2 (Stolaroff et al., 2005) to \$115/tCO_2 (Huijgen, 2007), showing most noticeably a lack of consistent approach to analysis and pricing.

7 References

Arasto, A., Tsupari E. et al. (2013a) Costs and Potential of Carbon Capture and Storage at an Integrated Steel Mill *Energy Procedia* Vol. 37, 7117-7124

Arasto, A , Tsupari, E. et al. (2013b) Post-combustion capture of CO_2 at an integrated steel mill – Part I: Technical concept analysis, *International Journal of Greenhouse Gas Control* Vol. 16, 271-277.

Barker, D.J., Turner, S.A. et al. (2009) CO_2 Capture in the Cement Industry. *Energy Procedia* Vol. 1, 87-94.

Birat, J.P., Hanrot, F. et al. (2003) CO_2 mitigation technologies in the steel industry: a benchmarking study based on process calculations, *3rd International Conference on Science and Technology of Ironmaking* [Online] Available at: http://ulcos.org/en/docs/Ref12%20-%20Birat_Sonderdruck.pdf [Accessed: 30th Oct. 2014]

Birat J.P. (2009) Steel and CO_2 – the ULCOS Program, CCS and Mineral Carbonation using Steelmaking Slag, *ULCOS* [Online] Available at: http://www.ulcos.org/en/docs/Ref01__Birat_slag_finaal.pdf [Accessed: 30th Oct. 2014]

Boot-Handford et al., (2014). Carbon capture and storage update. *Energy & Environmental Science,* Vol. 7, 130-189.

British Geological Survey (2006). Industrial Carbon Dioxide Emissions and Carbon Dioxide Storage Potential in the UK [Online] Available at: http://decarboni.se/publications/industrial-carbon-dioxide-emissions-and-carbon-dioxide-storage-potential-uk/2-industrial-sources-co2-emissions-uk [Accessed: 21st Oct. 2014]

Brown, T., Gambhir, A. et al. (2012) Reducing CO_2 emissions from heavy industry: a review of technologies and considerations for policy makers *Grantham Institute for Climate Change* [Online] Briefing Paper No.7 Available at: https://workspace.imperial.ac.uk/climatechange/Public/pdfs/Briefing%20Papers/Reducing%20CO2%20emissions%20from%20heavy%20industry_Briefing%20Paper%207.pdf, [Accessed: 29th Oct. 2014]

CEPCI (2011) List of CEPCI indices to 2011 [Online] Available at: http://www.nt.ntnu.no/users//magnehi/cepci_2011_py.pdf [Accessed: 21st Oct. 2014]

CheResources, (2012) CEPCI 2012 Reference. [Online] Available at: http://www.cheresources.com/invision/topic/14583-chemical-engineering-plant-cost-index-cepci-2012/ [Accessed: 21st Oct. 2014]

Dean C.C., Blamey J. et al. (2011a) The calcium looping cycle for CO_2 capture from power generation, cement manufacture and hydrogen production. *Chemical Engineering Research and Design*. Vol. 89, 836-855.

Department for Energy and Climate Change (2013*)* UK Greenhouse Gas Emissions, Provisional Figures and 2012 UK Greenhouse Gas Emissions, Final figures by End Type and User [Online] Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/295968/20140327_2013_UK_Greenhouse_Gas_Emissions_Provisional_Figures.pdf [Accessed: 30th Oct. 2014]

UK Department for Trade and Industry (2003). Our Energy Future - creating a Low Carbon Economy [Online] http://webarchive.nationalarchives.gov.uk/+/http:/www.dti.gov.uk/files/file10719.pdf [Accessed: 22nd Oct. 2014]

Doctor, R., Palmer, A. et al, (2005) Transport of CO_2 *IPCC Special Report on Carbon dioxide Capture and Storage*, [Online] Ch. 4, 181-192, Available at: www.ipcc.ch/pdf/special-reports/srccs/srccs_chapter4.pdf [Accessed: 21st Oct. 2014]

European Commission (2011) Roadmap for moving to a competitive low carbon economy [Online] Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0112:FIN:EN:PDF [Accessed: 12th Oct 2014]

Farla, J.C.M, Hendriks, C.A. et al., (1995), Carbon dioxide recovery from industrial processes *Climatic Change* Vol. 29, Issue 4, 439-461.

Fennell, P.S., Florin, N. (2012) CCS from Industrial Sources, *Sustainable Technologies, Systems and Policies.* [Online] Carbon Capture and Storage Workshop: 17. Available at: http://www.qscience.com/doi/pdf/10.5339/stsp.2012.ccs.17@cop18.2012.2012.issue-1 [Accessed: 25th Oct. 2014]

Gazzani, M., Romano, M., et al. (2013) Application of Sorption Enhanced Water Gas Shift for Carbon Capture in Integrated Steelworks, *Energy Procedia* Vol. 37, 7125-7133.

Gielen, D. (2003) CO_2 removal in the iron and steel industry, *Energy Conversion and Management* Vol. 44, 1027-1037.

Global CCS Institute (2013) Large-Scale Integrated CCS Projects [Online] Available at: http://www.globalccsinstitute.com/projects/browse [Accessed: 19th Oct. 2014]

Hegerland, G., Pande, J.O. et al. (2006). Capture of CO2 from a Cement Plant – Technical Possibilities and Economic Estimates, *8th International Conference on Greenhouse Gas Control Technologies* [Accessed 22nd Oct. 2014]

Ho, M.T., Allinson, G.W. et al. (2011) Comparison of MEA capture cost for low CO_2 emissions sources in Australia, *International Journal for Greenhouse Gas Control* Vol.5, 49-60.

Huijgen, W. J. J., Comans, R. N. J. et al. (2007) Cost evaluation of CO_2 sequestration by aqueous mineral carbonation *Energy Conversion and Management* Vol 48, 1923-1935.

IEA (2008) CO_2 Capture and Storage: A Key Carbon Abatement Option [Online] Available at: http://www.iea.org/publications/freepublications/publication/CCS_2008.pdf [Accessed 29th Oct. 2014]

International Monetary Fund, (2014) Exchange Rate Tool. [Online] Available at: http://www.imf.org/external/np/fin/ert/GUI/Pages/CountryDataBase.aspx [Accessed: 30th Oct. 2014]

IPCC, (2013): Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley(eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp

IPCC, (2014): Climate Change 2014, Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA]

Jönsson, J. and Berntsson, T. (2012) Analysing the potential for implementation of CCS within the European pulp and paper industry. *Energy* Vol. 44, 641-648.

Kjärstad, J., Ramdani, R. et al (2011) Establishing an integrated CCS transport infrastructure in northern Europe - challenges and possibilities. *Energy Procedia*, Vol. 4, 2417-2424.

Kuramochi, T., Ramirez, A et al., (2010) Comparative assessment of CO_2 capture technologies for carbon-intensive industrial processes. Progress in Energy and Combustion Science. Vol. 38, 87-112.

Li, J., Tharakan, P, (2013) Technological, economic and financial prospects of carbon dioxide capture in the cement industry *Energy Policy* Vol. 61, 1377-1387.

McGrail, B.P., Freeman, C.J. et al (2012) Overcoming business model uncertainty in a carbon capture and sequestration project: Case study at the Boise White Paper Mill*. International Journal of Greenhouse Gas Control* Vol. 9, 91-102.

Melien, T. and Roijen, S.B, (2009) Carbon Dioxide Capture for Storage in Deep Geological Formation, *Economics* Vol. 3, 237-264.

Melien, T., (2005) Economic and cost analysis for CO_2 capture costs in the CO_2 capture project scenarios. In: Thomas, D.C., Benson, S.M. (Eds.), Carbon Dioxide Capture for Storage in Deep Geologic Formations *Results from the CO_2 Capture Project - Capture and Separation of Carbon Dioxide from Combustion Sources*, *Elsevier* Vol. 1, 44 (Chapter 3)

Möllerston, K., et al. (2003) Potential and cost-effectiveness of CO_2 reductions through energy measures in Swedish pulp and paper mills, *Energy* Vol. 28 691-710.

Möllerston, K., Gao, L., Yan, J. & Obersteiner, M. (2004) Efficient energy systems with CO_2 capture and storage from renewable biomass in pulp and paper mills. *Renewable Energy*, Vol. 29, 1583-1598.

Okereke, C., McDaniels, D (2012) To what extent are EU steel companies susceptible to competitive loss due to climate policy? *Energy Policy*, Vol. 46, 203-215.

OPEC (2012) World Oil Outlook [Online] Available at: http://www.opec.org/opec_web/static_files_project/media/downloads/publications/WOO2012.pdf [Accessed: 28th Oct. 2013]

Ozcan, D. (2014) Techno-economic Study of the Calcium Looping Process for CO_2 capture from Cement and Biomass Power Plants

Pan, S.Y., Chang, E.E. et al. (2012) CO_2 Capture by Accelerated Carbonation of Alkaline Wastes: A Review on Its Principles and Applications, *Aerosol and Air Quality Research* Vol. 12, 770-791.

Pettersson, K & Harvey, S. (2011) Comparison of black liquor gasification with other pulping biorefinery concepts - Systems analysis of economic performance and CO_2 emissions, *Energy* Vol. 37, 136-153.

Rai, V. & Victor, D. et al. (2010) Carbon capture and storage at scale: Lessons from the growth of analogous energy technologies, *Energy Policy* Vol. 8, 4089-4098.

Romeo, L.M., et al. (2011) Reduction of greenhouse gas emissions by integration of Cement Plants, Power Plants and CO_2 Capture Systems. Greenhouse Gases Science and Technology, Vol. 1, 72-82.

Rodriguez, N., Murillo, R. and Abanades Garcia J.C. (2012), CO_2 Capture from Cement Plants Using Oxyfired Precalcination and/or Calcium Looping,. Environ. Sci. Technol. Vol. 46, 2460−2466.

Rodriguez, N., Alonso, M. et al. (2009) Analysis of a process to capture the CO_2 resulting from the pre-calcination of the limestone feed to a cement plant. *Energy Procedia*. Vol. 1, 141-148.

Said, A., Mattila, H.P. et al. (2013) Production of precipitated calcium carbonate (PCC) from steelmaking slag for fixation of CO_2 *Applied Energy* Vol. 112, 765-771.

Stolaroff, J.K., Lowry, G.V. et al. (2005) Using CaO- and MgO-rich industrial waste streams for carbon sequestration *Energy Conversion and Management* Vol. 46, 687-699.

True, W.R. and Koottungal, L. (2009) Special Report: Global refining capacity advances; US industry faces uncertain future *Oil and Gas Journal* [Online] Vol.107, Issue 47.

Tsupari, E., Kärki,J. et al. (2013) Post-combustion capture of CO_2 at an integrated steel mill – Part II: Economic feasibility *International Journal of Greenhouse Gas Control* Vol. 16, 278-286.

ULCOS (2013) ULCOS Overview [Online] Available at: http://www.ulcos.org/en/about_ulcos/home.php [Accessed: 29th Oct. 2014]

United Nations Industrial Development Organisation (2010), Carbon Capture and Storage in Industrial Applications: Technology Synthesis Report [Online] Available at: http://www.unido.org/fileadmin/user_media/Services/Energy_and_Climate_Change/Energy_Efficiency/CCS_%20industry_%20synthesis_final.pdf, [Accessed 25th Oct. 2014]

United Nations (1998) Kyoto Protocol to the United Nations Framework Convention on Climate Change [Online] Available at: http://unfccc.int/resource/docs/convkp/kpeng.pdf [Accessed: 27th Oct. 2014]

Van der Stel, J. (2008) Developments and evaluation of the ULCOS Blast furnace process at LKAB Experimental BF in Luleå *ULCOS Scrap Substitutes and Alternative Ironmaking V* [Online] Available at: http://www.ulcos.org/en/docs/Ref25%20-%20ULCOSpublic.pdf [Accessed: 26th Oct. 2014]

Van Straelen, J., Geuzebroek, F. et al. (2010) CO_2 capture for refineries, a practical approach *International Journal for Greenhouse Gas Control* [Online] Vol. 2, 316-320.

Vatopoulus, K. & Evangelos, T. (2012) Assessment of CO_2 capture technologies in cement manufacturing process, *Journal of Cleaner Production* Vol. 32, 251-261.

Wiley, D.E., Ho, M.T. et al. (2011) Assessment of Opportunities for CO_2 Capture at Iron and Steel Mills: An Australian Perspective *Energy Procedia* Vol. 4, 2654-2661.

World Resources Institute. (2009) World Greenhouse Gas Emissions in 2005, [Online] Available at: http://www.wri.org/publication/world-greenhouse-gas-emissions-2005 [Accessed 30th Oct. 2014]

World Steel Association (2013) World Crude Steel Production, a Summary [Online] Available at: http://www.worldsteel.org/dms/internetDocumentList/press-release-downloads/2012/2012-statistics-table/document/2012%20statistics%20table.pdf [Accessed: 23rd Oct. 2014]

Xu, C. and Cang, D.Q. (2010) A Brief Overview of Low CO_2 Emission Technologies for Iron and Steel Making *Journal of Iron and Steel Research International* Vol. 17, 1-7.

8 Appendices

8.1 Appendix 1 - Search Terms and Numbers of Hits

Table A1: Initial search terms

Ref. No.	Search Term
1.	"Industrial" AND "Carbon Capture and Storage" OR "Carbon Capture and Sequestration"
2.	"Cement" AND "Carbon Capture and Storage" OR "Carbon Capture and Sequestration"
3.	"Chemicals manufacturing" AND "Carbon Capture and Storage" OR "Carbon Capture and Sequestration"
4.	"Iron Ore" AND "Carbon Capture and Storage" OR "Carbon Capture and Sequestration"
5.	"Smelting" AND "Carbon Capture and Storage" OR "Carbon Capture and Sequestration"
6.	"Refineries" AND "Carbon Capture and Storage" OR "Carbon Capture and Sequestration"
7.	"Industrial" AND "Policy" AND "Carbon Capture and Storage" OR "Carbon Capture and Sequestration"
8.	"Pulp and Paper" AND "Carbon Capture and Storage" OR "Carbon Capture and Sequestration"
9.	"Steel production" AND "Carbon Capture and Storage" OR "Carbon Capture and Sequestration"
10.	"Bulk metals" AND "Carbon Capture and Storage" OR "Carbon Capture and Sequestration"
11.	"Fine metals" AND "Carbon Capture and Storage" OR "Carbon Capture and Sequestration"
12.	"Steelworks" AND "Carbon Capture and Storage" OR "Carbon Capture and Sequestration"
13.	"Ironworks" AND "Carbon Capture and Storage" OR "Carbon Capture and Sequestration"
14.	"Foundry" AND "Carbon Capture and Storage" OR "Carbon Capture and Sequestration"
15.	"Industrial" AND "Cost" AND "Carbon Capture and Storage" OR "Carbon Capture and Sequestration"
16.	"Food and drink" AND "Carbon Capture and Storage" OR "Carbon Capture and Sequestration"
17.	"Industrial" AND "Economics" AND "Carbon Capture and Storage" OR "Carbon Capture and Sequestration"
18.	"Fine chemicals" AND "Carbon Capture and Storage" OR "Carbon Capture and Sequestration"

Table A2: Hits returned from initial search terms

Ref. No.	Number of Returned Articles			
	Science Direct	**Royal Society of Chemistry**	**EBSCO**	**Web of Science**
1.	2,899	147	1,300	173
2.	829	44	67	39
3.	21	6	261	0
4.	105	4	10	1
5.	66	0	1	2
6.	675	34	114	10
7.	1,879	60	243	26
8.	200	14	12	5
9.	155	17	3	1
10.	9	0	0	0
11.	2	0	0	0
12.	24	2	2	0
13.	5	1	0	0
14.	21	2	0	0
15.	2,489	125	263	44
16.	6	3	0	0
17.	1,501	44	294	6
18.	25	7	2	0
Total	**10,942**	**515**	**2,573**	**307**

Table A3: Refined search terms

Ref. No.	Search Term
19.	("cement production" OR "cement works") AND "Cost" AND "Carbon Capture" AND EXCLUDE(topics, "co2 emission, energy system") AND LIMIT-TO(topics, "co2 capture, ghg emission, carbon capture, cement industry, cement plant")
20.	"Petroleum refining" AND "refineries" AND "cost" AND "Carbon Capture" AND EXCLUDE(topics, "co2 emission, energy procedia, hydrogen production, fuel cell, renewable energy, hydrogen, oxygen carrier, life cycle, energy security") AND EXCLUDE(topics, "natural gas") AND EXCLUDE(contenttype, "2,3,4,5",",Book") AND EXCLUDE(topics, "injection project, kingdom, mixed alcohol")
21.	"Industrial" AND (("National Policy" OR "National Legislation")OR ("International Policy" OR "international Legislation")) AND "Cost" AND "Carbon Capture" AND NOT "wind farm" AND NOT "Solar" AND NOT "Photovoltaic" AND EXCLUDE(topics, "renewable energy, nuclear power") AND EXCLUDE(topics, "power plant, electricity generation") AND EXCLUDE(topics, "radiative forcing") AND EXCLUDE(topics, "fuel cell, natural gas") AND EXCLUDE(contenttype, "2,3,4,5",",Book") AND EXCLUDE(cids, "271486","Fuel and Energy Abstracts") AND EXCLUDE(topics, "marine energy, mercury emission, minh city, mixed conducting")
22.	("minerals processing" OR "rare earth metals processing") AND "Carbon capture" AND "Cost" AND NOT "Steel production" AND NOT "Iron ore extraction" AND NOT "Iron Ore processing" AND NOT "Aluminium Processing" AND NOT "Aluminium smelting" AND NOT "Aluminium extraction" AND NOT "Copper mining" AND NOT "Bulk metals" AND EXCLUDE(topics, "renewable energy, nuclear power, energy system") AND EXCLUDE(topics, "goldschmidt abstract")
23.	("iron production" OR "iron refining" OR "ironworks") AND "Carbon Capture" AND NOT "hydrogen production" AND ("cost" OR "economics")
24.	("Steel production" OR "steel refining" OR "steelworks") AND "Carbon Capture" AND ("cost" OR "economics") AND NOT "hydrogen production" AND NOT "mineralisation" AND EXCLUDE(topics, "china, mineral carbonation, India, developing country, minlp model") AND EXCLUDE(contenttype, "2,3,4,5",",Book")
25.	("Smelting" OR "foundry") AND "carbon capture" AND ("cost" OR "economics") AND NOT "hydrogen production" AND EXCLUDE(contenttype, "2,3,4,5",",Book") AND EXCLUDE(cids, "271486,271472","Fuel and Energy Abstracts, International Journal of Hydrogen Energy") AND EXCLUDE(topics, "china, goldschmidt abstract, wind power, bauxite residue, jiangsu province") AND EXCLUDE(topics, "liaoning province, MacArthur river, mercury emission, mineral carbonation")
26.	"food and drink" AND "carbon capture" AND ("cost" OR "economics") AND EXCLUDE(contenttype, "2,3,4,5",",Book")
27.	("paper manufacturing" OR "paper production") AND "carbon capture" AND ("cost" OR "economics") AND EXCLUDE(contenttype, "2,3,4,5",",Book") AND EXCLUDE(topics, "china, black liquor, brazil, fuel cell") AND EXCLUDE(cids, "271486","Fuel and Energy Abstracts")

Table A4: Hits returned from refined search terms

Ref. No.	Science Direct	Web of Science	EBSCO	Royal Society of Chemistry
19.	49	7	4	18
20.	34	6	65	25
21.	90	5	28	41
22.	38	9	5	3
23.	29	9	3	5
24.	93	42	3	0
25.	57	0	1	0
26.	7	29	14	0
27.	39	1	1	7
Total:	**436**	**108**	**124**	**99**

8.2 Appendix 2 - Questionnaire

Table A5: Tabulated questionnaire as applied to reviewed literature

Literature Questionnaire		
Topic	No.	Question
Paper	1.	Author
	2.	Title
Scope	3.	Primary Focus
	4.	Secondary
	5.	Specifically CCS?
	6.	Does the paper focus on Industrial or Power CCS?
	7.	Which sector is the paper relevant to?
	8.	Is the paper theoretical or experimental?
	9.	Specific to one geographical location?
Technology	10.	Relevant to Industrial CCS?
	11.	Does the paper focus on one tech or many?
	12.	Does the paper focus on carbon capture or storage?
	13.	Specific to one case or all?
	14.	Does the paper involve figures or calculations?
	15.	Technological Summary
Policy	16.	Is the paper general or specific?
	17.	Does the paper consider current policy or recommendations?
	18.	Are multiple or one policies mentioned?
	19.	Policy Summary
Costs	20.	Are costs mentioned?
	21.	Units of cost?
	22.	Capital or operational?
	23.	Economic Summary
Quality	24.	Publication Type
	25.	Publication Name
	26.	Is the paper peer reviewed?
	27.	No. of citations
	28.	Is the paper reliable or not (experiments etc.)?
	29.	Is the paper original research or an overview?
Ancillaries	30.	Date of Publication
	31.	Location of Publication
Relevance	32.	What level of relevance is the paper?
	33.	Why is the paper relevant to our study

8.3 Appendix 3 – Risk Analysis and Mitigation

Three key causes of risk to the systematic process were identified that could lead to inconsistency in the review process. Their consequences were assessed qualitatively, and prevention and mitigation steps were taken against them. A bowtie risk analysis model was built around the key hazard event of 'Papers are reviewed inconsistently', and is showed below in Figure A1.

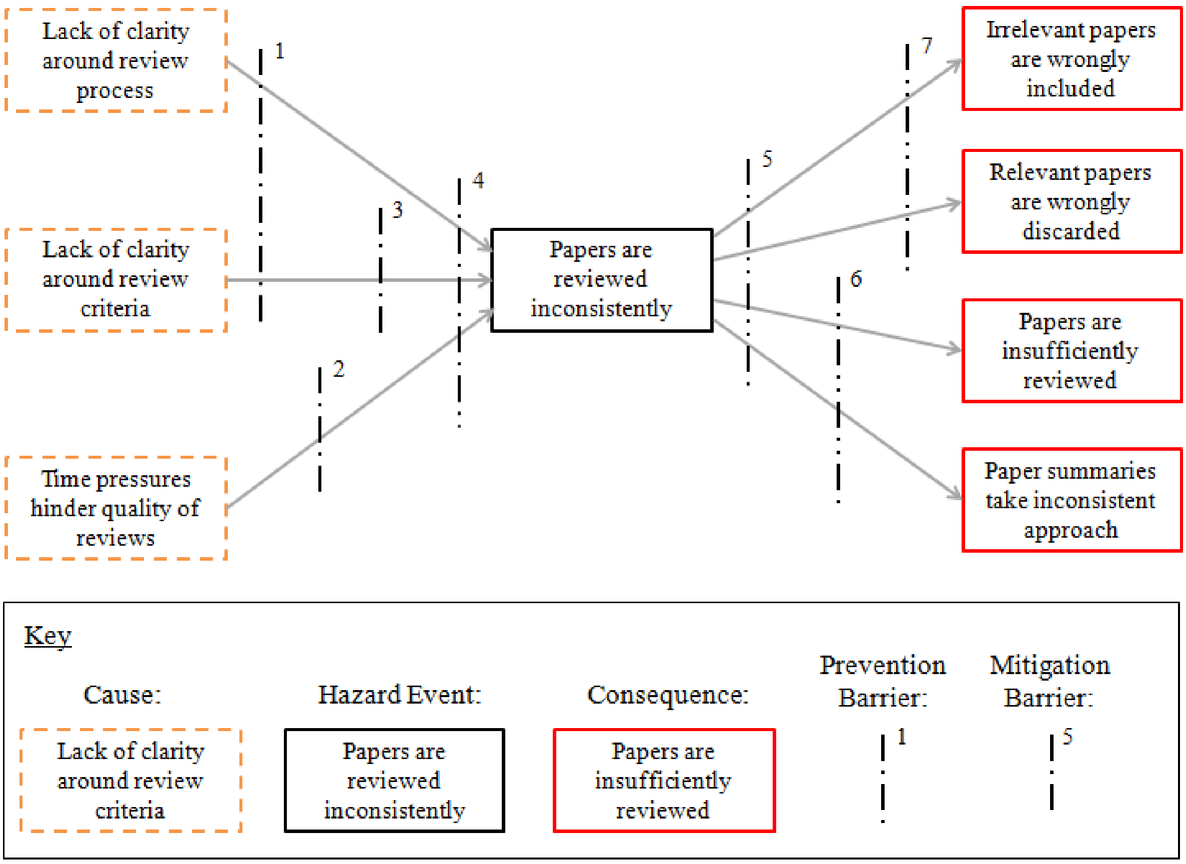

Figure A1: Bowtie risk analysis of review process

The bowtie shows how three key causes (lack of clarity of process, lack of clarity of criteria and time pressure) could lead to papers being reviewed inconsistently. In turn, inconsistent reviewing of papers could lead to papers being misallocated in terms of their relevance, and incorrectly discarded or included in later reviews. Further, it could also lead to literature being insufficiently summarized, or to the summaries being made in inconsistent manner with regard to their focus. The realisation of any of these consequences was regarded as unacceptable to the systematic nature of the review. Preventing these scenarios was of paramount importance due to the necessity of conducting the entire review again in the event of inconsistency in order to ensure the validity of the study.

Hence, in order to minimise the chances of such events occurring, prevention and mitigation barriers were constructed as shown in Figure A1, and are described in Table A6.

Table A6: Prevention and mitigation barriers for bowtie risk model

Prevention Barrier No.	Name	Description
1	Questionnaire	A structured questionnaire was built and agreed on in order to ensure that, *at the very least*, the minimum information required to be reviewed on each paper was read and recorded (See Appendix 2).
2	Work Plan	A work plan was constructed to provide feasible, traceable progress targets to ensure that sufficient time was allowed for each paper review.
3	Relevance Definition	Relevance criteria were discussed, decided on and defined in Boolean logic to ensure that as highly consistent a result as could be achieved between both reviewers.
4	Progress Reports	During the review process, regular progress reports were made between reviewers, at minimum every two days to clarify any points of confusion.
Mitigation Barrier No.	**Name**	**Description**
5	Meetings	Regular weekly meeting scheduled between reviewers, in which summaries of the week's reviews were shared, and any ambiguities were discussed.
6	Summary Cross-checks	The summaries of each reviewer were read by the other, and any discrepancies in the length, detail or focus of these summaries was discussed, with corrective action taken where necessary.
7	Prioritisation check	In order to ensure that suitable number of high, medium or low prioritisation ratings had been assigned to reviewed papers, and that a consistent approach had been taken, paper summaries were cross-checked with priority ratings.

8.4 Appendix 4 - Cost Data

Table A7: Averaged costs of CCS technologies applied across the industries

Industry	Post Combustion (Amine)		Chemical Looping		Mineral Carbonation		Oxyfuel Combustion	
	Cost	No.	Cost	No.	Cost	No.	Cost	No.
Iron & Steel	67.27	5	n/a	0	62.5	2	n/a	0
Refineries	77.60	5	51	1	n/a	0	65	1
Pulp & Paper	49.46	2	n/a	0	n/a	0	n/a	0
Cement	108.33	3	34	4	n/a	0	n/a	0

8.5 Appendix 5 - Full Paper List

Authors	Title	Relevance	Summary
Adams and Barton	High-efficiency power production from natural gas with carbon capture	L	The paper proposes a plan for a high efficiency power generating plant from natural gas with CCS, however it has no direct relevance to industrial CCS.
Adeyemo et al.	Capture of carbon dioxide from flue or fuel gas mixtures by clathrate crystallization in a silica gel column	M	The paper discusses the use of hydrate formation to separate flue gases (CO_2/N_2) and fuel gas (CO_2/H_2), which can be achieved at 98.8% for a 3 stage process for flue gas. Fuel gas could only reach 92% purity of CO_2 in the crystals, so may be less suitable than for flue gas. It is noted that the process could be as efficient from a CSTR as the gel column.
Akashi et al.	A projection for global CO2 emissions from the industrial sector through 2030 based on activity level and technology changes	L	This paper explores the increase in industrial CO_2 emissions that can be expected from now until 2030, with the findings that from just steel and cement, emissions will rise by about 15Gt CO_2 compared to 2005 if the same technology is used. By implementing savings at a cost of $100 per tonne CO_2, large savings can be made, especially in India and China which have two thirds of global reduction potential. Without larger savings, there will be insufficient potential to reduce emissions by enough to keep them at 2005 levels, never mind making emissions cuts.
Akashi et al.	GHG emission scenarios in Asia and the world: The key technologies for significant reduction	L	Useful projected energy source consumption patterns dependent on future cost of CO_2 emissions. Using model to provide useful projected world energy source consumption patterns dependent on future cost of CO_2 emissions.
Akimoto et al.	Economic evaluation of the geological storage of CO_2 considering the scale of economy	L	The paper discusses the economic impact of carbon storage in Japan, but nothing relating to capture. The paper discusses the best way to get carbon storage used in Japan, with a tech push and a demand pull to meet halfway. Too focussed on storage.
Akimoto et al.	Estimates of GHG emission reduction potential by country, sector, and cost	M	Considers policy recommendations for various countries based on the implementation potential in those countries. Looks at the required carbon price in each considered country for CCS to be viable. Good assessment of emission reduction potential and mitigation around the world.
Anton Ming-Zhi Gao	The Application of the European SEA Directive to Carbon Capture and Storage Activities: the Issue of Screening	L	Looks at SEA Directive on Carbon Capture and models likely response. A look at how CCS might develop in response to the 2008 introduction of the SEA Directive on CCS.
Arasto et al.	Costs and Potential of Carbon Capture and Storage at an Integrated Steel Mill	H	This paper compares the use of either a post combustion capture process or an oxygen blast furnace for reducing the CO_2 emissions from a steel mill. The O_2 furnace is still in research phase, so unfeasible to use for some time. The post combustion capture costs are from 46-90€/tCO_2, so carbon credits would need to be at this value to have any chance of being economical. Although the potential for the O_2 furnace is cheaper, it would have an effect on the steel production and is more sensitive to electricity prices etc, so

			post combustion capture is preferable. This paper discusses the costs and cost effectiveness of using post combustion capture on a steel mill with different solvents, including 30% MEA. For costs below 120€/MWh of electricity, using the oxygen blast furnace gives a lower break-even price than using MEA, but if above, MEA is more economically viable. The paper gives figure on the break even points of using MEA capture and an O_2 furnace at a steel mill, which can be used to provide evidence of the economic viability of different methods of CCS on steel plants.
Arasto et al.	Post-combustion capture of CO2 at an integrated steel mill – Part I: Technical concept analysis	H	This paper assesses the viability of using post combustion CCS by MEA at a 4Mt/yr steel mill in Finland, which is tech that is available for use now. The total CO_2 emission reduction is 50-75% in the most economically and technically feasible case, amounting to 2-3MtCO_2/yr (large number of small stacks so would need many small capture units unless massive refit of plant) The use of other carbon reducing options, such as a bio char, are discussed and discounted as being unavailable for large scale deployment, with a low mitigation potential compared to CCS. Good case study of CO_2 capture plant on a large steel mill, with no costs but technical considerations taken into account.
Armitage et al.	Diagenetic and sedimentary controls on porosity in Lower Carboniferous fine-grained lithologies, Krechba field, Algeria: A petrological study of a caprock to a carbon capture site	L	The paper discusses the classification of different rocks for carbon storage. Discusses geology of storage only.
Assabumrungrat et al.	Energy Efficiency Evaluation for a "green" Power Generation Process with Minimum Effort on Carbon Dioxide Capture and Storage	H	Considers pre-combustion capture of CO2 by cracking liquid fuels to syngas and carbon. A technical investigation of cracking process to remove carbon from hydrocarbon fuels prior to combustion, producing hydrogen-rich syngas.
Ayong Le Kama et al.	Optimal Carbon Capture and Storage Policies	L	The paper assesses how to optimise the CCS policy in a deterministic world, showing that CCS is a viable source so long as the price of fossil fuel extraction remains low, for the long term. The model however does not take into account CCS inefficiencies or the prospect of long term effects on the environments or leakage. Models future of CCS but with large assumptions, and little practical understanding of the intricacies of public acceptance and further consequences
Babu et al.	Medium pressure hydrate based gas separation (HBGS) process for pre-combustion capture of carbon dioxide employing a novel fixed bed reactor	L	The paper presents a medium pressure hydrate based gas separation unit for pre combustion which, due to low operating pressure, would have lower op-ex. The process uses a novel fixed bed reactor, so the technology is in use already, and adds 2.5%mol propane to reduce the necessary operating pressure. Decreasing the water saturation in the silica increased the gas uptake and hydrate growth, so a hydrate conversion of 64.3% in 4h was achieved with a 50% water saturated sand bed.
Bäckstrand et al.	The politics and policy of carbon capture and storage: Framing an emergent technology	M	The paper discusses the policy behind CCS, and the lack of a coherent set of policies and initiatives to develop it as a technology. It recommends 3 areas for further research: CS and the long term transition to a low carbon society, public dialogue and responses and policy and regulation, international dimensions and developing countries.
Baker et al.	Carbon capture and storage: combining economic analysis with expert elicitations to inform climate policy	M	The paper elicits the views of experts on CCS on a number of topics regarding the large scale implementation of the technology. It states that CCS is very likely to be implemented in the future, although a number of societal and technical issues remain to be solved. More info is needed on long term viability and to assess the probability of success of capture technologies. It concludes by stating the requirement for a consensus within the CCS community on how and when CCS should be implemented.

Balat and Öz	Technical and Economic Aspects of Carbon Capture and Storage - A Review	L	Considers the technical options available for CCS in 2007. Brief estimate of costs, concluding costs of around $43/tCO_2$. An interesting, but now slightly outdated, overview of CCS
Belaissaoui et al.	Membrane gas separations and post-combustion carbon dioxide capture: Parametric sensitivity and process integration strategies	H	Assesses and compares membrane technology to amine adsorption technology, presenting conclusions of limitations and optimum operating parameters. Useful investigation of applicability of membrane technology to CCS, and how under given flue-gas conditions, membrane separation can be more energy efficient that amine adsorption.
Benhelal et al.	Global strategies and potentials to curb CO2 emissions in cement industry	H	Considers legislative changes that must happen, and barriers that must be overcome, in order to make CCS a viable option for the cement industry. Contains a comprehensive literature review and summary. Describes the most promising technologies and implementation strategies for CCS in the cement industry, then goes on to take a well-justified look at where and what the largest barriers (both technological and legislative) are.
Bernier et al.	Multi-objective design optimization of a natural gas-combined cycle with carbon dioxide capture in a life cycle perspective	H	Considers the optimisation of an MEA absorption cycle. Estimates costs at $63.42/tCO_2$. Good investigation of MEA technology, and cost data.
Berstad et al.	Low-temperature CO_2 capture technologies - Applications and potential	M	Scientific study of the parameters that affect the efficiency of cryogenic separation of CO_2 from flue and out-gases. Good quantitative investigation and discussion of cryogenic technology for CCS.
Best et al.	Status of CCS development in Indonesia	L	Various technologies are investigated in terms of suitability for implementation in Indonesia. Looks into regulatory requirements needed to start scaled CCS implementation in Indonesia.
Billingham et al.	Corrosion and Material Selection Issues in Carbon Capture Plants	L	Analysis of Material selection issues in CCS plants, based on corrosion caused by CO_2 and other process fluids.
Birat et al.	CO_2 mitigation technologies in the steel industry: a benchmarking study based on process calculations	M	The article discusses the requirements for a deep cut in emissions from the steelmaking industry, and possible methods to achieve this. It states that efficiency savings alone can only contribute to 10-15%, and that due to the increased demand forecasted, there will likely be little overall change in emissions. It states that either a completely new method of steelmaking would be required, or that CCS could be used to help reduce emissions. It shows the necessity of CCS in the steel industry to conform to the targets imposed by Kyoto
Bistline and Rai	The Role of Carbon Capture Technologies in Greenhouse Gas Emissions-Reduction Models: A Parametric Study for the U.S. Power Sector	H	The paper summarises the use of a model to simulate the implementation of CCS into a GHG abatement program. The two most important factors are technology start date and diffusion rate and, at current rates, CCS will not play a large part in GHG abatement until after 2030. Either or both of these parameters must be urgently changed in order to promote CCS technologies in the USA, and the paper discusses the challenges of faster deployment. Displays drivers behind CCS implementation and discusses technological and logistical challenges associated with large scale deployment of CCS in the USA.
Blamey et al.	The calcium looping cycle for large-scale CO_2 capture	H	This paper assesses calcium looping technology as a proposed method of CCS for power stations and cement plants, with observations made about its suitability when compared to other methods of capture, and its successful pilot schemes. The paper states that due to the low cost of the sorbent when compared to oxygen, for example, the process becomes economically attractive when a CO_2 price is active, especially due to the sorbents being virtually unaffected by contaminants such as ash. However, the study warns of the need for further demonstration plants before it can be implemented on a large scale. However,

			the capture rate of CO_2 by calcium looping will be lower than these technologies due to it requiring a chemical equilibrium, although efficiencies of 90% may be feasible. The paper states that using a calcium looping cycle with additional power generating capacity, the cost would be about \$15/tCO_2 avoided, instead of \$23.8/tCO_2 for oxy-combustion CFBC process, although the capital costs would be higher. It is also found to be cheaper than amine scrubbing, which is found to be in the region of \$30-80/tCO_2. Synthetic solvents can also be used, but they are at a lower TRL and would require lengthy and expensive testing, as well as having a higher cost.
Bobicki et al.	Carbon capture and storage using alkaline industrial wastes	M	This paper discusses using industrial alkaline wastes such as steel slag and cement by-product for CCS, as the CO_2 would be stored permanently. The advantages to this include the higher environmental stability of this, the availability of thee wastes at low cost, and the permanent storage of the CO_2. Using the fresh minerals (CaSi and MgSi) requires energy intensive treatment, so this is saved by using these waste products. Comparison of different mineral sequestration data is difficult due to the different forms it is presented in not being readily convertible. Steelmaking slags and CaO waste from cement manufacture present the most promising candidates, though slags and tailings from many industries can be used. Storage of these residues is not mentioned, and is a large problem to be addressed, though some of these may be used as building materials etc.
Bounaceur et al.	Membrane processes for post-combustion carbon dioxide capture: A parametric study	M	Assesses and compares membrane technology to amine adsorption technology. Useful investigation of applicability of membrane technology to CCS, and how under given flue-gas conditions, membrane separation can be more energy efficient that amine adsorption.
Bouvart et al.	Environmental Assessment of Carbon Capture and Storage Deployment Scenarios in France	L	Focuses on quantitative and qualitative environmental outlook for CCS in France, not on the technology itself. Supporting information given on the full life-cycle of CCS on a national scale.
Bowen	Carbon capture and storage as a corporate technology strategy challenge	M	The paper discusses the current lack of policy with regards to CCS and the reasons behind that, such as high capital cost and high degree of risk, as well as non-unified message from within the CCS community. The paper makes assertions about the future of CCS and mentions specific details about the potential future of CCS, as well as making recommendations about future policy and investment for the governments involved, centralising around four core topics: the fact CCS will not impact industry, the fact that the current risk is small compared to future risks of climate change, the fact that CCS is an opportunity for countries to support national industry to promote manufacturing and the fact that investment is cumulative as avoided emissions now will sustain the avoidance every year the plant is in operation. Good recommendations about how to promote CCS to governments and the current barriers, as well as the proposed future of CCS within the energy and industrial sectors of the world.
Brúder et al.	Pilot study—CO_2 capture into aqueous solutions of 3-methylaminopropylamine (MAPA) activated dimethyl-monoethanolamine (DMMEA)	M	Pilot-scale investigation of carbon capture by amine adsorption cycle in absorber and stripper columns. Considers only technological issues, no economic data. Good investigation of amine adsorption technology for CCS.
Brunetti et al.	Membrane technologies for CO_2 separation	M	The paper advocates the use of membranes in CCS capture and presents a comparison of membranes, cryogenesis and absorption. The paper presents results of CO_2 removal from waste streams of varying concentrations considering membranes of varying selectivities. With current membranes, it is not possible to get good CO_2 recovery and purity simultaneously. Compares membrane and absorption and cryogenic

			separation in terms of performance, but no mention of cost - one of the major downsides of membranes.
Brunsting et al.	Social Site Characterisation for CO2 Storage Operations to Inform Public Engagement in Poland and Scotland	M	This paper presents the results of a survey, which has been used to characterise the best approach to public engagement and education of CCS prior to implementation. Good primary consideration of what needs to be done in order to make CCS publicly acceptable, and garner public support
Burton et al.	Accelerating Carbon Capture and Sequestration Projects: Analysis and Comparison of Policy Approaches	M	This paper discusses the current and recommended future policies for California, with a view to demonstrating what changes need to be made to allow CCS projects to be viable. It points to the failed projects and why they failed, and the poor US policy and how this has hindered development. It compares California's policies with other states, and how cutting GHG emissions through policy has in fact hindered research into CCS. It states that if CO_2 could be sold, e.g. for EOR, it would help the economics and reduce risk to the investor. This paper documents the development of policy in California, and in particular how current policy is hindering CCS research by using very short term goals, which do not give enough time for CCS to be used.
Câmara et al.	Regulatory framework for geological storage of CO_2 in Brazil – Analyses and proposal	L	Looks at regulatory change necessary to facilitate carbon storage in Brazil. Considers carbon sequestration in Brazil, not carbon capture.
Castilho et al.	Sorbents for CO2 capture from biogenesis calcium wastes	M	Considers use of crushed and calcified 'waste' shells from eggs and seafood for use in carbon capture. Discusses the available technology, using very specific shell-based waste materials as sorbents for CO_2.
Charlesworth and Okereke	Policy responses to rapid climate change: An epistemological critique of dominant approaches	L	Looks at the influence of natural scientists and their obligation to alert the international community to the limitations of science in predicting the capacity of the earth to continue to support us. Not particularly relevant to CCS.
Chicco and Stephenson	Effectiveness of setting cumulative carbon dioxide emissions reduction targets	L	The paper suggests using cumulative CO_2 emissions, so that targets have to be attained at a steady rate, rather than implementing the changes at the end of the period. It would also take into account the time that CO_2 stays in the atmosphere and the ways that changes are made over time. Not directly relevant to CCS.
Cho et al.	Reactivity of iron oxide as an oxygen carrier for chemical-looping hydrogen production	M	Discussion and results of using iron oxide as an oxygen carrier for CCS. Good analysis of iron-oxide O_2 carrier technology for chemical looping CCS.
Choi et al.	Effect of Impurities on the Corrosion Behaviour of CO_2 Transmission Pipeline Steel in Supercritical CO_2-Water Environments	L	The paper discusses the effects of impurities in the CO_2 gas flows on the material integrity of the steel pipelines used for CO_2 transport. Materials information for carbon storage.
Choi et al.	Mechanistic Modelling of Carbon Steel Corrosion in a Methyldiethanolamine (MDEA)-Based Carbon Dioxide Capture Process	L	The paper discusses the corrosion of carbon steel by an MDEA solvent, as may be used in a CCS plant for amine scrubbing. Details materials information for storage.
Cole et al.	State of the aqueous phase in liquid and supercritical CO_2 as relevant to CCS pipelines	L	The paper discusses the flow regimes and profiles of the aqueous phase in a CO_2 flow through a CO_2 pipeline, and the implications of this on corrosivity and the pipe structure.
Concrete Products	Cemex captures carbon abatement grant	L	This report discusses very briefly the example of Cemex USA receiving a grant from the American Recovery and Reinvestment Act. Discusses the $1.14m investment of the US DoE into this project. The paper discusses a specific example of an early US cement company initiative, and the government funding made available to them.

Cormos	Evaluation of iron based chemical looping for hydrogen and electricity co-production by gasification process with carbon capture and storage	L	The paper discusses an iron oxide chemical looping system to take place on an IGCC for a H_2 production/electricity generation coproduction scheme. No relevance to industrial CCS. Little relevance to industrial CCS.
Cormos	Hydrogen production from fossil fuels with carbon capture and storage based on chemical looping systems	L	The paper discusses the use of an iron oxide chemical looping system to produce H_2 from fossil fuels with intrinsic CO_2 capture, as well as a plant with 500MW capacity for electricity generation from H_2.
Damen et al.	Pathways towards large-scale implementation of CO_2 capture and storage: A case study for the Netherlands	M	Looks into what needed to happen in the Netherlands for CCS to be possible. It is an early study of the alternatives available and an assessment of rough costs. Concludes that CCS would become widely applicable when the carbon price reached between EUR15/tCO_2 and EUR40/tCO_2. References of historic research and expectations for CCS (in the Netherlands).
Damiani et al.	The US Department of Energy's R&D program to reduce greenhouse gas emissions through beneficial uses of carbon dioxide	L	The paper proposes alternate uses of CO_2 so that instead of geological sequestration, it can be used as a feedstock, for example in producing plastics or in EOR. Describes uses of CO_2 post-capture.
Darde et al.	Comparison of two electrolyte models for the carbon capture with aqueous ammonia	M	Looks into the performance of CO_2 adsorption process with aqueous ammonia (as supposed to MEA), using UNIQUAC and e-NRTL packages within Aspen. Good, technical investigation of ammonia absorption technology, but no cost data.
de Coninck and Backstrand	An International Relations perspective on the global politics of carbon dioxide capture and storage	M	This paper documents the current international treaties and policies that are being used to try and promote CCS. It compares the necessity for CCS with other large international agreements, such as the setting up of the world bank, IMF etc. and highlights the need for some of the major world powers such as the USA to take a lead in CCS policy, as there is a lack of clout behind calls for CCS regulation at the moment. The paper also considers the different organisations who may push for policy, and the different influences and drivers behind their decisions. Most major science led bodies, e.g. GEF, UNFCCC, IPCC, are all neutral on CCS, which hinders the deployment of technology. However, energy driven organisations like the IEA, IEF, CSLF and even OPEC all are positive towards CCS. Greater impetus from the science led bodies would go a long way to helping CCS policies. This paper highlights the difficulties of implementing pro-CCS policy due to the lack of backing from major international organisations, although it does summarise the positions of many major bodies on the technology. It considers the many viewpoints of bodies on CCS and explores how they may be used to push further for more binding policies on it.
Dean et al.	Investigation into potential synergy between power generation, cement manufacture and CO_2 abatement using the calcium looping cycle	M	This paper discusses the feasibility of combining CCS carbonate looping currently implemented in power plants with cement manufacture, using spent sorbent for cement feedstock. Interesting discussion of potential linking technology, but needs quantifying.
Dean et al.	The calcium looping cycle for CO_2 capture from power generation, cement manufacture and hydrogen production	H	This paper discusses calcium looping for carbon capture in power generation and cement plants. From the literature, it compares costs of calcium looping to other comparative CCS technologies. Great quantitative article describing calcium looping technology for the cement industry.
Doucet	Effective CO_2-specific sequestration capacity of steel slags and variability in their leaching behaviour in view of	L	The paper discusses the use of steelmaking slags for CCSM, so as to reduce the amount of waste and capture CO_2 at the same time. The experiment uses HNO_3 at RTP to extract Ca and Mg from the slags for use in carbonation. Details necessary prep work for mineral carbonation technologies.

	industrial mineral carbonation		
Dri et al.	Dissolution of steel slag and recycled concrete aggregate in ammonium bisulphate for CO_2 mineral carbonation	M	Investigates the dissolution of steel slag and recycled concrete in a solution of ammonium bisulphate, as part of the overall dissolution and absorption by mineralisation of CO_2 process. Good technical investigation of the crucial dissolution step in CO_2 mineralisation process.
Egenhofer	The Making of the EU Emissions Trading Scheme:: Status, Prospects and Implications for Business	L	Looks at implications and practical applications of the EU ETS. For the purposes of this investigation, the paper was considered outdated and not particularly relevant to CCS.
Fan et al.	Chemical looping processes for CO_2 capture and carbonaceous fuel conversion – prospect and opportunity	M	Paper focuses on chemical looping technology. While focus is on power, cement production is also considered. A couple of small mentions of case-study costs. It discusses chemical looping technology in some detail. Cost data is rare however, and the primary focus is on power CCS with some references to industrial cement production.
Favre	Carbon dioxide recovery from post-combustion processes: Can gas permeation membranes compete with absorption?	M	This paper compares membranes and absorption for CO_2 removal from feeds. If the CO_2 stream is under 10% purity, then adsorption is best. If CO_2 content exceeds 20%, membranes can compete with energy requirement, although they need a target selectivity of about 60, which is achievable with modern membranes. For 20% CO_2 content, using vacuum pumping and downstream compression instead of upstream compression decreases the energy requirement to similar to absorption. However, a lack of pilot studies means that there is a lack of investment behind the technology, so more studies must be done before confidence will be built.
Gazzani et al.	Application of Sorption Enhanced Water Gas Shift for Carbon Capture in Integrated Steelworks	M	This paper compares sorption-enhanced water gas shift separations (SEWGS) with natural gas combined cycle (NGCC) and with post-combustion MEA capture, and compares the energy requirements of the different technologies and the outputs of energy and CO_2 from them. The CO_2 avoided in the MEA scheme is much lower (39%) than SEWGS which is about 85%. This is much higher than using MEA due to not needing to regenerate the solvent and is a viable option for use at steel works. Compares capture rates and CO_2 avoided of MEA with SEWGS reactions for capture, although no mention of costs.
Gemayel et al.	Simulation of the integration of a bitumen upgrading facility and an IGCC process with carbon capture	H	The paper discusses using a membrane flash process using waste hear to regenerate DEA and separate CO_2 after post combustion capture, noting that best efficiencies and lowest energy capture is achieved at high CO_2 concentration streams. The paper compares the electricity consumption and costs of absorption and membrane flash process for iron production petroleum refining and power generation, and is found that petroleum refining is the cheapest of the three, with iron production the next cheapest for capture. Membrane flashes were also found to be cheaper to operate than chemical absorption with DEA for point source capture. Compares costs for a membrane flash process and absorption, and gives estimated costs for these at different CO_2 concentrations.
Gerlagh and Van der Zwaan	Options and Instruments for a Deep Cut in CO_2 Emissions: Carbon Dioxide Capture or Renewables, Taxes or Subsidies?	L	The paper considers the main drivers behind CO2 emissions reduction, and possibilities to effect this reduction by considering CCS and renewables through DEMETER modelling. The modelling is based on trying to achieve an atmospheric CO_2 concentration of 450ppm, and the study hopes to be able to use their suggested evolution of the energy landscape from now to 2150 to generate debate on the subject. Focussed entirely on power generation strategies.
Ghanbari et al.	Process integration of steelmaking and methanol production for suppressing CO2 emissions—A study	M	The paper discusses a novel steel plant with various technologies that would be able to reduce CO_2 emissions, whilst operating in tandem with a methanol production plant. The paper states that CO_2 emissions could be reduced by about 75% with respect to a traditional steel plant, by optimising a variety of

	of different auxiliary fuels		parameters and assessing the impacts of new technologies, such as top gas recycling. The paper does not give a clear optimal case, but states that implementation of CCS in a combined plant with methanol has great potential to not just reduce emissions, but also to make a useful, saleable product which would be attractive economically. The paper mentions the costs of operating the steelworks with different technology, at a price of storage of €20/tCO_2. No clear costs are given in €/tCO_2. Gives costs and processes for integration of a steelworks and a methanol plant. Gives accurate lists of drivers behind the costs of the processes, and suggests emissions savings attainable through the different processes.
Gielen	CO_2 removal in the iron and steel industry	H	Considers use of a shift reactor and Selexol as the CO_2 carrier fluid- the report finds this to be the most cost-effective technology. The paper finds: 'Based on the analysis in this study, it is concluded that alternative process schemes can result in a significant reduction of the CO_2 removal costs to about 16.7–18.8 US$/t of CO_2 for conventional blast furnaces.' Good costing information which can be used as part of a comparative study. It could be useful to compare the results and findings of this 2002 paper to more recent studies.
Gilotte and Bosetti	The Impact of Carbon Capture and Storage on Overall Mitigation Policy	L	The paper considers the effects of implementing CCS against the benefit of pursuing it instead of other low emissions technologies such as renewable energy. The paper suggests that the future availability of CCS isn't a reason to redirect funds from other mechanisms such as abatement measures, and claims that if CCS is a viable option, then more stringent policies should be made.
Goto et al.	Development of novel absorbents for CO_2 capture from blast furnace gas	M	The paper discusses the use of novel sorbents for CO_2 capture from blast furnace gas. Amines with a high adsorption rate and low enthalpy of absorption were investigated. No info about cost, and little performance difference. The paper discusses alternatives to using the traditional MEA solvent, but without enough information about their use on a large scale or about costs, no comparison can be made.
Gough et al	A roadmap for carbon capture and storage in the UK	H	This paper details the results of a conference and workshop where delegates discussed the barriers to adopting CCS in the UK - these were classified using a traffic light system of enablers, follow up and barriers. The main barriers identified were long term liability, follow up were risk acceptance, site approval, economics, monitoring and verification. By collating policy from the EU and the government through their white papers, the study aimed to use current policy to identify weaknesses and areas that need improving, and to address these by suggesting new policies. The delegates discussed the need for a demonstration project in the UK, as well as the uncertainty regarding the number of different technologies due to needing a demo for each of them. Roadmap graphics are displayed to show clearly the proposed pathways and explores different options to increase the viability of building CCS plants commercially. This paper recognises the difficulties associated with economics of carbon capture, and seeks to find policy to address this. It mentions EU directives to support CCS projects with a supporting fund of €10bn from the Emissions Trading Scheme. This paper provides a comprehensive overview of what is needed to bring about commercial carbon capture in the UK, which can be extended to provide details about the necessary steps required to bring about an effective climate for CCS to be viable in. The paper contains many useful links to very relevant papers and government policy documents that will be essential when comparing the policy requirements of CCS worldwide, and especially in the EU and UK.
Green et al.	Capture of carbon dioxide from flue gas using dry regenerable sorbents	M	Looks at the merits of a solid, regenerable sodium sorbent for CCS process on flue gas. Good investigation of sodium sorbent process
Green et al.	Challenges to a climate stabilizing energy future	L	Looks at legislative possibilities to slow climate change- focusing primarily on renewable energy. More relevant to renewable technology than CCS.

Griffiths et al.	A Framework for Understanding Institutional Governance Systems and Climate Change:: The Case of Australia	M	This paper discusses the differences in countries that have and have not signed the Kyoto agreement's willingness to reduce carbon emissions, and the different environmental pathways that they follow due to different systems of government. The paper discusses different countries' policies towards reducing carbon emissions and the drivers behind the different standpoints of these countries. This paper can be used to explain the differences in willingness to adopt low carbon technologies from different countries, and to try to explain why some countries are more involved in carbon capture research than others.
Groenenberg and de Coninck	Effective EU and Member State policies for stimulating CCS	H	This paper gives recommendations to ways that technological advancement and acceptance of CCS can be pushed by using policy. It discusses the way that current guidelines and ETS policies are pushing efficiency savings and the improvement of existing technology, instead of incentivising new technology. The maturity of a technology must be considered when making policies to avoid unnecessary costs and uncertainties, and the speed of policy making will increase as the technology becomes more mature. However, for some schemes such as EOR, and pre and post combustion capture, the technology is mature enough that policy could likely be made with a high degree of confidence about these cases. However, newer and more novel techniques such as calcium looping and oxy-fuel combustion need more research and demonstration projects before the confidence in them is at a level where policy can be made. Storage however is more difficult, with the issue of liability still keeping investors away due to insufficient confidence in the technology and an unclear framework with regards to liability from governments. Guaranteeing a CO_2 price would help in a similar way to a feed in tariff, by guaranteeing an economic advantage to the project and reducing one of the sources of risk; however, this could end up being very costly as more CCS projects are brought online. This would provide incentives for industry to capture the carbon at between 6 and 11€/tCO_2 for capture and storage in the Netherlands, so at a relatively low price, although capture from more expensive sectors such as steel or cement, a higher guaranteed cost would be required. A CO_2 emission phase-out, as suggested by the EU commission, would require all fossil fuel power stations would have to have CCS from 2020, and something similar could be applicable to ammonia production, refineries and hydrogen plants. Later development would allow cement and steel would be included as technological costs fell. A proposed timescale for the use of the different policies is presented at the bottom of the paper, where a clear pathway towards commercialisation of CCS is shown.
Grönkvist et al.	Oxygen efficiency with regard to carbon capture	L	Considers measuring CCS operations by their oxygen requirement. Investigates and present an alternative viewpoint from which to consider CCS operations.
Guan et al.	The drivers of Chinese CO_2 emissions from 1980 to 2030	L	The paper discusses the reasons for China's CO_2 emission rises from 1980 to today, and then explores scenarios for their increase in the future. Mentions CCS only briefly as part of one scenario into emissions abatement.
Guivarch and Hallegatte	2C or not 2C?	L	This paper addresses the current estimate of a 2 degree temperature rise due to global warming, and states that due to insufficient action being taken, we will likely have to deal with a higher degree of warming. This paper can be used in the introduction to illustrate the fact that we are behind the target, with the current target of 2 degrees likely too low.
Gupta et al.	Particulate matter and elemental emissions from a cement kiln	M	Investigates and reports on particulate composition of flue-gases from an Indian cement kiln. Only mentions quoted costs from references for carbon capture in cement kilns. Interesting study of particulate emissions from cement plant. Good references and conclusions including cost studies of cement kiln CCS.
Hamano et al.	Development of a Process for Aqueous Mineral Carbonation on	L	The paper discusses using a mineral carbonation process to capture CO_2 and produce $NaHCO_3$ and KCl from municipal solid waste incinerators. The process is done by using bottom ash from the incinerator, and

	Municipal Solid Waste Incinerator Bottom Ash with Recovery of Useful Chemicals		the economics of the process are improved by generating saleable chemicals. The cost given is $58/t$CO_2$ avoided, but the scope for emissions cuts is small; only 2,880 tCO_2 per year may be avoided in this way in Japan. Municipal waste incineration is not being considered by this study, although this is a cheap way of capturing CO_2.
Hanna et al.	Enzymatic CO_2 capture by immobilized hCA II in an intensified microreactor—Kinetic study of the catalytic hydration	L	Focuses on the use of an en enzyme for carbon capture at lab scale, but makes limited scale-up suggestions Useful new technology option to discuss. Not widely applicable or relevant yet.
Hasanbeigi et al.	Emerging energy-efficiency and CO_2 emission-reduction technologies for cement and concrete production: A technical review	H	The paper discusses methods of increasing energy efficiency of cement plants. It also discusses CCS on cement, with oxy combustion estimated at €40/tCO_2 for a 1Mt per year in Europe and €23/tCO_2 for a 3Mt plant in Asia - similar to oxy-combustion on a power station. Post combustion costs are €107/tCO_2 on a 1Mt plant in Europe and €59/tCO_2 for a 3Mt in Asia due to needing FGD and NOx reduction. Oxy combustion will avoid about 61% of CO_2 missions for just precalciner, but 100% for precalciner and kiln. V specific info about cement CCSN/AAs mentioned in tech. Lots of useful information about cement CCS.
Hawkins et al.	Twelve years after Sleipner: Moving CCS from hype to pipe	H	Looks at what exactly needs to be implemented and defined to encourage large-scale uptake of CCS. Good analysis of the major legislative barriers and omissions inhibiting the current deployment of CCS across the world.
Ho et al.	Comparison of MEA capture cost for low CO_2 emissions sources in Australia	H	Looks at MEA carbon capture, the retrofitting process and space requirements for the technology to be bolted onto existing plants. Largest focus of this paper is on the iron and steel producers, and the relative financial factors that affect their decisions to implement MEA CCS onto their plants. It also concludes that MEA CCS is not yet financially feasible for the Australian cement industry. Good report on CCS in Australian industry.
Houshmand et al.	Carbon Dioxide Capture with Amine-Grafted Activated Carbon	M	Considers and investigates the potential of fixing amine groups onto activated carbon for CO_2 absorption. Looks into attaching active amine groups onto carbon for looping for CO_2 capture
Hsieh et al.	Dense gas dispersion modelling of CO_2 released from carbon capture and storage infrastructure into a complex environment	L	The paper models the loss of containment of CO_2 from geological storage, an integral assessment for CO_2 storage. Not related to industrial CCS
Hu et al.	The impact of China's differential electricity pricing policy on power sector CO_2 emissions	L	The paper discusses the emissions reduction of the Chinese power sector through differential electricity pricing, which has not worked to slow the increase of emissions from 2004 to 2008. The paper recommends policies to try and address the fact that this initiative has benefitted some industries but not others. No mention of CCS.
Huijgen et al.	Cost evaluation of CO_2 sequestration by aqueous mineral carbonation	H	The paper discusses the use of steel slag and wollastonite as minerals for mineral sequestration. The costs associated with these are 77 and 102€/tCO_2 respectively, with steel slag being cheaper due to lack of costs for feedstock but also the smaller scope of the process. The costs associated with this are higher than other methods of CCS, but being able to store the carbon as a solid carbonate could have advantages compared to geological gas storage. The tech will find its main applications in niches, where there is demand for the mineral carbonate or there is a designated storage site. The paper lists costs both for CO_2 avoided and for CO_2 sequestered, meaning that calculations based on both can be made. The paper mentions costs for both the wollastonite and the steel slag, both for CO_2 sequestered and CO_2 avoided, and lists the source of the costs. This paper gives a fully costed flow sheet for using two different aqueous

			minerals for solid sequestration, meaning that the costs of this type of capture can be compared with others easily.
Hyder	Recycling revenue from an international carbon tax to fund an integrated investment programme in sustainable energy and poverty reduction	L	Looks into the feasibility and limitations of implementing an international carbon tax, and using the dividends to tackle climate change. Not relevant to CCS, although an interesting proposition.
Imbabi et al.	Trends and developments in green cement and concrete technology	L	Paper discusses novel types of cement and processes to reduce CO_2 emissions. No mention of CCS. No mention of CCS or useful facts regarding it.
Ingelson et al.	Long-Term Liability for Carbon Capture and Storage in Depleted North American Oil and Gas Reservoirs -- a Comparative Analysis	L	Looks at who will take responsibility for CO_2 storage in the future- private sector or state or insurance companies? Interesting debate, but not related directly to carbon capture policy.
Ishii and Langhelle	Toward policy integration: Assessing carbon capture and storage policies in Japan and Norway	M	This paper compares the CCS policies of Japan and Norway, and addresses the need for policy integration for a global concerted policy on CCS. It highlights the fact that Japan does not use policy to help influence its CCS policy, and does not address some of the 'hard' issues, such as liability, public acceptance, whereas Norway should focus on not limiting mitigation strategy to CCS. Useful to see how policy integration could be done for value added section, as well as potential issues with such.
Jansson and Northen	Calcifying cyanobacteria—the potential of biomineralization for carbon capture and storage	L	Use of cyanobacteria to form $CaCO_3$ from reaction with CO_2, however very little current research so tech a long way from being viable or useful. Too many unknowns so little relevance to study. Low TRL, so no feasible timescale before tech can be deployed, with little understanding of how the bacteria would behave.
Jensen et al.	A Phased Approach to Building a Hypothetical Pipeline Network for CO_2 Transport During CCUS	M	This paper compares the potential requirement for a national CO_2 pipeline network in the USA with existing pipelines, for example for natural gas and CO_2 for enhanced oil recovery. It discusses the technical difficulties associated with building large pipelines, but notes that in the 1950s the natural gas pipelines were built quickly and with little disruption to existing services. This paper discusses the implications of the rollout of CCS technology and its dependence on carbon taxes and tax credits, and can thus be used to discuss the pace at which CCS plants will be installed worldwide in the next 35 years. This paper can be used for its data about the estimated uptake of carbon capture and the number of plants, and therefore the estimated carbon removal by 2030 and 2050 dependent on different carbon tax scenarios. The information displayed here about the requirement for carbon transportation is also relevant when considering the viability of carbon capture at different, remote locations.
Jollands et al.	The 25 IEA energy efficiency policy recommendations to the G8 Gleneagles Plan of Action	L	Considers which next steps should be taken by the G8 countries to mitigate climate change. No in-depth discussion or application of CCS- not particularly relevant.
Jönsson and Berntsson	Analysing the potential for implementation of CCS within the European pulp and paper industry	H	Good investigation into the current state of technology within the PPI, where the largest sources of emissions lie and how CCS can be applied to mitigate against these. Considers what should be legislated for quite specifically to make CCS feasible for the PPI (eg. the subsidising of biogenically-derived CO_2, as

			is applicable to the bulk of PPI emissions. Great overview of CCS in the PPI.
Jung et al.	CO_2 transport strategy and its cost estimation for the offshore CCS in Korea	L	Looks into the infrastructure requirement for transportation of CO_2 in Korea. Estimates total costs for implementation of various proposed CO_2 transportation networks in Korea. Considers in useful detail and with justified cost estimates, the possibilities for a connected CO2 transportation network in Korea.
Jung et al.	CO_2 Transport Strategy for the Offshore CCS in Korea	L	As above for 'CO_2 transport strategy and its cost estimation for the offshore CCS in Korea'.
Kaarstad et al.	More than coal - Towards a broader role for CCS	H	Looks briefly at the available technology. This paper finishes by making eight recommendations to policy makers. Good, sound policy recommendations.
Kaithwas et al.	Industrial wastes derived solid adsorbents for CO_2 capture: A mini review	M	Gives thorough evidence of physical and chemical mechanisms for CO_2 adsorption by industrial, coal-derived fly-ash. Useful investigation of fly-ash use for flue-gas carbon capture.
Kärki et al.	CCS Feasibility Improvement in Industrial and Municipal Applications by Heat Utilisation	M	This paper discusses the potential of using waste heat from solvent regeneration from CCS to use in district heating. On a scale of 2MtCO2/a, there could be a potential saving of up to 3M€/a by using an advanced solvent for capture. The paper discusses using waste heat from CCS on a steel mill to be used in a district heating system. This gives economic benefits amounting to up to €3m per year dependent on solvent (MEA is not optimal here as regeneration costs are too high. Can be seen to demonstrate a method of reducing energy demand and improving economics of CCS on steel mills.
Karl et al.	Worst case scenario study to assess the environmental impact of amine emissions from a CO_2 capture plant	L	Discusses health impacts of any amine emissions to atmosphere from CCS with MEA. This could exceed limits for drinking water systems and aquatic ecosystems. Study says that levels could rise to dangerous levels which would be above limits, and may need some method of reducing them further. No information about CCS.
Kenarsari et al.	Review of recent advances in carbon dioxide separation and capture	M	Discusses the various CCS option technologies and their effectiveness in detail. Detailed technological performance analyses.
Koornneef et al.	The impact of CO_2 capture in the power and heat sector on the emission of SO2, NO_x, particulate matter, volatile organic compounds and NH_3 in the European Union	M	Discusses the impact of widespread CCS technology on levels of other air pollutants in Europe (particulates, SO_X, NH_3, NO_X). Good investigation into CCS effects on other air pollutant levels.
Krahé et al.	From Demonstration to Deployment: An Economic Analysis of Support Policies for Carbon Capture and Storage	H	The paper details a proposed strategy for the deployment of CCS on a large scale over 3 stages; technical demonstration, sector specific deployment, general deployment. The paper states that while a carbon tax would help CCS, implementing it too early, before research has finished, may drive investors elsewhere, and specific policy managing the risk associated with storage is necessary. Balancing the need for flexibility and certainty faced by governments and private companies, respectively, is a great challenge as an overall policy will need to satisfy both parties if any progress is to be made. The paper asserts the need for policies to be reviewed and altered over time to ensure that they still complement CCS and ensure that it is attractive for investors.
Kujanpää et al.	Cross-border CO_2 infrastructure options for a CCS demonstration in Finland	L	This paper discusses the international logistical problems associated with moving CO_2 between countries, as, for example, Finland has little domestic storage capacity. The paper mentions that ships are more economical than pipelines for offshore transport of over 300km and needs less permitting. The paper summarises the costs associated with transport of carbon through pipelines versus being shipped. The

			paper can be used to obtain some information about transport and storage, but nothing about capture. The costs of transport can be used as well.
Kuramochi et al.	Comparative assessment of CO2 capture technologies for carbon-intensive industrial processes	H	Technology alternatives discussed in detail, with well-justified uncertainties and applicability summaries. Qualifies a broad but thorough summary of all available cost information- largely based on pilot studies around the world. Brilliantly comprehensive structured and developed literature review of the current (2010) state and applicability of CCS to four major industries.
Kuramochi et al.	Effect of CO_2 capture on the emissions of air pollutants from industrial processes	M	Investigates the effects of implementing CCS technology on the emissions of PM, SO_2, NO_x and NH_3 from industrial sources in EU 27. Provides good evidence of co-benefits of CCS on non-CO2 emissions from industry.
Kuramochi et al.	Prospects for cost-effective post-combustion CO_2 capture from industrial CHPs	H	Considers techno-economic analysis of CCS technology retro-fitted onto industrial CHP units. Gives costs per tonne CO_2 emissions avoided for fitting CHP units with CCS. Very interesting quantitative application of CCS technology to industry. CHP specifically is rarely considered alone, as here.
Kuuskraa	The role of enhanced oil recovery for carbon capture, use, and storage	M	The article is an interview with Vello Kuuskraa, in which he discusses the merit of EOR with regards to getting CCS up and running by demo projects using EOR to increase profitability. Discusses industry expert's view of CCS and the importance of EOR, though care should be taken due to possible research bias.
Kuwahara and Yamashita	A new catalytic opportunity for waste materials: Application of waste slag based catalyst in CO_2 fixation reaction	L	This paper demonstrates that waste material from a blast furnace, BFS (blast furnace slag), can be used as a precursor to a catalyst for a reaction of epoxide with CO_2. However, due to the massive volumes of slag produced, this will likely only make a small impact on the quantity that needs disposal. In addition, the CO_2 could be captured on site, meaning that this technology could be deployed locally. By not having to dispose of the waste, this process could be favourable economically, whilst acting to reduce emissions. The product of the CO_2 addition to the epoxides are valuable as they can be used in plastics, pharma and fine chemicals, meaning that two waste products can be used up to create a saleable product. Whilst not strictly about carbon capture, this paper is useful in that it shows that another large environmental problem associated with iron and steel manufacture, which in turn utilises a small amount of CO_2.
Lackner and Brennan	Envisioning carbon capture and storage: expanded possibilities due to air capture, leakage insurance, and C-14 monitoring	H	The paper discusses the potential uses of CCS for large point sources, and identifies the main issues with them, such as public concerns about storage, and suggests possible ways to counteract them. The possibilities of air capture are discussed here. All technologies are relevant to the deployment of CCS as a viable technology, and the barriers that are preventing this are mentioned.
Lai et al.	Carbon Capture and Sequestration (CCS) Technological Innovation System in China: Structure, Function Evaluation and Policy Implication	M	The paper discusses the use of CCS in China, from the current perspective of where the industry is, to where it should go. The study aims to find out if China can bridge the gap from research to deployment. The study finds that China has a strong capacity for technology development, but is poor at knowledge diffusion, market formation and lack of opportunities for new market entrants. These weaknesses must be addressed before a large scale system of CCS can be adopted in China. However the method used does not address the effects a large scale deployment of CCS would have on other sectors within China, and expresses uncertainty regarding coal CCS in China due to the emergence of unconventional gas as a fuel source.
Lai et al.	Viability of CCS: A broad-based assessment for Malaysia	M	The paper discusses the feasibility of implementing CCS in Malaysia for carbon mitigation. The paper acknowledges the lack of demonstration projects and the high costs involved, especially when compared to a 'business as usual' approach, but stresses the importance of CO_2 mitigation for the future. The paper addresses the lack of quality storage capacity in Malaysia as a limiting factor, though there is potentially a

			larger capacity than currently recognised. No new data, but useful approach on how to structure a report with recommendations on tech uptake.
Lassagne et al.	Techno-economic study of CO_2 capture for aluminium primary production for different electrolytic cell ventilation rates	H	The paper discusses CO_2 capture from an aluminium plant using MEA scrubbing. The most suitable case was found to be when the CO_2 concentration in the flue is increased from 1.2% to 4%, at a cost of $100.15/t Aluminium, which is a 4.86% increase in the cost of production. However, 58% of the cost per tonne CO_2 can be removed by heat integration. Combined with thermal integration and potential tax incentives, the cost at the 4%vol CO_2 case was found to cost $42.39/tonne Al produced, with a cost rise of only 2.06% instead of the current comparative at 6.3% at 1.2%vol.
Lee et al.	CO_2 capture from flue gas using potassium-based dry regenerable sorbents	L	A comparison of different dry K_2CO_3 sorbents that were to be used in a fluidised bed was undertaken, with some of the sorbents reaching sorption capacities of over 6wt%, whilst satisfying the commercial requirements for a fluidised bed process. The sorbents can be regenerated at temperatures below 140ºC, so waste heat, e.g. from cement kilns, could be used to regenerate them. This paper demonstrates an alternative to the usual amine based solvents for CO_2 removal, but is still a tech with a low TRL so may not be feasible to be used for a while.
Li et al.	Energy demand and carbon emissions under different development scenarios for Shanghai, China	L	Considers the forecasts for China's energy requirements and carbon emissions based on Shanghai's recent consumption patterns. Briefly mentions CCS application to power generation. Good look at China's projected energy requirements and emissions, but hardly a mention of CCS
Li et al.	Opportunities and barriers for implementing CO_2 capture ready designs: A case study of stakeholder perceptions in Guangdong, China	H	Essentially a stakeholder survey looking into how various interested parties in China feel about the large-scale implementation of CCS. Interesting survey that highlights some of the strengths and challenges involved in current Chinese perspectives of CCS
Li et al.	Technological, economic and financial prospects of carbon dioxide capture in the cement industry	H	The paper discusses different methods of CCS in the cement industry and their advantages and disadvantages. **Post combustion with MEA**: Advantages: can be retrofitted, commercially mature, lower energy for separation due to higher concentration in flue. Disadvantages: 50% energy penalty so new energy unit or more power from grid required, higher SO_x and NO_x concentrations may lead to corrosion of process equipment, so expensive FGD and NO_x and NH_3 removal may be necessary. **Oxyfuel tech**. Advantages: Higher CO_2 concentration so easier or no separation required, 63-100% capture efficiency possible. Disadvantages: low TRL, needs retrofit of plant, needs ASU operation. Carbonate looping done elsewhere. This paper mentions the cost of post combustion capture at cement works at $161/tCO_2$ and $60/tCO_2$ for oxy-combustion, but that may be artificially low due to a low CO_2 reduction (only 52%), though an MEA cycle on a power plant was estimated to cost $68/tCO_2$ in Australia. Another study placed costs at $49/tCO_2$, but that was for CO_2 captured, not avoided. Post combustion capture at a cement plant was estimated to cost €110m. Full costs table of different research are presented, with mention of the differences and the reasons for these. Overview of cement industry CCS, with lots of costing and tech information. Highly relevant for that section.
Liang and Li	Assessing the value of retrofitting cement plants for carbon capture: A case study of a cement plant in Guangdong, China	H	The paper assesses the viability of retrofitting CCS onto cement plants in China, and the economic viability of this. It states that it would be worth making future plants 'retrofit ready' so they can be retrofitted in the future. However, the study also does not consider heat integration within the plant. The paper discusses the viability of retrofitting CCS onto Chinese cement plants. The cost for avoidance is $70/tCO2 with a capture efficiency of 85%. The economic viability of retrofitting the plants is highly dependent on carbon

			prices, with option values ranging from $1.2m to $20m depending on the price. Provides capital costs of retrofitting existing cement plants with CCS technology, and costs of operation.
Liang et al.	Perceptions of opinion leaders towards CCS demonstration projects in China	H	This paper is the write-up of a survey taken of significant stakeholders to Chinese CCS projects. Government ministers, infrastructure and energy bosses and local authorities are all consulted. Good summary of primary (Chinese) views on CCS.
Lin and Lin	Comparison of carbon sequestration potential in agricultural and afforestation farming systems	L	Studies use of planting trees or sugar cane to then be used as forms of carbon sequestration. Uses of CO_2 - no relation to CCS.
Lindfeldt and Westermark	System study of carbon dioxide (CO_2) capture in bio-based motor fuel production	L	The paper discusses the possibility of using CCS on a plant for using biofuels, but states that CO_2 emissions will still be high even if this is implemented, making it infeasible unless technology improves. Details CCS on biomass fuel plants, and concludes that it is ineffective.
Linga et al.	A new apparatus to enhance the rate of gas hydrate formation: Application to capture of carbon dioxide	L	The paper discusses a novel apparatus for forming hydrates from flue streams, which can improve efficiency due to a larger gas-liquid contact area, which was shown to have a greater CO_2 recovery. A new metric was proposed, normalised rate of hydrate production, was used to compare the experiments. One problem was the use of a CSTR that was required, with the mechanical agitation costs being very severe, highlighting the need for it to be able to be used without an agitator to be able to be comparable in cost for use industrially. New process for hydrate formation, but no info about cost or scale up.
Liu and Gallagher	Catalysing strategic transformation to a low-carbon economy: A CCS roadmap for China	M	Outlines possible future for industrial and power CCS in China, mentioning key blocks. A good regional study of the possibility of large-scale CCS implementation in China.
Liu and Liang	Strategy for promoting low-carbon technology transfer to developing countries: The case of CCS	H	Discusses macro-alternative technology options. Assesses current policy engagement around the world, makes recommendations and also presents results of opinion polls. Great overview of the major current policies for CCS, and recommendations for future policy.
Loisel	Environmental climate instruments in Romania: A comparative approach using dynamic CGE modelling	M	Looks at the establishing of carbon emission permits across industry in Romania, based loosely on the EU ETS. This is a computational modelling investigation, and shows that such a scheme can promote economic activity, unlike a carbon tax. Interesting applied investigation into tradable permits.
Lokey	Valuation of Carbon Capture and Sequestration under Greenhouse Gas Regulations	L	The paper discusses CCS and its potential for use globally, as well as economic factors that hinder implementation of CCS.
Lucas et al.	Long-term reduction potential of non-CO_2 greenhouse gases	L	The paper discusses reduction possibilities of non CO_2 GHG, but no mention of CCS- irrelevant to CCS.
Luckow et al.	Large-scale utilization of biomass energy and carbon dioxide capture and storage in the transport and electricity sectors under stringent CO_2 concentration limit scenarios	M	Looks at CCS applied to large-scale Biomass-derived energy suppliers. Finds that a carbon price of $150t/$CO_2$ would be required to make biomass CCS cost-effective. Theoretical paper on biomass energy uptake and, if that uptake were to be realised, how and under what conditions CCS could be feasible for those biomass power plants.
MacDowell et al.	An overview of CO_2 capture technologies	H	Paper discusses the advantages and disadvantages of three crucial carbon capture technologies: Chemisorption, carbonate looping and oxyfuel. It looks at specific examples and theory in its analysis. Paper gives case-study example costs, and also relative cost weightings between capital and operational financing. Three key technologies, and their implementations, are discussed here, as well as indicative cost studies for industrial carbon capture.

Mace et al.	Regulatory challenges to the implementation of carbon capture and geological storage within the European Union under EU and international law	H	Considers what is being done to create sound regulatory framework for CCS within a European setting, and what more needs to be done and where. Good summary of current (2007) EU policy relevant to CCS, and discussion of gaps and issues that need to be clarified and addressed specifically for CCS in these pieces of legislation.
Manzolini et al.	Integration of SEWGS for carbon capture in natural gas combined cycle. Part A: Thermodynamic performances	L	The paper discusses the usage of sorption enhanced water gas shift (SEWGS) as a pre combustion technology for CCS on an IGCC, and the integration of the technology within the plant to utilise waste heat. The efficiency penalty can be reduced to 7%, while capture efficiency depends on the energy recovery from the CO_2-steam purge. The maximum possible is 95.3% CO_2 capture efficiency and 50.9% energy efficiency. Related to power only.
Manzolini et al.	Integration of SEWGS for carbon capture in Natural Gas Combined Cycle. Part B: Reference case comparison	L	The paper compares the SEWGS to other methods of CCS on an IGCC, namely MEA and MDEA, to gauge the efficiency differences and CO_2 capture rates, as well as energy uses, to provide an accurate comparison with the SEWGS process. Related to power only, although includes comparison of CO_2 capture rates etc. for different solvents.
Martunus et al.	In situ carbon dioxide capture and fixation from a hot flue gas	M	The paper discusses the possibility of using mineral carbonation of NaCl and ammonia to produce soda ash, a saleable product, whilst using up the CO_2. The NH_3 and the NaCl can both be recycled. The energy cost of capture is 230kWh/tCO_2, which can be converted to cost, and for every 1t/h of CO_2 captured, 27kg/h are lost to atmosphere. 0.189kg/h of CO_2 can be converted to 0.409kg/h of soda ash. Principally a mineral carbonation paper, but with some info about costs and efficiencies.
McGrail et al.	Overcoming business model uncertainty in a carbon dioxide capture and sequestration project: Case study at the Boise White Paper Mill	H	This paper discusses using CCS on a paper mill. This could give up 1MtCO_2/yr. savings, whilst being used only at times when electricity prices are low enough for it to be viable. The CO_2 capture efficiency is up to 62%, with a payback period of 6.7-7.4 years. The paper discusses the costs required to fund a CCS project and the payback time, if there were to be a payment made for CCS. Gives info about a CCS system on a paper mill, including capital costs of a CCS system.
Mendiara et al.	Performance of a bauxite waste as oxygen-carrier for chemical-looping combustion using coal as fuel	L	Focuses on CCS using bauxite waste at a coal power plant- not relevant to industrial CCS.
Mertens et al.	On-line monitoring and controlling emissions in amine post combustion carbon capture: A field test	H	Investigates amine emission dependency on various operating parameters of a post-combustion carbon capture plant. Great investigation on pilot plant into amine emissions and operating parameters.
Mi et al.	Development and deployment of clean electricity technologies in Asia: A multi-scenario analysis using GTEM	L	The paper discusses the potential effects of CCS on the economies of Asian countries if it were to be implemented under different mitigation scenarios. The study found that the GDP of all countries would fall compared to a reference case due to the large investments required in CCS technology, with china falling in the region of 6% by 2050, India by 4% by 2040, although Japan will see little change due to it being a large technology exporter with a cleaner economy than the other two, based on a scale of CO_2 emissions per GDP (measured in kg CO_2/\$). The paper doesn't discuss costs of the technology, but rather the wider impact on the Asian economies of adopting CCS. Instead of the usual cost given per tonne of CO_2, this addresses long term changes in the economy, forecasting decreases in GDP from a reference case or 4-6% for India and China, and staying roughly level for Japan.

Mitchell et al.	Microbially Enhanced Carbon Capture and Storage by Mineral-Trapping and Solubility-Trapping	L	The paper discusses the use of microbes to enhance the solubility of CO_2 in brine, for use for storage in saline aquifers, and for speeding up mineral carbonation for mineral sequestration of CO_2. While it gives qualitative data, it lacks quantitative data for large scales and economic data. Low TRL. Potentially useful storage paper, but low TRL and no economic data.
Möllersten	Potential and cost-effectiveness of CO_2 reductions through energy measures in Swedish pulp and paper mills	M	Considers applicable technologies to the PPI that could reduce CO_2 emissions, and ultimately also mitigate against them. This paper focuses on the Kyoto protocol and its implications to the (Swedish) PPI. Outdated, but thorough, look at carbon saving in the PPI, with mentions of CCS.
Morks et al.	Mn-Mg based zinc phosphate and vanadate for corrosion inhibition of steel pipelines transport of CO2 rich fluids	L	The paper discusses the use of Mn-Mg based zinc compounds to be used to coat pipelines that would carry CO_2 rich gas to inhibit corrosion. Concerned with materials information for storage
Moya and Pardo	The potential for improvements in energy efficiency and CO_2 emissions in the EU27 iron and steel industry under different payback periods	L	The paper summarises the emissions reduction possible from iron and steel with technologies with a variety of different payback periods. No info about CCS.
Najafabadi	CO_2 chemical conversion to useful products: An engineering insight to the latest advances toward sustainability	L	The paper proposes alternate uses of CO_2 so that instead of geological sequestration, it can be used as a feedstock, for example in producing plastics or in EOR.
Naqvi et al.	Black liquor gasification integrated in pulp and paper mills: A critical review	L	Considers black liquor gasification implementation- not directly relevant to CCS
Naranjo et al.	CO_2 Capture and Sequestration in the Cement Industry	M	Considers feasibility of three main technologies for retrofitting in the cement industry. Good overview of applicability of CCS technology to cement, but lacks quantitative data.
Naude	Climate Change and Industrial Policy	L	The paper discusses ways to promote low carbon industrialisation of the developing world, as well as seeing how the developed world can reduce its emissions. Only brief mention of CCS, and little about different technologies.
Neal et al.	The economics of pressure-relief with CO_2 injection	L	Consider the use of down-hole pressure relief to assist CO2 injection and storage. Concerned with injection and storage as supposed to capture of CO_2.
Nilsson et al.	The missing link: Bringing institutions and politics into energy future studies	M	Looks at how governments and legislative bodies might be encouraged to study energy future in a similar way to the private sector. Not relevant to CCS, but rather considering how to more deeply involve and educate legislative bodies on energy future studies.
Northey et al.	Using sustainability reporting to assess the environmental footprint of copper mining	L	The paper discusses the use of sustainability data to assess the carbon emissions and emissions reduction potential of the copper industry, and the way these are reported. No mention of CCS or useful facts regarding it.
Oda et al.	Analysis of CCS Impact on Asian Energy Security	H	Introduces the concept of an Energy Security Index, which can be calculated for each country. The report then considers how this index is affected by three main factors: the geographical location, the capacity of domestic carbon storage and the domestic natural resources available. Provides a useful look at how prescribed increase in CCS uptake could affect international energy security.
Oda et al.	Diffusion of energy efficient technologies and CO_2 emission	L	The paper discusses the diffusion of energy efficiency technologies into the iron and steel industry. This is not directly related to CCS, although diffusion investigation may be applicable.

	reductions in iron and steel sector		
Okereke and McDaniels	To what extent are EU steel companies susceptible to competitive loss due to climate policy?	H	Considers the exceptions and free-allowances of emissions granted to iron and steel corporations under the EU ETS. The paper looks at how loss of competitivity claims have led to such measures as 'pass-throughs' (or the passing on of emissions cost to the customer) among others in order for the steel corporations to remain and thrive. Great insight into lobbying and policy challenges in the iron and steel industry.
Oraee-Mirzamani et al.	Risk Assessment and Management Associated with CCS	H	Uses a fault tree analysis and analytical hierarchy process to investigate and quantify the risks associated with the large-scale deployment of CCS technology. Great investigation into the major risks (particularly for insurance) of CCS development.
Orcutt	Can Carbon Capture Clean Up Canada's Oil Sands?	L	The article discusses the possibility of using CCS to help clean up oil sands by burning with CCS, so that all impurities and emissions can be captured. Although oil sands would not have as good a prospect as traditional sources, they would still contribute to a low carbon strategy. Only mentions power CCS.
Orr	CO_2 capture and storage: are we ready?	L	General discussions around alternative technologies. Some loose projected operating costs per kWh for power plants. Mainly qualitative information.
P R Newswire	Mantra Energy Alternatives Granted Patent for Carbon Capture and Recycling Process	L	Describes the patent granted to Mantra Energy by the Indian government for a process which captures CO_2 and reduces it to formic acid. A news release of a granted patent.
Packer	Algal capture of carbon dioxide; biomass generation as a tool for greenhouse gas mitigation with reference to New Zealand energy strategy and policy	L	The paper discusses the use of algae to capture CO_2, but cites a very low TRL. The paper proposes the use of algae to capture CO_2, and the policies required to help facilitate this. Low TRL, so policies are of relatively low relevance.
Padungthon et al.	Carbon dioxide sequestration through novel use of ion exchange fibres (IX-fibres)	H	The paper discusses the socio political implications of USA and China wanting to reduce their emissions, due to both countries having entrenched coal power generation and coal use for industry, and the need for CCS in this scenario. The paper discusses the importance of shifting away from coal, and the long term effects that this will have on the power generation industries of both countries. The paper highlights the disparity between other strategic goals for the two countries and CCS, due to the extra increased cost, increased energy consumption and slowed growth afforded by it. In the USA, at a state level, those without areas that CO_2 can be injected or hydrocarbon production areas may feel as if there is no benefit, highlighting the requirement for a central policy from the federal government, similar to the siting of Low level radioactive waste. In China, the need for growth is contrary to the deployment of CCS, but their experience of rapidly deploying and developing new technologies could provide global advantages due to them driving down the cost of gasifiers, for example. The West, and especially the USA, is ahead on the storage aspect, both geologically and with reinjection, previously for EOR. Displays differences in national priorities in USA and China that may hinder CCS deployment, but also the advantages that each country can offer.
Padurean et al.	Pre-combustion carbon dioxide capture by gas–liquid absorption for Integrated Gasification Combined Cycle power plants	L	Only power CCS was considered.

Palumbo et al.	Prospects for enhancing carbon sequestration and reclamation of degraded lands with fossil-fuel combustion by-products	L	Considers the incentives that might be required to promote the use of energy industry by-products as regenerative soil enhancing chemicals. Interesting, but irrelevant to industrial carbon capture.
Pan et al.	CO2 Capture by Accelerated Carbonation of Alkaline Wastes: A Review on Its Principles and Applications	L	The paper discusses the use of alkaline industrial wastes, such as from steel slags or metal wastewater, in mineral carbonation. As well as capturing CO_2, the process can also remove the alkaline components of the waste, for easier storage. This would reduce waste streams and make them easier to process. However the paper states that more research is needed before economics of the process are clear, and that the optimal operating conditions are not yet known.
Pardo and Moya	Prospective scenarios on energy efficiency and CO_2 emissions in the European Iron & Steel industry	M	Takes a close look at all currently available emissions reductions technologies for the iron and steel industry, and also at technologies expected to come into their own within the next few decades (including CCS by 2020). Considers three model worlds of the next 20 years- a baseline case, and high and low cost CO_2 cases (dependent on legislation). Great model of prospective scenarios in the EU Iron and steel industry, with a good review of technologies available.
Park et al.	Hydrate-based pre-combustion capture of carbon dioxide in the presence of a thermodynamic promoter and porous silica gels	M	Investigates gas hydrate formation as a means of CO_2 capture. Good information on gas hydrates, but no cost data.
Pettersson and Harvey	Comparison of black liquor gasification with other pulping biorefinery concepts – Systems analysis of economic performance and CO_2 emissions	H	Considers black liquor gasification implementation for paper mills. Looks in detail at process and emissions, and considers where CCS technology could be implemented on the production process. Good, qualitative look at how CCS could be included in black liquor gasification processes for PPI.
Pfennig et al.	Influence of heat treatment on the corrosion behaviour of stainless steels during CO_2-sequestration into saline aquifer	L	The paper details the effect that heat treatment can have on stainless steel for use in CO_2 transport and storage. Materials info for storage
Pielke Jr.	An idealized assessment of the economics of air capture of carbon dioxide in mitigation policy	L	Considers the costs and economic challenges to implementation of air-capture CCS.
Pires et al.	Carbon dioxide capture from flue gases using microalgae: Engineering aspects and biorefinery concept	M	This paper discusses the use of microalgae as a method of capturing CO_2, with the added benefits of the CO_2 being used to produce useful products such as fuel and pharmaceuticals, with solar energy as a catalyst for the fixation reaction. The process can be used for CCS from flue gas, wastewater treatment and biomass production, and all 3 can be integrated into one bioreactor. However, the tech is far from being ready to be used and as such no costs for such a process exist, although they are thought to be high (pumping the medium, compressing air, harvesting biomass etc) but it is yet to be seen whether the saleable products make this an economically viable option. Lack of economic data and low TRL, but interesting concept with potential for economic favourability.

Pollak et al.	Carbon capture and storage policy in the United States: A new coalition endeavours to change existing policy	M	The paper discusses the views of two rival factions when considering US policy on climate change, and more specifically on CCS. The two factions are climate coalitions who seek change to existing geological storage policy to maximise GHG reductions when climate policy is enacted, and the energy companies who wish to minimise harm to fossil fuel industries if climate policy were to be enacted. CCS can appease both of these groups, as it doesn't affect the ability of the energy groups to burn fossil fuels, but at the same time offers large CO_2 reductions for the climate lobby. The paper discusses the opposing views of EOR, whether CO_2 is put underground for storage or to maximise fossil fuel extraction, and states that the energy companies' view that it's important for extraction primarily is that that is used by policy makers. Further discussion of the topic will advance the cause of both sides, even if no large changes are made.
Pool	Deep down [alternative coal mining could see carbon dioxide plunging to new depths]	M	Underground coal gasification interview and article. Informal introduction to underground coal gasification.
Powell and Qiao	Polymeric CO_2/N_2 gas separation membranes for the capture of carbon dioxide from power plant flue gases	M	The paper discusses methods of separating CO_2 and N_2 in flue gases from power stations through the use of polymeric membranes. The membranes can also be used to separate O_2 and N_2 for oxy-combustion. The different types of polymers are considered and compared for their performance, with polyimide and polyethylene oxide polymers having good gas separation properties. However, the study highlights the amount of research needed before these polymers will be viable. Gives info about promising polymers for oxy-combustion and post combustion capture, but little detailed info about costs or TRL
Praetorius and Schumacher	Greenhouse gas mitigation in a carbon constrained world: The role of carbon capture and storage	M	The paper considers the drivers behind the acceptance of CCS; pros - will allow existing tech and resources to be used with smaller incurred cost for decarbonisation than going fully renewable, allows exploitation of domestic fossil fuel resources so satisfies energy security concerns (unless in fossil fuel-less area like Japan), possible first mover advantages to companies if new tech is pushed for. Disadvantages: only bridging strategy, untested, liability etc. This paper provides insight about the role of CCS in future energy mixes and the potential future for the industry, as well as challenges.
Radgen et al.	Too Early or Too Late for CCS-What Needs to be Done to Overcome the Valley of Death for Carbon Capture and Storage in Europe?	H	The paper discusses the necessary steps to get CCS from its current state to becoming a technology that is ready to be adopted on a large scale. It addresses the optimism about CCS in the past, when there was not enough support behind the technology to be able to deploy it, and discusses the changes required to get there. More appreciation of the legal and legislative framework must be taken into account, for example in not setting targets of 12 CCS demo projects by 2015 in the EU when this is unfeasible due to a lack of incentive and support for such a scheme. Consensus between national governments and larger bodies such as the EU must be made to allow a clearer strategy on CCS possible. Recent roadmaps have shown the importance of CCS, but the regulation surrounding it must be made attractive for the first step' to be made, with momentum required by at least 2 or 3 demo projects in Europe this decade. Contains discussion of EU policy over past decade and why CCS hasn't progressed as fast as hoped. Can be used to provide recommendations on future policies and the effects of them on CCS.
Rahman and Khondaker	Mitigation measures to reduce greenhouse gas emissions and enhance carbon capture and storage in Saudi Arabia	L	Considers Saudi Arabia's options to reduce its emissions. Localised, and containing little discussion of CCS.
Rai et al.	Carbon capture and storage at scale: Lessons from the growth of analogous	H	This paper uses the examples of nuclear power, LNG market and SO_2 scrubbing to identify the challenges and obstacles facing the widespread deployment of CCS worldwide, and seeks to use lessons learned

	energy technologies		from these three examples to suggest policies to speed up implementation. It discusses the fact that most current CCS plants have special circumstances or they would not be profitable, e.g. EOR or Norway's carbon tax. The paper discusses the S-curve of technology penetration as demonstrated by nuclear, SO_2 scrubbers and LNG market, and discusses the similarity of the three to CCS, of which nuclear is closest with high cap-ex, technological complexities etc. The rush to adopt nuclear power with government pressure and regulation on a short timescale is mentioned as something that would benefit CCS, but the different political climates and drivers mean this is unlikely to occur in this instance. The Japanese LNG market is used as an example of when governments can underwrite the risk associated with large scale tech deployment, meaning that companies are much more likely to invest and push tech deployment. The paper discusses ways of promoting private investment by the government taking or limiting the risk, improving the attractiveness of new tech. It also discusses the fall in costs associated with tech as more experience with it is gained, as well as an increase in effectiveness. The paper also discusses how to incentivise future CCS deployment, using the case of storage through EOR as an example of how it can be successful, with 100 examples currently in the USA. Until uncertainty su rrounding CCS is reduced, there will be only limited further development.
Ramírez et al.	A Comparison of national CCS strategies for Northwest Europe, with a focus on the potential of common CO_2 storage at the Utsira formation	H	This paper discusses the potential of using the Utsira field as a location for carbon storage, and the costs and implications associated with it. The paper considers potential future energy mixes in the year 2050, and the necessity of a large carbon storage reservoir for northwest Europe. This paper mentions the costs of transporting and storing the carbon dioxide, but not the costs associated with capturing it. This paper illustrates the potential of a carbon storage well, as well as presenting the costs of transport of CO_2. In addition to this, it discusses potential future energy mixes for major EU economies.
Randers	Greenhouse gas emissions per unit of value added ("GEVA") — A corporate guide to voluntary climate action	L	The paper discusses how organisations and individuals can make a big difference in reducing their CO_2 emissions, as the paper suggests that they think there will be little in the way of policy directives at a national level. It suggests CO_2 reductions at a smaller scale.
Rankin	Geologic Sequestration of CO_2: How EPA's Proposal Falls Short	L	Addresses EPA proposal for geological storage, in article where claims are refuted.
Rebitanim et al.	Potential applications of wastes from energy generation particularly biochar in Malaysia	M	Investigates the uses of biochar for CCS. Quantifies the volumes of production, and considers the use of biochar for CCS processes. Focus is on Malaysia, but could be applied more widely.
Renforth	The potential of enhanced weathering in the UK	M	Looks at the mining, milling and spreading of particular rocks to absorb CO_2 from the atmosphere via enhanced weathering. Derives costs of process per tCO_2 captured (around £44)Great analysis of enhanced weather potential (in the UK) but perhaps more of an offset technique than a direct industrial solution.
Renforth et al.	Contaminant mobility and carbon sequestration downstream of the Ajka (Hungary) red mud spill: The effects of gypsum dosing	M	Looks at emergency responses in terms of carbon sequestration for the large industrial spill of caustic bauxite processing residue. The addition of gypsum to act as a carbon sink is the favoured solution. Looks at ways to capture carbon emissions from an industrial spill in Hungary. Results have limited application to aluminium industry CCS.
Renforth et al.	Engineering challenges of ocean liming	L	This paper looks at the detailed process of mining, comminution, calcification, transport and spreading of calcine limestone in the oceans to both de-acidify the seas and allow them to act as a more effective carbon sink. Looks at the costs involved of large-scale ocean liming. Good paper on ocean liming, not directly relevant to this investigation.

Romão et al.	CO_2 fixation using magnesium silicate minerals. Part 2: Energy efficiency and integration with iron-and steelmaking	M	Investigates the energy input requirements of chemical adsorption and storage of CO_2 by rock-derived magnesium silicate materials. Looks in detail (aspen model) at the possible use of certain rock types for CO_2 capture and storage.
Romeo et al.	Reducing energy penalties in carbon capture with Organic Rankine Cycles	M	The paper discusses the use of an organic Rankine cycle (ORC) to generate power from waste heat to reduce the efficiency penalty associated with oxy-fuel CCS from a power station, although the same concept could also be utilised in industry. By assessing how the low grade waste heat can be used, the calculated effect is a 25% reduction in the efficiency penalty associated with the oxyfuel CCS, from 11% to 8.2%, by using either R123 or toluene. Can be used to demonstrate a way to reduce the energy demand of CCS.
Rootzen and Johnsson	Deployment of CCS in industrial applications in the EU – timing, scope and coordination	H	Summarises energy emissions from different industrial sectors in China, and compares with rest of world. Substantial steps toward the 80% reduction from 1990 levels can be made by the implementation of CCS on industrial plants if deployed from 2030, with a potential reduction of 80% from 2010 levels, although at a high financial and energy cost. 300 large industrial plants make up 8%. From refining and iron and steel, it was assumed that 60% of CO_2 emissions could be avoided, and between 65 and 92% for cement manufacture with oxyfuel or post combustion capture. The paper highlights the requirement for policy because CCS is very expensive and has no financial gain that is associated with it. The most promising locations and methods for CCS are discussed for each of the industries, and graphical representations of CO_2 emissions versus electricity demand, and it is concluded that the deep cuts cannot be made without CCS, but even if they are, the cost will be massive.
Rootzén and Johnsson	Exploring the limits for CO_2 emission abatement in the EU power and industry sectors—Awaiting a breakthrough	H	The paper discusses current techniques for reducing CO_2 emissions from industry and power generation and mentions abatement methods. However, the paper does not explicitly mention CCS apart from it being mentioned as a strategy; no in depth analysis is made. The paper presents recommendations on how to best decarbonise EU industry, though not explicitly to do with CCS. Presents large tables of data about the number and size of EU Industries.
Rubin et al.	The outlook for improved carbon capture technology	M	Looks into the current major technologies available for CCS, and potential upcoming improvements. Studies relative merits of each. Looks at current legislative roadmaps for CCS implementation.
Russo et al.	Post-combustion carbon capture mediated by carbonic anhydrase	L	The paper discusses using an enzyme, carbonic anhydrase, to capture CO_2 from combustion plants. However, there have not been any experiments regarding scale up and the technology is still in its infancy. TRL still too low to be certain whether the high potential translates into feasibility.
Said et al.	Integrated carbon capture and storage for an oxyfuel combustion process by using carbonation of $Mg(OH)_2$ produced from serpentinite rock	H	Considers the oxyfuel capture of CO_2 from flue gas using a $Mg(OH)_2$ solid absorbent, forming MgCO3 as the final product ready for storage. Aspen modelling is used to quantify. Good investigation into mineral carbonation technology.
Said et al.	Production of precipitated calcium carbonate (PCC) from steelmaking slag for fixation of CO_2	H	Looks into the processing of calcium carbonate from steel-making slag for application to CCS. Good investigation into this technology. No costs mentioned.
Sanna et al.	Post-processing pathways in carbon capture and storage by mineral carbonation (CCSM) towards the	H	Mineral carbonation is discussed here, along with detailed capacities of various mineral sequestration potential. Gives costs of £/tCO_2 for CCS applied in various industries. Gives costs of CCS applied in various industries, useful references for cost data also included.

	introduction of carbon neutral materials		
Sanna et al.	Waste materials for carbon capture and storage by mineralisation (CCSM) - A UK perspective	M	The paper discusses the potential for using mineral waste from industry for CCS through carbonation. The report has figures for the availability of different waste types for the UK and the potential capture potential of CCSM, up to 1MtCO_2/yr in the UK. Information about CCSM and its potential in the UK, though little in the way of costs. Acknowledges that applications are likely to be niche, since only 50% of the CO_2 in a flue stream will be captured.
Santos et al.	Accelerated mineral carbonation of stainless steel slags for CO_2 storage and waste vaporization: Effect of process parameters on geochemical properties	L	This paper investigates carbonation of steel slag. It finds this to be an effective method of cutting slag volume, but also that insufficient slag volume could possibly be too low to be of use in CCS large scale.
Santos et al.	Integrated Mineral Carbonation Reactor Technology for Sustainable Carbon Dioxide Sequestration: 'CO_2 Energy Reactor'	M	Mathematical study of carbon capture by mineralisation. Good, technical look into mineral carbon capture.
Sathre and Masanet	Prospective life-cycle modelling of a carbon capture and storage system using metal–organic frameworks for CO_2 capture	L	Discusses the option of using metal-organic frameworks. Interesting look at technology and life-cycle, but not highly relevant within the scope of this investigation.
Schneider et al.	Sustainable cement production—present and future	M	Briefly considers the technology available for CCS in the cement industry. Does not go into great detail at all however. A general look at costs for CO_2 capture technologies implemented onto cement plants. Good background information on energy requirement and emissions sources within the cement industry. However CCS section itself is relatively small and general.
Schwebel et al.	Comparison of natural ilmenites as oxygen carriers in chemical-looping combustion and influence of water gas shift reaction on gas composition	H	Looks at the use of a particular group of materials (rock ilmenites) as a CO_2 carrier material in carbon capture processes. The report analyses, under laboratory conditions, the relative technical performances of five different ilmenites. Good technical investigation of ilmenite rocks as CO_2 carriers.
Shah et al.	Application of Ultraviolet, Ozone, and Advanced Oxidation Treatments to Washwaters To Destroy Nitrosamines, Nitramines, Amines, and Aldehydes Formed during Amine-Based Carbon Capture	L	Looks at practical treatment of amine-derived substances from amine-based CCS processes. This paper focuses on the processing of CCS exhaust chemicals rather than on the capture process.
Sim et al.	Aqueous Corrosion Testing and Neural Network Modelling to Simulate Corrosion of Supercritical CO_2 Pipelines in the Carbon Capture and Storage Cycle	L	The article discusses corrosion issues with CCS process equipment, most relevant to materials for transport and storage.
Sim et al.	Investigating the effect of salt and acid impurities in supercritical CO2 as	L	The paper discusses corrosion issues associated with transport of CO_2 due to salts and acidic impurities in the CO_2 streams- mostly relevant to materials for transport and storage.

	relevant to the corrosion of carbon capture and storage pipelines		
Singh et al.	Comparative impact assessment of CCS portfolio: Life cycle perspective	L	Considers life-cycle analysis of CO_2 capture in gas or coal fired power plants. Life-cycle analysis of CO_2 captured from gas and coal power plants and hence not applicable to industrial CCS.
Singh et al.	Comparative life cycle environmental assessment of CCS technologies	M	Considers life-cycle analysis of CO_2 capture in gas or coal fired power plants. Considers environmental trade-offs of CCS applied to power plants.
Sjostrom et al.	Pilot test results of post-combustion CO_2 capture using solid sorbents	H	Looks at CO_2 absorbent potentials of carbon, amine and seolite based adsorbents. Good look at the relative performances and vulnerabilities of the three main types of CO_2 sorbent on a laboratory scale
Skjærseth and Wettestad	Making the EU Emissions Trading System: The European Commission as an entrepreneurial epistemic leader	H	This report is an investigation into how the EU brought about the ETS, only a few years after having been strongly opposed to its implementation. This paper investigates how epistemic, informed and entrepreneurial leadership can be used to bring about significant societal change in the area of carbon change, It cites and studies the ETS as its basis, then goes on to show how the technique could be applied to new policy and initiatives.
Smekens-Ramirez Morales	Response from a MARKAL technology model to the EMF scenario assumptions	M	Analyses the best cost-effective methods of CCS implementation to reach emission targets, the models costs and most cost-effective CO_2 implementation strategy. Gives good early cost model analysis of CCS
Song	Global challenges and strategies for control, conversion and utilization of CO_2 for sustainable development involving energy, catalysis, adsorption and chemical processing	L	Looks mainly at post-capture uses for CO_2. Capture technological overview is outdated, focus on end-uses of CO_2 was considered largely irrelevant to this investigation.
Song et al.	Evaluation of Stirling cooler system for cryogenic CO_2 capture	M	The paper discusses the application of Stirling cycles in CO_2 capture through cryogenic cooling. The recovery of CO_2 is up to 85% with 3.4MJ/kgCO_2 consumption. Because it operates cryogenically without a solvent, there is no energy penalty for regeneration of solvent, although there is a long idle operating time to get to the required temperature, and the frost layer of captured CO_2 will affect the heat transfer adversely and reduce the overall efficiency. Paper looks at novel capture method, but with little info on costs, potential for scale up. Could potentially be used on smaller point sources.
Sovacool et al.	From a hard place to a rock: Questioning the energy security of a coal-based economy	L	Considers both the energy security implications and the emission implications of continuing to operate a coal-based economy in the US and the world. Applicable to power more than industrial CCS, and not explicitly CCS in any case.
Spigarelli and Kawatra	Opportunities and challenges in carbon dioxide capture	H	The paper discusses all current capture techniques and their advantages and disadvantages when applied to flue gases. Due to their high relevance, these findings are summarized below. **Post combustion (amine sorbents)** Advantages: small impact of CO_2 partial pressure on capacity, favourable adsorption kinetics, Disadvantages: degrade at 100ºC, irreversible reactions with NO_x and SO_x, temp swing needed for desorption with loss in capacity following. **Activated carbon** Advantages: high thermal stability, good adsorption kinetics, large capacity at high T, easy desorption through pressure swing. Disadvantages: low CO_2 capacity at mild conditions, negative impact of H_2O, NO_x, SO_x. **Membranes** Advantages: low cap-ex, no solvent regeneration, compact, no foaming etc. Disadvantages: requires compression of flue gases, high selectivity membranes required, gas must be below 100ºC or damage, must be resistant to plasticisation and impurities in flue, low capture efficiency requiring 2 stages. **Cryogenics**: Advantages: no reagents required, Disadvantages: all H_2O must be removed, high cap-ex and refrigerant costs, efficiency

			decreases over time due to solid CO_2 build-up. **Selexol Adsorption** Advantages: physical adsorption, so minimal temperature rise, non thermal solvent regeneration, non corrosive so cheaper cap-ex, dry gas from adsorber. Disadvantages: needs high pressure. **Rectisol** Advantages: no foaming, miscible solvent, high chemical and thermal stability, non corrosive, non thermal solvent regeneration. Disadvantages: solvent absorbs trace metals like Hg at low temperature, refrigeration means high op-ex, complex operation scheme so high cap-ex. **Fluor** Advantages: CO_2 highly soluble, simple operation, regeneration doesn't require heating. Disadvantages: high flowrates required so high op-ex, expensive solvent. **Purisol** Advantages: no foaming, high thermal and chemical stability, noncorrosive, low volatility. Disadvantages: needs further compression after water gas shift. **Oxycombustion** Advantages: close to 100% CO_2 capture efficiency, higher CO_2 concentrations mean easier capture, suppressed NO_x formation (50% lower). Disadvantages: large O_2 volume required, difficult retrofit, air leaks into system degrade performance, must be dry, large plant required. **Chemical Looping Combustion** Advantages: no energy loss in CO_2 separation, no dilution of CO_2 stream with N_2 so easier capture, inherent reduction in NO_x, can be used for any fuel. Disadvantages: difficult operation of fluid bed reactors, sustained contact between MeO and fuel, deactivation of MeO due to unburned C, still low TRL, desulphurisation required before use.
Stechemesser and Guenther	Carbon accounting: a systematic literature review	L	A literature review aiming to find or derive a consistent definition and approach to carbon accounting. Useful for information around carbon accounting, not particularly for CCS
Stendardo and Foscolo	Carbon dioxide capture with dolomite: A model for gas–solid reaction within the grains of a particulate sorbent	L	The paper discusses the use of dolomite for mineral sequestration, with a number of small grains of mineral contacting the gas. Because of this, the void fraction increases as the particles grow when the reaction proceeds. However, there is no scale up or costing information, so a low TRL is inferred. Discussed elsewhere, low TRL and no mention of scale up or economics.
Stephens et al.	Characterizing the international carbon capture and storage community	L	This paper discusses the CCS community, categorising it as one that is fragmented into different areas that compete for resources, meaning that often groups with very similar overall aims are competing instead of collaborating. This is due to the different nature of CCS compared to other technologies, as it is not one tech but a collection of them, grouped together in policy documents. The community has problems with communication, often contradicting each other, but a strong message of support for CCS and a need for governments to do something. Explores the community's need to develop clear rhetoric on the subject, as policy makers may be loath to invest time in policies when there is not a unified message from the experts and they make decisions based on conflicting testimony.
Sterner and Damon	Green growth in the post-Copenhagen climate	L	The paper discusses green growth, and ways in which it would be possible to prove low-carbon technology. It states that action must be made soon to have any real effect due to opponents and sceptics. No information about CCS.
Stolaroff et al.	Using CaO- and MgO-rich industrial waste streams for carbon sequestration	H	The paper discusses the usage of steel slag and cement waste (CaO and $Ca(OH)_2$) in mineral sequestration, to be stored as $CaCO_3$, while removing a waste source at the same time. The paper details the make-up of a plant that could process varying amounts of waste per year, depending on the source. In order to sequester 32kt of CO_2 per annum, 32kt of steel slag would be needed, or 680kt of waste concrete or 200kt of concrete fines. While the study recognises that this is a small amount compared to global emissions, the economics of the process would make it very favourable. The study also concedes that the plants to process this waste would be small compared to the scale required to cut CO_2 emissions drastically, and the plants would all need to be different according to the specific niche of the location. The paper gives a total cost for the process at $8/t$CO_2$, which would be very favourable in the event of any

			subsidies which would likely be much larger, allowing the plant to operate profitably. The capital costs are given at $250,000 per annum for a 30 year life of the plant, meaning the total cost would be in the region of $7.5millionLow capture potential, but full op-ex and cap-ex provided.
Sun and Chen	The improved China CCS decision support system: A case study for Beijing–Tianjin–Hebei Region of China	L	Describes and suggests planned improvements to the proposed Chinese CCS infrastructure and pipeline systems. Interesting proposition for development of a CO_2 pipeline network within China.
Sun et al.	Sequestration of carbon dioxide by indirect mineralization using Victorian brown coal fly ash	M	Investigation into the use of brown-coal fly-ash for use in CO_2 capture and sequestration. Many operating parameters of the process have been investigated. Good experimental look at operating parameters and their relative influences on CO_2 uptake, but no mention of scale-up.
Tacke and Steffen	The impact of emissions trade on iron and steel technology	L	The paper presents the ISIM (Iron and Steel Industry Model) to simulate the iron and steel sectors from 1997-2030, and the changes that it would implement. No mention of CCS or useful facts regarding it.
Teir et al.	Prospects for application of CCS in Finland	H	Looks at the current state of Finland's carbon emitting industries and power sectors, and makes predictions based on empirical observations as to the likely future state and potential of Finland's CCS. Good, single-country study of CCS applicability and scope.
Thiruvenkatachari et al.	Application of carbon fibre composites to CO_2 capture from flue gas	M	The paper focuses on using carbon fibre honeycomb structures to capture CO_2 from a simulated flue gas of 13% CO_2. 98% capture efficiency was achieved, but that then had to be desorbed through heat and a vacuum, so a batch process would be required to achieve high degrees of CO_2 separation. After desorption, the CO_2 stream was almost 100% pure, with a recovery of about 97%. A novel capture technique, but very low TRL and requires batch process. Potentially applicable to batch processes, but no information on costs so unlikely to be deployed in near future.
Thiruvenkatachari et al.	Post combustion CO_2 capture by carbon fibre monolithic adsorbents	H	Investigates uses of carbon monoliths for carbon capture, detailing capture and regeneration processes and performance. Contains useful summary of available post-combustion CCS technologies, then goes on to investigate the potential of carbon fibre monolithic adsorbents in detail.
Thomson and Khare	Carbon Capture and Storage (CCS) Deployment -Can Canada Capitalize on Experience?	M	Technology only briefly discussed. This report more considers the potential scale of implementation of CCS in Canada then any particular policy approach. Discusses in great detail the challenges that large-scale implementation of CCS would encounter, albeit largely in a non-financial area.
Tong et al.	Continuous high purity hydrogen generation from a syngas chemical looping 25 kW(th) sub-pilot unit with 100% carbon capture	L	The paper discusses using a novel syngas chemical looping (SCL) system to generate syngas from gaseous fossil fuels by using ferrous compounds. This could be applied in industry where large amounts of heat are required, e.g. furnaces, and produces a stream of H_2 which can be sold or used as fuel. Long term trials were carried out which showed the equipment maintained operation at 99-100% for over 300 hours in a moving bed reactor. Novel technology but very low TRL, also difficult to apply and no mention of scale up or economics.
Troy and Wagner	Screening life cycle analysis of post combustion CO_2 -capture technologies–A comparison of construction phase results	L	The paper discusses the life cycle analyses of two different CCS technologies, membrane separation and amine scrubbing. The amine scrubbing is quite well known over the course of its lifetime, with it being in use for many years. However, the impact of using membranes is a lot more varied, with the performance of the membranes having large impacts on the emissions from the facility. Because of this and the uncertainty with calculations, few conclusions can be drawn with comparisons to amine scrubbing when considering CO_2 reductions over the life of a plant. Discusses mainly CO2 footprint of different plants, instead of the potential for the technology. Important for longer term planning etc., but not so much here.

Tsai et al.	Carbon Capture Regulation for The Steel and Aluminum Industries in the UAE: An Empirical Analysis	L	This paper considers the use of CCS as part of an EOR programme for UAE. An assessment is made as to the economic benefits of using EOR in Abu Dhabi, but the improvement is small so unfeasible at present. Little to no information about CCS in paper; mainly about economics of EOR.
Tsupari et al.	Post-combustion capture of CO_2 at an integrated steel mill – Part II: Economic feasibility	H	The paper investigates the necessary electricity price and cost of capture to make CCS an attractive investment in a given steel mill, and finds that the point at which CCS becomes economically more attractive than buying carbon credits is in the range of 58–78 EUR/tCO_2, if only electricity prices between 80 and 150 EUR/MWh are considered. Great, detailed look into costing and economic feasibility for CCS in the steel industry, with assumptions and calculations based on a steel mill called Rautaruukki Ltd.'s Raahe steel mill on the coast of the Gulf of Bothnia.
Tzanidakis et al.	Illustrative national scale scenarios of environmental and human health impacts of Carbon Capture and Storage	M	Considers the impacts, over the lifecycle of both retro-fitted and purpose built CCS units of power stations, of CCS on the environment. Considers the full environmental impacts of CCS, particularly with respect to air pollutants resulting directly from the application of CCS. A good look at the environmental consequences of large-scale CCS implementation in the UK
van Alphen et al.	Societal acceptance of carbon capture and storage technologies	H	Through analysing articles and reports from the Dutch media on CCS, this report looks at how the lay public- through the media- perceive CCS. Good study of press and public reactions to CCS propositions.
van den Broek et al.	An integrated GIS-MARKAL toolbox for designing a CO_2 infrastructure network in the Netherlands	L	Refers to relevant modelling software, investigating its relative merits.
van der Broek et al.	Impact of international climate policies on CO_2 capture and storage deployment: Illustrated in the Dutch energy system	H	Based on the Dutch electricity sector, this investigation aims to predict the global uptake of CCS in the coming years. Models costs and predicts a 2020 carbon price of between EUR20 and EUR47t/CO2. Great investigation with well-justified and modelled conclusions.
Van Puyvelde	CCS opportunities in the Australian "Industrial Processes" sector	H	The cement industry is one that is attractive to put CCS on as it provides a CO_2 rich flue gas (31%) which is easier to separate than one with lower concentration. The waste heat from the exhaust gases at 200C can be used to regenerate the solvent, reducing associated costs without impacting production. The cement plants in Australia produce 8Mt per year of cement and 5.7Mt per year of CO_2, so there is a large mitigation potential. The paper illustrates ways that using CCS on a cement plant can allow a reduction on a large scale of CO_2 emissions. It also highlights the potential advantages for using CCS on a cement plant instead of on power plants, using currently available technology, which could then be used to help push power generating industry towards CCS.
van Selow et al.	Carbon Capture by Sorption-Enhanced Water-Gas Shift Reaction Process using Hydrotalcite-Based Material	M	The paper discusses the use of SEWGS for CO_2 removal by a semi-batch process of adsorption and desorption at elevated temperatures and pressures. The use of a hydrotalcite-based sorbent was investigated over 1,400 cycles and was found to be a completely reversible reaction. In this reactor, CO can be converted to CO_2 with a conversion of 100% using steam to effect the pressure swing. The paper gives info about SEWGS, but specific to one sorbent. No costs or scaling information.
van Vuuren et al.	Exploring IMAGE model scenarios that keep greenhouse gas radiative forcing below 3 W/m(2) in 2100	L	No mention of CCS- this paper was considered irrelevant to the investigation.
Vatopoulos and Tzimas	Assessment of CO_2 capture technologies in cement manufacturing process	H	Three technologies: oxy-combustion, amine absorption and calcium looping are all considered in detail. The paper also mentions EU legislation. Great investigation into feasibility and scope for CCS in cement industry. Good references.

Verduyn et al.	Review of the various CO_2 mineralization product forms	L	The paper discusses the possibility of using mineral carbonation for CCS instead of geological storage after gas separation, and points to the example of two of Shell's processes giving good results in this. However, the demand for these carbonates is limited and only niche uses for them are discussed, potentially leading to problems with storage. The paper also discusses mineral carbonation, although there possibly isn't enough demand for it to be a feasible solution.
Vogeli et al.	Investigation of the potential for mineral carbonation of PGM tailings in South Africa	M	Use of platinum mining tailings for CCS by mineralisation. Another good look at mineralisation this time using platinum tailings. Also considers scope of potential tailings for CCS in the refineries industry.
Volkart et al.	Life cycle assessment of carbon capture and storage in power generation and industry in Europe	H	The paper analyses the life cycle emission reductions of implementing CCS at power plants and also at cement plants. The overall LCA reduction of CO_2 for a cement plant is between 39% and 78%, and 68-92% for power generation. However, there are trade-offs with respect to other environmental issues associated with CCS, meaning that these figures must be considered in context and cannot be used alone. For cement, the overall LC reduction of CO_2 is heavily dependent on the source of electricity due to the onsite waste heat being insufficient for the extra energy input required. The post combustion capture offered here is also advantageous as it can be retrofitted at a low cost with little impact on production. This paper provides LCA of cement based CCS and discussion of influences on the reduction potential for emissions. Can be used to provide a more balanced emissions reduction profile. Lack of costing data however.
von Stechow et al.	Policy incentives for carbon capture and storage technologies in Europe: A qualitative multi-criteria analysis	H	The paper considers policy incentives that could be used in the EU to reduce uncertainties and risk around CCS projects, and provides a table which details what effects different policies may have on CCS and electricity markets. Having a CCS mandate would negatively affect low-C investment and would distort electricity markets, while at the same time CCS may be postponed due to high uncertainty. CCS grants or tax breaks would reduce capital costs uncertainty, though at high short term public cost. However would have negative impact on electricity markets and other low carbon tech. A CCS quota would need to be funded by electricity price rises and tradable certificates, though this would have little impact on uncertainty and a negative impact on electricity markets. A CCS feed-in tariff would greatly reduce business risk of CCS, though increase electricity prices greatly. Guaranteeing a price of CO_2 would increase the electricity prices but reduce uncertainty, as well as negatively impacting other low CO_2 technologies. Having a CCS bonus would provide a smaller decrease in uncertainty, although would have less of an impact on electricity prices. Discusses options for reducing uncertainty, but also the impacts these would have on markets for electricity and other low carbon technologies
Wang and Maroto-Valer	Dissolution of serpentine using recyclable ammonium salts for CO_2 mineral carbonation	H	This paper investigates the barriers to mineral carbonation of CO_2, by studying a 'new' pH-swing mineralisation process using recyclable ammonium salts. Interesting application of different technology (particularly using pH-swing for CO2 absorption) to CCS.
Wang and Maroto-Valer	Integration of CO_2 capture and storage based on pH-swing mineral carbonation using recyclable ammonium salts	M	Use of recyclable ammonium salts and pH swing for carbonation of magnesium to mineral carbonates. Good look at looping ammonium salts to extract and carbonate magnesium and calcium.
Wang et al.	Reactivity of dolomite in water-saturated supercritical carbon dioxide: Significance for carbon capture and storage and for enhanced oil and gas	L	The paper discusses the reactivity of dolomite, a common mineral in geological areas relevant to carbon storage, and its reactivity with CO_2. Discusses geology of storage only, and so was not deemed relevant to this investigation.

	recovery		
Wang et al.	Trajectory and driving factors for GHG emissions in the Chinese cement industry	L	Overview of what is causing high CO_2 emissions in China's cement industry, and to what extent. Little discussion of alternative solutions or CCS.
Weimer et al.	Lime enhanced gasification of solid fuels: Examination of a process for simultaneous hydrogen production and CO_2 capture	L	The paper investigates the thermo of using a CaO looping system to capture CO_2 and produce hydrogen from brown coal, a 'dirty' fuel. The process can be used to produce cement as a by-product, meaning this would be best used on cement plants. Energy efficiency of the process is comparable to a power plant, so an integrated power plant/cement plant would be possible.
Wilday et al.	Addressing emerging risks using carbon capture and storage as an example	L	This paper uses the example of CCS as a demonstration of the hindrance that risk plays when assessing new technologies.
Wiley et al.	Assessment of opportunities for CO_2 capture at iron and steel mills: An Australian perspective	H	This paper assesses the different sources and costs of CO_2 capture within steel plants, with costs ranging from aus$77 to 600 AUD per tCO2 avoided. At the mini mills, the cost is generally over 200 AUD per tonne avoided, but from the integrated steel mill, capture from coke ovens, power plant and blast stoves are all possible for under 100 AUD per tonne. The blast furnace has comparable costs to the power plant, but the power plant is a direct source so capture there will reduce pump demand. The paper discusses the cost of capturing CO_2 from different sources in steel mills. It also gives costs of capture at different areas within a steel mill.
Wilson et al.	The socio-political context for deploying carbon capture and storage in China and the U.S	L	The paper discusses the upgrading of bitumen for use in an IGCC at 90% capture with an MEA solvent, however nothing relating to industrial applications, only power plants.
Wise and Dooley	The value of post-combustion carbon dioxide capture and storage technologies in a world with uncertain greenhouse gas emissions constraints	H	The paper discusses how applying constraints on GHG emissions on the most energy intensive region of USA would alter the outlook for post combustion capture of CO_2 with pulverised coal (PC + CCS) or with an IGCC (IGCC + CCS). Between the two, by 2045, there could be 3.2-4.9Gt of CO_2 stored in this one region. The paper states that CCS has the potential to vastly reduce the emissions of this region over the next 30 years, though states that the figures are estimates due to the lack of certainty about new plant construction. The paper discusses CCS implementations in USA for power grid and potential by 2045.
Xu and Cang	A Brief Overview of Low CO_2 Emission Technologies for Iron and Steel Making	H	Good discussion of pure oxygen top gas recycled blast furnace (TGRBF) and also of new technological options that reduce or eliminate the need for smelting and coking. Good, informed information on CCS applicability in iron and steel making. A lack of hard data, but lots of good theory.
Yamin Liu et al.	Carbon Dioxide Capture by Functionalized Solid Amine Sorbents with Simulated Flue Gas Conditions	M	Discusses a solid amine sorbent in use on a porous silica bed. Good investigation of adsorption behaviour of solid-bound amine sorbent.
Yang and Chen	Carbon footprint estimation of Chinese economic sectors based on a three-tier model	M	Summarises energy emissions from different industrial sectors in China, and compares with rest of world. Paper can be used to calculate estimated CO_2 emissions worldwide split into sectors.
Yang et al.	Incorporating environmental co-benefits into climate policies: A regional	M	Assesses impact of CCS technologies (among others) on cement production. The paper makes suggestions and justifications for the implementation of CCS and carbon reduction policy in Chinese cement industry. Discusses the cost of current pollution to the Chinese economy, and quantifies the difference that certain levels of emissions reduction could have on it. Useful supporting data on economic

			cost of current emissions, and economic impact of carbon reduction. Good general information on China and the cement industry.
Yoo et al.	Carbon dioxide capture capacity of sodium hydroxide aqueous solution	H	Looks into the potential of sodium hydroxide as a flue-gas CO_2 absorbent. This paper investigates the potential and performance of NaOH in capturing CO_2.
Zhang et al.	CO_2 emission reduction within Chinese iron & steel industry: practices, determinants and performance	H	This paper looks to make recommendations to legislators based on a quantitative survey undertaken of 85 Chinese Iron and Steel producers. The survey finds that while environmental benefits are both more clearly understood, and more easily attained through climate initiatives, it is the economic factors that mainly motivate the owners. Consideration of specific (although often unquantified) costs associated with Iron and Steel production and emission mitigation technologies. Good, primary source of evidence for how the iron and steel industry in China views climate change initiatives and policies.
Zhang et al.	Economic evaluation of CO_2 pipeline transport in China	M	The paper discusses the challenges associated with building a CO_2 pipeline network in China to allow the transport of CO_2 from the capture sites to the storage sites. Contains costs for CO_2 transport. The paper gives the costs for transporting CO_2 over large distances. The paper primarily discusses transport, including costs
Zhang et al.	Integrated Black Liquor Gasification Polygeneration System with CO_2 Capture in Pulp and Paper Mills to Produce Methanol and Electricity	H	Details polygeneration pulp and paper mill with biomass that can produce methanol and electricity from black liquor. Gives energy penalties and efficiencies of the cycles and costs. Paper details costs per tonne of CO_2 avoided and energy requirement of different options. Details how a plant could be made that combines waste heat from P&P with methanol and electricity production
Zhao et al.	Effect of reactor geometry on aqueous ammonia-based carbon dioxide capture in bubble column reactors	L	Studies the effects of reactor geometry on the performance of bubble-column reactors in capturing CO_2. A study of reactor geometry- not relevant to larger CCS picture considered in this investigation.
Zhao et al.	Rotary Bed Reactor for Chemical-Looping Combustion with Carbon Capture. Part 1: Reactor Design and Model Development	L	The paper discusses the use of chemical looping combustion in a power station and the design of the rotary bed reactor that enables the use of CLC technologies.
Zhaofeng et al.	Guidelines for safe and effective carbon capture and storage in China	M	The paper discusses the ways that CCS can be rolled out in China, with EOR first and then moving towards other forms as it becomes more economical. However, the paper discusses the lack of accurate solutions for CCS implementation due to uncertainty and a lack of technological knowledge. Scope for implementation of CCS in china, though lacks data and is sometimes vague regarding technology levels.
Zhou et al.	CO_2 emissions and mitigation potential in China's ammonia industry	M	The paper, as well as discussing non-CCS methods of reducing CO_2 emissions, mentions that there is potential for CCS to be used on ammonia plants. Almost half of ammonia plants have CO_2 capture installed to produce urea, so there is experience in the sector, however there is little experience of storage. This paper discusses the ways that CO_2 emissions can be cut from ammonia plants, and mentions Chinese government policy regarding climate change, whilst considering the governmental push for more nitrofertilisers, meaning the ammonia industry is a key one for mitigation. This paper can be used to quantitatively support ammonia CCS, and extrapolating from this, chemical manufacturing CCS, however it is very specialised towards NH_3.

9 About the authors

Duncan Leeson MEng

Duncan Leeson is a PhD student in Chemical Engineering at Imperial College London currently researching energy efficiency in refinery separation systems within the Centre for Process Systems Engineering. He obtained his degree in chemical engineering from Imperial College, with a particular focus on low carbon energy. He is currently collaborating with research on carbon capture and on industrial clustering.

Jamie Fairclough MEng

Jamie Fairclough received his degree in Chemical Engineering from Imperial College London, with a particular interest in Carbon Capture and associated technologies. He is currently employed as an Upstream Commercial Analyst for BP.

Dr Camille Petit

Dr Camille Petit is a Lecturer in the Department of Chemical Engineering Imperial College, where she leads the Multifunctional Materials Laboratory. Prior to her current position, she worked as a postdoctoral researcher at Columbia University, New York. She received her PhD in 2011 from the City University of New York (CUNY).

Her group's research interests broadly encompass the development of nanomaterials for applications relevant to the energy and environmental sectors. Specifically, her team focuses on metal-organic frameworks, graphene-based materials and nano-colloids to be used in gas/liquid adsorption (e.g. CO2 capture), catalysis or sensing.

Dr Petit is Associate Editor of the journal Frontiers in Carbon Capture, Storage and Utilization (CCUS). She is also the thrust leader of the NSF-funded research coordination network on CCUS.

Dr Petit has received several awards including: the Springer Thesis Award, the French Carbon Group Award, two CUNY Research Excellence Awards, and the American Carbon Society Mrozowski Award.

Dr Paul Fennell MA MEng PhD

Paul Fennell is a Reader in Clean Energy at Imperial College London. He obtained his degree in Chemical Engineering and PhD from the University of Cambridge. He also chairs the Institution of Chemical Engineers Energy Conversion subject panel, was a previous member of the International Energy Authority High-Temperature Solid Looping Cycles Network Executive, and has written reports for the Department for Energy and Climate Change (DECC) on future technologies for Carbon Capture and Storage (CCS) and carbon capture readiness. He is also the joint director of Imperial College's Centre for Carbon Capture and Storage and is the Research Area Champion for Industrial CO2 Capture and Storage for the UK CO2 Capture and Storage Research Centre. He has published 40 + papers since 2005.