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A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries.

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Abstract

A systematic review into the literature surrounding industrial carbon capture has been performed, with a particular focus on costs per tonne of CO_2 avoided. The authors have reviewed 250 research articles in order to extract data regarding industrial CCS, focusing on four main carbon-emitting industries; the iron and steel industry, the refining industry, the pulp and paper industry and the cement industry. Only 25 costs were returned as part of the search, and across the four industries they suggested that the cost of carbon capture on industries after conversion to 2013 US Dollars is $20-140 per tonne of CO_2 avoided. The highest costs were found using amine scrubbing, the most mature technology, with other less mature technologies reporting lower costs, for example, calcium looping applied to the cement industry was reported to have costs of in the range of $20-75 per tonne avoided, with the only lower costs reported being in the pulp and paper industry reported between $16 and $35. However, the paucity of costing data increases the uncertainty surrounding industrial CCS, meaning that more economic data are required before any conclusive decisions can be made.

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Keywords: Industrial CCS; Technoeconomics; Cement Industry; Iron and Steel CCS; Refineries CCS; Systematic Review; Cost Reduction.

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1. Introduction

The industrial sector is responsible for over 30% of total global anthropogenic carbon dioxide emissions [1]. In 2010, approximately 13.1 Gt of CO_2 were emitted globally from industry, highlighting the importance of emissions reduction in industry in low-carbon pathways. In many cases, the only technology that can be applied within the industrial sector for emission reduction is carbon capture. However, there are much greater levels of uncertainty surrounding the costs of industrial carbon capture.

In this study, we have focused on four industries, responsible for 75% of industrial CO_2 emissions; the iron and steel industry which accounts for 30% of industrial CO_2 emissions, the cement industry (26%), chemical manufacturing and petroleum refining (17%) and the pulp and paper industry (2%). The remaining emissions are associated with other mineral and ore processing, the food and drink industry and a range of other manufacturing industries. Due to their size, these industries are attractive for emissions reduction schemes. Since all industries have different processes and flue gas compositions, bespoke solutions must be devised for each industry.

Unlike electricity generation facilities, industrial facilities are often located in clusters instead of being widely distributed, as power stations are. This clustering represents opportunities for creating an interlinked network for the transport of CO_2 to storage sites, with the potential of sharing transport and storage provision where possible. For example, within Europe power emissions sources are distributed throughout the continent, whilst industrial emissions are clustered in small regions such as Teesside in the UK and the Ruhr in Germany.

This paper will discuss the results of a systematic review of the academic literature regarding industrial carbon capture, both in general and targeted at the four industries mentioned above. The search will be particularly focused on the costs associated with industrial carbon captures, with the view to determining which technologies can be applied to each industry in the most cost-effective manner.

2. Methodology of Systematic Review and Analysis

A list of search terms was drawn up, which was refined in order to target only the most relevant information, returning a total of 541 research articles. The abstracts of these were then read in order to more accurately target relevant information, narrowing down the search to 250 papers. Each of these papers were then read and relevant information extracted via a questionnaire. From this initial review, each resource was assigned a priority depending on how relevant the information inside was to this study, and each paper was then summarised in order to extract as much information as possible.

2.1. Results and Demographics of Systematic Review

Each paper was assigned to one of three categories depending on the primary focus of the paper; the three primary focusses of the literature were either the technology, the policy challenges or the economics of carbon capture. Out of the 250 papers classified, 152 focused on technology associated with carbon capture, with 90 related primarily to the policy challenges associated with carbon capture. By contrast, economics was the primary focus of only 8 articles.

Whilst the systematic review was targeted to return resources with information specifically about industrial carbon capture, often research articles were returned which focused more generally on carbon capture, with industrial carbon capture only one part of the research. Out of the 250 papers studied, 166 were focused entirely on industrial carbon capture, and 93 of these 166 focused on no particular industry. Out of the 73 sector specific research articles returned, 44% focused on the iron and steel industry and 36% on the cement industry, with other industries lagging far behind this.

When considering this uneven focus of the literature, one reason may be the relative homogeneity of industrial processes within the iron and steel industry and the cement industry when compared to other industries, meaning that any carbon capture methodologies will be applicable in a large number of instances. Another reason for this uneven focus of the literature may be on account of the iron and steel and cement industries being the two largest-emitting industrial sectors. In addition, a standard cement manufacturing process contains only two large sources of CO_2; the precalciner and the kiln [2]. By comparison, an oil refinery process will have a large number of smaller emissions sources, so is therefore not as suited to carbon capture even though oil refineries are responsible for some 17% of industrial emissions [3], and this is reflected by the literature with only seven research articles considering carbon capture in oil refineries or the chemical sector.

2.2. Historical Cost Escalation

Since any costs found within papers are given in a range of currencies and in different years, it is important to convert them into a single comparable basis. In order to allow this very approximate comparison, all costs have been converted into the basis of 2013 US dollars per tonne of CO_2 avoided. Costs extracted from the literature were first converted to USD for the year in which the paper was published or the costs attributed to using a purpose built cost converter, constructed using data from the International Monetary Fund [4] with exchange rates averaged over the course of a year. After conversion from the reporting currency to US dollars, costs were then escalated from the quoted year to 2013 through multiplication by the relevant change in the Chemical Engineering Plant Cost Index (CEPCI) [5]. The change in the value assigned to this index year-on-year represents the cost changes of process equipment over time, including both fixed and variable costs. Since many of the avoided costs from literature do not have a detailed breakdown, more detailed analysis of the price changes over time is not possible and the CEPC index has been chosen as an approximation.

3. Industrial Sector-Specific Challenges and Characteristics

Unlike carbon capture in the electricity generation industry, the heterogeneous processes found throughout industries necessitate different approaches for the implementation of carbon capture depending on the nature of the industrial process concerned. In particular, the high number of smaller point sources of variable CO2 concentration make industrial CCS more technically challenging than carbon capture in the electricity generation industry.

3.1. The Iron and Steelmaking Industry

The iron and steelmaking industry consists of two main sizes of plant; globally there exist roughly 180 large, integrated steel mills with average emissions of 3.5 Mt CO_2 per year and numerous smaller mini-mills, typically with emissions under 200 kt CO_2 per year. Evidently, the greatest potential for reducing emissions from the iron and steel industry is to decarbonise the large integrated mills, and these are the focus of the vast majority of research pertaining to carbon capture and storage in the iron and steel industry. Due to the industry having the greatest emissions of any industrial sector, carbon capture and storage in the iron and steel industry has the potential to lead to significant reductions in global carbon dioxide emissions.

Within a typical integrated steel mill, the largest single point source on site will be the blast furnace, responsible for a third of plant emissions, followed by the coke plant and sinter plant which are each responsible for a quarter of onsite emissions. The remainder of plant emissions come from a number of smaller sources such as the lime kiln and the mechanical processes associated with the finished product. Because of the three largest sources being of almost equal size, it is important to find some way to avoid having to build three separate carbon capture plants per integrated mill, with one suggestion to avoid this the use of a combined stack from the major onsite processes.

3.2. Petroleum Refineries and Chemical Manufacturing

Petroleum refineries have a large variety of configurations depending on the exact nature of the processes being carried out with a given installation. Similarly, the chemical manufacturing industry is very heterogeneous in its processes, with variations depending on the required product. Therefore, these two industries can be considered together for carbon capture as they have similar challenges to overcome, with these combined sectors responsible for 17% of total industrial CO_2 emissions [6]. One of the greatest challenges for implementing carbon capture on a refinery or chemical plant is the large number of small point sources with a wide range of carbon dioxide concentrations. In general, the largest point sources on sites of this kind are boilers and furnaces, accounting for roughly 60% of total emissions from refineries and chemical plants [3]. These are the areas targeted in the literature for this industry, often using a combined stack to aggregate as many emissions sources as possible.

3.3. Pulp and Paper Industry

The pulp and paper industry is the smallest of the sectors considered in this study and is responsible for 2% of industrial emissions, equivalent to 252 million tons of CO_2 per year [6]. Unlike other industries, pulp and paper plants are located predominantly away from industrial clusters to be closer to their feedstock. Across both major types of plant, the mechanical mills and the Kraft mills, the major emissions sources are the pulp boilers and the onsite lime kilns, with emissions coming in the kiln from both the calcination reaction and the burning of fuel oil for heating [7]. In general, Kraft mills are larger, with mean emissions over 500 kt per year, in Europe accounting for some 73% of emissions attributed to the pulp and paper industry [8]. There was very little information regarding pulp and paper industry CCS, with one possible explanation being the inability of the pulp and paper industry to integrate into localised industrial CO_2 transport networks due to their remote locations. In order to overcome this, it has been suggested that the pulp and paper industry could use either localised sequestration or transport of the liquefied CO_2 via ship to storage site [9].

3.4. Cement Industry

The cement industry is responsible for roughly 5% of total global CO_2 emissions [10], equivalent to 1.3 billion tons of CO_2 emitted per year [6], corresponding to between 0.6-1.0 tons of CO_2 per tonne of cement produced [11]. The two main emissions sources within the process are from fuel burning for kiln heating and the calcination reaction, in which the limestone feed decomposes to form quicklime and carbon dioxide. Both the kiln flue gas and the CO_2 evolved from the calcination reaction can be treated from the same combined stack, which is where carbon capture would be applied. In general, roughly 60% of the site emissions are attributable to the calcination reaction and the remaining 40% from the kiln heating [2, 12].

4. Results of literature survey

In order to decide on the capture technology for each source within an industry, it is necessary to know the size of source and concentration of CO_2 available in the flue gas. However, for many of the sources within the different industries, the information is either not publically available or inconsistent with a wide range of values reported. A summary of the flue flows and conditions is presented below in Table 1.

Table 1. Summary of CO_2 source conditions across industries. Flowrates have been calculated from average plant emissions across the industry assuming a standard plant design. [1]Combined flue from calciner and kiln. [2]Combined category for all onsite boilers and furnaces, cannot be captured together without combined stack. [3]Dependent on configuration used. † Data unavailable or dependent on process plant configuration. †† Pressures estimated as atmospheric for exhaust gases

		F (Mt/y)	T(°C)	P (bar)	y_{CO_2}	y_{O_2}
Iron and Steel	Lime Kiln	0.18	300	1	7%	2%
	Coke plant	0.93	100	1	27%	1%
	Sinter plant	0.93	100	1	8%	0%
	Strip mill	0.29	300	1	7%	2%
	Blast furnace	1.11	300	1	21%	1%
Cement	Combined flue[1]	0.79	-†	1††	14-33%	3%
Refineries & Chemicals	Boilers and Furnaces[2]	0.70	260	1	9%	3%
	Catalytic Cracker	0.17	-†	1††	12%	-†
	Flares	0.03	-†	1††	8-10%	-†
	Steam methane reforming	0.02	-†	1††	20-99%[3]	-†
	Incineration	0.01	-†	1††	3-12%	-†
	Utilities	0.14	-†	1††	3-12%	-†

As seen here, the information is incomplete, meaning that making informed decisions on which technologies to apply for each source is difficult. In particular, the heterogeneity of the refining and chemical industries mean that obtaining accurate data is only possible for specific facilities, with the variation in process meaning that ‘generic’ values are not available.

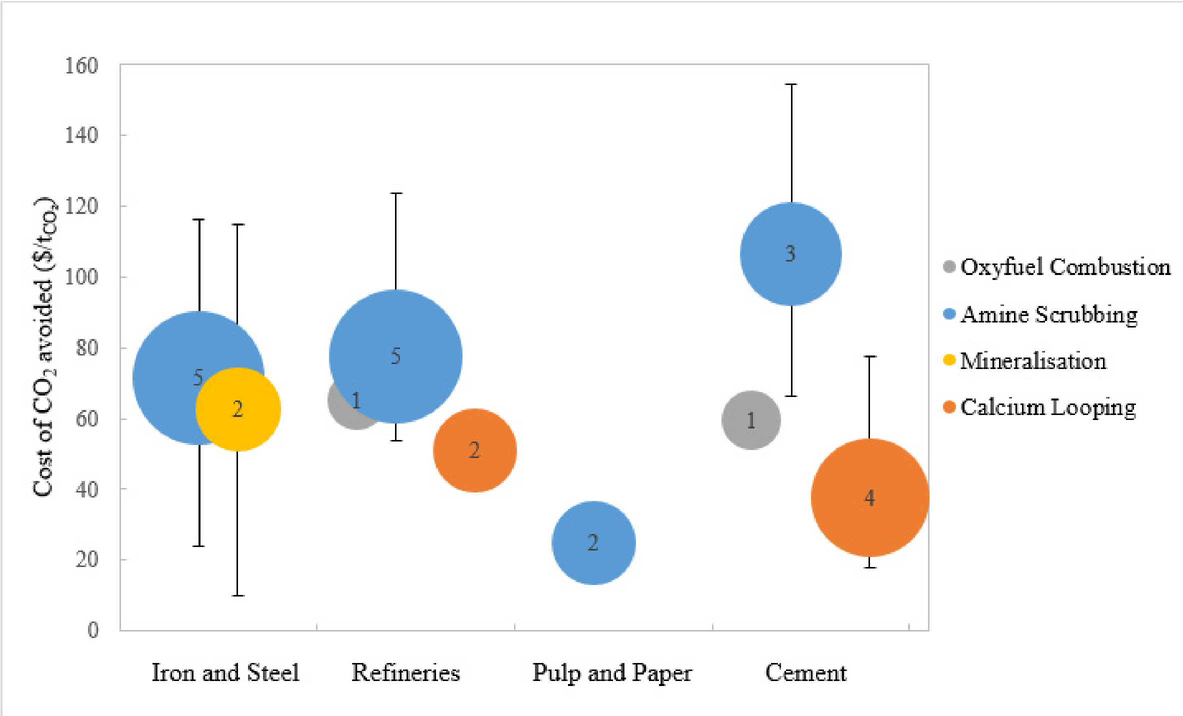

Figure 1 - Mean combined costs of technologies applied to different industries. The full range of costs for each technology is represented by the error bars. The diameter of the bubble is proportional to the number of sources of cost data found for each case.

As can be seen in Figure 1, costs for industrial carbon capture are scarce and exhibit a wide range of values. The most common technology within the literature was amine scrubbing of flue gases, which was investigated for each of the four industries. Amine capture costs have a wide range of reported values, in the range of $26 to $154 per tonne of CO_2 avoided depending on industry, with iron and steel lowest and cement highest. The exception to this is the pulp and paper industry where the reported costs were much lower, between $16 -33 per tonne of CO_2 avoided. By comparison, the other technologies found from the literature usually had lower costs associated with them, with calcium looping as applied to the cement industry reported to cost between $20 and $70 and oxyfuel combustion costing between $60 and $70 per tonne avoided.

Economic data for each of the industries was scarce, with the best researched industries only having eight reported costs each and the pulp and paper industry only having two. The use of oxyfuel or mineral carbonation had the fewest reported costs associated with them, both having only two cost sources compared to 15 for amine capture.

5. Conclusion

Out of the 250 research articles reviewed, there were only 25 individual costs for industrial carbon capture and storage returned across all technologies and industries. Where costs are reported, the assumptions are often not clearly stated and there is often no breakdown of contributions to the total cost, making comparison between the costs difficult. Therefore, it is difficult to draw firm conclusions based on these data.

This knowledge gap and the inherent challenges of finding carbon capture solutions for industries have increased the uncertainty surrounding the subject and make progress difficult. In order to be improve upon this, and to determine which capture technology would be most appropriate for each source of CO_2 for each industry, economic information should be reported with costs fully broken down into individual contributions to allow comparison. Greater reporting of proposed costs of industrial carbon capture would reduce the uncertainty surrounding the economics of industrial CCS and allow more accurate cost estimates to be made.

Based on the data collected, it is generally reported that amine capture is the most expensive technology for each sector, perhaps since it is a more mature technology than the others considered in the literature so cost estimates may be more accurate. In other words, cost estimates associated with less mature technologies may suffer from undue optimism. The lowest costs are associated with calcium looping, which is significantly cheaper for the cement industry and could also offer lower costs in the refining industry. Oxyfuel costs appear lower than comparable amine capture costs, though with relatively little supporting data, whilst mineralisation of steel slag for capture in the iron and steel industry has only two cost data sources with a range of $10-120. However, the variation in the maturity of the different technologies means that any conclusions drawn when comparing technologies must be considered carefully as the reported costs are liable to change greatly as a technology matures.

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