

# 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, as well as other high purity sources



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## ARTICLE INFO

### Article history:

Received 12 February 2016

Received in revised form 17 March 2017

Accepted 20 March 2017

Available online 10 April 2017

### Keywords:

Industrial CCS

Economic analysis

Cost reduction

Systematic review

Iron and steel industry

Cement industry

Refining industry

## ABSTRACT

In order to meet the IPCC recommendation for an 80% cut in CO<sub>2</sub> emissions by 2050, industries will be required to drastically reduce their emissions. To meet these targets, technologies such as carbon capture and storage (CCS) must be part of the economic set of decarbonisation options for industry. A systematic review of the literature has been carried out on four of the largest industrial sectors (the iron and steel industry, the cement industry, the petroleum refining industry and the pulp and paper industry) as well as selected high-purity sources of CO<sub>2</sub> from other industries to assess the applicability of different CCS technologies. Costing data have been gathered, and for the cement, iron and steel and refining industries, these data are used in a model to project costs per tonne of CO<sub>2</sub> avoided over the time period extending from first deployment until 2050. A sensitivity analysis was carried out on the model to assess which variables had the greatest impact on the overall cost of wide-scale CCS deployment for future better targeting of cost reduction measures. The factors found to have the greatest overall impact were the initial cost of CCS at the start of deployment and the start date at which large scale deployment is started, whilst a slower initial deployment rate after the start date also leads to significantly increased costs.

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## 1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) recommends global reductions of emissions of carbon dioxide by 50–80% based on 1990 levels by the year 2050 (Fischedick and Roy, 2014). This is necessary to avoid catastrophic warming and emissions must reach a maximum level no later than 2020 in order to mitigate the most serious effects of climate change. Industrial activities account for 30% of the total global anthropogenic emissions of carbon dioxide. In 2015, industrial emissions were approximately 14.5Gt CO<sub>2</sub>, comprising of direct, indirect, process and wastewater emissions (Fischedick and Roy, 2014), therefore any effort to move towards a low carbon economy must not neglect the emissions arising from the industrial sector, with carbon capture one of a suite of technologies that could have a large impact. However, work on industrial carbon capture significantly lags behind that in the power sector, and much greater levels of uncertainty exist surrounding the costs of industrial CCS relative to that of the power

sector. Despite this, carbon capture is arguably more important in industry than in the power sector due to a lack of alternatives for future low-carbon plants.

Large stationary sources of emissions from industry are widely distributed throughout the world. However, unlike electricity generation facilities, industrial facilities tend to form clusters in which a number of large facilities operate, such as Teesside in the UK and the Ruhr region in Germany. This industrial clustering represents opportunities for creating an interlinked network for the transport of CO<sub>2</sub> to storage sites, with the potential of sharing transport and storage provision where possible.

This paper systematically reviews and analyses the current academic literature regarding carbon capture and storage (CCS) applied in the industrial sector, with an emphasis on finding costs of capture and identifying key knowledge gaps. This information is then used to construct a model which will report the costs of capture associated with implementing carbon capture on different industries, and the sensitivities of these final costs to different input variables such as deployment start date. Since this study is being used to analyse future scenarios with a large quantity of uncertainty attached to them, the deployment profile and learning curves have been included in the sensitivity analysis.

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Nomenclature table

Symbol	Description	Default Value	Units
$c(y)$	Overall cost of CCS in the sector for year $y$	-	\$/yr
$c_{tot}$	Total cost across whole time period from 2016 to 2050	-	\$
CR	Cost reduction factor per generation	-	-
$CR_{min}$	Minimum threshold above which learning applies	-	-
$ec(y)$	Escalated cost of CCS per tonne of CO <sub>2</sub> avoided	-	\$/tCO <sub>2</sub>
$i(y)$	CEPC index value in year $y$	-	-
$lc(y)$	Learning curve cost multiplier in year $y$	-	-
LF	Learning curve factor	25%	-
$n(y)$	Number of plants with CCS applied to them in year $y$	-	-
$n_{max}$	Total number of plants in each industry worldwide	-	-
P	Cost of capture at start date from literature	-	\$
S	Size of emissions source in tons CO <sub>2</sub> per annum	-	tCO <sub>2</sub> /yr
SD	Start date of implementation	2020	yr
$tp(y)$	Technology penetration within an industry in year $y$	-	-
$tp_{max}$	Maximum technology penetration reached by 2050	80%	-
U	Uptake rate constant	3	-
$y$	year	-	yr

This study is focused on four of the main carbon emitting industries, responsible for a majority of industrial CO<sub>2</sub> emissions; the iron and steel industry, the cement industry, petroleum refining and the pulp and paper industry. Since these four sectors account for such a large proportion of industrial emissions, initiatives to reduce the emissions from these sources would have a large impact on the global emissions reductions targets. Also reviewed are the costs of CCS from near-pure sources of CO<sub>2</sub> from a number of other industries. Since industrial emission sources are diverse, bespoke solutions must be devised for each industry. It is important to note here that not all technology options were included in the study, and that no “risk” factor has been included to account for the different maturities of some processes compared to others—the key factor for the economic analysis was whether costing information was available in the academic literature.

This research article aims to assess current literature addressing industrial carbon capture and to identify knowledge gaps and weaknesses therein. By systematically reviewing the literature, this study will assist in guiding future research to address these weaknesses. Scenarios have been constructed to estimate the cost per tonne of CO<sub>2</sub> avoided for the major industries in the time period to 2050 with a large scale deployment. Due to the high degree of uncertainty within the calculations, a sensitivity analysis is used to determine the main contributors to the overall cost so that research may be targeted in the future to attempt to bring down prices.

## 2. Methodology of systematic review and analysis

Search terms, listed in the supplementary information, were constructed and refined in order to find the literature most relevant to industrial CCS, returning a total of 541 research articles. The first stage of the review process involved screening the abstracts of each article from the refined searches, returning 250 papers. A ‘relevant’ article’s abstract:

- ‘Appeared to contain information on the technology, economics or legislation of carbon capture in industry’ or
- ‘Appeared to contain indirect information relating to technology, economics or legislation of carbon capture in industry’ or
- ‘Appeared to contain supporting information that might reasonably be used to provide contextualising information on carbon capture in industry’

Literature satisfying these criteria was then reviewed, analysed using a standard questionnaire, and prioritised according to criteria shown in the supplementary information. Summary paragraphs

on each reviewed paper were written as part of the questionnaire based on the paper’s content concerning industrial CCS technology, costs and policy. A full list of the papers reviewed, and a short summary regarding the relevance of each to this study, is included in the supplementary information.

Where necessary, ‘grey literature’ from major industry and climate bodies such as the International Energy Agency and the Intergovernmental Panel on Climate Change has been used to provide additional costing data in order to compliment data from the academic literature. Although the information from these reports is sometimes less detailed than that found in the academic literature, the sparseness of cost data from the systematic review meant that adding these resources was useful to show consensus and validate some assumptions made.

### 2.1. Results and demographics of systematic review

Observations as to the nature of the literature in the final 250 research papers were as follows:

The primary area of focus of each paper was assessed and classified as either CCS technology, economics or carbon capture policy. A total of 152 of 250 papers focus on the technology of carbon capture, 90 on the policy challenges behind carbon capture but only 8 papers primarily investigated the economics of carbon capture on industrial systems.

There were 164 articles relating specifically to industrial CCS, of which 93 were not specific to any single industry. These papers instead tackled a number of industries in turn or were general papers that could be applied to any one of the four sectors, e.g. industrial carbon capture policy. Of the papers that were sector specific, 29 studied CCS in the iron and steel sector and 28 considered the cement industry. By contrast, only 7 papers focussed primarily on CCS in the refining sector, even though the sector accounts for 10% of all industrial emissions (van Straelen et al., 2010), and 6 in the pulp and paper sector.

The reasons for this uneven focus of the literature can be identified to be a function of industry size and ease of CCS technology application. As discussed earlier, the cement industry is the second largest industrial emitter of CO<sub>2</sub>, closely behind the iron and steel industry. Its emissions generally come from only two sources, the precalciner and kiln (Barker et al., 2009), compared to oil refineries where there are a much larger number of small emissions sources, making the implementation of carbon capture more technically difficult and expensive.

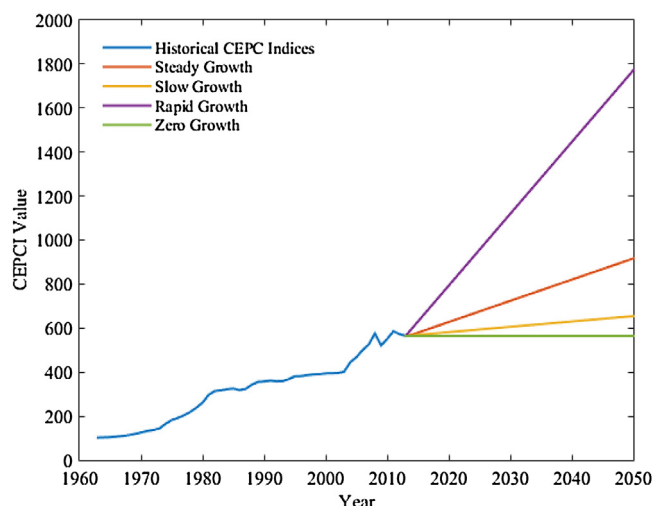


Fig. 1. Historical values of the CEPCI and different potential scenarios for future forecasting (Technology, 2011).

## 2.2. Cost escalation

In order to compare historically quoted costs, an escalation model was developed. Costs were first converted into USD for the year of publication of the paper (or the assumed date of deployment within the paper) using a historical exchange rate calculator using annualised mean exchange rates obtained from the International Monetary Fund (IMF, 2015). The majority of articles gave costs as cost per tonne of CO<sub>2</sub> avoided rather than captured, so throughout this study it was decided to use CO<sub>2</sub> avoided rather than captured in order to account for the efficiency penalties reported by different technologies. After conversion to USD, costs were escalated to from their base year to the year of comparison, chosen to be 2013, via multiplication by the Chemical Engineering Plant Cost Index (CEPCI) (Technology, 2011).

Based on the trend of the CEPCI index (1957–2013), extrapolations based on long term trends have been used to provide a range of potential future capital costs for plant construction. Within this period, three main behaviours of the index were identified. Across the entire reporting period, the average index increase was 9.6 points per year, equivalent to 1.7% per year in 2012 and shown in Fig. 1 above as steady growth. Between 1995 and 2003, the rate of growth slowed appreciably, increasing by an average of 2.4 points per year, equivalent to the slow growth scenario. The period from 2003 to 2008 characterised the rapid growth scenario, with a rate of increase of 32.6 points per year. A zero future growth scenario has also been considered, which strips out the effect of capital cost escalation. As a sample calculation, consider the cost of amine capture from high purity sources within a petroleum refinery reported by van Straelen et al. (2010) in 2010 at a cost of €30.0 per tonne avoided. This is converted first into 2010 USD, at an exchange rate of €1:\$1.230, so an equivalent cost of \$39.7 (2010). This is then escalated using the CEPCI process plant cost index, multiplying by the equivalent rise in the index year on year, equivalent to a multiplicative factor of 1.025. This is multiplied (Eq. (1) below) with the 2010 cost in dollars to give the overall 2013 cost of capture per tonne avoided, which in this example is equal to \$40.7 (2013 USD).

$$\text{Cost (2013)} = \text{Cost (2010)} \times \frac{\text{CEPCI (2013)}}{\text{CEPCI (2010)}} \quad (1)$$

## 3. Industrial sector-specific challenges and characteristics

Since the different industries have significant variation in the nature and volume of their emissions, it is important to consider

each industry in turn to assess the possible options for implementation of carbon capture technologies.

### 3.1. The iron and steelmaking industry

The iron and steel industry is the largest emitting industrial sector, accounting for 31% of industrial emissions (IEA, 2011). The majority of emissions from the iron and steel industry come from the 180 large integrated steel mills with average emissions of 3.5 Mt per year (IPCC, 2005), with other sites being predominantly smaller 'mini-mill' plants with an average emissions size of 170 kt of CO<sub>2</sub> per year. The greatest potential for reducing emissions is therefore on these integrated steel mills, due to the large point sources that exist there for capture.

One major problem associated with implementing carbon capture on integrated steel mills is the number of different point sources. The largest single point source is the blast furnace, from which 65% of the emissions can be captured, with the coke plant accounting for 27% of the overall emissions and the sinter plant for 6% of emissions (Birat, 2010). Because of the much larger emissions of these integrated steel mills compared to the mini-mills, integrated mills are the main focus of the capture costs and technologies. Since there are three primary sources of CO<sub>2</sub>, multiple carbon capture plants or some method of combining flue streams would be needed for each large mill in order to capture a large proportion of the total emissions.

In the European Union, a consortium called Ultra Low CO<sub>2</sub> Steelmaking (ULCOS) 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 (Steelmaking, 2015). One of the novel technologies it is researching is a top gas recycling blast furnace (TGR-BF) (Birat et al., 2003; Xu and Cang, 2010), which applies carbon capture to the flue gas, with the remaining flue recycled into the base of the blast furnace. By having the recycle, the flue concentration of 35% CO<sub>2</sub> is higher than that from a regular blast furnace, making carbon capture less energy intensive. The TGR-BF could be retrofitted to existing blast furnaces at primary steelmaking facilities and has the potential to mitigate 65% of CO<sub>2</sub> emissions compared to a normal steel mill (Birat, 2010).

The blast furnace is where the majority of the research has been focussed. Post combustion amine capture of blast furnace emissions can capture CO<sub>2</sub> emissions at a cost of \$65.1–119.2 per tonne avoided (Arasto et al., 2013a), after removal of costs associated with transport and storage. A joint stack, with flue streams from the main CO<sub>2</sub> emitting sources, gives amine capture the potential to mitigate 50–75% of emissions. One example is a case study examining an integrated steel plant in Raase, Finland (Arasto et al., 2013b), at which post combustion could be applied at a cost of \$68.7 per tonne of carbon dioxide avoided (Tsupari et al., 2013) after removal of storage and transport costs. If a Selexol solvent were used for capture from the blast furnace, it is claimed that the carbon dioxide can be captured by using a shift reactor at costs of \$17.7–19.4 per tonne avoided (Gielen, 2003) excluding transport and storage costs. 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 \$78.5 per tonne avoided, while capture from a coke oven cost \$85.6 per tonne avoided (Wiley et al., 2011). Use of a top gas recycling blast furnace, as discussed previously, is also an option (van der Stel, 2008). However, cost data are sparse, with costs of \$54.0–88.0 per tonne of CO<sub>2</sub> avoided suggested (Kuramochi et al., 2012).

A novel Sorbent Enhanced Water Gas Shift (SEWGS) process can potentially capture up to 85% of emissions from a steel plant, though has not been demonstrated on a large scale (Gazzani et al., 2013). The Stepwise project proposes using the SEWGS on a blast furnace at the Swerea plant in Sweden, where a consortium of 9 partners will deploy and operate a pilot plant to demonstrate the technology

(The Stepwise, 2017). Carbonation of steel slag, a waste product of the steelmaking process, in a fixed bed reactor has the potential to capture between 8 and 20% of the total carbon dioxide in the flue stream (Said et al., 2013), although as with other mineral sequestration methodologies it has a low capture rate and can only capture a small fraction of the total emissions, at a cost of up to \$115.8/t<sub>CO<sub>2</sub></sub> avoided (Huijgen et al., 2007). The other paper discussing mineral carbonation had a very different reported cost of \$9.8/t<sub>CO<sub>2</sub></sub> (Stolaroff et al., 2005). However, the small capture potential of mineral carbonation processes necessitate its use in conjunction with other capture technologies to obtain large reductions in emissions.

Grey literature costs generally agree with those proposed within the academic literature, with the majority falling between the more extreme cost estimates. Where the technology and capture rate are given, these data support the cost data found from the literature with similar capture rates and costs that range from \$50 to 90 per tonne of CO<sub>2</sub> avoided. Table 1 summarises the cost data found.

For the purposes of the model, it was assumed that post-combustion at the literature mean cost of \$76.6 per tonne of CO<sub>2</sub> avoided would capture 65% of total emissions from the blast furnace. In addition, utilising post-combustion capture on the coke oven, 27% of emissions can be avoided at a cost of \$86.4 per tonne after averaging out the costs of applying post-combustion capture on the two major sources in the plant. The sinter plant is responsible for an additional 6% of emissions from the plant, though a lack of cost data means that it cannot be considered with CCS within the model.

### 3.2. Petroleum refineries

The petroleum refining industry is responsible for 10% of industrial emissions (IEA, 2011). Because of the heterogeneity in refining plants, it would be necessary to design bespoke CCS systems and as such refineries are often overlooked as candidates for applying CCS. Overall, the largest sources of emissions are furnaces and boilers, which account for 65% of total emissions (van Straelen et al., 2010), making them the most appropriate targets for any carbon capture technologies. After this, the next most promising area of capture is the catalytic cracker or gasifier, which can account for up to 16% of emissions. However, in large facilities with numerous items of process equipment, some method to combine flue streams from the large number of process streams and multiple emissions sources would be required.

Post combustion capture, when applied to the gasifier or to a combined stack, was found by van Straelen et al. to have a price of carbon dioxide emissions avoided of \$40.7 and \$121.8 respectively (van Straelen et al., 2010). However, some discrepancy was found between this cost 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, with calculated costs of \$68.2, \$68.7 and \$83.9 per tonne of carbon dioxide avoided respectively (Farla et al., 1995; Melien, 2005; Ho et al., 2011). It is important to note the process obstacles preventing the use of a combined stack at many of these facilities, since aggregating emissions into one stream is not simple and is not currently done, meaning capture proportions are likely overestimates and costs underestimates. The application of oxy-combustion to boilers or furnaces on plant was also considered, however this would have to be applied to individual sources, rather than a combined stack. Oxy-combustion was found to have a cost of \$65.7 per tonne of carbon dioxide avoided (Melien, 2005).

By contrast to the relatively sparse academic literature for the refining sector, there exists a large quantity of cost data in the grey literature. In particular, the sectoral assessment carried out by Det Norske Veritas provided costs for a range of technologies for each capture source, though these were often more expensive than the

costs found in academic literature for a similar technology. Whilst the IEA technology roadmap for CCS quotes costs in different areas of refineries, the capture technology is not explicitly stated. As the technology with the most available data, post-combustion capture with amine solvents has been chosen for use in the model. The gasifier, typically responsible for 15% of emissions, has a cost of \$40.7 per tonne, while the 50% of emissions accountable to the boilers can be captured from a combined stack with a mean cost of \$98.0 per tonne of CO<sub>2</sub> avoided. Other unit operations had prohibitively high costs or a lack of data, so it is assumed that only 65% of emissions are captured from refineries. Table 2 summarises the cost data found from the literature.

### 3.3. Pulp and paper industry

The pulp and paper industry (PPI) contributes 252 million tonnes of CO<sub>2</sub> per year to global emissions (Herzog, 2009)—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 thus are not located near to heavy industry clusters and potential transport networks. Two main production pathways are in common use; mechanical mills and integrated Kraft mills, which comprise the vast majority and have on-site emissions greater than 0.5 Mt<sub>CO<sub>2</sub></sub>/yr. Kraft mills account for 73% of European PPI emissions, and thus hold the largest potential for capture of CO<sub>2</sub> (Jönsson and Berntsson, 2012). The majority of emissions are from the boilers, but there are also emissions from the lime kiln, both from the calcination reaction and also from the fuel oil used to heat the kiln (Mesfun and Toffolo, 2013). There is a notable paucity of data for this industrial sector with only a single cost source found in the academic literature, and one from the grey literature.

Although plant operations vary considerably (Mesfun and Toffolo, 2013; Möllersten et al., 2003; McGrail et al., 2012), the largest emission source in an integrated Kraft pulp and paper plant tends to be the recovery boiler in which black liquor is combusted, releasing biogenic CO<sub>2</sub>.

The literature made particular reference to the potential of black-liquor gasification (Möllersten et al., 2004; Pettersson and Harvey, 2012) as a rapidly developing technology that could significantly improve the efficiency of integrated Kraft plants, while also considerably assisting implementation of carbon capture technology.

Due to their location in remote areas, the pulp and paper industry is often overlooked in terms of building a carbon infrastructure. For example, 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 this could lead to greater independence and initiation of smaller, more localised sequestration projects including using mobile transport between the facility and storage sites (McGrail et al., 2012). Finding the same infrastructure integration problem as discussed above, the only source of costing data for PPI CCS found in the literature assumed that a dedicated, single pipeline would need to be constructed from the plant to a suitable storage site.

An investigation by McGrail et al. (2012) conducted a feasibility and costing study into CCS applied to a pulp and paper mill in USA using a post-combustion amine capture unit on to the primary recovery boiler, utilising energy from a biomass-fuelled generator.

Due to the scarcity of costing data and the bespoke nature of the studies where present, the pulp and paper industry was not included in the modelling below. Table 3 summarises the cost data from the literature.



**Table 1**

Summary of cost data from literature for iron and steel industry.

Author	Year	Technology	Emissions Captured (%)	Cost (\$/tCO <sub>2</sub> )
Stolaroff et al. (2005)	2005	Usage of steel slag for carbonation	8%	9.8
Gielen (2003)	2003	Shift Reactor and Selexol solvent on blast furnace	30%	17.7–19.4
IEA (2013)	2013	Unknown on blast furnace	35%	51.3
IEAGHG (2013a)	2013	Oxy-fueled blast furnace	41%	56.0
Kuramochi et al. (2012)	2012	Top-gas recycling blast furnace with post-combustion	65%	54.0–88.0
IEA ETP (2012)	2012	Unknown	Unknown	59.0–79.0
Tsupari et al. (2013)	2013	Post combustion capture of blast furnace emissions	50%	68.7
Wiley et al. (2011)	2011	Post combustion capture with MEA of blast furnace flue gas	55%	78.5
IEA (2013)	2013	Unknown on power plant	30%	71.8
Wiley et al. (2011)	2011	Post combustion capture with MEA of coke oven	20%	85.6
IEA (2013)	2013	Unknown on coke Oven	8%	87.1
Arasto et al. (2013a)	2013	30% MEA Post Combustion capture from blast furnace	50%	65.1–119.2
Huijgen et al. (2007)	2007	Use of steel slag for mineral carbonation of CO <sub>2</sub> from blast furnace	20%	115.8

**Table 2**

Summary of cost data from literature for petroleum refineries.

Author	Year	Technology	Emissions Captured (%)	Cost (\$/tCO <sub>2</sub> )
DNV (2010)	2009	Post-combustion on SMR	Unknown	28.7–80.1
IEA ETP (2012)	2012	Unknown	Unknown	39.0–128.0
van Straelen et al. (2010)	2010	Post combustion capture of carbon dioxide from gasifier	15%	40.7
Melien and Roijen (2009)	2009	Chemical looping on boiler (L/H replacement rate)	Unknown	49.9/63.5
Melien (2005)	2005	Oxyfuel combustion for boilers/furnaces	Unknown	65.7
DNV (2010)	2009	Oxy-combustion on boilers/furnaces	Unknown	66.5
Farla et al. (1995)	1995	Post combustion capture from combined stack	50%	68.2
Melien (2005)	2005	Amine scrubbing of gases from stack	50%	68.7
DNV (2010)	2009	Pre-combustion on heaters/boilers	Unknown	74.0–75.5
IEA (2013)	2013	Unknown on heaters	33%	82.0
Ho et al. (2011)	2011	MEA capture of combined stack	50%	83.9
IEA (2013)	2013	Unknown on FCC	8%	102.5
IEA (2013)	2013	Unknown on CHP	20%	107.6
DNV (2010)	2009	Post-combustion on heaters/boilers	Unknown	116.3–145.0
van Straelen et al. (2010)	2010	Post combustion capture from combined stack	50%	121.8
DNV (2010)	2009	Oxycombustion on FCC	Unknown	128.4
DNV (2010)	2009	Post-combustion on FCC	Unknown	128.4
Al Juaied and Whitmore (2009)	2009	Ammonia/amine post combustion from FCC or CHP	Unknown	182.0–250.0

**Table 3**

Summary of cost data from literature for the pulp and paper industry.

Author	Year	Technology	Emissions Captured (%)	Cost (\$/tCO <sub>2</sub> )
IEA (2013)	2013	Unknown	75%	56.4
McGrail et al. (2012)	2012	Amine capture of boiler flue gas	62%	59.0

### 3.4. Cement

The global cement industry has direct emissions of 1306 million tonnes of CO<sub>2</sub> per year (Herzog, 2009) (roughly 27% of total anthropogenic industrial carbon emissions (IEA, 2011)), corresponding to between 0.6 and 1.0 t of CO<sub>2</sub> emitted per tonne of cement produced (Dean et al., 2011a).

Raw 'meal', ground limestone and other materials, is fed into the preheater and precalciner centrifuge units. As it is mixed with the hot flue gas from the kiln, the lime calcines, releasing CO<sub>2</sub> which is carried to the stack by the upwards draught created in the centrifuge preheaters. Approximately 95% of the total CO<sub>2</sub> which is liberated from the limestone raw material is released in the preheaters (Barker et al., 2009). The calcined feed then enters the kiln, the other major source of CO<sub>2</sub> in cement manufacture, and is converted at high temperature to clinker, which is cooled, and milled downstream.

The general consensus in the literature is that about 60% of cement production emissions were process emissions from calcination (and hence cannot be reduced without lowering production) and the remaining 40% were attributable to heat generation for the kiln (Barker et al., 2009; Dean et al., 2011b), both sources are amenable to CO<sub>2</sub> capture. However, due to the potentially adverse

physical and financial consequences of altering the chemical nature of the cement product, the cement industry was noted by Fennell et al. (2012) to be naturally cautious regarding incorporation of new technology that might in any way affect the clinker composition.

Calcium-looping technology for the cement industry has been investigated in Monterrey, Mexico by CEMEX (Fennell et al., 2012). Vatopoulos and Tzimas (2012) found that for an equal capture efficiency of 85%, calcium looping capture was almost twice as energetically efficient as using the amine solvent MEA, with a reported energy penalty of 2.8 MJ/tCO<sub>2</sub>. However, it must be noted that MEA is not a solvent that is likely to be used in large scale industrial CCS when deployed owing to its high energy requirement for regeneration of up to 4 MJ/tCO<sub>2</sub>; more modern solvents such as piperazine or proprietary BASF/Linde solvents with regeneration heat duties of 2.5–3 MJ/tCO<sub>2</sub> are more likely to be used (Boot-Handford et al., 2014). These solvents have more comparable energy penalties to those reported for the calcium looping process by Vatopoulos and Evangelos as mentioned above, so the relative advantage reported there is overstated. The use of oxy-fired calcium looping further may increase the performance of the technology, leading to lower energy requirements and potentially reduced costs. Table 4 summarises the cost data from the literature.

**Table 4**  
Summary of cost data from literature for the cement industry.

Author	Year	Technology	Emissions Captured (%)	Cost (\$/tCO <sub>2</sub> )
Romeo et al. (2011)	2011	Oxy-combustion with calcium looping	94%	17.0
Rodriguez et al. (2012)	2012	Oxy-combustion with calcium looping	84%	23.0
IEA (2013)	2013	Unknown on precalciner	60%	35.9
Kuramochi et al. (2012)	2012	Oxy-combustion with calcium looping	60%	40.6
IEA ETP (2012)	2012	Unknown	Unknown	49–148
IEAGHG (2013b)	2013	Full oxy-combustion	Unknown	51.4
IEA (2008)	2008	Oxyfuel combustion	60%	59.5
IEA (2013)	2013	Unknown for whole-plant mitigation	90%	61.5
Hegerland et al. (2006)	2006	Post-combustion amine scrubbing	60%	66.0
IEAGHG (2013b)	2013	Partial oxy-combustion	Unknown	67.6
Barker et al. (2009)	2009	Oxy-combustion with calcium looping	52%	76.9
IEAGHG (2013b)	2013	Post-combustion on NGCC CHP	90%	87.8
Kuramochi et al. (2012)	2012	Post-combustion amine scrubbing	60%	89.0
IEAGHG (2013b)	2013	Post-combustion on coal power plant with CHP	90%	148.7
Barker et al. (2009)	2009	Post-combustion amine scrubbing	77%	164.6

Oxy-combustion utilises higher oxygen concentrations in the cement kiln to save energy that would otherwise be required to heat up nitrogen in the air, allowing for the kiln capacity to increase as the flue-gas volume decreases. However, it has been claimed that the practical limit of this capacity increase is approximately 23–50% due to a limit on the oxygen concentration of 30–35% by volume in the kiln, which serves to prevent damage to the kiln and formation of NO<sub>x</sub> compounds at high temperatures (Vatopoulos and Tzimas, 2012). More recent publications from the IEA (IEAGHG, 2013b) and the European Cement Research Academy (ECRA) (Technical Report, 2012) both state that there are potential advantages of using oxy-combustion in the cement industry, with the ECRA investigating the use of full oxyfuel technology on a laboratory test furnace and reporting no adverse effects on clinker composition, with no significant differences, including within the microstructure, with samples well within the range of normal product quality fluctuations. Similar findings have been reported by Zheng et al. (2016). While acknowledging that switching a kiln to use oxyfuel will alter the temperature profile within the kiln itself, it is not anticipated that this will have a significant negative impact on the process (Technical Report, 2012). The IEA report notes that the technology is promising for implementation on to cement plants and that multiple studies report that problems with altered temperature profiles can be overcome, though larger scale pilot testing is required.

Grey literature focussed primarily on either oxycombustion or post-combustion amine-based separation on either the precalciner or kiln; a CHP unit was frequently required to make up for the lack of low-grade heat in a cement plant to drive the amine reboiler. Costs were found for both partial and full oxycombustion to be largely similar to those found in the academic literature. The LEILAC project considers the implementation of a direct separation technology applied to Heidelberg Cement's Lixhe plant in Belgium (LEILAC, 2017), with construction scheduled to begin in 2018 (Hills et al., 2017).

Cost data were more readily available for the cement industry than for others investigated, and are presented below in Table 4. It is clear that combining oxy-combustion with calcium looping is more economically favourable than post-combustion amine scrubbing. A mean cost of \$39.4 per tonne of CO<sub>2</sub> avoided was found for calcium looping, with this value used as the mean cost in the modelling section.

### 3.5. High purity CO<sub>2</sub> sources

Processes that produce streams of CO<sub>2</sub> with in excess of 95% purity are discussed here. The systematic review did not identify any high purity source cost data within the academic literature, hence these sectors were not included in the model.

Examples of these high purity CO<sub>2</sub> sources include natural gas processing, ammonia production, ethylene oxide production and steam-methane reforming for hydrogen production. In total, these high purity sources account for some 7% of industrial emissions (IEA, 2011). These high purity CO<sub>2</sub> sources offer 'low hanging fruit' for industrial CCS owing to them not requiring expensive separation, with the streams requiring only compression, transport and storage. Because of this, these processes will have significantly lower costs for carbon capture than other industries and as such are ideally placed to be 'first-mover' industries. Many of the commercial CCS plants currently in operation use CO<sub>2</sub> from these industries, such as the Sleipner project in Norway which has used CO<sub>2</sub> from a natural gas processing unit for injection for the last 20 years. A large number of demonstration plants use CO<sub>2</sub> from the hydrogen production process for capture and storage, including Shell's QUEST project in Canada, CCS at In Salah in Algeria and the reinjection of CO<sub>2</sub> from LNG production into the Snøhvit field in Norway.

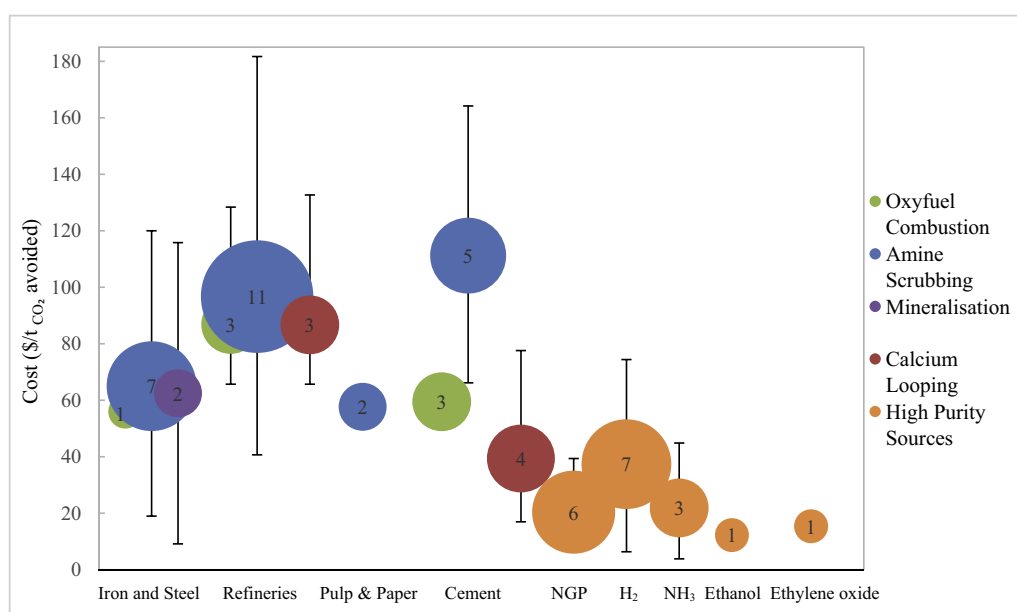
As is shown from the data in Table 5, in general ethanol production, ammonia production and natural gas processing are suggested to have the lowest costs, with costs significantly lower than those proposed for other industries, while hydrogen production has higher costs than the other high purity sources. Even so, using these streams for CCS gives costs significantly lower than those associated with other industries with an average of around \$30 per tonne of CO<sub>2</sub> avoided, with operational data from Shell's QUEST facility being on the upper end of the range of costs found. Table 5 shows the data found from the grey literature for high purity sources.

### 3.6. Summary of costs from literature

The cost data for each of the four major industries and selected high purity sources are presented in Fig. 2. Since both the iron and steel industry and the refining industries contain multiple different sources of CO<sub>2</sub>, the costs shown are the mean costs of applying a technology across all sources for each technology with the error bars illustrating the range of costs. The values used in the modelling may therefore not correspond to the mean costs shown in Fig. 2. The model splits the average cost of capture for a particular technology by source (e.g. blast furnace or coke plant in the iron and steel industry) within an industry. Costs for high purity sources have been included here for comparison, displaying the lower reported costs associated with these streams compared to other technologies. Economic data for the cement, refining and iron and steel sectors were relatively abundant. By comparison, only two sources of cost data for the pulp and paper industry were found. The largest discrepancy between the costs of two different technologies for the same industry came between amine scrubbing and calcium looping for the cement industry, where the cost of calcium looping was found

**Table 5**Summary of cost data from literature for high purity CO<sub>2</sub> sources.

Source	Year	Industry	Cost (\$/tCO <sub>2</sub> )
CCS Roadmap for Industry (Organisation, 2010)	2011	Ammonia (pure stream/flue gas)	3.9–45.3
IPCC Special Report on CCS (IPCC, 2005)	2005	Hydrogen production	6.0–66.0
CCS Roadmap for Industry (Organisation, 2010)	2011	Liquid natural gas production	8.7
IEA CCS Technology Roadmap (IEA, 2013)	2013	Natural gas processing	10.25
IEA CCS Technology Roadmap (IEA, 2013)	2013	Ethanol production	12.3
CCS Roadmap for Industry (Organisation, 2010)	2011	Hydrogen production	14.5
IEA CCS Technology Roadmap (IEA, 2013)	2013	Ethylene oxide production	15.4
CCS Roadmap for Industry (Organisation, 2010)	2011	Natural gas processing (onshore/offshore)	15.4–29.9
Carbon negative roadmap for Romania (Institute, 2012)	2012	Ammonia production	16.6
Realistic Costs of Carbon Capture (Al-Juaied and Whitmore, 2009)	2008	Natural gas processing	19.0–39.0
IEA Energy Technology Perspectives (IEA ETP, 2012)	2012	Hydrogen production	25.0–74.0
IEA CCS Technology Roadmap (IEA, 2013)	2013	Hydrogen production	35.9
Proceedings of CCS cost network workshop (Project Costs, 2016)	2016	Hydrogen production—QUEST project	41.6



**Fig. 2.** Mean costs of technologies on different industries. Error bars represent the complete range of costs found in the literature for each technology as applied to each industry, with the exception of one outlier for amine scrubbing in refineries at \$250 per tonne avoided. The diameter of the bubble is proportional to the number of sources of cost data for that industry and technology for the main industries, with the high purity sources included for comparison. Where ranges are not shown for sectors with more than one paper, the error bars lie within the bubble.

to be considerably lower than that of amine separation, both as an aggregate of costs found from the literature and from both sources which compared both technologies (Barker et al., 2009; Kuramochi et al., 2012).

In order to decide which capture technology is best suited for a given source, the quantity and thermodynamic state of the exhaust gas to be treated is a key piece of information. These data are summarised in Table 6.

Whilst there is reasonably good information regarding the exhaust gases arising from the iron and steel and cement sectors, there are notable gaps in the data describing the oil refining sector. This is partly due to the heterogeneity of the refining sector compared to other industrial sectors, with no 'standard' configuration, meaning it is difficult to make strong assertions about how carbon capture would be applied to refineries without finding strategies on a case by case basis.

Within each industry, the number of large sources and emissions from each of these sources have been identified based on the most recently available data, published in 2005. Within the iron and steel industry, integrated steel mills were chosen as the primary candidates for CCS, with 180 globally with average emissions of 3.5 MtCO<sub>2</sub> per year, and smaller mini-mills omitted from this study owing to

their much smaller individual emissions (IPCC, 2005). A total of 1175 plants from within the cement industry have been selected to be included in this study, with average individual emissions of 0.79 MtCO<sub>2</sub> per year. Within the refining sector, 638 plants have been considered in this study with average site emissions of 1.25 MtCO<sub>2</sub> per year. Since there are a far greater number of large plants in the cement sector, the emissions from large plants within this sector are greater than the others with total emissions of 930Mt per year, compared to only 630 Mt per year in the iron and steel sector and 800 Mt per year in the refining sector. This occurs due to the omission of the smaller steel plants where CCS would be less economical even though the iron and steel industry is a larger emitter overall.

#### 4. Future scenario forecasting and sensitivity analysis

A model was constructed in order to explore the main contributors to the cost of CCS in industry in the time period until 2050. As inputs, this model uses the number and size of large facilities for the cement, refining and iron and steel industries as quoted above. The pulp and paper industry has been omitted from the model because the lack of information about the costing of different technologies

**Table 6**Indicative summary of CO<sub>2</sub> emissions from industrial sources. Flowrates calculated from average plant emissions.

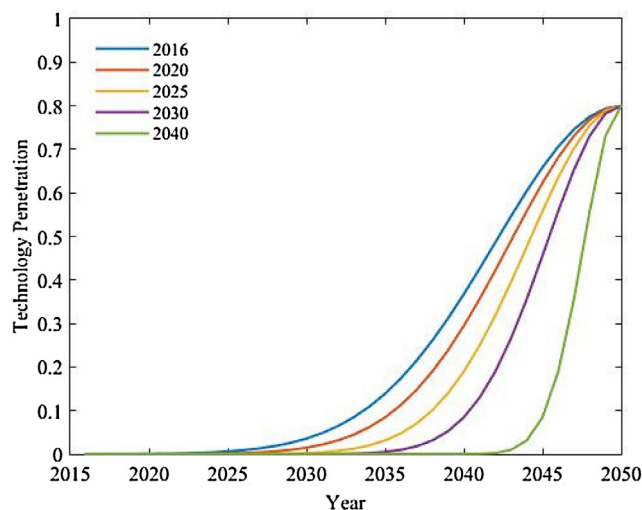
		F (Mt/y)	T (°C)	Y <sub>CO<sub>2</sub></sub>
2 Mt Integrated Steel mill (Carpenter, 2012)	Lime Kiln	0.09	300	30%
	Coke plant	0.74	100	25%
	Sinter plant	0.21	100	5–10%
	Strip mill	0.18	300	10%
	Blast furnace	2.28	300	25%
1 Mt Clinker Plant Refineries (van Straelen et al., 2010)	Combined flue <sup>1</sup>	0.79	–†	14–33%
	Boilers and Furnaces <sup>2</sup>	0.81	260	9%
	Catalytic Cracker	0.17	–†	12%
	Flares	0.03	–†	8–10%
	Steam methane reforming	0.02	–†	20–99% <sup>3</sup>
	Incineration	0.01	–†	3–12%
	Utilities	0.14	–†	3–12%
	Stack	2.52	55	12–14%
500 MW Coal Plant	Stack	1.32	100	3–8%

for CCS means that there are insufficient data to draw meaningful conclusions. Since this model is projecting the costs of CCS 35 years into the future, the number of assumptions made make the model arbitrary; it is not intended to be a realistic forecast of the future deployment of CCS technologies, but instead aims to give an estimate of costs in the event that 80% deployment of CCS is required, to see which variables have the greatest impact on the cost. To this end, conclusions about costs obtained from the model will mostly be qualitative, with the specific values of costs less important than the effects behind them.

Within the scenarios considered, it is assumed that the number of plants within an industry remain consistent in order to avoid additional complexity and uncertainty. The technologies chosen are calcium looping for CCS in the cement industry due to its lower cost, and post-combustion amine capture in the refining and iron and steel sectors. Mean values for costs as applied to different areas of the plant have been selected, as detailed above in the relevant sections for each industry, broken down by the magnitude and the cost of applying CCS to each emission source. This study does not assess the readiness of a technology to be deployed, as for the purposes of this model it is assumed that all technologies are at the same developmental stage and can be deployed when required. It is assumed that all plants considered in these scenarios are new build which are designed in tandem with a CCS unit, instead of designs with CCS retrofitted to existing industrial plants. This reflects the literature which predominately consists of costs for new plants.

Since the uncertainties involved in drawing conclusions about future behaviour and costs are high, the primary objective of the model is to carry out a sensitivity analysis on each of the major variables in order to see which have the greatest impact on the overall cost of CCS in each industry across a range of scenarios. To this end, base values of each variable are changed in order to evaluate the difference in mean cost per tonne of CO<sub>2</sub> avoided. This provides an insight into what must be prioritised to keep the costs of CO<sub>2</sub> mitigation on industrial systems as low as possible.

The baseline start date in the model was selected to be 2020, with a strict final condition of implementing CCS on 80% of plants within each industry by 2050, consistent with the IPCC recommendations (Fischedick and Roy, 2014). Because not all emissions from a plant are captured, it is worth noting that an 80% deployment of CCS is not equivalent to an 80% reduction in total emissions from a sector, as some sources are too difficult or small to capture effectively. This also only applies to the large plants within an industry; for example, within the iron and steel industry, only the large, integrated steel plants were considered, with the much smaller “mini-mills” not considered here due to their low emissions reduction potential of these sites and the likely higher cost of implementing CCS on them.



**Fig. 3.** Proportion of plants with carbon capture deployed on them by year based on a range of start dates from 2016 until 2050, with 2020 being the base case. The S-shaped curves represent the uptake of carbon capture throughout industries based on different start dates.

In general, the quoted costs from literature did not include the cost of transport and storage as these costs are more location specific than capture costs. In addition, transport and storage costs will be similar to those calculated within the power sector so additional research on these costs specifically for industrial CCS is unnecessary. Where costs have been given in the literature with transport and storage contributing to the overall cost per tonne of CO<sub>2</sub> avoided, new costs have been estimated, omitting these contributions.

#### 4.1. Scenario construction

The deployment profile used to model the rate of deployment of CCS across the industry globally was represented by an S-shaped curve. This is represented by the technology penetration variable,  $tp(y)$ , a function of an arbitrary uptake rate constant  $U$ , start year of first implementation  $SD$  and the maximum level  $tp_{max}$  of technology penetration

The technology penetration represents the fraction of plants from an industry that have CCS applied to them in year  $y$ , and is defined in Eq. (2). A visualisation of these deployment profiles across a range of start dates can be seen in Fig. 3.

$$tp(y) = \exp \left( - \left( U - U \left( \frac{y - SD}{2050 - SD} \right) \right)^2 \right) \times tp_{max} \quad (2)$$



The number of plants for each industry with CCS applied to them,  $n(y)$ , within any year  $y$  can be found from the technology penetration for any year using Eq. (3) as the technology penetration multiplied by the  $n_{\max}$  total number of plants of the type considered in this model

$$n(y) = tp(y) \times n_{\max} \quad (3)$$

The learning curve factor, here denoted  $lc(y)$ , represents the cost reduction associated with increased learning, with each generation of plants benefitting from previous generations to reduce the overall cost. It is assumed that the cost reduction per generation CR has a base value of 25% per generation, which is first applied when the technology penetration is greater than the minimum cost reduction threshold  $CR_{\min}$  which has a base value of 5% technology penetration. Each generation is assumed to take five years, with the learning factor being reduced every five years after the initial threshold is met.

$$lc(y) = (1 - CR) \times lc(y - 1) \forall tp(y) > CR_{\min}, lc(y - 1) = lc(y - 5) \quad (4)$$

The escalated cost, denoted as  $ec(y)$  and given in  $\$/t_{CO_2}$ , is calculated via Eq. (5) as the product of the initial cost used as an input to the model  $P$  (where  $P$  is the cost of applying a particular technology to a source within a particular industry, i.e. the value from the literature review) and the projected value of the CEPCI in that year  $i(y)$  and the learning factor  $lc(y)$ . The projected CEPCI value is taken from one of the scenarios selected in Fig. 1. This calculated value is used as the base cost in year  $y$  of CCS per tonne of  $CO_2$  avoided for each different source type within an industry.

$$ec(y) = P \times lc(y) \times i(y) \quad (5)$$

The overall cost of CCS in year  $y$  for each industry, denoted  $c(y)$ , can be calculated for each source as the sum across all sources considered for CCS as the product of the number of plants CCS is applied to in that year, the emissions of that source in  $t$  per annum, here denoted  $S$ , and the escalated cost,  $ec(y)$ , shown below in Eq. (6). This gives the annual cost of implementing CCS across all sources available within an industry. From this, the total cost, calculated in Eq. (7), is found by calculating the sum of the annual costs from the start date until 2050.

$$c(y) = \sum_{source} (n(y) \times S \times ec(y)) \quad (6)$$

$$c_{tot} = \sum_{y=SD}^{2050} c(y) \quad (7)$$

#### 4.3. Results of model calculations

The baseline scenario has a start date of 2020 and a 25% learning curve factor, with the learning cost reductions taking effect after there was a 5% technology penetration. By 2050, the model requires that CCS must be deployed on 80% of plants within an industry, and the technology penetration curve is constructed with an uptake constant of 3. The base costs ( $P$ ) at the start date are  $\$39.4/t_{CO_2}$  for calcium looping in the cement industry and  $\$76.6/t_{CO_2}$  for post-combustion capture at the blast furnace, and  $\$86.4/t_{CO_2}$  at the coke plant in the iron and steel industry, corresponding to 86% of emissions. Since refineries are highly heterogeneous, it is assumed that 15% of the emissions can be captured at a cost of  $\$40.7/t_{CO_2}$  corresponding to high purity sources such as the gasifier, with an additional 50% of emissions available for capture at  $\$98.0/t_{CO_2}$ , corresponding to boilers or furnaces. The remaining emissions, since they would be distributed among a large number of small, low quality sources, are assumed to be uneconomical to capture so are not considered in this model.

As can be seen in Table 7, the iron and steel industry and the refining industry have the smallest overall emissions mitigation,

with roughly 4 Gt of  $CO_2$  avoided in the period until 2050, due in part to the large number of smaller point sources in these industries; by comparison, the cement industry has avoided emissions of 7 Gt since a larger proportion of emissions can be captured economically from large plants. From 2020 to 2050, under a quarter of total emissions are avoided, owing to the initial low deployment rate associated with the deployment curves shown above in Fig. 3, especially evident in the refining industry where only 15% of total emissions over the time period are avoided.

The costs across the three industries fall within the range of  $\$190$ – $\$230$  billion over the time period, with an annualised cost in 2050 of between  $\$15$  billion for the cement industry and  $\$18$  billion for the refining industry. When considering the current economics of the refining industry, an average profit margin of  $\$5.50$  per barrel gives a total industry profit of around  $\$150$  billion per year (Tapia, 2017), with the cost found from this model accounting for about 12% of the total annual profit of the industry. By comparison, the annualised cost of CCS in the cement industry of  $\$14.8$  billion per year is equivalent to 7% of the total current revenue of  $\$216$  billion per annum (Birshan et al., 2015). With an average profit margin of 7.35% suggesting an annual profit of  $\$18.4$  billion, the cost of CCS accounts for 80% of current profits (Damodaran, 2017). In the iron and steel industry, an annual cost of  $\$23.7$  billion accounts for only 1.4% of the forecasted industry revenues for 2017 of  $\$1715$  billion (Bombourg, 2012), but due to the low profit margin of the industry in 2016 it would represent 230% of current annual profits of  $\$10.3$  billion. However, it is important to note that if all manufacturers were required to apply CCS, or there was a cross-border tariff between regulated and non-regulated areas, the increases in price in regulated areas would be manageable and could be passed on to the consumer.

It is important to note that the major difference between carbon capture as applied to the cement industry and the other two considered is that the cement industry uses calcium looping instead of post-combustion capture with amine solvents. By using calcium looping, the model suggests that the overall cost will be roughly  $\$27.6$  per tonne avoided over the course of the time period and  $\$19.9$  by 2050. By comparison, the costs in the other two industries are higher, at  $\$55.1$  and  $\$59.3$  for the iron and steel and refining industries respectively across the time period, and by 2050 the costs have fallen to  $\$40.0$  and  $\$42.9$  respectively. Alongside the lower projected cost, calcium looping in the cement industry would be able to capture a larger proportion of total emissions, making it a good industry to target for early carbon capture deployment. The iron and steel industry will be able to capture a lower proportion of total emissions due to the more distributed emissions sources, with the coke plant and blast furnace allow 86% to be captured between both sources. By comparison, it will be much more technically difficult and expensive to capture a larger proportion of emissions from the refining industry due to the low quality of carbon dioxide sources and the relative dispersal of these throughout the process plant. The refining industry is already the most expensive of the three industries investigated, but also has the lowest proportion of emissions captured, making them an unattractive target for early deployment of carbon capture unless there is a fundamental process redesign, which is unlikely due to inertia in the industry.

#### 4.4. Integrity of scenario assumptions

These scenarios are reliant on a large number of assumptions in order to obtain the output costs found in Table 7. The most fundamental assumption is that the standard plant is the same in terms of size, emissions source and scale. This is clearly debatable, for example in the iron and steel sector, industrial facilities can largely be assigned to one of two major groups, the larger integrated steel mills with average emissions of 3.5 Mt per annum, and the smaller,

**Table 7**  
Model Results of Forecasting across Industries for base values of variables.

Model Outputs	Iron and Steel	Cement	Refineries
Mitigated emissions to 2050 (Gt)	4.0	6.9	3.9
Total emissions to 2050 (Gt)	18.9	27.8	23.9
Total cost to 2050 (\$bn)	221.6	191.3	229.5
Annual cost in 2050 (\$bn)	17.3	14.8	17.8
Cost per tonne avoided in 2050 (\$)	40.0	19.9	42.9
Overall cost \$/t <sub>CO<sub>2</sub></sub> mitigated	55.1	27.6	59.3

more flexible mini-mills, which on average emit just 0.17 Mt per annum. However, the integrated steel mills have aggregate emissions 20 times higher than the mini-mills, justifying the exclusion of mini-mills from these scenarios. It is however, important not to forget the large cumulative emissions from these plants, which are not included.

One major source of uncertainty is the magnitude of the learning curve factor that was used. The base value chosen of a 25% reduction in costs per additional generation was estimated as an average of the 20% value suggested by literature for the energy industry (Jamashb and Köhler, 2008) and the 30% cost reduction claimed by SaskPower for the next iteration after the current Boundary Dam project (Institute, 2014). This conservative estimate was used instead of a 30% cost reduction as heavy industries such as those investigated in this paper will use a different learning curve factor to that of the energy industry. For ease of calculation, it is assumed that there will be no cost reduction up until the first large-scale deployment of CCS on the industry, accounting for over 5% of plants, and that the first generation will be installed with the costs found in literature. Subsequent generations will occur every five years after the 5% threshold has been reached, and will receive the cost reduction. Whilst this is an overly simplistic representation of the complex nature of cost reductions as a result of increased learning, this representation suggests the relative scale that these reductions would construe.

In order to compare the method used within this research to others within the literature, the calculations have been repeated using an alternative model for the learning cost reductions. Under the model proposed by Rubin et al. (2007), costs of CCS within the power industry will decrease per doubling of capacity at a fixed rate. Assuming a cost reduction of 3.5% per doubling of capacity, starting at first plant and active for each of the three industries, cost reductions varied between industries depending on the number of plants at which CCS was applied. This figure of 3.5% has been chosen as the cost reduction for the cost of electricity for CCS for a pulverised coal plant, considering both capital and operating costs. Coal was chosen as the concentration of CO<sub>2</sub> in the flue gas is closer to that of an industrial plant than a gas-fired power plant. This led to learning factors in 2050, representing the cost reduction per plant when compared to initial implementation of 0.75 in the iron and steel industry, 0.65 in the refining sector and 0.69 in the cement industry due to the greater number of plants with CCS applied to them in these sectors. This compared to a factor of 0.32, indicative of a 68% reduction in costs due to learning, in the scenarios presented in this research across all three industries, as cost reduction is based on percentage deployment rather than number of plants. Thus the model used in this study is likely to be overly optimistic, though as referenced within Section 4.2, still leads to a significant cost when compared to the profit of the three industries. If it was instead assumed that learning could be applied across industries (*i.e.* the three different industries could learn from each other), the overall learning factor was 0.63.

Technology penetration of CCS across the industries is another important metric, as CCS technologies will not be appropriate for all plants based on location and local legislation. The exact value will be dependent on a combination of legislation, severity of regulation

for industries to comply with and geographical location, and as such it is necessary to ascertain the impact that technology penetration has on overall costs and emission mitigation. The base figure of 80% was initially chosen as a rough analogy of the IPCC's recommended 80% reduction in emissions.

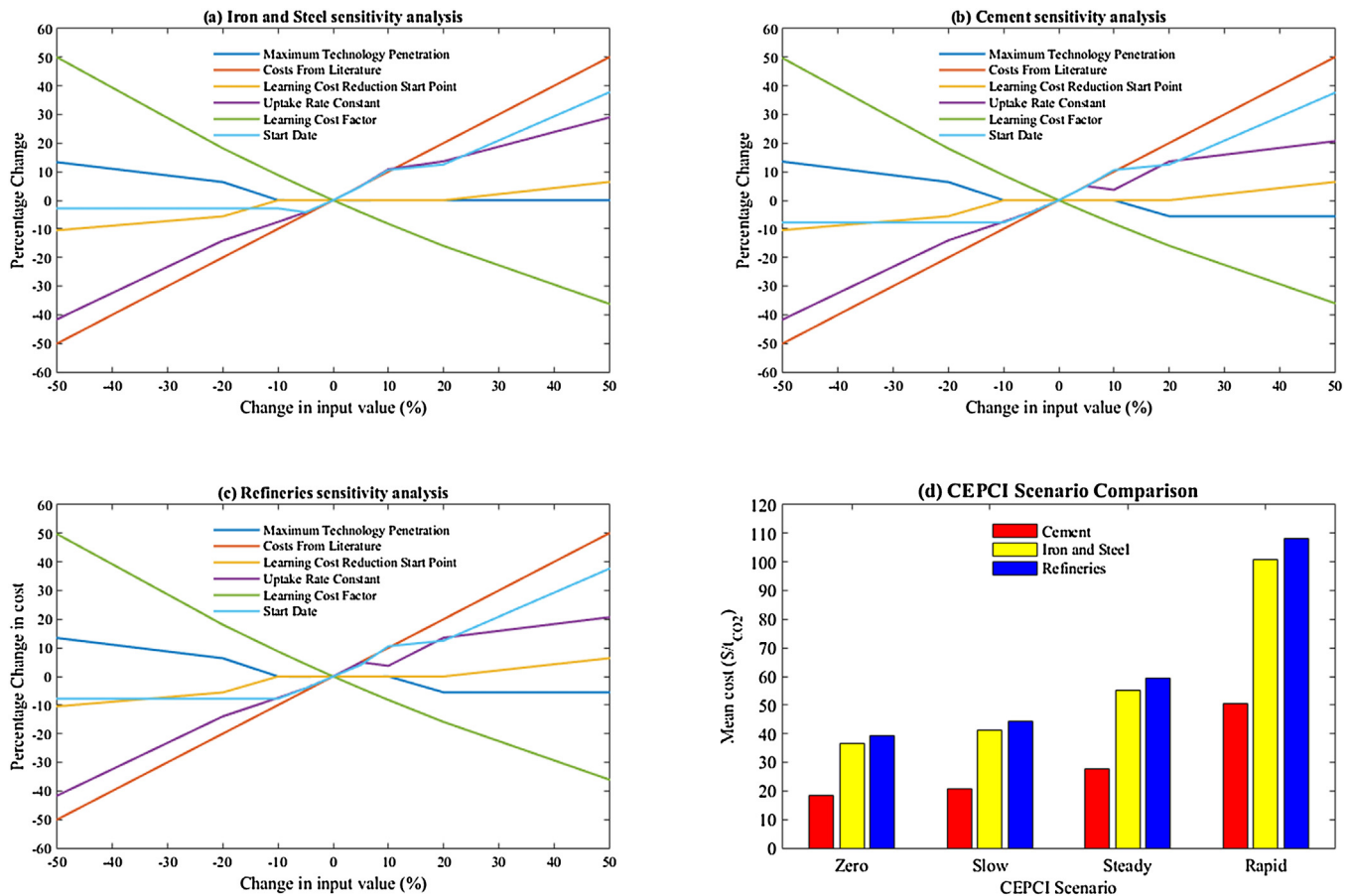
When comparing to the IEA ETP (2012), the costs found here fall within a similar range. Within the iron and steel industry, the IEA quote a cost of \$60–80 per tonne of CO<sub>2</sub> avoided, which compares favourably with the cost from the scenarios described above of \$55 per tonne, though all ETP figures include the costs of transport and storage so will be naturally slightly higher. CCS in the refining industry was found to have costs of \$50–130 dependent on the source quality, and the figure here of \$59 falls within this range. For the cement industry, the ETP quotes costs between \$50 and \$150 per tonne avoided, including transport and storage, which is significantly higher than the modelled costs of \$28 per tonne, but that may be considering the use of amine solvent as the capture method, which as discussed above is reported as being more expensive than calcium looping which was selected for the scenarios discussed here.

The IPCC special report on carbon capture and storage also lists costs for industrial CCS which are comparable to the figures found in these scenarios after being escalated to 2013 USD (IPCC, 2005). In the oil refining and petrochemical industries, the costs of carbon capture and storage is estimated to be roughly \$70–85 per tonne of CO<sub>2</sub> avoided, broadly similar to the cost estimation from the scenarios of \$59 per tonne of CO<sub>2</sub> avoided. Within the iron and steel industry, applying CCS to blast furnaces of integrated steel mills of the type considered within this study resulted in costs of \$52 per tonne of CO<sub>2</sub> avoided, similar to the costs found from this study of \$55 per tonne avoided. This IPCC research does not report the costs of carbon capture from the cement industry so cannot be used as a comparison for this cost.

#### 4.5. Sensitivity analysis

As seen in Fig. 3 above, deployment curves are generally similar for successively later deployment dates, though there is less opportunity for learning cost reductions to apply due to a faster deployment cycle. Considering the time period from 2020 to 2050, a 10% delay would mean that deployment begins in 2023. This delay of three years is responsible for costs rising by approximately 10% per tonne avoided, whilst starting in 2026 is responsible for a 12.5% increase. If deployment is delayed even further, starting in 2030 would represent a cost increase of between 20 and 28%, and starting in 2040 would lead to an estimated 57% increase in costs.

The results of the sensitivity analysis for each of the three industries are shown in Fig. 4a–c. The other variables with the greatest effect on the mean cost per tonne avoided are the learning curve factor and the base costs from literature. This demonstrates the importance of the literature data in predicting the cost of industrial CCS, and also highlights the propagation of uncertainties caused by the large error bars from the literature. Likewise, the learning curve factor has a large effect on the overall cost, showing the value of sharing learning outcomes widely.



**Fig. 4.** (a–c) Sensitivity analysis of costs of CO<sub>2</sub> avoided on each of the three industries showing percentage change of overall cost caused by changing variable values. (d) Impact of CEPCI escalation scenario on overall cost of CO<sub>2</sub> avoided.

As displayed in Fig. 4d, the overall cost per tonne avoided is highly dependent on the capital cost escalation scenario selected from Fig. 1. The zero, slow and steady growth scenarios give only small differences to the overall cost per tonne of CO<sub>2</sub> avoided across all three industries. The cost differences between industries are exaggerated in the event of the rapid growth scenario. Depending on the market conditions and their influence on the plant cost, the economic viability of applying carbon capture on these three industries can be severely impeded. The variation in costs is consistent across industries between scenarios, with the costs associated with the rapid growth scenario escalating to an average of over \$120 for CCS in refineries, corresponding to an increase of about 80% when compared to the steady growth scenario. While it is not expected that the index will follow one of the more extreme scenarios here, they provide bounds on the expected costs based on uncertainty regarding the future values of the index.

It is worth noting that some of the variables have non-linear effects on the overall costs, particularly start date and the learning cost factor. Since the effect of learning in this model is zero until the learning threshold has been met (initially at 5%), changing the rate at which CCS is deployed will lead to the threshold for cost reduction being met later, reducing overall cost reductions. Similarly, the uptake rate constant can be seen across all three industries to have a stronger influence on the overall cost at lower values, as a higher value of this constant leads to deployment curves being steeper, i.e. with a slower initial deployment rate followed by rapid late deployment, as seen in Fig. 5. Because of this, the overall cost increases significantly as this parameter increases, demonstrating

that not only should deployment begin as soon as possible, but that a slow initial deployment rate leads to cost increases.

## 5. Conclusions

In this paper, the results of an in-depth systematic literature review of CCS technology as applied to the industrial sector are presented, with a particular focus on four main industries; cement, iron and steel, refining and pulp and paper. The authors reviewed 250 papers from the academic and grey literature, using this information to construct a scenario-based assessment of potentially important parameters driving overall costs in this emerging area.

Costs from the academic literature were compiled by industry and by technology and compared to costs from the grey literature where applicable. Despite a targeted search of the literature, only about 10% of the reviewed papers contained costs, demonstrating the difficulty enumerating the costs of industrial CCS. In general, costs were broadly similar between the two types of literature, although the academic literature proposed more cost data for novel technologies. Costs for the majority of technologies throughout industries were found to range from \$20–120 though with large ranges found, leading to a great deal of uncertainty over the true costs of implementing CCS within the sector. Due to this, there is no benchmark against which costs of new technologies or improvements to current technologies can be made, making the choice of technology less clear for investors.

In addition to the costs found from the four main industries considered, grey literature was also utilised to determine the costs of applying CCS to high purity sources of CO<sub>2</sub> such as streams

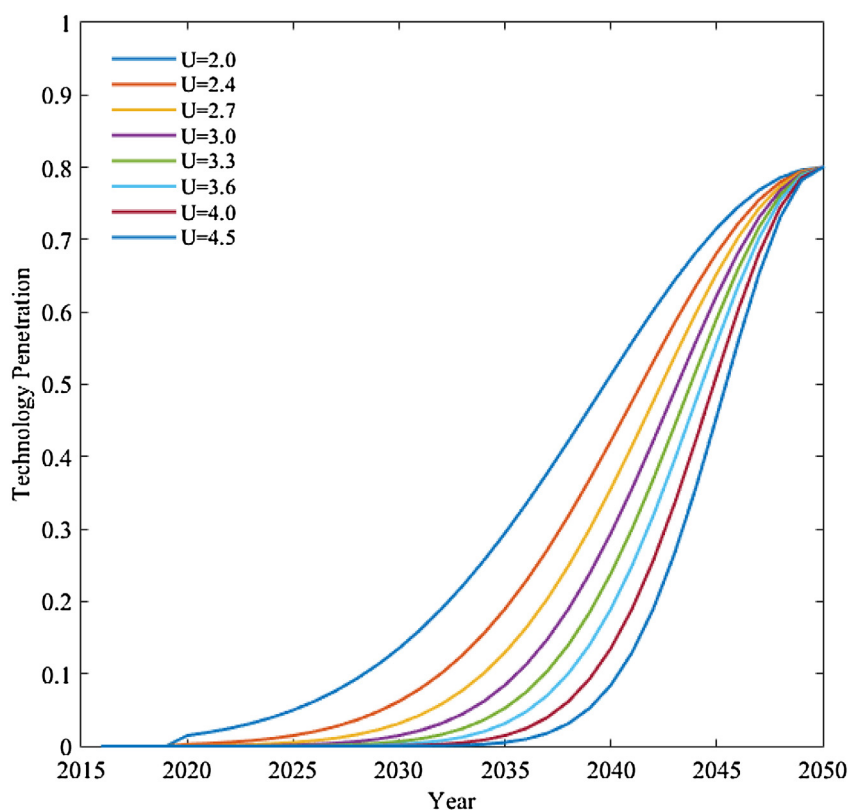


Fig. 5. Effect of changing uptake rate constant on the deployment profiles under an 80% final deployment scenario with a start date in 2020.

originating from natural gas production or hydrogen production. These sources offer low-cost options for applying CCS due to the high concentration of the streams, meaning that expensive capture and purification is not required in some cases. These sectors could be used as early movers to make quick reductions in industrial emissions at minimal cost, whilst simultaneously demonstrating transport and storage technologies to reduce the costs of implementing CCS on other industries.

A model was used to evaluate scenarios under which CCS would be deployed in the iron and steel, cement and petroleum refining sectors, omitting the pulp and paper industry due to a lack of cost data. The model considers the mean cost per tonne of CO<sub>2</sub> avoided if CCS were to be deployed to 80% of large industrial plants within each industry, using a sensitivity analysis to evaluate different scenarios whilst accounting for the inherent uncertainty associated with projecting 35 years into the future.

Of the three industries modelled, the cement sector is able to capture the highest proportion of emissions due to the simplicity of the process and the single flue stream; by comparison, petroleum refineries have many smaller and lower concentration sources. Since the iron and steel and refining industries both considered the use of post combustion amine capture, there is the potential for shared learning of the use of the technology on low quality sources. Costs throughout the time period considered in the model were found to fall within the range of \$20–70 per tonne of CO<sub>2</sub> avoided, with costs in 2050 lower due to the effect of increased learning making technologies cheaper than when first deployed. From this model, the cement industry has the lowest estimated mean costs of deployment over the entire time period considered at \$28 per tonne of CO<sub>2</sub> avoided through utilisation of a calcium looping system, with the cost falling to \$20 per tonne avoided by the end of the studied period. By comparison, the use of a more mature technology, post-combustion amine absorption, was found to be the most cost effective strategy for deployment on the iron and steel

industry and on petroleum refineries, but with higher projected mean costs over the time period; approximately \$55 for the iron and steel industry and \$59 for refineries, with final costs at the end of the study period in 2050 of \$40 and \$43 per tonne avoided respectively. Alternative technological options for each of the industries were also investigated, including oxyfuel combustion or mineral carbonation, but the data from these technologies was either very sparse or inconsistent, leading to greater uncertainty over costs.

From the sensitivity analysis, it can be seen that the factors with the greatest effect on the overall avoided cost of CO<sub>2</sub> are the start date, the learning cost reduction and the initial cost per tonne avoided from literature. The large effect caused by the base cost from literature demonstrates the necessity for a clear and consistent method of reporting costs than can be easily compared in order to draw firmer conclusions about the costs associated with CCS. What is readily apparent is that the large-scale deployment of CCS required to meet the emissions reduction targets of 80% by 2050 will be expensive, but that costs will only increase if deployment is delayed.

Even with deployment on 80% of plants by 2050, the cumulative emissions over the time period is very low, accounting for only 25% of emissions for the iron and steel industry or the cement industry, and 16% for the refining industry, which could potentially impact carbon budgets due to the low mitigation across the time period considered. In order to reduce cumulative emissions further, an earlier start date or a faster rate of deployment would be required.

Also important is the learning cost factor, which can lead to a 40–50% increase in costs if cost reductions are half as great as expected. Combined with the potential for a 80% increase in the event of the high growth rate scenario compared to the steady growth scenario, there exists a great deal of uncertainty surrounding future costs of carbon capture and storage as applied to industrial plants. Reducing this is necessary to attract investment from the private sector, however many of these uncertainties may



only be reduced through deployment and demonstration. Consequently, strong financial backing and risk sharing for industrial CCS from the public sector will be necessary in order to build confidence to a sufficient level to start large-scale deployment.

## Acknowledgements

This work was carried out as part of the ongoing research of the Imperial College London Clean Fossil and Bioenergy Research Group (<http://www.imperial.ac.uk/a-z-research/clean-fossil-and-bioenergy/>). The authors gratefully acknowledge funding from the UK Engineering and Physical Sciences Research Council (EPSRC) under the UK Carbon Capture and Storage Research Centre (UKCC-SRC) through grant number EP/K/000446/1. The authors would like to thank Jamie Fairclough for his assistance in carrying out the systematic review. The authors declare no conflicts of interest.

## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.ijggc.2017.03.020>.

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