GLOBAL COSTS OF CARBON CAPTURE AND STORAGE

2017 Update

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Background

This summary report presents data commissioned by the Global CCS Institute from Advisian (the consulting and advisory arm of WorleyParsons, a global engineering firm) of the current and likely future costs of CCS in power generation and industrial applications. Key results are presented here, with selected detailed assumptions contained in the Appendix. The Institute has reserved further unpublished information for its membership and clients but other stakeholders are encouraged to contact the Institute to discuss key parameters and assumptions.

This report provides cost estimates for CCS in seven industries, including power generation, iron and steel, cement and bio-ethanol production. Estimates are also provided for fourteen countries, including China, Germany, Canada, Indonesia, Morocco and South Korea.

The Institute commissioned this dataset to provide an independent and up-to-date reference for various stakeholders wishing to understand the cost and performance of facilities fitted with CCS technologies, including transport and storage. Standardised designs for each facility have been used and costs for these are transposed from the reference location to different countries, reflecting drivers such as local ambient conditions, labour rates and fuel cost and quality. The resulting cost estimates therefore involve a degree of uncertainty that is typical for studies of this type, but provide a sound representation of the likely cost of CCS using today's commercially available technologies, as well as cost reductions possible from learning-by-doing and by using better technologies that are currently in various stages of development.

General findings and contextual observations

"The cost" of CCS is a key issue in the public debate and has many dimensions. The Institute is one of many organisations involved in the production of cost information and in ongoing discussions about how this information is, and should be, used in broader debates around energy and climate change policy.

CCS on industrial applications

CCS is typically characterised as a "clean coal" technology. The number of industries covered in this report, while still not a full representation of all CCS applications, will hopefully demonstrate that it has uses beyond fossil fuel combustion. Even when viewed as a coal technology, coal-fired generators fitted with CCS emit around 90% less CO_2 than unabated coal plants, including even the most efficient new coal plants using ultra-supercritical technology.

The cost of CCS on several industrial applications is far below what many would expect given the repeated claims that CCS is 'too expensive'. Part of the Institute's mission is to improve the understanding of the emissions profile and mitigation options for the industrial sector, which is often overshadowed by controversy and public debate on coal and renewables technologies in the power sector. In the case of power generation, there is also a poor but growing understanding of life-cycle emissions from gas-fired power generation, including from upstream fuel processing, and the role CCS can play there.

CCS on coal-fired generators

The costs of CCS for coal-fired power generation are poorly understood and so tend to be misused or misinterpreted.

As of June 2017, the Institute has identified 11 actual and planned large scale CCS facilities on coal-fired power generators, two of which are in operation today and provide important data points on actual cost and performance. These operational facilities are retrofits to existing plant, involving various site specific issues and a resulting range of costs. A third facility is soon to be commissioned and involves new coal-gasification technology, rather than the standard post combustion amine technology which is itself still 'first-of-a-kind' in commercial scale power generation. This facility at Kemper County is frequently reported in the media and is heavily criticised given delays and cost overruns, now a cost of around $US7.5 billion. The cost of this facility has been thoroughly investigated and attributed to matters other than CO_2 capture.[1] The retrofitting of CO_2 capture at Boundary Dam incurred unexpected costs relating to plant refurbishment and attracted similar but inaccurate criticism. Performance data for Boundary Dam's start-up phase was also widely reported, with some erroneously suggesting this was typical of normal operations for all CCS facilities.[2] The world's second, large scale CCS-power facility at Petra Nova was completed without any controversy — at a relatively low cost, on time and on budget — and because of this has been largely ignored by media. While each of these three facilities provide important information for the public discussion of CCS, they provide somewhat limited cost information for "representative" facilities in coal-fired power generation, particularly outside of North America. Their costs are also unrepresentative of CCS facilities in other industries.

The costs for coal-fired power CCS facilities are also often expressed in terms of capital cost. New energy investment is dominated by onshore wind and solar PV projects, which are of smaller scale, have lower absolute investment costs and are most frequently reported in dollars per Watt or cents per kWh. The capital cost of CCS facilities is in the order of billions of dollars, making them seem excessive by many orders of magnitude. In the cases where scale is appropriately accounted for, comparisons between CCS and renewables presume like-for-like qualities in plant availability and value to electricity markets. Both advocates of CCS[3] and of renewables[4] are guilty of drawing stark conclusions from such simple and inappropriate comparisons, in addition to not being clear about key assumptions[5] or estimation methods (which the Institute and a wide range of other expert organisations have worked to address[6]).

Comparisons of the value and stage of CCS technologies

The reporting of CCS funding implicitly presumes poor value for money[7], even though analysis repeatedly finds that the deployment of CCS would actually avoid significant costs in achieving emission reduction targets.[8] By contrast, the reporting of the far greater amount of spending on wind and solar PV is celebrated, and value for money is simply presumed.[9] There are limited examples of independent scrutiny[10] applied to the amount of subsidies paid to renewables versus the emission reductions they achieve, and this scrutiny is readily criticised.[11]

Cost comparisons make no account for CCS on power generation still being at its earliest, highest cost stage. Because these facilities are large and complex, first attempts involved considerable contingencies and hence dramatic cost reductions are expected for second and subsequent attempts. Like all technologies, ongoing research and deployment will deliver further cost reductions from next generation capture technologies. The costs of solar PV were, until recently, much higher than current first-of-a-kind CCS plant. The dramatic reduction in costs of solar PV and (to a lesser extent) wind generation has been due to decades of public subsidies that continue to be paid globally. At the same time, the limited instances of subsidies paid to CCS facilities (numbering far less than subsidies announced but later withdrawn) are criticised even though they arguably deliver better value in achieving emission reductions.

[1] https://www.nytimes.com/2016/07/05/science/kemper-coal-mississippi.html?_r=0
[2] http://ieefa.org/a-carbon-capture-debacle-in-saskatchewan-raises-questions-about-a-technology-that-isnt-living-up-to-the-hype/
[3] http://www.co2crc.com.au/retrofitting-carbon-capture-storage-coal-cheaper-solar/
[4] https://www.bloomberg.com/news/articles/2017-01-03/for-cheapest-power-on-earth-look-skyward-as-coal-falls-to-solar
[5] http://reneweconomy.com.au/spinning-carbon-capture-storage-cheaper-renewables-61232/
[6] http://www.globalccsinstitute.com/publications/toward-common-method-cost-estimation-co2-capture-and-storage-fossil-fuel-power-plants
[7] https://www.bloomberg.com/news/articles/2017-01-20/u-k-carbon-capture-may-have-cost-11-billion-watchdog-says
[8] https://ukccsrc.ac.uk/news-events/news/national-audit-office-concludes-cancellation-ccs-competition-could-cost-uk-%C2%A330bn
[9] https://about.bnef.com/blog/clean-energy-defies-fossil-fuel-price-crash-to-attract-record-329bn-global-investment-in-2015/
[10] https://grattan.edu.au/wp-content/uploads/2015/05/822-sundown-sunrise5.pdf
[11] https://www.theguardian.com/commentisfree/2015/may/25/the-benefits-of-solar-do-outweigh-its-costs-some-have-a-hard-time-accepting-it
http://www.theaustralian.com.au/business/business-spectator/grattan-says-solar-a-10-billion-waste--id-agree-if-it-was-still-2009/news-story/72b73edb4261971b189a3e386505685c
https://www.crikey.com.au/2015/06/01/what-the-grattan-institute-gets-wrong-about-solar/

Costs and the business case for CCS

The lowest cost applications for CCS include natural gas processing, ammonia and bio-ethanol production. Because of their cost, these industries are obvious CCS opportunities for policy makers and others interested in achieving large emission reductions from important industrial facilities. Regardless of costs, the business case for applying CCS on all industrial applications is strong, in that it is one of the few, complementary and necessary methods available to achieve large emission reductions from these facilities.

Higher cost industrial applications for CCS include iron and steel production, and cement. Given the necessity of CCS for industrial facilities, costs must eventually be borne and will be best managed through policies that appropriately share the burden between industry and consumers, as well as those that continue to drive innovation and cost reductions in CO_2 capture.

Prospects for CCS in the power sector also depend on the willingness of policy makers to impose mitigation costs, which depends on the variety of other technologies that can form part of a stable, low emissions grid:

- investment in cheap onshore wind and solar PV has been significant and will continue, including in many markets that are heavily reliant on, and continue to invest in, centralised and cheap fossil fuel sources.
- high rates of intermittent renewable penetration with deep decarbonisation requires investment in other solutions to maintain system security, including gas-fired generation where fuel is available, and others that are more expensive or currently face other barriers to deployment such as battery storage, pumped hydro storage, demand side participation, geothermal, offshore wind, biomass and solar thermal.
- policy interventions and subsidies paid to date that encourage renewables, while significant, are still inadequate to achieve deep emission reductions in the power sector. They reflect a combination of instruments of varying strength and political uncertainty, and thus have only encouraged cheap onshore wind and solar PV. The shift away from carbon-intensive generation assets has been slow, and their use has even expanded in countries like the United States due to an abundance of cheap gas and Japan due to the closure of nuclear plant.
- stronger and more refined policy settings are necessary to provide a clear pathway towards full decarbonisation. Appropriately designed policies based on achieving emission reductions at least cost will encourage more exotic forms of renewable generation and energy storage, and will also encourage investment in CCS in markets where it is cost competitive. Taking an ideological approach and ruling out a technology like CCS will almost certainly result in higher costs of achieving climate outcomes.

This report contains cost estimates of applying CCS to a bioethanol plant. However other BECCS applications, for example in power generation, are not costed given no other commercial scale plants are currently in operation. There is a wide variety of integrated assessment models that illustrate the importance of BECCS in limiting global temperature rises to below 2 degrees. It is suspected, however, that the volumes of biomass required for this scale of BECCS deployment may be infeasible. This infeasibility is sometimes levelled as a criticism of CCS however it underlines an important and growing concern that alternatives to BECCS, which are necessarily more risky or expensive, would need to be relied upon. If this is true, much more aggressive action must be taken now to reduce reliance on negative emissions technologies. This tends to underline the importance of deploying all available emission reduction technologies, including CCS.

Costs in the context of hitting climate targets

A common element to each of the points above is that the concerns around the cost of CCS, while important to address, do not detract from its necessity and do not affect the imperative to take strong policy intervention. The scale of emission reductions required under the Paris Agreement is large, and a wide range of technologies in all sectors will be required. CCS may appear expensive relative to some technologies already being deployed, however the more pertinent comparison is to the cost and feasibility of technologies that would need to be deployed if CCS were not available. This is borne out by comparisons of the cost of CCS to carbon pricing, estimates of the social cost of carbon and marginal abatement costs inferred from modelling of 2 and 1.5 degree scenarios. That is, these carbon values are all significantly above the cost of CO_2 avoided in the full range of CCS applications, as illustrated below.

Key cost data

The key measures used to report the costs of CCS facilities are the life-cycle or 'levelised' unit cost of production and cost per tonne of CO_2 avoided. Levelised costs are an important comparative measure because they account for the scale and rate of production of the plant over its lifetime. However, as noted above, levelised costs in the power sector are frequently and inappropriately used to compare technologies that do not share the same characteristics, particularly that some renewable technologies are subject to weather variability and so have different value to the electricity system. The cost per tonne of CO_2 avoided is a further measure that enables comparisons across various technology types in terms of their value for money in reducing greenhouse gas emissions. Such measures are important in discussing the net benefits of CCS facilities, which typically involve large initial investments in comparison to other important low emission technologies.

Costs for the reference location (United States of America) are reported in Table 1. Key observations are:

- Based on 'first-of-a-kind' technologies currently deployed at commercial scale, the addition of CCS to unabated power and industrial facilities can result in additional costs of as low as 2% and up to 70% to the lifecycle or levelised unit cost of production.
- Those facilities with the lowest cost increases already produce concentrated CO_2 streams as part of the process, which is otherwise currently vented into the atmosphere. These processes are natural gas (increase of 2%), fertiliser (4%) and bio-ethanol production (5%).
- The higher cost increases for power generation (45 to 70%), steel (30 to 41%) and cement production (68%) reflect that CO_2 separation is not included in the process without CCS. Therefore, a greater incremental cost is incurred to separate CO_2 when compared to the processes with inherent CO_2 separation.
- Industries where the addition of CCS adds relatively higher incremental costs are also industries in which capture techniques and technologies are developing. For these industries, the potential future cost reductions are likely to be relatively larger.
- The deployment of technologies that are still in development can reduce the cost of applying CCS by up to approximately 30% in the power sector, 17% in iron and steel, and 16% in cement production.

Table 1: Costs of CCS technologies at the reference location (USA) – first-of-a-kind

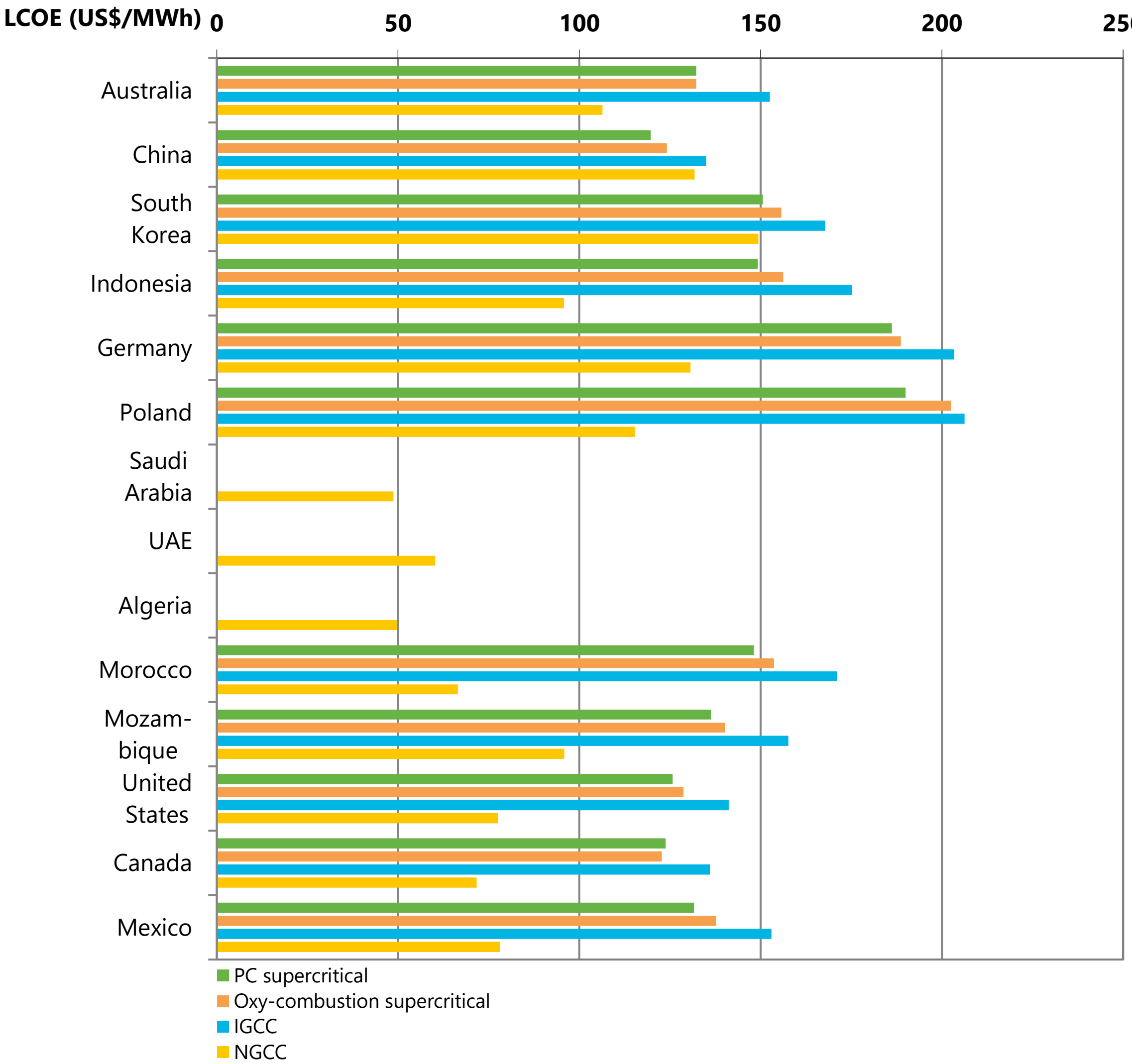
	PC super-critical	Oxy-comb. super-critical	IGCC	NGCC	Iron and steel	Cement	Natural gas	Fertiliser	Biomass to ethanol
Levelised cost	US$/MWh	US$/MWh	US$/MWh	US$/MWh	US$/tonne	US$/tonne	US$/GJ	US$/tonne	US$/litre
Without CCS	75-77	-	95	49	280-370	101	3.75	400-450	0.40-0.45
With CCS - FOAK	124-133	118-129	141	78	114	69	0.061	13	0.018
With CCS - NOAK	108	107	102	62	95	58	0.058	12	0.017
Increase for FOAK w. CCS	60-70%	51-64%	45%	57%	30-41%	68%	2%	3-4%	4-5%
% decrease FOAK to NOAK	-13 to -19%	-9 to -16%	-28%	-21%	-17%	-16%	-5%	-8%	-6%
Cost of CO_2 avoided (US$/tonne CO_2)									
FOAK	74-83	66-75	97	89	77	124	21.5	25.4	21.5
NOAK	55	52	46	43	65	103	20.4	23.8	20.4

Notes: For industrial processes, levelised costs are expressed on an incremental basis relative to current market commodity prices which have been used as an analogue for the cost of production without CCS. Ranges are presented for technologies that represent a family of multiple reference plants. This includes the variability in market price identified for industrial commodities (such as iron and steel). The transport and storage costs applied are between 7 and 12 US$/tonne CO_2 for all power generation technologies. A combined 11 US$/tonne CO_2 is included for the industrial case transport and storage costs.

The differences in levelised costs are also reflected in the cost per tonne of CO_2 avoided. The cost of CO_2 avoided (all figures in USD) ranges from $21.5/tonne for gas processing and bio-ethanol production, around $78/tonne for coal-fired power generation, $89/tonne for gas-fired power generation and up to $124/tonne for cement production.

Cost estimates for CCS in various countries are presented in Figure 1 (for power generation, on a levelised costs basis) and in Table 2 for all industries (cost per tonne of CO_2 avoided). All costs include transport and storage.

Figure 1: Levelised cost of CCS plant by location, first-of-a-kind



Key observations of the LCOE for power generation in different countries are:

- NGCC with CCS is the cheapest technology (in US$/MWh) in almost all the fourteen countries examined.
- The cheapest locations for NGCC with CCS (in US$/MWh) are large gas producing nations such as Saudi Arabia, UAE and Algeria. Expensive locations like South Korea and Germany reflect higher imported gas prices.
- The cheapest locations for coal-fired generation with CCS (in US$/MWh) are the United States, Canada, Mexico and China. These results reflect:
  - — the low coal price in Canada, which offsets relatively higher labour and equipment costs.
  - — significantly low labour costs in Mexico.

— the relatively low cost of labour and equipment in China.

- The most expensive locations for coal-fired generation with CCS (in US$/MWh) are Germany and Poland because of:
  - — higher coal prices and equipment costs in Poland, which offset lower labour and materials costs.
  - — high labour costs in Germany.
- IGCC with CCS (in US$/MWh) is the most expensive option in all countries.

Table 2: Cost of CO_2 avoided by location, first-of-a-kind

	Cost of CO_2 avoided (US$/tonne CO_2)							
	PC super-critical	IGCC	NGCC	Iron and steel	Cement	Natural gas	Fertiliser	Biomass to ethanol
ANZ								
Australia	104	135	160	119	194	26.9	33.0	26.9
Asia								
China	60	81	99	74	129	24.2	27.8	24.2
South Korea	93	120	119	92	159	26.9	31.6	26.9
Indonesia	74	106	96	76	125	22.8	26.9	22.8
Europe								
Germany	121	148	138	113	188	27.3	33.1	27.3
Poland	70	87	92	72	130	25.7	29.2	25.7
ME and Africa								
Saudi Arabia	-	-	80	67	104	19.7	23.3	-
UAE	-	-	97	90	140	21.9	26.7	-
Algeria	-	-	87	76	116	20.3	24.4	-
Morocco	81	113	95	80	125	21.5	25.8	-
Mozambique	96	134	104	86	140	23.5	28.1	23.5
Americas								
United States	74	97	89	77	124	21.5	25.4	21.5
Canada	115	143	101	92	146	22.3	27.0	22.3
Mexico	81	114	88	71	113	21.3	25.0	21.3

Key observations on the cost of CO_2 avoided in the different countries are:

- Countries with lower labour costs (such as China, Mexico, Indonesia and Poland) and low energy costs (such as Saudi Arabia) have the lowest cost for implementing CCS.
- Germany has the highest costs in each of the five industrial processes largely due to high labour costs.
- While China is a relatively cheap location, it has recently experienced rising costs of production because of increasing labour costs and the addition of an import tax.
- Costs in natural gas processing, fertiliser and bio-ethanol have a relatively narrow band of variance across all countries, with a range of $20 to $27/tonne of CO_2 avoided. Avoided CO_2 costs in cement have a much larger range, from $104 to $194/tonne, while iron and steel costs vary from $71 to $119/tonne.

Other findings based on sensitivity analyses, recent cost trends and other data examined by Advisian are:

- Levelised costs for NGCC plants with CCS are relatively sensitive to fuel price changes. For example, an increase in the price of natural gas from USD$3/GJ to USD$6/GJ (doubling) in the reference location would increase the LCOE of NGCC by approximately $25/MWh or around 30%. A tripling of coal prices in the reference location increases the LCOE of coal-fired plants by approximately 20%.

- Conversely, the higher proportion of capital costs for coal-fired plant makes them more sensitive to non-fuel input costs. For example, increasing labour costs by 100% increases the installed capital cost of PC coal plant by 29%, and the LCOE increases by 14%.
- The cost of CO_2 storage contributes relatively small amounts to overall project costs. For onshore storage, the combined cost of transport and storage is estimated to be between USD$7 and $12/tonne of CO_2. Offshore transport and storage costs are estimated to be between $16 and $37/tonne CO_2.
- Estimates of levelised costs for coal-fired plant increased substantially in several locations since 2011[12]:
  - Costs for Poland were between 82% and 116% higher due to a very large increase in coal prices (USD$0.67/GJ to $5.16/GJ) and an increase in equipment costs.
  - Costs for Germany increased by between 20% and 36%, also due to rising coal prices and labour costs.
- China showed significant increases for all power generation technologies since 2011, ranging from 65% for NGCC and 100% for IGCC. This is due to a very large increase in the cost of labour and introduction of equipment import taxes.
- The levelised cost of NGCC in locations like the United States and Canada has decreased significantly (on average by 40 %) since 2011 due to significant declines in natural gas prices.

The cost estimates presented in this report were produced following a similar methodology used by Advisian/WorleyParsons in reports published in 2009[13] and 2011. Detailed plant estimates are built up from published cost and performance data as well as Advisian's/WorleyParsons' database of real-world cost data, gained from delivering numerous CCS and large capital intensive infrastructure projects. Additional information is included from governmental and industrial research partners. Project costs are first generated for a reference location then adjusted to reflect the costs in other countries due to a range of factors like local wage rates and fuel prices. All stages of the CCS project cycle including CO_2 capture and compression, transportation, storage, site closure and monitoring are included in this analysis.

The cost estimates presented above reflect a standard design and estimation method, using information current as of 2015. The estimates should not be used as a predictor of actual project costs in a specific location. Costs of CCS projects within a country or region will vary significantly depending on a range of factors.

Comparisons to carbon pricing and similar policy incentives

Figure 2 reports the cost per tonne of CO_2 avoided for each of the seven industries and fourteen countries from Table 1 above. It shows that the costs of CCS in natural gas processing, fertiliser and bioethanol are lower than or comparable to selected instances of carbon pricing in place today.

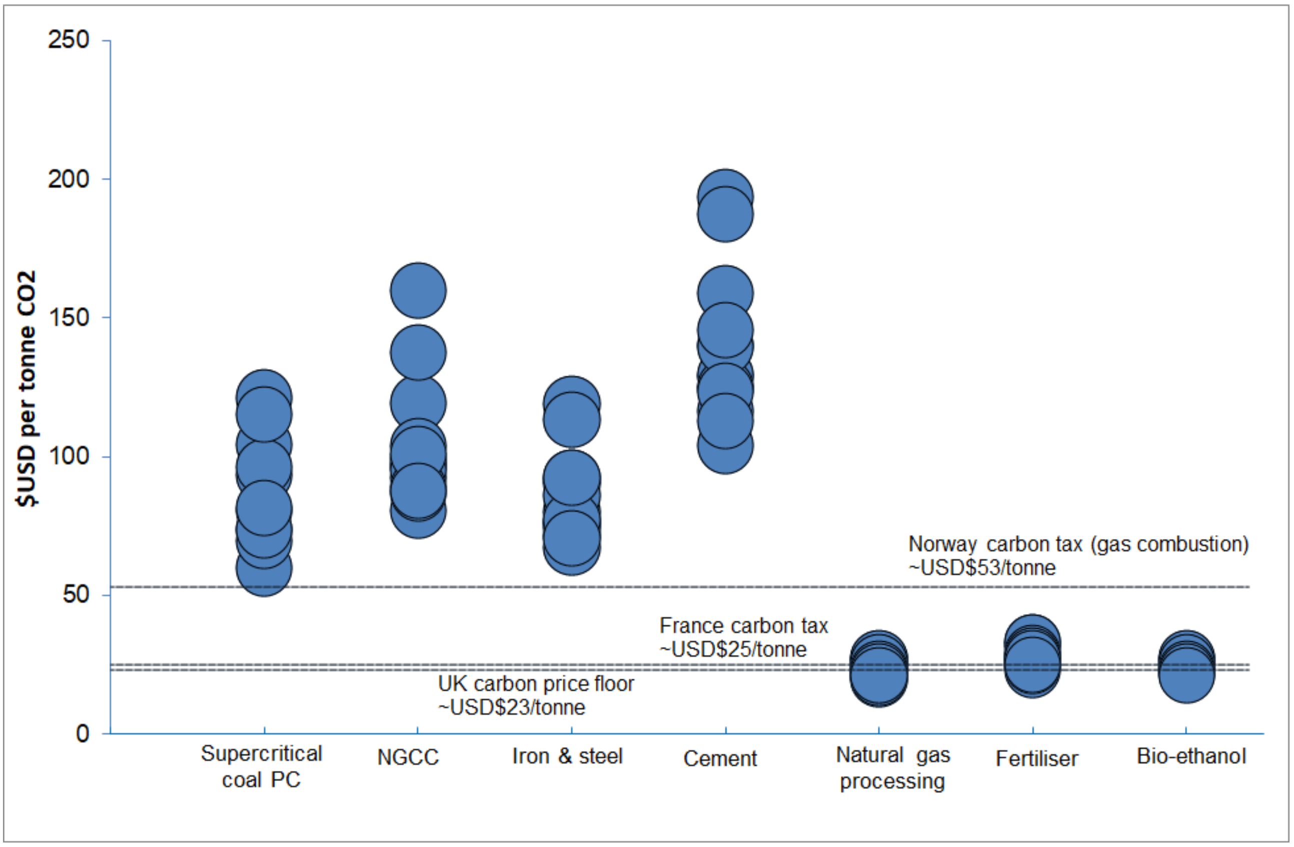
These relative cost differences are reflected in the composition of the 17 large scale CCS facilities currently in operation or construction, with nine of these being for natural gas processing, three for fertiliser production and one for bioethanol.

For industries and jurisdictions without effective policy to encourage CO_2 emission reductions, revenues from the sale of captured CO_2 for enhanced oil recovery (EOR) have been the principal means to bring many large-scale CCS facilities to market. For example, the reporting of Boundary Dam suggests CO_2-EOR sale prices of around US$20 per tonne, noting this is dependent on the market price of extracted oil which has declined significantly since 2014. The cases of Gorgon, Sleipner and Snøhvit, with dedicated geological storage and no EOR revenues, suggest carefully targeted penalties or licencing conditions relating to CO_2 emissions can help overcome the cost of CCS in some industries, rather than large public subsidies which has spurred deployment of emission reduction technologies in power generation. As with renewable technologies, the need for direct subsidies to support CCS deployment in power generation is expected to

[12] https://www.globalccsinstitute.com/publications/economic-assessment-carbon-capture-and-storage-technologies-2011-update
[13] http://www.globalccsinstitute.com/publications/strategic-analysis-global-status-carbon-capture-storage-Report-2

decrease over time as second and subsequent rounds of facilities learn from their predecessors and are constructed at lower cost and investment risk. Experiences from 'first-of-a-kind' power facilities are being closely examined[14] and will likely be applied to other post-combustion CCS applications in iron and steel and cement.

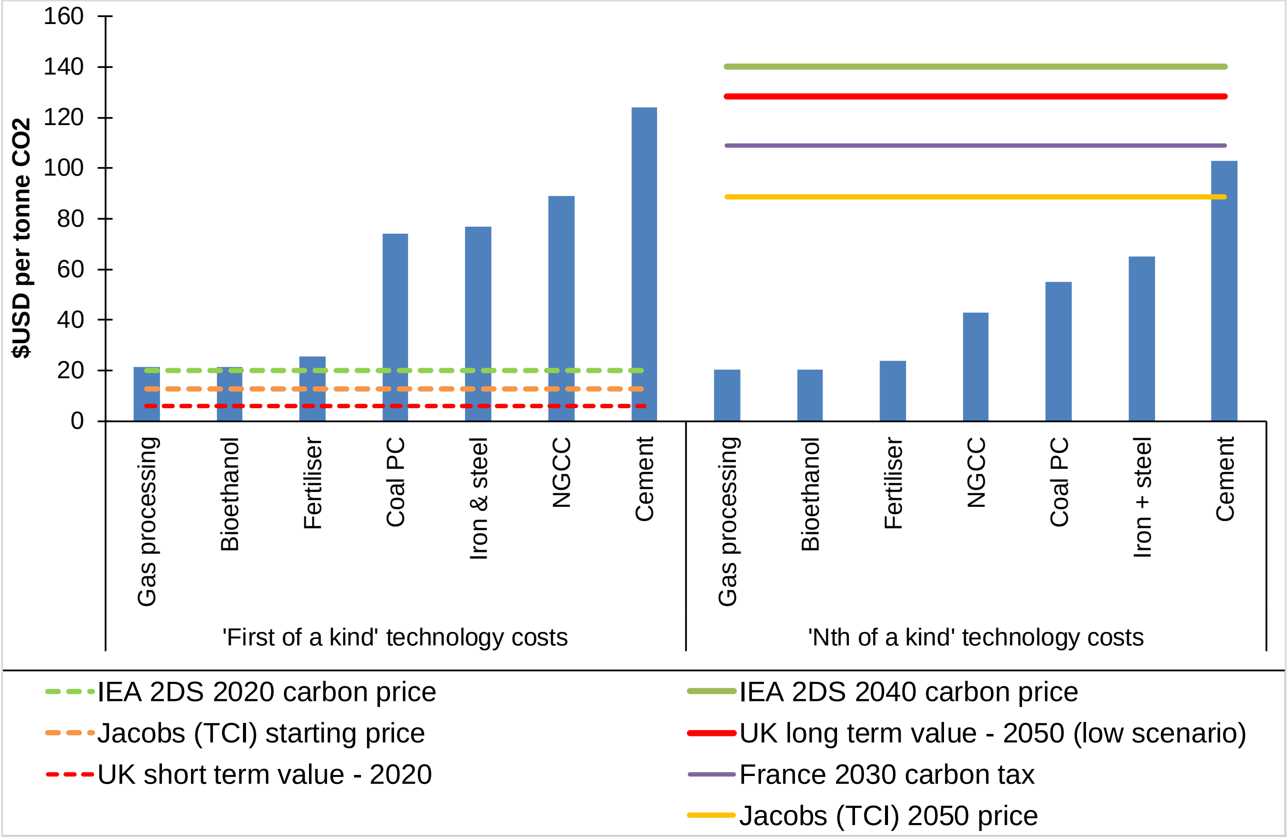
Figure 2: First-of-a-kind costs in different countries and example carbon prices in place today



There are many uncertainties in expected cost reductions via increased deployment and from the large amount of testing and pilot scale activities being undertaken.[15] Figure 3 provides a comparison of the current 'first-of-a-kind' and reasonable estimates 'nth-of-a-kind' costs of CCS reflecting expected cost reductions. These are compared to carbon incentives under selected scenario modelling of Paris commitments. As discussed above, policy interventions required to push economic activity towards 'net zero' emissions are aggressive, and easily overcome the perceived high cost of CCS, even without anticipated cost reductions.

[14] http://www.bhpbilliton.com/media-and-insights/news-releases/2016/02/bhp-billiton-and-saskpower-establish-carbon-capture-and-storage-knowledge-centre
[15] http://www.globalccsinstitute.com/projects/pilot-and-demonstration-projects http://www.globalccsinstitute.com/projects/test-centers-and-other-initiatives

Figure 3: Reference location costs and carbon values in scenario modelling



Notes and sources: IEA World Energy Outlook 2016[16]; Jacobs for The Climate Institute (2016)[17], carbon prices were modelled for the Australian electricity sector only, value reflects carbon price assumed by investors under the 'suboptimal' policy scenario; UK short term value for policy evaluation reflects modelling/ expectations of carbon pricing for ETS traded sector[18], the long term 2050 value was derived from modelling of EU long term targets and reflects the "low scenario"[19]; France value is its 2030 legislated carbon tax. All values were converted to USD using May 2017 exchange rates.

Conclusions

This summary report provides independently prepared costs of CCS across a range of applications and countries. Stakeholders are encouraged to approach the Institute for further information underlying this dataset and on issues related to cost estimation generally.

The data in this report and the Institute's more broader observations on the costs of CCS are:

- There are several applications where the cost of adding CCS to existing emitting facilities is relatively low. These are where CO_2 is already separated as part of the production process, including natural gas processing, fertiliser and bioethanol.
- Higher cost applications are those where waste CO_2 is produced in a more diluted form, namely power generation, iron and steel and cement.
- Countries with lower labour costs (such as China, Mexico, Indonesia and Poland) and low energy costs (such as Saudi Arabia) have the lowest cost for implementing CCS. Germany has the highest costs in each of the five industrial processes largely due to high labour costs

[16] http://www.iea.org/newsroom/news/2016/november/world-energy-outlook-2016.html
[17] http://www.climateinstitute.org.au/verve/_resources/Jacobs_-_Electricity_Sector_Impacts_of_Policies_to_Cut_Emissions_of_Greenhouse_Gases_Report.pdf
[18] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/600710/Updated_short-term_traded_carbon_values_for_appraisal_purposes_2016.pdf
[19]https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48108/1_20100120165619_e____carbonvaluesbeyond2050.pdf

- The cheapest locations for gas fired power generation with CCS are large gas producing nations such as Saudi Arabia, UAE and Algeria. Expensive locations like South Korea and Germany reflect higher imported gas prices.
- The cheapest locations for coal-fired generation with CCS are the United States, Canada, Mexico and China.
- The perception of CCS being a high cost emission reduction technology largely stems from estimates for the power sector. These estimates are inappropriately compared to renewable technologies that do not provide equivalent grid services or dispatchable power and hence have lower economic value. There is also selective reporting of the limited examples of CCS facilities in commercial operation today.
- Comparisons of the cost of CCS and concerns over its expense must be considered in the context of the very large scale of CO_2 reduction required to achieve climate goals, and of the wide range of emission sources where there are no feasible or more expensive alternatives to CCS.

Appendix – selected assumptions and data tables

Table A: Process modelling and economic assumptions for power and industrial reference cases

			Process modelling and economic assumptions
Capital cost estimate basis			
	Constant 2015 US$ (2015 US$)		
	The reference location is the US Mid-West.		
	Labour is based on non-union rates		
Transportation: onshore pipeline			
	CO_2 pipeline length		100 km
	CO_2 pipeline inlet temperature		25 °C
	CO_2 pipeline inlet pressure		20.2 MPa
	CO_2 pipeline outlet pressure		15.3 MPa
Storage: saline formation (reference case was for 'Good' reservoir, onshore)			
	Reservoir pressure		17 MPa
	Reservoir thickness		50 m
	Reservoir depth		1,700 m
	Reservoir absolute permeability		120 mD
	Site screening and evaluation		US$66 M
Financial: general			
	Levelisation period		30 years
	Construction duration for power projects		4 years
	Capacity factor (measure of utilisation)		85 %
	Owners' costs		15 %
	AFUDC		9 %
	CO_2 emission price		0 US$/tonne CO_2
Financial: cost of capital and escalation rates		Per-cent	Rate
	Debt	40 %	6 %
	Equity	60 %	12 %
	Tax rate for debt interest deduction		33 %
	Fixed O&M cost escalation rate		0 %
	Variable O&M cost escalation rate		0 %
	Real CO_2 emissions escalation		0 %
	Real fuel escalation rate		3 %

Table B: Electric Power Generation (supercritical, ultra-supercritical, and IGCC) facility parameters with and without capture

		PC supercritical		PC supercritical 2[1]		Ultra-supercritical		IGCC	
	CO_2 capture	No	Yes	No	Yes	No	Yes	No	Yes
	Fuel	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal
Gross power output	MW	580	642	580.2	661.1	576.6	644.4	737	673
Auxiliary power	MW	30	91	30.2	111.1	26.6	94.4	108	177
Net power output	MW	550	550	550	550	550	550	629	497
Net plant efficiency, HHV	%	40.7	32.5	39.4	28.3	44.6	33.2	42.1	31.2
Net plant heat rate	GJ/MWh	8.85	11.10	9.15	12.74	8.08	10.84	8.55	11.54
CO_2 generated	tonne/hr	426	534	440	613	389	522	455	485
CO_2 emitted	tonne/hr	426	53	440	61	389	52	455	49
CO_2 captured	tonne/hr	0	480	0	551	0	469	0	436
Emission intensity	kg/MWh	774	97	800	112	707	95	724	99
Plant capital costs (US$)									
CC equipment	M	556	865	544	978	557	951	934	1,032
CC materials	M	56	136	54	69	53	65	83	116
CC labour	M	352	588	344	553	334	522	363	400
Eng., CM, HO & fees[3]	M	96	154	88	150	88	145	138	155
Process contingency	M	0	68	0	68	41	111	51	82
Project contingency	M	127	253	123	261	126	251	253	295
Total Plant Cost	M	1,187	2,065	1,155	2,079	1,199	2,045	1,822	2,080
Total Plant Cost	US$/kW	2,158	3,754	2,099	3,781	2,180	3,717	2,896	4,186
Variable O&M (US$)									
VOM equipment	US$/MWh	3.19	6.03	3.13	6.07	2.70	5.07	1.69	3.07
VOM material	US$/MWh	1.63	2.89	1.51	2.88	1.63	2.77	4.30	5.61
VOM labour	US$/MWh	4.82	8.92	0.00	0.00	0.00	0.00	5.99	8.68
Total	US$/MWh	9.64	17.84	4.64	8.95	4.34	7.84	11.97	17.37
Fixed O&M (US$)									
FOM equipment	M	-	-	-	-	-	-	-	-
FOM material	M	11.6	19.3	15.4	27.2	15.4	26.1	35.9	36.7
FOM labour	M	11.0	13.8	11.3	12.1	10.7	12.0	14.5	15.2
Total	M	22.6	33.1	26.6	39.3	26.1	38.1	50.4	52.0

Notes:

1. The PC supercritical 2 case is included as the reference plant for the oxy-combustion cases.
2. Costs are based on US Mid-West merit rates.
3. Engineering, Home Office and Construction Management expenses.

Table C: Electric Power Generation (Oxy-combustion and NGCC) facility parameters with and without capture.

		Oxy-combustion supercritical		Oxy-combustion ultra-supercritical		Oxy-combustion ITM supercritical		NGCC	
	CO_2 capture	No	Yes	No	Yes	No	Yes	No	Yes
	Fuel	Coal	Coal	Coal	Coal	Coal	Coal	NG	NG
Gross power output	MW	-	785.9	-	759.2	-	687.9	641	601
Auxiliary power	MW	-	235.9	-	209.2	-	137.9	11	42
Net power output	MW	-	550	-	550	-	550	630	559
Net plant efficiency, HHV	%	-	29.3	-	33.0	-	29.3	51.5	45.7
Net plant heat rate	GJ/MWh	-	12.31	-	10.93	-	12.28	7.00	7.88
CO_2 generated	tonne/hr	-	634	-	558	-	560	225	225
CO_2 emitted	tonne/hr	-	42	-	33	-	47	225	22
CO_2 captured	tonne/hr	-	592	-	525	-	514	0	202
Emission intensity	kg/MWh	-	76	-	60	-	85	356	40
Plant capital costs (US$)									
CC equipment	M	-	978	-	853	-	837	243	365
CC materials	M	-	69	-	68	-	64	28	77
CC labour	M	-	553	-	586	-	607	83	201
Eng., CM, HO & fees[2]	M	-	150	-	143	-	143	32	56
Process contingency	M	-	68	-	71	-	60	0	45
Project contingency	M	-	261	-	206	-	204	47	113
Total Plant Cost	M	-	2,079	-	1,924	-	1,916	432	856
Total Plant Cost	US$/kW	-	3,781	-	3,499	-	3,483	686	1,531
Variable O&M (US$)									
VOM equipment	US$/MWh	-	3.44	-	3.05	-	3.36	0.48	1.01
VOM material	US$/MWh	-	2.75	-	2.68	-	2.46	0.69	1.29
VOM labour	US$/MWh	-	0.00	-	0.00	-	0.00	0.00	0.00
Total	US$/MWh	-	6.19	-	5.73	-	5.82	1.18	2.30
Fixed O&M (US$)									
FOM equipment	M	-	-	-	-	-	-	-	-
FOM material	M	-	26.4	-	25.3	-	23.2	5.6	9.1
FOM labour	M	-	11.9	-	11.9	-	11.6	4.2	5.6
Total	M	-	38.3	-	37.2	-	34.9	9.7	14.8

Notes:

1. Costs are based on US Mid-West merit rates.
2. Engineering, Home Office and Construction Management Expenses

Table D: Emission intensities, process parameters, and commercial applications for industrial processes

	Iron and steel production[1]	Cement production[2]	Natural gas processing	Fertiliser production	Biomass-to-ethanol
CO_2 emission intensity	2 tonne CO_2/ tonne steel[1]	0.83 tonne CO_2/ tonne cement[2]	0.13 kg CO_2/ Sm^3 natural gas[3]	0.57 tonne CO_2/ tonne ammonia[6]	0.82 kg/litre
Product production Rate	40 tonne steel/hr	40 tonne cement/hr	1,100 Sm^3/hour 46 GJ/hour	46 tonne ammonia/hr	130,000 litre ethanol/hr
CO_2 concentration in gas stream to CO_2 capture equipment	22 %	19 %[2]	100 %[4]	100 %[4]	100 %[4]
Per-cent heat for solvent regeneration recovered from process	100 %	50 %	NA	NA	NA
Annual CO_2 flow of single plant (tonne/year)	706,000[5]	293,000[5]	1,000,000[5]	194,000[5, 6]	1,000,000[5]
Commercial example	Abu Dhabi CCS Project[7]	No commercial operating facility	Sleipner, Norway[7]	Coffeyville gasification facility	Archer Daniels Midland, Decatur[7]

Notes:
1. CO_2 capture located after blast furnace.
2. CO_2 capture after heat recovery from rotary kiln. CO_2 concentration based on the values published by operator of Norcem Brevik plant, Norway "Showcasing global progress on CCS / Norcem Brevik CCS-project." (Heidelberg Cement 2015).
3. CO_2 concentration corresponds to 6 % CO_2 by volume; additional CO_2 in NG source will require larger equipment and incur more capital cost. Note that unitised capture and storage costs (per tonne of CO_2) will decrease at elevated CO_2 separation rates.
4. These processes produce an essentially pure CO_2 stream by design of the process.
5. Emission rates from "Tracking Industrial Energy Efficiency and CO_2 Emissions" (International Energy Agency 2007).
6. Calculated from "Use of Selexol in Coke Gasification to Ammonia Project" (W. Breckenridge 2000). The Coffeyville gasification facility produces both ammonia and urea ammonium nitrate. The generation of both products produces 1 Mtpa of CO_2 for capture and storage. The reference facility for this study considers only the magnitude of the CO_2 capture from ammonia production at a rate of 194,000 tonne/year.
7. Commercial example processing scheme is used as reference. Costs are estimated for a similar scheme constructed in the reference location then translocated to regions of interest.

Table E: Capital and O&M cost breakdown for industrial applications

		Iron and steel production	Cement production	Natural gas processing	Fertiliser production	Biomass-to-ethanol
Plant capital costs (US$)						
CC equipment	M	57	34	22	7	22
CC materials	M	19	12	4	1	4
CC labour	M	46	28	11	4	11
Eng., CM, HO & fees[3]	M	11	7	4	1	4
Process contingency	M	14	8	-	-	-
Project contingency	M	26	16	8	2	8
Total Plant Cost	M	173	106	49	15	49
O&M						
Variable O&M[1]	M US$/yr	4.8	2.9	1.5	0.5	1.5
Fixed O&M[2]	M US$/yr	4.8	2.9	1.5	0.5	1.5

Notes:
1. Variable O&M based on 3 % of CC Total Plant Costs. These are reasonable "rule of thumb" estimates applied in industry and reflect plant utilisation upwards of 85 %.
2. Fixed O&M based on 3 % of CC Total Plant Costs. These are reasonable "rule of thumb" estimates applied in industry and reflect plant utilisation upwards of 85 %.
3. Engineering, Construction Management and Home Office expenses.