UKERC Technology and Policy Assessment

Cost Methodologies Project:

CCS Case Study

Working Paper

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This working paper was produced as part of the TPA Cost Methodologies project.

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1. Introduction

Global aspirations for carbon capture and storage (CCS) technologies are high. According to the International Energy Agency's BLUE map scenario, achieving a 50% global greenhouse gas reduction by 2050 requires CCS-fitted plant to account for 17% of total electricity generation (IEA, 2009)[1]. Yet, despite its central role in future energy scenarios, CCS is still yet to be demonstrated at utility scale. This means that CCS cost estimates are not informed by practical experience of building commercial-scale plant.

With high aspirations present and utility-scale empirical data absent, CCS technologies provide an interesting case study for analysing cost estimation methodologies. As such, this Working Paper examines global trends in current and future projections of CCS costs in the power sector, aiming to:

- Examine key trends in contemporary and forecast CCS cost estimates;
- Understand the drivers underlying these key trends; and
- Identify implications for CCS cost estimation methodologies.

A systematic literature review was conducted as a basis for analysing CCS cost estimates, with approximately fifty relevant academic articles and grey literature reports being identified (as detailed in the Appendix). The focus for analysis was estimates of levelised and capex costs for CCS. It is recognised that the decision to analyse these cost metrics – instead of CO_2 avoidance costs – has implications for the relative attractiveness of coal CCS and gas CCS technologies. However, these metrics bring the benefit of enabling the comparison of CCS with other power sector technologies analysed in this Working Paper series (UKERC, 2011).

The paper begins by considering trends in current cost estimates for CCS (Section 2), and then progresses to examining future projections (Section 3). Following this, implications for CCS cost estimation methodologies are identified (Section 4).

[1] Scenario assumes that greenhouse gas reduction is achieved by 2050 at least cost, relative to 2005.

2. Current cost estimation

The literature adopted a range of approaches to estimating CCS costs – spanning engineering assessments, Front-End Engineering and Design (FEED) studies, the application of experience curves, expert elicitation, and derivation from secondary sources. This Section presents contemporary CCS cost estimates from the literature, identifying trends and then considering the potential drivers of such trends.

Trends

Figure 1 below plots contemporary levelised cost estimates for CCS technologies from 36 different sources. The estimates reflect the cost of both CCS *and* the generating power plant (rather than just the additional cost of CO_2 pollution abatement).

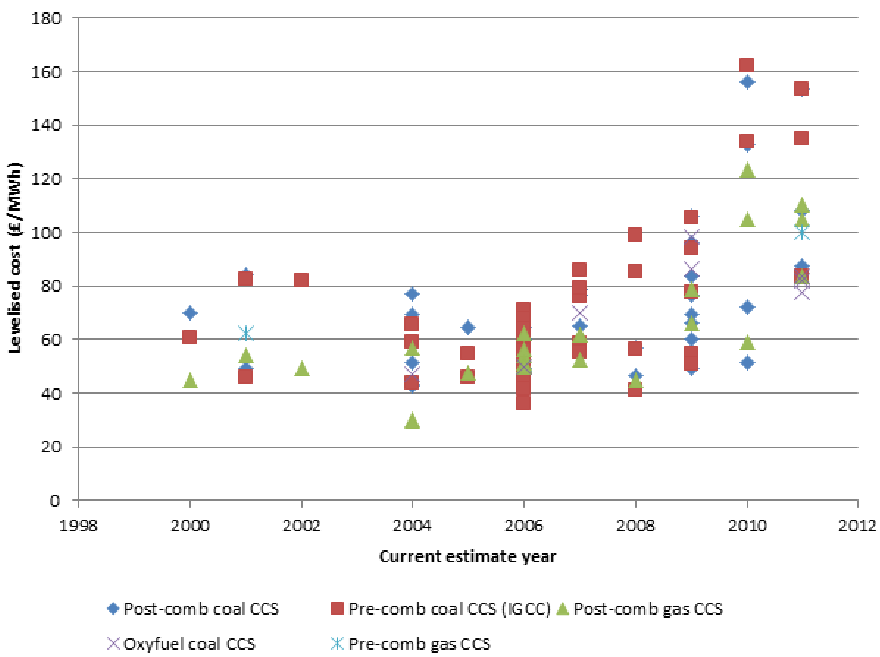

Figure 1: Current levelised cost estimates of CCS technologies since 2000.[2]

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[2] The graph illustrates cost estimates for five CCS technologies (and associated generating plant), distinguishing between CO_2 capture process and fuel type. It is important to distinguish between differing CCS technologies since they have differing cost structures; for instance, gas CCS tends to be less capital intensive than coal CCS. Figures are presented in 2011 GBP – see Appendix for details of data selection and treatment.

The graph indicates that there has been a substantial increase in levelised cost estimates for all CCS technologies since 2005. In addition, the graph displays widespread variation in cost estimates for CCS technologies, even within the same year.

Figures 2 and 3 below demonstrate the extent to which CCS cost escalation is associated with the cost escalation of the underlying generating power plants, such as combined cycle gas turbines (CCGT) and advanced supercritical (ASC) coal-fired plant. The graphs indicate that the capex costs of CCS-fitted generating plants roughly move in parallel with the capex costs of unabated power plants.

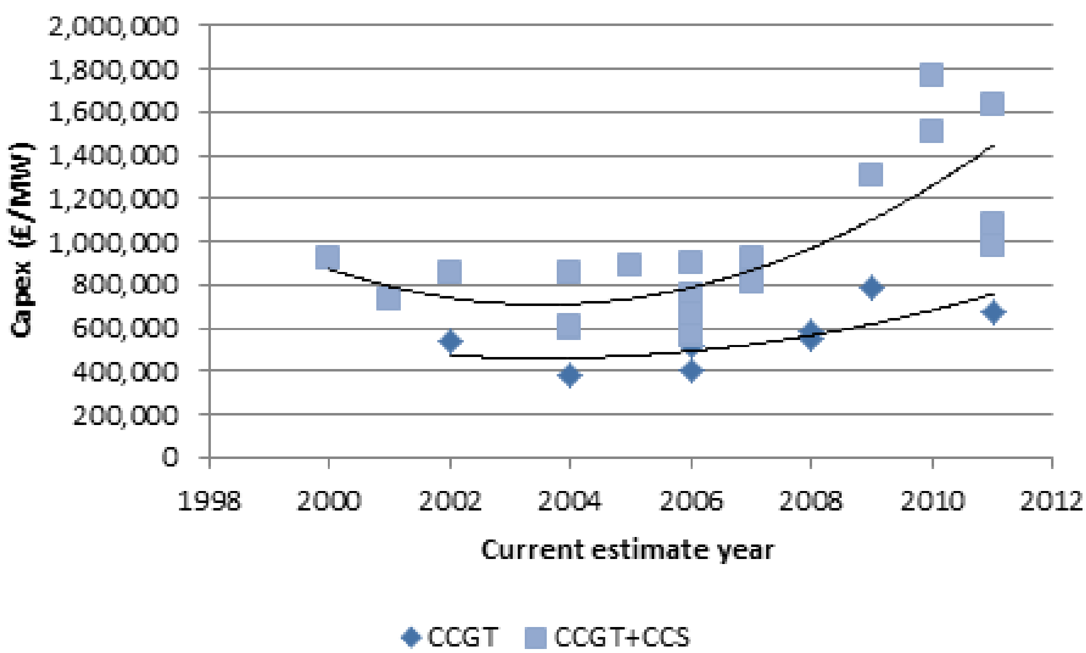

Figure 2: Estimated capital costs for CCGT plant, both unabated and abated.

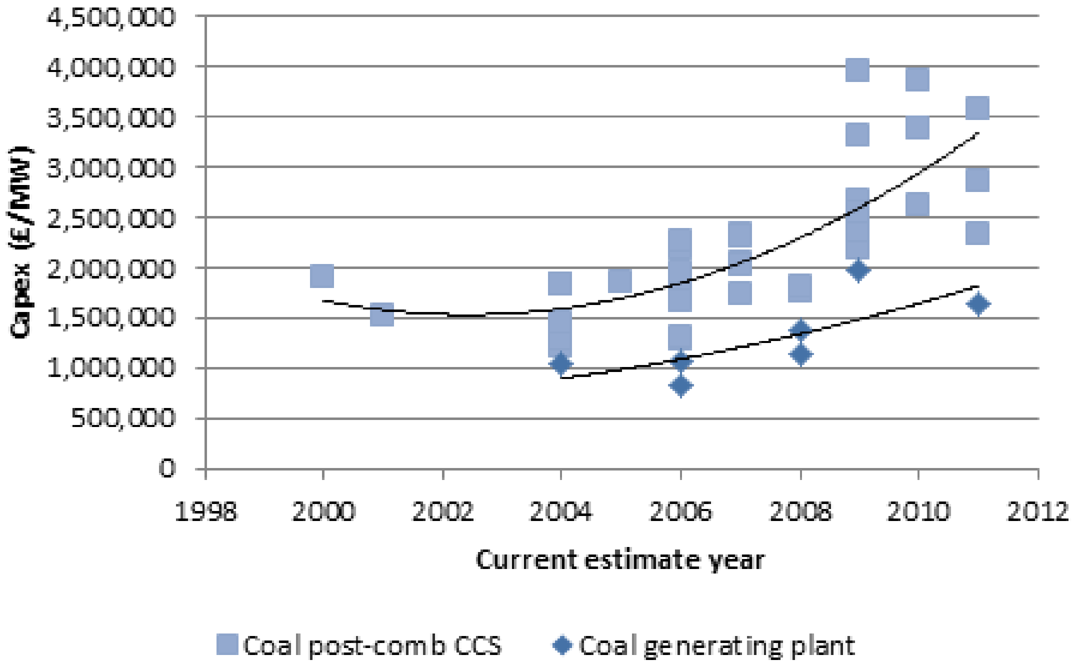

Figure 3: Estimated capital costs for coal plant, both unabated and abated (excluding integrated gasification combined cycle).

Discussion – cost escalation

This Section analyses *why* CCS levelised cost estimates have increased over time. Adopting the terminology of this Working Paper series, it distinguishes between *methodological*, *exogenous* and *endogenous* drivers.

- Exogenous drivers: broad, macroeconomic drivers that are *external* to the power sector – which policymakers and industry have limited scope to mitigate.
- Endogenous drivers: drivers emerging from *within* the power sector – which policymakers and industry can potentially mitigate.
- Methodological drivers: drivers arising from the *way* in which costs are estimated – rather than reflecting 'real-life' phenomena.

Exogenous drivers

From the early 2000s until 2008, high global demand dramatically pushed up the cost of raw materials, such as steel, cement and copper (Davison and Thambimuthu, 2009). This in turn led to increased estimates of construction costs, and in particular the costs of constructing coal- and gas-fired power plants (rather than specifically CCS technology). Since the economic downturn, commodity prices have reduced (DoE/NETL, 2010). However, this has been counteracted by ongoing increases in operating costs, through rising fuel prices (IEA, 2010).

Endogenous drivers

Although not strictly a reflection of bottom-up costs, supply chain bottlenecks have significantly increased engineering, procurement and construction (EPC) prices for coal and gas power plants. Full order books for vendors and manufacturing capacity constraints have increased prices for plant components (Mott MacDonald, 2010), and caused delivery delays that have increased project financing costs (Chupka and Basheda, 2007).

Such supply chain bottlenecks have affected the price of generating plant to which CCS is fitted, rather than that of CCS technology itself. Nonetheless, by increasing the prices of the generating plant, market congestion has led to an increase in overall price estimates for CCS-fitted power plants. Since advanced supercritical coal plant have been particularly vulnerable to supply chain bottlenecks, the effect on post-combustion coal CCS is particularly pronounced, increasing estimates by almost 17%. This is illustrated in Figure 4 below.

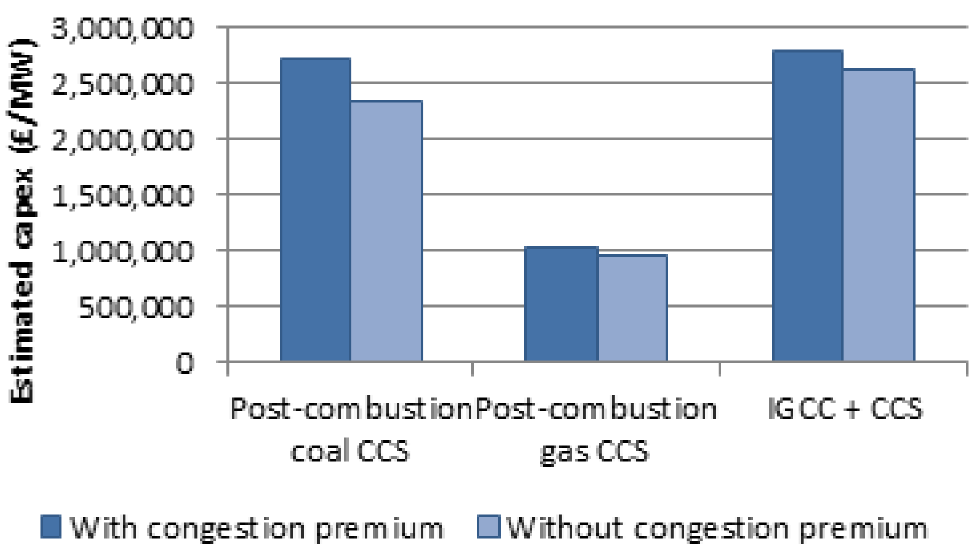

Figure 4: The estimated 'congestion premium' for CCS cost estimates arising from supply chain bottlenecks. Based on estimates by Mott MacDonald (2010).

Methodological drivers

In addition to exogenous and endogenous cost drivers, a further cause of cost escalation is the apparent tendency of early-stage engineering assessments to demonstrate appraisal optimism, which then appears to be 'corrected' in later cost estimates. The term 'appraisal optimism' refers to the propensity of prospective developers to underestimate costs – be it due to natural enthusiasm or due to the incentive of securing public funding (Scrase and Watson, 2009). In particular, it appears that early cost estimates of projects tend to be more optimistic – i.e. lower – than later estimates, due to over-simplified system designs and underestimating risks. Later, once projects are defined in greater detail and costs are more rigorously calculated, estimates tend to be revised upwards.

The case study of retrofitting CCS to one of the four units at Longannet coal-fired power station helps to illustrate this point (ScottishPower CCS Consortium, 2011). Figure 5 below compares the estimates of this CCS retrofit *before* detailed Front-End Engineering Design work ('Outline Solution') and *after* more detailed engineering assessments ('post-FEED').

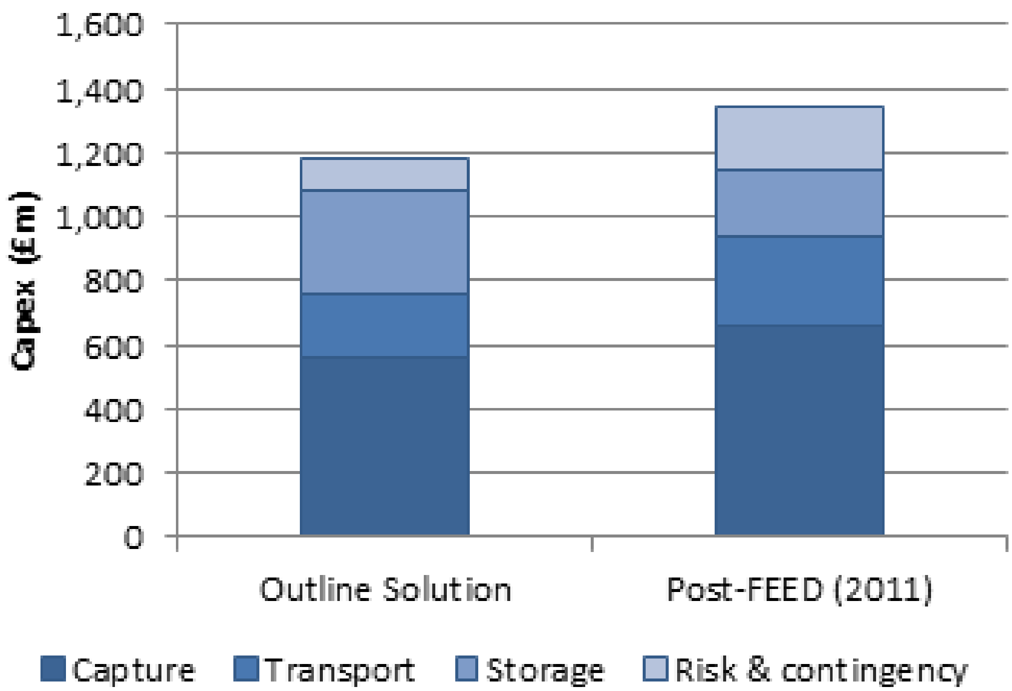

Figure 5: Estimated project capital costs prior to, and following, Front-End Engineering Design (FEED) study for CCS retrofit at Longannet coal-fired power station (ScottishPower CCS Consortium, 2011).

The figure illustrates that overall estimated project capex increased by 13.6% from the initial Outline Solution. The Consortium explained that the FEED study revealed a need for a more sophisticated capture and transportation system, such as the requirement for tunnelling under the Firth of Forth river instead of the horizontal directional drilling originally proposed. Another notable driver of the increased post-FEED cost estimates was the increase in allowance for risk and contingency costs by 89.5%, 'reflecting the better identification and quantification of risks' (ScottishPower CCS Consortium, 2011). Overall, the Outline Solution could be interpreted as displaying initial appraisal optimism, which is then revised and made more 'realistic' post-FEED.

The increased magnitude of risk premiums in CCS cost estimations over time is also noted in other reports as a driver of the upward revision of cost estimates. Indeed, there has been a move to factoring in significantly higher contingency figures than was the case in the early 2000s, to reflect first-of-a-kind costs (EPRI, 2007). For instance, a revised cost estimate of CCS retrofit of Kårstø gas-fired power station in Norway factors in substantially higher contingency reserves than the initial cost estimate; this is in recognition that CCS investments are 'mega-projects' with substantial risks of cost overruns (Osmundsen and Emhjellen, 2010).

Discussion – variation

In addition to cost escalation, Figure 1 indicates substantial variation in CCS current cost estimates. It would appear that part of this variation is reflective of *inherent variation*, since the choice of CCS technology and location brings distinct costs. However, the remaining variation in cost estimates appears to reflect not real-life differences, but rather *imperfect knowledge* and *unstandardized methodologies*. These are discussed below.

Inherent variation

There are two drivers of inherent cost variation:

- The *specific design* of a project; and
- The *location* of the project.

In terms of project design, the choice of capture technology – post-combustion, pre-combustion or oxyfuel – significantly affects the cost profile of projects, as does the capture efficiency and project size (Chen and Rubin, 2009). More broadly, the specific financing arrangements associated with the project are crucial. Factors such as the cost of capital and the ability of the project developer to manage outgoings are significant (Mott MacDonald, 2010, Simbeck and Beecy, 2011).

Meanwhile, locational differences can also significantly affect CCS costs. In particular, geographical location substantially affects the transportation and storage options available – for instance, whether there is potential to reduce transport network costs through clustering with other CCS installations. Moreover, the cost and type of fuel varies significantly depending on location; for instance, levelised cost estimates for gas

CCS in Saudi Arabia are relatively low due to cheap local natural gas supplies (WorleyParsons, 2009).

Other locationally-differentiated drivers of costs are labour rates, which are particularly low in China and India (WorleyParsons, 2009); legal costs such as acquiring permits and licences; and national policies such as carbon taxes. The local characteristics of each particular market can also affect the cost of financing, which is especially significant for coal CCS given its capital intensity (IEA, 2010).

Imperfect knowledge

In addition to inherent variation, there is a significant degree of uncertainty surrounding cost estimates for CCS, since it is not possible to verify estimates with empirical commercial-scale cost data (Shackley et al. 2009). Although many of the technology components are mature, CCS as an integrated technology is itself immature, leading to high levels of uncertainty about performance (Giovanni and Richards, 2010). Other key uncertainties include the expected economic life of the plant and how it will be operated, which leads to differing assumptions about the levelisation period and load factors (Global CCS Institute, 2011b, Chen and Rubin, 2009). Future fuel prices are also highly uncertain (Davison and Thambimuthu, 2009). This uncertainty about the appropriate values of key input variables can lead to widely varying cost estimates, especially since CCS costs tend to demonstrate a high sensitivity to fuel prices and load factors (Mott MacDonald, 2010).

Methodological

A further reason for the range in current cost estimates is methodological. The Global CCS Institute (2011a) suggests that the differing methodologies used for calculating CCS costs limits the comparability of different studies. This point was also a key theme of a CCS Cost Workshop organised by the IEA (2011), with the conference proceedings indicating that the diverse group of actors estimating CCS costs adopt differing methodologies and use differing assumptions for underlying economic parameters.

For instance, it is striking that many of the papers reviewed did not factor in costs for CO_2 transportation, storage and monitoring, instead focusing on CO_2 capture only. As Rubin et al (2007a) highlight, this omission can lead to differing conclusions about the relative total cost of different CCS technologies. Although the capture stage dominates the total cost of the CCS process (Kheshgi et al., 2010), nonetheless the additional £5-10/kWh cost associated with CO_2 transportation and storage is significant. Another example of inconsistency between cost estimates was the presentation of the year to which the cost estimate applies – with some reports focusing on the commissioning date, others the date of first capital investment, and others not clearly defining the year to which the cost estimate applied.

3. Forecast cost trajectories

This Section examines forecast CCS cost trajectories until 2050, identifying trends and then considering potential explanations for such trends.

Trends

Figure 6 below displays estimates of forecast cost trajectories for post-combustion gas CCS. These future projections are mostly based on experience curve analysis, such as the application of historical experience curves for flue gas desulphurisation to carbon capture technology. The graph indicates consensus across the literature that gas CCS costs are projected to steadily decrease over time. Although different sources project differing rates of cost reduction, the literature mostly suggests relatively steady rates of learning. Projections for other key CCS technologies (such as post-combustion and pre-combustion coal CCS) demonstrate similar patterns.

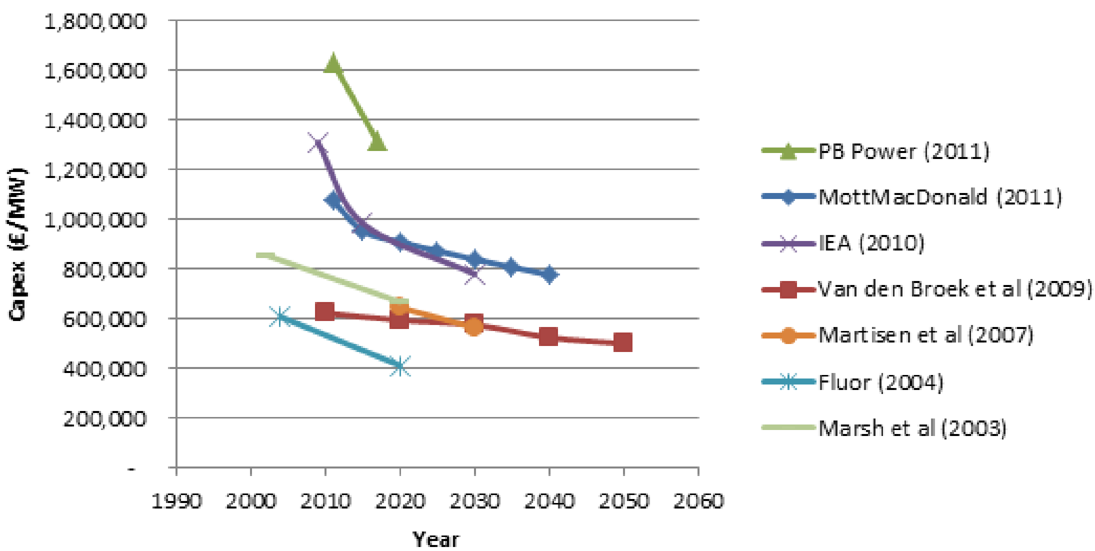

Figure 6: Estimates of future capital costs of post-combustion gas CCS.[3]

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[3] The first cost estimate of each series (i.e. line) is typically a 'current' cost estimate; the remaining estimates of each series are forecast projections of CCS costs.

Discussion

The key drivers of cost reduction in future CCS cost projections are increased project size, process integration and technological innovation (Al-Juaied and Whitmore, 2009), reduced construction lead times (IEA, 2010), and the development of an efficient carbon transport and storage network (PB Power, 2011). Yet the learning rate is expected to be relatively steady, compared with technologies such as solar PV, partly due to the relatively long lead times involved in designing and building CCS-fitted power plants (Al-Juaied & Whitmore, 2009). For instance, Rubin et al (2004) suggest a learning rate of 12% on the capital cost for CCS systems, which excludes generating plant.

The overall potential for learning is limited by two key factors. Firstly, the generating plants to which CCS will be fitted (with the exception of IGCC) are already technically mature, and the various components of CCS have already been demonstrated separately, which limits the scope for further improvement (Al-Juaied and Whitmore, 2009, Viebahn et al., 2007). Secondly, lessons from nuclear power learning rates highlight the potential for costs to continue to go up rather than down due to increased regulatory and safety demands, particularly in regard to radioactive waste (Rai et al., 2010). Like nuclear power, CCS also has 'waste' to dispose of (CO_2), and it is possible that the costs associated with safely storing CO_2 might rise due to tighter compliance requirements in the future (Mott MacDonald, 2011).

Experience curve methodology

It is important to acknowledge the limitations of the application of experience curves to CCS. The approach of applying historical learning rates of analogous technologies such as flue gas desulphurisation and selective catalytic reduction of NO_x to CCS might initially be considered apt, since they are all pollution abatement technologies operating in the power sector. However, Rai et al (2010) highlight the contingent nature of learning rates. Their work indicates that CCS learning depends not just on technological potential, but also on the pace of roll-out, the regulatory regime and market structure. The literature also indicates that there could be delays before learning begins. As Rubin et al (2007) illustrate, there is historical precedent for technologies deployed in the power sector to demonstrate cost *increases* during early commercialisation, suggesting that CCS costs could rise before they fall.

In addition, the application of experience curves depends on assumptions about future CCS *deployment* levels, since learning rates describe a relationship between cost reduction and installed capacity. However, future CCS installed capacity is itself highly uncertain. Rubin et al (2007b) make projections for future costs after 100GW of installed CCS capacity, yet it is not known *when* CCS installed capacity will reach this level.

4. Conclusions

This paper illustrates that there has been both significant escalation and substantial variation in CCS cost estimates. The literature also displays a consensus that, with deployment, CCS costs are expected to steadily decline. Some key drivers of cost estimates are exogenous (e.g. commodity prices), whilst others are endogenous (e.g. supply chain bottlenecks). Yet many are also methodological in nature, resulting from the way in which estimates are calculated, rather than necessarily reflecting 'real-life' phenomena.

The paper's findings have four key implications for the formulation and interpretation of CCS cost estimation methodologies.

1. Standardisation of calculation and presentation

The data analysis of this paper was complicated by the lack of standardisation in the way in which cost estimations are calculated and presented. As such, the author reiterates the overarching call of the IEA's CCS costs workshop (2011) of the need to establish a common framework for cost estimation methodology and terminology. This would help to facilitate comparison between differing cost estimates, and such transparency would also enable easier identification of which assumptions/parameters are driving the variation in cost estimates.

Standardisation would involve defining a list of items to be factored into the cost calculation, and explicitly stating assumptions and key parameters. For instance, it should be clear whether CO_2 transportation costs assume point-to-point transportation, or alternatively assume the economies of scale of a clustered transportation network. It is also particularly important that the location of the project is clearly defined, due to the inherent cost variation that arises from location – for instance, differing labour productivity, carbon policies and CO_2 storage sites.

2. Cautious application of experience curves

A further finding is the need to treat CCS experience curves with caution. CCS cost estimates initially appear to have reflected appraisal optimism, with costs escalating as the full complexities of system design become apparent. Even once CCS has been demonstrated at scale, future cost projections should be treated with caution until the likely deployment rates of CCS are better understood. Ultimately, cost reduction is driven by increases in installed capacity rather than the mere progression of time, so until the likely pattern of CCS deployment can be predicted with greater confidence, future cost projections should be recognised as highly uncertain.

3. Greater consideration of risk and congestion premiums

Often, bottom-up engineering assessments focus on CCS *costs*, rather than additionally giving sufficient weight to *risks* and *prices*. The ScottishPower Consortium FEED Study illustrates the highly important – though initially underestimated – allowance for risk and contingency. Following a detailed FEED Study, the risk allowance was almost doubled, thus accounting for 14.5% of total estimated capex costs. In addition, market congestion and supply chain bottlenecks are often overlooked – particularly in academic papers – yet could add up to 17% to the prices of CCS-fitted plant (Mott MacDonald, 2010). Risk premiums and congestion premiums are significant and thus deserve greater attention in future CCS cost estimates.

4. Distinction between generating plant and CCS technologies

Many of the exogenous and endogenous factors discussed in this paper apply primarily to generating plant, whereas the methodological factors tend to apply to CCS technologies. It is important to make explicit this distinction between cost drivers affecting generating plant (which can be quantified with greater certainty) and cost drivers affecting CCS technology itself (which are less certain). The literature does not always make this distinction clear.

Overall

Fundamentally, it is important to remember that CCS cost estimates are just that – *estimates,* rather than actual cost data. As estimates, they are subject to significant uncertainties. To a certain extent these uncertainties can be reduced. As argued in this conclusion, calculations can be standardised; deployment rates can be better projected; risk and congestion premiums can be more closely analysed; cost drivers of generating plant and pollution abatement can be explicitly distinguished.

Yet ultimately, refined methodologies achieve only so much; they are a poor substitute for empirical utility-scale experience. The best way to discover CCS costs, it would seem, is to get building.

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Appendix

Systematic search

The findings of this Working Paper were informed by a systematic search using defined search strings and Boolean terminology. Four academic databases were searched, as detailed in Table A below.

Database	Search string
Science Direct	TITLE-ABSTR-KEY("carbon capture and storage" or "CCS") AND TITLE-ABSTR-KEY("cost")
ISI Web of Science	TS=("carbon capture and storage" OR "CCS") AND TS=("cost")
CSA Illumina	KW=("carbon capture and storage" OR "CCS") AND KW=("cost")
Compendex	("carbon capture and storage" OR "CCS") wn KY AND ("cost") wn KY

Table A: Systematic review search strings.

Following this, the search engine Google was used to locate relevant documents in the grey literature. Duplicates were removed, and documents of little or no relevance (based on their title or abstract) were discarded. A small number of other relevant documents were then additionally revealed via citation trails.

The documents were assigned a 'relevance rating' between 1 and 4 (with '1' indicating a very relevant document), based on their title or abstract. Articles with a relevance rating of 1 (36 sources) were used as numerical data sources. Articles with a relevance rating of 1 or 2 (over 50 sources) were used to understand the underlying drivers affecting cost estimates.

Data analysis

Data characterisation

<u>Geographical</u>: Data was not limited geographically, though the literature search was dominated by OECD – and particularly US – data sources, where most CCS cost estimations appear to have been conducted.

<u>Technology</u>: Only numerical data applying to newly built CCS-fitted power stations was analysed, rather than additionally considering CCS retrofit cost estimates. The notable exception to this is data from the ScottishPower FEED Study. The literature search

covered the full range of CO_2 capture technologies – post-combustion, pre-combustion and oxyfuel – applied to both coal- and gas-fired power plants. However, biomass CCS and industrial applications were not considered.

Sources: Numerical data was drawn from 36 studies, namely (PB Power, 2010, IEA, 2010, PB Power, 2011, Mott MacDonald, 2010, Mott MacDonald, 2011, Kheshgi et al., 2010, IPCC, 2005, EPA, 2010, Fluor, 2004, Gerbelová et al., 2011, Giovanni and Richards, 2010, David and Herzog, 2000, Narula et al., 2002, Rubin et al., 2004, Rubin et al., 2007a, Global CCS Institute, 2011b, Martinsen et al., 2007, DoE/NETL, 2010, Rubin et al., 2007b, Hamilton et al., 2009, Davison, 2007, MIT, 2007, WorleyParsons, 2009, van den Broek, 2009, EPRI, 2007, DoE/NETL, 2007, Marsh et al., 2003, Chen and Rubin, 2009, Julianne M, 2009, Chan et al., 2011, IEA GHG, 2008, Falcke et al., 2011, Ordorica-Garcia et al., 2006, Viebahn et al., 2007, CCC, 2008, DTI, 2006). The following sources were additionally used for data specifically on fossil fuel generating plant (not for CCS data): (PB Power, 2004, PB Power, 2006, SKM, 2008). Some of the more recent estimates are updates of previous figures by the same source – for instance the 2011 report by the consultancy Mott MacDonald builds on the findings of its 2010 report.

Treatment of data

Normalisation: All cost estimates were converted into 2011 GBP (an average of Jan-Nov 2011 since December figures were not available at the time of calculation). The data was *not* normalised to account for differences in discount rate, load factors, carbon price etc.

Selection of representative cost estimates: Some data sources provided multiple data estimates. In order to prevent any particular source (i.e. a source with extensive sensitivity/scenario analysis) from dominating the data and thus skewing the results, efforts were made to select key 'representative' cost estimates from each source:

- Where the same source provided multiple cost estimates resulting from sensitivity or scenario analysis, the 'medium' or 'baseline/reference' figure was selected, or – where this did not exist – an average was calculated.

- Where the source provided estimates for both (a) carbon capture and (b) full CCS, the full CCS figure was plotted. Nb. Almost half of the sources only provided estimates for carbon capture – with CO_2 transportation and storage costs not being factored in.

- Where both first-of-a-kind (FOAK) and n^{th}-of-a-kind (NOAK) figures were presented the FOAK figure was selected for current cost estimates. This is because CCS is as yet undemonstrated at utility scale.

However, where the source provided estimates for different CCS technologies, a representative figure for each technology was plotted. Similarly, where the source provided estimates for multiple countries, a representative figure for each country was plotted.

To summarise, the data reflects the full variation arising from location and CCS technology type, but does not reflect the range of uncertainties arising from other parameters.

Estimate year: For current cost estimates, often the year to which the estimate applied differed from the year of publication. This typically occurred with academic papers, due to the time lags entailed by the peer review process. Where this difference occurred, the data analysis was based on the year to which the cost estimate applied, rather than the publication year.