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Post-Combustion Carbon Dioxide Capture Cost Reduction to 2030 and beyond

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Post-combustion CO_2 capture (PCC) can be achieved using a variety of technologies. Importantly it is applicable to a wide range of processes and may also be retrofitted in certain cases. This paper covers the use of PCC for low carbon power generation from new natural gas combined cycle (NGCC) plants that are expected to be built in the UK in the 2020s and 2030s and that will run into the 2050s. Costs appear potentially comparable with other low carbon and controllable generation sources such as nuclear or renewables plus storage, especially with the lower gas prices that can be expected in a carbon-constrained world. Non-fuel cost reduction is still, however, desirable and, since CO_2 capture is a new application, significant potential is likely to exist. For the NGCC+PCC examples shown in this paper, moving from 'first of a kind' (FOAK) to 'n'th of a kind' (NOAK) gives significant improvements through both reduced financing costs and capital cost reductions. To achieve this the main emphasis needs to be on 'commercial readiness', rather than on system-level 'technical readiness', and on improvements through innovation activities, supported by underpinning research, that develop novel sub-processes; this will also maintain NOAK status for cost-effective financing. Feasible reductions in the energy penalty for PCC capture have much less impact, reflecting the inherently high levels of efficiency for modern NGCC+PCC plant.

Introduction

This paper considers the scope for cost reductions in post combustion capture (PCC) units being built in the UK market to decarbonise a new generation of natural gas combined cycle (NGCC) plants that are expected to be commissioned in the 2020s and 2030s and that will run into the 2050s. The CCS technology deployed in these plants, and as subsequently upgraded, will therefore be critical in achieving the UK's challenging 2050 80% carbon reduction target.

Given the current state of the global CCS market these NGCC+PCC plants would be at the leading edge of CCS deployment, with limited opportunities for market-led development of PCC technology before then (and mostly on coal, at Boundary Dam and NRG Parish) and, with possibly a few exceptions, no major commercial pull for the development of alternative CCS technologies for natural gas in non-UK markets. One such possible exception is the Allam Cycle, currently being developed by NET Power[1] in the USA. This is predicted to be able to operate with CO_2 capture and compression at efficiencies comparable to current unabated NGCC plants but capital costs, especially for GW-scale outputs, naturally remain to be demonstrated.

Effective innovation approaches for PCC for NGCC power plants could therefore deliver major societal benefits for the UK and will become particularly topical if UK Government measures to incentivise significant amounts of NGCC construction are successful. This will immediately raise the question of how to avoid 'carbon lock-in' for these new fossil fuel plants. Consequently it is reasonable for this paper to look at NGCC+PCC technology in some detail. The analysis method used would be generally applicable to other CO_2 capture situations but readers are advised to note that the statements made in this paper refer to NGCC+PCC in particular rather than to all possible CO_2 capture applications.

Discussion on cost reduction mechanisms for PCC

Electricity output penalty

When assessing the potential for cost reduction in PCC due to improved performance it is necessary to consider the electricity output penalty (EOP) for power plants (or analogous output-oriented measures for other energy-intensive processes fitted with CCS) with high pressure CO_2 delivered at the plant boundary, although percentage points efficiency penalty can also be a useful measure for rapid estimates; reference 2 discusses assessment and optimisation principles for post-combustion capture that could also be adapted for a wider range of processes.

Significant attention is given in the literature to the estimated energy that would be required to operate novel capture processes but sometimes on the basis of regeneration energy alone, without considering the effect this will have on EOP. If the energy is required in the form of low-grade heat, as is the case with liquid solvent based PCC, then the power plant electricity output is reduced by only about 200kWh for each

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MWh of such energy consumed by the capture process, a ratio of 1:5[2]. If an alternative process requires the energy as electricity then the ratio is 1:1. Furthermore, the additional energy required for CO_2 compression to ~100 atmospheres for pipeline transport is sometimes also neglected. If the CO_2 is released at around atmospheric, or lower, pressure in an alternative process then obviously additional penalties would be incurred compared to most solvent PCC processes, which produce CO_2 at somewhat above atmospheric pressure. These two factors mean that the EOP for advanced amine solvent PCC is currently only around twice the thermodynamic limit for CO_2 separation and compression[3].

Reducing capital costs

Capital costs have a large impact, particularly if there is a high cost of capital as with private sector financing. Absolute costs are hard to predict (and vary with market conditions) but reducing capital costs and technology risks (and hence financing costs) is always likely to be advantageous. Approaches to do this for PCC amine units were discussed at a recent UKCCSRC meeting led by one of the authors[4], with the following conclusions:

- PCC amine-based technologies appear currently to have largely converged, with relatively minor differences in requirements between amine plants (temperatures, pressure etc.).
- As in many other process industries there is a cost penalty associated with must-run "critical service" that can be three times the cost of general industrial practice.
- Some aspects of PCC installations are too large for transportable modules to be practical but targeting a few plant sizes will allow for standardisation.
- A general rule of thumb for practical and cost effective manufacture and transportation of balance of plant (BOP) equipment is that doubling capacity can create a 25% cost increase so larger units become more affordable. However, this rule only applies over a limited range. Above certain critical sizes a doubling could produce excessive cost increases.
- Given the different minimum–cost size thresholds as above for different types of equipment the question is, "What is the practical unit size to get the maximum size 'sweet spot' for minimising cost per unit output?".
- One factor may be sensible vessel size limitations, e.g. $2MtCO_2$/year coal or $1MtCO_2$/year gas.
- Other factors with peripheral cost impacts:
    - sourcing materials e.g. large forgings
    - manufacture
    - delivery cycles
    - civils
    - transportation
    - damage in transit
    - site erection costs
    - site erection schedule
    - commissioning

Activities to achieve cost reductions

Concerted action by all players, e.g. industry, government, research councils and research organisations, is needed to reduce perceived cost for new CCS plants. Much of the perceived cost is associated with perceived risk driving up finance cost. To reduce the perception of risk amongst investors, governments need to be consistent in their incentive regimes to facilitate investment decisions and reduce regulatory risk perception, industry needs to share best practices and real world experience and academia needs to focus on applicable and timely innovation. There is also some scope for further cost reductions in PCC units in service; this may be particularly important for earlier generations of CCS plants.

Going forward, many current major industry players in the power plant sector are likely to retain their roles; CO_2 capture for power plants is a variation on power plant engineering or chemical process engineering and has been widely used industrially (e.g. in the oil and gas industry) for decades, so is not something completely new (and analogous considerations are likely to apply in other industries). People developing commercial projects to be built and operated in the 2020s and 2030s need to shape the R&D agenda for the following reasons:

- Developers have access to their own proprietary data as well as to public domain data so are better placed to enumerate the known unknowns.
- Developers gain access to operational data from their own plants so are well positioned to evaluate incremental improvements
- Developers have the most sophisticated understanding of cost so they can identify where the 'biggest wins' may be.

However, developers are unlikely to have the strength and depth of technical teams required to do all the R&D and will have little financial motivation to take risk.

When considering how fundamental and academic research can contribute to cost reduction it is important to disregard system-level Technology Readiness Levels (TRLs). Only 'current generation' CCS (reference plant at TRL 9 now / soon) will be sufficiently 'bankable' for large scale deployment in the 2020s and 2030s. While academic research is typically considered to be more appropriate at low TRLs it is necessary to consider sub-system / component level TRLs. Innovation in sub-systems or improvements to components can start at TRL 1 long after the overall technology has arrived at TRL 9.

Government should fund R&D that will evolve 'current' CCS technologies based on a Commercial Readiness Index (CRI) that continues beyond TRL 9, as shown in Figure 1.

In order to reduce cost for UK CCS deployment in the 2020s and 2030s and operation through the 2050s, CCS R&D must evolve 'current' technologies; CCS 'clock speed' (the time to design, build and test each technology iteration) is measured in decades for power plants, too slow for fundamental revolution. Fundamental revolution would also increase risk perception, which would increase perceived cost. Consequently, to make a difference in the 2020s and 2030s it is necessary to forget system-level TRLs and instead focus on innovative new low TRL level sub-systems that will make incremental benefits, with the aim being to raise the system CRI to make CCS 'bankable'. While the involvement of project developers is essential to focus the agenda, governments must fund research until CRI 6.

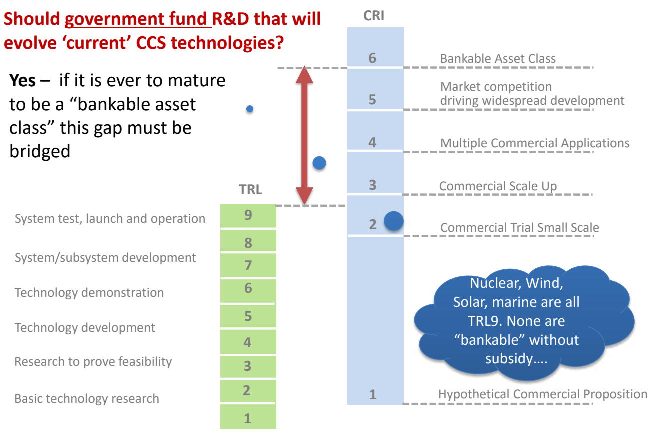

Figure 1 The difference between Technical Readiness and Commercial Readiness

R&D also continues to deliver value long after the product has achieved full commercial readiness, provided the market is operating efficiently. Consequently CCS R&D will continue for centuries, until the last CCS plant is closed and the last CO_2 storage site is confirmed to be stable – but once CCS is at CRI 6 this R&D will be mostly funded by the private sector.

Illustrative effect of improvements on overall cost reduction for NGCC+PCC power plants

Simplified Levelised Cost of Electricity Model

A simple LCOE model is used to illustrate the effect of changes in key parameters on the overall LCOE. This simplicity is justified given the uncertainty and variability in the absolute values for the input parameters for more complex models and the benefit of transparency for the methods used; it should not invalidate the overall conclusions that can be drawn.

The main parameters for the model, which is purely illustrative, are:

- Gas price (£/MWh, HHV basis): 35 (Expensive); 20 (Cheap); 10 (Very Cheap)
- Plant thermal efficiency without capture: 60% LHV
- Capture EOP: equivalent to 8 %'age points drop in LHV efficiency (normal); 4%'age points drop (extremely low)
- Base power plant capital cost: £1000/kWe
- Capture plant capital cost: £1250/kWe (before capture) for FOAK, less 10% for NOAK, less 50% for low cost option
- WACC (weighted average cost of capital): 15% for FOAK, 8% for NOAK
- Plant economic life: 20 years
- Operating costs: 3% of capital costs per year
- CO_2 emission charges: £30/tCO_2

No costs are included for CO_2 transport and storage; the values only cover capture and compression of CO_2.

The illustrative results are shown in Figure 4 overleaf.

The main conclusion for unabated natural gas cases (A-C) is that fuel price is obviously the main factor determining the LCOE. Although not shown explicitly, it can additionally be seen by inspection that large changes in CO_2 emissions costs (i.e. doubling or more) would also start to become significant.

To place the gas prices selected above in context, Figure 2 below shows IEA predictions for natural gas prices[5] and Figure 3 observed market prices[6,7]. Figure 2 illustrates an expectation that in the 2DS (two degree scenario), where allowable global cumulative CO_2 emissions are well below global fossil fuel resources (even likely well below extractable gas and oil resources), the existence of 'unburnable fuel' naturally depresses prices. It can be expected that the world will have agreed to limit emissions on a 2DS type of trajectory if large amounts of CCS are to be deployed so, at least in the longer term, if CCS is used it is likely to be with lower-cost fuel. Figure 3 shows how an oversupply of natural gas can also depress prices much further in the short term, with the futures market trends suggesting that this oversupply is expected to continue.

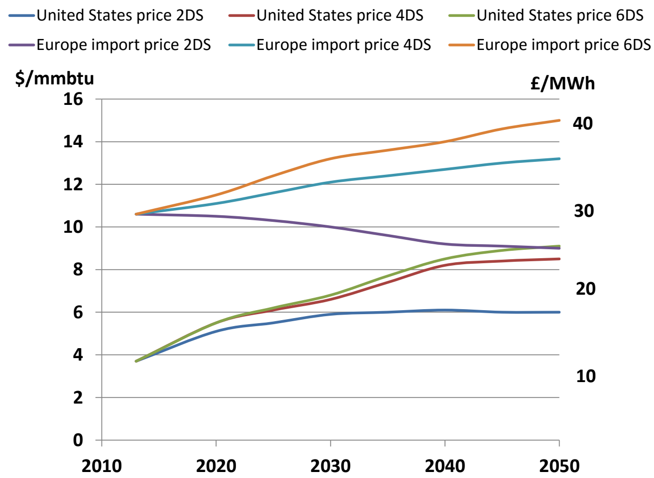

Figure 2 IEA Energy Technology Perspectives 2015 – Natural gas prices by scenario

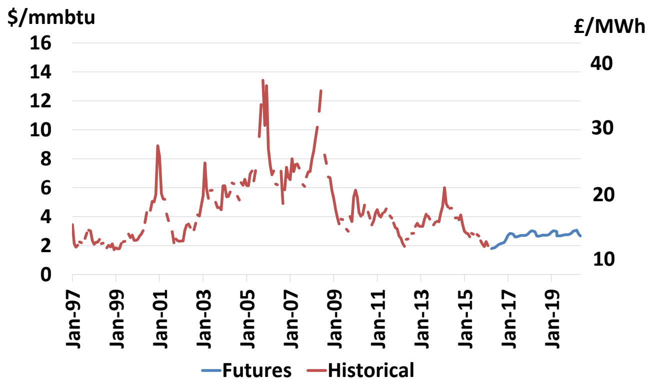

Figure 3 Natural gas historical and forward prices in the USA, currently reflecting an oversupply on the market

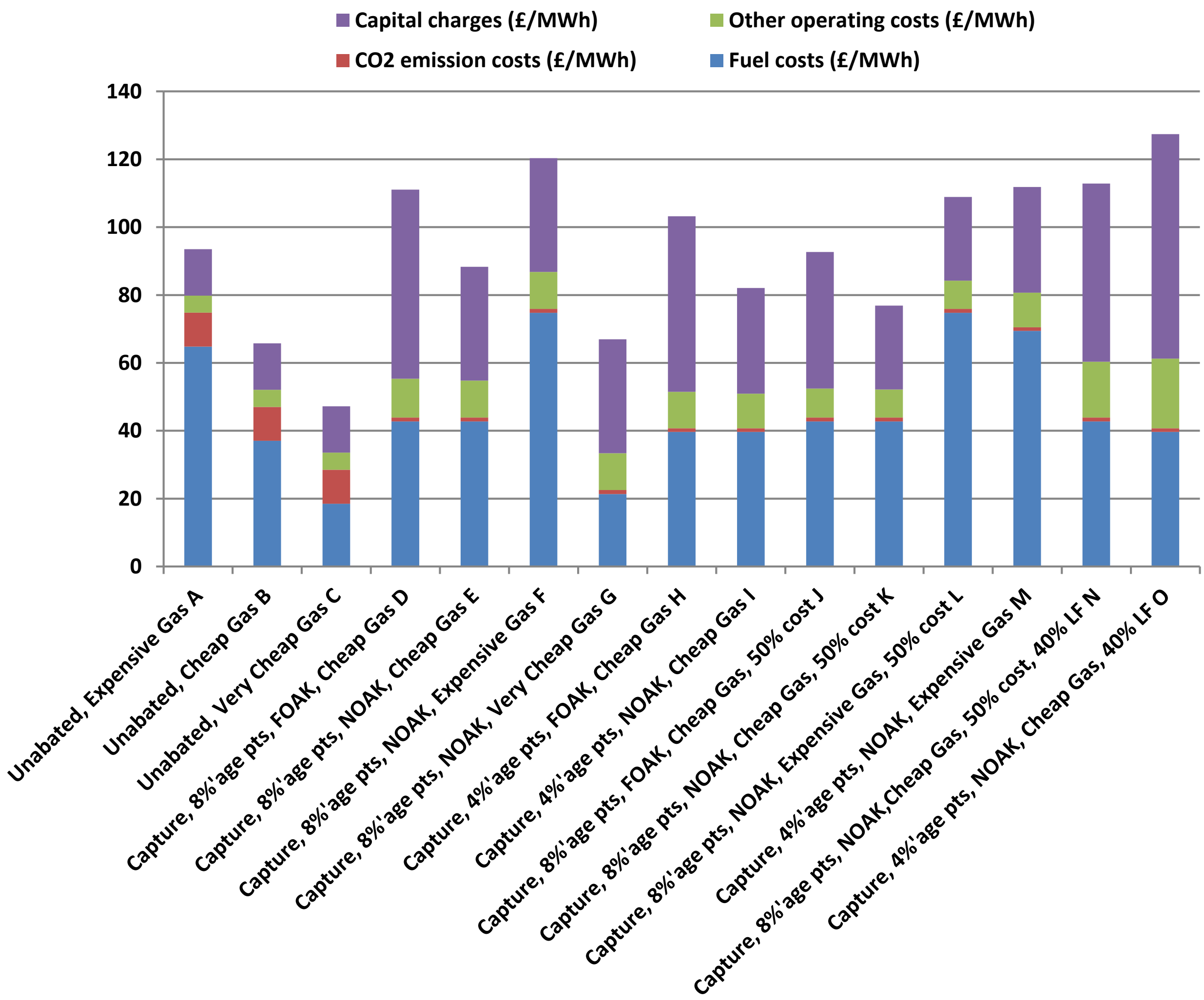

Figure 2 Illustrative LCOE (£/MWh) trends for NGCC with post-combustion capture under various assumed input scenarios

In Figure 4, the LCOE increases significantly for the FOAK plant with CO_2 capture (Case D) but there is a subsequent cost reduction of around 20% that might be expected for the NOAK plant in that series (Case E). LCOE values are still very sensitive to fuel price though (Cases F and G).

Improving capture equipment performance, particularly the energy for CO_2 separation, is a major area of research but, as shown in Cases H and I, even an heroic halving of the penalty to 4 percentage points is shown, using this model, to result in an initial increase, relative to Case E, of nearly 20% in LCOE for the necessary FOAK plant and a very modest 6% decrease in the LCOE for the NOAK plant.

Reducing the capital cost of the capture equipment by 50% is much more effective, as well as not facing inherent thermodynamic limits. The FOAK plant (Case J) is about 5% more expensive than Case E and the NOAK plant (Case K) over 10% less expensive.

As shown by comparison between Cases L and M, even with the 'expensive' gas price a 50% lower cost plant gives a lower LCOE than one with a 50% lower EOP; a lower energy solvent is not a remedy for higher gas prices. And, as would be expected, reduced capital costs are the only effective measure to control the apparent LCOE increase when plant load factors are reduced (Case N vs Case O). Although a detailed discussion is beyond the scope of this paper, these results also suggest that changes in configuration which reduce overall efficiency but give large equipment cost reductions, e.g. which involve burning additional fuel in the gas turbine exhaust gases, could be effective, especially for flexibly-operated plants.

The effects of EOP, fuel prices and capital costs (construction and financing) can also be seen by the following comparison, for this model and input data:

To reduce the LCOE by 10% from Case E you could either:

- Reduce the EOP by (a probably infeasible) 70% to around 2 %'age points
- Reduce the cost of capital by 50% to around 4% WACC
- Reduce capture plant capital cost by around 40% (or overall capital cost by 20%)
- Reduce the cost of gas by around 20%

Effect of average load factor – and how to present it

Even with today's level of wind deployment, the UK electricity demand for firm flexible power from fossil plant can vary by a factor of three across each daily cycle (e.g. from <10GWe overnight to 30GW in the evening peak).

Many CCS economic models assume CCS power plants will operate 'baseload', running at maximum output for 85% or more of the year.

Any plant contracted to run baseload will increase balancing costs for the system operator because, at the margin, it will increase the frequency with which the system operator needs to pay e.g. wind farms to turn off when there is insufficient demand or grid capacity. However, already in most months the system operator (National Grid) pays wind farms to turn off – these costs are rising sharply from ~£5M in 2012 to >£50M in 2014.

Overall balancing costs are an order of magnitude higher than wind constraint payments but the bulk of these involve asking a fossil generator to turn off – which, because the fossil generator is keen to reduce their fuel bill, will be much cheaper.

A CCS plant contracted to operate baseload would appear 'cheaper' on a LCOE basis because the capital investment is spread over more MWh. However, if many of those MWhs are unwanted – and will actually force the system operator to turn off renewable capacity elsewhere - this metric may not be the most appropriate.

A flexible CCS plant would be more capital intensive to build but running at 50% LF rather than at 85% LF would burn significantly less gas and cause significantly smaller constraint payments so would in absolute terms be lower cost - although the LCOE would appear to be higher.

Conclusions

For the NGCC+PCC power plant examples discussed in this paper fuel costs are the dominant factor in determining baseload electricity costs. At present, market prices for natural gas are low due to abundant supplies and there is an expectation that, if the world is on an ambitious emissions reduction trajectory, all fossil fuel prices will tend to fall over time. Beyond fuel costs, as NGCC+PCC technology is perceived to have become routine (i.e. NOAK instead of FOAK) the cost of capital will fall and so reduce the LCOE. In addition, significant equipment cost reductions can be expected from R&D that will evolve 'current' CCS technologies to raise their Commercial Readiness Index (CRI). The focus should be on the development of innovative new low TRL level sub-systems for incremental benefits, thus increasing the system CRI to make CCS more 'bankable'. A 50% reduction in equipment costs could reduce NGCC+PCC LCOE by over 10%; feasible reductions in the energy consumption for capture have much less impact. Particularly for flexibly-operated plant, low capital costs are a priority and might advantageously be traded off against somewhat-reduced efficiencies.

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