Opportunities for Efficiency Improvements in Power Plants with Carbon Capture

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Abstract

The current technologies for CO_2 capture from power generation processes result in significant plant efficiency penalties. This paper identifies the main efficiency penalties and explores potential technology solutions to improve the overall plant efficiency of plants which include carbon capture.

A number of large-scale power generation schemes will be considered, including pulverised coal, natural gas combined cycle, and integrated gasification combined cycle (IGCC) schemes. The carbon capture schemes considered will include a number of available technologies for both pre- and post-combustion capture, considering the implications for both new-build and retrofit projects. The paper will explore areas where there is potential for significant reductions in either parasitic load or improved efficiency of key unit operations, reduction in steam demand and/or increased capture efficiency.

It can be seen that in a few specific areas of each power generation flow scheme, there are significant efficiency improvements which can be achieved. While some of these are emerging technologies, which require further development and demonstration, and may be five or more years in the future, others can be achieved simply through improved process and heat integration and could be realised immediately. Many of these possible improvements have not been fully explored during carbon capture literature paper studies or in the operation of pilot plants.

Introduction

Climate change resulting from increased levels of atmospheric greenhouse gases such as carbon dioxide (CO_2) could, many believe, be a serious threat to the environment and the world economy. A significant portion of these CO_2 emissions are emitted into the atmosphere when hydrocarbon fuels are burned to produce energy, particularly in the power sector. One emerging technology, or set of technologies, that has been proposed to mitigate future CO_2 emissions is carbon capture and storage (CCS).

Carbon capture can be applied to oil-, coal- or natural gas-based electricity generation, and there are three process routes that can be considered. These are:

- pre-combustion capture
- post-combustion capture
- oxyfuel combustion.

This paper aims to identify areas in which significant improvements to the efficiency of carbon capture power generation schemes may be anticipated and to quantify the impact on the overall efficiency of a plant with carbon capture.

The power generation systems considered within the scope of this paper are an ultra-supercritical pulverised coal-fired steam cycle, a natural gas combined cycle and an integrated gasification combined cycle. Oxyfuel combustion has also been studied by Foster Wheeler, however, it has not been included in this paper in order to limit it to a reasonable scope. The baseline configurations for each type of plant are outlined below:

Ultra-Supercritical Pulverised Coal (USCPC)

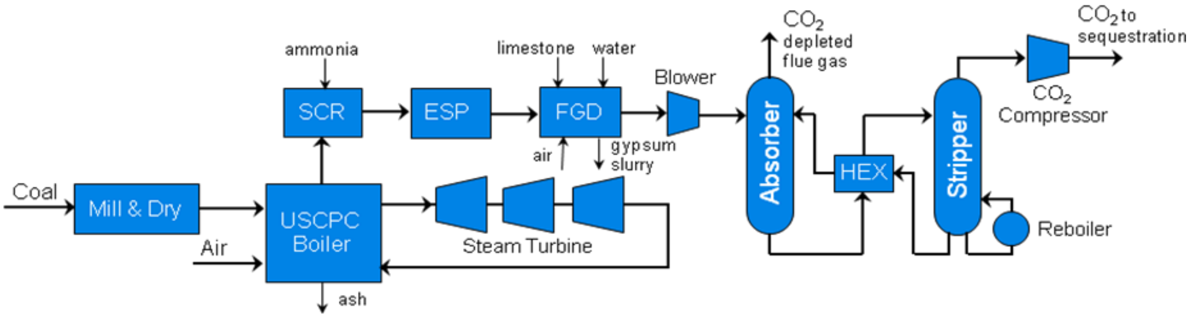

Figure 1: Pulverised Coal Simplified Flowscheme

For this case a single pulverised coal-fired unit of nominally 800 MWe capacity was assumed. The boiler was simulated as raising steam at 275 bara/600°C with single reheat to 600°C, and incorporating selective catalytic reduction (SCR) for nitrous oxides (NOx) removal, an electrostatic precipitator (ESP) for particulate removal and limestone scrubbing for sulphur dioxide (SO_2) removal. An amine-based post-combustion carbon capture process was applied to this plant, followed by CO_2 compression to 150 barg with CO_2 dehydration.

Natural Gas Combined Cycle Gas Turbine (CCGT)

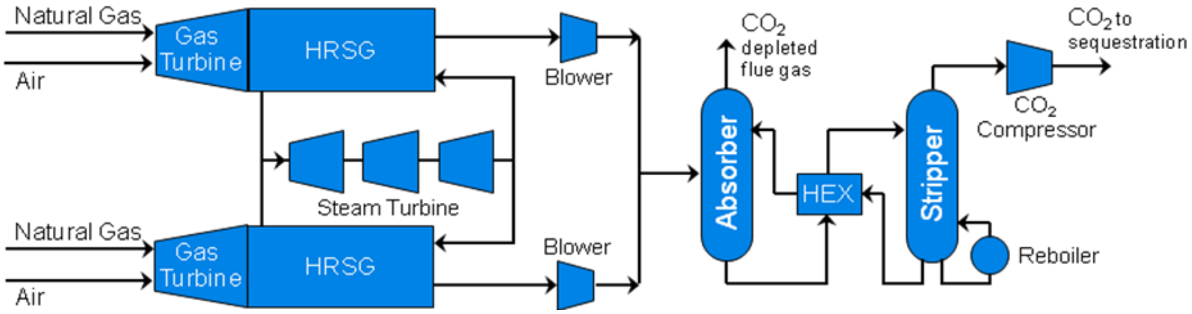

Figure 2: Natural Gas Combined Cycle Simplified Flowscheme

A modern arrangement of two G-class gas turbines and a single steam turbine producing approximately 1,000 MWe was used for the combined cycle gas turbine case (CCGT) with CO_2 capture. Each gas turbine is fitted with its own heat recovery steam generator (HRSG) feeding the single steam turbine. An amine-based post combustion carbon capture process was applied to this plant followed by CO_2 compression to 150 barg with CO_2 dehydration, very similar to that applied to the pulverised coal plant.

Integrated Gasification Combined Cycle (IGCC)

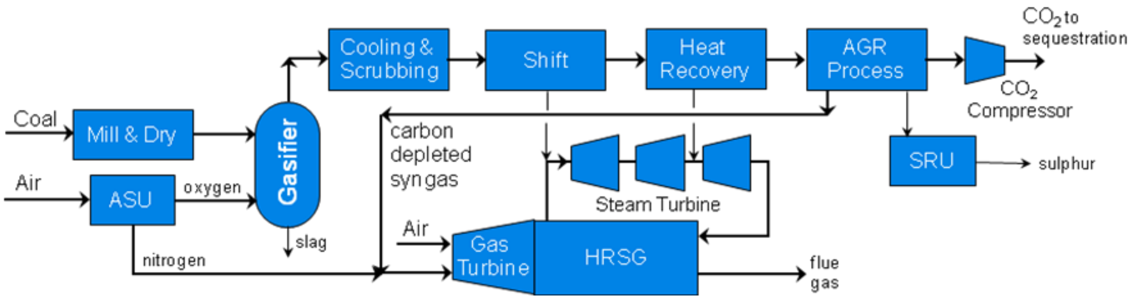

Figure 3: Integrated Gasification Combined Cycle Simplified Flowscheme

The IGCC plant comprises two gasification lines supplied by a common air separation unit (ASU), two F-class gas turbines with heat recovery steam generators (HRSGs) and a common steam turbine. The conventional air separation unit (ASU) supplies oxygen to the gasifiers and sulphur recovery unit and also supplies nitrogen for coal conveying and for dilution of hydrogen-rich gas turbine fuel gas.

In each gasification line coal is milled and dried and fed to an entrained-flow gasifier. The product gas flows through heat recovery with steam generation, particulate removal filtration, sour shift (which also performs COS hydrolysis) and syngas cooling with heat recovery. A selective DEPG (polyethylene glycol dimethyl ether) unit first removes hydrogen sulphide (H_2S) and then CO_2. The H_2S rich stream is treated in a Claus sulphur removal unit (SRU) and tail gas treating unit (TGTU), while the CO_2 rich stream is compressed to 150 barg and dehydrated for export to storage. The hydrogen-rich stream is diluted with nitrogen before combustion in the gas turbines.

Parasitic Loads due to addition of Carbon Capture

When carbon capture is applied to power generation it reduces the overall efficiency of the plant by introducing a number of parasitic loads resulting in more energy being used internally to the power plant leaving less available for export. These parasitic loads can be caused either by electrical loads such as additional rotating machinery or as thermal loads such as the heat required for regenerating solvents. The heat requirement reduces the power produced since steam which would have been used for generating electrical power has instead been used as a heat source.

In order to improve the overall efficiency of a power plant with carbon capture it is necessary to reduce or eliminate as much energy demand as possible whether it is thermal or electrical. Improving the performance of a solvent by additional cooling, hence requiring less heat for regeneration, is not always a solution if it requires a significant increase in electrical load due to the requirement for chilling or refrigeration systems. It is therefore necessary to consider the power plant system as a whole in order to identify sensible targets for savings that can be made.

Ultra-Supercritical Pulverised Coal (USCPC)

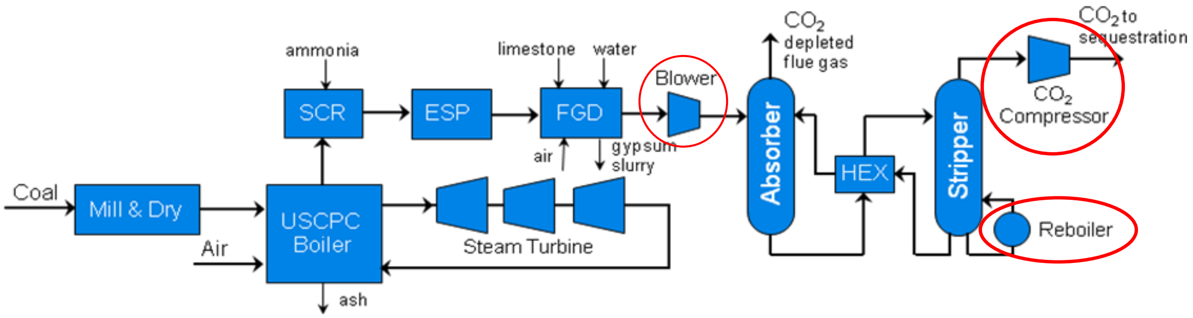

Figure 4: Pulverised Coal Key Parasitic Loads

Applying a monoethanolamine (MEA)-based post-combustion unit (currently the most demonstrated type of technology for post-combustion carbon capture) to the pulverised coal plant introduces two main parasitic loads and a number of lesser loads. Firstly a significant quantity of low pressure steam is required for solvent regeneration, reducing the electrical output of the steam turbine generator. The second load is the power needed to drive the CO_2 compressor.

Of the lesser loads, the largest is often the flue gas blower required to elevate the pressure of the entire flue gas stream sufficiently to overcome the pressure drop across the absorption column and any associated heat exchangers. Other lesser loads include pumping power and or fan power associated with a significant quantity of cooling medium and transport of the solvent around the capture plant loop. Based on previous work by Foster Wheeler the typical loads are as follows;

Load added to apply CO_2 Capture	% of total additional load
Solvent Reboiler	56 %
CO_2 Compression	33 %
Flue Gas Blowers	4 %
Others	7 %

Table 1: Pulverised Coal Parasitic Load Breakdown

Solvent regeneration reboiler – This duty has been extensively targeted for reduction by improving or changing solvents, or by flashing a portion of the lean solvent to generate a semi-lean stream(1). Study work undertaken by the International Energy Agency Greenhouse Gas Research & Development (IEA GHG R&D) Programme estimates that savings of from 27 to 40% on regeneration energy requirement can be made compared to conventional processes(5). A saving of 30% on reboiler duty will be considered for the purposes of this paper.

CO_2 compressor power – Recently much work has also been done to investigate means of reducing the power requirement for CO_2 compression. In a recent paper by GE(2) savings of up to 20% are anticipated by varying the compression route and achieving liquefaction at the lowest possible pressure for the available cooling medium. Further savings could be achieved by introducing refrigeration cycles, however, the power requirement of the refrigeration cycle was shown to offset the benefit of increased CO_2 compression chain efficiency. A saving of 20% on CO_2 compressor power will be considered for the purposes of this paper, in line with GE's findings(2).

Integration – There is a significant requirement for cooling in the amine-based post-combustion carbon capture flow scheme which results in low grade waste heat which may be recovered elsewhere on the plant. It has been shown that, depending on the individual site circumstances (such as available cooling medium temperature), a greater degree of compressor intercooling can be preferable in overall plant efficiency terms to recovery of CO_2 compressor waste heat. There is, however, still a significant quantity of recoverable waste heat available from the stripper condenser and solvent coolers to integrate with the power island boiler feed water preheating. This integration reduces the quantity of steam which is extracted from the steam turbine to preheat the boiler feed water, hence increasing the electrical output of the steam turbine generator. A saving of one percentage point on overall power plant efficiency will be considered for the purposes of this paper based upon the results of previous Foster Wheeler study work integrating carbon capture with this type of plant.

Incorporating each of the suggested improvements above into our base case flowscheme for the pulverised coal plant results in an increase in the net power output of approximately 9% and consequently an increase of approximately three percentage points in overall efficiency.

Natural Gas Combined Cycle Gas Turbine (CCGT)

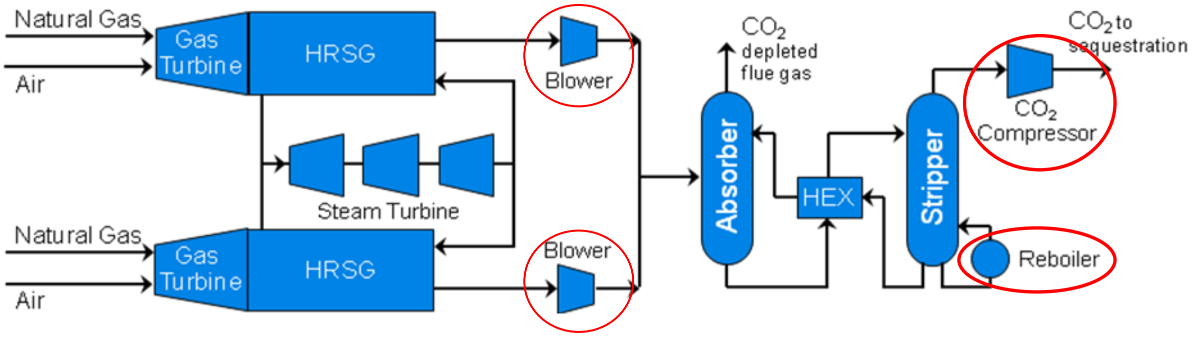

Figure 5: Natural Gas Key Parasitic Loads

The natural gas flowsheme with post-combustion carbon capture is characterised by similar parasitic loads as for the pulverised coal case above. The main difference is the proportion of these loads. Since the flue gas from a combustion turbine is significantly more dilute, the blower power is proportionately higher, and hence is a more significant parasitic load on the plant. In general however, other parasitic loads, all those associated with the total mass of CO_2 to be captured, are lower due to the smaller quantity of CO_2 generated by combustion of natural gas compared with combustion of coal. Based on previous work by Foster Wheeler the typical parasitic loads are as follows,

Load added to apply CO_2 Capture	% of total additional load
Solvent Reboiler	54 %
CO_2 Compression	20 %
Flue Gas Blowers	19 %
Others	7 %

Table 2: Natural Gas Parasitic Load Breakdown

Solvent regeneration reboiler & CO_2 compressor power – Since the post-combustion flowscheme is almost identical for a natural gas plant as for a pulverised coal plant the same improvements can be assumed for the reboiler duty (30% reduction in thermal energy) and the CO_2 compression power (20% reduction in electrical power) as for the pulverised coal case.

Flue Gas Blower – Less industry work has focused on investigating potential reductions in the flue gas blower power. The blower is required to overcome the pressure drop incurred through the CO_2 absorber and any heat exchangers and ducting between the power island and the carbon capture plant. While one option would be to consider future improvements in blower efficiency, an alternative solution would be to give high priority to minimising pressure drop between the power island and the capture plant. This could be achieved by minimising the physical distance between the two and modifying design of the heat exchangers and pipework to minimise losses. An assumed saving of 10% on blower power due to reduced system pressure losses will be considered for the purposes of this paper in order to assess the impact such a saving would have on the overall plant efficiency.

Gas Turbine Improvements – The design of gas turbines is under constant scrutiny to find areas for improvements in efficiency. Since the gas turbines produce approximately two-thirds of the total combined cycle power any small improvement in efficiency results directly in a proportionate improvement in the plant overall efficiency. Gas turbines are improved both by the introduction of new models and by modifications to existing designs. Gas Turbine World publishes historic information on improvements made to currently available gas turbine designs varying from 0% to 7% depending on the type of machine(4). Using this data as a basis to extrapolate future GT improvements an increase of 3% in GT efficiency will be considered for the purposes of this paper.

Integration – Recovery of carbon capture plant waste heat is more challenging in the natural gas combined cycle case due to the high level of thermal integration already applied within the power island(3). Boiler feed water preheating is already achieved within the coolest section of the HRSG, hence more complex integration studies would be required on a project-specific basis if further heat integration savings were to be identified. Solutions such as optimisation of steam generation pressure levels, integrating boiler feed water preheating with the capture plant direct contact cooler, preheating rich solvent upstream of the stripper and reboiling a portion of the stripper bottoms in the HRSG might be considered. This degree of integration should be performed in conjunction with capital and operating cost estimation in order to determine the appropriate degree of integration without excessive additional investment cost. This has not been undertaken for this paper. Hence no efficiency improvement due to additional heat integration has been assumed for the natural gas case.

Incorporating each of the suggested improvements above into the our base case flowscheme for the natural gas combined cycle plant results in an increase in the net power output of approximately 7% and consequently an increase of approximately three percentage points in overall efficiency.

Integrated Gasification Combined Cycle (IGCC)

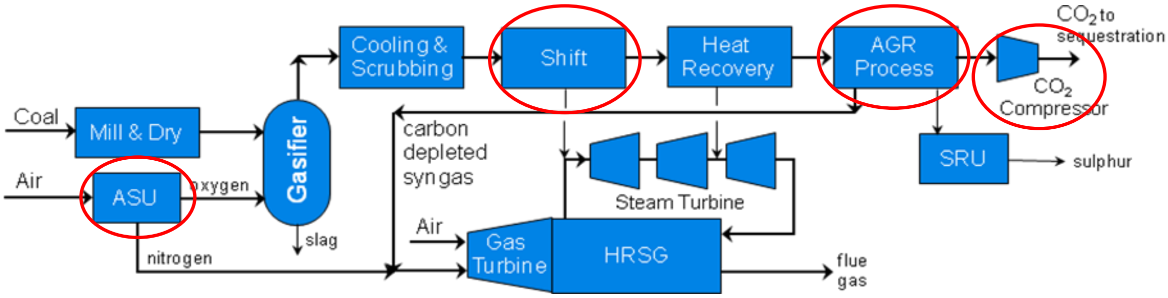

Figure 6: IGCC Key Parasitic Loads

The integrated gasification combined cycle scheme consists of a more complex process scheme than the post-combustion capture cases, with more process units requiring either heat or power or both. The main power users are the air separation unit (ASU), CO_2 compression and acid gas removal unit (AGR), while the main users of steam are the AGR and the Shift.

Based on previous work by Foster Wheeler the following table summarises the distribution of the additional parasitic loads of an IGCC power plant due to adding carbon capture:

Load added to apply CO_2 Capture	% of total additional load
DEPG-based CO_2 Removal	46 %
CO_2 Compression	26 %
Others	28 %

Table 3: IGCC Parasitic Load Breakdown Due to Addition of CO_2 Capture

Table 3 above shows the very significant contribution to the parasitic loads resulting from the use of steam in the AGR. However, when all of the parasitic power loads (excluding heat loads) on the plant, not just those due to adding carbon capture, are compared the picture looks somewhat different:

Parasitic Power Load	% of total power load
DEPG-based CO_2 Removal	14 %
Air Separation Unit	47 %
CO_2 Compression	21 %
Others	18 %

Table 4: Overall IGCC Plant with CO_2 Capture Parasitic Load Breakdown

Table 4 shows that nearly half of all power which is consumed within the power plant is due to the ASU, which only increases in duty by a relatively small amount when adding carbon capture to the IGCC scheme.

The contribution of “others” to the plant parasitic loads is also significant. Improving the efficiency of heat recovery from gasification, energy conversion in the gasifiers and operation of the gas turbines also present opportunities for improving the efficiency of the overall IGCC plant with carbon capture.

Gasification Improvements -

- Entrained flow gasifiers can be provided with mechanical coal pumping, avoiding need for high pressure coal conveying nitrogen.
- Medium temperature gasification with outlet gas around 1000°C reduces oxygen consumption, reduces cost of heat recovery and increases the gas turbine contribution to total power output. Medium temperature gasifiers include two-stage entrained flow, fluidised bed and transport gasifier types.
- Fixed bed gasification with outlet gas around 500°C further reduces oxidant consumption and may be an attractive but so far little explored option.
- Medium- and low-temperature gasification open the way to practical use of air or enriched air in place of oxygen.

Based on these factors it is anticipated that an overall efficiency improvement of 0.5 percentage points could be realised due to gasification improvements and hence 0.5 percentage points improvement has been assumed for this paper.

Gas Turbine - One factor, not often recognised, limiting the thermal efficiency of IGCC with carbon capture is the generally low firing temperature of gas turbines fuelled with decarbonised fuel (basically hydrogen with nitrogen or steam dilution). The installed GT exhaust temperature of F-class GTs firing natural gas is around 600°C – Gas Turbine World quotes 602°C for the GE 9FA in open cycle and 638°C for the 9FB in combined cycle[4] - while representative exhaust temperatures recommended by manufacturers for firing of decarbonised fuel gas are of the order of 50°C to 80°C lower. Several factors are seen as contributing to this downrating:

- Potential hot component corrosion by higher steam content from combustion of H_2-rich fuel
- Lower calorific value of the decarbonised fuel increases exhaust flow rate, increasing mechanical stresses – this can be alleviated by air extraction
- Perceived need to meet NO_X emission limits with existing diffusion burners without resort to SCR
- Understandable conservatism in absence of significant operating experience.

A simulation performed by Foster Wheeler has shown the potential for increasing the thermal efficiency of an IGCC plant with carbon capture by approximately four percentage points just through increasing the GT exhaust temperature to 626^{o}C. This represents the best single potential improvement in gasification-based power with carbon capture, far more significant than any improvement in the syngas production process.

Other potential GT improvements include:

- higher GT fuel gas preheat
- lower burner pressure drop, reducing the fuel gas pressure upstream of the GT and hence reducing the resulting oxygen and diluent nitrogen supply pressures requirements
- improved burners and other hot components, permitting high firing temperatures and/or less dilution of the decarbonised fuel gas with nitrogen or steam
- premix burners for use with higher firing temperatures, as alternative to SCR for NOx emission control
- reduced capacity GT air compressor, as substitute for air extraction

An overall efficiency improvement of four percentage points has been applied for this paper due to GT performance improvements, mainly due to increased exhaust temperature.

Air separation unit - Large oxygen production plants currently use cryogenic air distillation, which has been practiced for more than 100 years. Cryogenic oxygen production is a highly energy intensive process, with typical power consumption for 95% purity oxygen of approximately 320 to 350 kWh / tonne O_2 delivered at gasifier pressure using current technology. Large quantities of oxygen are required by IGCC and oxyfuel power generation, for example, approximately 4,700 tonnes/day for a 700MWnet IGCC plant with carbon capture. Oxygen production plants also account for a significant portion of the capital cost of IGCC with carbon capture plants - approximately 10%. The significant contributors to the inefficiency of the air separation process are the air compression, the process pressure drops (notably heat exchangers and distillation columns) and heat exchanger temperature differences. Improvements in one or more of these increases in air compression efficiency and the use of more complex and integrated air separation unit process cycles have the potential to reduce the energy consumption of cryogenic air separation.

Alternatively, Ion Transport Membranes (ITM) or Oxygen Transport Membranes (OTM) technologies are currently being developed. ITMs use dense mixed metallic oxides which are oxygen selective. They operate at between 800 – 900°C producing a high purity oxygen permeate stream and a nitrogen rich non-permeate stream suitable for syngas fuel dilution. Studies indicate that ITM's could significantly reduce the net capital and power costs for oxygen production by around 35%. However, ITMs have not been demonstrated in large scale plants, so their savings are not yet proven[6] .

Work undertaken by others indicates that an overall efficiency improvement of approximately 1.2 percentage points is achievable through the use of ITM compared with a cryogenic ASU[6], therefore 1.2 percentage points improvement has been assumed for this paper.

CO_2 compressor power – Similarly to the USCPC and CCGT cases much recent work has been done to investigate possible means of reducing the power requirement for CO_2 compression. Similar levels of power and efficiency savings as in the USCPC and CCGT cases would be anticipated for the IGCC case. A saving of 20% on CO_2 compression power will be considered for the purposes of this paper.

Incorporating all of the suggested improvements above into the our base case flowscheme for the integrated gasification combined cycle plant results in an increase in the net power output of approximately 17% and consequently an increase of approximately six percentage points in efficiency.

Shift - Another important point to consider in IGCC schemes is the reduction in efficiency due to the water gas shift reaction. Greater conversion of CO to CO_2 is necessary as the required CO_2 capture rate increases. To achieve this increased quantities of steam are required for the shift reaction. This in turn reduces the steam available to the steam turbine and correspondingly the steam turbine electrical output, combined with increasing the quantity of make-up water required. Use of a lower CO_2 capture rate would reduce the impact of this aspect of the IGCC process, however this has not been considered in this paper.

Results

Three generic power plant configurations with carbon capture have been considered, investigating potential for reductions in parasitic power and heat demand and improved integration. The suggested improvements were incorporated into a baseline design to quantify the resultant total improvements in plant efficiency with carbon capture from the baseline.

The following table summarises the improvements applied to the baseline flowschemes for this study:

Case	Technology	Impact
Ultra-Supercritical Pulverised Coal (USCPC)	Capture Plant Regeneration Duty	30% reduction in heat load
	CO_2 Compressor Power	20% reduction in power load
	Integration	1% point increase in overall LHV efficiency
Natural Gas Combined Cycle Gas Turbine (CCGT)	Capture Plant Regeneration Duty	30% reduction in heat load
	CO_2 Compressor Power	20% reduction in power load
	Blower Duty	10% reduction in power load
	Gas Turbine Efficiency	3% increase in GT efficiency
Integrated Gasification Combined Cycle (IGCC)	Gasification Improvements	0.5 % point increase in overall LHV efficiency
	Gas Turbine Improvements	4 % point increase in overall LHV efficiency
	CO_2 Compressor Power	20% reduction in power load
	Air Separation Unit Power	1.2 % point increase in overall LHV efficiency

The following table summarises the results calculated for this paper, where carbon capture has been abbreviated to "CC":

	Penalty due to addition of conventional CC		Penalty due to addition of CC with suggested technological improvements		Benefit due to potential technological improvements	
Case	Net Power (%)	LHV Efficiency (1)	Net Power (%)	LHV Efficiency (1)	Δ Net Power (%)	Δ LHV Efficiency (1)
Ultra-Supercritical Pulverised Coal (USCPC)	20.7	8.9	13.4	5.7	7.3	**3.2**
Natural Gas Combined Cycle Gas Turbine (CCGT)	15.4	9.0	9.6	5.7	5.8	**3.3**
Integrated Gasification Combined Cycle (IGCC	20.1	9.0	6.4	2.8	13.7	**6.2**

Note 1. Efficiency units are quoted as percentage points.

Conclusions

It is clear that carbon capture has a key part to play in decarbonising the power generation sector. However, it is widely recognised that current carbon capture technologies and configurations exhibit a significant efficiency and electrical output penalty compared with unabated power plant design. This paper has identified a number of potential areas of improvement. In all individual plant cases there will be variations in the efficiency improvements that can be realised, depending amongst other things, on the baseline design employed and specific basis of design.

In the USCPC case our study has shown a cumulative efficiency improvement of over three percentage points can be made. Considering a current delta of approximately nine percentage points between the efficiency of USCPC schemes with and without carbon capture this represents 35% improvement.

This compares to the CCGT case for which our study has identified a potential cumulative efficiency improvement of over three percentage points. Considering a current delta of approximately nine percentage points between the efficiency of CCGT schemes with and without carbon capture this again represents almost 40% improvement.

Most encouraging of the three is the IGCC case. Our study has shown a cumulative efficiency improvement of more than six percentage points can be made, dominated by the gas turbine. Considering a current delta of approximately nine percentage points between the efficiency of IGCC schemes with and without carbon capture this represents almost 70% improvement.

Further analysis is recommended to understand the capital and operating costs associated with the design adjustments necessary to achieve the efficiency improvements reported, thereby enabling the economic impact to be understood, in terms of levelised cost of electricity, cost of CO_2 captured and cost of CO_2 avoided.

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