UTS
UNIVERSITY OF TECHNOLOGY SYDNEY
PAM Review
Subject 68412 www.uts.edu.au

A meta-study on the feasibility of the implementation of new clean coal technologies to existing coal-fired power plants in an effort to decrease carbon emissions

Kenneth Davies[1,*], Abhishek Malik [2], Jimmy Li [3], and Thiha Nanda Aung[4]

University of Technology Sydney, P.O Box 123, MaPS, Broadway NSW 2007.

[1] E-Mail: kenneth.s.davies@student.uts.edu.au
[2] E-Mail: abhishek.malik@student.uts.edu.au
[3] E-Mail: jia.j.li-2@student.uts.edu.au
[4] E-Mail: thiha.nandaaung@student.uts.edu.au

* Author to whom correspondence should be addressed; E-Mail: kenneth.s.davies@student.uts.edu.au

DOI: http://dx.doi.org/10.5130/pamr.v4i0.1455

Abstract: The renewable energy sector has experienced an incredible growth in the last 15 years. The dependency on fossil fuel based power plants is still likely to continue well into the next half century. The global thermal efficiency of coal-fired power plants (CFPPs) since the 1980s has largely remained stagnant at 30-39% (high heat value basis) (2). Recent advances in materials and thermodynamics technologies has allowed for the efficiency of new pilot plants to be increased to 45%, even beyond 50% in some cases (3). The manufacture of these new highly efficient ultra-supercritical (USC) steam cycle CFPPs is an economically and politically difficult prospect. Therefore, it is necessary to investigate methods to apply the thermodynamic improvements available in modern USC CFPPs to the currently operating majority of subcritical (SubC) power plants without a large overhaul in infrastructure i.e. through retrofitting. This meta study provides an analysis of the overall and intra-system efficiency of CFPPs, the development of new clean coal technologies, then discusses and concludes the feasibility of applying these processes to current power plant infrastructure. A thermodynamic analysis of the most promising clean coal technologies, i.e. advanced pulverized coal combustion systems, oxy-fuel, pre- and post-combustion carbon capture systems, steam reheat cycles, co-firing systems, will allow the investigation into whether retrofitting current power plants will generate a significant increase in efficiency. Thereby allowing for the discussion of the viability of retrofitting for the reduction in carbon emissions and the recommendation of specific options. It was concluded that the most viable technology to be retrofitted was CCS combined with Oxy-fuel combustion as it significantly reduces emissions for a small drop in efficiency.

Keywords: Coal-fired power plant; clean coal technologies; carbon emissions; thermodynamic efficiency; pulverized coal; oxy-fuel; carbon capture; integrated gasification combined cycle; biomass co-firing

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Table 1. *Nomenclature*

CCS	Carbon Capture and Storage
CFPP	Coal fired power plant
PC	Pulverised-coal
SubC	Subcritical
SC	Supercritical
USC	Ultra-supercritical
LHV	Low Heat Value
HHV	High Heat Value

1. Introduction

Coal is an important part for world power generation. Over the last decade 41% of energy produced globally was from coal-fired power plants with an average global efficiency of 33% (5, 6). Since the year 2000 coal-fired power plant efficiency has increased by approximately 0.3% according to the World Energy Council. This is largely attributed to coals abundance and cheap, stable market price as well as the longevity of power plants, between 30 and 40 years, which provides no incentive for companies to invest. In recent years there has been strong global sentiment for the reduction of CO_2 emissions for fossil fuel power generations, as per the Kyoto Protocol which calls for a reduction of CO_2 emissions by the year 2020 (7). Reducing emissions can be achieved by increasing the efficiency of existing coal-fired power plants, retrofitting newer more efficient technology. This has strict limitations due to the material and constraints of the boiler and turbines (8). As the public's attitude towards government spending on fossil fuels, such as building entirely new coal-fired power plants, retrofitting more efficient technology to reduce emissions is a more viable and attractive option.

1.1 Advanced Pulverised-coal Combustion

For the most common form of coal power generation – Pulverised-coal (PC) combustion – the principle research and development ideologies regarding the reduction of emissions involve methods that increase system efficiency by increasing steam main and reheat temperature and pressure parameters (9). Steam cycle regeneration involves reheating the steam after the initial turbine stage to increase steam pressure and temperature parameters, thereby greatly increase efficiency. This can be employed multiple times at different stages of the Rankine cycle to further increase efficiency and reduce emissions (2).

1.2 Carbon Capture and Storage Systems

Even with the steadfast improvements in CFPP thermal efficiencies and thus the lowering of carbon emissions, the power sectors reliance on coal-fired power generation – expected to remain at an approximate constant 40% of total power consumption, but increase from a world-wide 105 Quadrillion Btu in the year 2000 to 472 Quadrillion Btu – means that more responsible means of carbon emissions management than atmospheric release must be developed (9). Understanding this issue, there has been a surge towards developing systems that can be retrofitted to existing power plants, whilst balancing their undeniable reduction in plant efficiency with a relatively small economic and financial footprint. The four commercially viable and developed Carbon Capture and Storage (CCS) systems are on the next page:

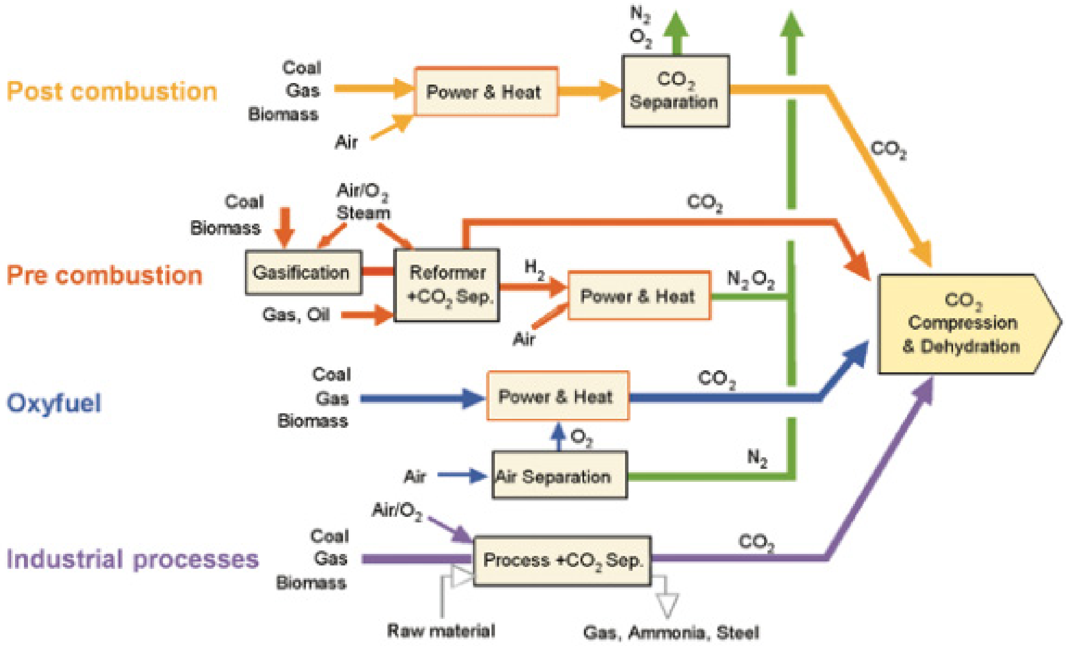

Figure 1. *CCS system classifications. Post combustion capture shows the separation and capture of carbon dioxide from the flue gasses released from the combustion chamber and turbine. Pre-combustion capture is shown through the carbon dioxide separation following the fuel gasification cycle and prior to the turbine phase, these gases are then captured via storage system. Oxy-fuel combustion involves the generation of an incredibly high carbon concentrated flue gas, which does not need separation and is directly captured (10).*

1.2.1 Post-combustion

Post-combustion carbon capture is the most fundamental CCS technology and is the most well developed. It is used to capture and separate the flue gases ejected from the turbine post combustion. The carbon dioxide in the flue gas is separated using one of many physical methods, chemical absorption methods such as amines and alternative solvents, adsorption methods or alternative methods such as membranes or cryogenics (2). Due to the large amounts of energy required to separate and capture the carbon dioxide this method of reducing emissions also reduces the efficiency of the plant. This balance is regained through the substantial decrease in greenhouse gas emissions can be greater than 80%, justifying the decrease in efficiency (11). This technology is possible as a retrofit system for PC and co-firing power plants.

1.2.2 Pre-combustion (Integrated Gasification Combined Cycle)

Pre-combustion CCS is a technology used to reduce greenhouse gas emissions by either removing CO_2 before the coal is burnt via Integrated Gasification Combined Cycle (IGCC) technology. The IGCC is a clean method of coal-fired power generation, it allows for the use of coal fuels in an efficient combined steam cycle, whilst generating an environmental impact similar to that of a natural gas-powered plant. The basic principle of IGCC is to gasify the coal fuel using an air or oxygen combustion gas, thus producing a synthetic gas that is (syngas) composed mainly of hydrogen and carbon monoxide particles (2, 12). This syngas is then filtered for impurities such as sulphide, nitride and dust particles. Following the filtration process, the syngas is then mixed with steam in a catalytic reactor known as a shift convertor, to convert the carbon monoxide particles into carbon dioxide while creating more hydrogen particles as well. The carbon dioxide is then separated by chemical or physical processes, resulting in a hydrogen rich syngas that can be used for a clean and efficient burn (2, 10). This process not only increases the coal transfer and heat efficiency, but also increases the quality of the gasified coal thus improving the burn characteristics (13, 14). A simplified IGCC model incorporating the carbon separation is shown below:

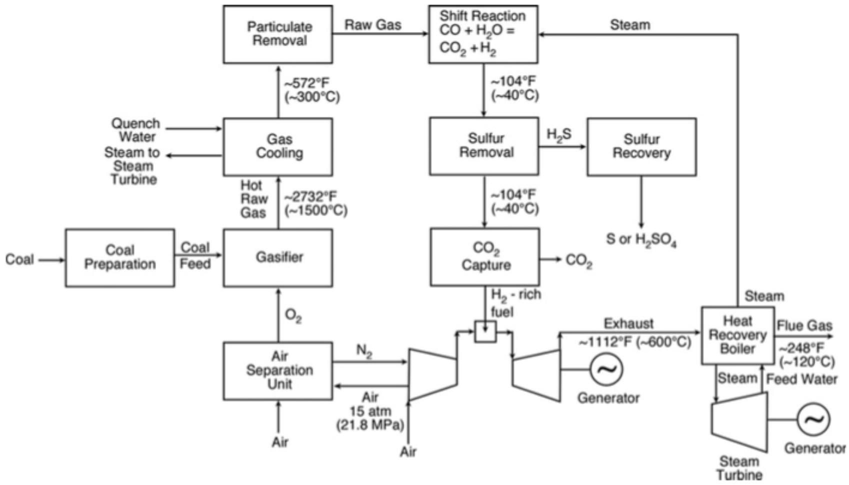

Figure 2. *IGCC flowchart detailing carbon separation and capture processes that occur prior to the turbine phase. This allows for a hydrogen rich combustion. The refeed into the air separation unit is also shown, along with the nitrogen and sulphur separation cycles that occur pre combustion (2).*

1.2.3 Oxy-fuel combustion

Oxy-fuel combustion is a method used to increase the energy generated by the combustion process. Oxygen is fed into the air-inlet chamber through an air separation unit (ASU), mixing with the combustion air to create an oxygen-rich (and nitrogen-depleted) environment. When the resulting oxy-fuel is fed into the combustion chamber to be fired, the resulting reaction is incredibly much more volatile than a standard air reaction. Due to this reason, oxy-fuel combustion – though a feasible retrofit option – requires the implementation of advanced materials that are able to cope with the increased pressure, temperature characteristics of the combustion (2, 15). Following the oxygen heavy combustion reaction, the flue gasses generated are incredibly concentrated with carbon dioxide (levels of up to 90%). This allows for seamless mating with a post-combustion CSS, as shown below in the CPU subsystem.

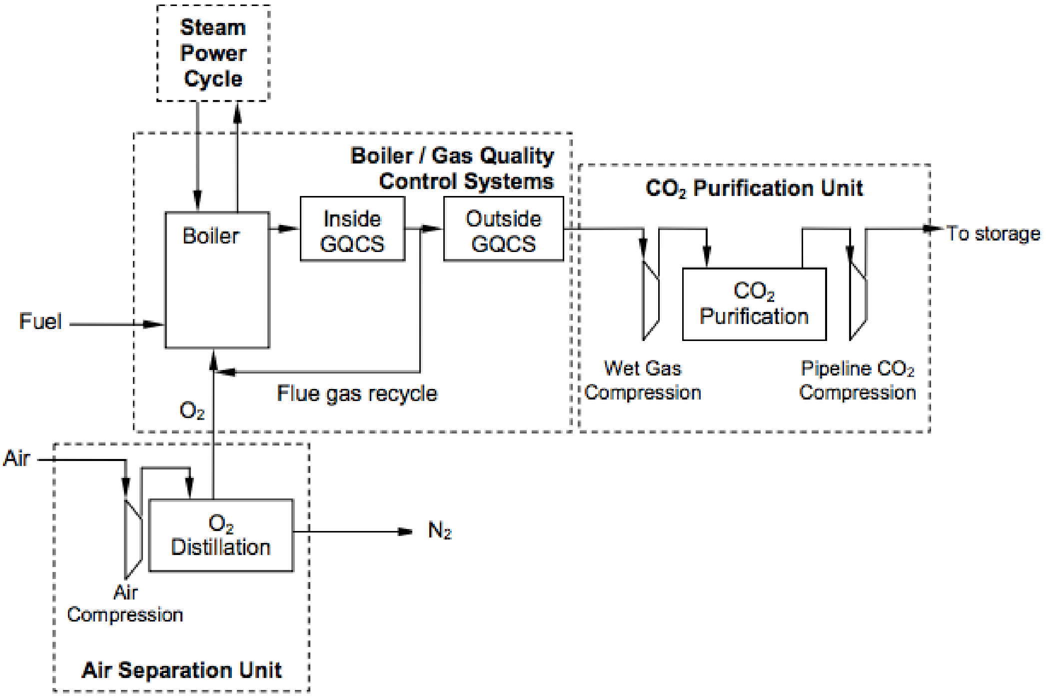

Figure 3. *This simplified Oxy-fuel combustion diagram has the oxy-fuel system separated into three sub-systems, the third of which is a post-combustion capture system. The first sub-system shows the oxygen distillation (nitrogen depletion) through the air-separation unit. This combustion gas then travels into the boiler/gas quality control sub-system, which contains the combustion cycle and flue gas recycle. This flue gas is then purified, the carbon separated and sequestered for storage (16).*

1.3 Biomass Co-firing

Torrefaction of biomass, such as wood or grain, increases its quality and combustibility to make it a suitable substitute for coal while producing the same energy output with less fuel. This technology requires no mechanical change to the power plant, the only change is that of the feed stock (2). The biomass is converted via a thermo-chemical process at 200-300°C for approximately 1 hour to produce a solid fuel that is competitive with coal (17). A complication with this technology is the degradation of boiler efficiency due to fouling of the boiler walls.

1.4 Pre-drying of lignite

Pre-drying of lignite(brown) coal to reduce moisture content is a very effective method of increasing efficiency and reducing emissions. Brown coal typically has a moisture content of 20%-55% and has a significantly lower amount of available energy than bituminous black coal (18). By reducing the moisture content before pulverizing the coal, thermal efficiency is greatly increased due to hotter burn temperatures and less coal being used for the same power output. The two most effective methods of pre-drying lignite which are air-drying and fluidized bed dryers (19). Air drying is achieved by heating air to between 50°C and 80°C and in turn heating the coal to evaporate the water (1). These temperatures are lower than that of fluidized bed dryers which operate up to 300°C (4).

Fluidised bed dryers pass air up through the wet coal to fluidise it and can dry a significant amount of fuel at one time.

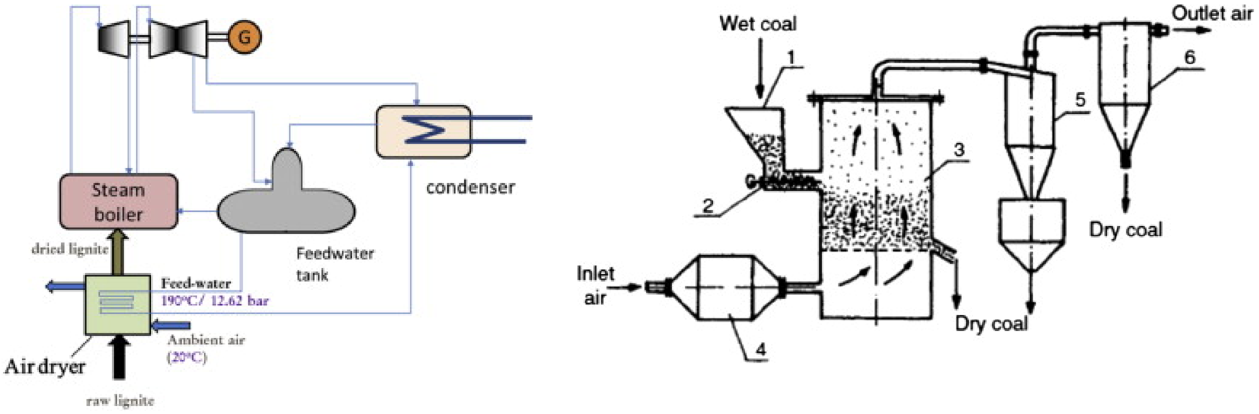

***Figure 4: Left:** air dryer with feedwater as heat source, showing the reheat cycle combined with ambient air (1). **Right:** fluidised bed dryer system is show in the feed section, prior to the combustion stages(4)*

In this paper, the net energy efficiency increase and emissions reduction across multiple implementations of each technology will be examined and the feasibility of retrofitting these technologies into existing coal-fired power plants will be determined.

2. Methods

This meta-study was conducted by obtaining multiple sources related to each technology, comparing the efficiency and identifying which is most suitable to retrofit to existing coal fired power stations. Tools used to gather resources were Google Scholar, Scopus, Science Direct database, and the University of Technology, Sydney online library. Biased material was avoided where possible by noting the researcher's sources and the organizations affiliations. Data and content analysed from potentially biased sources such as industrial papers from RWE Power, or government advisory group project such as the Intergovernmental Panel of Climate Change, were always confirmed with unbiased technical papers from academic institutions such as the Massachusetts Institute of Technology.

A thermodynamic analysis of each component was performed to demonstrate how the efficiency was gained and from where within the cycle of the coal fired power plant. The first requirement of these technologies was their ability to create a net increase in efficiency of the power plant; to gain the same or more power output for the same or less coal. Following this, it also had to be possible for the technologies to be implemented on an existing power plant. The remaining options were then researched further and their efficiencies compared where appropriate. It was noted that each technology achieved the efficiency increase in a different section of the power plant and as such, only overall output efficiency was possible to be compared.

3. Results and Discussion

3.1 Advanced PC Combustion

Classifications for the different stages of steam cycle technologies within PC combustion are shown in Table 1. These technologies focus on the increase in steam reheat cycles, pressure and temperature parameters within the boilers. This is due to the fact that for every 20°C that steam superheat and reheat temperature is increased, system efficiency will increase by 1% (3). These methods are often bound by materials and fabrication technologies that restrict the reliable and consistent operation of boiler and turbine systems at increased pressure and temperature. The improvement in materials technologies has allowed for the use of alloys such as austenitic-chromium, chrome-moly-vanadium steels and nickel based super alloys - which have allowed pilot testing to see systems reliably reach maximum temperatures of 760°C (2). Well above the minimum requirements for systems to be classified as ultra-supercritical power plants, these advancements move CFPPs into the future with the eventual development of advanced ultra-super critical plants.

Table 2. *Critical classifications of power plants*

Classification	Main Steam Pressure (MPa)	Main Steam Temperature (°C)	Reheat Steam Temperature (°C)	Efficiency % (HHV, bituminous)
Subcritical (SubC)(2)	<22.1	0-565	0-565	33-39
Supercritical (SC)(2)	22.1-25	540-580	540-580	38-42
Ultra-supercritical (USC)(2)	>25	>580	>580	>42
Advanced Ultra-supercritical (3)	>37	>760	>760	>48

PC plants work on the basic principle of crushing raw coal fuel into superfine particles, devolatilising them mating the particles with combustion gases in the furnace to efficiently generate heat. Supercritical steam cycle PC plants were initially introduced in the early 1950s in both the United States and Europe and were eventually commercialised by the late 1960s (9). Due to the increased number of forced plant outages due to a myriad of problems ranging from materials issues to malfunctioning systems, such as the boiler tubes, industry consensus moved towards the more reliable subcritical (SubC) units with lower steam pressures and temperatures (2, 3). Now due to the renewed interest in increasing plant efficiency for the sake of lower emissions, along with the advancements in materials to allow for more subsystem reliability, SC technology is beginning to be discussed once again. Apart from increasing steam main and reheat pressure and temperature parameters (the difference steam cycles make to a PC system is shown in Table 3, which collates relevant data from an MIT study on clean coal technology), it is possible to increase the thermal efficiency of a PC SC plant from the low range of 38% to 43% (HHV) by altering the air/carbon ratio, lowering stack gas temperature and lowering condenser temperature (3).

Table 3. *Comparison of thermodynamic and economic parameters of different classifications of PC CFPPs*

	Subcritical PC	Supercritical PC	Ultra-Supercritical PC
Heat rate* (Btu/kWh)(9)	9950	8870	7880
Efficiency (%, HHV)(9)	34.3	38.5	43.3
Coal feed (kg/hr)(9)	208000	185000	164000
Coal feed^2 (x10^6, tonnes/year)(3)	1.55	1.38	1.22
CO_2 emitted (kg/hr)(9)	466000	415000	369000
CO_2 emitted^2 (x10^6, tonnes/year)(3)	3.47	3.09	2.74
CO_2 emissions reduction from SubC PC (%)	-	10.95	21.03
Basis: 500 MWe net output			
^{1}(*)efficiency = 3414 Btu/kWh (heat rate); ^{2}using 85% operational availability			

Without taking into consideration any post combustion carbon capture technologies, the change from a 500MW SubC to USC plant operating at 85% capacity reduces carbon dioxide emissions by 21.03% in a year. If an average 20-year plant lifespan is considered, the potential carbon emissions saved is on the order of 14.6 million metric tonnes. This trend is also seen in a study completed at the Electrical Power Research Institute, where the increase in PC plant efficiency shows a significant percentage reduction in CO_2 emissions.

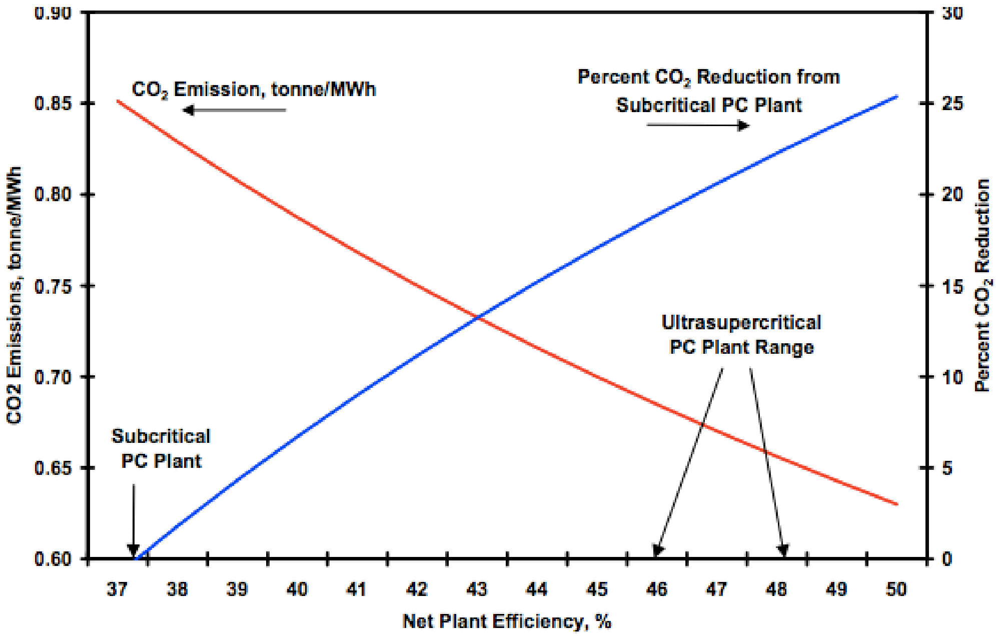

Figure 4: *EPRI study on the relationship between CO2 Emissions, CO2 Emissions reduction and PC plant efficiency. The study demonstrates the increase in the reduction of carbon dioxide emissions against the net plant efficiency. This is specifically relevant in the USC range (12).*

3.2 CSS Systems

3.2.1 Pre-combustion Carbon Capture (Integrated Gasification Combined Cycle)

When applying carbon capture technologies during pre-combustion in an Integrated gasification combined cycle emissions are significantly reduced at the cost of energy efficiency.

Table 4. *A comparison of efficiencies with and without pre-combustion capture for multiple CO2 solvents*

Solvent for CO2 capture	efficiency without capture	Emission	efficiency with capture	Δefficiency
	%	g/kWh	%	%
Glycol	36.6	227	33.2	3.4
Selexol	45.9	70	38.7	7.1
Selexol	45.9	146	40.44	5.42
Selexol	45.9	409	42.8	3.1
DEA–MDEA 25–25%	46.4	130	38.8	7.6
Methanol	43.5	112	34.6	8.9

The benefit of IGCC for CCS is its high efficiency, as seen in the table above (20). The loss of efficiency is still significant in most cases. The combination of IGCC and pre-combustion CCS is determined to be the most effective at mitigating efficiency loss for a significant reduction in CO2 emissions (21).

3.2.2 Oxy-fuel combustion

With the current limitations in CCS due to its infancy and also due to the materials limitations present, there is an efficiency penalty for the power generation of approximately 7-10% per system with the use of any of the analysed CCS systems (22). This is verified by the results of an air-fuel vs oxy-fuel ultra-supercritical power plant comparison conducted by the Global CCS Institute at the Electric Power Research Institute (16).

Table 5. *Oxy-fuel vs Air-fuel power generation comparison*

	Air-fuel (%)	Oxy-fuel (%)
Gross Generation (MW)	106	107*
ASU Power Use (MW)	-	14
CPU Power Use (MW)	-	9**
Other Power Use (MW)	6	7
Net Power Use (MW)	100	77
(*) Increased gross generation includes thermal recovery from ASU and CPU (**) CO2 delivered at 150 bar, 99.99+% purity		

As expected, all of the CCS auxiliary system used the CO2 Purification Unit(CPU as references in Table 5), there was a power generation penalty of between 7-10%. For the ASU the penalty was much higher due to the energy heavy cryogenic oxygen production method used. There are lower cost and lower energy dependant options such as chemical looping combustion and ion transport membrane methods (16). The nature of oxy-fuel combustion and its dependency on post-combustion capture, in order to be a fully rounded system means that the emissions are ultra-low. There are traces of SO_2, NO_x, and CO found in the systems after laboratory testing, these are due to boiler leakage and flame combustion instability and burnout (23). Long term material stability, flue gas equilibria and kinetic parameters of the carbon dioxide during combustion, concentrations of contaminants are many similar low-level issues present in current oxy-fuel combustion systems that demote it's rank as a currently viable retrofit option (2, 16).

3.3 Co-firing biomass and coal

The process of supplementing coal for a suitable biomass was found to degrade boiler efficiency across three different biomass types, as seen in Table 1 below. This is due to increased fouling of the boiler by biomass (24). A comprehensive exergy analysis revealed 77% of exergy destruction to be present within the boiler of an USC power plant (6). The resulting loss of boiler efficiency from co-firing biomass with coal is more impactful when it is made apparent how valuable the boiler can be for efficiency gains. It has been found that the biomass addition to coal would improve the combustion efficiency as a result of the lower CO concentrations and higher char burnout level in co-firing (25). Biomass absorbs carbon dioxide during growth, and emits it during combustion. Utilization of biomass as fuel for power production offers the advantage of a renewable and CO2-neutral fuel (26). The efficiency of all supply chains and reduction in efficiency of power generation implies that introduction of biomass does not lead to a more energy conserving or efficiency system, as well as not meeting viable emission reductions (17).

Table 6. *The reduction in boiler efficiency for 3 different biomass types between 0% and 20%*

	Type	0%	2%	5%	10%	20%
Boiler efficiency (24)	Wood	91.94	91.82	91.66	91.37	90.78
Boiler efficiency (24)	Straw	91.94	91.86	91.8	91.69	91.4
Boiler efficiency (24)	Dried sewage	91.94	91.61	91.18	90.66	89.82

3.4 Pre-drying

Pre-drying of lignite is an effective way of heavily increasing the efficiency of a coal-fired power plant that uses low-rank-coal. The table below quantifies the efficiency of each pre-drying method (27).

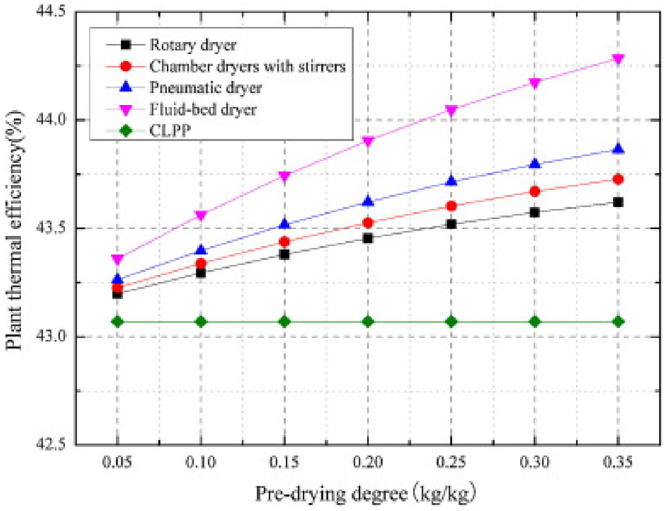

Figure 1. *Comparison of net efficiency improvement from different pre-drying methods (27)*

Evidently from the table above, there is already a desirable net efficiency improvement. Also seen from the table above, fluidised bed dryers are far more effective at increasing efficiency when compared to different methods of air drying. This is due to the energy penalty associated with the fans and heat exchangers involved in air drying (1). As the moisture content drops, the efficiency increases as seen below (1, 28).

Table 7. *Average change in efficiency at different moisture contents*

Drying type	Dried fuel moisture (%)	Δeff. (%)
Air drying	25	0.46
Fluidised bed	25	1.30
Fluidised bed	12	1.63

As well as increasing efficiency, pre-drying the lignite can reduce fuel consumption of the power plant as well, up to 20 wt%. When steam is extracted for the pre-drying process, the efficiency increase is met with a decrease in total output power. This suggests that retrofitting an existing lignite coal fired power plant with a steam pre-drying system is not viable and the addition of a pre-drying system on a new power plant is recommended (29).

4. Conclusions

In conclusion, this study has demonstrated the opportunity for the decrease in gross carbon dioxide emissions within CFPPs through the use of a wide range of technologies. Advanced PC combustion is a technology crucial improving any plant due to the increased combustibility of fine particles. This tech combined higher-grade steam cycles amount to the reduction in carbon emissions upwards of 20% and a net thermal efficiency nearing 48%. It is difficult and not worthwhile to retrofit pulverised coal facilities to existing power plants; any newly commissioned power plant should use PC combustion systems. Focusing on reduced emissions, CCS is the most effective method due to its near zero-emission quality and can be retrofitted to any existing CFPP designs. CCS systems reduce efficiency at the cost of reduced emissions, increase wear, stress and fatigue on system materials and are therefore expensive to retrofit at present. Though reducing system exergy, co-firing biomass with coal is widespread due to its reduction in CO emissions and a promising technology due to its lack of mechanical interference. It is not recommended as a retrofit option due to the reduction in efficiency and boiler fouling. Conversely, even with a net efficiency gain of 1.6%, pre-drying systems are difficult to retrofit to existing plants due to their mechanical interference. The recommendation for this technology is to invest research in external pre-drying or dewatering systems for plants running high moisture content coal such as lignite. All technologies analysed throughout this paper have evident advantages weighed evenly against disadvantages.

The technology with the most promise as a retrofit system to current plants is CCS, specifically oxy-fuel combustion when incorporated with a post-combustion carbon capture system due to its near zero-emission quality. For newly commissioned plants, CCS tech combined with a PC combustion system with materials able to withstand an advanced USC steam cycle, would reach efficiencies upwards of 50% whilst maintaining zero-emissions - i.e. the ideal scenario. To close, each technology must be investigated with respect to the individual coal fired power plant in question to determine the feasibility of being retrofitted. In the case of a new coal-fired power plant being built, most of these technologies, if not all, can be used to their fullest extent and are recommended.

Acknowledgments

We acknowledge the UTS Library support staff, ePress staff, guest lecturers, the subject tutors – Blake Regan and Liam Martin and finally the subject coordinator and lecturer – Dr. Jurgen Schulte for their support throughout the research and writing process.

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