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Hybrid coal-fired power plants with CO_2 capture: A technical and economic evaluation based on computational simulations

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ABSTRACT

Pulverized coal-fired (PC) power plants are the major technology used to generate electricity for power generation around the world. These processes are generally considered to make a significant contribution to global climate change since they have high CO_2 emissions, with the exception of those coal-fired power plants that employ CO_2 capture and storage (CCS) technology.

With regard to coal-fired power plants, two main options for capturing CO_2 from flue gases can be adopted, namely post-combustion and oxy-fuel combustion systems. The former technology option separates CO_2 from the flue gas generated by the combustion of coal with air. For chemical absorption, generally a solvent such as MEA is used. However, there is a serious concern about the energy consumption required for regeneration of the solvent MEA. Oxy-fuel combustion systems, on the other hand, involve separating the oxygen from air and then burning the coal in a mixture of pure oxygen and recycled flue gas. This approach reduces the amount of flue gas substantially and simplifies the separation process due to the absence of nitrogen and argon in the stream. However there are some drawbacks in connection with some components, such as air separation units (ASU), which require high capital and operating costs and are energy intensive.

A new idea was proposed by Zanganeh et al. [1]. This was a hybrid of oxy-combustion and post-combustion capture and would use air with O_2 enrichment. Such PC power stations would use an ASU plant to obtain O_2 enrichment and would still require the CO_2 purification and compression processes. The ASU plant would be smaller than for oxy-fuel and the CO_2 purification and compression systems would be smaller than for air-firing. This paper is to evaluate the proposed process technically and economically based on detailed simulation. The hybrid coal-fired power plant with CO_2 capture system has the potential advantage of reducing energy consumption and costs. To explore the advantages and disadvantages of the hybrid process with CO_2 capture, a comparative analysis of the supercritical PC power plant is carried out. The technical design and the mass and energy balances are implemented by using the ECLIPSE simulation package.

1. Introduction

There is a great deal of concern about global warming and the potential catastrophic effect that this could have on the environment. According to the Intergovernmental Panel on Climate Change (IPCC) reports [2] the major cause which contributes to global climate changes is carbon dioxide (CO_2) emissions, an important greenhouse gas (GHG). There are enormous sources of natural CO_2 but manmade emissions represent a significant addition. Many climate scientists believe that the main source of the increase in global CO_2 emissions is from the combustion of fossil fuels [3]. Power generation systems are major users of fossil fuels and the demand for electricity is growing steadily throughout the developed world and exponentially in the less developed countries. Therefore in order to reduce global CO_2 emissions from today's fossil fired power stations, short-term commitments can be met through the replacement of aging and inefficient power plants by pursuing state of the art technologies with more efficient energy conversion rates. For the longer term, carbon dioxide capture and

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storage (CCS) has been recognized as an important technology to reduce greenhouse gas emissions significantly [4].

Since the capture and storage of CO_2 is recognized as a promising and relatively quick solution to reduce global CO_2 emissions, which again enables power generators to continue tapping remaining fossil fuel reserves, there are considerable number of international collaborations to establish coal-based technologies that minimize CO_2 emissions without significantly increasing the costs [2]. Regarding the pulverized coal-fired (PC) power plants, there are two leading technologies currently proposed to control CO_2 emissions, namely post-combustion and oxy-fuel combustion systems. Post-combustion CO_2 capture systems separate CO_2 from the flue gas generated by the combustion of coal with air. For chemical absorption, generally a solvent such as MEA is used. However, there is a serious concern about the energy consumption required for regeneration of the solvents. Oxy-fuel combustion systems, on the other hand, involve separating the oxygen from the air and burning the coal in a mixture of pure oxygen and recycled flue gas. This approach reduces the amount of flue gas substantially and simplifies the separation process due to the absence of nitrogen and argon in the stream. However there are some drawbacks in connection with some components, such as air separation units (ASU), which require high capital and operating costs and are energy intensive.

The hybrid coal-fired power plant with CO_2 capture system, as proposed by Zanganeh and Shafeen [1] and by Doukelis et al. [5] is a combination of enhanced O_2 combustion and a CO_2 processing unit (CPU). Such PC power plants would use an ASU plant to obtain O_2-enrichment and would still require the CPU and compression processes [6]. The ASU plant would be smaller than for oxy-fuel and the CO_2 purification and compression systems would be smaller than for air-firing. This paper is to evaluate the proposed process technically and economically based on detailed simulation. The hybrid CO_2 capture system has the potential advantage of reducing energy consumption and costs. To explore the advantages and disadvantages of the hybrid process with CO_2 capture, a comparative analysis of the advanced supercritical PC (ASPC) power plant is carried out. The technical design, the mass and energy balances, and the optimization technologies are implemented by using the ECLIPSE [7] simulation package.

2. Methodology

For the assessment of the selected plant, the ECLIPSE process simulation package, as shown in Fig. 1, is used. This software was initially intended for the use of coal liquefaction research projects of the European Commission. However, since its development, it has been used for simulating many different chemical and engineering processes. Through a large number of real industrial process simulations, ECLIPSE has been validated over the years and gained recognition worldwide among research institutes, governments and industrial companies for the techno-economic analysis of power plants. The verification of the performance of ECLIPSE is found in many projects and research activities such as the JOULE clean coal technology programme [8] or advanced coal fired utility boilers [9], where the ECLIPSE simulation package is described in more detail [22].

At the initial stage, process flow diagrams composed of modules and streams are generated within ECLIPSE. After specifying the stream inputs and technical features of individual modules, the mass and energy balance is determined via enthalpy calculations for each stream. This is achieved by converging the information specified in the compound database, as well as in the input streams and modules. The latter contains details such as efficiencies, stream manipulations and splits in reference to individual power plant components with the exception of chemical reactors, whose output streams are specified through the yield and elemental balance. The information gained during this second stage of simulation forms the base for identifying critical components within the plants that may be subjected to extreme physical and chemical exposure conditions. In the third stage, the package computes the amount of energy consumed by individual utilities and compounds and provides the power plant net output. This simulation module has access to a utility database, which predominantly contains information about the process utility systems, the electricity supply options and the mechanical efficiency of integrated modules such as turbines, pumps and compressors.

Finally, the economic viability of the examined systems is evaluated. Whilst every effort is made to validate the capital cost estimation data, using published information and actual quotations from equipment vendors, the absolute accuracy of this type

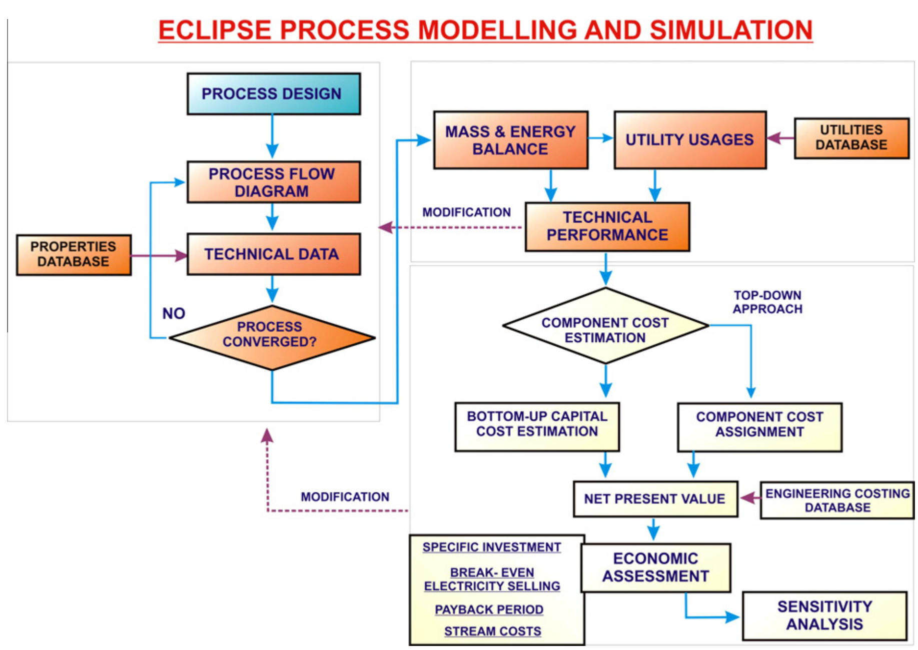

Fig. 1. ECLIPSE process modelling and simulation.

of capital cost estimation procedure has been estimated at about ± 25–30%. However, although the absolute accuracy of a single cost estimate may be only ±25–30%, what has been done in these studies is to compare families of similar technologies, composed of similar types of equipment. Therefore, the comparative capital cost estimates, which are based on the accurate calculation of a difference in a basic design by the mass and energy balance program, should be valid.

3. Simulation scenarios

The criteria for selecting potential CO_2 capture options are based on techno-economic factors defining the key characteristics such as commercial power plant viability, minimum cost increase relative to a selected base case technology without a CO_2 capture coupled with the maximum reduction in specific CO_2 emissions and the degree of confidence which can be placed in the emissions reduction, both in the short- and long-term. In each case, the likely capital expenditures along with operating and fuel costs for the power plant with and without the CO_2 capture additions will be determined. From this, the marginal cost arising from the addition of CO_2 capture [10] can be determined. The selected cases are as follows:

Case study 1: Reference air-fired ASPC plant without CO_2 capture.
Case study 2: Air-fired ASPC plant with the full scale cryogenic CO_2 capture.
Case study 3: ASPC plant with the full scale oxy-fuel based CO_2 capture.
Case study 4: ASPC plant with the hybrid enhanced O_2 method for CO_2 capture:

- A: 10% air addition.
- B: 20% air addition.
- C: 30% air addition.
- D: 40% air addition.
- E: 50% air addition.

The current analysis is based on cryogenic CO_2 capture for consistency with the earlier work of Zanganeh and Shafeen [1]. The parameter used to define the cases in this study is the '% air addition'. This is defined as the actual air (as opposed to ASU output) entering the furnace. The feedstock chosen in this study is the American Federal coal which serves as a reference fuel [11]. Table 1 contains the basic properties of this coal type, which is used in the ASPC system simulation. Relative to other coal types, Federal coal has a medium calorific value, a low moisture content and a low ash content. The sulphur content, on the other hand, is relatively high. The key economic factors and indices [12] as used in this assessment are given in Table 2. With regard to the ASU oxygen output, an oxygen purity of 95% by volume is assumed [13,14] for both the oxy-fuel combustion and the hybrid carbon capture system. This information serves as a basis for estimating the energy requirement for the air separation unit.

Table 1
Coal analysis.

Moisture	(wt.%, ar)	6.3
Ash	(wt.%, db)	6.6
Heating value	MJ kg^{-1} (LHV, daf)	34.4
Ultimate analysis		
Carbon	(wt.%, daf)	84.0
Hydrogen	(wt.%, daf)	5.7
Oxygen	(wt.%, daf)	6.1
Nitrogen	(wt.%, daf)	1.5
Sulphur	(wt.%, daf)	2.6
Chlorine	(wt.%, daf)	0.1

Table 2
Economic factor and indices.

Construction time (years)	3
Discounted cash flow rate (%)	8
Owner's cost (% EPC)	15
Capital allocation during construction time (%/year)	40/40/20
Project contingencies (% TCI[a])	10
Plant occupancy (%, first year)	50
Plant occupancy (%, rest year of plant life)	85
Plant life (years)	25
Operating cost (% TCI)	2.0
Maintenance cost (% TCI)	3.0
Insurance cost (% TCI)	1.5
Coal price (€/GJ) LHV basis	1.6

[a] TCI: total capital investment.

4. Technical description

4.1. Base air-fired supercritical PC plant case without CO_2 capture

The base cycle is an 800 MWe supercritical PC power plant with flue gas desulphurization (FGD), as shown in Fig. 2. The general cycle information is given in Table 3. Normal coal storage facilities are provided from where the coal is pulverized in mills and then pneumatically transferred using preheated primary air to a two pass once through boiler, with a spirally wound single furnace and tangentially fired low NO_x burners. Most of the unburned coal and ash is removed at the base of the furnace, with the rest carried forward with the hot gases and removed in cold-side electrostatic precipitators. Before reaching these electrostatic precipitators the hot gases are cooled first by transferring heat to steam in the super-heater tubes and the re-heater tubes, then by transferring heat to condensate in the economizer section and finally by transferring heat to combustion air in the air pre-heater section.

The steam cycle is a supercritical single reheat system. The steam that leaves the super-heater is sent to the turbine stop valve. It is then expanded in the high pressure turbine. The steam turbines have facilities for steam extraction and allow for steam to be tapped off to the regenerative feed-water heaters. Drains from the three high pressure feed-water heaters are fed to the deaerator. The steam from the high pressure turbine is then reheated before passing through one double flow intermediate pressure and three double flow low pressure turbines. At the crossover from the intermediate to the low pressure turbines steam is extracted for the deaerator. The steam from the low pressure turbine is condensed and the condensate is pumped through the four low pressure feed-water heaters to the deaerator. Drains from the four low pressure feed-water heaters are pumped in with the condensate feed. From the deaerator tank the boiler feed pump forces the condensate through the three high pressure surface-type feed-water heaters and the economizer before entering the boiler and completing the steam cycle.

The cooled flue gases are exhausted via the induced draught fan to a wet limestone FGD system where most of the SO_2 is removed. The flue gas from the electrostatic precipitators is first cooled against the clean gas and then fed to the base of the spray tower. Limestone solution is circulated through the sprays in the tower and the SO_2 in the flue gas reacts to form calcium sulphite. In the base of the spray tower the calcium sulphite is oxidized to gypsum which then settles out. The gypsum solution is pumped through a hydrocyclone and then fed onto a filter table where most of the water and impurities are removed. The gypsum is then ready for sale for use in plasterboard manufacture and the wastewater is

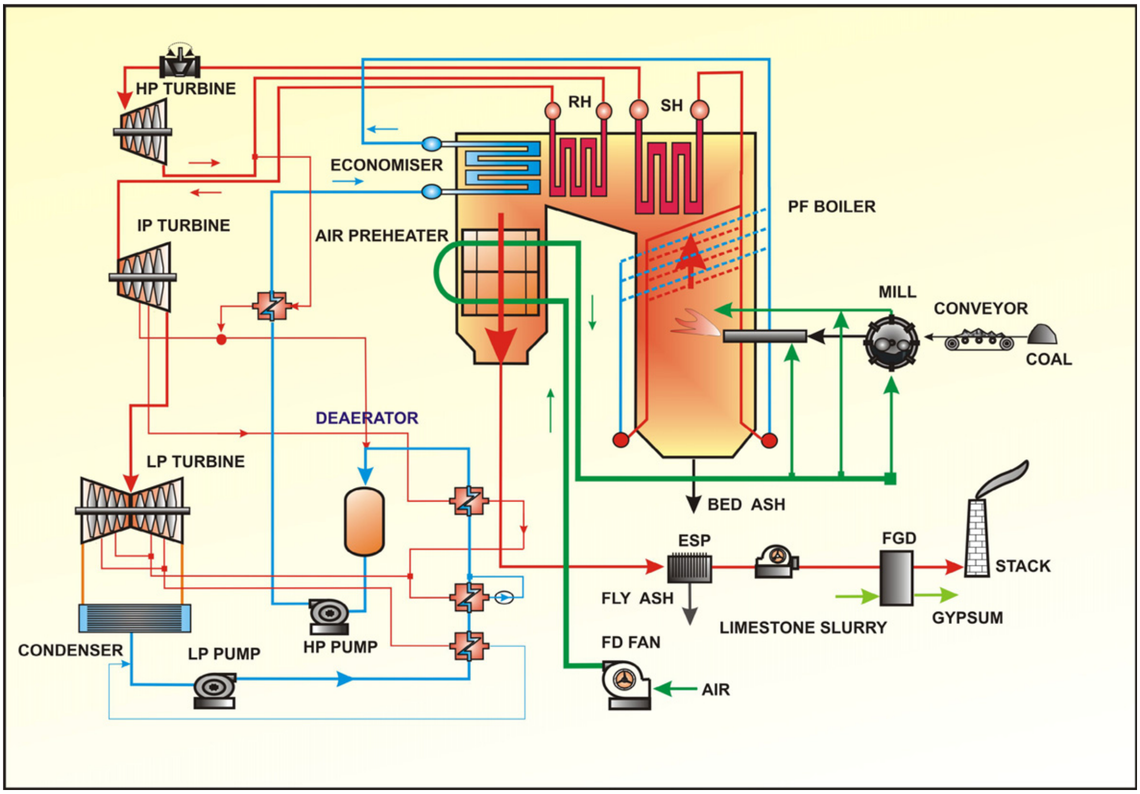

Fig. 2. Schematic diagram of the ASPC plant without CO_2 capture.

Table 3
General technical details of the advanced supercritical PC plant.

	Advanced supercritical PC plant
Excess air (%)	15
Air/O_2 pre-heater (°C)	170
Super-heater pressure (bar)	290
Super-heater temperature (°C)	600
Re-heater pressure (bar)	60
Re-heater temperature (°C)	622
Economizer exit temperature (°C)	340
Isentropic efficiency of turbine (%)	81–91
Condenser pressure (bar)	0.048
Deaerator pressure (bar)	11.8
Pump volumetric efficiencies (%)	85–90
Fan/comp. polytropic efficiencies (%)	78
Removal of sulphur dioxide (SO_2) (%)	95

treated to separate the impurities. The clean gas is then reheated before being vented up the stack to the atmosphere.

4.2. Oxy-fuel based supercritical pulverized coal boiler with CO_2 capture

The principle of oxy-fuel combustion in a PC boiler can be seen in Fig. 3. The oxy-fuel process, where the combustion air is replaced with oxygen supplied by the ASU, burns the fuel in a mixture of oxygen and recycled flue gases to produce a CO_2-rich flue gas [13]. The oxy-fuel combustion is associated with higher temperatures compared with conventional air-firing. The heat control mechanism is governed by means of flue gas recirculation. The proportion of flue gases recycled is adjusted in order to keep the temperature profile equivalent to those of air-fired boilers. At the same time, the excess oxygen levels are optimized to ensure complete combustion of the fuel in the boiler. Since nearly pure oxygen (greater than 95%) is used for combustion the flue gas stream consists mainly of CO_2 and water vapour together with a small concentration of inert gases and nitrogen. Taking into account the effect of removing the nitrogen when operating an oxy-fuel combustion boiler where the partial pressures of acidic gases are increased, resulting in a high acid dew-point, we may not need both FGD and SCR for oxy-fuel combustion capture [15]. In the case of a very low level of SO_x concentration in the CO_2 stream specified, a FGD could be deployed before the CPU. However this arrangement results in an additional drop in efficiency. The water vapour may be removed from the flue gas by a cooling system. As a result, only simple gas purification is required to deal with captured CO_2 in the process [16], which is relatively inexpensive. The purified CO_2 gas is then compressed and liquefied ready for delivery to storage.

4.3. The arrangement for the hybrid (i.e. enhanced O_2) CO_2 capture plant

Using the oxy-fuel combustion technology for CO_2 capture, very large quantities of oxygen are required to complete the combustion in the furnace. This results in high capital and operating costs of ASU. In order to remove the economic constraints on the oxy-fuel combustion systems, a hybrid process as an alternative option is proposed to lower the energy demand of oxygen production. The hybrid carbon capture system, as shown in Fig. 4, is based on the combination of the partial oxy-fuel mode and the post-combustion CO_2 capture. The ASU would provide part of the O_2 requirements, and the rest would come with the air. Compared to oxy-fuel combustion, this option would need less O_2 from ASU, and have lower gas temperature. As a result, a smaller ASU capacity is required, which reduces both operating and capital costs sharply. Furthermore, the lower gas temperature in the furnace reduces the consumption of power for the flue gas recirculation. Particularly, due to a lower CO_2 concentration in the flue gas than oxy-fuel

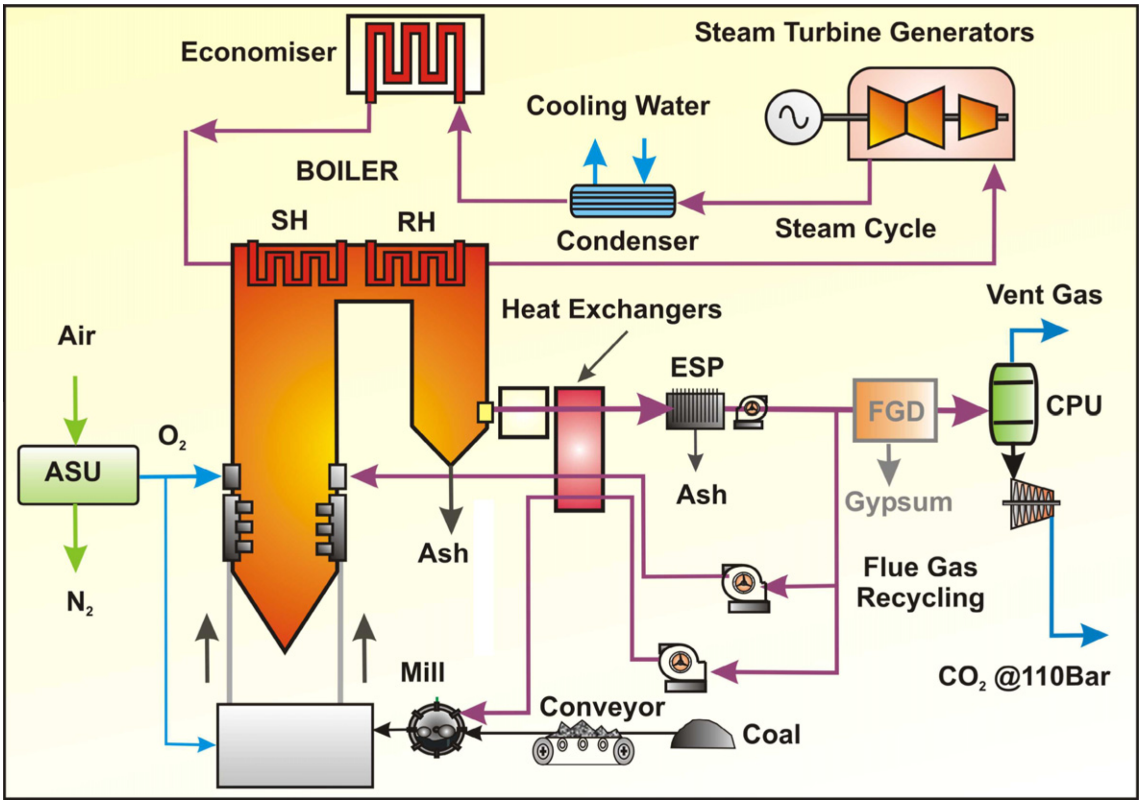

Fig. 3. .Schematic diagram of the oxy-fuel-based ASPC boiler with CO_2 capture.

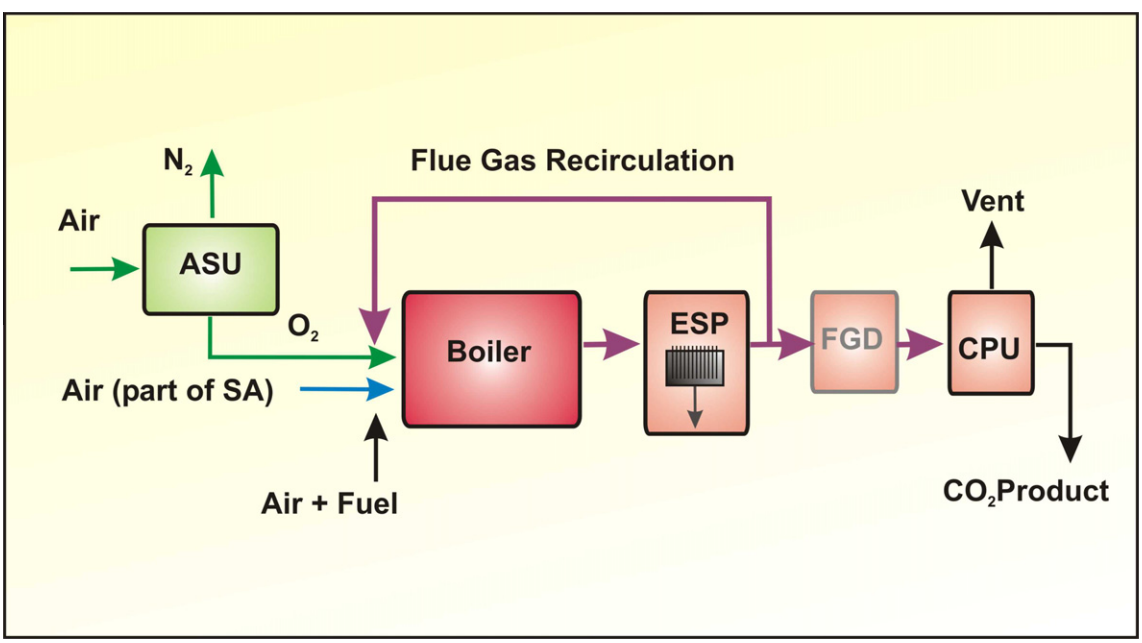

Fig. 4. Schematic diagram of a hybrid (i.e. O_2 enhanced) CO_2 capture plant.

combustion, air ingress would be less of a problem than in systems with oxy-fuel combustions. In addition, safety issues related to mills and pulverized coal transport are also not required to be so stringent [1]. On the other hand, the higher CO_2 concentration in the flue gas mass flow compared to the post-combustion system using a conventional air-firing, the oxy-fuel cycles would be smaller resulting in lower power demands. For this arrangement there are three inlet streams: (a) air, (b) recycled flue gas and (c) oxygen. Primary air composed of ambient air carries coal from the mill to the boiler. The secondary air composed of oxygen and recycled gas forms what would be the actual secondary air in an air-firing boiler. It is added directly in the furnace around the burner.

4.4. CO_2 purification and compression process

With both oxy-fuel combustion and the hybrid enhanced O_2 approach to CO_2 capture processes a certain amount of the CO_2-rich exhaust gas would be recycled back to the boiler. The remaining part of the flue gas consists mainly of CO_2, water vapour, some quantities of nitrogen, oxygen, argon, acidic gases and various other trace impurities. Before the CO_2 stream is introduced into transportation process, it will be purified to the levels required to avoid two-phase flow conditions in the pipelines [17] and then liquefied by using a cryogenic purification and compression process. The carbon dioxide separation and liquefaction with a cryogenic purification unit are based on the physics of condensation through a series of compression, cooling and expansion steps, as shown in Fig. 5 [18]. The first step of this technique consists of drying the flue gas by simple condensation, where the water content, ash and dissolved gases are removed from the flue gas stream. Thereafter, the flue gas is compressed in a dual bed desiccant drier to reduce the moisture content. The dry gas is then passed to a cryogenic distillation unit, where most of inert gases from the CO_2 are removed using CO_2 refrigeration. The separated inert gases can be heated and expanded through a turbine to produce additional power and thus improve the overall efficiency. At the final stage the purified CO_2 product is further compressed to a pressure of about 110 bar in the liquid form for transport through pipelines.

5. Plant performance, emissions, and economic analyses

The ECLIPSE process simulator has been successfully used to perform technical, environmental, and economic analyses for all the case studies. The fuel definition is summarized in Table 1,

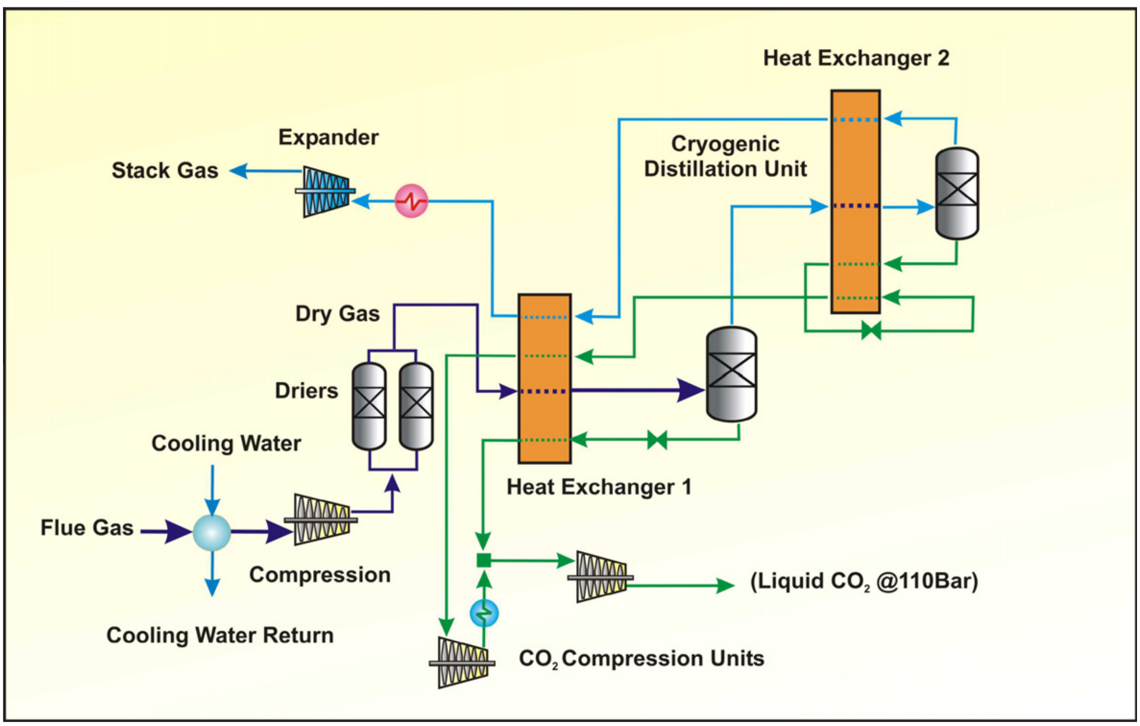

Fig. 5. Schematic diagram of the CO_2 purification and compression unit.

Table 4
Technical performance of chosen cases.

	Case 1	Case 2	Case 3	Case 4A	Case 4B	Case 4C	Case 4D	Case 4E
	Base case	Cryogenic CO_2 capture	Air addition (oxy-fuel or enhanced O_2 approach to CO_2 capture)					
			0% (oxy-fuel)	10%	20%	30%	40%	50%
Thermal input (MW) LHV	1849.80	2196.20	1849.80	1849.80	1849.80	1849.80	1849.80	1849.80
Power consumption (MWe)								
Air separation unit			118.41	108.11	97.81	87.50	77.20	66.90
Flue gas desulphurization	12.80	12.80						
CO_2 Compression/purification		263.52	76.10	83.50	93.88	107.24	123.58	142.90
Auxiliary power usages on site	64.95	64.95	61.65	61.55	61.48	61.42	61.37	61.32
Total auxiliary power consumption	77.75	341.27	256.55	255.67	256.80	259.96	265.12	272.28
Power production (MWe)								
Steam turbine output	903.66	903.66	926.83	924.93	923.03	921.13	919.23	917.33
Net electricity production (MWe)	825.91	562.39	670.28	669.27	666.23	661.18	654.12	645.05
Overall plant efficiency % (LHV)	44.65	30.40	36.24	36.18	36.02	35.74	35.36	34.87
Overall efficiency reduction, % due to CO_2 capture		14.25	8.41	8.47	8.63	8.91	9.29	9.78
CO_2 emission factor (g CO_2/kW h)	782.88	56.84	47.69	47.76	47.98	48.35	48.87	49.56

Table 5
Economic assessment for both the ASPC plants with and without CO_2 capture.

	Case 1	Case 2	Case 3	Case 4A	Case 4B	Case 4C	Case 4D	Case 4E
	Base case	Cryogenic CO_2 capture	Air addition (oxy-fuel or enhanced O_2 approach to CO_2 capture)					
			0% (oxy-fuel)	10%	20%	30%	40%	50%
ASU cost, M€	0.0	0.0	245.0	227.6	209.6	190.9	171.4	150.8
CPU cost, M€	0.0	211.8	135.0	143.6	152.0	160.1	168.0	175.7
ASU share of total EPC, %	0.0	0.0	18.6	17.4	16.2	14.9	13.5	12.0
CPU share of total EPC, %	0.0	17.8	10.3	11.0	11.7	12.5	13.2	13.9
Total EPC, M€	985.8	1193.0	1314.3	1305.0	1295.2	1284.6	1273.3	1261.1
Owner cost, M€	147.9	179.0	197.1	195.8	194.3	192.7	191.0	189.2
Total capital investment, M€ (excluding contingencies)	1133.6	1372.0	1511.4	1500.8	1489.5	1477.3	1464.2	1450.3
Total capital investment, M€ (including contingencies)	1232.2	1491.3	1642.8	1631.3	1619.0	1605.8	1591.6	1576.4
Specific investment, €/kWe (gross)	1254.5	1518.3	1630.7	1622.6	1613.7	1603.8	1592.9	1581.0
Specific investment, €/kWe (net)	1372.6	2439.6	2254.9	2242.5	2235.6	2234.4	2238.5	2248.4
BESP (€/MW h)	46.9	79.3	71.7	71.4	71.3	71.4	71.7	72.5
Breakdowns of BESP, %								
Fuel component	27.7	24.1	22.4	22.5	22.6	22.8	22.9	23.1
CapEx component	49.6	52.2	53.4	53.3	53.2	53.1	53.0	52.9
No fuel OpEx component	22.6	23.8	24.3	24.2	24.2	24.2	24.1	24.1
Extra cost due to CO_2 capture (€/MW h)		32.4	24.8	24.5	24.4	24.5	24.8	25.6
CO_2 avoidance cost (€/tonne)		44.6	33.7	33.3	33.2	33.4	33.8	34.9

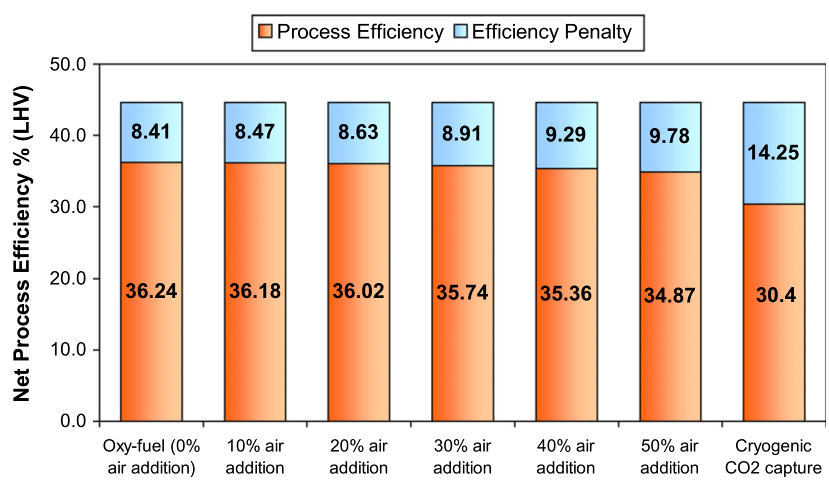

Fig. 6. Plant efficiency, showing efficiency penalty of the oxy-fuel or enhanced O_2 approaches to with CO_2 capture.

and the economic factors and indices used are summarized in Table 2. The main results are illustrated in Tables 4 and 5. Further results, such as the overall thermal efficiency, CO_2 emissions, process capital cost, and breakeven electricity selling price are displayed in Figs. 6–9.

The main criteria [19,20] that have been used for comparing the economic performance of ASPC plants are the total capital investment, the specific capital cost (€/kWe), and the breakeven electricity selling price. The total capital investment is the engineering and procurement cost of building the power plant, starting from a 'green field' site, including the normal infrastructure that would be contained within the boundary. Added to this is an allowance for the working capital, capital fees, and contingencies. Since the information available on capital and operating costs is limited, and although every effort is made to validate the capital cost estimation using published information and actual quotations from equipment vendors, the absolute accuracy of this type of cost estimation procedure has been estimated at about ±30% [9]. The calculation of the specific capital investment is a function of the electricity production or electricity sent out. The breakeven electricity selling price is the value that the generator must charge for the electricity that is sent out to the grid in order to achieve a net present value of zero over the lifetime of the power plant.

5.1. Case study 1: reference ASPC plant without CO_2 capture

From the detailed results shown in Tables 4 and 5, it can be seen that the thermal input of the ASPC reference case is 1850 MW t h (LHV), which is equivalent to a coal feed of 265 tonnes/h (as received basis). The power produced from the steam turbine is 904 MWe. With the plant auxiliaries adding up to 78 MWe, this gives a net power output of 826 MWe and an efficiency of 44.7% (LHV). Table 4 also indicates that the CO_2 emissions are 783 g/kW h. The total capital cost is estimated at 1232.2 M€ (inc. contingencies), which is equivalent to a specific capital investment of €1373/kWe (net). Using a reference coal price of €1.6/GJ, a BESP of €46.9/MW h is calculated according to NPV computation over the lifetime of the plant.

5.2. Case study 2: air-fired ASPC plants with a full scale cryogenic CO_2 capture

Tables 4 and 5 indicate the results for the options of the cryogenic and oxy-fuel CO_2 capture plants. In order to maintain a similar range of the plant gross output as the reference study, the thermal input is still set to 1850 MW t h. For case study 2 (cryogenic CO_2 capture), the power produced from the steam turbine

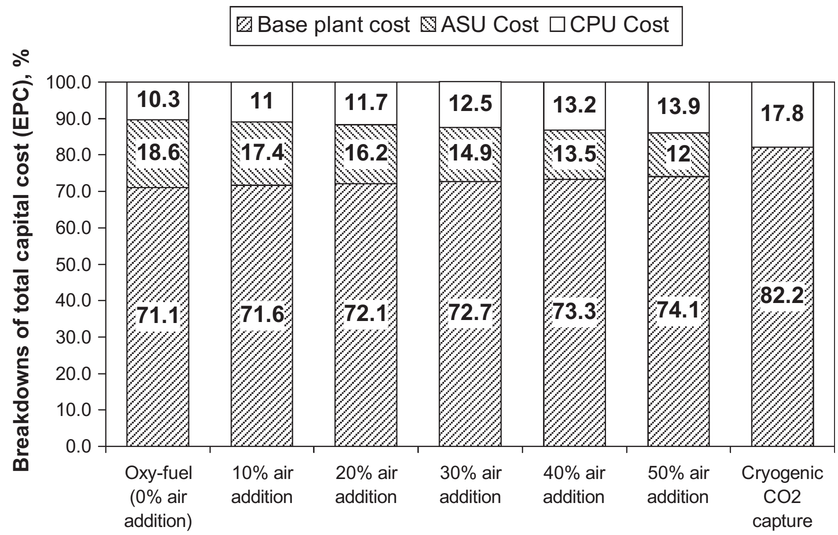

Fig. 7. Breakdowns of capital costs.

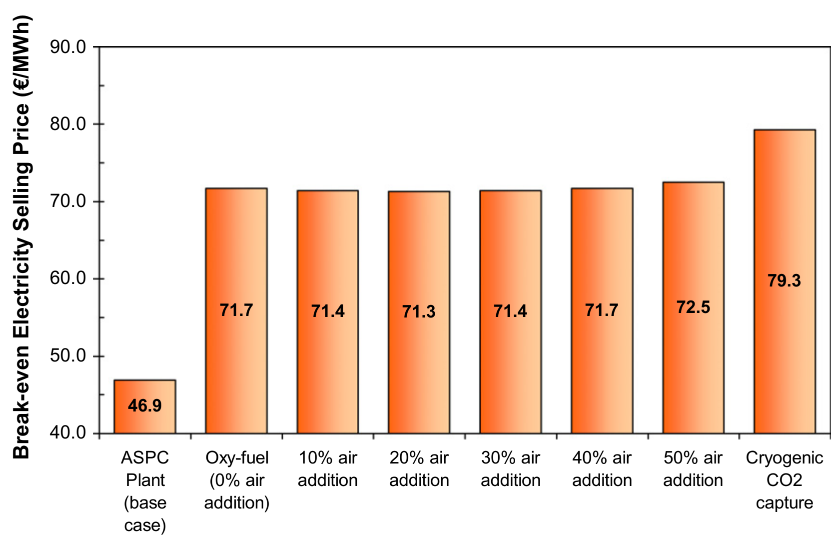

Fig. 8. Comparison of breakeven electricity selling price (BESP).

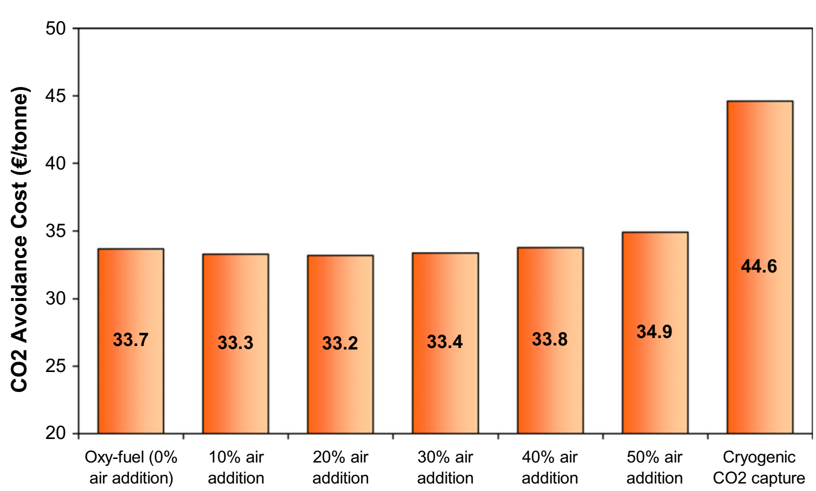

Fig. 9. Comparison of CO_2 capture avoidance cost relative to the reference case.

is 904 MWe. With the plant auxiliaries adding up to 341 MWe, this gives a net power output of 562 MWe and an efficiency of 30.4% (LHV). Compared with the reference case the total efficiency loss for CO_2 capture with the full scale cryogenic separation is predicted to be 14.25 points, which is higher than the MEA process [12]. Since the concentration of CO_2 in flue gas is about 15% and the energy used to compress the rest 85% of flue gas is significantly intensive. Therefore the cryogenic separation should not be used from dilute CO_2 streams. The CO_2 emissions are considerably lower than those of conventional systems without a CO_2 capture facilities resulting in a low value at around 57 g/kW h. As a result, the total capital cost is increased to 1491.3 M€ (inc. contingencies), giving a specific capital investment of €2440/kWe (net), which is significantly higher than for case study 1, due mainly to its poor efficiency. If coal cost of €1.6/GJ is still assumed, a BESP of €79.3/MW h is estimated.

5.3. Case study 3: ASPC plant with the full scale oxy-fuel based CO_2 capture

For case study 3 (oxy-fuel based power plant with CO_2 capture), the power produced from the steam turbine goes up to 927 MWe at the same level of the thermal input as reference case. With the plant auxiliaries adding up to 257 MWe, this gives a net power output of 670 MWe and an efficiency of 36.2% (LHV). CO_2 emissions are slightly lower at 48 g/kW h than case study 2. The total capital cost is estimated at 1642.8 M€ (inc. contingencies) but gives a specific capital investment of €2255/kWe (net), which is lower than that for case study 2. If coal cost of €1.6/GJ is still assumed, it gives a BESP of €71.7/MW h. Because of the CO_2 capture introduced to chosen systems for case studies 2 and 3, the CO_2 avoidance costs are 44.6 and 33.7€/tonne, respectively, relative to the reference plant without CO_2 capture.

5.4. Case study 4: ASPC plant with the hybrid enhanced O_2 approach for CO_2 capture

In case study 4, the overall power plant efficiency decreases in response to the additional air intakes. Fig. 6 shows the relationship between plant efficiency and the proportion of air introduced to the boiler. In comparison with the full scale oxy-fuel based CO_2 capture case (case study 3), case 4A displays a 0.06% (LHV) reduction of net efficiency when air addition rises from 0% to 10%. Further increase in air supply results in a rise in overall plant efficiency losses. For example, varying the air addition ratio from 10% to 50%, the net plant power output decreases from 669.3 MWe to 645.1 MWe, resulting in efficiency losses up to 1.37 point-% versus the full scale oxy-fuel case at a same level of the thermal input. With 1.37 point-% efficiency drop, case study 4E reflects the relative significance and quantities of nitrogen content present in the flue gas stream. Since the CO_2 processing unit uses a cryogenic CO_2 separation, an even greater quantity of inert gases is fed to the compressor compared to the oxy-fuel power plant with CO_2 capture (Case 3). As a result, it is not surprising that more auxiliary compression power is incurred in order to effect the inert gas removal.

The capital cost comparison of all the hybrid enhanced O_2 approaches to CO_2 capture (Case studies 4A–4E) is illustrated in Fig. 7. When the air additions are incorporated from 0% to 50%, the total capital costs decrease from 1642.8 M€ to 1576.4 M€, which gives a reduction in capital cost of about 4%. This drop in capital cost for the hybrid CO_2 capture process is due to the reduction in ASU capacity with the proportion of air addition even with the increase of CPU size. Similarly, the minimum specific investment (gross) is reduced from €1631/kWe to €1581/kWe. The net specific investment changes from €2255/kWe to €2248/kWe, which means that the reduction ratio in net specific investment is much lower than that of gross specific investment, due mainly to the reduction of its net power production. Considering the assumptions stipulated in this work, the BESP varies between €71.7/kW h to €72.5/kW h when the percentage of air input is changed. The CO_2 avoidance cost ranges between 33.7 and 34.9€/tonne when compared with the reference plant without CO_2 capture.

Figs. 8 and 9 demonstrate that there is little impact on BESP and the CO_2 avoidance cost from the percentage of air addition between 0% and 40%. In other words, if we consider a CO_2 capture operation for an ASPC power plant using a partial oxy-fuel mode with up to 40% air addition, it is possible to get nearly the same economic performance characteristics as that of a full scale oxy-fuel capture system. On the other hand, the specific investment of ASCP with CO_2 capture can be improved using the hybrid system.

According to the above analysis, a full cryogenic CO_2 separation system is not techno-economically viable and should not be selected for an option where the CO_2/flue gas ratio is below a certain level as in the case of air fired systems. The cryogenic option starts becoming an attractive alternative to an oxy-fuel system if the CO_2 concentration level in the gas stream exceeds a certain level. This level was achieved in this work at a volumetric CO_2 percentage above 45%, which corresponds to oxy-fuel hybrid systems with up to 30% air addition. The inadequate techno-economic performance attributes of the hybrid systems with air addition rates above 30% are mainly due to the existence of a more diluted CO_2 stream and higher flue gas mass flow rates. In comparison to the work done by Zanganeh and Shafeen [1], where the net power output decreases linearly in relation to increased air addition levels, the values found in this study did not behave entirely linearly. The net power output decreases slightly when 10% air is introduced to the system. Above this point, the plant output starts to decrease rapidly. This could be due to different air leakage rates. A preliminary study done by Stephenson et al. [21] shows that the net energy production of a hybrid system is inferior to an amine based post-combustion or complete oxy-fuel systems. The values were however scaled to a level comparable to the work done by Zanganeh and Shafeen [1].

Most current work is limited to technical assessments of power plant output and ignores the economic significance of such a system. The economic assessment in this study shows that increasing the air intake would cause a more positive influence on the economics than it would do on the technical performance characteristics. Best economic values are found for an air addition of between 20% and 30%.

6. Conclusions

The techno-economic evaluation of the ASPC plants in connection with CO_2 capture facilities was implemented in this paper using the ECLIPSE process simulation package. All of the CO_2 capture cases result in large decreases in thermal efficiency with significant cost penalties in terms of both specific investment and levelized cost of electricity. One reason why the full scale oxy-fuel plant with CO_2 capture shows better efficiency than air-firing plus post-combustion capture is that the current modelling based on cryogenic CO_2 capture plant requires a very high compression power due to the presence of nitrogen in the flue gas. The enhanced O_2 and straight air-firing cases would have efficiencies closer to that for oxy-fuel. The full scale oxy-fuel option needs more capital investment than the cryogenic CO_2 capture system because the former needs three components: (a) ASU, (b) flue gas recirculation, and (c) CO_2 compression and the latter only requires a CO_2

processing unit (CPU). Combining the two systems in a hybrid enhanced O_2 capture system has beneficial results both reducing the efficiency penalties and the cost.

Based on the above explanation, it can be concluded that:

- It is technically and economically feasible to use the hybrid enhanced O_2 approach to capture CO_2 for the partial oxy-fuel combustion power plant.
- The hybrid system needs less auxiliary power from the ASU and flue gas recycle fans but consumes more energy for the CPU than the pure oxy-fuel combustion CO_2 capture.
- The process efficiency of hybrid process is higher than that of full scale cryogenic post-combustion CO_2 capture processes, but is slightly lower than that of the full scale oxy-fuel based CO_2 capture configuration.
- The CO_2 emissions for all these case studies are around 50 g CO_2/kW h, and no significant differences are found.
- The efficiency of hybrid process is only negligibly affected by changing the air addition from 0% to 30%. From the efficiency point of view this percentage would be the optimum amount of air addition.
- The hybrid mode would be beneficial to the economic performance of the ASPC power plants with CO_2 capture. Increasing air addition from 0% to 30% will reduce not only the capital cost by 2.3%, but the specific investment, while the BESP and CO_2 avoidance cost are at the same level as the full scale oxy-fuel power plant with CO_2 capture.

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