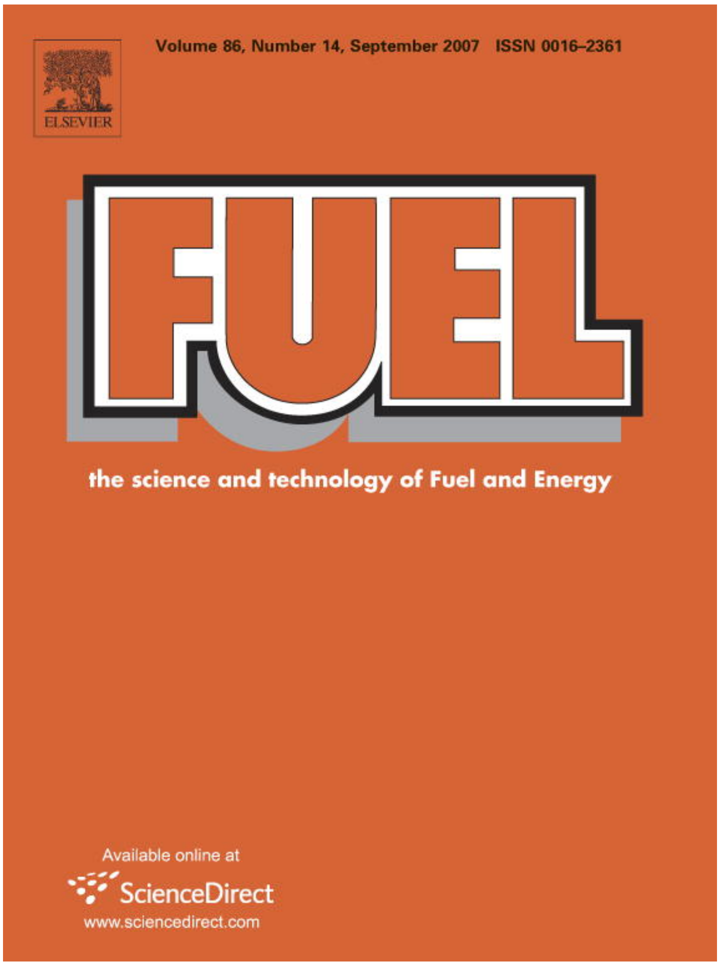
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Comparative assessment of sub-critical versus advanced super-critical oxyfuel fired PF boilers with CO_2 sequestration facilities

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Abstract

This work focuses on the techno-economic assessment of bituminous coal fired sub- and super-critical pulverised fuel boilers from an oxyfuel based CO_2 capture point of view. At the initial stage, two conventional power plants with a nominal power output of above 600 MWe based on the above steam cycles are designed, simulated and optimised. Built upon these technologies, CO_2 capture facilities are incorporated within the base plants resulting in a nominal power output of 500 MWe. In this manner, some sensible heat generated in the air separation unit and the CO_2 capture train can be redirected to the steam cycle resulting in a higher plant efficiency. The simulation results of conventional sub- and super-critical plants are compared with their CO_2 capture counterparts to disclose the effect of sequestration on the overall system performance attributes. This systematic approach allows the investigation of the effects of the CO_2 capture on both cycles. In the literature, super-critical plants are often considered for a CO_2 capture option. These, however, are not based on a systematic evaluation of these technologies and concentrate mainly on one or two key features. In this work several techno-economic plant attributes such as the fuel consumptions, the utility usages, the plant performance parameters as well as the specific CO_2 generation and capture rates are calculated and weighed against each other. Finally, an economic evaluation of the system is conducted along with sensitivity analyses in connection with some key features such as discounted cash flow rates, capital investments and plant efficiencies as well as fuel and operating costs.

Keywords: Air separation unit (ASU); Oxyfuel-based CO_2 capture (O_2/CO_2); Sub-critical (SUBPF) and advanced super-critical pulverised fuel boiler (ASCPF); Techno-economic analysis

1. Introduction

In order to reduce the greenhouse gas emissions from coal-fired power plants, state of the art technologies with their conventional gas cleaning systems need to be further upgraded towards dependable and economically viable CO_2 capture facilities. As a dominant and widely accepted technology, pulverised fuel boilers with sub-critical steam cycles have come under scrutiny when it comes to obtaining higher efficiency levels. This characteristic is particularly significant in the case of CO_2 capture allowing the compensation of increased internal power consumptions caused by additional utilities such as air separation and CO_2 compression units. The operation of advanced super-critical steam cycles is geared to improve the overall power plant performance attributes and seem to be a reasonable and practical solution for the compensation of efficiency losses. On the other hand, this emerging technology as a prospective alternative to the sub-critical steam cycles suffers the preconceived development phase mainly characterised by a more frequent incidence of technical failures and lower partial load operating ranges. As part of an ongoing system progression, engineers utilise and develop novel components and advanced materials to enhance plant reliability and flexibility, which can only be obtained at higher costs.

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To address the above-mentioned dichotomy, a techno-economic assessment is carried out within this paper in connection with sub-critical and advanced super-critical bituminous coal fired pulverised fuel plants. For this assessment, the ECLIPSE chemical process simulation package was utilised to emulate the real process. The nominal power outputs for this case study is selected at slightly above 600 MWe for the conventional systems and at 500 MWe net for the sub-critical and super-critical plants with CO_2 capture facilities. The process simulation of the conventional plants without the CO_2 capture as the base technology is required for assessing the impact of the CO_2 capture for sub-critical and super-critical cycles.

The CO_2 sequestration is achieved through an oxyfuel firing approach supported by a two-stage CO_2 recirculation and subsequent CO_2 cleaning and compression facilities. A cryogenic air separation unit is used to generate oxygen at a purity level of 95%. The CO_2 leak is assumed at around 5%. The CO_2 leaving the plant is further purified removing uncondensable constituents and water vapours through a cryogenic system as part of the CO_2 compression train. The final gas condition ready for the transport through pipelines lies at above 95% purity pressurised at 110 bar and cooled to normal temperature.

Although the sub-critical cycles are generally accepted to be a low risk option, over the last two decades, however, operational experiences and developments in advance super-critical systems have resulted in similar reliabilities. Today, sub-critical plants dominate the market worldwide by a large margin. This is mainly due to a proven and long-term record of reliability. The power plant performance, however, improves significantly in connection with the super-critical cycle. The higher capital cost of super-critically operated plants – mainly due to high quality materials to support the super-critical steam condition – is marginalised by lower gas cleaning costs as well as lower fuel and ash-handling expenses as a result of reduced fuel consumption. Additionally, the higher power plant efficiency of the super-critical cycle results in favourable techno-economic attributes. Over several decades, engineers have been making constant efforts to optimise the overall power plant designs of the super-critical and ultra-critical cycles ensuring improved technical and economic plant operations. In the near future, advanced super-critical boilers will gain more acceptance as currently observable. This trend makes this type of cycle a good candidate for oxyfuel-based CO_2 sequestration systems if the techno-economic frameworks are propitious such as acceptable plant capacity factor, reasonable operating and maintenance works as well as adequate plant overall costs.

This paper is structured into three main parts. The next section looks into the technical issues of sub- and super-critical cycles without any CO_2 capture as the reference plants. The subsequent chapter investigates the integration of the oxyfuel-based CO_2 capture within the reference plants. The last section analyses the economics of CO_2 capture in connection with the above-mentioned cycles.

1.1. Methodology

For the assessment of the selected plants, the ECLIPSE process simulation package is used. This software was initially intended for the use of power plant 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. In the literature in connection with many projects and research activities such as the JOULE clean coal technology [1] or advanced coal fired utility boilers [2], abundant sources of information can be found, where ECLIPSE simulation package is described in more detail.

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 of simulation forms the base for identifying critical components within the plants subjected to extreme physical and chemical exposure. 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. The simulation of an air separation unit and a CO_2 compression train is also performed using ECLIPSE.

Finally, the economic viability of the examined systems is evaluated. In this phase of work, the breakeven-electricity selling price is computed using the net-present value considering all the essential financial factors such as the interest rate payments, annual operating and maintenance costs as well as soft-costs and outlays incurred as a result of plant construction and plant commissioning time along with the main cost contributors capital investment and annual fuel expenses. Since the economics cannot be summarised in clear-cut values and depend on multivariate factors, sensitivity analysis are performed in connection with several key factors such as discounted cash flow rates, capital investments and power plant efficiencies as well as fuel price levels and operating costs. To disclose the effect of

CO_2 capture on the plant economics, the CO_2 avoidance costs for both cycles are calculated and juxtaposed.

2. Reference plants

To assess the impact of CO_2 capture facilities on the overall power plant performance attributes, the sub- and super-critical pulverised fuel boiler systems were initially simulated in the conventional mode. Accordingly, the CO_2 capture concept is built upon the conventional system, which is examined in this section. The CO_2 capture provision is devised with several additional integration points to include the heat energy generated during the compression phase to the power plant. In this way, the direct comparisons of the two power plant types provide useful information such as CO_2 avoidance rate, efficiency loss and the difference in power consumptions between individual modules.

The nominal power output selected for the reference plants (sub-critical and super-critical cycle) is set to above 600 MWe. In this manner, the oxyfuel-based counterparts with CO_2 capture facilities are supposed to provide around 500 MW of electricity. The selected plant size lies within the typical pulverised fuel boiler size range worldwide. The ultimate analysis of the bituminous coal utilised within the designed power plants shows a carbon, hydrogen and oxygen content of 85%, 4% and 7% dry ash-free, respectively. The amount of sulphur and nitrogen lies in the order of 1% and 2%. This elemental configuration results in a calorific value of 25 MJ/kg (LHV). The moisture and ash content of the coal amounts to 8% and 14%, respectively. From the feedstock point of view, coal is not the best candidate for CO_2 capture because of its high carbon content. However, compared to the fuel types with lower carbon proportions such as natural gas, coal is economically more competitive. Furthermore, coal fired pulverised fuel boilers offer reasonable combustion and cycle efficiencies tolerating different fuel qualities [3]. With regard to emissions, nowadays, advanced control systems are available to curb and limit the amount of anthropogenic release of greenhouse and hazardous gases such as SO_X, NO_X, and trace elements in to the atmosphere.

2.1. Sub-critical pulverised fuel boiler (SUBPF)

The sub-critical plant designed as part of this research work using the ECLIPSE simulation package consists of 153 modules and 241 streams. The latter is used to transfer the mass flow of feedstock materials with different properties through various modules such as heat exchangers, turbines, compressors, etc. These modify the physical and chemical properties of the materials. The heat generation and absorption during this process is transferred from one stream to the next (through modules). The system is converged, when the enthalpy error in the material balance of the entire system is minimized to a permissible level. Only at this point of the simulation, a picture of the real process can be provided. A simplified diagram of the pulverised fuel boiler system is presented in Fig. 1. The general cycle information is given in the first column of Table 1. With an average boiler gas exit temperature of 860 °C to a flue gas temperature downstream of economiser at around 330 °C, the heat recovery and steam generation

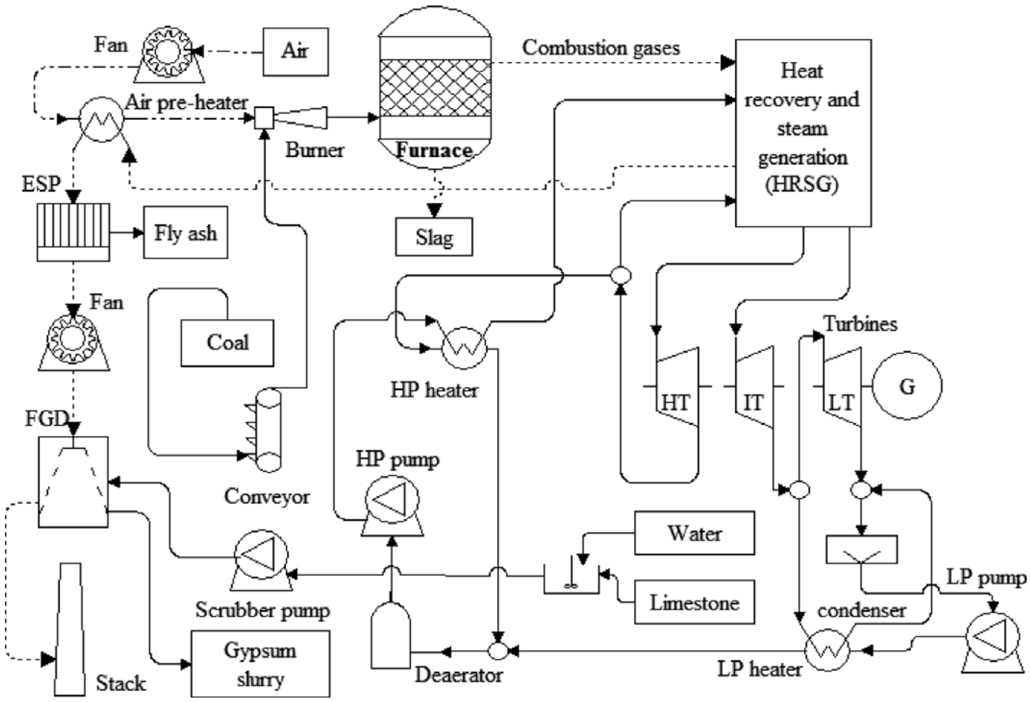

Fig. 1. Schematic presentation of the conventional system without CO_2 capture (HRSG mainly includes the super heater, reboiler and economiser).

Table 1
General technical details of the sub-critical (SCPF) and the advanced super-critical (ASCPF) pulverises fuel boilers

	SUBPF	ASCPF
Excess air (%)	15	15
Air/O_2 pre-heater (°C)	170	170
Super-heater pressure (bar)	160	280
Super-heater temperature (°C)	540	600
Re-heater pressure (bar)	60	60
Re-heater temperature (°C)	540	622
Economiser exit temperature (°C)	340	340
Polytropic efficiency of turbine (%)	81–91	81–91
Condenser pressure (bar)	0.048	0.048
Deaerator pressure (bar)	11.7	11.7
Pump volumetric efficiencies (%)	85–90	85–90
Fan/Comp. isentropic efficiencies (%)	70	70

Table 2
Conventional SCPF and SCPF O_2/CO_2 power plant performance details

Bituminous Coal	SUBPF	SUBPF-O_2/CO_2
	Air	Oxyfuel
Feedstock HHV (MW)	1715.31	1715.31
Feedstock LHV (MW)	1646.13	1646.13
Fuel input (kg/s)	65.39	65.39
HHV (MJ/kg (as received))	26.23	26.23
LHV (MJ/kg (ar))	25.17	25.17
ASU (MW)	0.00	110.00
CO_2 compression (MW)	0.00	75.38
Fuel, ash and FG processing (MW)	22.00	12.00
Pump (MW)	14.31	15.14
Cooling water (MW)	8.61	8.86
Air fan (MW)	5.87	4.55
Total AUX (MW)	50.79	225.93
Steam turbine output (MWe)	678.70	727.15
Net electricity production (MWe)	627.91	501.22
Overall plant efficiency (% HHV)	36.61	29.22
Overall plant efficiency (% LHV)	38.14	30.45
Efficiency loss due to capturing (%)	0	7.78
Power loss due to CO_2 capturing (MW)	0	127.99
CO_2 output (million tonnes/year)	4.29	4.28
CO_2 output (kg/s)	158.82	158.50
Specific CO_2 output (kg/kW h)	0.91	1.14
CO_2 captured (kg/kW h)	0	1.08
CO_2 released (kg/kW h)	0.91	0.06

arrangement provides a sub-critical steam cycle with a pressure of 160 bar at 540 °C.

Table 2 (second column) shows the energy input, utility usages and performance attributes of the plant along with the specific CO_2 emissions. Through iterative simulations, the plant efficiency was optimised giving a value of above 38%. Further improvements were limited and would have required changes in cycle design.

2.2. Advanced super-critical pulverised fuel boiler (ASCPF)

A logical approach to improve the power plant efficiency is the use of a super-critical cycle. Apart from a higher electricity generation rate, the increase in plant efficiency brings further benefits such as the drop in fuel consumption and cost, reduction in specific emissions of CO_2, NO_X and SO_2. In the simulations given in this paper, the specific CO_2 emission for the super-critical plant is 12% lower than the one for the sub-critical system. Similarly, all other emissions would also be reduced per specific energy rate generated. These benefits have led to the growing use of super-critical cycles and, between 1995 and 1999, 19.4 GWe of super-critical coal-fired power plant capacity was commissioned in OECD countries compared with just 3.0 GWe of sub-critical capacity [4], although still larger number of sub-critical plants are operational worldwide. Notwithstanding the facts, which speak for the advance super-critical cycle, sub-critical pulverised fuel boiler systems are still considered as more reliable rendering them a lower complexity and risk insurance level [5]. Many years of successful plant operations at super-critical levels, however, testify how well-proven this technology is [6].

Fig. 1 shows the simplified design of the power plant cycle. This presentation is similar to the sub-critical model. Although the designs of both cycles are similar, the increase in temperature and pressure require a more frequent usage of high-quality materials such as chrome tubing or thicker component sections [4]. Table 3 (second column) shows the power plant performance attributes of the conventional air-fired super-critical cycle along with the energy input, the utility usages and the specific CO_2 production. The flue gas exit temperature of the boiler is around 970 °C. This value is around 110 °C higher than the sub-critical cycle offering higher plant efficiency. The use of the advanced super-critical system results in an annual coal saving at around 250,000 tonnes corresponding to a yearly value of around

Table 3
Conventional ASCPF and ASCPF O_2/CO_2 power plant performance details

Bituminous coal	ASCPF	ASCPF-O_2/CO_2
	Air	Oxyfuel
Feedstock HHV (MW)	1474.24	1474.24
Feedstock LHV (MW)	1414.78	1414.78
Fuel input (kg/s)	56.20	56.20
HHV (MJ/kg (ar))	26.23	26.23
LHV (MJ/kg (ar))	25.17	25.17
ASU (MW)	0.00	94.00
CO_2 compression (MW)	0.00	63.20
Fuel, ash and FG processing (MW)	18.00	10.00
Pump (MW)	19.13	21.34
Cooling water (MW)	6.84	7.09
Air fan (MW)	5.77	4.07
Total AUX (MW)	49.73	199.71
Steam turbine output (MWe)	660.31	699.12
Net electricity production (MWe)	610.57	499.41
Overall plant efficiency (% HHV)	41.42	33.88
Overall plant efficiency (% LHV)	43.16	35.30
Efficiency loss due to capturing (%)	0	7.86
Power loss due to CO_2 capturing (MW)	0	111.16
CO_2 output (million tonnes/year)	3.69	3.69
CO_2 output (kg/s)	136.7	136.50
CO_2 (kg/kW h)	0.80	0.99
CO_2 captured (kg/kW h)	0	0.94
CO_2 released (kg/kW h)	0.80	0.05

€10 million. Furthermore with the exception of the pumping work, which is required to sustain a high-pressure level within the steam cycle, the utility usage is reduced. The overall efficiency of the advanced super-critical plant is 5% higher than the one of the sub-critical system resulting in around 600,000 tonne less CO_2 release to the atmosphere each year.

Due to a significantly higher pressure and temperature level, it is believed that the plant availability is affected as a result of its susceptibility to higher maintenance occurrences. Modern super-critical plants, however, display comparable availabilities to their sub-critical counterparts [4]. The simulations show that the availability of the sub-critical system needs to be at least 14% higher than the one of the super-critical cycle in order to make it financially more attractive. The plant costs are comparable with sub-critical boiler technology. Although a higher investment is required for the high-pressure and temperature cycle, the cost for several modules such as fuel and ash handling, compressors and gas cleaning systems are reduced. Moreover, the overall economics are more favourable because of the increase in cycle efficiency achieved.

3. Oxyfuel-based pulverised fuel boilers with CO_2 capture (O_2/CO_2)

This section elucidates the simulations of oxyfuel fired sub- and super-critical pulverised fuel boiler systems with CO_2 capture. The plant layout is based on technologies described in the previous chapter. For the CO_2 sequestration, three main units were added to the base system. These are the air separation unit, the flue gas looping and the CO_2 compression train. Furthermore, in most cases, there will be no provision for flue gas desulphurisation. Fig. 2 shows a simplified illustration of the process, which applies to both cycles, sub- and super-critical. The technical features of both plants, however, are not identical. The following sections describe some of the technical details and the performance attributes of both power plants, sub- and super-critical cycles. Moreover, the integration of the air separation unit and the CO_2 compression train is delineated.

3.1. Air separation unit and CO_2 compression

The cryogenic air separation is currently the most efficient and cost-effective technology for producing large quantities of oxygen, nitrogen, and argon as gaseous or liquid products [7]. Compared to methods such as ceramic auto-thermal recovery (CAR), chemical looping and ion transport membrane (ITM) as well as mixed conducting membrane, the cryogenic air separation method is considered as a well-proven technology. Alternative systems promise lower power consumptions and improved economics. CAR, for instance, is supposed to decrease the power consumption by between 30% [8] and 70% [9] compared to cryogenic systems while slashing the capital investment by half. The development, however, was confined just to a laboratory scale. Similarly, ITM, which promises even lower power consumption than CAR, requires more development work towards a large-scale implementation. Chemical looping, another promising technology, which uses oxygen carriers such as metal oxides, eliminates virtually any kind of energy penalties resulting in high power efficiencies. Multi-criteria analyses performed by Haines from

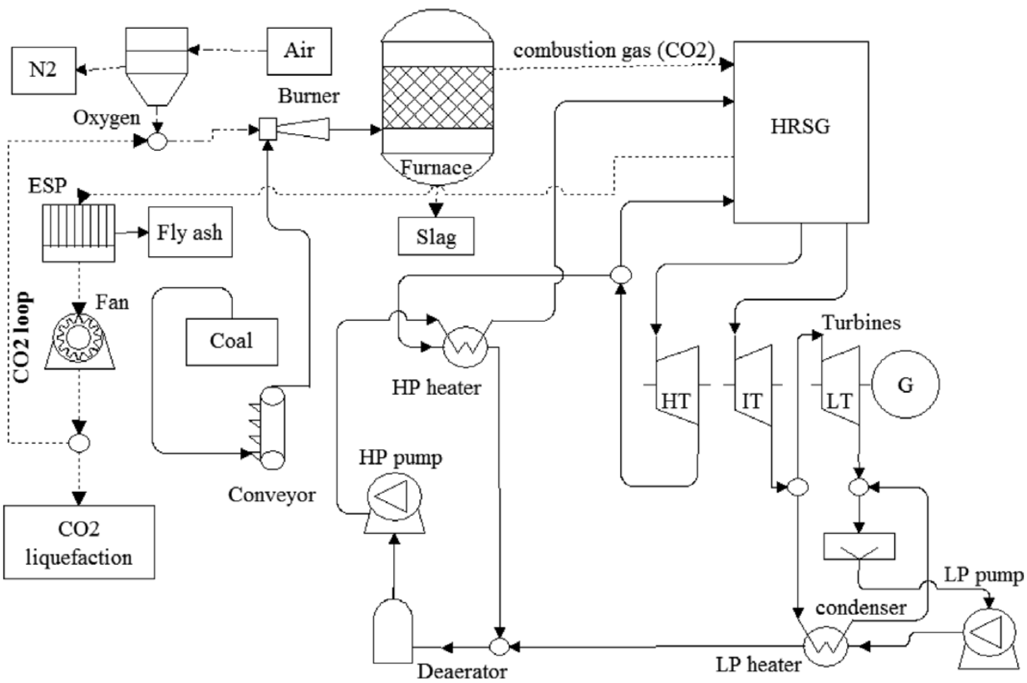

Fig. 2. Schematic presentation of the oxyfuel-based pulverised fuel boiler with CO_2 capture.

IEA give high scores to partial oxidation and chemical looping methods while cryogenic systems are positioned at the bottom of the list [10]. From a practical point of view, however, at present time, cryogenic systems are the preferred method for large-scale systems [11] and they are economically more viable [12]. Partial oxidations, although practically proven, are currently complex, expensive and inappropriate for retrofits. Observing the current industrial development trends and the academic research endeavours, a less energy intensive and costly system can be forecasted for the near future.

Table 4 shows the technical details of the air separation unit (ASU) used for both cycles. The system simulated in ECLIPSE consists of several compressors, air cleaning system for removing moisture and CO_2 from the sucked air and cryogenic heat exchangers (aluminium plate-fin heat exchangers) [13] followed by two distillation columns. The separated gases are vented through two small turbines [14]. The expansions of gases reduce the temperature of the exiting nitrogen stream to around −195 °C and that of oxygen to −184 °C. Low-pressure compressors are used to pressurise the air to 4.2 bar. Higher compression rates are conducive to a reduction of unit size but increase the overall compression work. Chemical companies like Airliquide developed and exploit methods, which are 10–20% more economical than the system simulated in this paper. These technologies are configured and optimised using sequences of compressors and intercoolers for minimal compression work. In the literature, the electric power consumptions of cryogenic ASU's are set roughly to around 20% of the plant gross power output [15]. In this work, the simulated power consumption amounted to 15% of the gross power output for sub-critical and to 13% for the advanced super-critical cycle.

The compression of CO_2 is achieved through a sequence of compression units and a cryogenic gas cleaning system, which is designed to remove non-condensable gases from the CO_2 gas mixture. Table 5 shows some of the technical details of the CO_2 compression train. The purity of the exhaust gas entering the compression unit is measured at 89 and 89.2 mass% for sub- and super-critical cycles, respectively. The water is separated from the gas through a flue gas condenser. The dehydration of the CO_2-rich gas is important to avoid corrosion, especially when SO_2 compounds are not removed [15]. The non-condensable compounds within the CO_2-rich flue gas are removed using a cryogenic process as part of the CO_2 compression unit. This purification process is implemented by harnessing the CO_2 triple point temperature. The CO_2 purification procedure results in gas purities above 95 mass%.

Table 4
ASU details

	SUBPF	ASCPF
Integrated system	O_2 preheating	O_2 preheating
Air input (kg/s)	572	513
Compressor (bar)	4.2	4.2
Distillation columns	2	2
Cryogenic plate fin HX	10	10
Power consumption (MW)	110	94
O_2 outlet temperature (°C)	170	170
O_2 availability (kg/s)	143.5	122.7
O_2 purity (mass%)	95.3	95.3
N_2 availability (kg/s)	452.5	600
N_2 temperature (°C)	−43	−47
N_2 purity (mass%)	98.6	98.6
TSA (kg/s)	3.95	3.38

Temperature swing absorption (TSA) is used for air cleaning.

Table 5
CO_2 compression train

	SUBPF O_2/CO_2	ASCPF O_2/CO_2
CO_2 train integration within HRSG (MJ/s)	40	40
CO_2 pressure (bar)	110	110
CO_2 production (kg/s)	158.5	136.5
Final CO_2 temperature (°C)	30	30
CO_2 purity without cryogenic cleaning (mass%)	89	89.2
Final purity (mass%)	95	95

3.2. SUBPF O_2/CO_2

Table 2 (first column) shows the energy input, the utility usage and the plant power output as well as the specific CO_2 emission. The system simulated in this study operates on 95% pure oxygen and 87% CO_2-rich gas, which along with bituminous coal are fed to the burners of the pulverised fuel boiler. The system applies a two-stage flue gas recirculation mode for temperature control. The flue gas-recycling rate is set to 68% of the gas leaving the furnace (for both cycles). The higher molecular weight of CO_2 compared to nitrogen, which is present in the boiler during a normal air firing process, results in a more compact boiler design. This is achieved through a lower volumetric throughput. Furthermore, the specific heat capacity of CO_2 needs to be considered for the boiler design. This attribute increases as a function of the cycle temperature, exceeding the values of nitrogen at temperatures above 330 °C (at lower temperatures nitrogen has a higher specific heat transfer). This cycle propensity results in a higher furnace temperature and consequently in a slightly more efficient boiler providing the steam turbine with an extra 48.45 MW power. As a result, the flue gas exit temperature of the boiler is around 240 °C higher than the reference case. Through the integration of the ASU and the CO_2 compression train, some sensible heat energy could also be transferred to the cycle. Moreover, the removal of flue gas desulphurisation gives a power saving of 10 MW. Despite the above beneficial issues, the efficiency of the plant was limited to 29.22%. This is 7.8% lower than that of the reference plant. Slightly higher performance rates can be attained if more efficient ASU and CO_2 compression trains can be established.

The specific CO_2 generation of the oxyfuel-based system is 25% higher than that of the reference plant. This is mainly due to the additional power usage for oxygen generation and CO_2 compression. The total CO_2 capture rate is calculated at 4.06 million tonnes per annum. The CO_2 avoidance – this is the difference between the rate of CO_2 release from the reference plant and the amount CO_2 discharged from the plant with the capture facilities – amounts to 3.2 million tonnes per annum.

3.3. ASCPF O_2/CO_2

Although the layout of the super-critical pulverised fuel boiler is similar to the one shown for the sub-critical plant (see Fig. 2 for the simplified layout), this cycle exhibit much higher pressures and temperatures within some parts of the steam cycle (see Table 2). The oxyfuel combustion and a CO_2 recycling rates of 70% increase the furnace temperature resulting in a boiler flue gas exit temperature of around 180 °C higher than the reference case. A steam driven pump raises the water pressure to over 330 bar compared to 195 bar within the sub-critical system. The water leaving the condenser is pressurised to 12 bar and heated in a series of heat exchangers to a temperature of 163 °C before it enters the steam driven pump. The pressurised water is led through a set of heat exchangers – the temperature rises to 293 °C – and enters the economiser, the main boiler and finally the super-heater (see Table 1 for temperatures and pressures). The steam leaving the super-heater is expanded through a set of high-pressure (HP) steam turbines to 65 bar and 364 °C. From there, a large part of the steam is led through the reheater, where its temperature rises to 622 °C. The other fraction of the steam is extracted and directed through a HP heat exchanger, deaerator and HP pump to the feed water cycle. The reheated stream from the re-heater is fed to a series of intermediate-pressure (IP) turbines where it is expanded to generate power. The main part of the steam coming from the IP turbine is lead to a sequence of low-pressure (LP) steam turbines. The other fraction is extracted through a LP heater joining the feed water cycle. Critical components, which require a special design to stand out the super-critical conditions compared to sub-critical one, are identified in the section starting from HP pump up to IP turbine.

The above cycle configuration results in a considerably higher plant efficiency – a 4.7% higher efficiency compared to that of the sub-critical plant. This characteristic makes the system to run more economically cutting around 248,000 tonnes coal per annum. This is equivalent to €10 million per year at a coal price of 1.6€/GJ. Additionally, the overall utility usage is reduced by 26.22 MW (1.05 MW in the case of conventional plants without a CO_2 capture).

Since a lower amount of fuel is consumed to run the power plant, logically the CO_2 emissions are reduced in comparison with that of the sub-critical system. An annual CO_2 decline of 0.6 million tonnes is anticipated within this case study. For the CO_2 sequestration, this means a 13% lower CO_2 capture rate. Fig. 3 shows the specific amount of CO_2 leak, capture and avoidance. For more details about the utility usage, the overall plant performance and the CO_2 production, refer to Table 3.

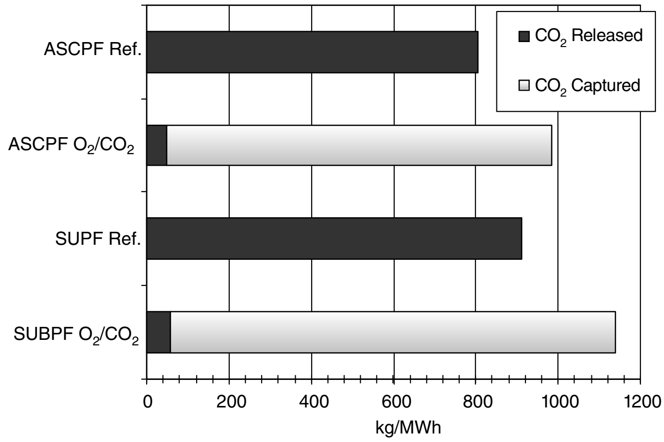

Fig. 3. CO_2 avoidance rate.

4. Economic assessment

This section looks into the economics of CO_2 capture. Table 6 presents the estimated cost for each power generation option. The capital investment is divided into two parts: Engineering and procurement cost (EPC) and the owner's cost, which include the contingencies, the capital fees and the working capital. The investment level of the super-critical plant lies just slightly over the cost estimated for the sub-critical cycle. In the case of CO_2 capture, however, the advanced super-critical system is less costly. This is mainly due to a lower cost of the air separation unit (ASU), the gas cleaning system and the CO_2 compression train (see Table 7). Similar cost estimations have been implemented in the literature for other capturing types e.g. the MEA based option [12]. The cost breakdown does not account for any oxygen storage tanks, CO_2 transportation and storage facilities. The former is conducive to increasing the power plant capacity factor in the event of ASU breakdown.

Since the economics of power generation is not a clear-cut assessment and it depends on many factors – manage-

Table 6
Typical power plant cost details

	SUBPF	ASCPF	SUBPF O_2/CO_2	ASCPF O_2/CO_2
Avg EPC (€/kWe)	860.00	890.00	1450.00	1400.00
Owner's cost (€/kWe)	129.00	133.50	217.50	210.00
Typical SI (€/kWe)	989.00	1023.50	1667.50	1610.00
Avg capital cost in (M€)	540.00	543.41	726.77	699.17
Owner's cost (M€)	81.00	81.51	109.02	104.88
Total cost (M€)	621.00	624.92	835.78	804.05

Table 7
Specific investment for main components

Figures given (€/kWe)	SUBPF	ASCPF	SUBPF-CC	ASCPF-CC
Fuel and ash-handling	85.00	70.00	85.00	70.00
Boiler house	240.00	300.00	240.00	300.00
Electrical, BOP	250.00	250.00	250.00	250.00
Turbines	180.00	180.00	180.00	180.00
FG condensing	0.00	0.00	52.00	40.00
ASU	0.00	0.00	422.00	370.00
FG cleaning	105.00	90.00	41.20	35.00
CO_2 train	0.00	0.00	179.80	155.00
Total EPC	860.00	890.00	1450.00	1400.00

Table 8
Economic assumption

Owner's cost (%)	15%
Project lifetime (years)	25
Load factor (%)	85
Fuel price (€/GJ)	1.6 (sensitivity: 1, 2 and 3)
Construction time (CT) (years)	3
Capital allocation during CT (%/a)	40 (first year)/40 (second)/20 (third)
Commissioning time (month)	4
Discounted cash flow (%)	8% (sensitivity 4% and 12%)
Total annual fixed O&M (€/kWe a)	26 (44 CO_2 capture option)
Total variable O&M cost (€/MWh a)	1

rial, political, technical and/or financial – it is important to implement a sensitivity analysis to disclose the effect of some key factors on the economic value of the project, in this case the breakeven-electricity selling price (BESP). The calculation uses the net-present value (NPV) to calculate the BESP. For the calculation, a set of assumptions has been set. These are listed in Table 8. The sensitivity analyses are performed in connection with the EPC, the plant efficiency and the coal price as well as the operating and maintenance cost (fixed and variable). Fig. 4 shows a variation of BESP versus EPC. Each case is presented with three lines signifying three different discounted cash flow rates (DCF). The lines on the left present the conventional

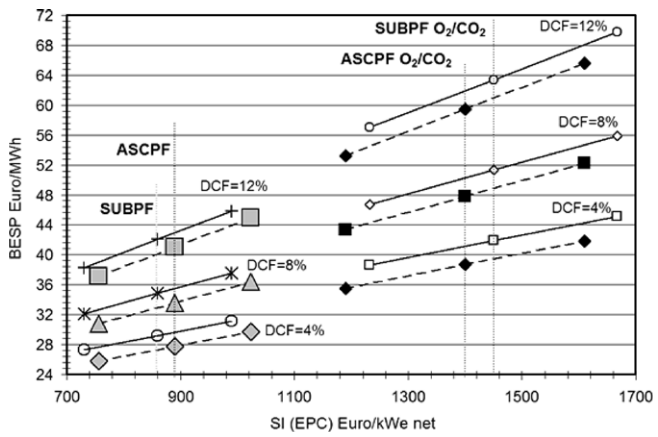

Fig. 4. BESP versus specific investment at different DCF rates (ASCPF: dotted lines).

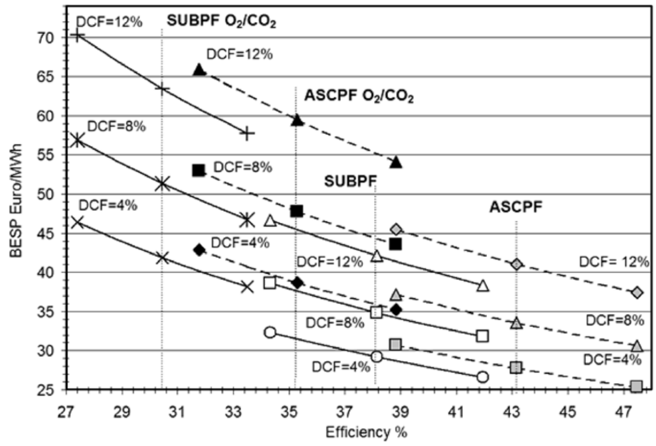

Fig. 5. BESP versus plat efficiency at different DCF rates (ASCPF: dotted lines).

systems whereas the right part marks out the CO_2 capture options. As it can be seen from the figure, the economic importance of super-critical system (dotted lines) becomes more significant for CO_2 capture ($\Delta BESP_{conventional} < \Delta BESP_{CO_2\text{-capture}}$). Securing favourable financial frameworks, for example through lower government supported public sector discount rates and CO_2 tax exemptions, the economic values can become more attractive towards CO_2 capture options.

Fig. 5 illustrates the economics in connection with the proposed DCF and the efficiency changes (±10%). The latter could be due to many factors such as unstable power cycles, operational problems, slagging and fouling propensities of the boiler. The capacity factors have similar impact on the economics. This, however, can take wider dimensions.

Fuel price is probably the most significant economic factor, if the technical and financial options are sound. Fig. 6 demonstrates the electricity cost versus the coal price at a DCF of 8%. As it can be seen from the figure, the economic benefit of the super-critical plant becomes more significant when the fuel costs increase (the lines are not parallel).

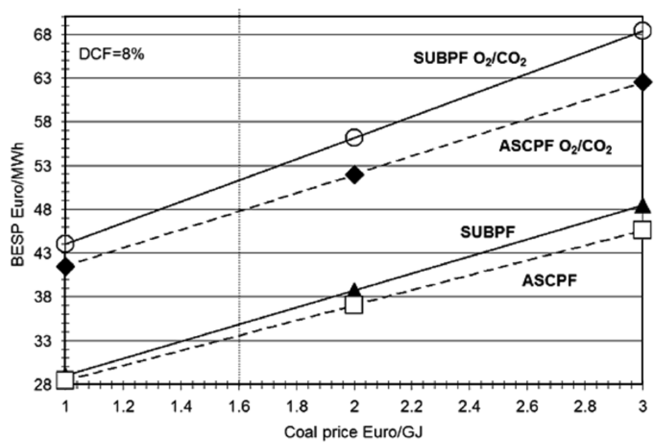

Fig. 6. BESP versus fuel price at a DCF rate of 8% (ASCPF: dotted lines).

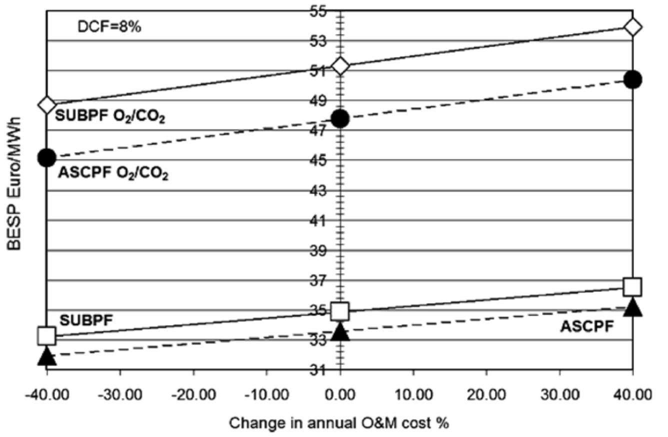

Fig. 7. BESP versus operating and maintenance cost at a DCF rate of 8% (ASCPF: dotted lines).

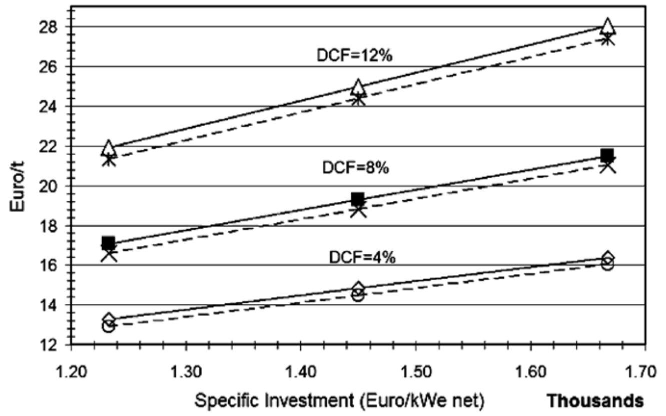

Fig. 9. SUBPF O_2/CO_2 and ASCPF O_2/CO_2 (dotted lines) avoidance costs at different DCF rates.

In connection with the operating and maintenance (O&M) cost, a 40% cost expansion results in a small change of BESP (4–6%). Although the effect of O&M on economics is not very significant for the conventional system, the outcome is, however, magnified in the case of CO_2 capture (see Fig. 7). Moreover, problems with first-of-a-kind engineering projects and new plant designs could lead to unexpected O&M problems, which could increase the costs above the expected level stipulated within Fig. 7.

Fig. 8 shows schematically the effect of the specific investment variation on changes in BESP. The figure indicates that the sub-critical plant O_2/CO_2 can become competitive to super-critical systems if the specific cost could be reduced by around €160/kWe at a DCF of 8% and at the assumed economic conditions laid out in this paper. The current study, however, suggests a 50€/kWe (±10) higher cost for the sub-critical-cycle. Other cost variations such as an improved lifetime, increased efficiency and lower O&M costs do give a very unlikely picture of a favourable scenario for a sub-critical system. This could mean either an over 11% higher capacity factors at a DCF of 8% or more than 50% lower O&M cost. With regard to the plant lifetime, a 150% higher life span would give the sub-critical cycle the competitive edge, which is very improbable.

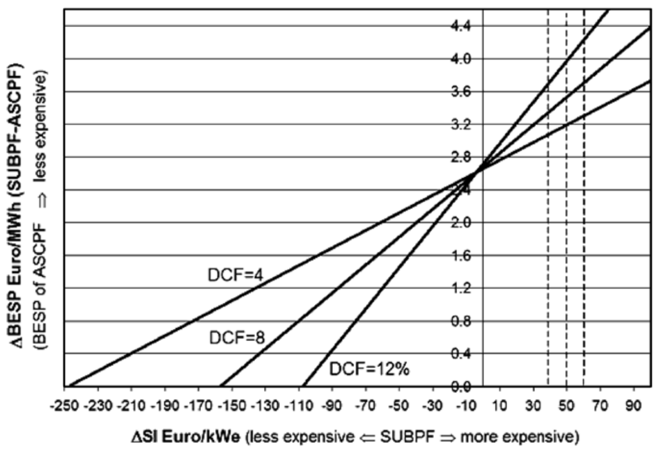

Fig. 8. Economic comparison between SUBPF $O_2/CO_2$and ASCPF O_2/CO_2.

Fig. 9 demonstrates the CO_2 avoidance cost of both cycles in connection with the specific investment. Although the sub-critical cycle displays just a slightly higher avoidance cost than the super-critical one, it should be borne in mine that a considerably lower amount of CO_2 is generated in the super-critical plant. The outlook that the cost for emission allowances will increase to 20€/ton of CO_2 or higher depending on reduction demand by 2015 [11] makes both cycles candidates for CO_2 capture. Other significant factors, for example the storage of CO_2 contaminated with SO_2 may be difficult from both a legal and public acceptance point of view. Still, the results show that combined storage has a marginal effect on the overall cost situation [16,17].

This paper focuses on power generation and CO_2 capture. Transport and storage costs are not studied within this scope. IEAGHG developed a model for estimating the pipeline capital investment and O&M costs for onshore and offshore transportation [18]. Other factors such as booster stations [19], storage types [20] and layers [21] as well as financial range in saline reservoirs [22] are studied in the literature to a modest extent.

5. Conclusion

A techno-economic evaluation of sub-critical and super-critical pulverised fuel boilers in connection with oxyfuel-based CO_2 capture facilities was implemented in this paper using the ECLIPSE process simulation package. Although sub-critical plants are categorised as a less risky enterprise, over two decades of operational success of super-critical plants have shown nearly comparable reliability figures. The technical features of super-critical plants such as higher efficiency, lower fuel consumption and lower specific emissions make these systems predestined for CO_2 capture. Nonetheless, the sub-critical cycle simulated in this paper shows satisfactory economics, which could be balanced by adequate emission allowances of around 20€/ton of CO_2. Considering the fact that worldwide sub-critical plants represent the most ubiquitous technology in the current market, this type of technology should be considered for retrofit options if economic and technical conditions are appropriate. This deliberation may require a steam cycle retrofit to an advanced super-critical state to compensate for the efficiency deficit and to subsequently overcome the higher specific CO_2 production of conventional sub-critical systems. On the other hand, the overall plant economics can be affected by this twin overhaul project necessitating a careful assessment of techno-economic circumstances such as the extended project life prospects, plant reliability implications and the consequent energy costs. With regard to oxyfuel-based CO_2 capture facilities, the current studies need to be extended in the direction of integrating the main components – the air separation unit and the CO_2 compression train – with the entire power plant layout in order to optimise the energy exploitation and to diminish any power loss penalties. A further challenge is to reduce the power required for air separation units (ASU) and CO_2 compression trains. The simulated ASU in this work consumed up to 15% of the energy produced. Different technologies like ceramic auto-thermal recovery, chemical looping and ion transfer membranes are suggested in the literature. These, however, are not market mature for large-scale systems. Some companies, such as Vattenfall, have opted for cryogenic oxyfuel methods. The highest exergy loss within an oxyfuel fired plant with CO_2 capture is caused by the compressors. Employing compressors with higher polytropic efficiencies configured in elaborated stages with intercoolers can reduce the exergy loss by around 25% [23]. This optimisation has its limits too and could add to the overall cost of the plant. In general however, the economics depend strongly on the financial background and technical viability of the system such as high capacity factors, low government supported discounted cash flow rates and low operating cost. If these are adequate, even sub-critical systems can be techno-economically sensible options.

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