OXY-FIRED FLUDIZED BED COMBUSTORS WITH A FLEXIBLE POWER OUTPUT USING CIRCULATING SOLIDS FOR THERMAL ENERGY STORAGE

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ABSTRACT

This paper presents a power plant concept based on an oxy-fired circulating fluidized bed combustor (oxy-CFBC) combined with thermal energy storage on a large scale. The concept exploits to full advantage the large circulation flows of high temperature solids that are characteristic of these systems. Two solid storage silos (one for high temperature and the other for low temperature solids) connected to the oxy-fired CFBC allow variability in power output without the need to modify the fuel firing rate and/or the mass flow of O_2 to the combustor. During the periods of high power demand the system can deliver additional thermal power by extracting heat from a series of fluidized bed heat exchangers fed with solids from the high temperature silo. Likewise, during period of low power demand, the thermal power output can be reduced by using the energy released in the combustor to heat up the low temperature solids on their way from the low temperature silo to the oxy-CFBC and storing them in the high temperature silo located below the cyclone. A preliminary economic analysis of two designs indicates that this highly flexible system could make this type of power plant more competitive in the electricity markets where fossil fuels with CCS will be required to respond to a large variability in power output.

Keywords: CO_2 capture; oxy-fired combustion; energy storage; circulating fluidized bed; power plant.

1. Introduction

Fossil fuels will continue to play a major role in meeting the world's energy needs because of their very competitive cost, widespread distribution and the massive infrastructure available for burning them. CO_2 capture and storage (CCS) technologies are considered to be one of the least-cost options for mitigating climate change [1]. In addition, CO_2 capture and storage is the only low carbon technology that can make the vast economic assets linked to fossil carbon reserves or unburnable carbon compatible [2, 3].

Moreover, it is becoming increasingly common in the major electricity markets to operate fossil fuel power plants with large load changes and even periods of complete shut down, in order to be able to adjust to the variability in energy demand and to the increasing share of renewables in the electricity mix. Renewable energies like wind and solar power are characterized by their intermittency, so they need energy storage systems and/or back up infrastructures to adapt their supply to demand [4]. The use of air-fired fossil power plants to accommodate changes between minimum and full load by ramping up and down is a common practice [5]. However, there are substantial energy and economic penalties when the power generation equipment is forced to operate with load changes and offline periods [6-8]. In addition, the cycling mode of operation in fossil fuel power plants leads to low capacity factors, which obviously increases the cost of electricity compared to when operating at base-load. All these problems are aggravated in power plants with CCS because these are complex and integrated systems that are inherently capital intensive [1, 9, 10] and better adapted to base load operation. However, since the flexible mode of operation may be imposed by regulators or market conditions, there is a growing interest in developing CCS systems that allow a wide flexibility and load change [11-14] and ensure minimum impact on the unit of product (i.e., the kWh_e and/or the tonne of CO_2 avoided).

For post-combustion CO_2 capture systems that employ amine-based solvents, the use of tanks has been proposed as a means of storing the rich solvent leaving the absorber during peak demand periods [15]. This allows the regeneration of the solvent and the compression of the CO_2 captured to be postponed to periods of low power demand. During the high power demand periods, the net power plant output is increased as the energy penalty associated with the consumption of the steam in the regenerator and electricity during the compression of CO_2 is avoided [16]. However, even the storage of solvent for a few hours of operation will require the storage of large masses of costly amine.

In pre-combustion CO_2 capture systems, the power generation block can be decoupled from hydrogen production by using an intermediate hydrogen storage system provided that a geological suitable structure is available [11, 15]. More commonly, the clean syngas can be diverted in polygeneration systems to a chemical production line for the production of fuels such as methanol or dimethyl ether when there is a low power demand [17].

For oxy-fuel combustion power plant systems, the use of oxygen cryogenic tanks for backup storage [15, 18] has been proposed to overcome the flexibility constraints during boiler load changes imposed by the slow response of the air separation unit (ASU). This increases the cost of the oxygen produced, mainly as a result of the additional energy requirements for the liquefaction and re-evaporation of the oxygen. Another proposal for improving the flexibility of oxy-fired systems is to design a combustor that is able to operate in oxy-fuel or air mode. The combustor could then operate in air mode during high demand peaks to avoid the high energy penalty associated with consumption in the ASU and CPU [19]. However, this solution implies a substantial amount of carbon leakage, as CO_2 is emitted during air combustion periods.

One of the possible approaches to introduce flexibility in power plants would be to build an energy storage system within the power plant boundary. This would allow variability in power output irrespective of the thermal power input. The idea of implanting an energy storage system inside the fossil fuel power plant is not new and several conceptual designs were proposed in the late 70's [20]. For example, Drost et al. [21] proposed a concept in which a coal-fired power plant heats up molten salt from 288ºC to 566ºC and stores the salt in a high-temperature tank during periods of low electricity demand. During peak demand periods, the hot salt is withdrawn from the high temperature tank and used as a heat source for a steam generator after which the cold molten salt is returned to a low temperature tank (at 288ºC). Molten salt thermal energy storage systems are today commercially available and employed in concentrated solar power plants [22]. Another type of system for this kind of solar plant is to use moving solids to store energy as latent heat [23-25]. These systems typically consist of two silos for storing solids at different temperatures and at least one heat exchanger to transfer the energy from the solar field to the solids during the charging periods and another heat exchanger to release the energy stored in the solids to a working fluid during discharge periods [23-25].

Another example of thermal energy storage in fossil fuel power plants is to use hot water tanks integrated within the steam cycle [21]. During high demand peaks, the hot water can be discharged into the cycle to avoid steam consumption in the water preheaters. This can boost the amount power delivered and allow primary and secondary frequency support responses [26]. The use of rapid changes in the solids circulation flows and inventories in high temperature solid looping cycles for CCS has also been proposed recently for the same purpose [27]. However, these solutions are intended for very small quantities of energy and cannot be considered effective for large-scale energy storage systems.

The oxy-fired CFBC concept [28] presented in this work incorporates a large-scale thermal energy storage system that exploits the inherent capacity of circulating fluidized bed combustors to handle and circulate large flows of solids at high temperature. Oxy-fired CFBC technology has been developed very rapidly in recent years [29-31] due to its similarity to existing commercial air-combustion systems, that have already reached scales of up to 600MW$_e$ [32]. By exploiting the elements already present in CFBC power plants, a basic economic analysis of the proposed system has been carried out in order to compare its expected electricity costs with those of equivalent oxy-CFBC and air-CFBC power plants forced to operate with low capacity factors.

2. Process description

The oxy-fired CFBC power plant concept proposed in this work is represented in Figure 1. It is composed of several elements (marked in grey) that are common to all oxy-fired CFBC power plants: a CFB combustor, cyclones, convective heat exchangers and air preheaters (all marked with the symbol of HX_1 to simplify the diagram), an external fluidized bed heat exchanger ($FBHX_1$), an air separation unit (ASU) and CO_2 compression and purification units (CPU). The combustor chamber of the power plant depicted in Figure 1 is assumed to operate in adiabatic conditions by extracting as much heat as possible from the combustor chamber. Maximum extraction is achieved by using the circulating solids ($G_{S\ CFBC}$) as a heat carrier. Although not a common practice in existing boilers (where a substantial fraction of the power released during the combustion is recovered inside the combustor chamber by transferring the heat to water pipes or wing walls within the combustor), this heat management option is feasible with the currently available CFBC technology and it is also a design option for oxy-CFB boilers [29, 33-37] thanks to the large heat carrying capacity of the solids circulating in and out the combustor. In these conditions, the external fluidized bed heat exchanger ($FBHX_1$) is one of the main thermal power outputs from the combustion system of Figure 1 to the steam cycle (not shown in the Figure for simplicity). The fluidized bed heat exchanger is located in the return path of a fraction of circulating solids (labelled as stream 4 in Figure 1). Another stream of circulating solids (stream 5) can by-pass the heat exchanger and enter the combustor directly [38]. This makes it possible to operate with lower thermal loads and fuel inputs to the combustor and to maintain the same circulation of solids and combustion conditions [38].

The novel components in Figure 1 with respect to other Oxy-CFBC designs are the two storage silos and the second series of external fluidized bed heat exchangers ($FBHX_2$). The purpose of $FBHX_2$ is to reduce the temperature of the solids coming from the cyclone so that they can be stored as cold solids in a low temperature silo during periods of high demand. This allows increasing the power delivered during high demand periods. To achieve this objective, $FBHX_2$ is composed of a series of fluidized bed heat exchangers in countercurrent flow to the water-steam flows, such as those proposed by Schwaiger et al. [24]. At the same time as thermal power is extracted from $FBHX_2$, the high temperature silo connected to $FBHX_1$ feeds solids at high temperature into this heat exchanger. The cooled solids are then fed to the CFBC. This will give rise to a total thermal power output (P_{max}), the sum of the thermal power extracted from

HX_1, $FBHX_1$ and $FBHX_2$ which is substantially higher than the thermal power released during the combustion of the fuel (P_{comb}).

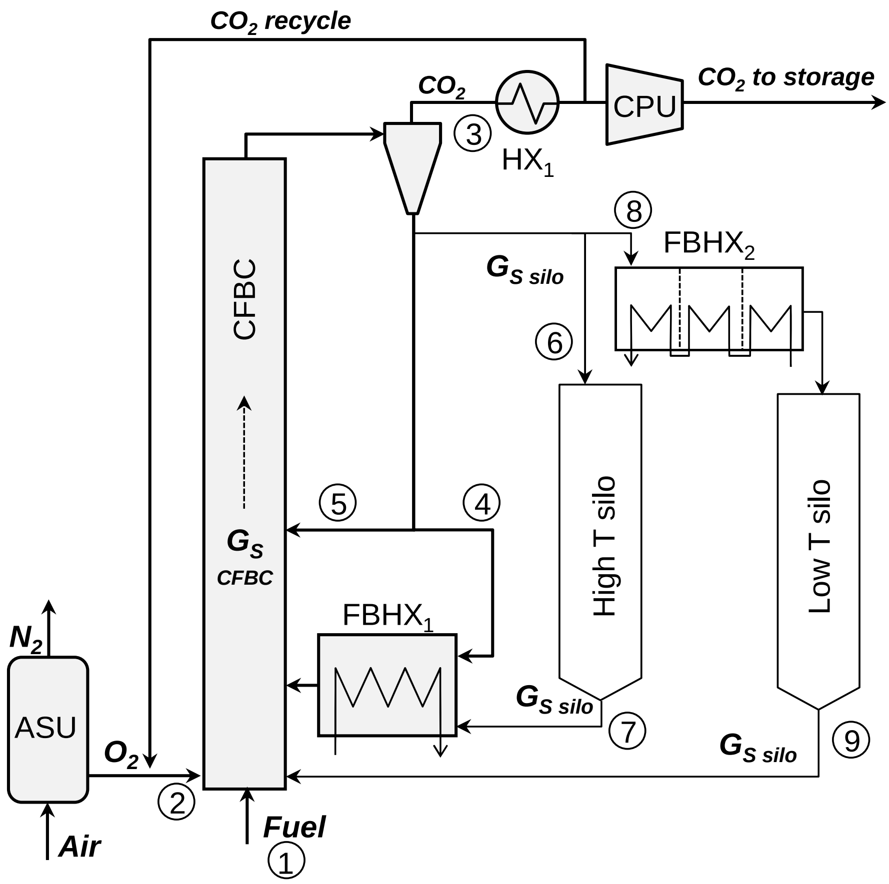

Figure 1. Scheme of the Oxy-CFBC power plant concept with energy storage as proposed in this work.

On the other hand, during periods of low power demand, the thermal power output from the system towards the steam can be drastically reduced by storing the high temperature solids leaving the CFBC in the high T silo connected to the exit of the cyclone. At the same time, the low temperature silo feeds cold solids to the combustor in order that heat continues to be extracted from the combustion process taking place in the adiabatic CFBC and to be stored in the high temperature silo. In this operation mode, the thermal power output (P_{min}) only comes from the hot flue gas leaving the CFBC which is extracted in HX_1.

In the scheme of Figure 1, the downwards movement of the solids is due to gravity and the upwards movement takes places in the CFBC, as long as the silos are located between the minimum height of the cyclone and the lowest point of the circulating fluidized bed combustor.

The power plant depicted in Figure 1 is able to operate in different operation modes (different thermal power outputs between P_{max} and P_{min}) and can also gain flexibility in power output through changes to the fuel firing rate (P_{comb}) in the combustor following the existing practice of load modifications used in commercial CFBCs. Also, it should be pointed out that the system represented in Figure 1 allows changes to be made to the thermal power output available for the steam cycle without modifying the combustion conditions inside the CFBC. This is a significant benefit for oxy-fired CFBC systems because the operation of the ASU and CPU can be simplified and made to be more cost-effective as it will be operating in steady state conditions. Uncoupling P_{max} from P_{comb} will also allow oxy-fired combustion under steady state conditions which in turn will minimize emission problems on the combustion side of the system during rapid load changes [39]. The system proposed in this work will also be able to deliver P_{max} to a steam cycle with a smaller circulating fluidized bed combustor (because $P_{comb}<P_{max}$). This will lead to lower equipment cost in all the elements associated with the combustion island, at the expense of an increase in the cost of the storage system, as will be discussed below.

A conceptual design of the proposed system has been carried out by solving the mass and energy balances for some reference cases assuming reasonable silo dimensions and energy storage cycle durations. In order to illustrate the different possible operation modes, a sensitivity analysis of the main variables that may affect the system has also been performed. To facilitate a transparent examination of the main assumptions, this work focusses on the thermal power outputs of the heat exchangers of Figure 1. A detailed integration of these heat flows with steam power cycles is considered outside the scope of the present work and will be the subject of future investigation.

The conceptual design of the system in Figure 1 is based on four main variables. These are the thermal input to the combustor (P_{comb}), the power output delivered during the minimum and maximum power periods (P_{min} and P_{max} respectively) and the operating time at maximum power output (t_{max} at P_{max}). Before defining the reference values corresponding to these variables, we shall discuss their implications for the operation of the system.

The thermal input to the combustor (P_{comb}) defines the size of the combustor chamber (the cross-sectional area of CFBC is proportional to P_{comb}) and the scale of all auxiliary equipment linked to the combustion of coal (including the scale of the air separation unit and the CO_2 purification and compression units in oxy-fired CFBCs). This parameter also defines the size of the heat exchangers $FBHX_1$ and HX_1.

In principle, the thermal power delivered in maximum conditions (P_{max}) can be freely chosen within the conservative limits imposed by the volume of the silos, the properties of the circulating solids (bulk density and heat capacity) and by the temperature of the solids stored in the silos. Critically, P_{max} defines the scale of the second fluidized bed heat exchanger ($FBHX_2$). It is convenient to introduce at this point the concept of the power ratio (PR) which is defined as:

$$PR = \frac{P_{comb}}{P_{max}} \tag{1}$$

In the case of a conventional power plant, PR=1 because $P_{comb}=P_{max}$. Therefore, when the plant of Figure 1 is operating in extreme design conditions (only at P_{max} or P_{min}), a full charge and discharge cycle in the energy storage system consists of two steps: the loading of the high temperature silo with high temperature solids from the CFBC while minimum power (P_{min}) is delivered and the discharge from this silo at maximum power (P_{max}) while the cooled solids are being stored in the low temperature silo. The thermal energy released from the high temperature silo during high demand periods needs to be the same as that stored during low demand periods. Thus:

$$(P_{max} - P_{comb})t_{max} = (P_{comb} - P_{min})\, t_{min} \qquad (2)$$

where t_{max} is the operating time at maximum power and t_{min} is the operating time at minimum power required to charge the silo with hot solids so that it is ready for the next discharge period with a thermal output of P_{max}. Rearranging:

$$\frac{t_{max}}{t_{min}} = \left(\frac{1 - P_{min}/P_{comb}}{1/PR - 1}\right) \qquad (3)$$

Figure 2 shows the effect of the maximum power delivered during a period of high demand (P_{max}) on t_{max}/t_{min}. High values of P_{max} imply the need to release the energy stored in a short period of time as this will lead to low t_{max}/t_{min} ratios. Figure 2 also shows that the ratio t_{max}/t_{min} is higher for the systems with lower P_{min} as more energy can be stored during low demand periods.

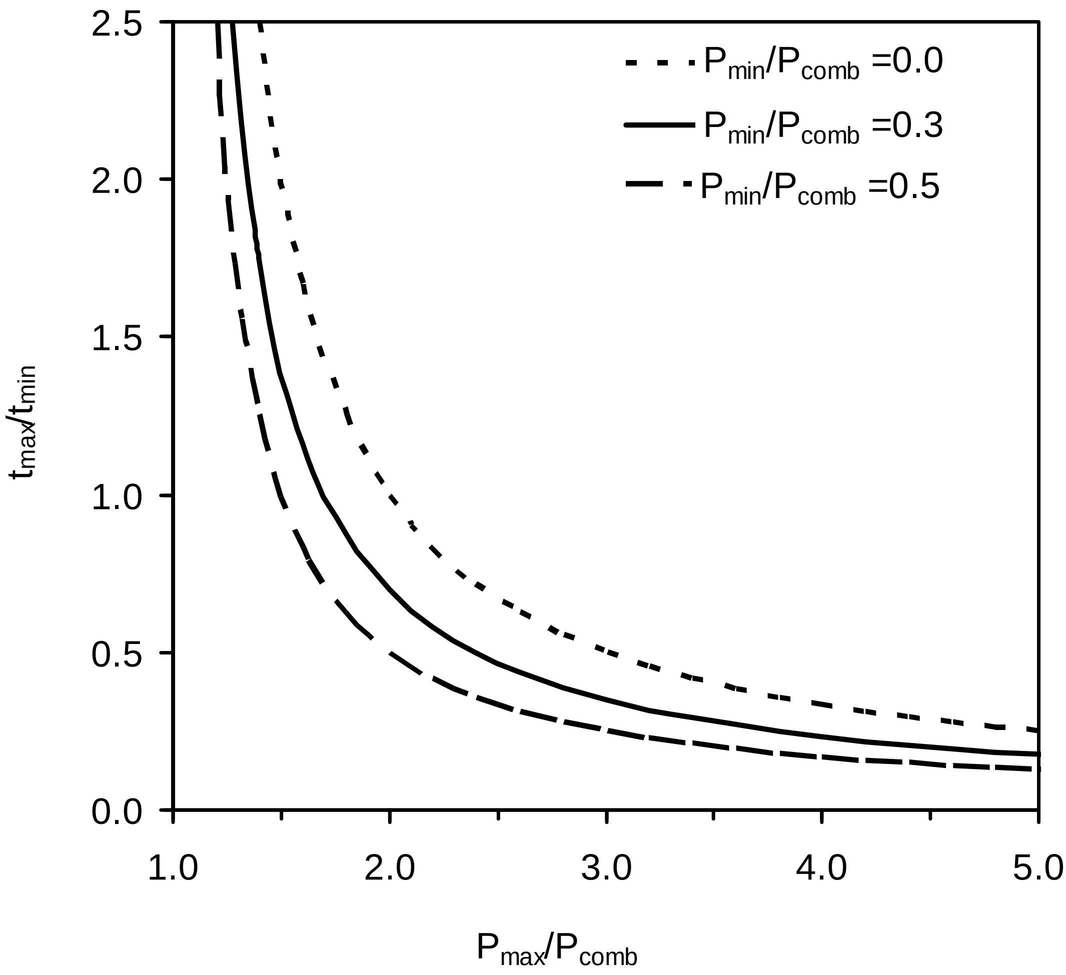

Figure 2. Power ratio and t_{max}/t_{min} ratio as a function of P_{max}/P_{comb} for different values of P_{min}/P_{comb}.

The choice of an operating time (t_{max}) to operate at maximum power P_{max} is the key variable for assigning dimensions to the solid storage silos of Figure 1, together with the thermal properties of the stored solids and the temperature difference between the high and the low temperature silo, that define the energy storage density (ESD):

$$ESD = \rho_s \, c_{ps} \, (T_{HTS} - T_{LTS}) \quad (4)$$

where ρ_s is the bulk density of the solids, c_{ps} is the heat capacity of the solids, and T_{HTS} and T_{LTS} are the temperatures of the high and low temperature silos respectively. Heat losses from this type of silo with a low surface-to-volume ratio and solids with a low thermal conductivity can be ignored in this study. We also assumed that the intrusion of air to the high temperature silo can be minimized to avoid the combustion of the char present in the inventory of solids circulating in the CFBC system. Therefore, T_{HTS} is determined by the operation temperature in the CFB combustor and T_{LTS} by the temperature of the solids leaving the series of fluidized bed exchanger $FBHX_2$.

To illustrate a simple conceptual design case, a reference CFBC power plant with a combustion thermal input (P_{comb}) normalized to 100 MW_t is used as reference. A bituminous coal (C=65%wt, H=3%wt, S=1%wt, O=8%wt N=1%wt, H_2O=7%wt, Ash=15%wt, LHV=26.3 MJ/kg) is burned in the combustor using a mixture of O_2/CO_2 with 30% oxygen at a temperature of 900 ºC. The combustion is carried out with an oxygen excess of 6% and an oxygen supply of 7.7kg/s is delivered by the ASU for this purpose. The flue gas flow of 35.8 kg/s leaving the combustor transports 9.1 kg/s of CO_2 to be compressed and stored. For the combustor chamber, we have assumed a typical gas velocity of 5 m/s that gives a cross-section of 16.4 m^2. The solids stored in the silos and circulating through the combustor could be a mixture of ash and calcium derived solids that are routinely used in CFBCs as SO_2 sorbents. However, in order to minimize the volume of the silos, it would be preferable to run the system using a circulation of low cost inert solids of high particle density such as ilmenite or olivine. A certain make-up of inert dense solids (not shown in Figure 1 for simplicity) will be needed and/or a device to separate a substantial fraction of the coal ash from the denser solids used as heat carrier. For this design exercise, we have assumed that the solids circulating through the combustor and stored in the silos are composed mainly of ilmenite with an average heat capacity of 1300 J/kgºC and a bulk density of 2400 kg/m^3 [40].

As pointed out above, the combustor is designed to operate as an adiabatic reactor. Therefore, most of the power released during combustion is transferred to the circulating stream of solids. In order to minimize the fraction of power that abandons the system with the flue gas, part of this power is used to preheat the comburent up to a temperature of 350 ºC. This leaves a power of 29.7 MW_t available in the HX_1 which is the minimum power (P_{min}) during low demand periods and a ratio P_{min}/P_{comb} of 0.297.

It is important to note that the power plant has internal power consumption requirements due to the air separation unit (ASU), CO_2 compression and purification units (CPU), and the power plant auxiliaries that must be met even during low demand periods. Assuming a typical specific energy consumption of 160 kWh_e/t_{O2} in the ASU and 100 kWh_e/t_{CO2} in the CPU [41], 5% of the gross electric power output (P_{max}) for the auxiliaries [42] and 45% net efficiency for the steam cycle, the thermal energy requirements for this internal electricity consumption will be 27.1 MW_t. This almost matches the thermal power available from HX_1, which means that during minimum electricity demand periods, the CCS plant can consume all the electricity that is generated from the thermal output from HX_1 and it should be possible to reduce the electricity flow to the grid to almost zero.

The solids circulation rate through the combustor has been fixed at a value of 15 kg/m^2s which is in the range of typical CFB combustors [43]. In order to extract 70.3 MW_t from the circulation of solids leaving the combustor (245.8 kg/s), the temperature of the solids at the exit of the heat exchanger ($FBHX_1$) needs to be around 680 ºC.

In order to design the volume of the silos, a maximum power output (P_{max}) of 200 MW_t is assumed. This results in a power ratio of 0.5 and a t_{max}/t_{min} ratio of 0.7 according to Eq. 3. The volume of the silos is proportional to the time t_{max} that the plant needs to be operating at P_{max} without interruption. There are typically two peak periods (early morning and evening) in the electricity demand curves in most countries, separated by several hours of lower activity. However, as stated in the Introduction, a flexible power generation system with energy storage devices needs to be ready to operate at P_{max} randomly, during periods of normal electricity demand on the assumption that there will be gaps in the electricity supply due to renewables intermittency or other variable power sources. In this particular reference example, the silos have been designed to operate at maximum power (t_{max}) during a period of just 2 hours (equivalent to 200 MWh_t), which must be followed by a period of 2.8 h at P_{min} with a maximum frequency of 5 charge/discharge periods per day. Obviously, if higher frequencies between the charge and discharge modes of operation are desired, t_{max} and the volume of the silos can be reduced. The energy storage density (ESD) will be 607 kWh_t/m^3 (assuming 200 ºC to be the temperature of the cold solids leaving $FBHX_2$). The volume needed for the silos will then be 330 m^3. A cross-section of 16.5 m^2 has been calculated for the silos assuming they will have a height of 20 m to allow for the inclusion of the high temperature silo between the discharge point of the cyclone and the inlet point of solids entering the combustor. This cross-section compares reasonably well with that corresponding to the combustor delivering P_{comb} (16.4 m^2).

Table 1 shows the main mass flow streams and the power available from the different heat exchangers during operation in maximum, minimum and normal (without using the energy storage system) modes. During t_{max}, part of the total solids circulation (G_{Ssilo}= 6.7 kg/m^2s referred to the cross-sectional area of the CFBC) is diverted towards the $FBHX_2$ heat exchanger. The rest of the solids circulating from the combustor (equivalent to 8.3 kg/m^2s) and the solids from the high temperature silo are fed to the main heat exchanger ($FBHX_1$) to ensure a solids flow of G_{SCFBC}=15 kg/m^2s through the combustor and the delivery of 70.3 MW_t by $FBHX_1$.

Table 1. Main mass flows involved in the systems depicted in Figure 1 and 4 and

the power delivered under the different operation modes.

	PR=0.5						**PR=0.2**					
	Normal		**Maximum power**		**Minimum power**		**Normal**		**Maximum power**		**Minimum power**	
	Mass flow	**Temp.**	**Mass flow**	**Temp.**	**Mass flow**	**Temp.**	**Mass flow**	**Temp.**	**Mass flow**	**Temp.**	**Mass flow**	**Temp.**
Stream	kg/s	ºC	kg/s	ºC	kg/s	ºC	kg/s	ºC	kg/s	ºC	kg/s	ºC
1	3.8	20	3.8	20	3.8	20	3.8	20	3.8	20	3.8	20
2	32.3	350	32.3	350	32.3	350	32.3	350	32.3	350	32.3	350
3	35.8	900	35.8	900	35.8	900	35.8	900	35.8	900	35.8	900
4	245.8	900	135.9	900	0	0	245.8	900	245.8	900	0	0
5	0	0	0	0	168.6	900	0	0	0	0	168.6	900
6	0	0	0	0	77.2	900	0	0	0	0	77.2	900
7	0	0	109.9	900	0	0	---	---	---	---	---	---
8	0	0	109.9	900	0	0	0	0	439.6	900	0	0
9	0	0	0	0	77.2	200	0	0	0	0	77.2	200
Power output												
HX_1	29.7		29.7		29.7		29.7		29.7		29.7	
$FBHX_1$	70.3		70.3		0		70.3		70.3		0	
$FBHX_2$	0		100.0		0		0		400		0	
Total	100		200		29.7		100		500		29.7	

The system has been designed with extreme power outputs in mind but it can also be operating for longer periods of time (see Figure 3b) at intermediate power outputs between P_{max} and P_{min} by adjusting the split of the solids flow from the CFBC (G_{SCFBC}) to the high and low temperature silos ($G_{S\ silo}$) (streams 6 and 8 in Figure 1 and dotted line of Figures 3a and 3b). This particular example has been chosen to illustrate that the thermal power output of the system can be adapted to virtually any shape in the demand curve by controlling the solids circulation ratios Gs_{silo}/Gs_{CFBC} while the combustion conditions in the oxy-CFBC are kept constant. This high level of flexibility can be achieved by means of methods and equipment used for the control and operation of external fluidized bed heat exchangers in commercial CFBC boilers [44, 45]

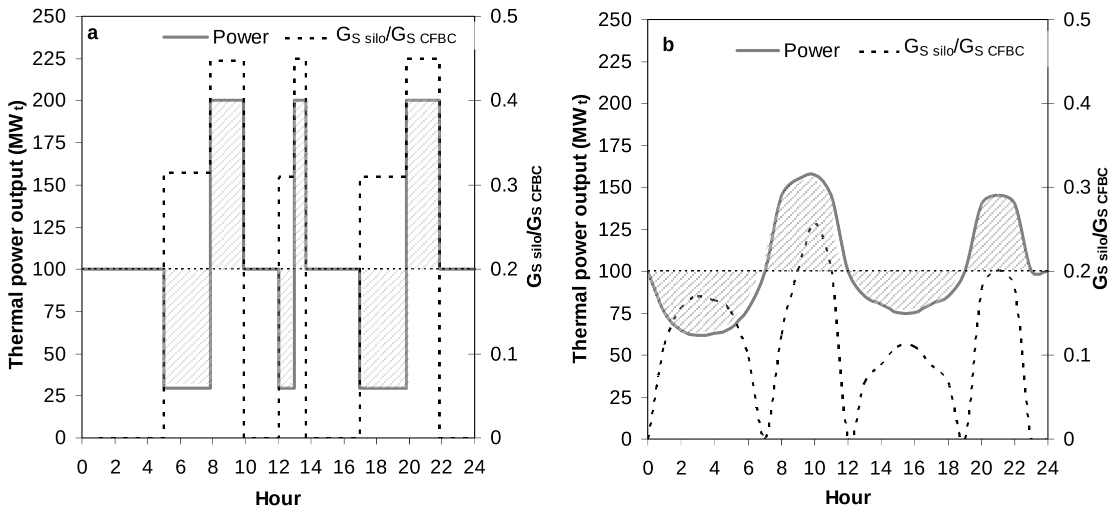

Figure 3. Examples of thermal power output curves of the system with a power ratio of 0.5 of Table 1: a) operating the system to fit peaks of maximum power output; b) operating the system to follow a curve of power output by adjusting solids circulation ratios in the system (dotted line).

Table 1 also includes the conditions corresponding to a different design case with an even lower power ratio (PR=0.2) for a system intended to operate at a maximum power of 500 MW_t (P_{max}) for a maximum of 2.5 hours followed by a long period of time at P_{min} where the high temperature silo is charged overnight for 12 hours. The remaining time (9.5 hours) could be used in this particular example for the operation at P_{comb} (to cover, for example, the period between the morning and night peaks) or for recharging the high temperature silo and increasing the duration of the night peak at P_{max}.

As can be seen from the new scheme in Figure 4 based on a design with a PR=0.2, the scale of the full oxy-fired CFBC subsystem (including ASU and CPU) has been considerably reduced (as P_{comb} is only 1/5 of P_{max}), while the relative volume of the silos and its associated heat exchanger have been increased. This makes it necessary to redesign the method to increase the amount of solids circulating in the system as the solids flow between the silos will have to increase to over 439.6 kg/s (see Table 1) in order to allow a much larger thermal power output from $FBHX_2$. In these conditions, it will probably be necessary to set up two separate steam cycles (one standard cycle for the oxy-CFBC marked in grey in Figure 4, to deal with the sum of HX_1 and $FBHX_1$ power outputs) and a second steam cycle driven by the stream of hot solids flowing through $FBHX_2$. As indicated in Figure 4, this large $FBHX_2$ could be located below the high temperature silo and be connected to an independent transport line of cold solids to the top of the low temperature silo.

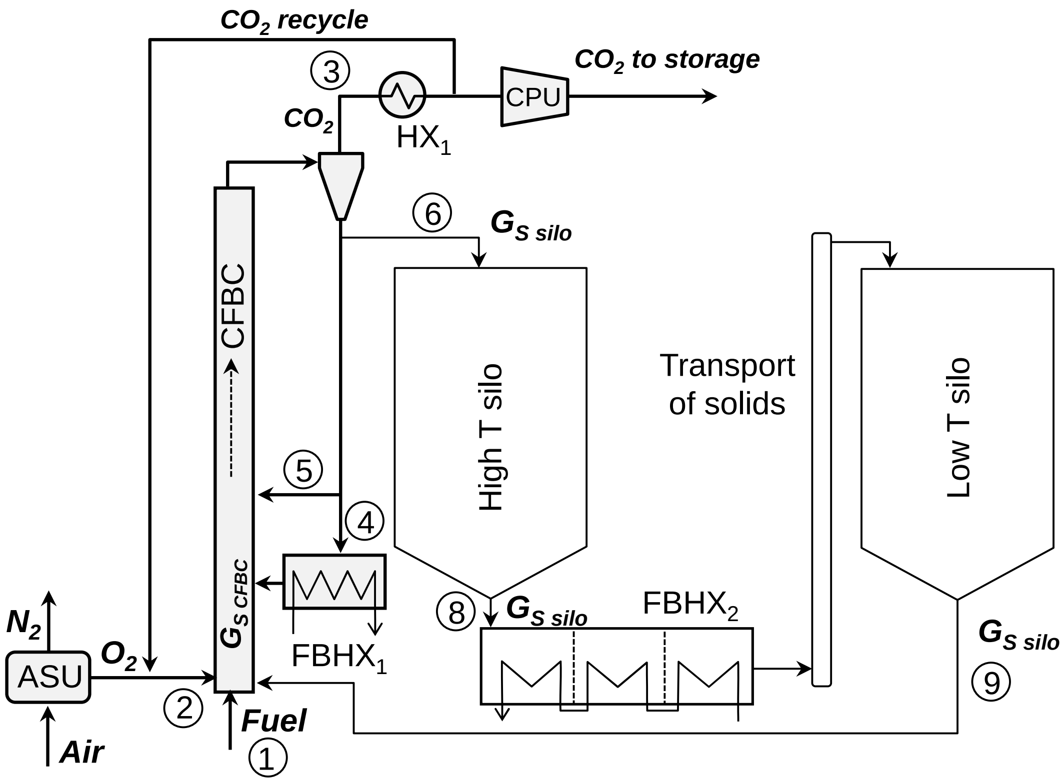

Figure 4. Scheme of the proposed Oxy-CFBC power plant concept with energy storage with a PR=0.2.

As will be discussed below, this system could be economically interesting in certain market conditions because the contribution to the overall specific equipment cost of the first subsystem (the costly CCS part marked in grey in Figure 4) is relatively small compared to the contribution required by the subsystem with the lower specific equipment cost (the silos and the steam cycle driven by P_{max}). As will be discussed below, although a low power ratio (PR=0.2) will always be detrimental to specific electricity costs, the advantage of such a system is that it could be used to cover short by highly rewarding peaks. To our knowledge, no other CCS system could operate with such a low capacity factor without incurring very severe economic penalties.

3. Cost analysis

A basic economic analysis has been carried out in order to explain the cost structure of the proposed system and the conditions that must be met for the system to be viable with respect to existing CFBC power plant designs (oxy-fired and air-fired). The cost of electricity (COE) has been estimated for all the systems using the following equation for a levelized cost [1]:

$$\mathrm{COE} = \frac{\mathrm{TCR} \times \mathrm{FCF} + \mathrm{FOM}}{\mathrm{CF} \times 8760} + \mathrm{VOM} + \frac{\mathrm{FC}}{\eta} \qquad (5)$$

where TCR is the specific total capital requirement to build any of the power plants discussed below, FCF is the fixed charge factor, FOM are the fixed operating costs, VOM are the variable operating costs, FC the fuel cost and η is the net plant energy efficiency.

The cost of CO_2 avoided (AC) [1] in oxy-fired CO_2 capture systems is used to quantify the cost of reducing CO_2 emissions by one unit (usually one tonne of CO_2) while delivering the same amount of power as a reference plant without CO_2 capture, and is defined as:

$$\mathrm{AC} = \frac{\mathrm{COE}_{\mathrm{capture}} - \mathrm{COE}_{\mathrm{ref}}}{\left(\mathrm{CO_2 kWh_e^{-1}}\right)_{\mathrm{ref}} - \left(\mathrm{CO_2 kWh_e^{-1}}\right)_{\mathrm{capture}}} \qquad (6)$$

where $CO_2kWh_e^{-1}$ is the CO_2 mass emission rate per kWh_e. The application of these equations to a CFBC and oxy-CFBC without energy storage is straight forward because there is sufficient aggregated cost information on TCR for both air fired and oxy-fired CFBC power plants [10, 35, 46-48]. For reference purposes, we have chosen representative numbers for all these variables as shown in Table 2, based on detailed reports by Naskala et al. [35] and DOE [48] because these two studies provide detailed costs of the components of power plants, that will be used below to discuss the TCR of the power plants with energy storage represented Figure 1 and 4.

Table 2. Summary of cost assumptions for the CFBC power plants without energy storage.

		Oxy-fired	Air-fired (ref)
Reference plants without energy storage			
Total capital requirements, TCR	$\$/kW_e$ ($\$/kW_t$)	3600 (1296)	2000 (900)
Fixed fraction cost, FOM	$\$/kW_e$	50	35
Fixed charge factor, FCF	yr^{-1}	0.1	0.1
Variable cost, VOM	$\$/kWh_e$	0.007	0.005
Fuel cost, FC	\$/GJ	3	3
Capacity factor, CF		0.9	0.9
Net plan efficiency, η	kW_e/kW_t	0.36	0.45
CO_2 emission factor, $CO_2kWh_e^{-1}$	t_{CO2}/MWh_e	0.045*	0.724
COE	$\$/kWh_e$	0.087	0.057
AC	$\$/t_{CO2}$	43.2	---

*For a 90% of capture efficiency

We have assumed that the fuel cost, the net energy efficiencies and the fixed and variable operating costs reported in Table 2, are the same for all systems considered in this work. The focus in the following paragraph is on estimating the TCR and CF variables of equation (5) for the different systems considered.

For convenience, the discussion that follows is based on the specific cost of equipment per unit of thermal power (kW_t) as can be seen in Table 2 with the numbers in brackets referring to the reference systems. In these conditions, the total cost ($) of a complete system incorporating energy storage that must be able to generate a maximum thermal power output of P_{max} is simply TCR P_{max}. To estimate the value of TCR ($/kW$_t$), three main components of the power plant with the energy storage system are considered:

- $TCR_{Power\ w/o\ Comb}$. This is the specific capital requirement to build a power plant excluding the equipment related with the fuel combustion (TCR_{Comb}). Therefore, this comprises the full steam cycle (i.e. steam turbine and feed and cooling water systems) for absorbing a thermal power of P_{max}. It also includes all the costs related to the conditioning of the site, the building of the structures, the instrumentation and control and accessory electric plant.
- TCR_{Comb}. This is the specific capital requirement of all the fuel combustion equipment for delivering a thermal power given by P_{comb} (i.e. equipment marked in grey in Figures 1 and 4). This includes all the equipment associated with the combustion chamber (including $FBHX_1$, $HX_1$and the fans used for fluidization), the fuel feeding system, the flue gas cleaning, ash handling and the ASU and CPU units in the oxy-fired systems. According to the data available in the literature [35], this capital requirement represents about 60% of the total TCR of an oxy-CFBC power plant and about 50 % of the total TCR of an air-fired CFBC power plant. As indicated in Table 3, we have assumed that the P_{comb} is sufficiently large to yield identical specific capital costs to those reported in Table 2 for standalone power plants designed for the same thermal output.
- $TCR_{Storage.}$ This is all the equipment necessary to deliver a thermal power of P_{max}-P_{comb} (mainly the power generation equipment related to $FBHX_2$, the

two silos and their solids transport equipment). Therefore, the scale of the equipment (and its total capital cost) is assumed to be proportional to P_{max}-P_{comb}.

In these conditions the total cost of the energy storage system of Figures 1 or 4, designed to deliver a maximum thermal power P_{max} will be:

$$TCR\ P_{max} = TCR_{Power\,w/o\,Comb}\,P_{max} + TCR_{Comb}P_{comb} + TCR_{Storage}\left(P_{max} - P_{comb}\right) \qquad (7)$$

or:

$$TCR = TCR_{Power\,w/o\,Comb} + TCR_{Comb}PR + TCR_{Storage}\left(1 - PR\right) \qquad (8)$$

The estimation of $TCR_{Storage}$ is uncertain. On the basis of similar components in existing power systems and/or cement plants handling large flows of similar materials, the cost can be split into three main equipment cost components:

$$TCR_{Storage} = TCR_{FBHX2} + TCR_{Solids\ handling} + 2\,TCR_{Silo}\,t_{max} \qquad (9)$$

In oxy-CFB power plants, the largest fraction of the heat is extracted from the boiler and mainly from the external heat exchangers. The specific cost of $FBHX_2$ (TCR_{FBHX2}) is assumed to be identical to the cost of the boiler of an oxy-CFBC power plant. This assumption can be considered conservative and is supported by the fact that $FBHX_2$ is mechanically and thermally similar to the equipment used today in power plants incorporating external fluidized bed heat exchanger technologies [29, 33, 38]. Furthermore, in accordance with reference [35, 48], the cost of the boiler in an oxy-CFBC power plant represents approximately 15% of the total TCR of the plant.

The specific equipment cost of the solids handling, $TCR_{Solid\ handling}$ in the energy storage system has been assumed to be zero for the system in Figure 1 because the circulating fluidized bed combustor has already incorporated the necessary transport of solids from the bottom of the silos to the top of the silos. However, for the system with a PR lower than 0.2 represented in Figure 4, the solids circulation rate required throughout the CFBC takes on a value of more than 25 kg/m^2s and it would be appropriate therefore to incorporate an additional transport line of cold solids leaving $FBHX_2$ to the top of the low temperature silo. The specific cost for this equipment is assumed to be 20 $/(kg/h) the same value as that of reference [49] for typical equipment in cement plants used to transport the clinker from the cooler to the storage silo. This specific cost can be considered conservative because it is likely to go down in view of the large scale of the solids handling in the energy storage system of Figure 4. In order to change this figure into the units of Table 3 ($TCR_{Solids\ handling}$ of 79.2 $/$kW_t$), we have assumed the equipment cost to be proportional to the solids circulation flows Gs_{silo} in Figure 1 or 4 required to transfer one kW_t from the high temperature silo to the low temperature silo ($1.1*10^{-3}$ kg/s for the solids used in this work with a heat capacity of 1300 J/kgºC and a difference of temperature between the silos of 700 ºC).

Finally, the specific cost of the high temperature and low temperature silos is assumed to be 1.5 $/kg which is similar to the specific cost of silos used to store the ashes extracted from coal boilers [35, 48]. As in the case of the solids handling equipment, the TCR_{Silo} value of 5.9 $/$kWh_t$ adopted in Table 3 was obtained for the typical design base reported in the previous sections (3.95 kg of stored solids to satisfy an energy storage of 1 kWh_t, for the solids used in this work with a heat capacity of 1300 J/kgºC and a difference of temperature between silos of 700 ºC).

Now that the methodology used to estimate TCR has been discussed, it is important to consider again the definition of the capacity factor (CF in eq. 5) with reference to the different systems employed in this work. For the reference cases of Table 2, the value of $CF=CF_{comb}=0.9$ is a standard capacity factor value for power plants with a "base load". It indicates the ratio between the energy produced over the year (for example in kWh_e of electricity) divided by the maximum energy that could be produced if the plant were operating at full load all year. However, the value of CF in the energy storage systems must take into account that "full load" at the maximum power P_{max} is only available for a certain period of time even when the combustor is operating continuously at P_{comb}. Therefore:

$$CF = CF_{Comb} PR \tag{10}$$

which shows once again that the systems incorporating energy storage are limited (by PR) to the fraction of time during which they can deliver full power.

Another important difference between Table 2 and Table 3 concerns the choice of net plant efficiency for the different systems compared in this work. It is well known that lower values of CF are associated to relevant energy penalties when a low CF is linked to part load operation. The penalty would be less severe if the CF was linked to long periods at full load followed by long shut-down periods. It is beyond the scope of this conceptual paper to analyse the dependencies of the net power efficiencies with CF. Therefore, all efficiencies in Table 3 are assumed to be identical to the reference systems at high CF and the comparison of cost that follows in the following paragraphs focuses on relative differences between systems at identical CF (which are likely to have similar penalties associated to the low CF).

The application of the previous assumptions and equations to estimate the costs reported in Table 3 allows a preliminary comparison of costs for the systems without energy storage reported in Table 2. As expected, the COE is substantially higher in the cases chosen as examples of systems incorporating energy storage with respect to the reference plants in Table 2 operating with a large CF. However, this is essentially because the systems being compared have very different overall CFs. A power plant with no energy storage will deliver electricity at the lowest cost if, and only if, the capacity factor of the plant is sufficiently high. However, the reverse applies when similar capacity factors are considered.

Table 3. Summary of cost assumptions for the CFBC power plants with energy storage for different power storage ratios (PR), using a CF_{comb}=0.9, and FC, VOM and FCF values as in Table 2

Reference plants with energy storage		Air-fired PR=0.2	Oxy-fired PR=0.5	Oxy-fired PR=0.2
Type of system		Figure 4	Figure 1	Figure 4
TCR	$/kW$_t$	782	1016	916
$TCR_{Power\ w/o\ Comb}$	$/kW$_t$	450	518	518
TCR_{Comb}	$/kW$_t$	450	778	778
$TCR_{Storage}$ (Eq. 9)	$/kW$_t$	303	218	303
TCR_{FBHX2}	$/kW$_t$	194	194	194
$TCR_{Solid\ handling}$	$/kW$_t$	79	0	79
TCR_{Silo}	$/kWh$_t$	5.9	5.9	5.9
t_{max}	h	2.5	2	2.5
Capacity factor, CF_{comb} PR		0.18	0.45	0.45
Net plan efficiency, η	kW_e/kW_t	0.45	0.36	0.36
CO_2 emission factor, $CO_2kWh_e^{-1}$	t_{CO2}/MWh_e	0.724	0.045*	0.045*
COE	$/kWh$_e$	0.157	0.118	0.233
AC	$/t$_{CO2}$	---	45.9 (88.9**)	71.7 (243.5**)

*For a 90% capture efficiency

** For PR=1 in the reference plant and CF=0.9

Figure 5 compares the cost of electricity produced by a CFBC power plant as a function of the capacity factor for oxy-fired and air-fired systems with and without storage. Since PR=1 for the systems without energy storage, the reduction in the capacity factor comes from the reduction in CF_{comb} and the COE rapidly escalates to high values as CF decreases, especially in the case of the oxy-fired CFBC since the costly equipment is underused for low values of CF_{comb}. In contrast, for the three systems with energy storage, where CF_{comb} remains constant, the impact of the lower capacity factor is in the decreasing values of the power storage ratio (PR). Since a decrease in this power ratio increases the contribution of the lower cost components of the system ($TCR_{Storage}$ is lower than TCR_{Comb}) to the total power plant cost TCR (Eq. 8), the levelized cost of electricity increases less sharply than in the case of power plants without energy storage.

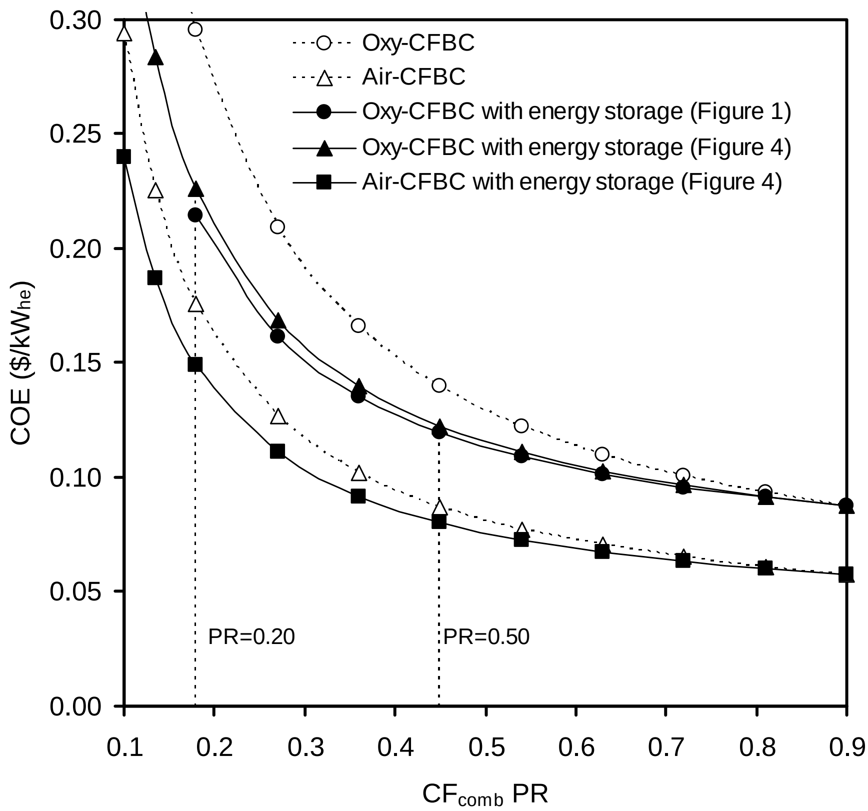

Figure 5. Cost of the electricity (COE) as a function of the capacity factors of the systems in Table 2 and 3. Dotted lines: reference systems (air and oxy-CFBC with PR=1).

Figure 5 indicates that, if a power plant is designed to operate in a market with low capacity factors (low $CF=CF_{comb}$), a system that incorporates energy storage with the same overall capacity factor (CF) achieved with the maximum technical value of CF_{comb} but lower values of PR should be cost effective. The differences in COE are larger for oxy-fired power plants with energy storage than for similar oxy-fired systems, in Table 2 that operate with a low CF_{comb}. The difference in COE in the case of air-fired systems is less favorable to energy storage systems. This indicates that the storage system proposed in this work would be a good alternative if cost intensive oxy-fired CO_2 capture systems operated with low capacity factors, since the impact of low PR in reducing the average TCR of the systems would be greater (see Eq. 8). For a given capacity factor, the COE of the system depicted in Figure 1 is slightly lower than that of Figure 4, as there is no need of a solid handling system.

It is important to point out that the costs of the electricity presented in Table 3 and Figure 5 for the power plants incorporating an energy storage system have been calculated assuming that the CF_{Comb} is 0.9 as the combustor can operate continuously irrespective of the power output. The cost benefits of this steady state operation in the combustion part of the system (and all the remaining auxiliaries) have not been quantified in the simple cost analysis carried out above on the systems with energy storage. Therefore, it could be argued that the cost estimates considered in the previous paragraphs are too conservative and that we have been somewhat pessimistic in our cost assumptions for these energy storage systems.

To turn to the differences in avoided cost of CO_2 obtained with Eq. 6, it is important to choose an adequate reference plant without capture. Generally, this is a power plant of the same type and design as the plant with CO_2 capture [1, 10]. Therefore, for this study an air-fired CFBC power plant was selected as reference. The results for the avoided costs in Tables 2 and 3 and in Figure 6 have been calculated assuming that the reference power plant operates with the same capacity factor as the oxy-CFBC systems with and without energy storage. For a conventional oxy-CFBC power plant operating at “base load” with a CF=0.9, the cost of CO_2 avoided is 43.2 $\$/t_{CO2}$. However, the AC for this type of power plants increases sharply as the capacity factor decreases in accordance with the evolution of the COE with CF as shown in

Figure 5.

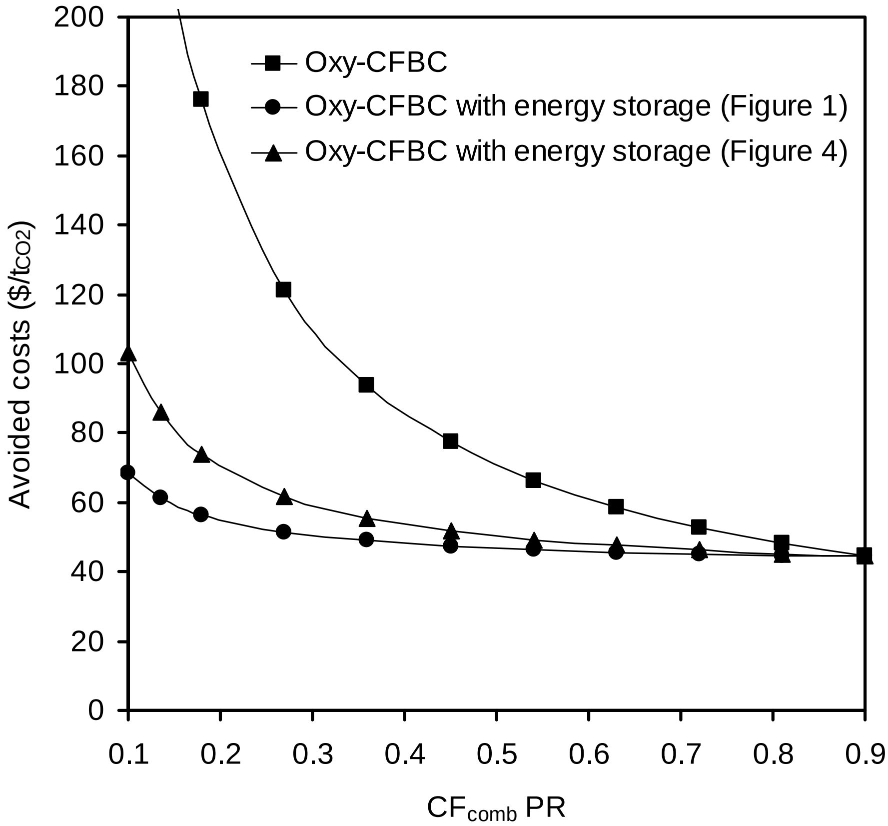

Figure 6. Cost of CO_2 avoided as a function of the capacity factors of the systems in Table 2 and 3.

In the case of the oxy-CFBC power plants with energy storage, the increase in the cost of avoided CO_2 with CF is less pronounced. This is due to the lower increase in the COE with CF for these systems. This is obviously linked to the assumption that the capacity factor in the energy storage system is the same as that in the reference plant. As mentioned above, the energy storage systems discussed in this work would be less economical than the reference plants if the reference plants were allowed to work with very high capacity factors (see cost of AC in brackets in Table 3). But from Figure 6, it can be seen that standard oxy-fuel combustion systems would also be uneconomical, and possibly technically unviable if they operate with low capacity factors and/or very large load changes.

An important point to bear in mind when comparing the COE and cost of CO_2 avoided of the different systems in Figures 5 and 6 is that the CF value in the reference system without energy storage can change over the whole scale of capacity factors (i.e. the power plant could be operated at different periods of time with different capacity factors). In contrast, with the energy storage system, the average capacity factor is an irreversible design choice that cannot be increased beyond the value of PR adopted when designing the storage equipment. This is obviously a constraint that will favor the standard systems (without energy storage) when there is a lot of uncertainty in the electricity markets, though there is a substantial probability of high capacity factors. The value of this additional flexibility in the standard systems is not represented in Figures 5 and 6, and could sway decisions in favor of the standard systems (with no energy storage) when capacity factors are much higher than CF=0.5. However, the differences in COE and avoided costs are substantial when capacity factors are below 0.5 and increase if there is a further decrease in CF. Therefore, in view of the uncertainties and trends discussed above, we can conclude that there is a wide range of conditions in which the systems with energy storage will be competitive.

4. Conclusions

Circulating fluidized bed combustor power plants, CFBC, in particular those operating under oxy-fired conditions have limited flexibility for both technical and economic reasons associated to the large impact of the capacity factor on energy cost. The ability of CFBCs to handle and circulate large flows of high temperature materials makes it possible to design a large scale thermal energy storage system composed of two solid storage silos connected to the circulating fluidized bed combustor. The thermal energy stored in the high temperature silo of solids during low power demand periods can generate a large amount of thermal power even with a small circulating fluidized bed combustor. This is particularly important for highly integrated and costly oxy-fired CFBC. During low power demand periods, the CFBC is fed by a low temperature stream of solids from a silo while the high temperature solids circulating in the combustor are stored in the high temperature silo. In this study, two conceptual designs of energy storage systems in oxy-CFBC power plants able to deliver between 2 and 5 times the nominal thermal power capacity of the combustor have been carried out to illustrate the flexibility in power outputs that can be achieved by controlling the solid circulation rates between the silos and through the combustor. With a constant combustion conditions and a coal feeding rate equivalent to $100MW_t$ in the CFBC, the system should be able to modify the power output between a minimum of 29.7 MW_t and a maximum of 200 and 500 MW_t, respectively.

According to a preliminary cost analysis of these design examples, there is a clear window of opportunity for these systems to be competitive in markets where the power plants (with or without CO_2 capture) are forced to operate at very low capacity factors, CF. This is because the specific capital cost of the energy storage components of the system (heat exchanger + silos + solids handling at low temperature) appears to be lower than that of equivalent fuel combustion equipment in conventional power plants. For oxy-CFBC power plants incorporating energy storage with an overall capacity factor below 0.45, the cost of electricity appears to be highly competitive compared to the cost of the electricity produced by an equivalent system without energy storage. On the other hand, costs are always higher in systems with energy storage when compared to systems without storage operating with very high capacity factors. Energy storage systems can operate at full load only during relatively short periods of time with respect to other periods when the thermal energy is stored in silos. The storage systems proposed in this work are especially attractive when cost intensive oxy-fired CFBC systems are forced to operate with low capacity factors. However, more research is clearly needed to close gaps of knowledge and cost uncertainties in the new concept.

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