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Techno-Economic Evaluations and Benchmarking of Pre-combustion CO_2 Capture and Oxy-fuel Processes Developed in the European ENCAP Project.

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Abstract

ENCAP (ENhanced CAPture of CO_2) is a major technology development project under the 6th Framework Programme of the European Commission, involving leading European power and energy industries and equipment suppliers, and high ranked research institutes and universities. The project aims at developing cost efficient pre-combustion CO_2 capture and oxy-fuel technologies for power generation based on fossil fuels, to substantially reduce the cost of CO_2 capture. The industries have established a set of defined baseline power plants without CO_2 capture for lignite, bituminous coal, pet-coke and natural gas, and boundaries for technical and economic analysis. Of several concepts for power plants with CO_2 capture, developed in ENCAP, the most promising have been evaluated, compared and benchmarked with respect to technical performance, costs and level of technical maturity versus needs for further R&D and technical risks.

Keywords: Clean fossil fuels; IGCC; IRCC; Pre-combustion; CO_2 Capture; Decarbonisation; Oxy-fuel; CLC; Chemical Looping Combustion; ENCAP

1. Introduction

ENCAP (ENhanced CAPture of CO_2) is a 22 M€ technology development project under the 6th Framework Programme of the European Commission, involving European power and energy industries, equipment suppliers, research institutes and universities. The project aims at developing cost efficient pre-combustion CO_2 capture and oxy-fuel technologies for power generation based on fossil fuels, to substantially reduce the cost of CO_2 capture. ENCAP targets at least 90% CO_2 capture rate and 50% CO_2 capture cost reduction, compared to typically 50 – 60 € per tonne CO_2 reported before the project started early 2004 (see e.g. IPCC[1] or CCP[2]).

The industries have established a common framework for the development and evaluation of concepts for power plants with CO_2 capture, including a set of defined baseline power plants without CO_2 capture for lignite, bituminous coal, pet-coke and natural gas, as well as boundaries for technical and economic analysis. Of several concepts for power plants with CO_2 capture, developed in ENCAP, the most promising have been evaluated, compared and benchmarked with respect to technical

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performance, costs and level of technical maturity versus needs for further R&D and technical risks. This paper describes the major results from these evaluations, which are reported in Ekström et. al. [3]

More information about the technologies and the development work performed within the SP:s (Sub-Projects), including links to several published scientific papers, can be found at the ENCAP project website [4].

2. Techno-economic evaluations and benchmarking

The evaluated technologies have different levels of maturity, resulting in that the power plant concepts with CO_2 capture have different time horizons of commercial availability. The *"1st" generation power plant concepts with CO_2 capture* – from SP2, Pre-Combustion Decarbonisation Technologies, and SP3, Oxy-Fuel Boiler Technologies - are the most investigated and developed, and are likely candidates for the first large scale demonstration projects in Europe, with the aim to bring to commercial readiness by year 2020. The *"More future" power plant concepts with CO_2 capture* – from SP4, Chemical Looping Combustion, SP5, High-Temperature Oxygen Generation for Power Cycles, and SP6, Novel Pre-Combustion (and Oxy-fuel) Capture Concepts - are more new, and therefore still less validated, than the "1st generation" concepts. Depending on the outcome of further optimisations and validations, they may however become valuable complements to the 1st generation technologies.

The results presented in this paper serve as a comparison of technologies. The technology and cost data for power plant concepts with and without CO_2 capture correspond to state-of-the-art year 2004, since most concept design work was performed during years 2004 and 2005. Fuel prices were chosen to be representative for large European power plants up to year 2004, and corresponded also well with long term projections available at that time, i.a. by IEA [5]. Plant equipment costs as well as fuel prices have however increased considerably during the latest years, resulting in that the absolute levels of calculated costs generally are lower than they would be if the investment and cost estimates had been performed during 2007 or 2008. Moreover, the estimates for novel and immature technologies are based mainly on R&D methods and not on vendor quotes, in some cases omitting or simplifying much of the costs related to civil, utility, electric, tie-in etc.

The concepts include the power plant with CO_2 capture and compression up to 110 bar, but not transport and storage of CO_2.

2.1. Bituminous coal and lignite fired power plant concepts

The evaluated power plant concepts with CO_2 capture, together with their corresponding reference power plant concepts without CO_2 capture, are summarized in Table 1.

Table 1. Evaluated bituminous coal and lignite fired power plant concepts with and without CO_2 capture.

Power Plant Concepts	**Bituminous coal**		**Lignite German*/Greek**	
	Gross, MWel	Net, MWel	Gross, MWel	Net, MWel
Ref. case: Steam cycle PF (Pulverized Fuel) fired power plant, state-of-the art year 2004	600	575	1000/385	920/335
"1^{st}" generation power plant concepts with CO_2 capture				
SP2 Pre-combustion: IGCC (Integrated Gasification Combined Cycle) with pre-combustion CO_2 capture and cryogenic ASU (Air Separation Unit) for oxygen production to the gasifier. Entrained flow gasifier (Shell) for bit. coal and fluidised bed gasifier (HTW, High Temperature Winkler) for lignite. [6] Two parallel F-class gas turbines in a combined cycle of the same type as natural gas fired combined cycles state-of-the art year 2004**	956	737	899/-	717/-
SP3 Oxy-fuel: Steam cycle Oxy-fuel PF plant with cryogenic ASU for oxygen production. [7] Same boiler sizes and steam cycle parameters as the PF reference cases.	633	472	1048/403	767/271
"More future" power plant concepts with CO_2 capture				
SP5 Oxy-fuel CAR: Steam cycle Oxy-fuel PF plant with CAR (Ceramic Autothermal Recovery) reactor for oxygen production. CAR is a BOC/Linde technology for separating air with a high temperature Pressure Swing Adsorption (PSA). [8] Same boiler size and steam cycle parameters as the PF reference case. Additional natural gas, corresponding to 207 MWfuel, (10% of total fuel input) is combusted for CAR absorber heating.	-	-	980/-	790/-

Power Plant Concepts	**Bituminous coal**		**Lignite German*/Greek**	
	Gross, MWel	Net, MWel	Gross, MWel	Net, MWel
Ref. case: Steam cycle CFB (Circulating Fluidized Bed) fired power plant, state-of-the art year 2004	445	403	-	-
"1st" generation power plant concepts with CO_2 capture				
SP3 Oxy-fuel: Steam cycle Oxy-fuel CFB plant with cryogenic ASU for oxygen production. [9] Same gross electricity output and steam cycle parameters as the CFB reference case.	445	327	-	-
"More future" power plant concepts with CO_2 capture				
SP4 CLC: Chemical looping combustion (CLC) based on CFB technology, with a steam power cycle. [10] Same fuel mass flow and steam cycle parameters as the CFB reference case.	455	387	-	-

*Pre-drying of lignite, from around 50% moisture down to 12%, with recovery of heat of evaporation, is included in all German lignite-fired concepts. Pre-drying technology is under demonstration by RWE Power.

** In the ENCAP project, development work has been performed, aiming at adaptation of burners for hydrogen rich gases to the design requirements of modern high temperature F-class gas turbines.

Compared to the reference cases, the major additional energy demands are:

- Pre-combustion IGCC; the cryogenic ASU, the conversion of raw syngas to hydrogen rich gas, the CO_2 separation, and the CO_2 compression.
- Oxy-fuel PF and CFB: the air separation processes - cryogenic ASU for the "1st generation" concepts and the natural gas combustion to heat the CAR absorber for the Oxy-Fuel PF CAR concept - and the CO_2 compression.
- CFB CLC concepts; mainly the CO_2 compression; only a small ASU is required.

The resulting net electric efficiencies for the bituminous coal fired concepts are presented in Table 2.

Table 2. Net electric efficiencies (calculated based on fuel LHV) for bituminous coal and lignite fired power plant concepts with CO_2 capture compared to the corresponding reference power plants without capture.

	Bituminous coal		**Lignite**	
Reference case: **Net electric efficiencies, %**	**Steam cycle 600 MW gross PF**	**Steam cycle 445 MW gross CFB**	**Steam cycle 1000 MW gross PF (German)**	**Steam cycle 385 MW gross PF (Greek)**
Reference case:	45	44	49*	42
SP2 Pre-combustion:	36	-	41*	-
SP3 Oxy-fuel:	36	37	41*	34
SP5 Oxy-fuel CAR:	-	-	38*	-
SP4 CLC:	-	42	-	-

*Pre-drying of lignite, from around 50% moisture down to 12%, with recovery of heat of evaporation, is included in all German lignite-fired concepts.

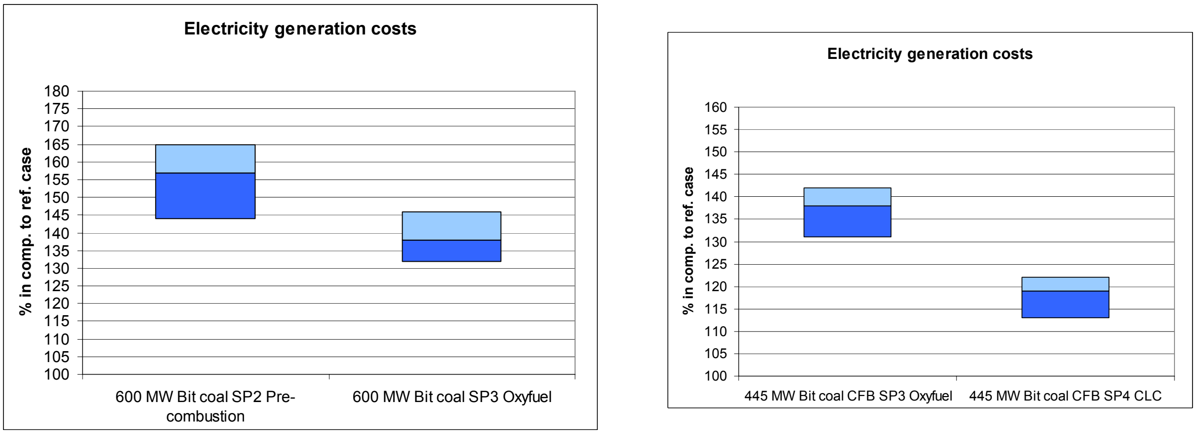
The specific investments for the power plant concepts with CO_2 capture increase compared to the corresponding reference cases, due to the net electric efficiency penalties and costs for additional and/or more expensive equipment.

The major cost increases compared to the corresponding reference cases are due to:

- Oxy-fuel PF and CFB concepts; additional equipments, mainly air separation processes - cryogenic ASU for the "1st generation" concepts and the CAR absorber for the Oxy-Fuel PF CAR concept - and CO_2 compression and conditioning.
- CFB CLC process uses to CFB reactors (compared to one CFB boiler for the reference case); also costs for a small ASU and CO_2 compression equipment. Oxygen carrier replacement for the CLC process adds to the O&M (Operation and Maintenance) costs.
- Pre-combustion IGCC; In total more expensive equipment, resulting in total specific investments that are slightly higher than for the oxy-fuel PF concepts, fired with the same fuel. Costly maintenance of gas turbines in general as well as high service costs estimated for gasifiers and gas conditioning units increase calculated O&M costs.

The net electric efficiency penalties of course also increase the fuel costs.

The calculated resulting electricity generation costs for the bituminous coal fired concepts with CO_2 capture, in relation to the corresponding reference cases, and their calculated CO_2 avoidance costs, are presented in Figures 1 and 2 respectively. The lignite fired concepts all show almost the same cost increases compared to their respective reference cases, similar to for the bituminous coal fired oxy-fuel PF. The cost differences between the bituminous coal fired pre-combustion IGCC and oxy-fuel PF concepts are however within the ranges of uncertainty that can be expected at the current level of development. The CO_2 avoidance costs vary analogously.

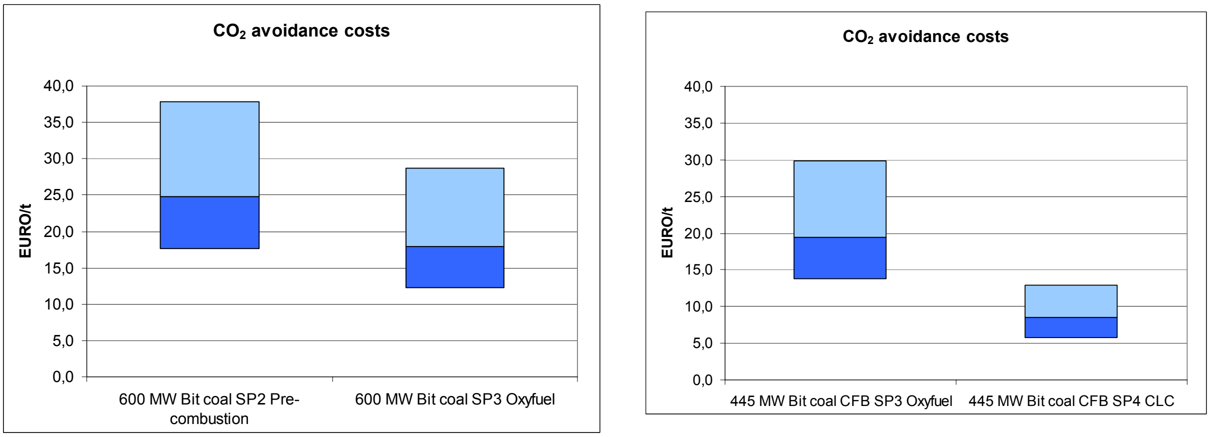


Concepts with CO_2 capture evaluated against
600 MWgross PF power plant

Concepts with CO_2 capture evaluated against
445 MWgross CFB power plant

Base case: 1.6 €/GJ fuel (LHV) 8% real interest rate 40 years 7500 hrs/y
Sensitivity analysis: 1.2 – 3.2 €/GJ fuel 4 - 12% real interest rate 25 years

Figure 1. Calculated electricity generation costs for bituminous coal fired power plant concepts with CO_2 capture in relation to the corresponding reference power plants without capture. Min and max values show the bandwidth of the electricity generation costs, resulting from combined sensitivity analysis on fuel price, interest rate and economic lifetime.



Concepts with CO_2 capture evaluated against
600 MWgross PF power plant

Concepts with CO_2 capture evaluated against
445 MWgross CFB power plant

Figure 2. Calculated CO_2 avoidance costs for bituminous coal fired power plant concepts with CO_2 capture in relation to the corresponding reference power plants without capture. CO_2 avoidance cost is the ratio of the difference in electricity generation costs and the difference in spec. CO_2 emissions between the CO_2 capture technology and the reference case. The result shows how much the avoidance of 1 ton CO_2 costs. At the same time it shows at which level of CO_2 penalty the CO_2 capture technology starts to become economic in comparison to the reference case. Min and max values show the bandwidth of the CO_2 avoidance costs, resulting from combined sensitivity analysis on fuel price, interest rate and economic lifetime.

For the “1st generation” concepts, the individual processes are based on mature technologies with proven reliabilities. For the CFB CLC, the Air and Fuel Reactors are comparable to conventional CFB:s. The integration of ASU and CO_2 capture technologies for oxy-fuel concepts and of ASU, IGCC and CO_2 train for the pre-combustion concepts, are expected to reduce availabilities by a few %-points, at least for the 1st generation of plants.

Start-up-times are expected to increase for all the studied concepts with CO_2 capture. Restrictions from ASU operation will slightly reduce maximum load change rates for the oxy-fuel and pre-combustion IGCC concepts; for pre-combustion gas conditioning units also contribute to this.

Oxy-fuel fired PF and CFB boilers are at pilot plant stage, the other processes for the “1st generation” oxy-fuel concepts are proven technology. For pre-combustion IGCC, all components are commercially available, but not with operation experience for similar conditions. Especially, development of high efficient (F-class) gas turbine with enriched H_2 fuel combustors is ongoing. The CAR process is based on state-of-the-art cyclic adsorption, but the oxygen adsorption application for high temperature air separation is up to now tested in laboratory scale. CLC CFB technology for gas and solid fuels is proven at small pilot scale (10kW).

2.2. Natural gas fired power plant concepts.

The evaluated power plant concepts are summarized in Table 3, together with their electricity output capacities and net electric efficiencies.

Table 3. Evaluated natural gas fired power plant concepts with and without CO_2 capture, together with electricity output capacities and net electric efficiencies (calculated based on fuel LHV).

Power Plant Concepts for Natural Gas	**Electricity output**		**Net electric efficiency**
	Gross, MWel	Net, MWel	% of fuel LHV
Ref. case: Natural gas-fired F-class Gas Turbine Combined Cycle, state-of.-the art year 2004	393	385	56.5
“1st” generation power plant concepts with CO_2 capture			
SP2 ATR Pre-combustion ASU: IRCC (Integrated Reforming Combined Cycle) with cryogenic ASU (Air Separation Unit) for oxygen production to the ATR (Autothermal Reformer), and MDEA (MethylDiEthanolAmine) for pre-combustion CO_2 capture [6]. Same concept as described by Kvamsdal [11] but with less integration with respect to heat and air compression, giving a lower energy efficiency but higher flexibility. Two parallel F-class gas turbines in a combined cycle of the same type as in the reference case*	873	755	41
“More future” power plant concepts with CO_2 capture			
CLC (Chemical Looping Combustion) CC:s (Combined Cycles): One CLC reactor before each air turbine stage. The air is used to generate steam for a bottoming cycle after the last air turbine stage. One CO_2 turbine, with CO_2 added at different pressure levels. The turbines have parameters as similar to the reference case gas turbine as possible. CLC reactor outlet temperatures (turbine inlet temperatures) are however reduced to 1000°C. The fuel mass flows are slightly (2%) higher than the reference case. The process is described in i.a. Naqvi et al [12] and Pavone [13]			
- SP4 CLC CC Double reheat Air turbine, rotating reactors: Three air turbine stages, rotating CLC reactors	379	362	52
- SP4 CLC CC Double reheat Air turbine, membrane assisted reactors: Three air turbine stages, membrane assisted CLC reactors.	379	362	52
- SP4 CLC CC Single reheat Air turbine: Two air turbine stages	375	357	51
SP5 Pre-combustion CAR: The concept is a hybrid between pre-combustion and oxy-fuel..CAR (Ceramic Autothermal Recovery) is a BOC/Linde technology for separating air with a high temperature Pressure Swing Adsorption (PSA) [8]. The process consists of a CAR unit, oxy-fuel steam reformer (tubular reactor) and a conventional PSA unit for separating the synthesis gas into H_2 from a fuel stream (CH_4, CO, CO_2). The H_2 is combusted in a similar combined cycle as for SP2. The fuel stream is combusted in the steam reformer with O_2 from the CAR unit, for providing heat to the synthesis gas production in the tubes. A part of the steam reformer combustion product (mainly CO_2) is used for sweeping the CAR unit, and recycled to the steam reformer. The rest is compressed for geological storage. This is a novel and immature concept developed in ENCAP, see De Koeijer et al [14]. Two parallel F-class gas turbines in a combined cycle of the same type as in the reference case*	940	801	44
Oxy-fuel cycles: The turbines have parameters as similar to the reference case gas turbine as possible. These are considered as quite novel cases and are described and evaluated in more detail in Kvamsdal et al [11], Woollatt et al [15], Hammer et al [16] and Rezvani et al [17]. The fuel mass flows are the same as for the reference case.			

Power Plant Concepts for Natural Gas	**Electricity output**		**Net electric efficiency**
	Gross, MWel	Net, MWel	% of fuel LHV
Ref. case: Natural gas-fired F-class Gas Turbine Combined Cycle, state-of.-the art year 2004	393	385	56.5
- SP6 Water cycle: A reheat oxy-fuel cycle where liquid water is recirculated to the first combustion chamber for temperature control, e.g. theClean Energy Systems cycle. Turbine efficiencies stated as not consistent to reference case, as this cycle will require totally new designs of the turbo-machinery.	391	294	43**
- SP6 Graz Cycle: CO_2 and a small quantity of steam is recirculated to the combustion chamber for temperature control. (Original Graz Cycle). Turbine efficiencies stated as not consistent to reference case, as this cycle will require totally new designs of the turbo-machinery.	389	304	45**
- SP6 S-Graz Cycle: Steam and CO_2 is recirculated to the combustion chamber for temperature control. More steam is recirculated than in the original Graz cycle. Turbine efficiencies stated as not consistent to reference case, as this cycle will require totally new designs of the turbo-machinery.	420	334	49**
- SP6 SCOC-CC: A semi-closed oxy-fuel combined cycle where most of the CO_2-rich gas from the condenser is recirculated to the gas turbine compressor. HRSG (Heat Recovery Steam Generator) with two pressure levels and one reheat.	409	325	48**

* In the ENCAP project, development work has been performed, aiming at adaptation of burners for hydrogen rich gases to the design requirements of modern high temperature F-class gas turbines.

** For the SP6 oxy-fuel cycles, contents of argon, nitrogen and water in the CO_2 stream are too high to meet the design CO_2 quality requirement scenario. These must be separated from the stream, and the energy requirement for this will lower the cycle net electrical efficiencies

Compared to the reference case, the major additional energy demands are:

- Pre-combustion concepts; the air separation processes - cryogenic ASU for the "1st generation" concept and the natural gas combustion to heat the CAR absorber for the Pre-combustion CAR concept -, the reforming (ATR and ST respectively) of natural gas to hydrogen rich gas, the CO_2 separation, and the CO_2 compression.
- Oxy-fuel cycles: the air separation processes and the CO_2 compression.

The resulting net electric efficiencies are presented in Table 3.

The efficiency of the Pre-combustion CAR concept (44%) is significantly higher than that of ATR Pre-combustion ASU concept (41%), due to the use of new but immature air separation technology, a PSA instead of an amine unit for CO_2 separation, and a higher level of integration. The ATR Pre-combustion ASU concept is based on conservative assumptions; i.e. its efficiency can be improved by more integration and less conservative assumptions.

The CLC Combined Cycles have the highest cycle efficiencies, but this includes pressurized chemical looping reactors, which is immature technology.

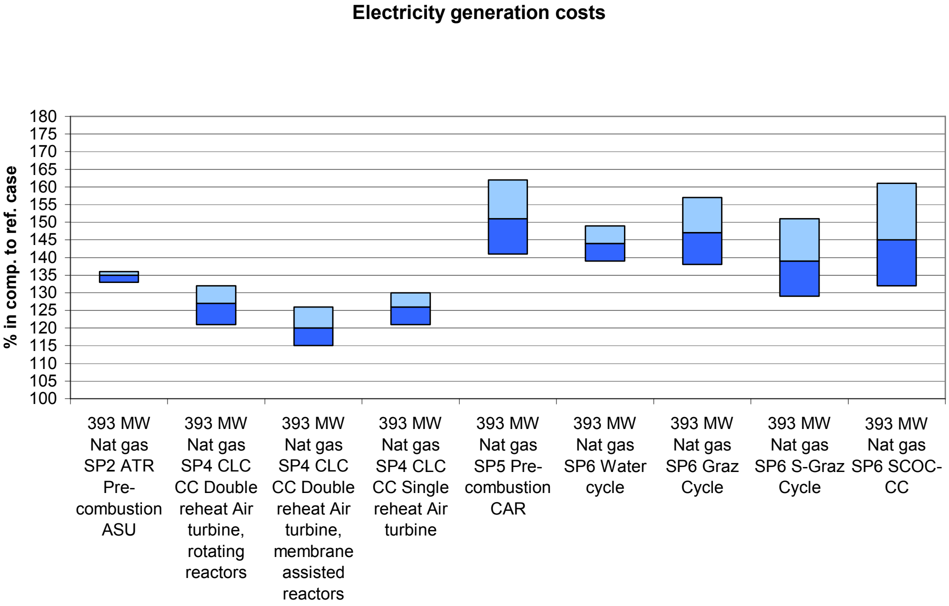
The specific investments for the power plant concepts with CO_2 capture increase compared to the corresponding reference cases, due to the net electric efficiency penalties and costs for additional and/or more expensive equipment.

The major cost increases compared to the corresponding reference cases are due to:

- Pre-combustion concepts; the air separation processes - cryogenic ASU for the "1st generation" concept and the natural gas combustion to heat the CAR absorber for the Pre-combustion CAR concept -, natural gas reforming, CO-shift, CO_2 separation, and CO_2 compression.
- Oxy-fuel cycles: In total more expensive equipment, the air separation processes and the CO_2 compression.
- CLC CC concepts; In total more expensive equipment.

The net electric efficiency penalties of course also increase the fuel costs.

The calculated resulting electricity generation costs for the concepts with CO_2 capture, in relation to the corresponding reference case, are presented in Figure 3.



Base case: 3.5 €/GJ fuel (LHV) 8% real interest rate 40 years 7500 hrs/y
Sensitivity analysis: 2.6 – 5.2 €/GJ fuel 4 - 12% real interest rate 25 years

Figure 3. Calculated electricity generation costs for natural gas fired power plant concepts with CO_2 capture in relation to the reference power plant without capture. Min and max values show the bandwidth of the electricity generation costs, resulting from combined sensitivity analysis on fuel price, interest rate and economic lifetime.

The resulting CO_2 avoidance costs vary correspondingly between the evaluated concepts. For the SP2 ATR Pre-combustion ASU, it is around 35 € per tonne CO_2, with sensitivity analysis variations from 25 up to 50 € per tonne CO_2, mainly depending on natural gas price. The resulting CO_2 avoidance costs for CLC CC cycles are lower, between around 15 and 30 € per tonne CO_2. The SP5 Pre-combustion CAR cycle and the SP6 Oxy-fuel cycles show CO_2 avoidance costs close to the SP2 ATR Pre-combustion ASU concept.

The investment cost for the Pre-combustion CAR concept is based on several conservative assumptions, considering that the immature CAR technology, at the same time as the calculated O&M costs for the ATR Pre-combustion ASU concept are at a low level compared to the reference case. Consequently, the presented results indicate a too large difference.

All the CLC CC and Oxy-fuel cycles have a high degree of integration, giving uncertainties for part-load and start-up/shut-down of the cycle.

The CLC technology is not proven in large scale yet, but is currently being investigated in pilot scale. The natural gas fired oxy-fuel concepts investigated here require a substantial design modification in the gas turbines and turbomachinery, and will thus require more development. This is the main issue that shows a difference for these cases.

3. Conclusions

Compared to the corresponding baseline power plants without CO_2 capture, net electric efficiencies were reduced with 6 – 9% points for the IGCC pre combustion capture technologies, oxy-fuel PF and CFB technologies, and around 15% points for the natural gas fired IRCC pre-combustion capture technology. Calculated electricity generation costs for those technologies increase around 30 – 60% compared to the baseline power plants, with resulting CO_2 avoidance costs of around 10 – 40 € per tonne CO_2 for the solid fuel based technologies and – mainly depending on natural gas price – from 25 up to 50 € per tonne CO_2 for the natural gas fired IRCC. The cost differences between pre-combustion IGCC and oxy-fuel PF concepts for the same fuel are within the ranges of uncertainty that can be expected at the current level of development. The large bandwidths for calculated costs result from the sensitivity analysis on fuel prices, interest rate, and economic lifetime.

Of the evaluated more new, and therefore less validated technologies, CLC (Chemical Looping Combustion) for coal, pet-coke and natural gas appear promising, with potentially higher electric efficiencies and lower costs, but need more research and development.

The presented evaluations and comparisons of technologies are still valid, but the absolute levels of calculated costs are generally lower than they would be if the investment and cost estimates had been performed during 2007 or 2008 instead of during year 2004 and 2005, when most concept designs was performed. Most of the considerable increases in fuel prices are however covered by the sensitivity analysis performed.

Acknowledgements

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