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SUMMARY

The project ENCAP, under the Sixth framework programme of the European Commission, aims at technologies that meet the target of 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) by developing new pre-combustion and oxy-fuel CO_2 capture technologies and processes for power generation based on fossil fuels. This report presents the results of the following activities:

- Collection of technical and economic data for power plants with CO_2 capture investigated in SP2-SP6.
- Economic calculations, e.g. break-even electricity generation costs, specific CO_2 emission avoidance cost etc.
- Comparison and evaluation of concepts with CO_2 capture, and with reference power plants without CO_2 capture.

The selected reference cases are:

- Natural gas-fired 393 MWe gross Combined Cycle Gas Turbine
- Bituminous / pet coke-fired 445 MWe gross Circulating Fluidised Bed
- Bituminous-fired 600 MWe gross pf
- Lignite-fired 1000 MWe and 380 MWe gross pf

A basic principle of the benchmarking in this report is that only CO_2 capture technologies and the reference case with the same fuel will be compared. There is no comparison between different fuels.

Compared to the corresponding reference cases, the net electric efficiencies are reduced with 6 – 9% points for the IGCC pre-combustion capture technologies and oxy-fuel PF and CFB technologies, and with around 15% points for the natural gas fired IRCC pre-combustion capture technology. The calculated electricity generation costs for those technologies increase around 30 – 60% compared to the reference cases, 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. Of the evaluated more new, and therefore less validated technologies, CLC (Chemical Looping Combustion), for coal and pet-coke as well as for natural gas, appear promising with potentially higher electric efficiencies and lower costs, but need more research and development.

Contents

1 Introduction

Two of the objectives of the ENCAP SP1, “Process and Power Systems” are to:

1. Establish methodology to ensure consistency in evaluations and benchmarking of capture technologies subjected to ENCAP (refer SP2-SP6)
2. Assess the impact of candidate concepts on the economy of power production and in reflection of their technical maturity and development risks

The 1st objective was met by the definition of “Reference cases and guidelines for technology concepts”. This work was performed by all industrial partners in ENCAP under the lead of Vattenfall Nordic (formerly ENERGI E2), during year 2004 and with some updates during 2005 and beginning of 2006. The result is a report containing:

- Reference power plants without CO_2 capture (state-of-the-art year 2004):
    - Natural gas-fired 393 $MW_{el\ gross}$ Combined Cycle F-class Gas Turbine
    - Bituminous coal/ pet coke-fired 445 $MW_{el\ gross}$ Circulating Fluidised Bed Boiler
    - Bituminous coal-fired 600 $MW_{el\ gross}$ Pulverized Fuel Boiler
    - Lignite-fired 1000 $MW_{el\ gross}$ and 380 $MW_{el\ gross}$ Pulverized Fuel Boilers
- Guidelines and common basis for technical analysis and economic evaluations.
- CO_2 quality requirement scenarios for transport and storage
- Description of how the different CO_2 capture technologies from the other SP:s will be evaluated on quantitative and qualitative parameters

These reference power plants and guidelines have then served as basis for the development of power plant concepts with CO_2 capture in SP2 – SP6, and for the work with benchmarking of these concepts in SP1 – the 2nd objective for ENCAP SP1.

In the benchmarking work, the selected CO_2 capture concepts and technologies addressed in SP2–SP6 are evaluated in terms of technical performance, cost and level of technical maturity versus scale-up requirements, R&D needs and development risk, and benchmarked.

A 1st evaluation and benchmarking was performed during 2005 and beginning of 2006, and served as one input to ENCAP’s decision process for pilot plant/large scale test facilities in phase 2 of ENCAP.

A 2nd updated evaluation and benchmarking, based on further developed and more complete data that have been elaborated within SP2 – SP6, was performed during 2007 and beginning of 2008.

This report contains a final update to include bituminous coal based and natural gas based pre-combustion capture concepts, developed in SP6 and provided to SP1 during spring 2008.

2 Overview of proposed technologies for large commercial power plants with CO_2 capture

2.1 Meaning of the reference cases

In work package WP1.1 (Determination of robust guidelines for technology concepts) a set of reference power plants was specified. A reference power plant is a typical conventional power plant which is normally built in case of no CO_2 capture. Such a power plant depends on the fuel. Therefore reference power plants (or reference cases) were specified for each fuel: lignite, bituminous coal and gas.

- Lignite

The typical type of power plant for lignite is a conventional steam cycle pf-fired power plant with around 1000 $MW_{el\ gross}$. The abbreviation is **1000 MW Lignite PF**.

- Bituminous coal

The typical type of power plant for bituminous coal is a conventional steam cycle pf-fired power plant with around 600 $MW_{el\ gross}$. The abbreviation is **600 MW Bit. coal PF**.

- Natural gas

Gas-fired power plants are normally combined-cycle power plants with a size depending on the gas turbine. In ENCAP, a combined cycle with a state-of-the-art (at year 2004) F-class gas turbine is used as reference. The abbreviation is **393 MW NGCC**.

There are two further special reference power plants. The first is for the situation in Greece. Power plants are fired with lignite, but the size is smaller than in i. a. Germany. The second is for the CFB technology with bituminous coal and pet coke as fuel.

- Greek lignite

The typical type of power plant for greek lignite is a conventional steam cycle pf-fired power plant with around 380 $MW_{el\ gross}$. The abbreviation is **380 MW Lignite PF**.

- Bit. coal/pet coke CFB

Depending on the CFB technology the typical size for such a plant is 445 $MW_{el\ gross}$. As a consequence the abbreviation is **445 MW Bit. coal/pet coke CFB**.

In order to evaluate the effects of CO_2 capture on power production, the proposed concepts for CO_2 capture must be compared with the power plant, which is normally built without CO_2 capture <u>for the same fuel</u>, i. e. with the related reference case. E. g. each CO_2 capture technology based on lignite is compared with the reference case *1000 MW Lignite PF*, even if the capture technology includes a completely different firing system or is based on gasification like the SP2 technologies. As a consequence only CO_2 capture technologies belonging to the same reference case will be compared. There is no comparison between different fuels. This is a basic principle of the benchmarking in ENCAP WP1.2.

2.2 Overview of proposed technologies

The tables, diagrams and evaluations in this report follow the principle described below:

The following table gives an overview of the number of CO_2 capture concepts submitted by the Subprojects 2 to 6 with technical an economic data available. The left column shows the reference cases. The number of CO_2 capture concepts are related to the reference cases. E. g. SP3 has submitted 1 concepts related to the *600 MW Bit. coal PF* reference case, because this concept is based on bituminous coal (and in addition not based on the special CFB technology for which another reference case is valid). It does not necessarily mean that the SP3 concept includes a pf firing system. It only means that normally without CO_2 capture a *600 MW Bit. coal PF* power plant would be built instead of the SP3 power plant.

	SP2	SP3	SP4	SP5	SP6	all SPs	Evaluated in chapter
1000 MW Lignite PF	1	1		1		3	4
600 MW Bit. coal PF	1	1			2	4	5
393 MW NGCC	1		2	1	6	10	6
380 MW Lignite PF		1				1	7
445 MW Bit. coal/pet coke CFB		1/1	1/1			2/2	8

2.3 Short description of the proposed technologies

In order to handle the processes in text, tables and diagrams they are identified by means of a simple code. For concepts coming from SP2 (gasification) and SP3 (oxyfuel) it was easy to use an abbreviation which could be used and also be understood. But the processes from SP4, SP5 and SP6 are new and not well-known and there is no clear and unique abbreviation. On the other hand a long title for a process cannot be used for diagrams and tables. Therefore each concept gets a code.

The code contains the related reference case, the subproject number and a consecutive short-name for the capture technology

Example:
1000 MW Lignite SP2 Pre-combustion
The related reference case is *1000 MW Lignite PF*. That means the power plant is lignite-fired and will be compared to this reference case and to other CO_2 capture concepts related to *1000 MW Lignite PF*. The technology is designed by SP2, so that it is a pre-combustion IGCC technology (for solid fuels) or a pre-combustion IRCC technology (for natural gas). For natural gas, both SP2 and SP6 have developed different pre-combustion IRCC technologies, and the short-names include specific features for those. *Example:* “**SP2 ATR Pre-combustion ASU”** means that the pre-combustion power plant process from SP2 uses an auto-thermal reformer (ATR) and a cryogenic air separation unit (ASU)

By this the code directly tells the reader which fuel is used and what the basic technology is (e. g. SP4 -> chemical looping combustion). Further information about the technologies is given in the following text. Here you can find a short description of all processes:

2.3.1 "1st" generation power plant concepts with CO_2 capture

These concepts 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. Status and R&D needs for major technologies of interest have been examined by expert groups within the ETP-ZEP, EU Technology Platform for Zero Emission Fossil Fuel Power Plants:

http://www.zero-emissionplatform.eu/website

2.3.1.1 Power plant concepts from SP2

code: **1000 MW Lignite SP2 Pre-combustion**
Lignite-fired IGCC (Integrated Gasification Combined Cycle) process with precombustion CO2 capture with CO shift and CO_2 scrubbing in a rectisol unit. O_2 for gasification is produced in a cryogenic ASU (Air Separation Unit).

code: **600 MW Bit Coal SP2 Pre-combustion**
Bituminous coal-fired IGCC precombustion CO2 capture process with CO shift and and CO_2 scrubbing in a rectisol unit. O_2 for gasification is produced in a cryogenic ASU.

code: **393 MW Nat Gas SP2 ATR Pre-combustion ASU**
Pre-combustion cycle with an autohermal reformer which is fed with O_2 from a cryogenic ASU. The synthesis is shifted in a HT (high temperature) and LT (low temperature) shift. Afterwards the CO_2 is captured in a MDEA unit. The remaining hydrogen is fed to a H_2 combined cycle.

2.3.1.2 Power plant concepts from SP3

code: **1000 MW Lignite SP3 Oxyfuel**
Oxyfuel PF plant for German lignite with cryogenic air separation and a 2-flash CO_2 compression and processing system to produce >96%(v) CO_2 at supercritical conditions.

code: **600 MW Bit Coal SP3 Oxyfuel**
Oxyfuel PF plant for bituminous coal with cryogenic air separation.

code: **380 MW Lignite SP3 Oxyfuel**
Oxyfuel PF plant for Greek lignite with cryogenic air separation.

code: **445 MW CFB SP3 Oxyfuel**
Oxyfuel plant for pet coke/bituminous coal and CFB firing with cryogenic air separation.

2.3.2 "More future" power plant concepts with CO_2 capture

These 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.

2.3.2.1 Power plant concepts from SP4

Chemical looping combustion (CLC) is an oxyfuel technology where the separation of oxygen from air is integrated in the combustion process. Metal particles are oxidised in an air reactor, the resulting metal oxide particles are transported to a fuel reactor, where they are reduced as fuel is oxidised and fuel heat is released. The metal particles are transported back to the air reactor where they can be oxidised again.

code: **445 MW CFB SP4 CLC**
When applied for solid fuels, a CLC boiler is typically based on CFB technology, with a steam power cycle (c.f. WP3.4).

code: **393 MW Nat Gas SP4 3-reactors CLC CC with double reheat air turbine**
Further development of the SP4 CLC combined cycle, where the air turbine is split into three parts with a CLC reactor before each air turbine. There is still only one CO_2 turbine, with CO_2 added at different pressure levels. As in the CLC combined cycle, the air is used to generate steam for a steam bottoming cycle after the last air turbine stage. There are 2 versions of reactors:
version a: rotating reactors
version b: membrane assisted reactors

code: **393 MW Nat Gas SP4 CLC CC with single reheat air turbine**
Further development of the SP4 CLC combined cycle, where the air turbine is split into two parts with a CLC reactor before each air turbine. There is still only one CO_2 turbine, with CO_2 added at two pressure levels. The air is used to generate steam for a steam bottoming cycle after the last air turbine stage.

2.3.2.2 Power plant concepts from SP5

code: **1000 MW Lignite SP5 Oxyfuel CAR**
Oxyfuel PF process with CAR (Ceramic Autothermal Recovery) reactor for O_2 production.

code: **393 MW Nat Gas SP5 Pre-combustion CAR**
Pre-combustion cycle with an O_2 fired steam reformer followed by HT&LT shift and a PSA (Pressure Swing Adsorption). The hydrogen fuel is fed to a H_2 combined cycle, while the purge gas is used as fuel for heating the steam reformer. The O_2 is delivered by a CAR (Ceramic Autothermal Recovery) unit.

2.3.2.3 Power plant concepts from SP6

code: **600 MW Bit Coal SP6 Pre-combustion**
IGCC process with CO_2 capture using physical absorption. Before the CO_2 separation a CO-shift reaction takes place. The gasification and the combined cycle is similar to IGCC without CO_2 capture. 100 % of the air for the ASU is delivered by an external compressor.

code: **600 MW Bit Coal SP6 Pre-combustion, Air integration**
As CT01, but 100 % integration of the ASU into the gas turbine. All air for the ASU is extracted from gas turbine compressor. The heat from the compressed air is used in the steam section of the combined cycle.

code: **393 MW Nat Gas SP6 Water cycle**
A reheat oxyfuel cycle where liquid water is recirculated to the first combustion chamber for temperature control, e.g. theClean Energy Systems cycle.

code: **393 MW Nat Gas SP6 Graz Cycle**
Original Graz Cycle: an oxyfuel cycle where CO_2 and a small quantity of steam is recirculated to the combustion chamber for temperature control.

code: **393 MW Nat Gas SP6 S-Graz Cycle**
An oxyfuel cycle where both steam and CO_2 is recirculated to the combustion chamber for temperature control. More steam is recirculated than in the original Graz cycle

code: **393 MW Nat Gas SP6 SCOC-CC**
A semi-closed oxyfuel combined cycle where most of the CO_2-rich gas from the condenser is recirculated to the gas turbine compressor. HRSG with two pressure levels and one reheat.

code: **393 MW Nat Gas SP6 Pre-combustion Membrane**
Pre-combustion cycle with an ATR membrane reactor with an oxygen permeable membrane (ceramic) with a higher total pressure on the permeate side of the membrane than on the retentate side. Water-gas-shift membrane reactor with a hydrogen-permeable membrane (Pd).

code: **393 MW Nat Gas SP6 Pre-combustion Membrane, High Pressure**
Pre-combustion cycle with an ATR membrane reactor with an oxygen permeable membrane (ceramic) with a higher total pressure on the permeate side of the membrane than on the retentate side. Water-gas-shift membrane reactor with a hydrogen-permeable membrane (Pd). Relative to 393 MW Nat Gas SP6 Pre-combustion Membrane, this cycle has a higher pressure on the permeate side of the membrane.

3 Input data and basic economic boundary conditions

3.1 Technology and cost levels

It must be noted that the major work within SP1 to elaborate the "Reference cases and guidelines for technology concepts", as well as most concept design work within SP2 – SP6, were performed during year 2004 and 2005. This means that:

- *The technology and cost data for the reference power plants, as well as for power plant data that have been used for the concepts with CO_2 capture (SP2 – SP6), correspond to state-of-the-art year 2004.*
- *Fuel prices were chosen to be representative for large European power plants up to year 2004, and corresponded also well with forecasts given in "IEA World Energy Outlook" (2004).*

Plant equipment costs have however increased considerably during the latest years. Since beginning of year 2004, CEPCI (Chemical Engineering Plant Cost Index) has increased with around 20%. Power plant equipment has most certainly increased in the same order of magnitude, or possibly even more.

Most of the considerable increases in fuel prices during the same period are covered by the sensitivity analysis performed (see chapter 3.6).

Consequently, the evaluations and comparisons of the technologies in this report 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 2006 or 2007.

Further it is important to consider the degree of uncertainty in technology and costs. Even the more developed capture technologies may still be 10 years before commercial availability. Process designs in this study were performed before the first 30 MW_{th} oxyfuel pilot plant was erected and before the project development of the first zero-CO_2 IGCC demonstration plant started. In addition some of the resulting economic figures are sensitive to small changes of input data. This must be taken into account when technologies are evaluated and compared.

3.2 Collection of input data

For each power plant concept with CO_2 capture, a set of input data and information was collected:

- Check list on to what extent certain parameters were consistent with or deviated from in ENCAP developed boundary conditions
- Technical data for quantitative evaluations
- Cost data for economic evaluations
- Existence of certain technical documentation
- Questionnaire on information needed for qualitative assessments of operation characteristics, environmental aspects, properties of the captured CO_2 stream and technical maturity

The tables shown in this chapter were used to collect these input data for the benchmark. As an example the tables for the reference case “Lignite PF 1000 MW” are given. For all other reference cases similar tables were prepared.

3.2.1 Checklist

SP1 / WP1.2 Power systems evaluation and benchmarking

Sub-project	**SP x**
CO_2 capture Technology	**CT xx**
Corresponding reference case	**1000 MW lignite pf**

Checklist

	yes/no	comment no
Fuel specification according guidelines, chapter 2.6		
Cooling water conditions according guidelines, chapter 2.1		
Ambient air condition according guidelines, chapter 2.1		
Turbine efficiencies consistent to reference case		
Costs for consumables according guidelines, chapter 3.2		
CO_2 quality according guidelines, chapter 4, design case		
Estimates of additional needs for extra cleaning for EOR case		
Estimates of additional needs for extra cleaning for severe limit case		

3.2.2 Technical data

SP1 / WP1.2 Power systems evaluation and benchmarking

Sub-project **SP x**
CO_2 capture Technology **CT xx**
Corresponding reference case **1000 MW lignite pf**

Technical data

Design case		Reference power plant	CO2 capture power plant	comment no
Overall energy balance				
Gross el. capacity	MW	1000,00		
Auxiliary power demand	MW	80,00		
Net capacity	MW	920,00	0,00	
Fuel mass flow	kg/s	206,56		
LHV	kJ/kg	9010,00		
Net efficiency	%	49,43	#DIV/0!	
CO2 balance				
CO2 "input"				
C content of fuel	%	27,30		
Total theoretical CO2 input via fuel	kg/s	206,62	0,00	
CO2 input via air	kg/s	0,39		
CO2 "output"				
Flue gas mass flow (to atmosphere)	kg/s	951,00		
CO2 content flue gas	%	21,77		
CO2 emissions	kg/s	207,01	0,00	
CO2 to storage	kg/s	0,00		
CO2 "loss" due to unburnt carbon, etc.	kg/s	0,00	0,00	
CO2 capture performance				
Spec. CO2 emissions (C from fuel)	g/kWh	808,53	#DIV/0!	
CO2 avoidance rate (based on reference)	%		#DIV/0!	
CO2 capture rate (ENCAP design target)	%		#DIV/0!	

		Guidelines	CO2 capture power plant	comment no
CO2 conditions				
CO2 delivery pressure	bar	110		
CO2 delivery temperature	°C max	30		

If results for "EOR case" or "Severe limit case" are available, please copy the table and fill in the data.

3.2.3 Economic data

SP1 / WP1.2 Power systems evaluation and benchmarking

Sub-project	**SP x**
CO_2 capture Technology	**CT xx**
Corresponding reference case	**1000 MW lignite pf**

Economic data

Design case		Reference power plant	CO2 capture power plant	comment no
Investment				
EPC costs	Euro/kWe gross	1025		
Owners' costs	%	20		
Owners' costs	Euro/kWe gross	205		
Total investment	Euro/kWe gross	1230	0	
Operational costs				
Personnel, administration, insurance etc.	Euro/kWe gross per year	10,5		
Maintenance (incl. spare parts and overhaul)	Euro/kWe gross per year	16,5		
Total fixed O&M costs	Euro/kWe gross per year	27,0	0,0	
Total variable O&M costs (without fuel [1]))	Euro/MWhe gross	1		
Construction time	months	48		
Allocation of investment	% for year 1	15		
	% for year 2	30		
	% for year 3	35		
	% for year 4	20		
Lifetime for base load operation	years	40 [2)]		
Estimated need for reinvestment to prolong lifetime of the CO2 capture plant if its estimated lifetime is shorter than for the power plant	Euro/kWe gross			

[1)] fuel costs will be calculated separately based on fuel mass flow and price variations given in the guidelines
[2)] calculations of economic key figures in WP1.2 will also been made for 25 years lifetime

If results for "EOR case" or "Severe limit case" are available, please copy the table and fill in the data.

3.2.4 Documents

SP1 / WP1.2 Power systems evaluation and benchmarking	
Sub-project	**SP x**
CO_2 capture Technology	**CT xx**
Corresponding reference case	**1000 MW lignite pf**
Documents	

	yes/no	comment no
Drawings		
Simple schematic/flow diagram of the process		
Heat &mass balance diagram		
Layout drawing		
Lists		
Equipment list with costs of all main components		

3.2.5 Questionnaire

SP1 / WP1.2 Power systems evaluation and benchmarking

Sub-project	**SP x**
CO_2 capture Technology	**CT xx**
Corresponding reference case	**1000 MW lignite pf**

Questionnaire (please use the accompanying Word document for the answers)

Operational flexibility

Q1	Will the CO2 capture technology affect the flexibility of the power plant – does it put restrictions on start-up and shut down frequency, does it change minimum load or maximum load change rate in comparison to the reference case (guidelines, chapter 2.2)?

Emissions

Q2	How does the CO2 capture technology affect emissions – can emission limits (guidelines, chapter 2.5) still be observed both at full load and part load operation and does the CO2 capture technology cause higher emissions during start-up or shut down?
Q3	Does the CO2 capture technology cause any harmful waste water condition (see waste water concentration limits described in chapter 2.5 of the guidelines), changes in ash quality or any other environmentally harmful by-product streams?

CO2 requirements

Design case

Q4	What is the purity of the CO2 captured and are there any problems in achieving the limits stated in Chapter 4. Are there any other compounds in the captured CO2 stream?

"EOR case" or "Severe limit case"

Q5	Please provide the estimated needs for additional cleaning?
Q6	What are the critical components?

CO2 compression data

The optimal design/layout of the CO2 compression (number of compressor stages, intercoolers etc.) depends on the pressure, temperature and composition of the CO2 stream at the inlet of the 1st compressor, and will consequently vary depending on type of power plant and CO2 capture technology. The CO2 compression must therefore be designed by each SP. To enable the coming evaluations in SP1 to assess what difference other delivery pressures would have on efficiencies, costs etc., the following data on the CO2 compression and processing should be given for all power plants with CO2 capture:

Design case

Q7	• Energy consumption (electricity and/or steam) • Investment (estimated EPC cost) • Yearly average O&M cost (approximate) • Calculated/estimated contents of other compounds in the captured CO2 stream at inlet of the 1st compressor and at outlet of the last compressor according to Section 4.6 for Design case quality requirements • Flow rate, pressure and temperature of the captured CO2 stream at inlet of the 1st compressor.

Ship transport conditions

Q8	For each power plant with CO2 capture, to the extent the budget in the respective SP allow: • Provide estimated energy consumption, investment and O&M costs for CO2 compression and processing to meet these conditions.

Operational restrictions or special characteristics, technical maturity

Q9	How does the CO2 capture technology influence the availability of the plant – will failure of the CO2 capture technology (including failure of a CO2 pipeline) lead to failure of the power plant due to technical ties, or because the emission limits are exceeded or due to other causes? In SP6 two methods of evaluating the complexity of systems are described and may be applied in the benchmarking, report D6.1.1. What is the expected availability of electricity production and the availability of CO2 capture (in comparison to the reference plant with 90 % availability taking into account planned and unplanned unavailabilities)?
Q10	If the CO2 capture technology reduces the electrical output compared to the reference case, it should be indicated whether it is possible to bypass the CO2 capture for shorter periods to achieve higher electrical output. (This could be periods with attractive electricity prices or periods with an extraordinary need for capacity).
Q11	Does the CO2 capture technology impose additional restrictions on the fuel quality – is a certain CO2 capture technology especially sensitive to a certain component like sulphur or any other component?
Q12	What is the technical life of the CO2 capture technology – does it differ from the life of the power plant?
Q13	How mature, technically stable and reliable is the CO2 capture technology – is it proven technology, is it at demonstration stage, at pilot plant stage, only investigated at laboratory scale or is it just an idea on paper and are any difficulties with respect to operability anticipated? The anticipated time before realization of the technology shall be stated.
Q14	Does the CO2 capture technology influence the construction time?
Q15	If there are any other restrictions, risks or technical characteristics of importance, these must be specified.

3.3 Basic economic boundary conditions

The following economic boundary conditions were used for the calculation of economic key figures (base case and variations for sensitivity analysis):

Fuel prices:
with variations -25% and + 50%:
Cost of bituminous coal: 1.6 euro/GJ, variations 1.2 – 3.2 euro/GJ*
Cost of lignite (Germany and Greece): 1.1 euro/GJ, variations 0.8 – 1.7 euro/GJ
Cost of natural gas: 3.5 euro/GJ, variations 2.6 – 5.2 euro/GJ
Cost of pet coke 0.5 euro/GJ, variations 0.0 – 1.0 euro/GJ

*1 As bituminous coal prices have been increasing, the variations for bituminous coal are set to -25% and + 100 %.

Interest rate:
A combined real term interest rate is used taking into account equity rate, inflation and required rate of equity, defined as a weighted average cost of capital = 8.0 % with variations from 4.0 to 12.0 %.

Economic lifetime:
Base case: 40 years
Variation: 25 years

Yearly operation hours:
7500 h/a

Discussion of results for individual reference cases

In the following chapters the CO_2 capture technologies for large commercial power plants are discussed. The discussion is separately done for each reference case, i. e. there is no comparison of technologies for different fuels.

In connection with the comparison it must be taken into account that the technologies have a very different level of maturity so that the power plants have a completely different time horizon of commercial availability.

It must be emphasized that all data only include the power plant with CO_2 capture and compression. Transport and storage of CO_2 are not considered. A complete evaluation of CCS must therefore take into account higher investment costs, operation costs and auxiliary power consumption due to transport and storage.

The first part of the discussion of technologies is a comparison of techno/economic data:

- Gross and net electricity output
- Net electric efficiency
- Electricity generation costs in relation to reference case
- CO_2 avoidance costs

For the “1st generation” power plant concepts with CO_2 capture (from SP2 and SP3), additional further detailed techno/economic data are compared:

- Specific CO_2 emissions
- CO_2 avoidance rate
- Specific investment costs compared to reference case
- Split of electricity generation costs

For the “more future” power plant concepts with CO_2 capture (from SP4, SP5 and SP6), the uncertainties are larger in all data, especially for investments and costs. For those concepts, specific CO_2 emissions, CO_2 avoidance rate and cost relations are discussed qualitatively.

In this comparison, the same boiler size or type and size of gas turbine are maintained in the power plant concepts with and without CO_2 capture, so that all components that are not directly influenced by the CO_2 capture technologies remain unaffected. A consequence of this is that reference cases and power plants with CO_2 capture (CCPP) have different net capacities.

To investigate the influence on the results, additional calculations were made for reference cases and CCPP with the same net capacity. For this purpose the capacity of the reference cases was individually adjusted to the capacity of each CCPP. This adjustment leads to other specific investment and maintenance costs, while technical data remain the same. Since herewith the CCPP’s are not changed, all absolute techno/economic figures and all technical figures in relation to the reference case keep constant as well. Only cost figures which show the relation to the reference cases are changed:

- Electricity generation costs in relation to reference case
- CO_2 avoidance costs
- Specific investment costs in relation to reference case

These changes have been discussed qualitatively in the report.

But it must be noted, that in some cases this capacity adjustment is artificial and not realistic. There are other criteria for the determination of the unit size like maximum size of the generator, maximum size of a gas turbine, number of parallel trains in the flue gas pass. If you decide on the unit size, the size of a (in that moment virtual) corresponding CCPP is no criteria and vice versa, so that the original reference cases and as a consequence the comparison to them are normally the realistic ones, because these reference cases and also the CCPP’s take into account normal criteria for the unit size.

3.4 CO_2 quality requirement scenarios

The quality requirements on the captured CO_2 stream will be determined by technical concerns for CO_2 compression and processing, transport of CO_2 to a storage site and injection of it into geologic reservoirs for storage. To this come requirements related to HSE (Health Safety and Environment) mainly associated to not anticipated leakages from the transport and storage systems and slow releases from the storage reservoir. A systematic summary of available knowledge on these aspects (at year 2004) was elaborated in ENCAP.

One of the ENCAP objectives is to develop cost efficient processes for CO_2 capture. Therefore, the power plant concepts with CO_2 capture should be designed with no more cleaning of the captured CO_2 stream than needed to reduce the concentration of the impurities in the captured stream to acceptable levels for compression, transport and storage and to meet given environmental and legal requirements.

Because of this and the uncertainties and knowledge gaps in limit values, ENCAP therefore defined three CO_2 quality requirement scenarios as a basis for the work in SP2 – SP6:

- **Design case.** *Pipeline transport and geologic storage.* All power plant concepts with CO_2 capture should be designed to fulfil this requirement scenario considering only removal of major impurities. This requirement scenario was based on CO_2 transport in pipelines at 100 – 150 bar and temperatures down to 0°C followed by storing the CO_2 in geologic formations.

- **EOR (Enhanced Oil Recovery) case.** *Pipeline transport and EOR*. *Conservative water content requirement.* The need for and costs for additional cleaning regarding contents of water (conservative requirement) and mainly oxygen and sulphur compounds to meet the somewhat stricter requirements for EOR was assessed/estimated for concerned power plants with CO_2 capture, to the extent the budgets in the respective SP allowed. This requirement scenario was based on CO_2 transport in pipelines at 100 – 150 bar and temperatures down to 0°C followed by storing CO_2 combined with EOR.

- **Severe limit case.** *Ship transport and EOR combined with strict limit values for toxics.* The need for and costs for additional cleaning to meet this more strict limit scenario regarding water contents (ship transport at very low temperatures) combined with strict limit values for all toxic compounds (to avoid severe safety procedures when handling the CO_2 stream at places with severe HSE regulations), was assessed/estimated for power plant concepts with CO_2 capture, to the extent the budgets in the respective SP allowed. This requirement scenario was based on CO_2 transport using future larger ships at 6 - 7 bar and temperatures down to -50°C followed by storing the CO_2 combined with EOR.

4 Capture technologies for reference case “1000 MW Lignite PF”

The following power plant concepts with CO_2 capture are evaluated against the lignite fired 1000 $MW_{el\ gross}$ PF reference case:

“1st” generation power plant concepts with CO_2 capture

- 1000 MW Lignite SP2 Pre-combustion
- 1000 MW Lignite SP3 Oxyfuel

“More future” power plant concepts with CO_2 capture

- 1000 MW Lignite SP5 Oxyfuel CAR

See Chapter 2.3 for short descriptions of these technologies.

Ongoing development work aims at adaptation of burners for hydrogen rich gases to the design requirements of modern high temperature F-class gas turbines. Therefore, the power plant concept with pre-combustion CO_2 capture from SP2 is designed with F-class gas turbine combined cycle of the same type as the natural gas fired 393 $MW_{el\ gross}$ combined cycle reference case.

4.1 Overview of quantitative data (technical and economic data)

For the “more future” power plant concepts with CO_2 capture, the uncertainties are larger in all data, especially for investments and costs. Only electricity outputs, net electric efficiencies, electricity generation costs in relation to reference case, and CO_2 avoidance costs, are presented for those technologies.

4.1.1 Electricity outputs

- The SP2 pre-combustion IGCC, uses two parallel gas turbines, anticipated to be derived from the gas turbine used in the natural gas fired 393 $MW_{el\ gross}$ combined cycle reference case (compare Chapter 6). This results in a slightly (4%) decreased fuel mass flow compared to the1000 MW lignite PF reference case.
- The SP3 and SP5 Oxyfuel PF both have the same boiler size and the same fuel mass flow as the 1000MW lignite PF reference case. For SP5, additional natural gas, corresponding to 207 MW_{fuel}, (10% of total fuel input) is combusted for CAR absorber heating.

The resulting gross and net electricity output capacities are as follows:

Electricity output capacities

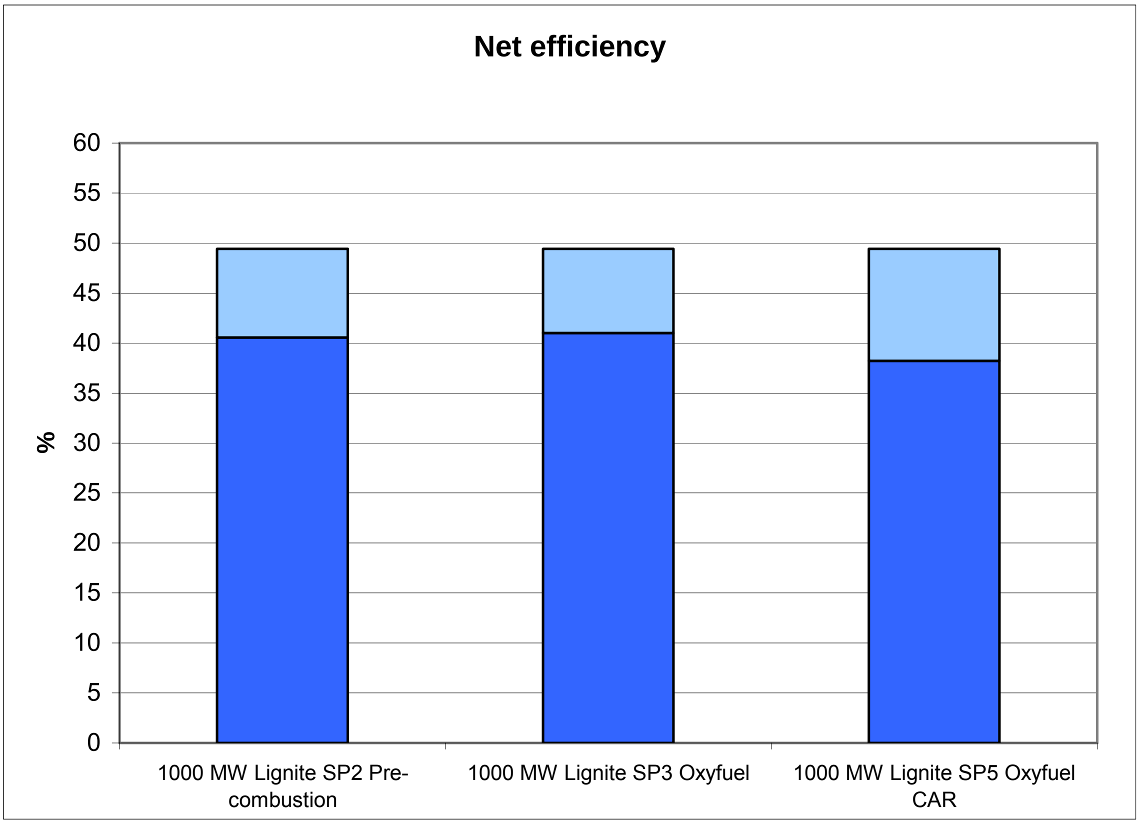
Reference case	Power plant	Gross, MWel	Net, MWel
1000 MW Lignite PF	Ref. case	1000	920
	SP2 Pre-combustion	899	717
	SP3 Oxyfuel	1048	767
	SP5 Oxyfuel CAR	980	790

4.1.2 Net efficiency

Net efficiency is the ratio of the net power production and the heat input via fuel (fuel mass flow x LHV).

Net efficiency

Reference case	Power plant	%	% ref. case	Delta %-points	Delta %
1000 MW Lignite PF	SP2 Pre-combustion	40,6	49,4	8,8	18,0
	SP3 Oxyfuel	41,0	49,4	8,4	17,1
	SP5 Oxyfuel CAR	38,2	49,4	11,2	22,7

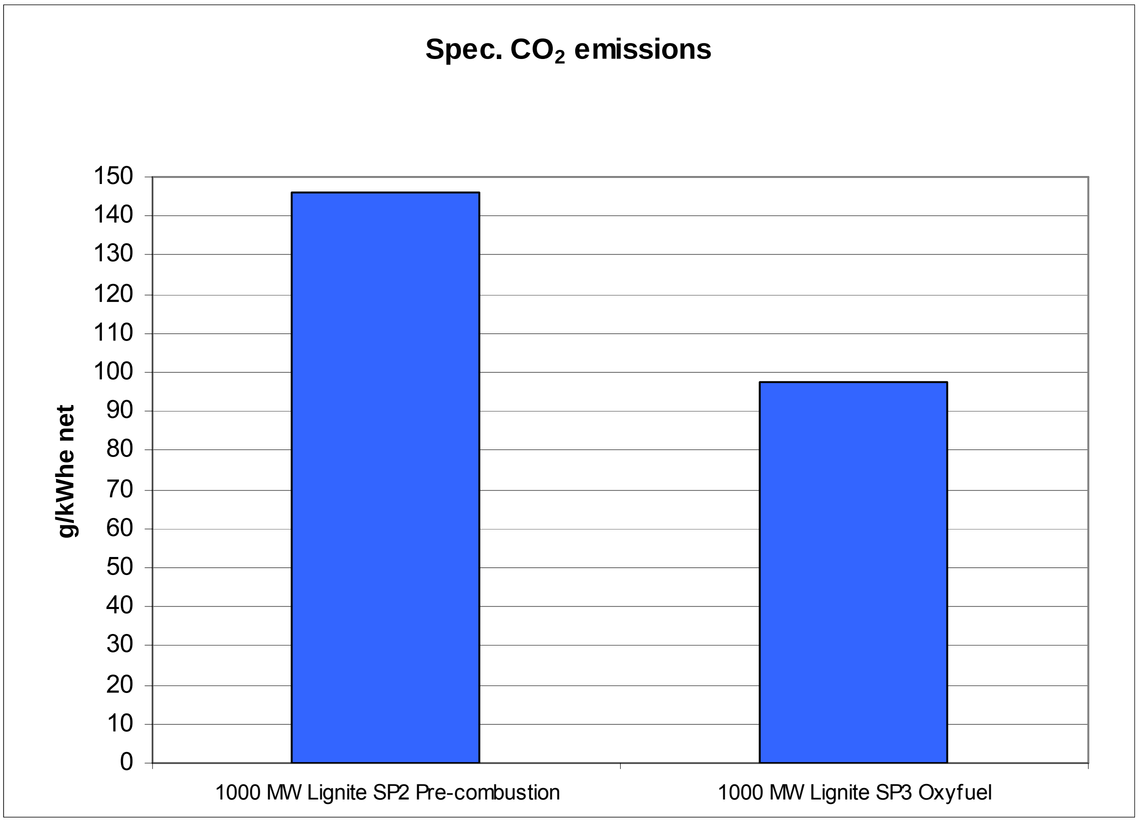


4.1.3 Specific CO_2 emissions

Spec. CO_2 emissions are the CO_2 emissions to the atmosphere in relation to the net power production.

Spec. CO2 emissions

Reference case	Power plant	g/kWhe
1000 MW Lignite PF	Ref case	808
	SP2 Pre-combustion	146
	SP3 Oxyfuel	97,5

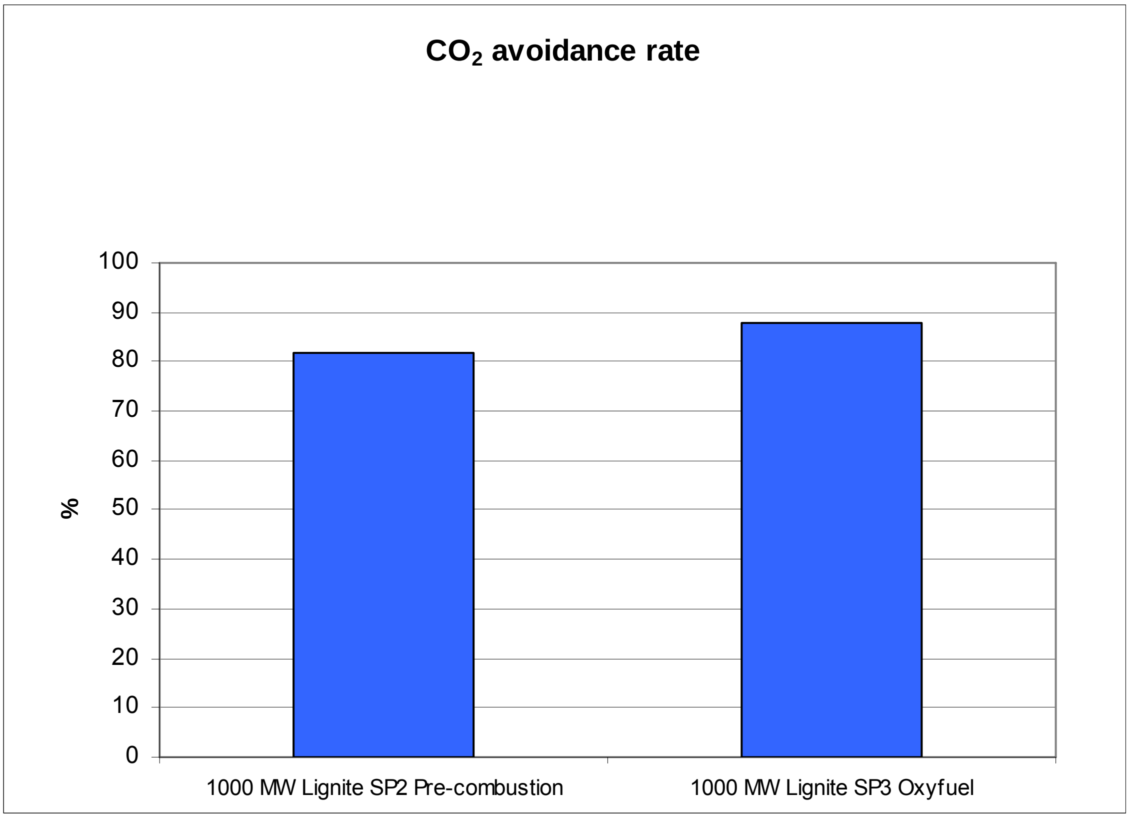


4.1.4 CO_2 avoidance rate

CO_2 avoidance rate is the difference between the spec. CO_2 emissions of the power plant with CO_2 capture and of the reference case in relation to the spec. CO_2 emissions of the reference case. It shows the CO_2 reduction in % achieved by the CO_2 capture technology when keeping the net power production constant.

CO2 avoidance rate

Reference case	Power plant	%
1000 MW Lignite PF	SP2 Pre-combustion	81,9
	SP3 Oxyfuel	87,9

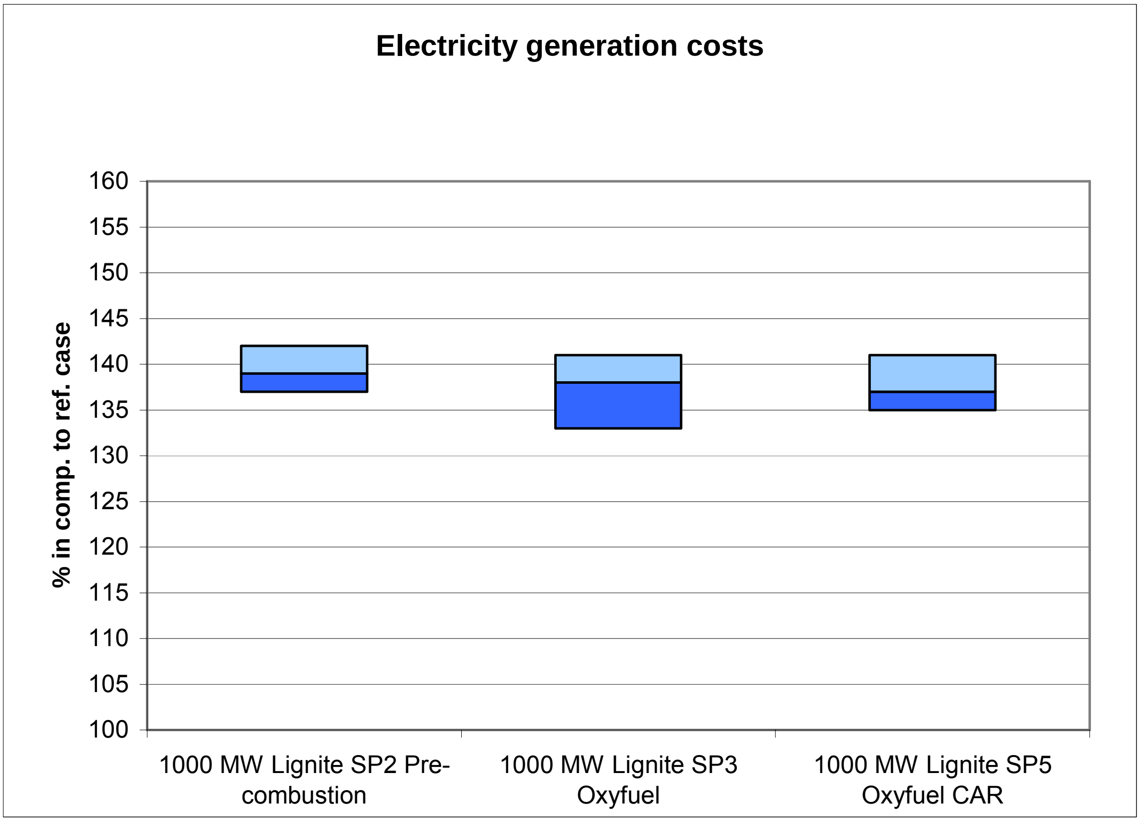


4.1.5 Relative Electricity generation costs

The figures give the electricity generation costs of the CO_2 capture concepts in relation to the corresponding reference case. Base case refers to basic economic conditions, i. e. 40 years commercial life time, 8 % interest rate and 1.1 Euro/GJ fuel price. Sensitivity analysis was made by varying these 3 parameters. Min and max values show the bandwidth of the resulting electricity generation costs.

Relative Electricity generation costs (compared to the reference power plant without CO2 capture)

Reference case	Power plant	Min %	Base case %	Max %
1000 MW Lignite PF	SP2 Pre-combustion	137	139	142
	SP3 Oxyfuel	133	138	141
	SP5 Oxyfuel CAR	135	137	141

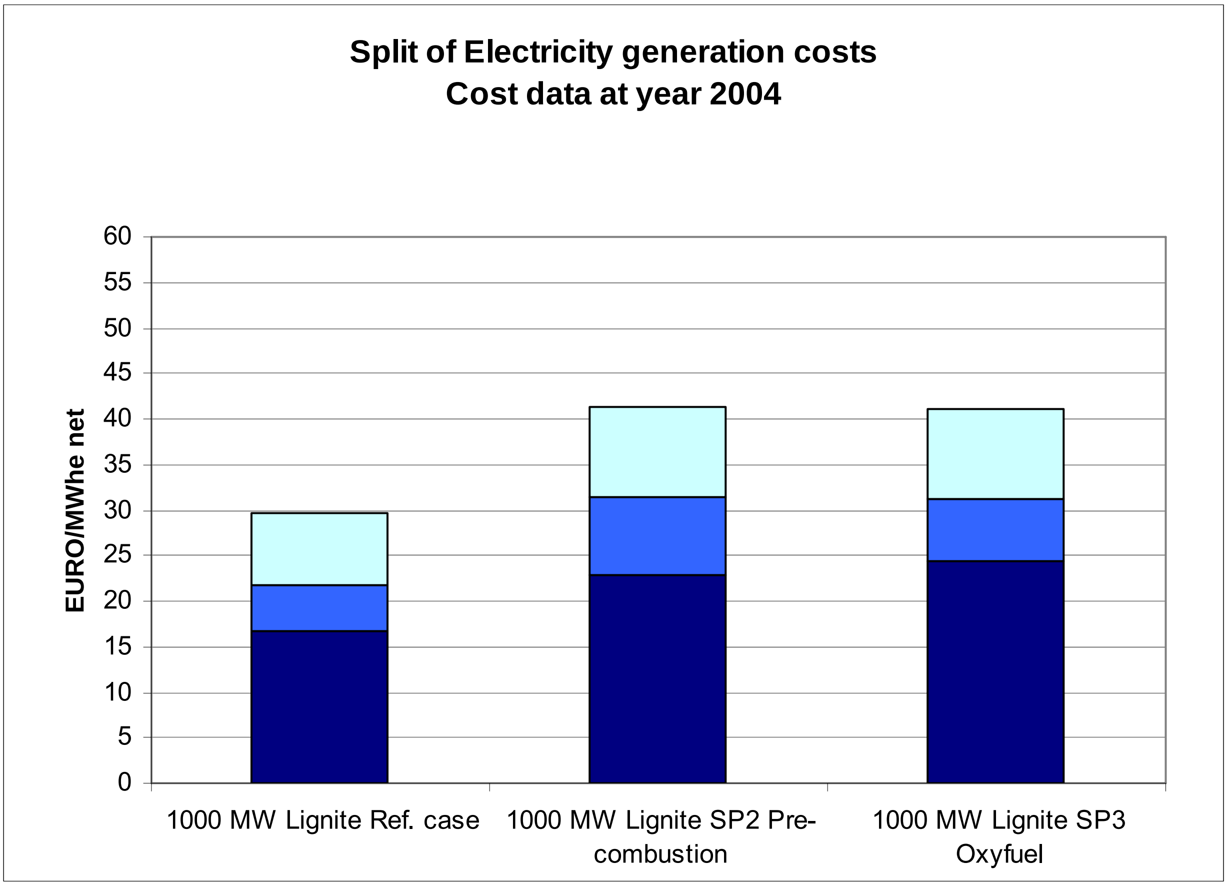


4.1.6 Split of electricity generation costs

The table and the diagram give the composition of the electricity generation costs for the base case of economic parameters (40 years of economic life time, 8 % interest rate and 1.1 Euro/GJ fuel price).

Split of electricity generation costs

		EURO/MWhe net		
Reference case	Power plant	Capital ■	O&M ■	Fuel ■
1000 MW Lignite PF	Ref. case	16,7	5,0	8
	SP2 Pre-combustion	22,9	8,6	9,9
	SP3 Oxyfuel	24,5	6,8	9,7

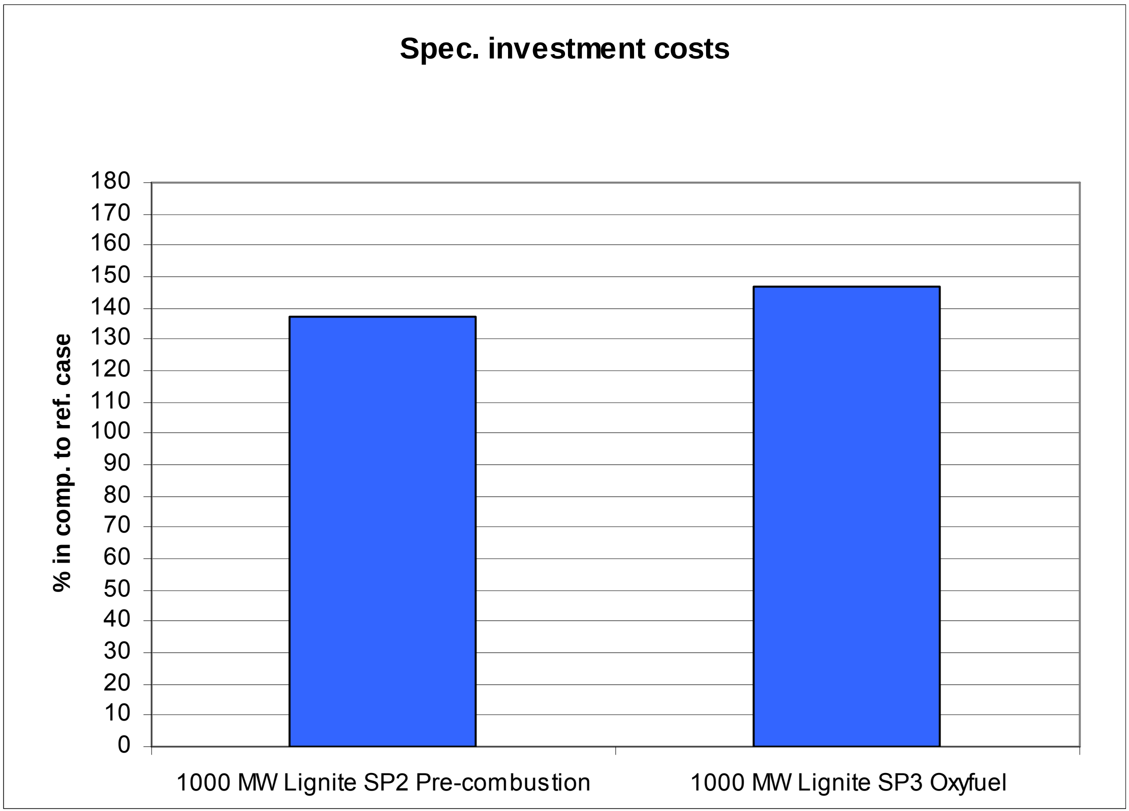


4.1.7 Relative Specific investment costs compared to reference case

Spec. investment costs are the investment costs including owner's costs in relation to the net capacity of the power plant. They are calculated as Net Present Value at start of operation in order to take into account differences in the schedule of payments. The figures belong to the base case of economic parameters (here only 8 % interest rate is of importance). In this chapter the spec. investment costs are expressed in relation to the corresponding reference case.

Relative Spec. investment costs as NPV at start of operation comp. to ref. case

Reference case	Power plant	%
1000 MW Lignite PF	SP2 Pre-combustion	137
	SP3 Oxyfuel	147

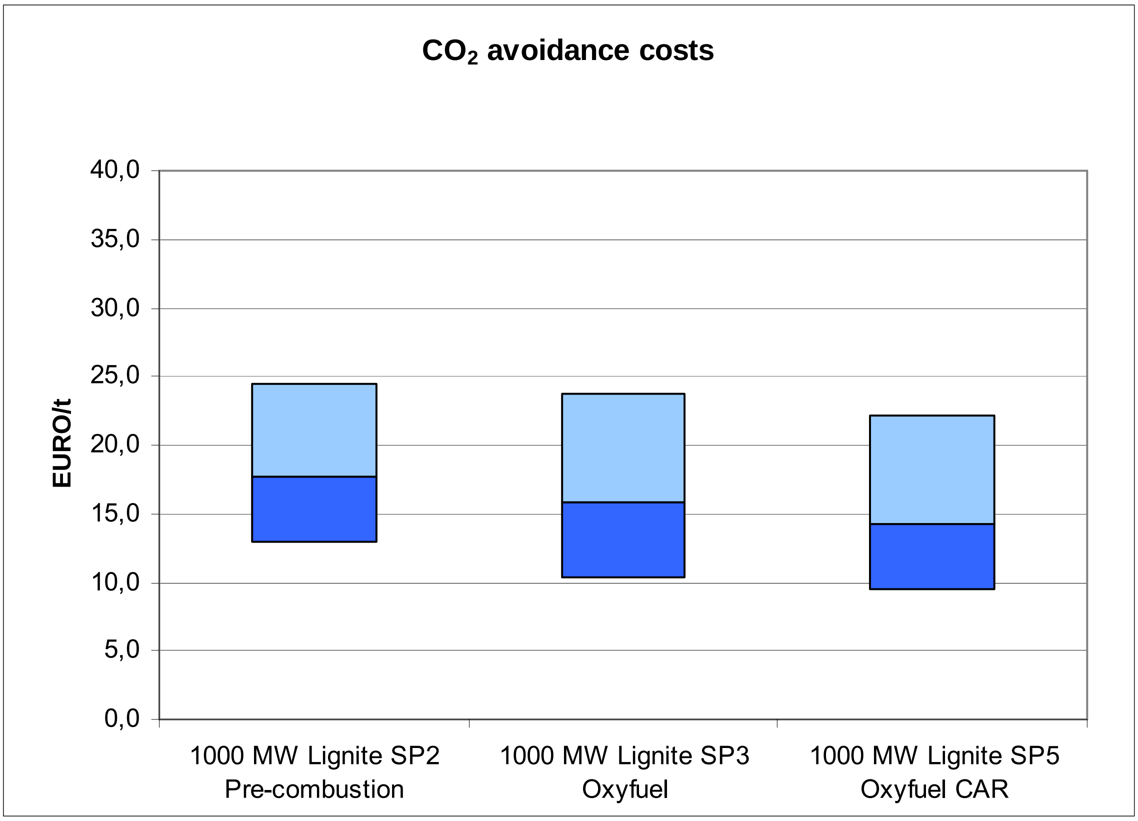


4.1.8 CO_2 avoidance costs

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. Base case refers to basic economic conditions (40 years of economic life time, 8 % interest rate and 1.1 Euro/GJ fuel price). Sensitivity analysis was made by varying these 3 parameters. Min and max values show the bandwidth of the resulting CO_2 avoidance costs.

CO2 avoidance costs

		EUR/ton avoided CO_2		
Reference case	Power plant	min	base case	max
1000 MW Lignite PF	1000 MW Lignite SP2 Pre-combustion	13,0	17,7	24,5
	1000 MW Lignite SP3 Oxyfuel	10,4	15,8	23,7
	1000 MW Lignite SP5 Oxyfuel CAR	9,5	14,3	22,1



4.2 Discussion of results

4.2.1 Cost Factors

Net Efficiency
The net efficiencies for the SP2 and SP3 technologies are both calculated to be just above 40% for lignite case, while the net efficiency for the SP5 technology is slightly lower, just below 40%.

Major additional (compared to the reference case) energy consumers for the SP2 IGCC pre-combustion capture case are the cryogenic ASU (Air Separation Unit), the conversion of raw syngas to hydrogen-rich gas and CO_2 separation, and the CO_2 compression. For the SP3 and SP5 PF oxy-fuel cases, the major additional energy consumers are the air separation processes – cryogenic ASU for SP3 and natural gas combustion to heat the CAR absorber for SP5 – and the CO_2 compression.

All three capture technologies reduce the net efficiency compared to the reference case around 10 %-points (corresponding to around 20 % efficiency loss) The differences between the technologies are probably within uncertainty margin at this stage and dependent on the selected strategies in the optimisation of the plants.

Total Investment and O&M costs
For the SP3 and SP5 cases the total investment costs (based on gross electricity output) are calculated to increase by more than 15 %, mainly due to additional investments in Air Separation Units – cryogenic ASU for SP3 and CAR for SP5 – and in CO_2 compression and conditioning equipments. For the SP3 case, the total fixed O&M costs are considered to increase with more than 15 % while the variable O&M costs (without fuel costs) decreases slightly from the reference case of 1 Euro/MWhe gross (due to no FGD). For the SP5 technology, no major additional O&M costs due to the CAR process are expected.

For the SP2 case, the total investment costs are calculated to increase by more than 20 % compared to the conventional lignite pulverized fired reference power plant. The total fixed O&M costs are considered to increase with about 40% while the variable O&M costs (without fuel costs) increases significantly or nearly twice from the reference case of 1 Euro/MWh_{el} gross. The significant cost difference reflects the costly maintenance of gas turbines in general and also high service costs estimated for the gasifier and gas conditioning units as well.

The cost calculations are carried out in cost basis 2004, although cost escalations have occurred since that time due to e.g. an increased market demand, the difference in relative investment costs are considered to remain the same.

Electricity Generation Costs
For all three cases, the calculated resulting electricity generation costs increase nearly 40% compared to the PF reference plant. This corresponds to just above 40 EUR/MWh_{el} in cost basis 2004 (base case with 40 years economic lifetime).

Although the investment and fuel costs have increased significantly the last couple of years, and the specific generation costs often are considered to be much higher in present cost levels, the relative comparisons between the technologies should still be valid.

Availability
Overall availability due to forced outage is expected to be slightly below the reference case without capture for all the capture technologies.

Both ASU and PF boiler are considered mature technologies that have proven their reliability in large scale applications. So, for the oxy-fuel SP3 case an estimated decrease of availability of 2-4 %-points is expected for the first generation of plants, mainly due to the integration level of the CO_2 capture technology and the O_2 related components.

The availability for a CCGT is slightly higher than compared to the PF (RC). For SP2 CCGT island a slightly decrease of availability is considered due to syngas with enriched H_2 operation compared to a NG CCGT. Due to the syngas with a diluent mass flow the IGCC can compensate the CCGT ambient temperature dependency and give an enhanced output and energy availability. The ASU and CO_2 trains are similar to refinery industrially proven units. An overall decrease of availability is however expected because of the gasifier and integrated IGCC with ASU and CO_2 train.

4.2.2 Operation Characteristics

Maximum Load Change Rate
Compared to a conventional PF boiler with a maximum load change rate of 5 %/min (RC 50-90% MCR), the maximum load change rate of the SP3 oxy-fuel PF is reduced to 4%/min. due to ASU operation.

SP2 pre-combustion IGCC load change rate is considered to be less than 4%/min. due to ASU operation and gas conditioning units.

Minimum Load
Minimum load for a conventional PF corresponds to the Benson min. load point for a once through boiler, for the lignite RC it is said to be 50%**.** For the SP3 oxy-fuel boiler a minimum load of 50% could be maintained, as the new components (ASU and CO_2 with parallel compressor trains) will not be the limiting part.

For the SP2 case, minimum load of 40/50% would be able to achieve without any significant lack in efficiency, considering operation with one train at 80% load.

Start-Up Time
Compared to the conventional air-fired reference case the start-up time will be increased for both SP3 and SP5 cases. During start-up there will be a period with air-firing before switching to oxy-combustion. Unless additional equipment to keep SOx and NOx emissions below the limit values also during start-up are installed, emission limits will be exceeded during start-up and shut-down.

SP2 case: Compared to the conventional air-fired PF reference case the start-up time will be increased due to the ASU and gas conditioning unit. Until the gas conditioning unit is in steady state operation, the emissions will be increased. Due to the enriched H_2 syngas it would require a separate start up fuel for the gas turbine of safety reason.

Operation Flexibility
The applied CO_2 capture technology (oxy-fuel) for both SP3 and SP5 is integrated in the process and it is not possible to bypass this. To bypass the CO_2 processing plant or operate the boiler with air instead of O_2/CO_2, would require installation of back-up systems for heat recovery and additional cleaning systems for SOx and NOx. (This has not been evaluated but could technically be done)

SP2: The applied CO_2 capture technology AGR (Acid Gas removal) is integrated in the process and it is not possible to bypass this.

Safety Issues and Environmental Impacts
For all capture technologies SP2, SP3 and SP5 the safety issues regarding handling of oxygen for these applications need further evaluation.

SP2: Safety issues regarding Gas Conditioning and solvent handling in the Rectisol absorption processes and effluents handling which would need further evaluation

For SP 5 the dust, mechanically generated when filling the CAR adsorber vessels with the perovskite adsorbent, has to be removed (blown out by inert gas) and taken properly care of before operation.

There is also a common safety risk for all capture technologies related to the handling of CO_2.

For oxy-fuel combustion in SP3 and SP5 cases there is a potential risk that the quality and the application of the ash products may change. However, this has not been shown experimentally in a consistent manner. Initial tests within SP3 show no difference in ash quality between air-firing and oxy-fuel firing.

SP2: The HTW fluidised bed gasifier expects to give an ash quality which due to high char content not will be able to store unless the ash char is burnt in a boiler, e.g. FBC.

For the SP 5 case, the CAR unit may be sensitive to the sulphur in the recycled CO_2 stream, and to what degree additional sulphur cleaning will be needed require experimental verifications. The CAR unit may also be sensible to the particle content of the recycle stream used for sweeping.

4.2.3 CO2 capture and quality

CO_2 Capture Rate
The ENCAP target of a CO_2 capture rate of 90% is reached by the SP3 and SP5 oxy-fuel PF technologies but not by the SP2 pre-combustion IGCC technology.

For the SP3 case, 90% CO2 capture rate was assumed as input data in the assessment. Higher capture rate could be reached. Conditioning of the CO_2-stream is necessary due to air-in-leakage in the boiler and ESP and partially due to the selected 95% O2 purity. The SP5 technology reaches around 95%, but SP5 did not include any boiler air in-leakage, and therefore no conditioning, that would result in loss of CO_2.

The SP2 technology is considered to reach a capture rate of about 85%, mainly due to that the selected fluidised bed gasifier is expected to produce a syngas with relatively high methane content (which will generate CO_2 when combusted in the gas turbine) and an ash with a high content of ungasified carbon (that has to be burnt in a separate boiler). The CO_2 avoidance rate and the remaining specific CO_2 emissions differ correspondingly.

CO_2 Product Quality
For the SP2 case, the CO_2 quality meets severe limit case standards, i.e. a very high CO_2 purity is reached.

SP3 case: If the final CO_2 product stream should reach the target of the "EOR" or the "more severe" product quality, this may require deNOx, deSOx and deOx units and deeper removal of non-condensables, requiring a distillation rather than just a flash and further recycle of CO_2. All this would increase the total investment, and somewhat increase the auxilliary consumption and the CO_2 capture rate.

SP5 case: Additional drying of the CO_2 product stream (additional investment) will be required to meet the requirements in the "design case" as well as for the other cases. As for the SP3 case, to reach the target of the "EOR" or the "more severe" product quality, may require deNOx, deSOx and deOx units which will increase the total investment.

4.2.4 Technical Maturity

For the SP3 oxy-fuel case, most of the processes are proven technology. The oxy-fuel-fired PF boiler and the full integration of the technologies are however still at pilot-plant stage.

For the SP5 case, the CAR process is up to now only tested in lab scale. In principal, a process with cyclic adsorption is state of the art, but the stability of the oxygen adsorbent in this application determines how mature the CAR process can be considered to be for air separation. Most of the other processes are proven technology. The oxy-fuel-fired PF boiler and the full integration of these other technologies are at pilot-plant stage.

For the SP2 case, all components are commercially available, but not with operation experience for similar conditions. IGCC with AGR and shift reactor has to be demonstrated reliable. Development of high efficient (F-class) gas turbine with enriched H_2 fuel combustors is ongoing. The integration of the gas turbine with the ASU and discharge of (bleed off) compressor air would require dual fuel possibilities for the gas turbine, which is designed for diluted fuel. Transient operation modes and implication on process to be evaluated remains.

4.2.5 Changes in results to adjusted reference cases (see explanation in chapter 3.3)

Only minor, not significant changes in the relative assessment were observed by adjusting the reference case to the same net capacities as for the power plants with CO_2 capture (as explained in chapter 3.3). The power plant concepts with CO_2 capture, that are evaluated in Chapter 4, have lower net electricity capacities than the reference power plant. The adjusted reference PF power plants consequently become smaller, resulting in slightly higher specific investments and fixed O&M costs. This decrease the cost differences between the power plants with CO_2 capture and the adjusted reference power plants.

5 Capture technologies for reference case “600 MW Bit. coal PF”

The following power plant concepts with CO_2 capture are evaluated against the bituminous coal-fired 600 $MW_{el\ gross}$ PF reference case:

“1st” generation power plant concepts with CO_2 capture

- 600 MW Bit coal SP2 Pre-combustion
- 600 MW Bit coal SP3 Oxyfuel

“More future” power plant concepts with CO_2 capture

- 600 MW Bit coal SP6 Pre-combustion
- 600 MW Bit coal SP6 Pre-combustion, Air integration

See Chapter 2.3 for short descriptions of these technologies.

Ongoing development work aims at adaptation of burners for hydrogen rich gases to the design requirements of modern high temperature F-class gas turbines. Therefore, the power plant concept with pre-combustion CO_2 capture from SP2 is designed with F-class gas turbine combined cycle of the same type as the natural gas fired 393 $MW_{el\ gross}$ combined cycle reference case.

5.1 Overview of quantitative data (technical and economic data)

5.1.1 Electricity outputs

- The SP2 pre-combustion IGCC, uses two parallel gas turbines, anticipated to be derived from the gas turbine used in the natural gas fired 393 $MW_{el\ gross}$ combined cycle reference case (compare Chapter 6). This results in increased (60%) fuel mass flow compared to the 600 MW bit. coal PF reference case.
- The SP3 Oxyfuel PF has the same boiler size as the 600 MW bit. coal PF reference case. This results in a slightly (2%) higher fuel mass flow.
- The SP6 pre-combustion IGCC uses one gas turbine with similar parameters as the gas turbine used in the natural gas fired 393 $MW_{el\ gross}$ combined cycle reference case (compare Chapter 6). This results in decreased (15%) fuel mass flow compared to the 600 MW bit. coal PF reference case.

The resulting gross and net electricity output capacities are as follows:

Electric power output

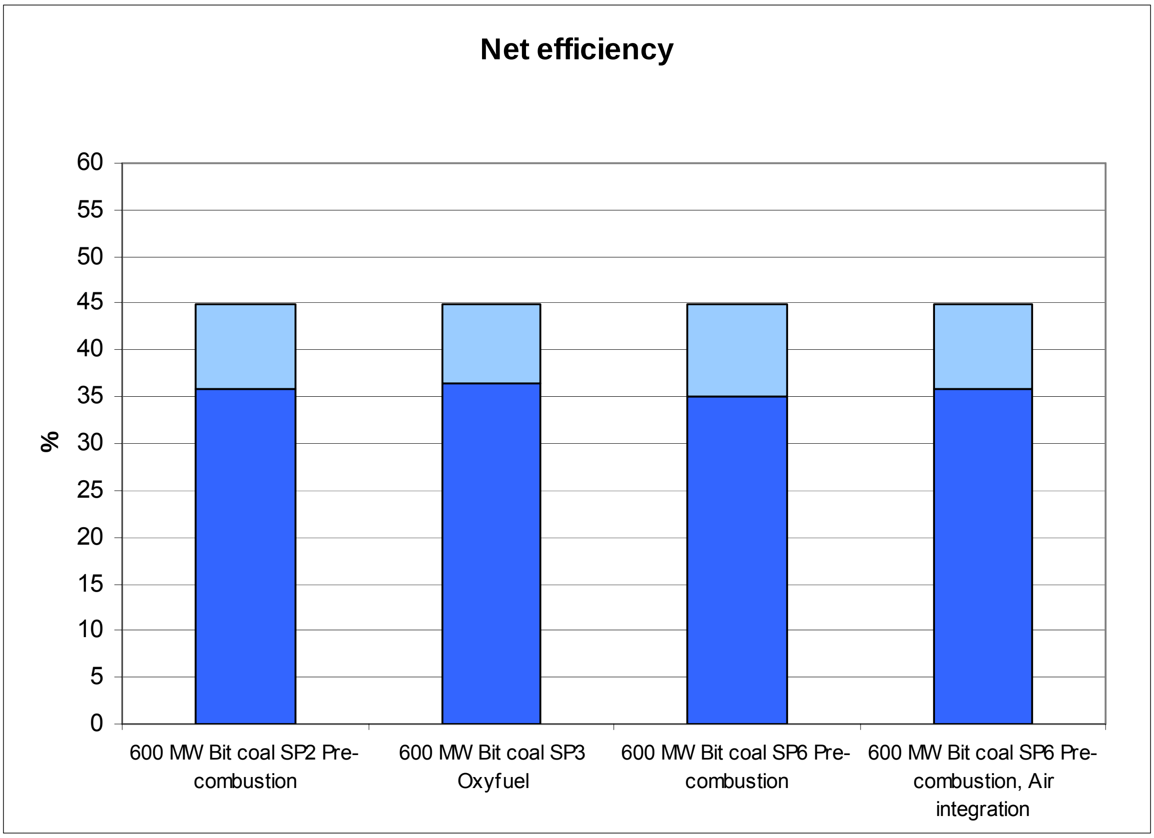
Reference case	Power plant	Gross, MWe	Net, MWe
600 MW Bit coal PF	Ref. case	600	575
	SP2 Pre-combustion	956	737
	SP3 Oxyfuel	633	472
	600 MW Bit coal SP6 Pre-combustion	495	381
	600 MW Bit coal SP6 Pre-combustion, Air integration	441	389

5.1.2 Net efficiency

Net efficiency is the ratio of the net power production and the heat input via fuel (fuel mass flow x LHV).

Net efficiency

Reference case	Power plant	%	% ref. case	Delta %-points	Delta %
600 MW Bit coal PF	SP2 Pre-combustion	35,9	45,0	9,1	20,2
	SP3 Oxyfuel	36,4	45,0	8,6	19,2
	600 MW Bit coal SP6 Pre-combustion	35,1	45,0	9,9	22,0
	600 MW Bit coal SP6 Pre-combustion, Air integration	35,8	45,0	9,2	20,4

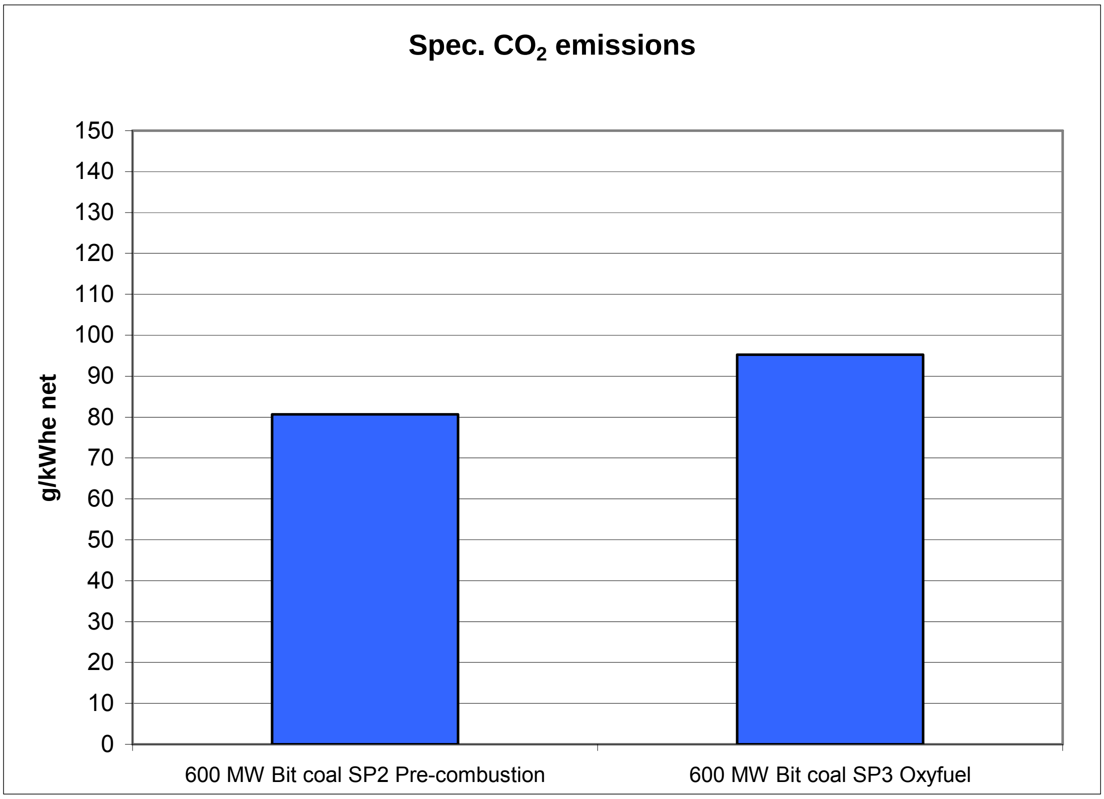


5.1.3 Specific CO_2 emissions

Spec. CO_2 emissions are the CO_2 emissions to the atmosphere in relation to the net power production.

Spec. CO2 emissions

Reference case	Power plant	g/kWhe
600 MW Bit coal PF	Ref case	774
	SP2 Pre-combustion	80,6
	SP3 Oxyfuel	95,2

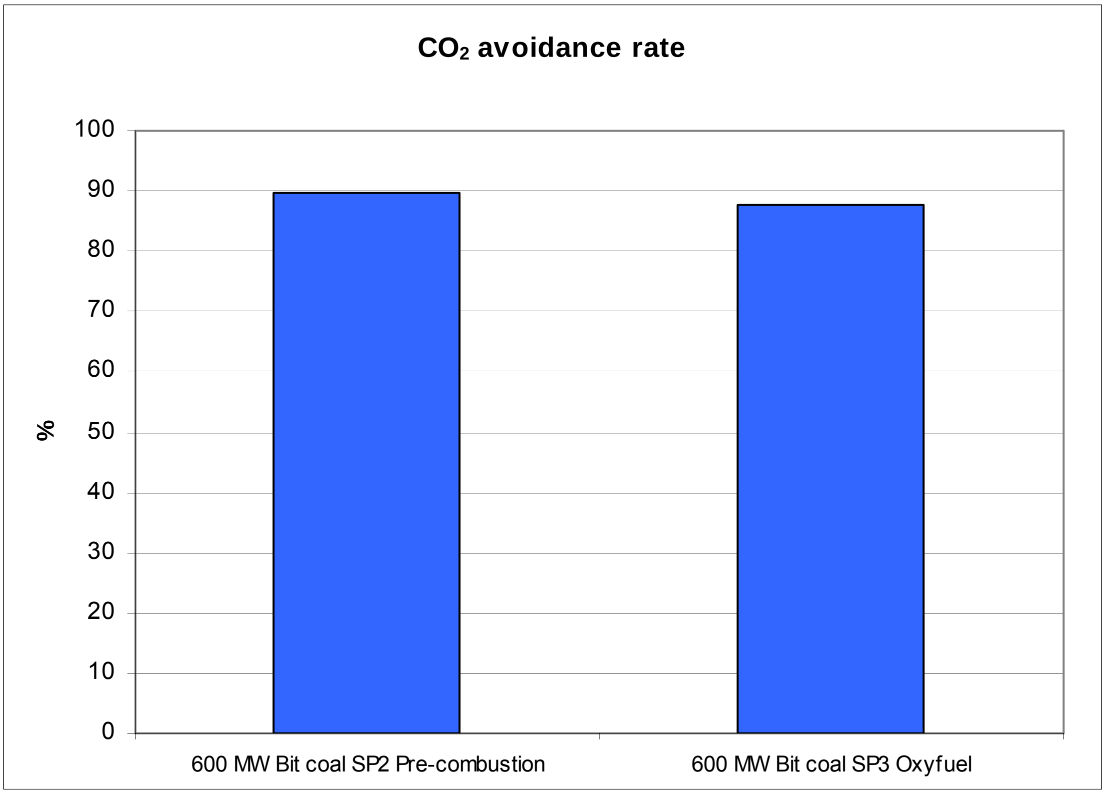


5.1.4 CO_2 avoidance rate

CO_2 avoidance rate is the difference between the spec. CO_2 emissions of the power plant with CO_2 capture and of the reference case in relation to the spec. CO_2 emissions of the reference case. It shows the CO_2 reduction in % achieved by the CO_2 capture technology when keeping the net power production constant.

CO2 avoidance rate

Reference case	Power plant	%
600 MW Bit coal PF	SP2 Pre-combustion	89,6
	SP3 Oxyfuel	87,7

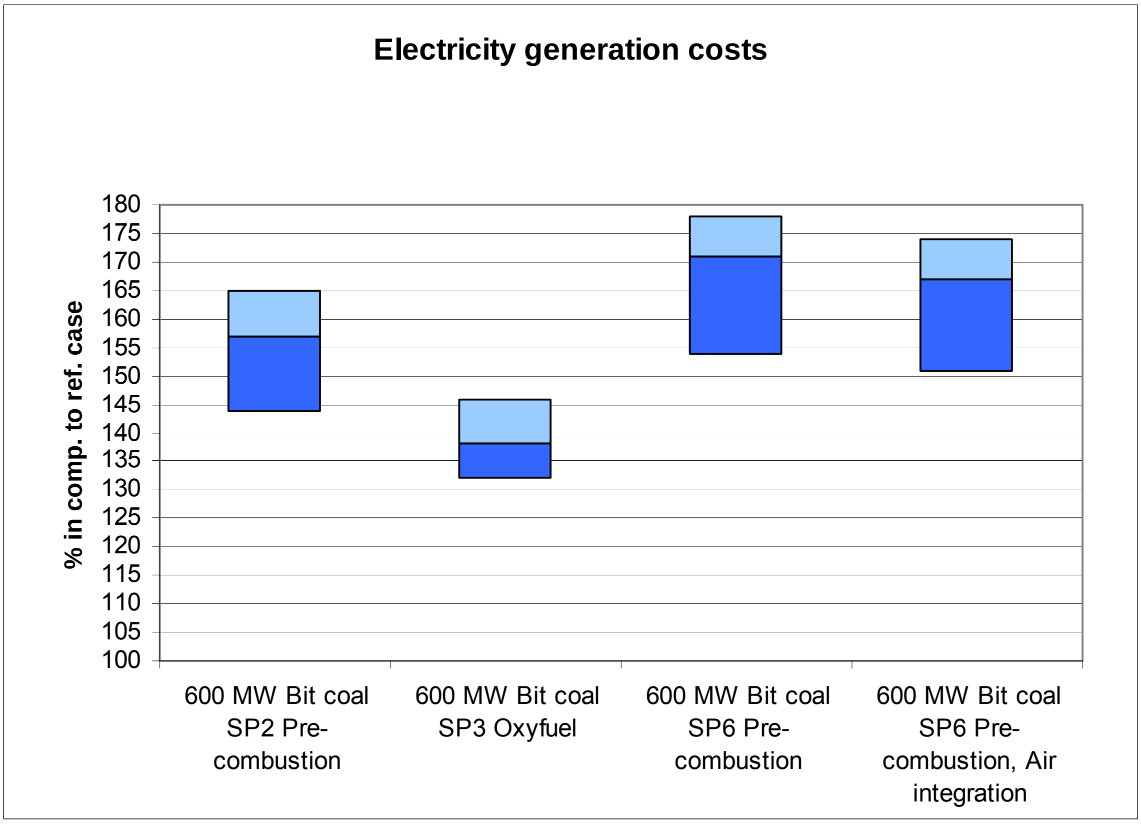


5.1.5 Relative electricity generation costs

The figures give the electricity generation costs of the CO_2 capture concepts in relation to the corresponding reference case. Base case refers to basic economic conditions, i. e. 40 years commercial life time, 8 % interest rate and 1.6 Euro/GJ fuel price. Sensitivity analysis was made by varying these 3 parameters. Min and max values show the bandwidth of the resulting electricity generation costs.

Relative electricity generation costs (compared to reference power plant without CO_2 capture)

Reference case	Power plant	Min %	Base case %	Max %
600 MW Bit coal PF	SP2 Pre-combustion	144	157	165
	SP3 Oxyfuel	132	138	146
	600 MW Bit coal SP6 Pre-combustion	154	171	178
	600 MW Bit coal SP6 Pre-combustion, Air integration	151	167	174

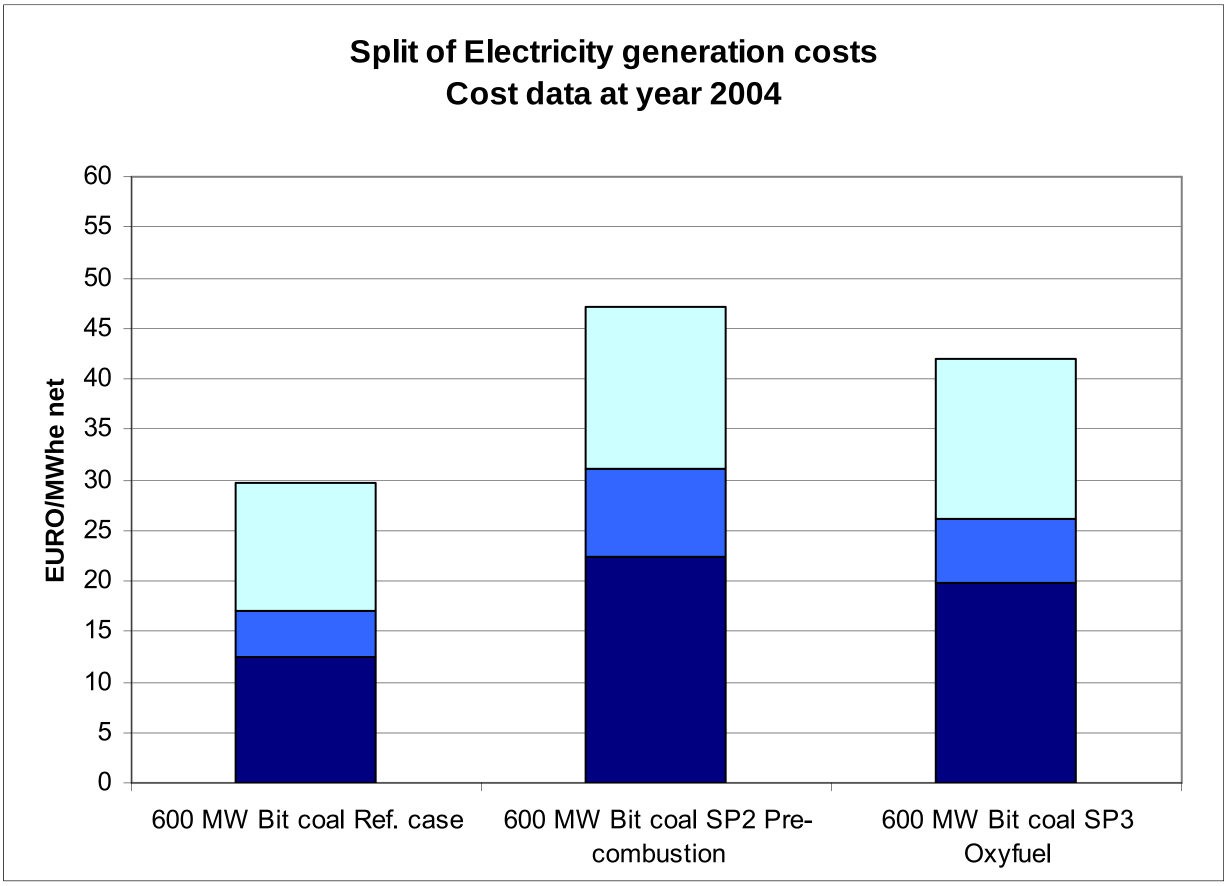


5.1.6 Split of electricity generation costs

The table and the diagram give the composition of the electricity generation costs for the base case of economic parameters (40 years of economic life time, 8 % interest rate and 1.6 Euro/GJ fuel price).

Split of electricity generation costs

		EURO/MWhe net		
Reference case	Power plant	Capital ■	O&M ■	Fuel ■
600 MW Bit coal PF	Ref. case	12,5	4,5	12,8
	SP2 Pre-combustion	22,3	8,8	16
	SP3 Oxyfuel	19,8	6,4	15,8

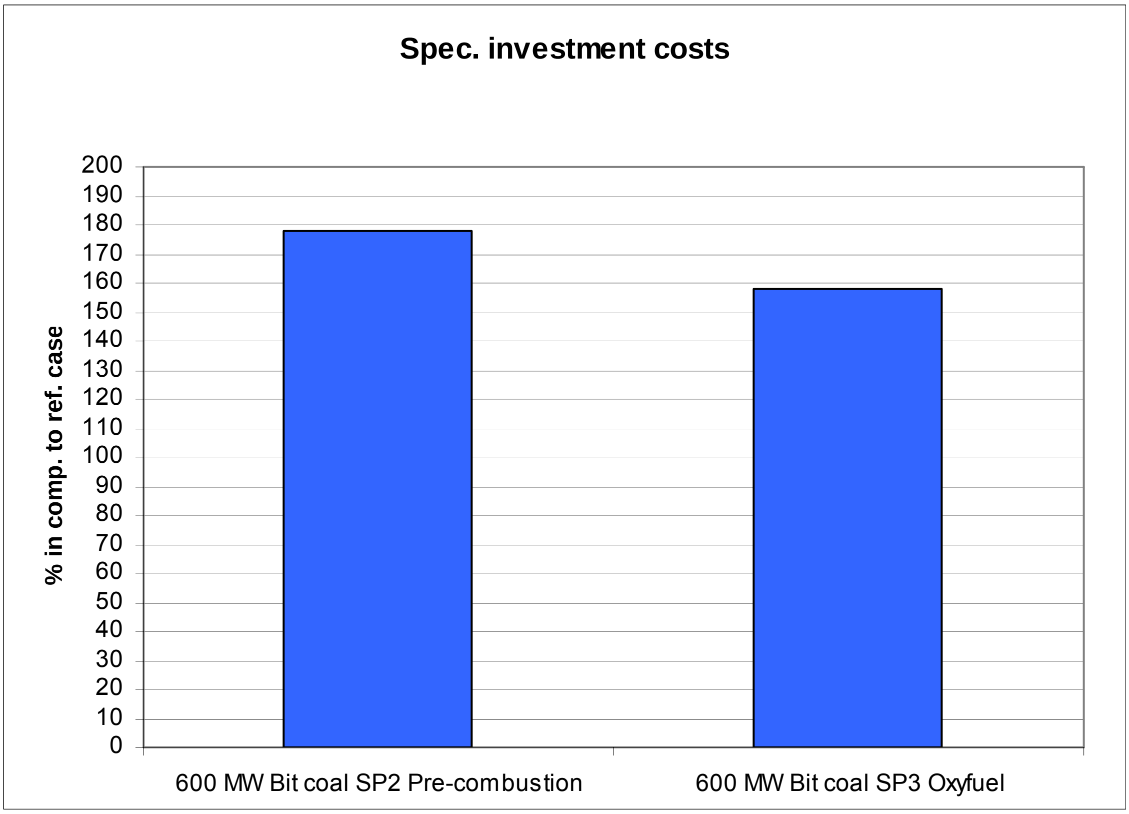


5.1.7 Relative specific investment costs compared to reference case

Spec. investment costs are the investment costs including owner's costs in relation to the net capacity of the power plant. They are calculated as Net Present Value at start of operation in order to take into account differences in the schedule of payments. The figures belong to the base case of economic parameters (here only 8 % interest rate is of importance). In this chapter the spec. investment costs are expressed in relation to the corresponding reference case.

Relative spec. investment costs as NPV at start of operation comp. to ref. case

Reference case	Power plant	%
600 MW Bit coal PF	SP2 Pre-combustion	178
	SP3 Oxyfuel	158

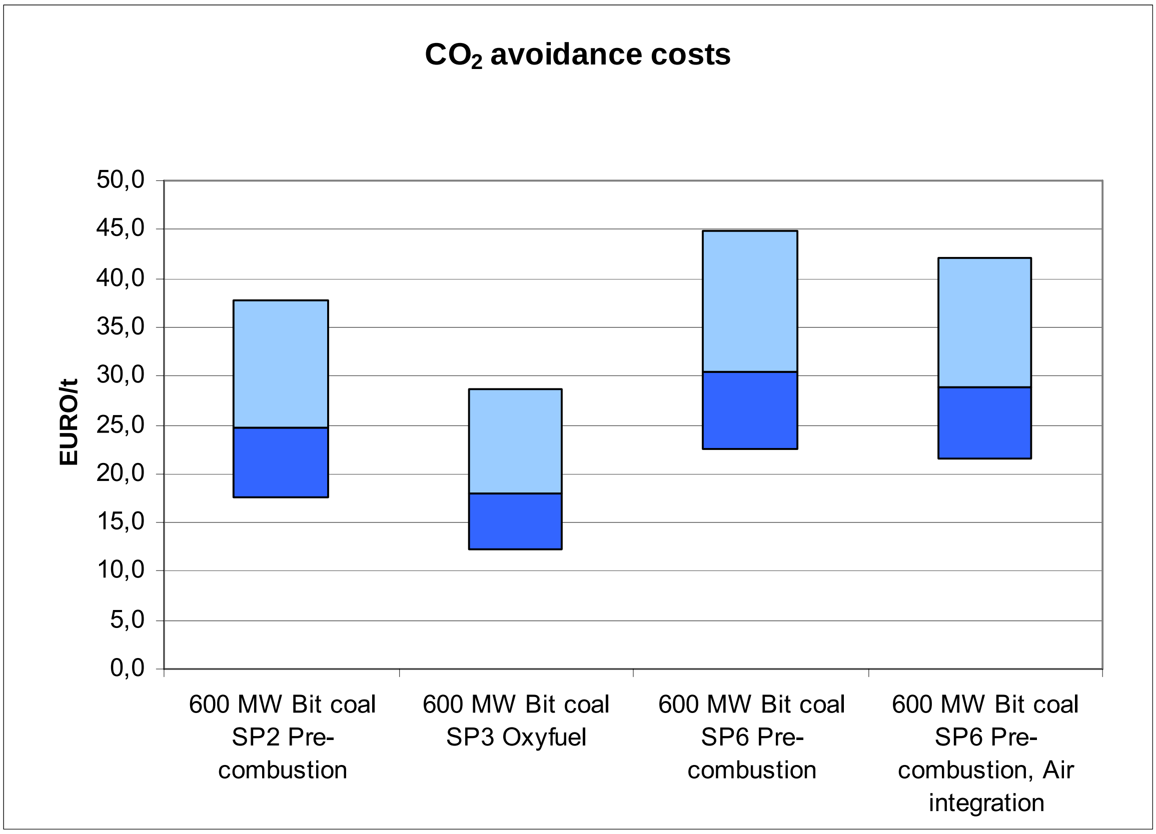


5.1.8 CO_2 avoidance costs

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. Base case refers to basic economic conditions (40 years of economic life time, 8 % interest rate and 1.6 Euro/GJ fuel price). Sensitivity analysis was made by varying these 3 parameters. Min and max values show the bandwidth of the resulting CO_2 avoidance costs.

CO_2 avoidance costs

		EUR/ton avoided CO_2		
Reference case	Power plant	min	base case	max
600 MW Bit coal PF	SP2 Pre-combustion	17,6	24,8	37,8
	SP3 Oxyfuel	12,2	17,9	28,7
	600 MW Bit coal SP6 Pre-combustion	22,5	30,4	44,8
	600 MW Bit coal SP6 Pre-combustion, Air integration	21,6	28,9	42,0



5.2 Discussion of results

5.2.1 Cost Factors

Net Efficiency
All three capture technologies from SP2, SP3 and SP6 reduce the net efficiency to just above 35% compared to the net efficiency of 45% in the PF reference power plant without capture, corresponding to an efficiency loss of approximately 10 %-points.

Major additional (compared to the reference case) energy consumers for the SP2 and SP6 IGCC pre-combustion capture case are the cryogenic ASU (Air Separation Unit), the conversion of raw syngas to hydrogen-rich gas and CO_2 separation, and the CO_2 compression.'

For the SP3 PF oxy-fuel case, the major additional energy consumers are the cryogenic ASU and the CO_2 compression.

Total Investment and O& M costs
For the SP2 case, the total investment costs (based on gross electricity output) are calculated to increase with more than 40 % compared to the conventional bituminous pulverized fired reference power plant (PF RC). The total fixed O&M costs are considered to increase with more than 30% while the variable O&M costs (without fuel costs) increase more than twice from the reference case of 1 Euro/MWh$_{el}$ gross. The significant cost difference reflects the costly maintenance of gas turbines in general and also high service costs estimated for the gasifier and gas conditioning units as well.

For the SP3 case the total investment cost is calculated to increase by around 20 % compared to the conventional PF case, mainly due to additional investments in cryogenic ASU and in CO_2 compression and conditioning equipments. The total fixed O&M cost is estimated to increase with around 20 % while the variable O&M cost (without fuel costs) decreases slightly from the reference case of 1 Euro/MWhe gross (due to no FGD).

For the SP6 cases the total investment cost is calculated to increase by around 50 and 65 % respectively for the non integrated and integrated ASU compared to the conventional PF case. The higher specific investment for SP6 compared to SP2 is a consequence of a smaller plant compared to the reference case. The total fixed O&M cost is estimated to increase with the double, while the variable O&M cost (without fuel costs) increases approximately twice from the reference case. For the integrated SP6 case the increase of the variable O&M cost is nearly 3 times the reference case.

The cost calculations are carried out in cost basis 2004, although cost escalations have occurred since that time, the difference in relative investment costs are considered to remain the same.

Electrical Generation Costs
The resulting electricity generation costs have been calculated to slightly below 50 EUR/MWh$_{el}$ in cost basis 2004 for the SP2 case and for the SP3 case to slightly above 40 EUR/MWh$_{el}$ (base case with 40 years economic lifetime, fuel price 1,6 EUR/GJ, and interest

rate 8%). For the SP6 cases the electricity generation costs have been calculated to be slightly higher compared to SP2.

The major difference between the electricity generation costs for the pre-combustion IGCC and oxy-fuel PF technologies is due to lower specific investment and variable O&M costs for SP3 oxy-fuel PF. The differences are however within the ranges of uncertainty that can be expected at the current level of development.

Although the investment and fuel costs have increased significantly the last couple of years, and the specific generation costs often are considered to be much higher in present cost levels, the relative comparisons between the technologies should still be valid

Availability
For all three capture technologies the overall availability due to forced outage is expected to be slightly below the reference PF case without capture.

For SP3, this reduction in availability is estimated to 2-5 %-points for the first generation of plants and this is mainly because of the integration level of the CO_2 capture technology and the O_2 related components. Both ASU and boiler are considered mature technologies with proven reliability in large scale applications.

The availability for a CCGT is slightly higher than compared to the PF (RC). For CCGT island in these gasifier applications (SP2 and SP6) a slightly decrease of availability is considered due to syngas with enriched H_2 operation compared to a NG CCGT. Due to the syngas with a diluent mass flow the IGCC can compensate the CCGT ambient temperature dependency and give an enhanced output and energy availability. The ASU and CO_2 trains are similar to refinery industrially proven units. An overall decrease of availability is however expected because of the gasifier and integrated IGCC with ASU and CO_2 train. For the SP6 case in which the gas turbine compressor is integrated with the ASU on air side the availability can be expected to be even less.

5.2.2 Operation Characteristics

Maximum Load Change Rate
For the SP3 oxy-fuel PF, the maximum load change rate is reduced to 4%/min. due to restrictions from the ASU operation, compared to a conventional PF with maximum load change rates of 4-6%/min (RC 50-90% MCR).

Maximum load change rate of the SP2 and SP6 pre-combustion IGCC is considered to be less than 4%/min. due to ASU operation and gas conditioning units.

Minimum Load
Minimum load for a conventional PF correspond to the Benson min. load point for a once through boiler, for the bituminous coal fired RC it is said to be 30%. For SP3 oxy-fuel boiler a minimum load of 30% could be reached, however an O_2 tank may then be required.

SP2: Minimum load of 40/50% would be able to achieve without any lack in efficiency, accounting operation with one train at 80% load.

SP6: Minimum load less than 80% would effect the efficiency of the gas turbine, this is due to single gas turbine train configuration in this case. Minimum load for the ASU is considered to be 50%.

Start Up Time

Compared to the conventional air-fired reference case the start-up time will be increased for the SP3 oxy-fuel PF due to the ASU. During start-up there will be a period with air-firing before switching to oxy-fuel where emission limits will be exceeded. Additional equipment to keep SOx and NOx emissions within limit values also during start-up, will require additional investments.

SP2 case: Compared to the conventional air-fired PF reference case the start-up time will be increased due to the ASU and gas conditioning unit. Until the gas conditioning unit is in steady state operation the emissions will be increased. Due to the enriched H_2 syngas it would require a separate start up fuel for the gas turbine of safety reason.

SP6: Compared to SP2, the SP6 case with integrated ASU will also need a separate start up fuel to maintain supply of pressurized bleed air for the ASU.

Operation Flexibility

The SP3 oxy-fuel CO_2 capture technology is integrated in the process and it is not possible to bypass this without considerable additional investment costs. To bypass the CO_2 processing plant or operate the boiler with air instead of O_2/CO_2, would require installation of back-up systems for heat recovery and additional cleaning systems for SOx and NOx. (This has not been evaluated)

SP2 case: The applied CO_2 capture technology AGR (Acid Gas Removal) is integrated in the process and it is not possible to bypass this. The CO shift reactor requires a significant steam amount and the integration with the steam turbine plant might limit the operation flexibility at part load.

For the SP6 case with sweet physical absorption the CO_2 capture process can be by passed if necessary.

Safety Issues and Environmental Impacts

For all three technologies (SP2,SP3 and SP6) will the safety issues regarding handling of oxygen for these applications need further evaluation.

SP2 and SP6 pre-combustion IGCC cases: Safety issues regarding Gas Conditioning and solvent handling in the Rectisol absorption processes and effluents handling would need further evaluation. Fluorides and H_2S may also be a potential risk for these cases, where special attention must be taken.

There is also a common safety risk for all capture technologies of the handling of CO_2.

For the SP3 oxy-fuel combustion, there is a potential risk that the quality and the application of the ash products may change. However, this has not been shown experimentally in a consistent manner and tests within SP3 show no difference between air-firing and oxyfuel firing.

SP2 and SP6 cases: The Shell gasification will, due to the high temperature and slagging of the ash, produce a frit ash quality, which would be more stable from soaking leaching point of view.

5.2.3 CO2 Capture and Quality

CO_2 Capture Rate

The ENCAP target of a CO_2 capture rate of 90% is reached by all three capture technologies. The SP3 oxy-fuel technology has a capture rate of 90%, however it has not been optimised in the SP3 analysis, and higher capture rate could be achieved. The SP2 and SP6 pre-combustion IGCC technologies are considered to reach a capture rate of over 90% for the bituminous coal cases.

CO_2 Product Quality

For the SP2 and SP6 pre-combustion IGCC cases, the CO_2 quality meets severe limit case standards, i.e. a very high CO_2 purity is reached

If the final CO_2 product stream from the SP3 oxy-fuel process should reach the target of the "EOR" or the "more severe" product quality, this may require deNOx, deSOx and deOx units, which will increase the total investment.

5.2.4 Technical Maturity

For the SP3 oxy-fuel case, most of the processes are proven technology. The oxy-fuel-fired PF boiler and the full integration of the technologies are however still at pilot-plant stage.

For the SP2 and SP6 pre-combustion IGCC cases, all components are commercially available, but not with operation experience for similar conditions. IGCC with AGR and shift reactor has to be demonstrated reliable. Development of high efficient (F-class) gas turbine with enriched H_2 fuel combustors is ongoing. The integration of the gas turbine with the ASU and discharge of (bleed off) compressor air would require dual fuel possibilities for the gas turbine, which is designed for diluted fuel. Transient operation modes and implication on process to be evaluated remains.

5.2.5 Changes in results for to adjusted reference cases (see explanation in chapter 3.3)

Only minor, not significant changes in the relative assessment were observed by adjusting the reference case to the same net capacities as for the power plants with CO_2 capture (as explained in chapter 3.3). The pre-combustion IGCC process in SP2 has a higher net electricity capacity than the reference PF power plant. The adjusted reference power plant consequently become larger, resulting in slightly lower specific investments and fixed O&M costs. This increases the cost differences between the SP2 process and the adjusted reference case. The oxy-fuel PF process in SP3 and the pre-combustion IGCC processes in SP6 have lower net electricity capacities than the PF reference power plant. Their adjusted reference power plants consequently become smaller, resulting in slightly higher specific investments and fixed O&M costs. This decrease the cost differences between the SP3 and SP6 processes and their adjusted reference cases.

By comparing the pre-combustion IGCC-processes from SP6 with a smaller reference power plant, their resulting cost increases become slightly smaller than for the larger pre-combustion IGCC-process from SP2. Except for this effect, no changes in relative assessments were observed by adjusting the reference cases.

6 Capture technologies for reference case " 393 MW Nat. gas CC"

The following power plant concepts with CO_2 capture are evaluated against the natural gas fired 393 MW_el_{gross} Combine Cycle Gas Turbine reference case:

"1st" generation power plant concepts with CO_2 capture
- 393 MW Nat gas SP2 ATR Pre-combustion ASU

"More future" power plant concepts with CO_2 capture
- 393 MW Nat gas SP4 CLC CC Double reheat Air turbine, rotating reactors
- 393 MW Nat gas SP4 CLC CC Double reheat Air turbine, membrane assisted reactors
- 393 MW Nat gas SP4 CLC CC Single reheat Air turbine
- 393 MW Nat gas SP5 Pre-combustion CAR
- 393 MW Nat gas SP6 Water cycle
- 393 MW Nat gas SP6 Graz Cycle
- 393 MW Nat gas SP6 S-Graz Cycle
- 393 MW Nat gas SP6 SCOC-CC
- 393 MW Nat gas SP6 Pre-combustion Membrane
- 393 MW Nat gas SP6 Pre-combustion Membrane, High pressure

See Chapter 2.3 for short descriptions of these technologies.

Ongoing development work aims at adaptation of burners for hydrogen rich gases to the design requirements of modern high temperature F-class gas turbines. Therefore, the power plant concepts with pre-combustion CO_2 capture from SP2 and SP5 are designed with F-class gas turbine combined cycles of the same type as the natural gas fired reference case.

6.1 Overview of quantitative data (technical and economic data)

For the "more future" power plant concepts with CO_2 capture, the uncertainties are larger in all data, especially for investments and costs. Only electricity outputs, net electric efficiencies, electricity generation costs in relation to reference case, and CO_2 avoidance costs, are presented for those technologies.

6.1.1 Electricity outputs

- The SP2 and SP5 pre-combustion IRCC:s, use two parallel gas turbines, anticipated to be derived from the gas turbine used in the reference case. This results in increased (2.7 times) fuel mass flows compared to the reference case (with only one gas turbine).
- The SP4 CLC CC:s use turbines with parameters as similar to the reference case gas turbine as possible. Reactor outlet temperature (turbine inlet temperature) is however reduced to 1000°C. The fuel mass flows are slightly (2%) higher than the reference case.
- The SP6 oxyfuel cycles use turbines with parameters as similar to the reference case gas turbine as possible. For the Water cycle, the Graz Cycle and the S-Graz Cycle, turbine efficiencies are however stated as not consistent to reference case, as these cycles will require totally new designs of the turbomachinery. The fuel mass flows for all SP6 oxyfuel cycles are the same as for the reference case
- The SP6 Pre-combustion cycles use one gas turbine with similar parameters as the reference gas turbine, and the fuel mass flows are the same as for the reference case.

The resulting gross and net electricity output capacities are as follows:

Electricity output capacities

Reference case	Power plant	Gross, MW_{el}	Net, MW_{el}
393 MW Nat gas CC	Ref. case	393	385
	SP2 ATR Pre-combustion ASU	873	755
	SP4 CLC CC Double reheat Air turbine, rotating reactors	379	362
	SP4 CLC CC Double reheat Air turbine, membrane assisted reactors	379	362
	SP4 CLC CC Single reheat Air turbine	375	357
	SP5 Pre-combustion CAR	940	801
	SP6 Water cycle	391	294
	SP6 Graz Cycle	389	304
	SP6 S-Graz Cycle	420	334
	SP6 SCOC-CC	409	325
	SP6 Pre-combustion Membrane	353	303
	SP6 Pre-combustion Membrane, High Pressure	337	327

6.1.2 Net efficiency

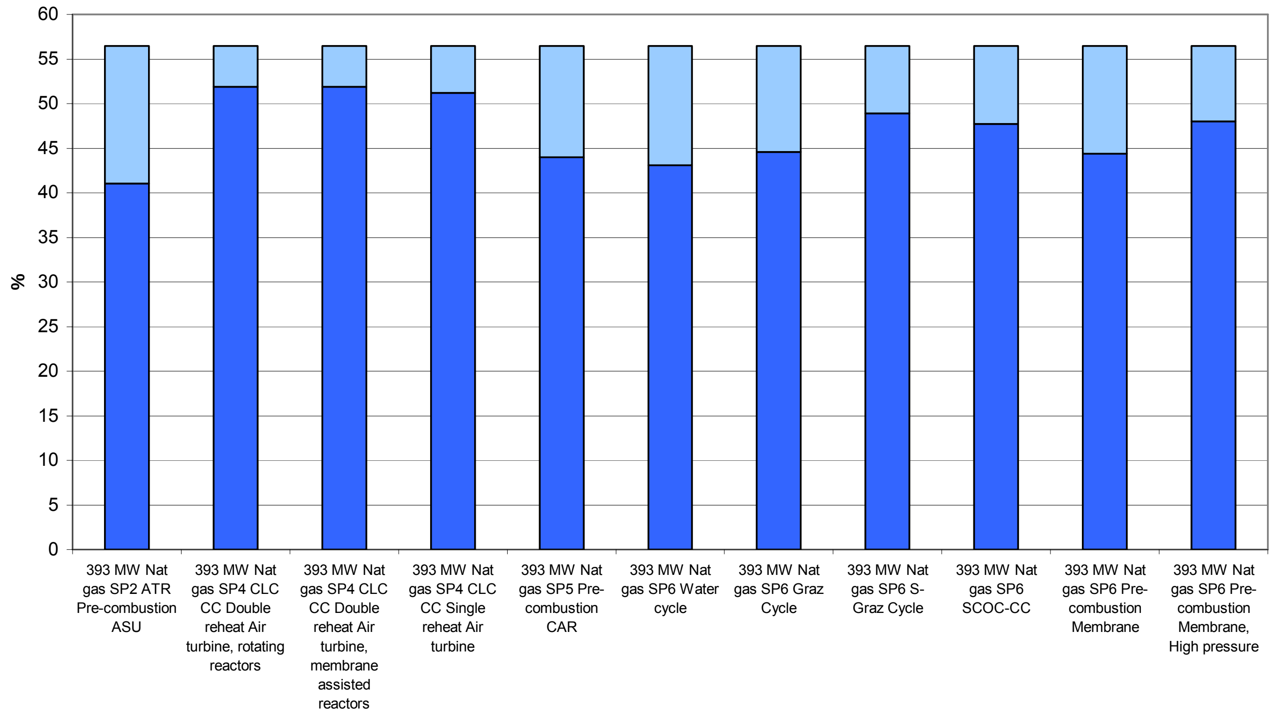
Net efficiency is the ratio of the net power production and the heat input via fuel (fuel mass flow x LHV).

- For the SP6 oxyfuel cycles, contents of Ar, N_2 and H_2O 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

Net efficiency

Reference case	Power plant	%	% ref. case	Delta %-points	Delta %
393 MW Nat gas	SP2 ATR Pre-combustion ASU	41,0	56,5	15,4	27,3
	SP4 CLC CC Double reheat Air turbine, rotating reactors	51,9	56,5	4,6	8,1
	SP4 CLC CC Double reheat Air turbine, membrane assisted reactors	51,9	56,5	4,6	8,1
	SP4 CLC CC Single reheat Air turbine	51,2	56,5	5,3	9,4
	SP5 Pre-combustion CAR	44,0	56,5	12,5	22,1
	SP6 Water cycle	43,1	56,5	13,4	23,7
	SP6 Graz Cycle	44,6	56,5	11,9	21,0
	SP6 S-Graz Cycle	48,9	56,5	7,6	13,4
	SP6 SCOC-CC	47,7	56,5	8,8	15,5
	SP6 Pre-combustion Membrane	44,4	56,5	12,1	21,4
	SP6 Pre-combustion Membrane, High Pressure	48,0	56,5	8,5	15,0

Net efficiency

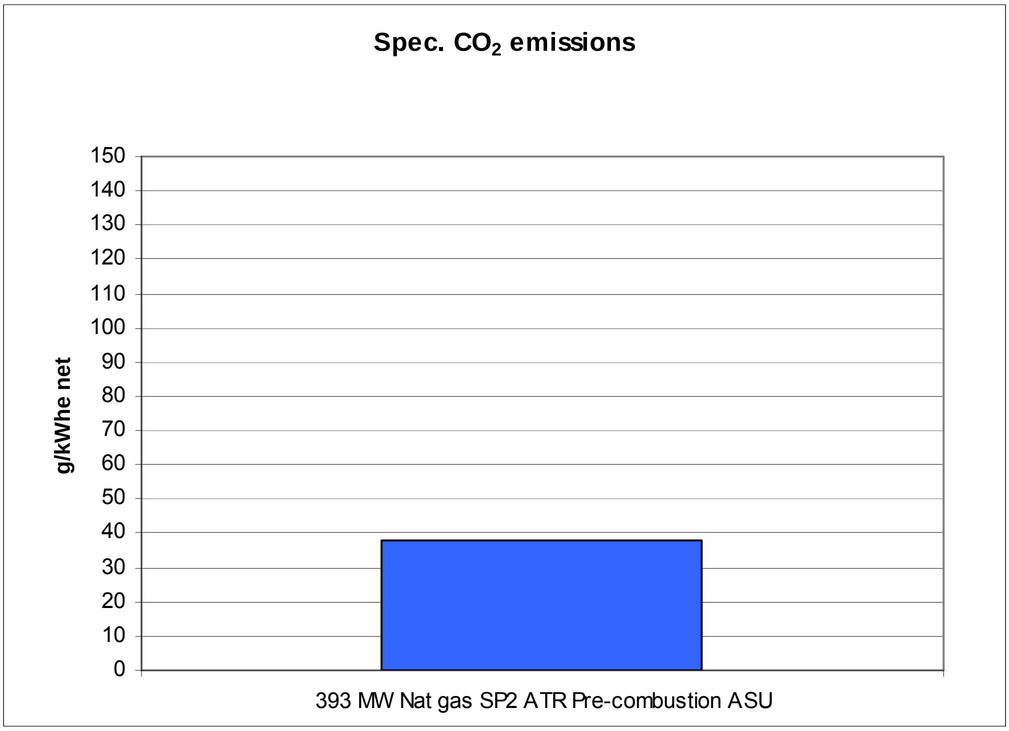


6.1.3 Specific CO_2 emissions

Spec. CO_2 emissions are the CO_2 emissions to the atmosphere in relation to the net power production.

Spec. CO2 emissions

Reference case	Power plant	g/kWhe
393 MW Nat gas	Ref case	363
	SP2 ATR Pre-combustion ASU	37,9

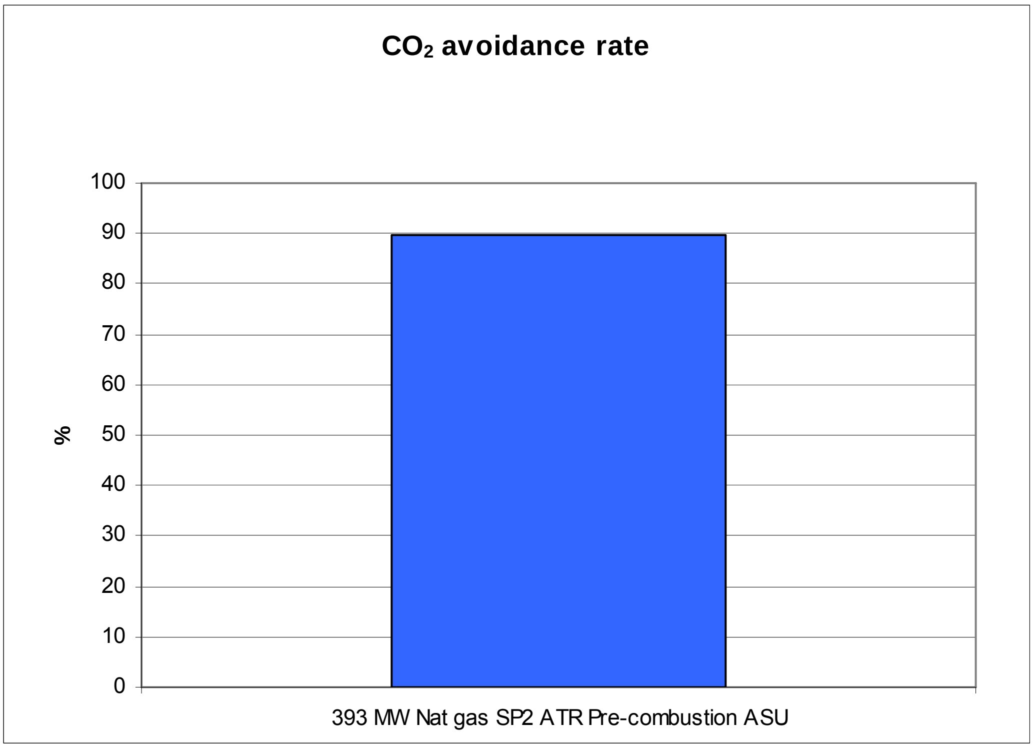


6.1.4 CO_2 avoidance rate

CO_2 avoidance rate is the difference between the spec. CO_2 emissions of the power plant with CO_2 capture and of the reference case in relation to the spec. CO_2 emissions of the reference case. It shows the CO_2 reduction in % achieved by the CO_2 capture technology when keeping the net power production constant.

CO2 avoidance rate

Reference case	Power plant	%
393 MW Nat gas	SP2 ATR Pre-combustion ASU	89,6



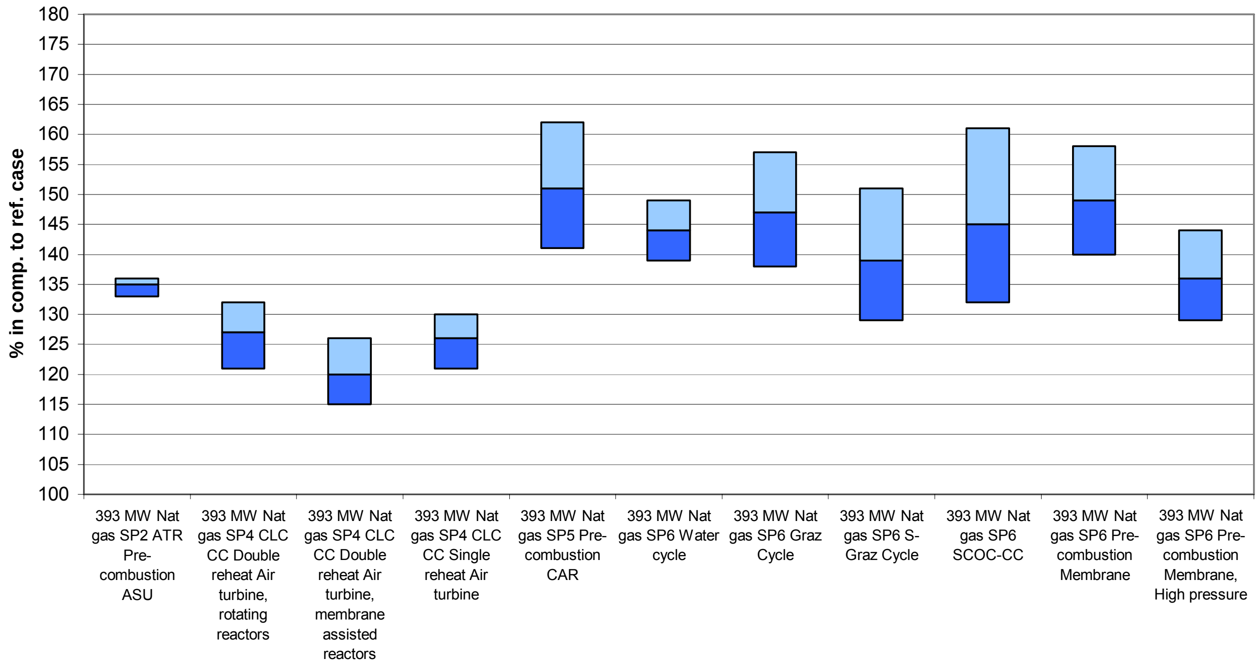
6.1.5 Relative electricity generation costs

The figures give the electricity generation costs of the CO_2 capture concepts in relation to the corresponding reference case. Base case refers to basic economic conditions, i. e. 40 years of economic life time, 8 % interest rate and 3.5 Euro/GJ fuel price. Sensitivity analysis was made by varying these 3 parameters. Min and max values show the bandwidth of the resulting electricity generation costs.

Relative electricity generation costs (compared to reference power plant without CO_2 capture)

Reference case	Power plant	Min %	Base case %	Max %
393 MW Nat gas	SP2 ATR Pre-combustion ASU	133	135	136
	SP4 CLC CC Double reheat Air turbine, rotating reactors	121	127	132
	SP4 CLC CC Double reheat Air turbine, membrane assisted reactors	115	120	126
	SP4 CLC CC Single reheat Air turbine	121	126	130
	SP5 Pre-combustion CAR	141	151	162
	SP6 Water cycle	139	144	149
	SP6 Graz Cycle	138	147	157
	SP6 S-Graz Cycle	129	139	151
	SP6 SCOC-CC	132	145	161
	SP6 Pre-combustion Membrane	140	149	158
	SP6 Pre-combustion Membrane, High Pressure	129	136	144

Electricity generation costs

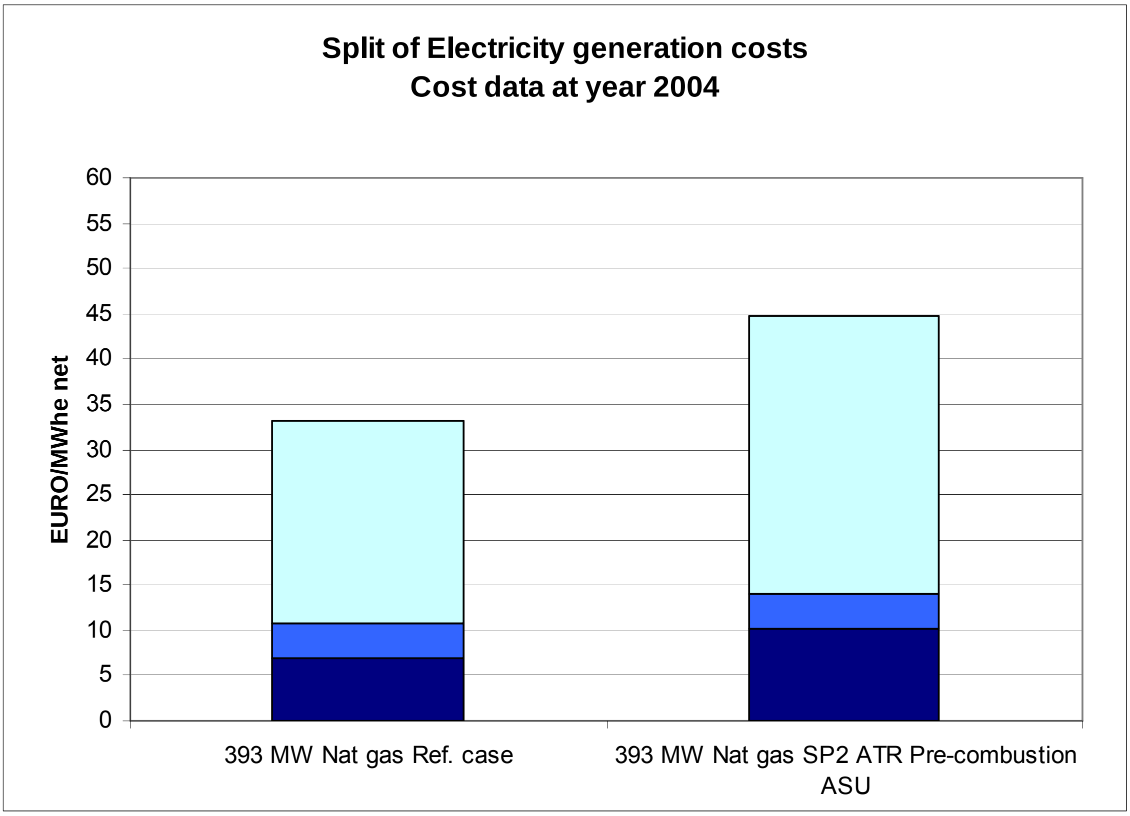


6.1.6 Split of electricity generation costs

The table and the diagram give the composition of the electricity generation costs for the base case of economic parameters (40 years of economic life time, 8 % interest rate and 3.5 Euro/GJ fuel price).

Split of electricity generation costs

		EURO/MWhe net		
Reference case	Power plant	Capital ■	O&M ■	Fuel ■
393 MW Nat gas	Ref. case	7,0	3,8	22,3
	SP2 ATR Pre-combustion ASU	10,1	3,9	30,7

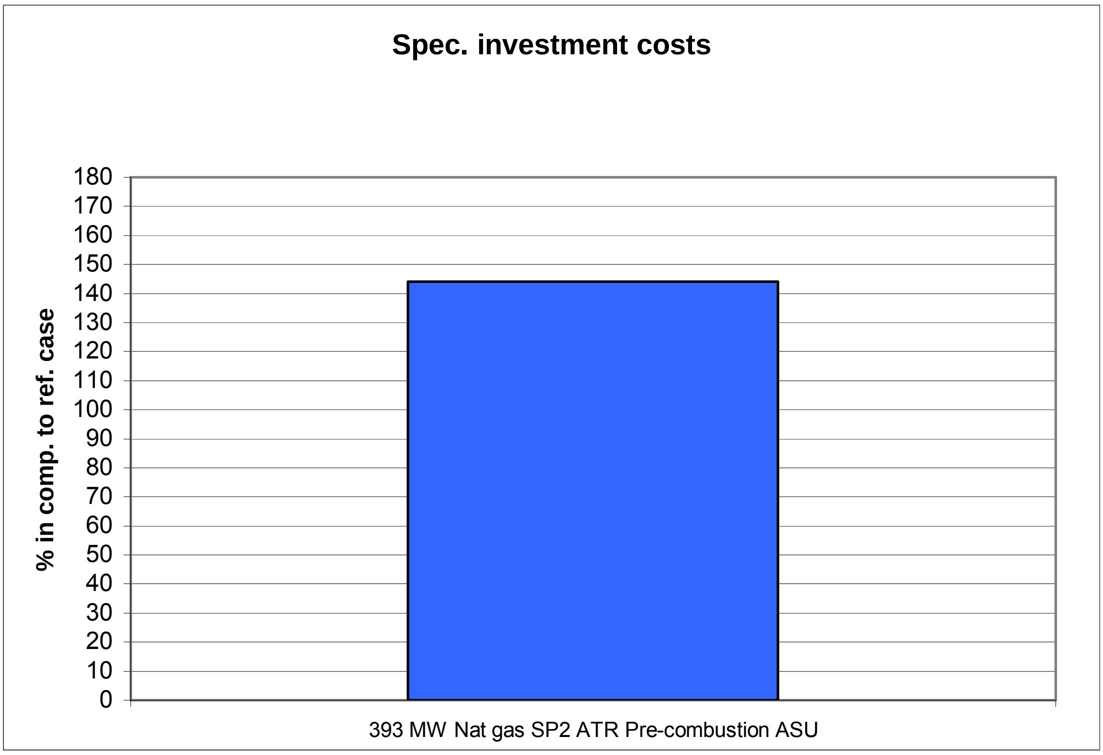


6.1.7 Relative specific investment costs compared to reference case

Spec. investment costs are the investment costs including owner's costs in relation to the net capacity of the power plant. They are calculated as Net Present Value at start of operation in order to take into account differences in the schedule of payments. The figures belong to the base case of economic parameters (here only 8 % interest rate is of importance). In this chapter the spec. investment costs are expressed in relation to the corresponding reference case.

Relative spec. investment costs as NPV at start of operation comp. to ref. case

Reference case	Power plant	%
393 MW Nat gas	SP2 ATR Pre-combustion ASU	144



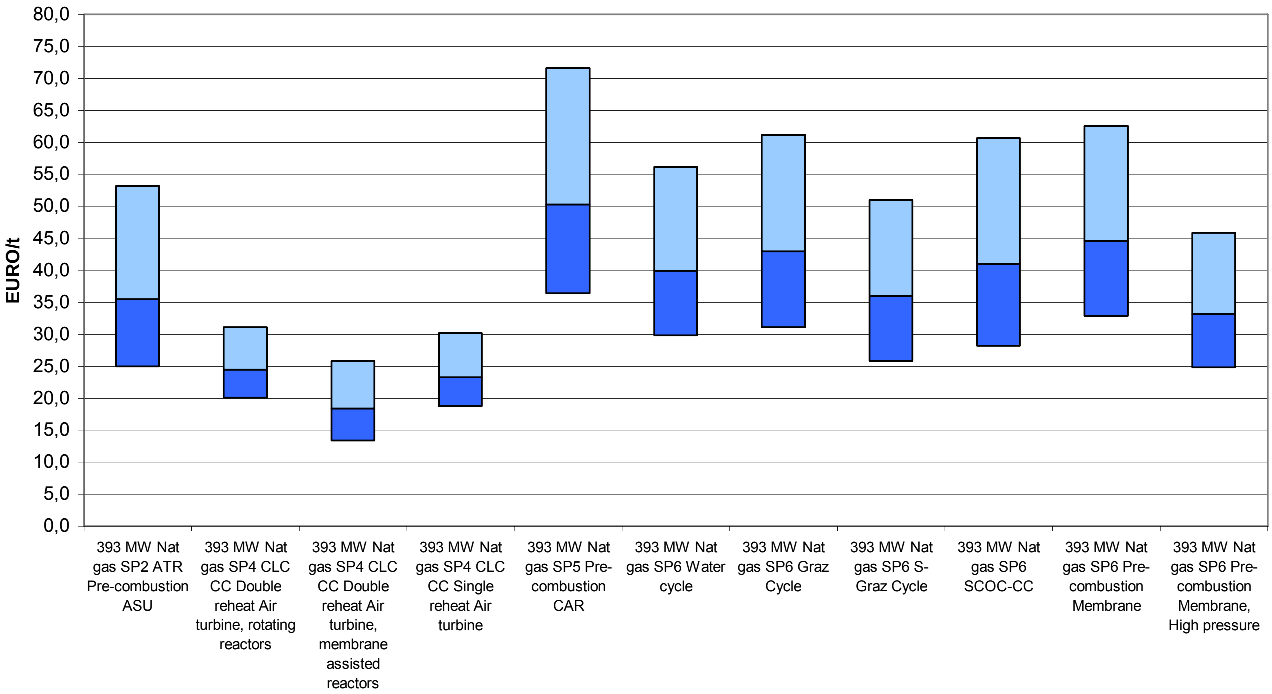
6.1.8 CO_2 avoidance costs

CO_2 avoidance costs 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. Base case refers to basic economic conditions (40 years of economic life time, 8 % interest rate and 3.5 Euro/GJ fuel price). Sensitivity analysis was made by varying these 3 parameters. Min and max values show the bandwidth of the resulting CO_2 avoidance costs.

CO_2 avoidance costs

		EUR/ton avoided CO_2		
Reference case	Power plant	min	base case	max
393 MW Nat gas	SP2 ATR Pre-combustion ASU	25,0	35,5	53,2
	SP4 CLC CC Double reheat Air turbine, rotating reactors	20,1	24,5	31,1
	SP4 CLC CC Double reheat Air turbine, membrane assisted reactors	13,4	18,4	25,8
	SP4 CLC CC Single reheat Air turbine	18,7	23,3	30,2
	SP5 Pre-combustion CAR	36,4	50,3	71,6
	SP6 Water cycle	29,8	39,9	56,1
	SP6 Graz Cycle	31,1	43,0	61,2
	SP6 S-Graz Cycle	25,8	36,0	51,0
	SP6 SCOC-CC	28,2	41,0	60,7
	SP6 Pre-combustion Membrane	32,9	44,6	62,6
	SP6 Pre-combustion Membrane, High Pressure	24,9	33,2	45,9

CO_2 avoidance costs



6.2 Discussion of results

For each of the evaluated issues in this chapter, the CT:s (Capture Technologies) are "scored" in relation to the RC (Reference Case) in the following way:

++ significantly superior to reference case
+ superior to reference case
o equal to reference case
- inferior to reference case
-- significantly inferior to reference case

For "CO_2 capture rate", the "scoring" is in relation to the ENCAP target of a CO_2 capture rate of 90%, where "o" means that this target is reached.

In the texts below, the various CT:s are identified with the following code nr:s

"1st" generation power plant concepts with CO_2 capture
- SP2 CT01: ATR Pre-combustion ASU

"More future" power plant concepts with CO_2 capture
- SP4 CT02a:CLC CC Double reheat Air turbine, rotating reactors
- SP4 CT02b: CLC CC Double reheat Air turbine, membrane assisted reactors
- SP4 CT03: CLC CC Single reheat Air turbine
- SP5 CT01: Pre-combustion CAR
- SP6 CT05: Water cycle
- SP6 CT06: Graz Cycle
- SP6 CT07: S-Graz Cycle
- SP6 CT08: SCOC-CC
- SP6 CT09: Pre-combustion Membrane
- SP6 CT11: Pre-combustion Membrane, High Pressure

6.2.1 Comparison and discussion of quantitative data - highlights

Oxyfuel cycles including chemical looping

The ENCAP target of a CO_2 capture rate of 90% is achieved by all oxy-fuel technologies. This is provided that water is condensed out from the captured CO_2 in the CLC cases reported from SP4. The condensing/compression process of CO_2 and the water contents of the final CO_2-rich streams have not been reported. Above 99 % CO_2 capture rate is actually reported – particulate matters from the CLC carrier must however be considered further.

The avoidance rate for all technologies is very close to 100%,. A small fraction of CO_2 is lost since it is dissolved in condensed water.

	SP4 CT02a	SP4 CT02b	SP4 CT03	SP6 CT05	SP6 CT06	SP6 CT07	SP6 CT08	*Favour-able CT*
CO_2 capture rate of 90%	+	+	+	+	+	+	+	**All**
Net efficiencies	51.9	51.9	51.2	43.1	44.6	48.9	47.7	**CLC cases**
Relative Electricity generation costs, % of RC	127	120	126	144	147	139	145	**CLC cases**

Pre-combustion capture cycles

The net power output (and hence the fuel input) varies from case to case. SP2 CT01 and SP5 CT01 have two turbines for taking advantage of economy of scale, while the reference only has one. So the net power output is roughly doubled (754 and 801 MW) in comparison to the reference case (393 MW). Moreover, they use the compressed nitrogen in the turbine for producing even more power. All concepts reach the 90% CO_2 captured. SP2 CT01 is at 89.6% while SP5 CT01, SP6 CT09 and SP6 CT11 overperform.

SP6 CT11 has the highest efficiency with 48% but is also the most immature. The efficiency of SP5 CT01 (44%) is significantly higher than that of SP2 CT01 (41%), partly due to the use of new but immature air separation technology and a PSA instead of an amine unit. The efficiency of SP6 CT09 (44%) is lower than the one of SP6 CT11 due to the use of lower pressure on the permeate side that may be more mature. But still the SP6 cases seem less mature than the SP5 CT01 case, due to the use of high temperature membranes. It seems that developing the CAR technology can take less time than the high temperature membranes.

The electricity generation cost of SP2 CT01 seems significantly lower than the other cases, but different assumptions are used. The O&M costs of SP2 CT01 are at a lower level than the one for the reference case, which seems to be too positive. In the cost for SP5 CT01, SP6 CT09 and SP6 CT11 several conservative assumptions on the investment costs are taken since it contains assumptions on immature technology. So, SP2 CT01 has likely a lower electricity generation cost than SP5 CT01 and SP6 CT09, but the presented results seem to indicate a too large difference. This means that the reliability of the cost numbers is low. SP6 CT11 and SP2 CT01 have similar costs but are very different in maturity. SP5 CT01 and SP6 CT09 are comparable in costs but SP6 CT09 may be less mature.

	SP2 CT01	**SP5 CT01**	**SP6 CT09**	**SP6 CT11**	***Favourable CT***
CO_2 capture rate of 90%	+	+	+	+	**All**
Net efficiencies	41	44	44	48	**SP6CT11**
Relative Electricity generation costs, % of RC	135	151	149	136	**SP2 CT01/ SP6 CT11**

6.2.2 Comparison and discussion of qualitative data - highlights

Oxyfuel cycles including chemical looping

All SP4 NG-based oxyfuel concepts produce very high purity of CO_2

For the SP6 oxyfuel cycles, contents of Ar, N_2 and H_2O 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 – a loss that has not been quantified so far.

All cycles have a high degree of integration, giving complications for part-load and start-up/shut-down of the cycle.

The CLC technology (similarly as all the oxyfuel NG-based cases) is not proven in large scale yet, but is currently being investigated in pilot scale. The NG-based oxyfuel cases 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.

None of the cycles can bypass the CO_2 capture unit.

	SP4 CT02a	SP4 CT02b	SP4 CT03	SP6 CT05	SP6 CT06	SP6 CT07	SP6 CT08	***Favour-able CT***
CO_2 product quality	+	+	+	-	-	-	-	**CLC cases**
Part-load, shut-down	-	-	-	-	-	-	-	**No**
Life-time	+	+	+	0	0	0	0	**CLC cases**
Fuel quality restrictions	0	0	0	0	0	0	0	
Additional emissions	+	+	+	+	+	+	+	
CO_2 capture technology possible to bypass	0	0	0	0	0	0	0	**No**
Technical maturity	--	--	--	---	---	---	---	**CLC cases**

Pre-combustion capture cycles

SP5 CT01 has some excess nitrogen and oxygen in the CO_2, and can only meet design case. SP2 CT01 has a slightly too high water content, but it is assumed that this can be relatively easily removed by molecular sieves. So, it can reach the severe and ship cases. SP6 CT09 and SP6 CT11 report around 0.8% N_2.

The maturity and level of integration varies from case to case. Since SP2 CT01 is based on conservative assumptions, it has a relatively low level of integration, but a high level of maturity. It needs the development of a low NO_x H_2 turbine which is common for all pre-combustion cases. SP5 CT01 seems to have a medium level of maturity, but a high level of integration. SP6 CT09 and CT11 have the lowest maturity due to the membrane modules. More than 10 years are claimed to be needed for their development, These differences have a clear effect on the energy efficiency: the most immature ones have the highest efficiency.

In theory, SP5 CT01, SP6 CT09, SP6 CT11 and SP2 CT01 concepts can bypass the CO_2 capture and operate at part-load, but they all need a dedicated strategy due to the integration. This is common for reformer technologies.

SP5 CT01 reports the lifetime of the CAR adsorbent as an unknown. The economic success is dependent on it. Moreover, sulphur may affect the adsorbent, adding a small requirement to the fuel. SP6 CT09 and SP6 CT11 report nothing on life time of membrane.

Minor additional emissions are reported for all cases during start-up/shut-down and part-load.

SP6 CT09 and SP6 CT11 report traces of sulphur in the fuel as a possible poison for the membrane.

SP5 CT01, SP6 CT09 and SP6 CT11 report concerns about increased NO_x levels at start-up and part-load operation. Moreover, dust control is needed since CAR is particle based technology for SP5 CT01.

	SP2 CT01	**SP5 CT01**	**SP6 CT09**	**SP6 CT11**	***Favourable CT***
CO_2 product quality	+	0	+	+	SP2 CT01
Part load operation, shut down	-	-	-	-	0
Life-time	+	-	0	0	SP2 CT01
Fuel quality restrictions	+	-	0	0	SP2 CT01
Additional emissions	-	-	-	-	0
CO_2 capture technology possible to bypass	0	0	0	0	0
Technical maturity	-	--	---	---	SP2 CT01

6.2.3 Discussion of effects of CO_2 capture on power generation in comparison to conventional power plants

Oxyfuel cycles including chemical looping

All these capture technologies reduce the net efficiency compared to the reference case. For differentiation, the S-Graz cycle efficiency is decreased by 8 % and the SCOC-GT efficiency is decreased by 9% whereas the decrease is ~12 % for the Graz and ~13% for the Water cycle, compared to the base case 56.5%.

The SP4 CLC Combined cycles have the highest cycle efficiencies (51 - 52%) but this includes pressurized chemical looping reactors, which is quite advanced technology.

In general, the novel cycles in from SP6 are immature in comparison to the CLC cycles and will be more expensive in investment and more particularly in time – the construction time towards commissioning will be longer with a higher degree of integration and complexity.

	SP4 CT02a	SP4 CT02b	SP4 CT03	SP6 CT05	SP6 CT06	SP6 CT07	SP6 CT08	***Favour-able CT***
Reduction of energy efficiency	-	-	-	---	---	--	--	**CLC cases**
Costs	-	-	-	--	--	--	--	**CLC cases**
Construction time	0	0	0	-	-	-	-	**CLC cases**

Pre-combustion capture cycles

The main effect is that all these capture technologies reduce the energy efficiency significantly compared to the reference case.

The highest efficiency is reported by SP6 C11 in a range from 48%. This is 8 % point decrease. However, the technology is very immature and requires a high level of integration. Next best is SP5 CT01 and SP6 CT09 with 44%.

The lowest efficiencies are reported by SP2 CT01 with around 41%. The latter could be improved by more integration and less conservative assumptions

It seems though that SP5 CT01 and SP6 CT09 have a higher overall cost than SP2 CT01 due to immature technology with unknown costs. Their increased efficiency seems not to compensate enough. SP6 CT11 seems to take advantage of its highest efficiency and gets similar cost to SP2 CT01 (which may be estimated too low).

The construction time is for all cases longer than for the reference case, due to extra equipment. No significant differences were reported between the cases.

	SP2 CT01	SP5 CT01	**SP6 CT09**	**SP6 CT11**	***Favourable CT***
Reduction of energy efficiency	---	--	--	-	SP6 CT11
Costs	-	--	--	-	SP2 CT01 / SP6 CT11
Construction time	-	-	-	-	0

6.2.4 Changes in results for to adjusted reference cases (see explanation in chapter 3.3)

No changes in the relative assessment were observed by adjusting the reference case to the same net capacities as for the power plants with CO_2 capture (as explained in chapter 3.3).. It should be noted that the size of large-scale gas fired turbines can not be adjusted at will. These are as large as possible for obtaining the best economy of scale.

7 Capture technologies for reference case " 380 MW Lignite PF"

The following power plant concepts with CO_2 capture are evaluated against the lignite fired 380 MW_el $_{gross}$ PF reference case:

"1st" generation power plant concepts with CO_2 capture

- 380 MW Lignite SP3 Oxyfuel

See Chapter 2.3 for short descriptions of these technologies.

7.1 Overview of quantitative data (technical and economic data)

7.1.1 Electricity outputs

- The SP3 Oxyfuel PF has the same boiler size and the same fuel mass flow as the reference case.

The resulting gross and net electricity output capacities are as follows:

Electricity output capacities

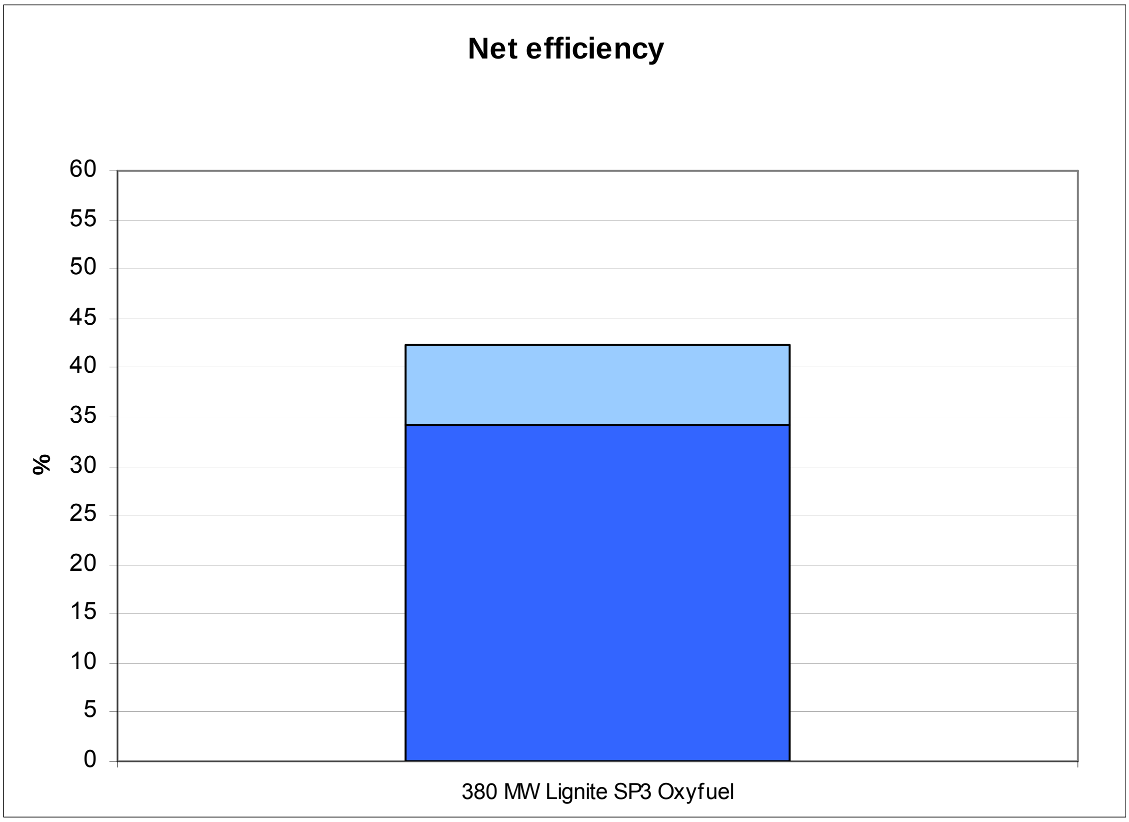
Reference case	Power plant	Gross, MWel	Net, MWel
380 MW Lignite PF	Ref. case	385	335
	SP3 Oxyfuel	403	271

7.1.2 Net efficiency

Net efficiency is the ratio of the net power production and the heat input via fuel (fuel mass flow x LHV).

Net efficiency

Reference case	Power plant	%	% ref. case	Delta %-points	Delta %
380 MW Lignite PF	SP3 Oxyfuel	34,2	42,3	8,1	19,1

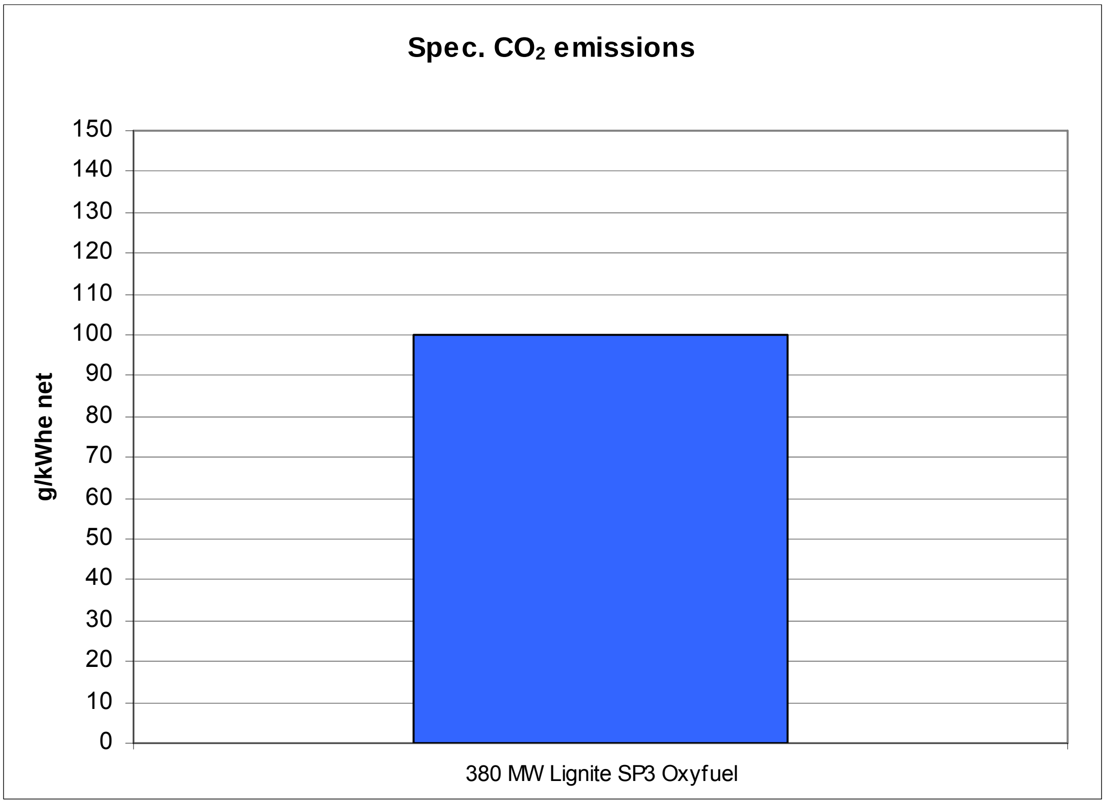


7.1.3 Specific CO_2 emissions

Spec. CO_2 emissions are the CO_2 emissions to the atmosphere in relation to the net power production.

Spec. CO2 emissions

Reference case	Power plant	g/kWhe
380 MW Lignite PF	Ref case	899
	SP3 Oxyfuel	100

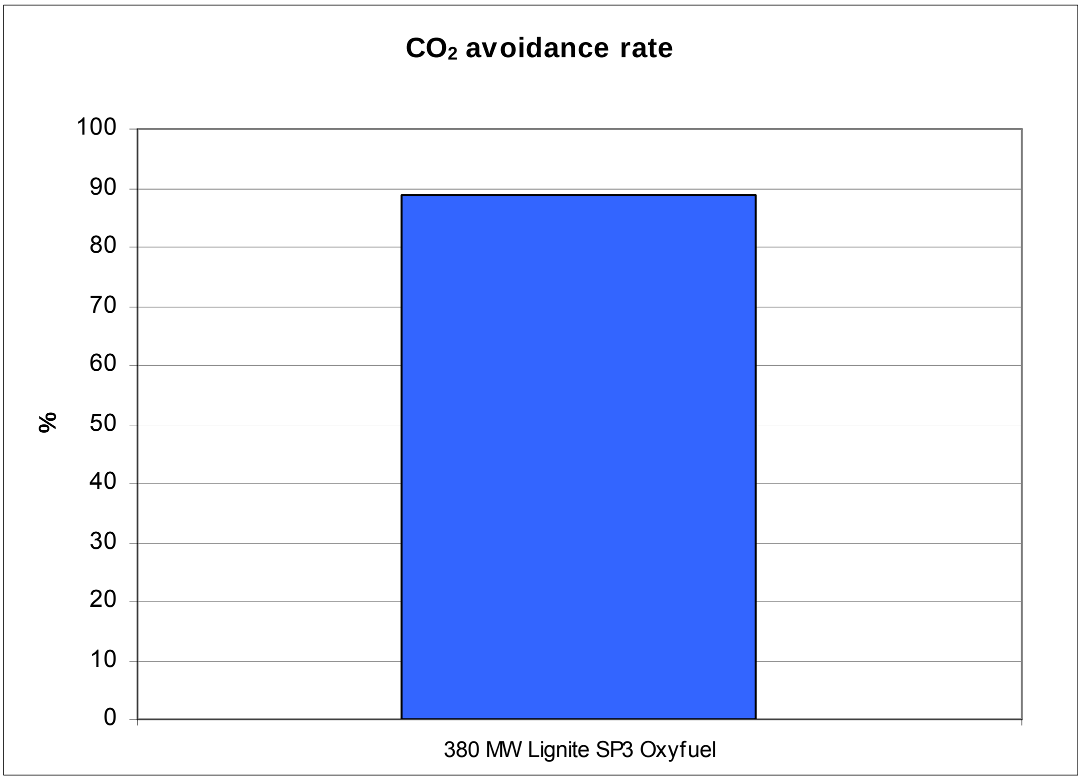


7.1.4 CO_2 avoidance rate

CO_2 avoidance rate is the difference between the spec. CO_2 emissions of the power plant with CO_2 capture and of the reference case in relation to the spec. CO_2 emissions of the reference case. It shows the CO_2 reduction in % achieved by the CO_2 capture technology when keeping the net power production constant.

CO2 avoidance rate

Reference case	Power plant	%
380 MW Lignite PF	SP3 Oxyfuel	88,9

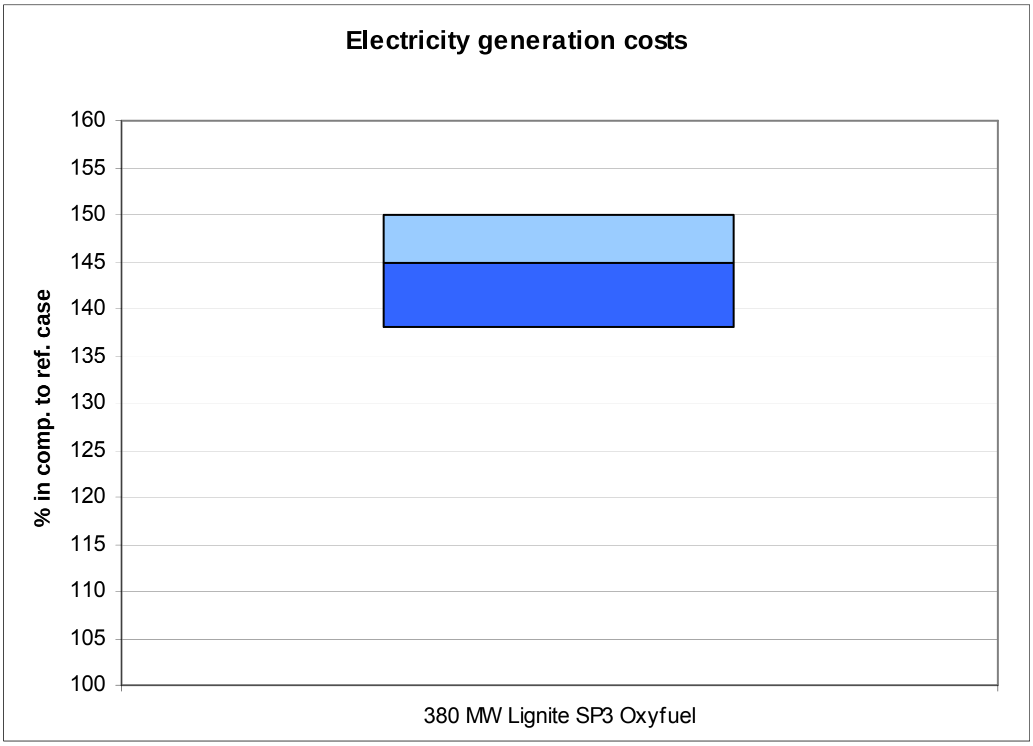


7.1.5 Relative electricity generation costs

The figures give the electricity generation costs of the CO_2 capture concepts in relation to the corresponding reference case. Base case refers to basic economic conditions, i. e. 40 years commercial life time, 8% interest rate and 1.1 Euro/GJ fuel price. Sensitivity analysis was made by varying these 3 parameters. Min and max values show the bandwidth of the resulting electricity generation costs.

Relative electricity generation costs (compared to reference power plant without CO_2 capture)

Reference case	Power plant	Min %	Base case %	Max %
380 MW Lignite PF	SP3 Oxyfuel	138	145	150

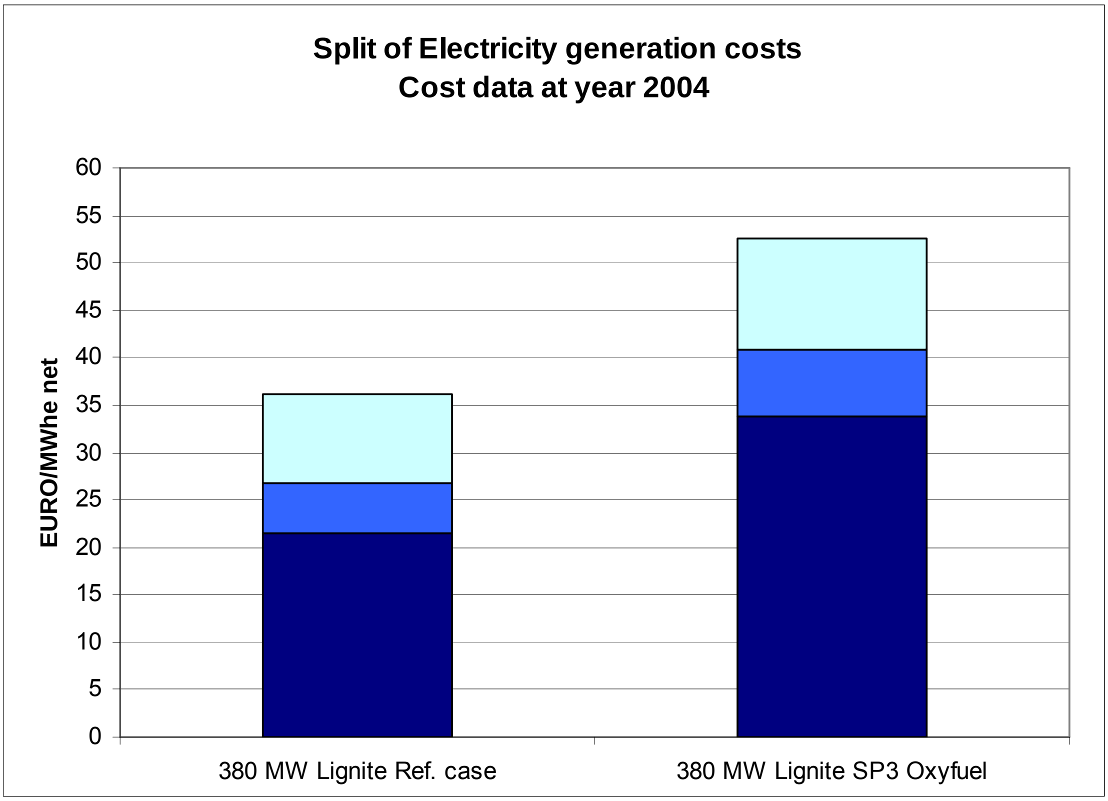


7.1.6 Split of electricity generation costs

The table and the diagram give the composition of the electricity generation costs for the base case of economic parameters (40 years of economic life time, 8 % interest rate and 1.1 Euro/GJ fuel price).

Split of electricity generation costs

		EURO/MWhe net		
Reference case	Power plant	Capital ■	O&M ■	Fuel ■
380 MW Lignite PF	Ref. case	21,5	5,2	9,5
	SP3 Oxyfuel	33,9	7,0	11,7

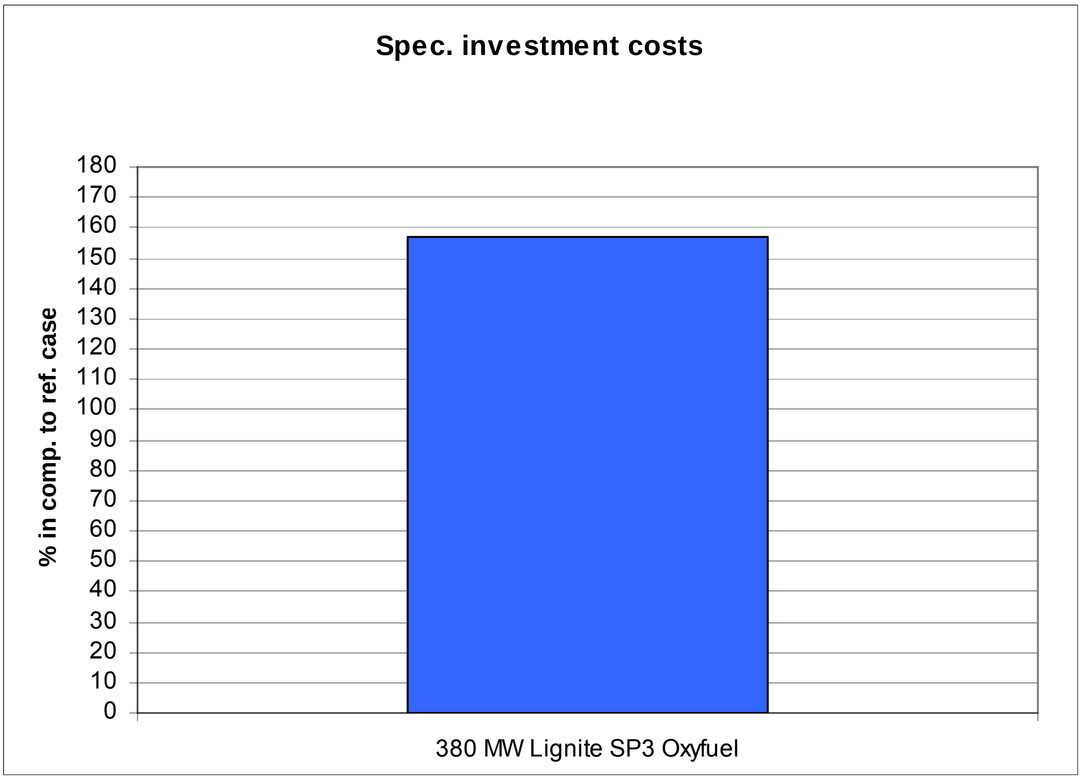


7.1.7 Relative specific investment costs compared to reference case

Spec. investment costs are the investment costs including owner's costs in relation to the net capacity of the power plant. They are calculated as Net Present Value at start of operation in order to take into account differences in the schedule of payments. The figures belong to the base case of economic parameters (here only 8 % interest rate is of importance). In this chapter the spec. investment costs are expressed in relation to the corresponding reference case.

Relative spec. investment costs as NPV at start of operation comp. to ref. case

Reference case	Power plant	%
380 MW Lignite PF	SP3 Oxyfuel	157

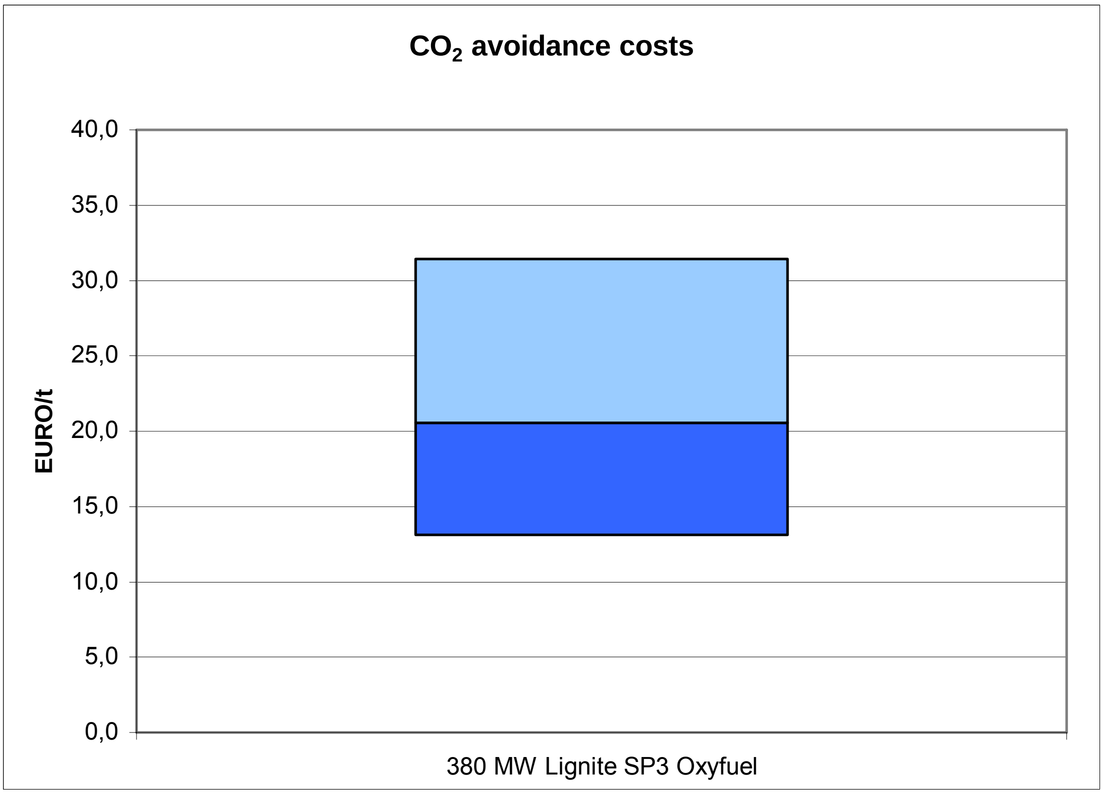


7.1.8 CO_2 avoidance costs

CO_2 avoidance costs 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. Base case refers to basic economic conditions (40 years of economic life time, 8 % interest rate and 1.1 Euro/GJ fuel price). Sensitivity analysis was made by varying these 3 parameters. Min and max values show the bandwidth of the resulting CO_2 avoidance costs.

CO2 avoidance costs

		EUR/ton avoided CO_2		
Reference case	Power plant	min	base case	max
380 MW Lignite PF	SP3 Oxyfuel	13,1	20,5	31,4



7.2 Discussion of results

7.2.1 Comparison and discussion of quantitative data - highlights

The gross power output of the oxyfuel power plant is ca. 5% higher than the reference air-fired power plant, while the net power output for the PF power plant with CO_2 capture is ca. 20% lower than the power plant without CO_2 capture, mainly due to the high demand for auxiliary power for the ASU (Air Separation Unit) and the CO_2 compression. The net cycle efficiency is thus significantly reduced.

7.2.2 Comparison and discussion of qualitative data - highlights

The CO_2 capture technology is expected to increase the start-up and shut-down duration and thus decrease the flexibility of the power plant. No adverse impact on the availability of the plant is expected from the ASU and the CO_2 compression/liquefaction plant. In the case of a failure of the CO_2 capture system, the power plant could be able to continue operation, if additional systems are included. Construction times for the ASU and the CO_2 compression/liquefaction plants are not expected to have a detrimental impact on the overall construction time. In terms of emissions, for the air-fired start-up and shut-down it is expected that the SO_X and NO_X emission limits will be exceeded, unless $DeNO_X$ and $DeSO_X$ equipment is installed. No harmful waste water conditions are expected. The purity of the captured CO_2 is within the limits defined in the Guidelines.

The CO_2 capture technology reduces the net power output of the plant. In order to have the ability to bypass the CO_2 capture train and regain the capacity loss for short time periods, a back-up system for heat recovery would be necessary, together with additional equipment for SOx and NOx cleaning, to observe emission limits for these pollutants.

7.2.3 Discussion of effects of CO_2 capture on power generation in comparison to conventional power plants

Despite the increase in gross generation of the Lignite PF oxy-combustion power plant with CO_2 capture, the high demand for auxiliary power results in an overall decrease in the net power output. The penalty in terms of net cycle efficiency associated with oxy-combustion with CO_2 capture is calculated at ca. 8 percentage points. In terms of capital costs, the total investment costs are increased by approximately 27%, whereas fixed O&M costs are increased by 11.5% and total variable costs are reduced by 20%.

7.2.4 Changes in results for to adjusted reference cases (see explanation in chapter 3.3)

Only minor, not significant changes in the relative assessment were observed by adjusting the reference case to the same net capacity as for the power plant with CO_2 capture (as explained in chapter 3.3)..

8 Capture technologies for reference case " 445 MW Bit coal/pet coke CFB"

The following power plant concepts with CO_2 capture are evaluated against the bituminous coal/pet coke fired 445 MW_el_{gross} CFB reference case:

"1st" generation power plant concepts with CO_2 capture
- 445 MW Bit coal CFB SP3 Oxyfuel
- 445 MW Pet coke CFB SP3 Oxyfuel

"More future" power plant concepts with CO_2 capture
- 445 MW Bit coal CFB SP4 CLC
- 445 MW Pet coke CFB SP4 CLC

See Chapter 2.3 for short descriptions of these technologies.

8.1 Overview of quantitative data (technical and economic data)

For the "more future" power plant concepts with CO_2 capture, the uncertainties are larger in all data, especially for investments and costs. Only electricity outputs, net electric efficiencies, electricity generation costs in relation to reference case, and CO_2 avoidance costs, are presented for those technologies.

8.1.1 Electricity outputs

- The SP3 Oxyfuel CFB has the same gross electricity output as the 445 MW CFB reference case. This result in slightly lower fuel mass flows (3% for bit coal and 5% for pet coke).
- The SP4 CFB CLC has the same fuel mass flows as the 445 MW CFB reference case (1% higher for bit coal and 0.2% higher for pet coke).

The resulting gross and net electricity output capacities are as follows:

Electricity output capacities

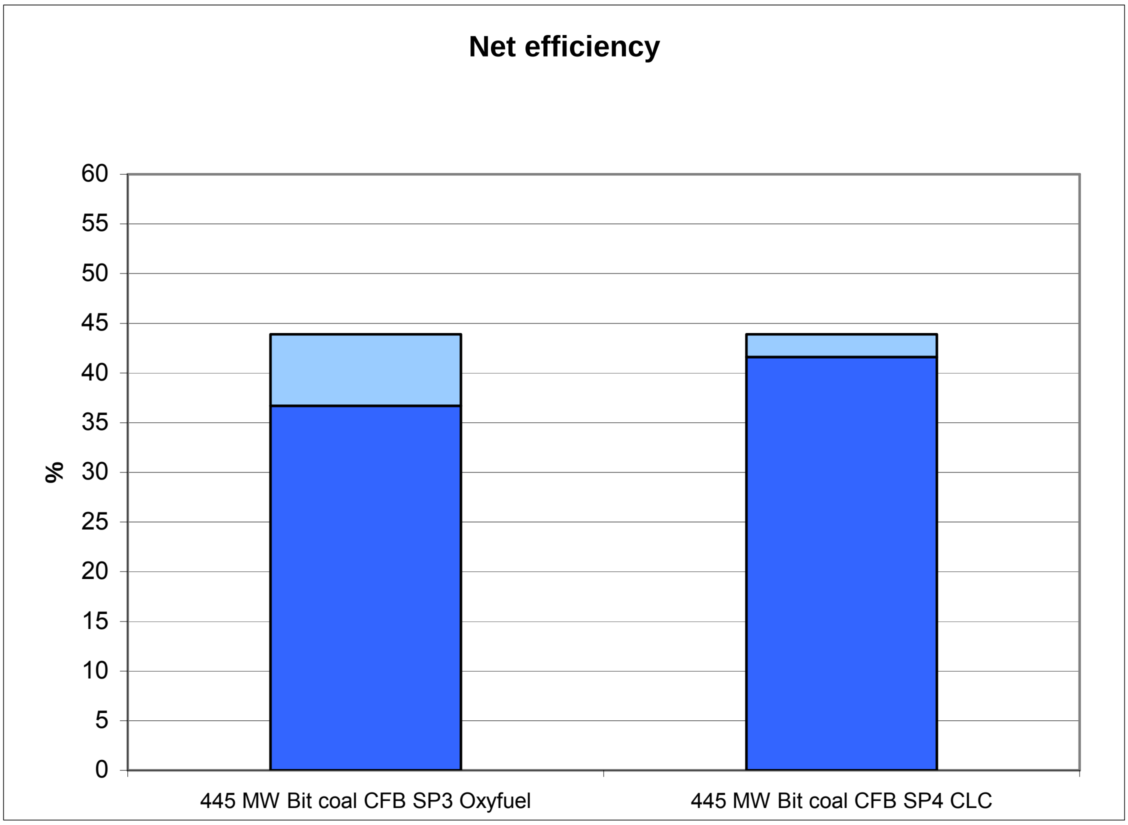
Reference case	Power plant	Gross, MWel	Net, MWel
445 MW Bit coal CFB	Ref. case	445	403
	SP3 Oxyfuel	445	327
	SP4 CLC	455	387
445 MW Pet coke CFB	Ref. case	445	403
	SP3 Oxyfuel	445	328
	SP4 CLC	455	388

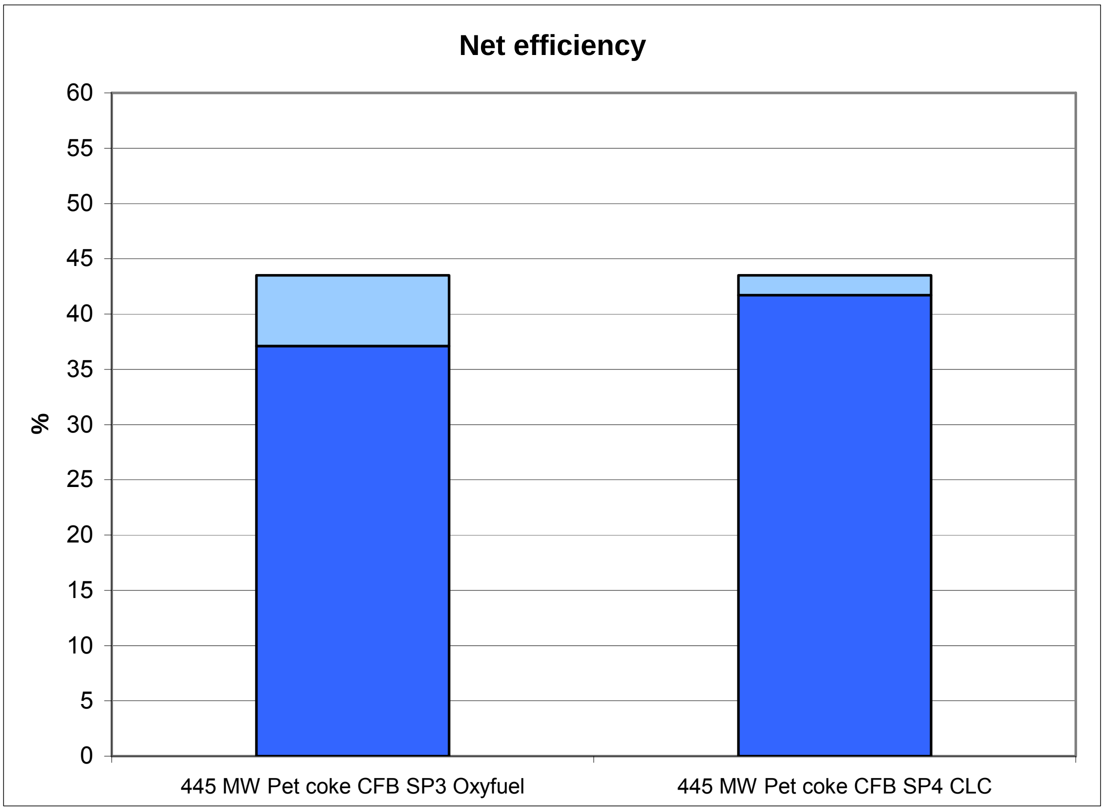
8.1.2 Net efficiency

Net efficiency is the ratio of the net power production and the heat input via fuel (fuel mass flow x LHV).

Net efficiency

Reference case	Power plant	%	% ref. case	Delta %-points	Delta %
Bit coal CFB 445 MW	SP3 Oxyfuel	36,7	43,9	7,2	16,4
	SP4 CLC	41,6	43,9	2,3	5,2
Pet coke CFB 445 MW	SP3 Oxyfuel	37,1	43,5	6,4	14,7
	SP4 CLC	41,7	43,5	1,8	4,1



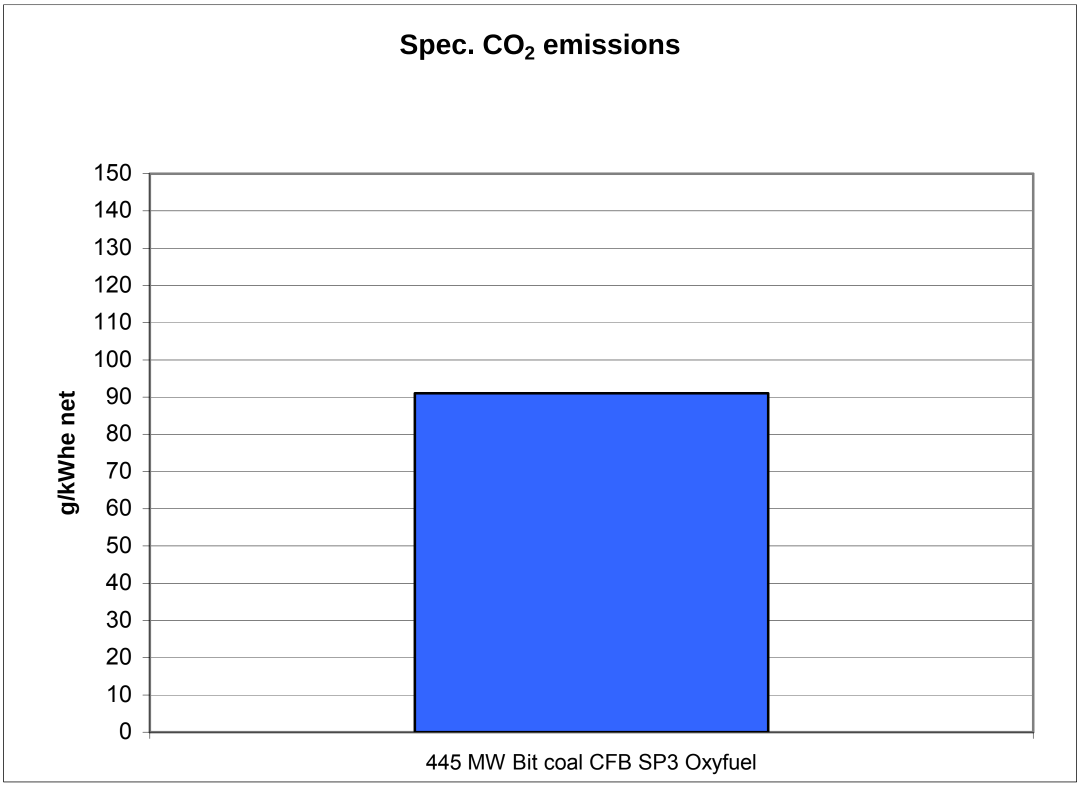

Net efficiency
%
60
55
50
45
40
35
30
25
20
15
10
5
0
445 MW Pet coke CFB SP3 Oxyfuel
445 MW Pet coke CFB SP4 CLC

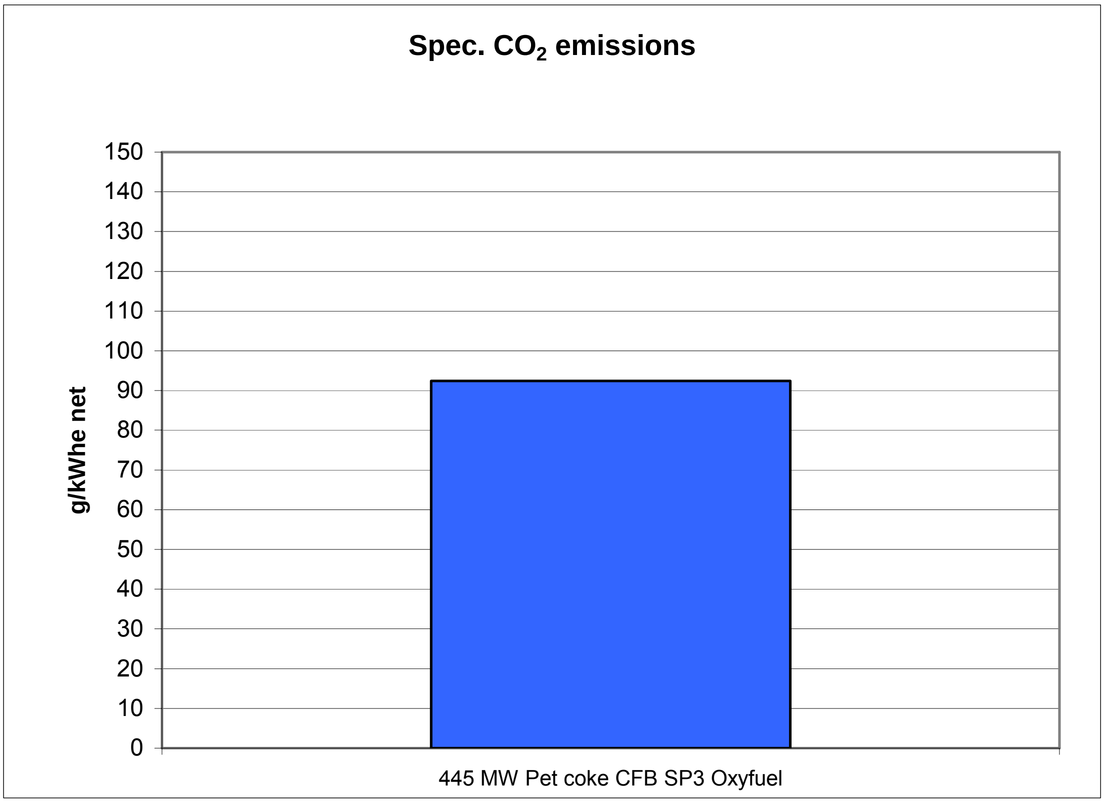
8.1.3 Specific CO_2 emissions

Spec. CO_2 emissions are the CO_2 emissions to the atmosphere in relation to the net power production.

Spec. CO2 emissions

Reference case	Power plant	g/kWhe
445 MW Bit coal CFB	Ref case	781
	SP3 Oxyfuel	91,0
445 MW Pet coke CFB	Ref case	842
	SP3 Oxyfuel	92,4



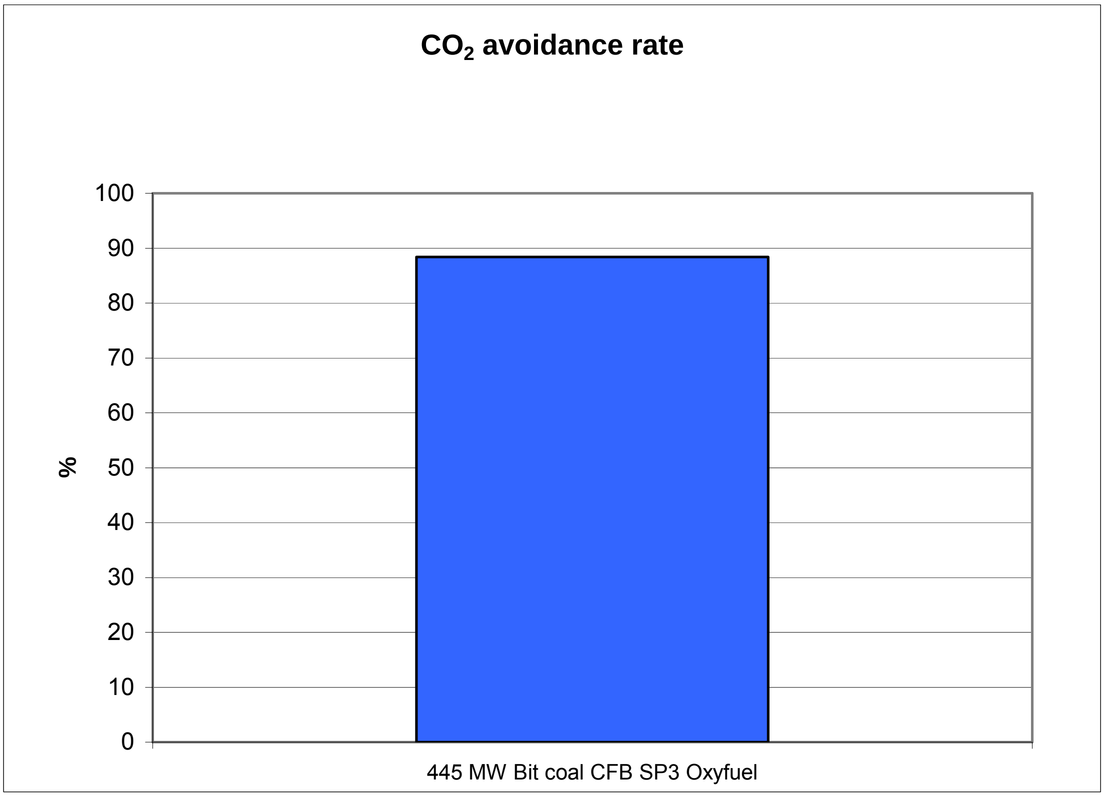

Spec. CO_2 emissions
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
g/kWhe net
445 MW Pet coke CFB SP3 Oxyfuel

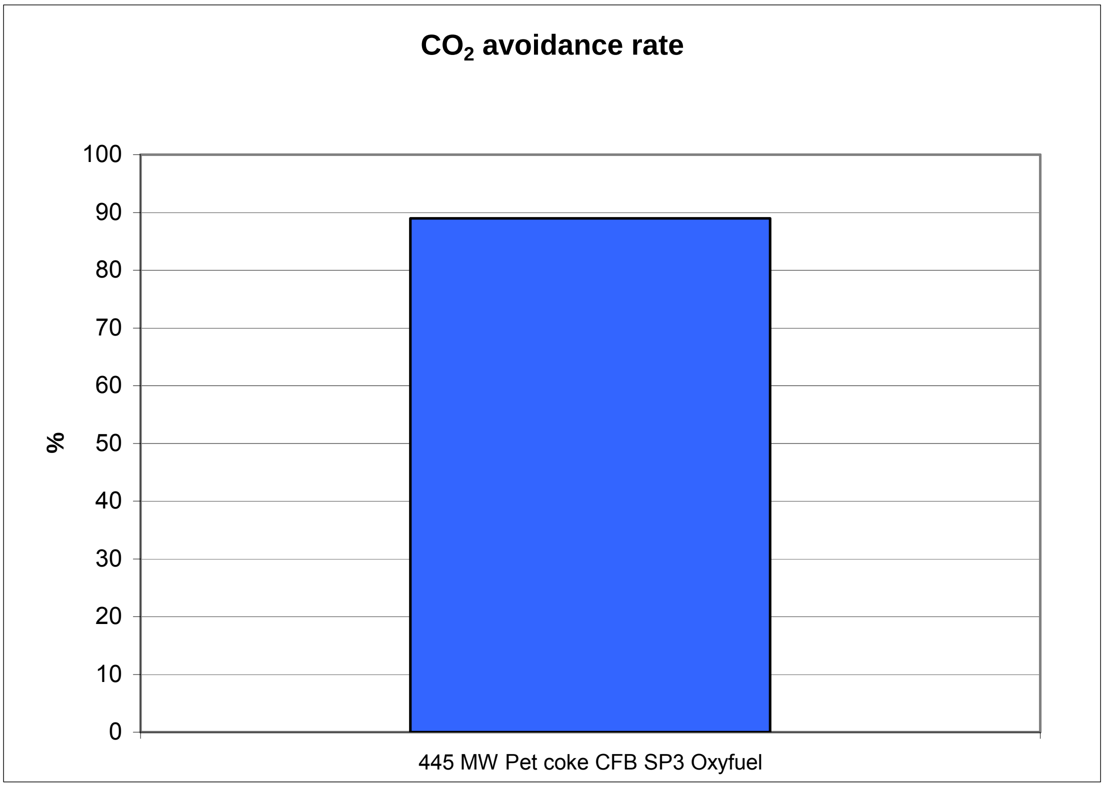
8.1.4 CO_2 avoidance rate

CO_2 avoidance rate is the difference between the spec. CO_2 emissions of the power plant with CO_2 capture and of the reference case in relation to the spec. CO_2 emissions of the reference case. It shows the CO_2 reduction in % achieved by the CO_2 capture technology when keeping the net power production constant.

CO2 avoidance rate

Reference case	Power plant	%
445 MW Bit coal CFB	SP3 Oxyfuel	88,4
445 MW Pet coke CFB	SP3 Oxyfuel	89,0





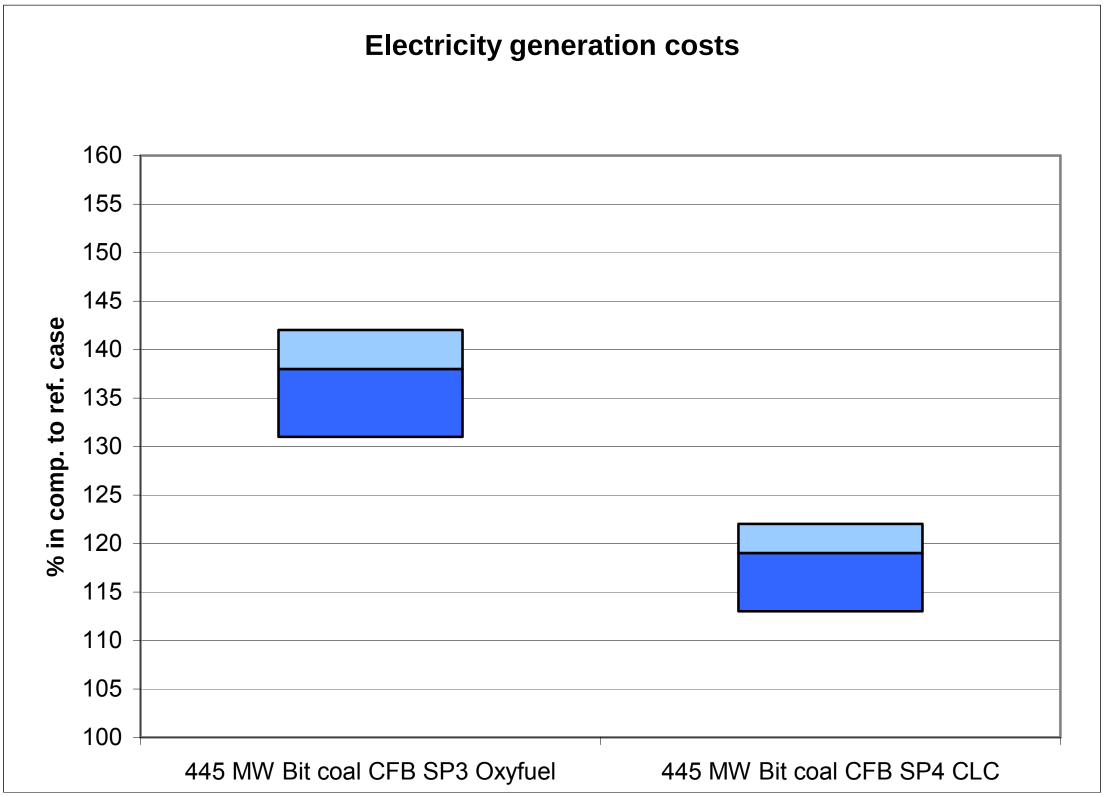
CO_2 avoidance rate
%
100
90
80
70
60
50
40
30
20
10
0
445 MW Pet coke CFB SP3 Oxyfuel

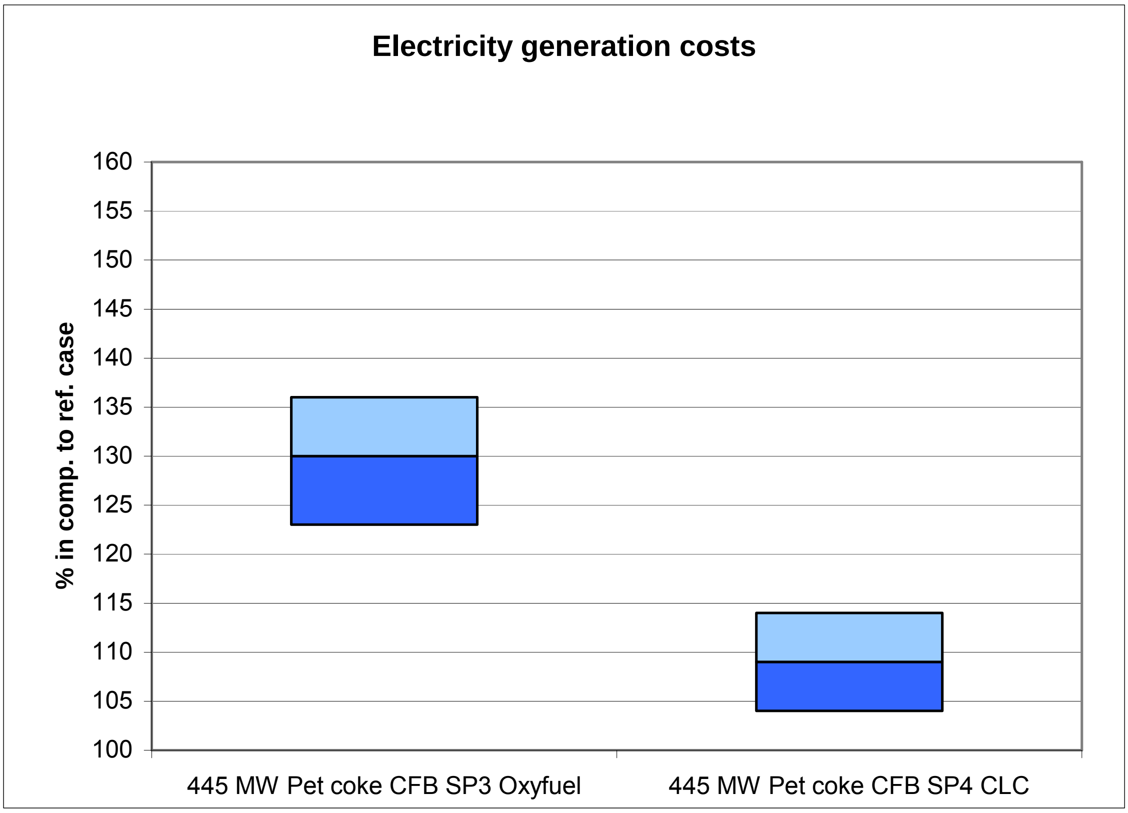
8.1.5 Relative electricity generation costs

The figures give the electricity generation costs of the CO_2 capture concepts in relation to the corresponding reference case. Base case refers to basic economic conditions, i. e. 40 years commercial life time, 8 % interest rate and 1.6/0.5 Euro/GJ fuel price. Sensitivity analysis was made by varying these 3 parameters. Min and max values show the bandwidth of the resulting electricity generation costs.

Relative electricity generation costs (compared to reference power plant without CO_2 capture)

Reference case	Power plant	Min %	Base case %	Max %
445 MW Bit coal CFB	SP3 Oxyfuel	131	138	142
	SP4 CLC	113	119	122
445 MW Pet coke CFB	SP3 Oxyfuel	123	130	136
	SP4 CLC	104	109	114



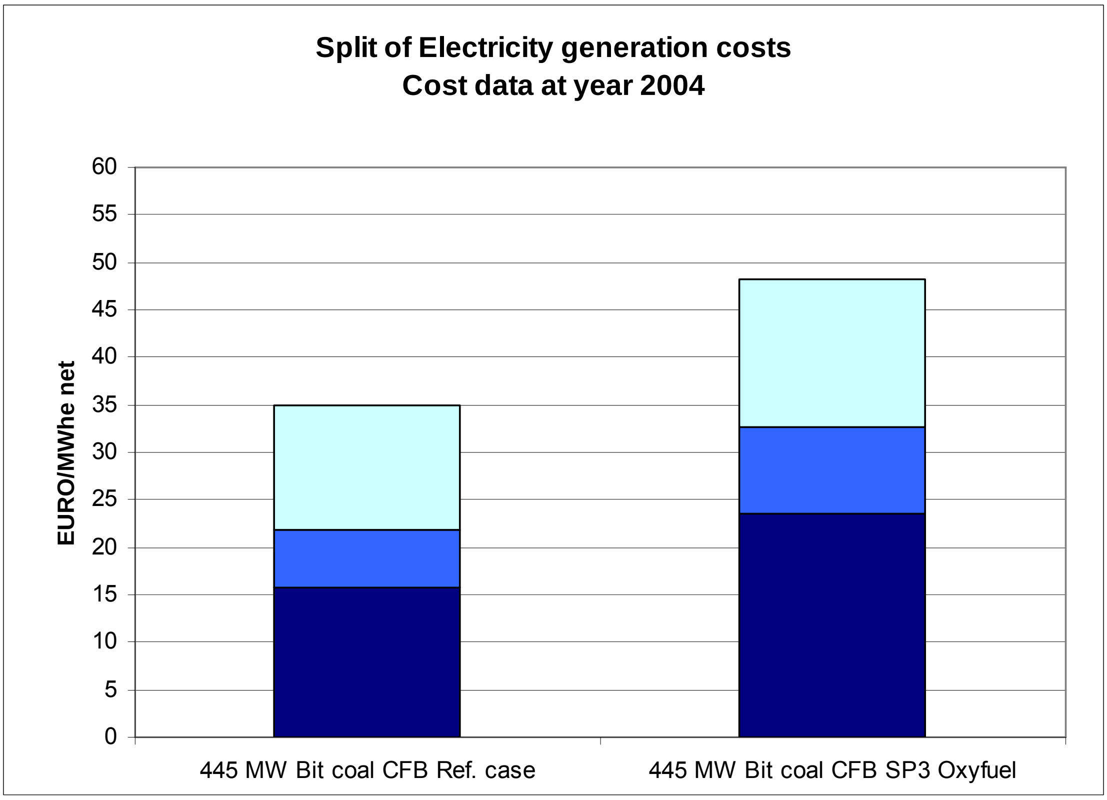

Electricity generation costs
% in comp. to ref. case
160
155
150
145
140
135
130
125
120
115
110
105
100
445 MW Pet coke CFB SP3 Oxyfuel
445 MW Pet coke CFB SP4 CLC

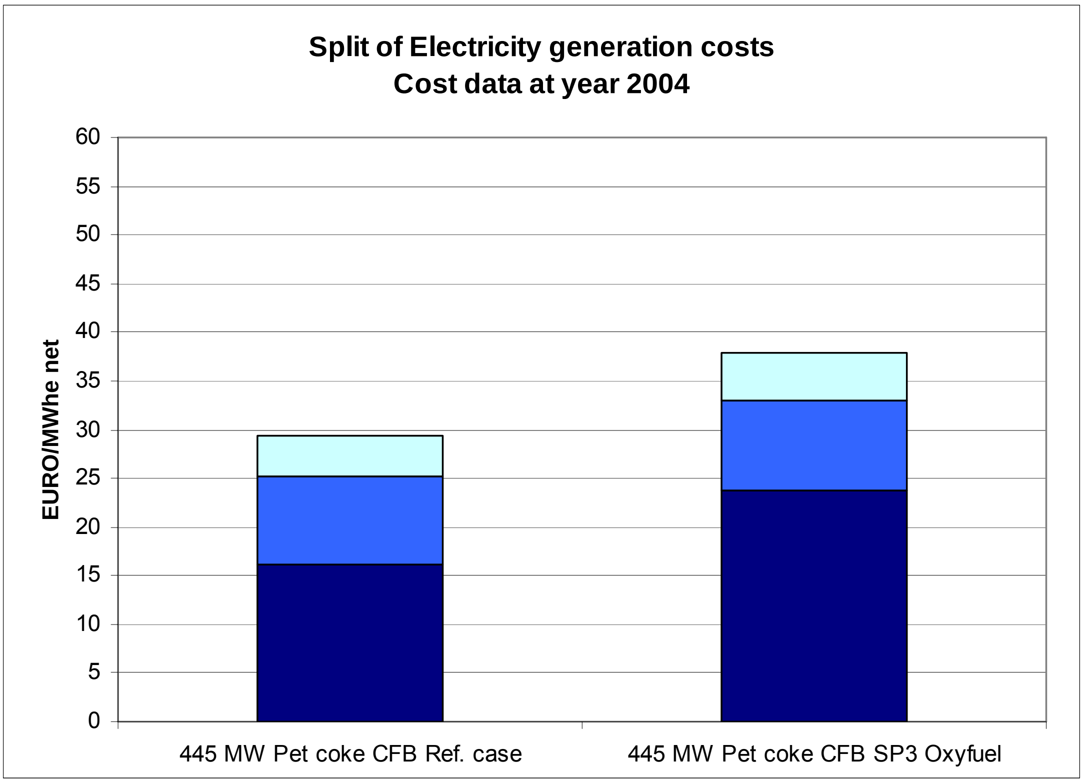
8.1.6 Split of electricity generation costs

The table and the diagram give the composition of the electricity generation costs for the base case of economic parameters (40 years of economic life time, 8 % interest rate and 1.6/0.5 Euro/GJ fuel price).

Split of electricity generation costs

		EURO/MWhe net		
Reference case	Power plant	Capital	O&M	Fuel
Bit coal CFB 445 MW	Ref. case	15,8	6	13,1
	SP3 Oxyfuel	23,5	9,1	15,7
Pet coke CFB 445 MW	Ref. case	16,1	9,1	4,1
	SP3 Oxyfuel	23,8	9,2	4,9



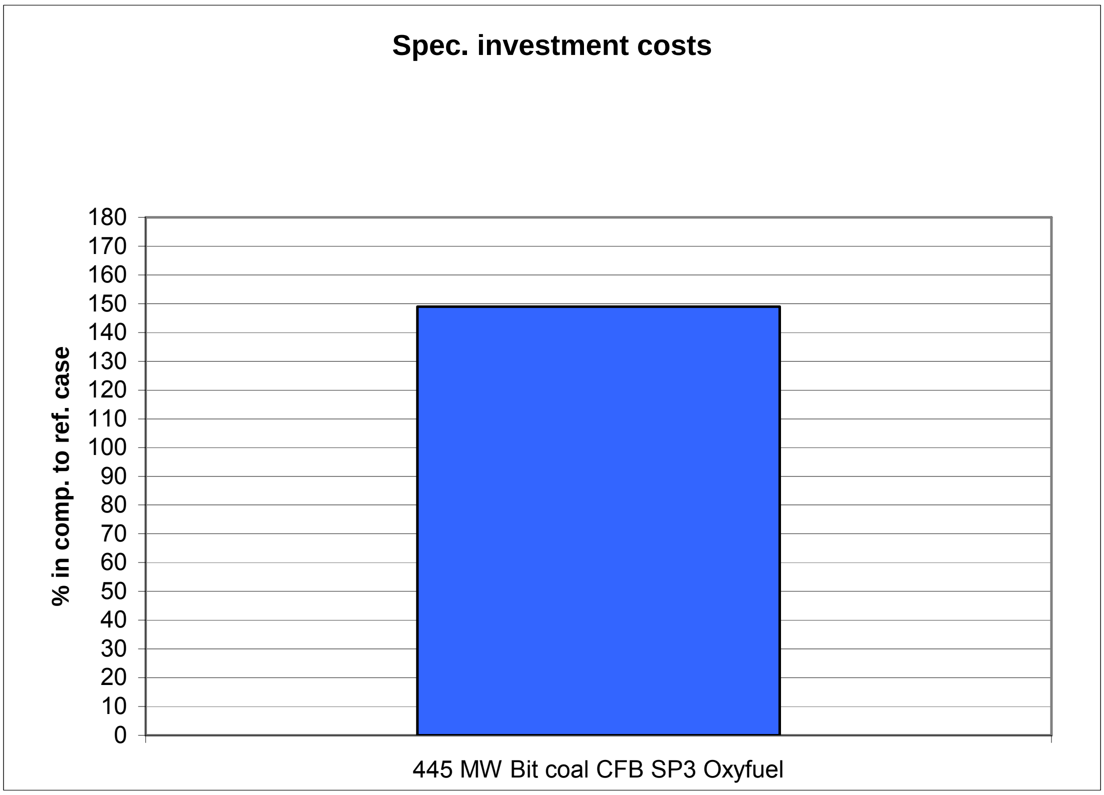

Split of Electricity generation costs
Cost data at year 2004
EURO/MWhe net
60
55
50
45
40
35
30
25
20
15
10
5
0
445 MW Pet coke CFB Ref. case
445 MW Pet coke CFB SP3 Oxyfuel

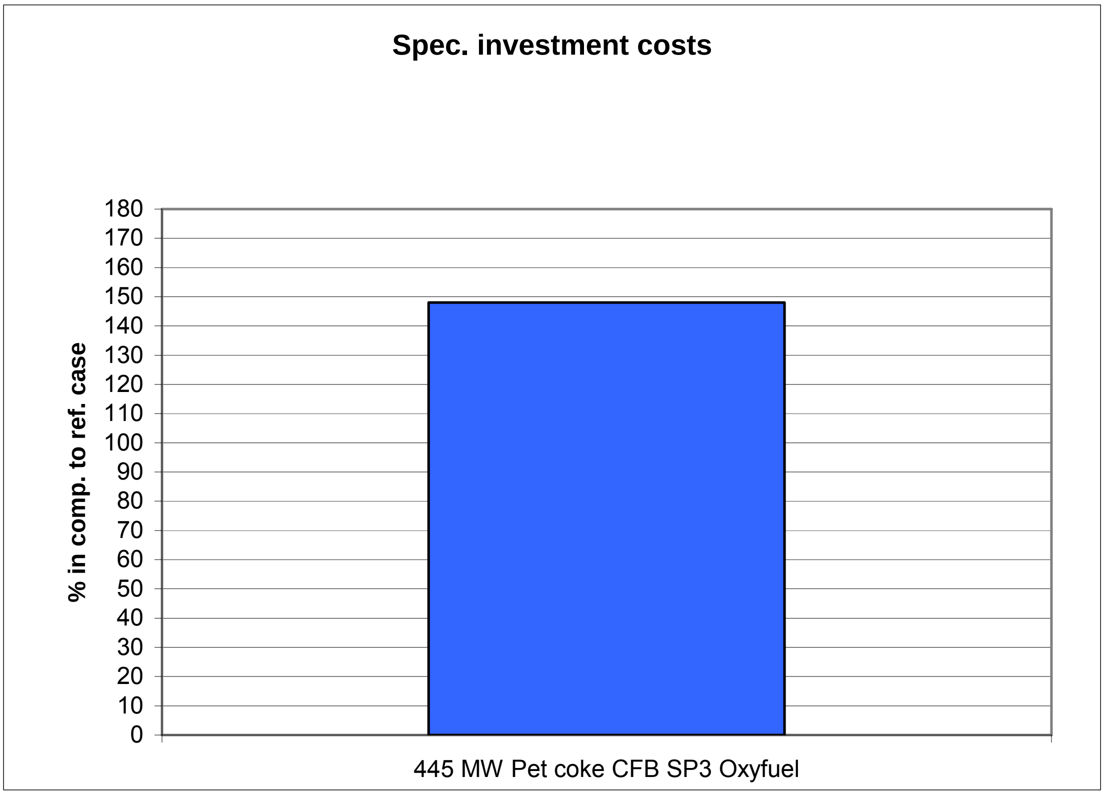
8.1.7 Relative specific investment costs compared to reference case

Spec. investment costs are the investment costs including owner's costs in relation to the net capacity of the power plant. They are calculated as Net Present Value at start of operation in order to take into account differences in the schedule of payments. The figures belong to the base case of economic parameters (here only 8 % interest rate is of importance). In this chapter the spec. investment costs are expressed in relation to the corresponding reference case.

Relative spec. investment costs as NPV at start of operation comp. to ref. case

Reference case	Power plant	%
445 MW Bit coal CFB	SP3 Oxyfuel	149
445 MW Pet coke CFB	SP3 Oxyfuel	148





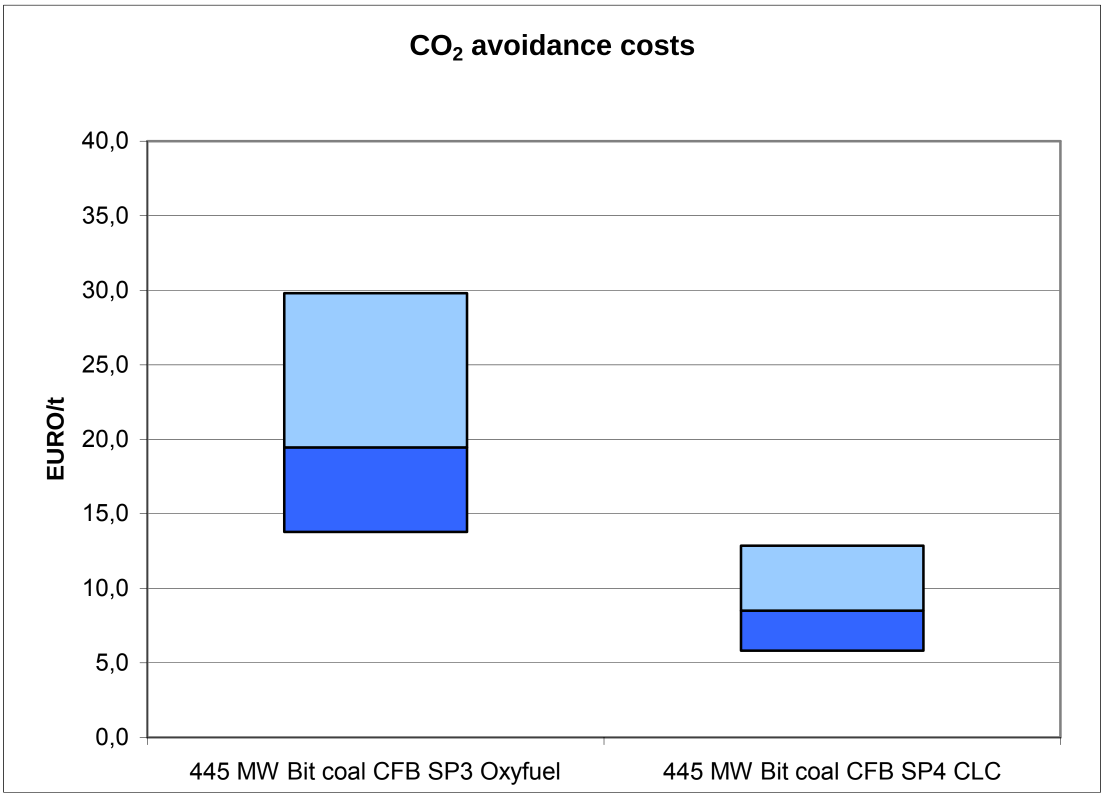
Spec. investment costs
% in comp. to ref. case
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
445 MW Pet coke CFB SP3 Oxyfuel

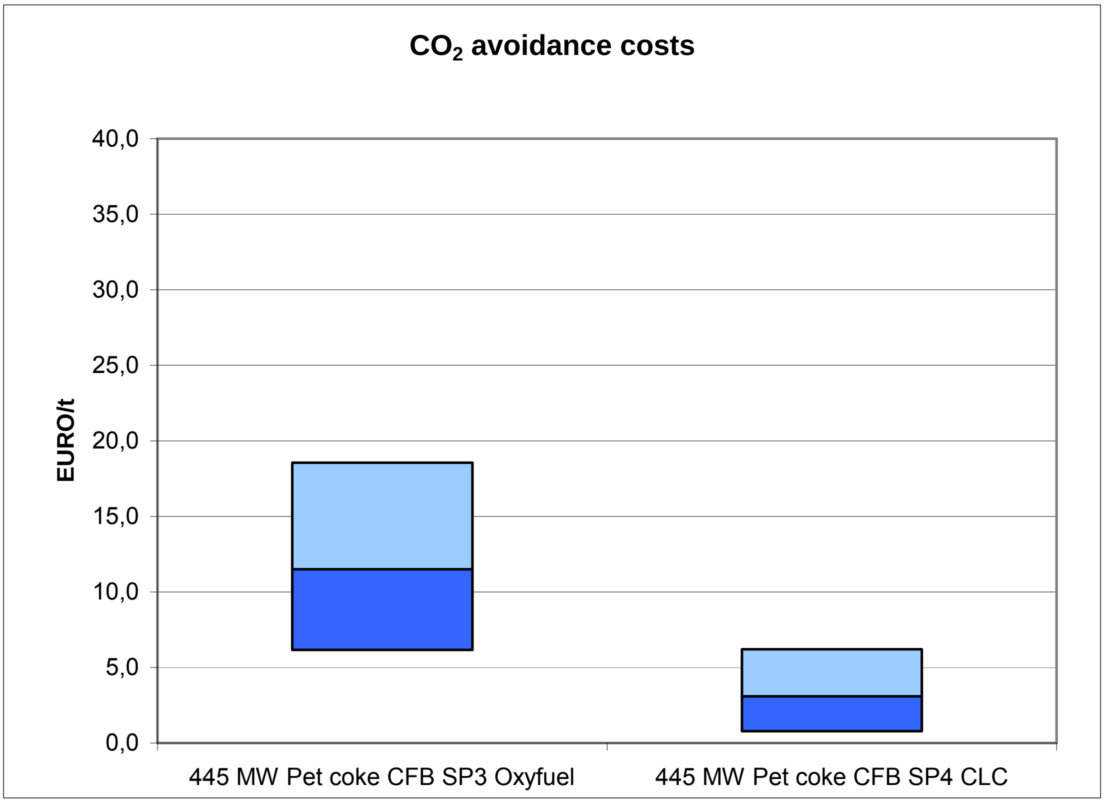
8.1.8 CO_2 avoidance costs

CO_2 avoidance costs 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. Base case refers to basic economic conditions (40 years of economic life time, 8 % interest rate and 1.6/0.5 Euro/GJ fuel price). Sensitivity analysis was made by varying these 3 parameters. Min and max values show the bandwidth of the resulting CO_2 avoidance costs.

CO2 avoidance costs

		EUR/ton avoided CO_2		
Reference case	Power plant	min	base case	max
445 MW Bit coal CFB	SP3 Oxyfuel	13,8	19,5	29,8
	SP4 CLC	5,8	8,5	12,9
445 MW Pet coke CFB	SP3 Oxyfuel	6,2	11,5	18,6
	SP4 CLC	0,8	3,1	6,2





CO2 avoidance costs
EURO/t
40,0
35,0
30,0
25,0
20,0
15,0
10,0
5,0
0,0
445 MW Pet coke CFB SP3 Oxyfuel
445 MW Pet coke CFB SP4 CLC

8.2 Discussion of results

8.2.1 Cost Factors

Investment costs
For SP3 oxy-fuel CFB the boiler is smaller than that of the reference case because of a much lower flue gas flow-rate and so the corresponding investment cost is lower and the construction time is reduced. However, the investment cost is increased by the cost of additional equipment such as the Air Separation Unit and the CO_2 compression train.

For SP4 CFB CLC, the investment cost is increased, compared to the reference case, because in Chemical Looping Technology there are two CFB reactors instead of one, as in the conventional CFB technology. There is also additional equipment: a small Air Separation Unit and a CO_2 compression train.

Availability
Overall availability is expected to be slightly (1-2%) below the conventional case for both CTs, mainly because of the integration level of the plant. Individually, the ASU, the CO_2 train and the CFB boiler are mature technologies and have proven their reliability in large-scale commercial applications. Air and Fuel Reactor for the CLC are comparable to conventional CFBs.

Lifetime
The life time for both technologies is considered to be similar to that of conventional CFBs.

Penalties on net efficiencies and additional O&M costs
The penalty in net electricity production is between 6-7 points for SP3. It is mainly due to the auxiliary consumption of the Air Separation Unit and the CO_2 compression train.

The penalty in net electricity production is between 2-3 points for SP4. It is mainly due to the auxiliary consumption of the CO_2 compression train.

There is additional O& M cost in SP4 due to oxygen carrier replacement.

8.2.2 Operation Characteristics

The CO_2 capture technology will also have an influence on the general operation of the plant:

Maximum Load Change Rate
The Maximum Load Change Rate of SP3 oxy-fuel CFB is slightly reduced, as compared to a conventional CFB, due to the ASU operation, while SP4 CFB CLC is expected to be similar to a conventional CFB in this respect.

Minimum Load
The Minimum Load is expected to be 50% and 45/50% for the technologies in SP3 and SP4 respectively, compared to 40% for the conventional CFB reference.

Start-up Time
The start-up time is expected to be higher for SP3 and SP4 technologies. The ASU start-up, in SP3, is longer than the CFB start-up.

8.2.3 Restrictions on fuel quality

The fuel flexibility is an inherent feature of CFB, probably the most prominent one, and this advantage is kept in the oxygen blown configuration of SP3 and in the Chemical Looping configuration of SP4. There is no foreseen limitation, mainly due to the same operating conditions in terms of temperature, excess O_2 and residence time. Sulphur is controlled by limestone injection (SP3) or by an air pollution control system (SP3 and SP4). Depending on the fuel type, different oxygen carriers might be selected in SP4.

8.2.4 Emissions and additional environmental impact

There is no impact of CTs on flue gas emissions. A conventional CFB boiler does not have any liquid waste, whereas both CTs integrate a flue gas condenser that imposes an effluent, which requires filtration and pH control.

Additional environmental impact can occur, depending on the nature of the oxygen carrier in the SP4 CLC. Proper operation of the fly ash / oxygen carrier recovery unit is essential to avoid any environmental impact.

8.2.5 CO_2 quality

SP3 and SP4 technologies are able to produce high purity CO_2 (97 to 98%). Depending on its planned use, a specific purification system can be added to the CO_2 processing unit in order to reduce some minor species.

8.2.6 Maturity

Oxy CFB technology has been validated at pilot scale up to 3 MWt. This technology is currently considered in different projects of industrial demonstration units in the range of 10-60 MWe. After such successful demonstration(s), the next step will be commercial deployment of Oxy CFB power plants can .

CLC CFB technology for gas and solid fuel has been proven at small pilot scale (10 kw). The next step of development will be a 1/3 MWt pilot and then a demonstration unit. Considering these different development steps, the technology could be industrially available within approximately ten years.

8.2.7 Changes in results for to adjusted reference cases (see explanation in chapter 3.3)

Only minor, not significant changes in the relative assessment were observed by adjusting the reference case to the same net capacities as for the power plants with CO_2 capture (as explained in chapter 3.3).