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SUCCESS

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Industrial steam generation with 100% carbon capture and insignificant efficiency penalty - scale-up of oxygen carrier for chemical-looping combustion using environmentally sustainable materials

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Final report of assessment methodology

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<tr><td>BERTSCH</td><td>DELIVERABLE 8.2</td></tr>
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<tr><td>SUCCESS - Industrial steam generation with 100% carbon capture and insignificant efficiency penalty - scale-up of oxygen carrier for chemi-cal-looping combustion using Environmentally sustainable materials

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- Establish the assessment technology and the reference natural gas steam-generation units for benchmarking, also based on existing published work by the EBTF (European Bench-marking Task Force).</td></tr>
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1 Introduction

This document presents a collection of parameters that should serve as basic parameters for comparison of CLC fired boilers to common fired boilers. Calculations within the SUCCESS project for comparison of efficiency and economy should be based on the parameters of the paper.

For the assessment of efficiency we propose a calculation according to EN 12952 – part 15 (water tube boilers and auxiliary installations – acceptance tests) with adaptions suitable for SUCCESS.

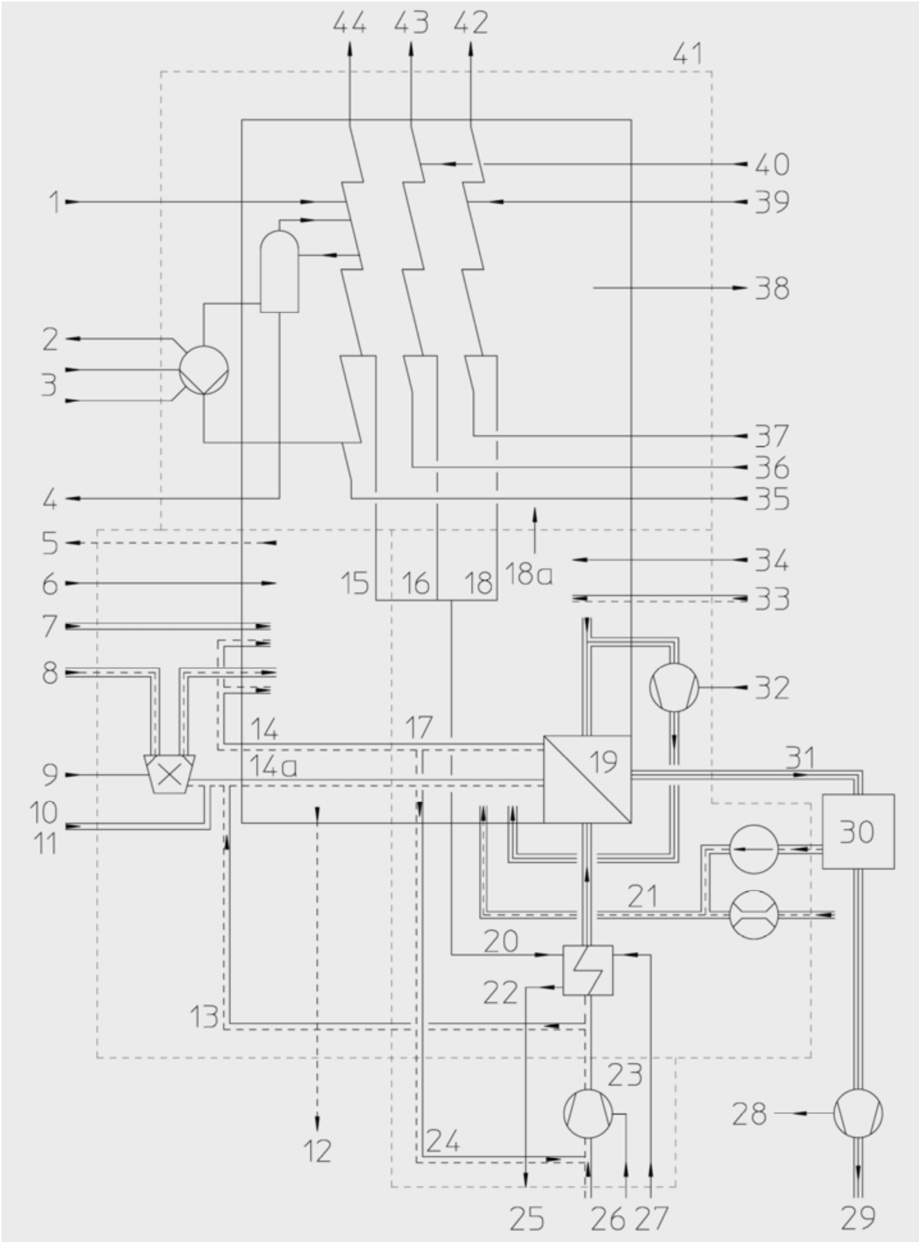
In a first step the collection of parameters from EBTF – especially from deliverable D4.9 European best practice guidelines for assessment of CO2 capture technologies – CAESAR - FP7 project Nr. 213206 was done.

The second step was the expanding and adjustment of parameters for using in project SUCCESS

2 System boundary - Calculation of efficiency

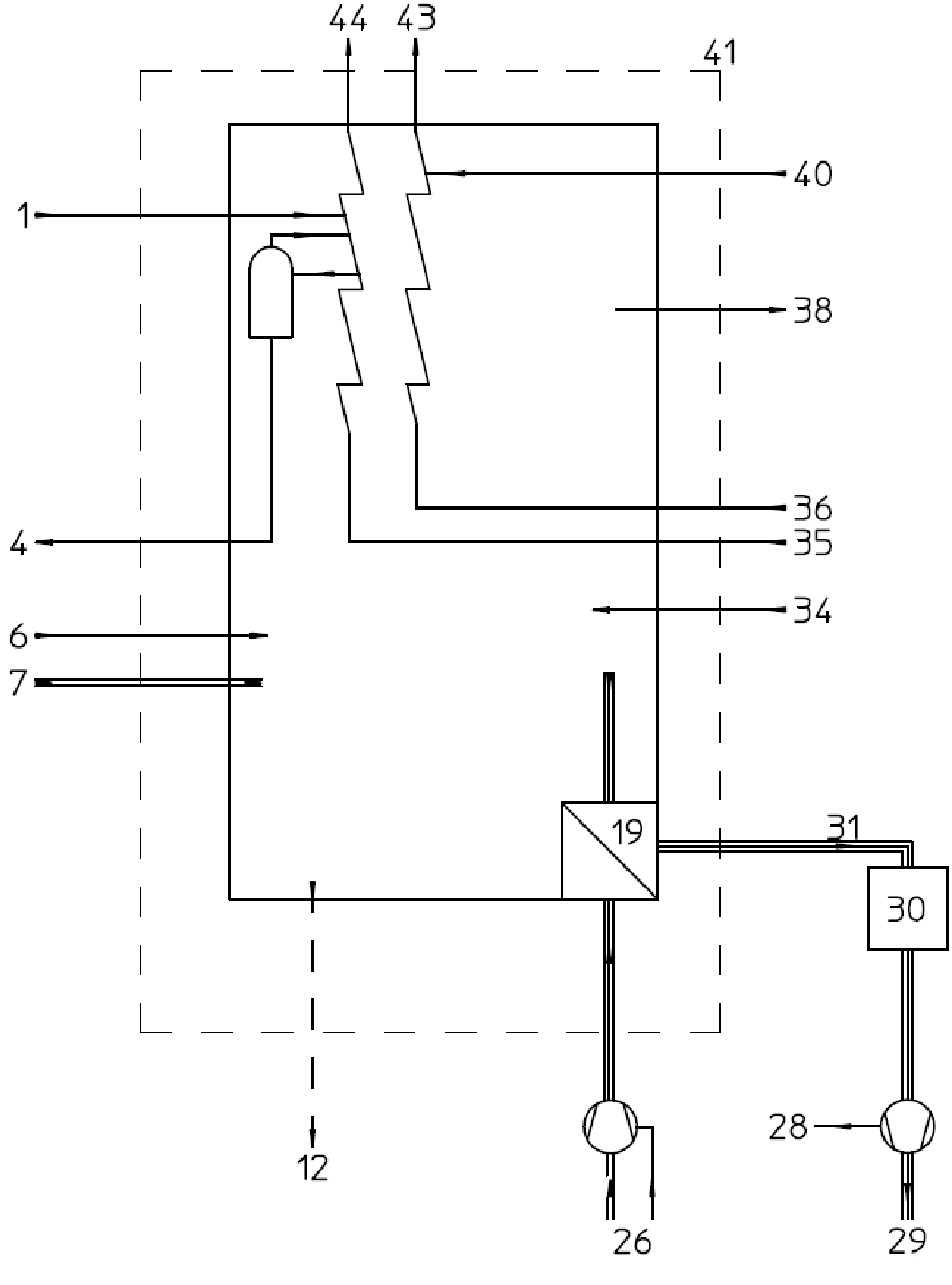
The EN 12952 is a standard for water tube boilers.
In part 15 of this standard the calculation formulas for efficiency are explained.
For the calculation of efficiency the basic boundaries of a system have to be fixed.

Picture of the system boundaries from EN12952-15 is presented below.



This standard picture gives a large number of possibilities for system relevant connections and streams for different medium streams. For CLC fired boiler and gas fired boilers not all components of this system are relevant resp. necessary and can be deleted. (e.g. Nr. 9 coal mill)

For SUCCESS an adapted picture was generated – see below



In according to EN12952 the numbers in this picture have following meanings resp. applications. Unspecified numbers are caused to deleted components.

1	water for temperature control (not relevant – because this water quantity is taken from 35 (feed water))
4	desalting
6	steam for atomizing – used as steam for loop seals
7	natural gas (for normal operation and start up)
12	ash loss - used for oxygen carrier flow
19	air preheater (flue gas heated)
26	fresh air - power for fan
28	ID fan – used for both fans - CLC has two flue gas streams
29	dust loss – used for loss of unburned
30	dedusting device if necessary
31	loss for CO content and other unburned media
34	other electric consumers
35	feed water
36	intermediate steam entrance
38	radiation loss
40	water for temperature control of intermediate steam
41	system boundary
43	intermediate steam outlet
44	high pressure steam outlet

With this adapted picture it is able to compare not only efficiency, but also other important streams of the plant.

Beside the calculation of the thermal efficiency of the boiler (resp. plant) following other efficiencies could be established.

- methane (gas) converson
- achievement of CO_2 yield
- recycling possibilities of oxygen carrier losses (fines; dust)
- combustion efficiency based on lower heating value

3 Benchmarking cases for gas-fired CLC power production

CLC has been discussed mainly to reduce the energy penalty for carbon capture from fossil fuel power plants. For power production from natural gas, the state of the art technology is the gas turbine combined cycle (GT-CC) reaching net electric efficiencies of up to 60 % without CO_2 capture. In GT-CC concepts, CLC would need to be operated at increased pressure up to 20 bar. This certainly means a critical challenge since the reaction intensity on the solid oxygen carrier surface increases proportional to pressure. Dual fluidized bed systems have only been operated at atmospheric pressure so far. Therefore, alternating fixed bed vessel systems have been proposed for pressurized CLC operation in combination with gas turbines. However, these systems suffer from heat transfer issues as a result of the poor heat transfer performance of fixed beds. Additionally, the common inlet specifications of large scale gas turbines cannot be met with CLC AR off gas and the relative pressure drop exposed by a CLC AR route is considerably larger than the pressure drop of current gas turbine combustion chambers. This will result in an expectable efficiency drop of the GT-CC arrangement in case that CLC is used.

Therefore, in the comparison performed within the SUCCESS project, the CLC unit operates at atmospheric pressure and a state of the art steam cycle is used for power generation, the net electric efficiencies can be expected to reach 46 % without compression and purification of the CO_2. Such a process needs to compete to a GT-CC in combination with state-of-the-art CO_2 capture technologies based on gas separation.

Given the limitation of the SUCCESS project focus on natural gas as fuel, the following benchmark cases will be described and considered in the project:

1. Gas turbine combined cycle power plant with post combustion CO_2 capture

2. Atmospheric pressure gas fired steam cycle power plant with post combustion CO_2 capture

3. Atmospheric pressure CLC of natural gas with steam cycle power plant

4. Pressurized CLC of natural gas with gas turbine combined cycle power plant

Cases 1 and 3 are technologically most realistic scenarios and thus relevant for the benchmarking. Case 2 is of interest in order to distinguish effects of the technological switch and to assess replacement of common once-through natural gas steam boilers in use for process steam generation in industry.

4 Assessment of CO_2 capture performance

Capturing CO_2 during or downstream of thermal power plants requires additional energy (either heat, electricity or both) and, thus, inevitably leads to net efficiency penalties for the power plant. The following terms are used in connection to the phenomena related to CO_2 capture from power plants:

1. Efficiency penalty $\Delta\eta$ [-]: $\Delta\eta = \eta_{base} - \eta_{CC}$

$\Delta\eta$ expresses the drop of net electric efficiency of the power plant based on fuel power input (lower heating value) due to CO_2 capture. Since the efficiency penalty is expressed in percentage points, it needs to be reviewed together with the base plant efficiency (without CO_2 capture). The same value of $\Delta\eta$ is more critical in case of lower base plant efficiencies. Further, it is important to note that the efficiency penalty depends on the fraction of CO_2 captured from the exhaust gas. If more CO_2 is removed the efficiency penalty will be higher.

2. Specific fuel consumption increase ΔP_{th} [-]: $\Delta P_{th} = \frac{P_{th,CC}}{P_{th,base}} - 1 = \frac{\Delta\eta}{\eta_{CC}} = \frac{\Delta\eta}{\eta_{base} - \Delta\eta}$

ΔP_{th} relates, for a given net electric output, the necessary additional fuel power to the fuel power input in the base plant without carbon capture. It directly expresses the conversion efficiency drop caused by CO_2 capture and can be calculated from the efficiency penalty and the base plant efficiency. It is as well a function of the fraction of CO_2 captured.

3. CO_2 capture rate [-]: $CO_{2,capt} = \frac{\dot{m}_{CO_2,capt}}{\dot{m}_{CO_2,total}} = 1 - \frac{\dot{m}_{CO_2,FG,clean}}{\dot{m}_{CO_2,total}} = 1 - \frac{\dot{n}_{FG,clean} \cdot y_{CO_2,FG,clean}}{\dot{n}_{FG,raw} \cdot y_{CO_2,FG,raw}}$

The CO_2 capture rate relates the mass flow of captured CO_2 of the plant with CO_2 capture to the total mass flow of CO_2 resulting from all fuel carbon fed to the plant with CO_2 capture. In case of post combustion capture, it is equal to the separation efficiency of the CO_2 separation process and can be calculated from the molar flow rate and mole fraction of CO_2 in the flue gas before and after the separation unit.

4. CO_2 avoidance rate [-]: $CO_{2,avoid} = 1 - \frac{\dot{m}_{CO_2,released,CC}}{\dot{m}_{CO_2,released,base}} = 1 - (1 - CO_{2,capt}) \cdot (1 + \Delta P_{th})$

The CO_2 avoidance rate is the relevant quantity to use if processes with partial CO_2 capture are benchmarked against processes with a different capture rate or without CO_2 capture. It relates the difference between the CO_2 released from the CO_2 capture plant and the CO_2 released from the base plant without capture to the CO_2 released from the base plant. It is a direct expression of the amount of CO_2 emission avoided by carbon capture when a certain amount of electricity is produced. During benchmarking of CCS processes, situations of equal CO_2 avoidance rate should be compared.

5 Parameters

3.1 General definitions and conditions

Units: In all calculations, reports and presentations SI-units have to be used

Ambient conditions:

Air pressure	0,101325 MPa
Air temperature	15 °C
Air relative humidity	60 %

Air composition	volume % dry fraction	volume % at 60% humidity
N2	78,09	77,30
CO2	0,03	0,03
H2O	0	1,01
Ar	0,932	0,923
O2	20,95	20,74
Gas constant (J/kg K)	287,06	288,16
Molecular weight	28,964	28,854

Ambient air for natural draught cooling towers

Condensing pressure 48 mbar

Cooling water temperature 18,2 °C

For further explanations about these values refer to CAESAR D 4.9.

3.2 Fuel

For SUCCESS project only natural gas is foreseen as fuel

Composition, calorific value and CO_2 emissions of natural gas used in the calculations are listed below.

Natural gas

Component		Volume %
CH_4		89,00
C_2H_6		7,00
C_3H_8		1,00
C4-i		0,05
C4-n		0,05
C5-i		0,005
C5-n		0,004
CO_2		2,00
N_2		0,89
S		< 5 ppm
HHV (MJ/kg)	higher heating value	51,473
LHV (MJ/kg)	lower heating value	46,502
CO_2 emissions g/kWh LHV		208

It is assumed that natural gas is supplied at 10 °C and 7 MPa pressure.

3.3 Oxygen carrier

Benchmarks:
- costs, availability, delivery time,
- attrition rate (particle lifetime); O_2 capacity;
- HSE-aspects - environmental and human toxicity - exposure of man and the environment during operation - life cycle of the OCs including production and waste stage;
- quantity for necessary inventory per MW

3.4 Flue gases

AR flue gas:	excess air ratio (O2-content); CO2-content H20-content
	Further values according TA-Luft (boiler with gas firing)
	dust 5 mg/Nm3
	NOx 150 mg/Nm3
	SO2 10 mg/Nm3
	CO 50 mg/Nm3
FR flue gas:	CO2-content H2O-content
	Further values dust H2-content CO-content CH4-content

6 Parameters for Gas Turbines

F-class large-scale gas turbines could be described by the following operating parameters and performance

Pressure ratio:	18,1
Pressure drop:	
Inlet filters	dp= 0,0001 MPa
Exhaust	dp= 0,0001 MPa (no HRSG)
natural gas pressure at the combustor inlet:	23,1 MPa
Net efficiency	38,5 %
Specific work	420 kJ/kg (defined as turbine output divided by the compressor intake mass flow rate
Turbine outlet temperature (TOT)	603 °C

7 Steam Cycle

In the previous EU-project called "Innocuous", a next scale plant for steam production was designed to show the possibility for the usage of CLC as heating unit for steam production and further on production of electric energy.

The next scale plant in "Innocuous" was 10 MW fuel power.
For this power capacity only low grade steam parameters seem to be useful, because of cost effective availability of equipment and materials in this range of power.

For SUCCESS the fuelpower is foreseen to be much higher
– up to several 100 MW

5.1 Boiler parameters

For different boiler types and power ranges different parameters are useful.
In the following collocation parameters are described depending on power range; type of firing (direct fired or waste heat)

5.1.1 Basic steam parameters

Low grade steam parameters up to a fuel power of 100 MW could be the same as for Innocuous - single steam circuit with 65 bar and 485°C and 105°C feedwater temp. For plants with more power than 100MW it is suggested to have two steam grades.

For oil and gas industry it is proposed to use up to appr. 200 - 300 MW power following low grade steam parameter: 60-70 bar; 450 °C.
The need is for kinetic energy and thermal energy.

High grade steam parameters for power plants with more than 300MW fuel power – we can use the suggestion from EBTF

Conditions at boiler outlet: 300 bar; 600°C

5.1.2 Temperature loss live steam

From superheater / reheater to turbine: 2 °C for fired boilers; 1 kJ/kg for HRSG

5.1.3 Type of circulation

For low grade steam: natural circulation is considered

For high grade steam: forced circulation

5.1.4 Pressure losses for direct fired boiler

delta p cold = 3% for each heat exchanger

delta p reheat_cold = 10%

delta p steam_pipe+valve = 7%

.

5.1.5 Pressure losses for HRSG

delta p HRSG_hot = 3% kPa

delta p HRSG_cold = 3% for each heat exchanger

delta p reheat_cold tot = 10%

delta p steam_pipe+valve =

HP = 7%
IP = 9%
IP = 9% for reheat IP steam mixing
LP = 12 %

5.1.6 Temperatur differences for HRSG

Delta T steam_gas	= 25 °C
Delta T pinch_point; gas_boiling - liquid	= 10 °C
Delta T gas - liquid	= 10 °C
Delta T approach_Eco	= 5 °C

5.1.7 Efficiency direct fired boilers (gas)

Low grade steam boilers: 92 %
High grade steam boilers: 95 %

5.1.8 Pressure levels

Direct fired boilers: 1 pressure level
High grade steam boilers: triple pressure with single reheat

5.2 Condenser

Natural draft cooling tower – water cooled steam condenser

Condenser pressure:	0,0048 MPa at saturation temperature of 26 °C
Cooling water pump work:	0,5% of steam turbine power
Cooling water pressure:	0,2 -0,25 MPa

Saturated condensate is assumed at the condenser outlet

5.3 Steam Turbines

5.3.1 Isentropic efficiencies

etha HP:	92%
etha IP:	94%
etha LP:	88%

5.3.2 Pressure loss for steam extraction

HP extraction pipe + preheater:	3%
LP extraction pipe + preheater:	5%

5.4 Pumps

multistage centrifugal pumps:	Efficiency:	70%

5.5 Fans

Air fans:	Efficiency:	82 %
Induced draught fans:	Efficiency:	82 %

5.6 Compressors

Relevant compressors are needed only for CO_2 compression.

CO_2 outlet pressure is atmospheric in CLC case but not in post combustion cases where it can achieve between 2 and 5 bars depending on the technology. This implies that the CLC compressor should be oversized compared to post combustion (maybe one more stage needed). The benchmark has to take this into account.

5.7 Heat exchangers

Reference guidelines for heat exchangers outside steam cycle

5.7.1 Pinch points

Gas / gas:	25°C
Gas / boiling or liquid phase:	10°C
Liquid / Liquid:	10°C
Condensing / Liquid:	3°C

5.7.2 Pressure drops

Liquid phase pressure drop for cold and hot side:	0,04 MPa
Gas phase pressure drop for cold and hot side:	2 %

5.7.3 Bed material cooler

Inside the reactors of CLC (air reactor and fuel reactor) no heat exchangers for bed cooling are foreseen. The only cooling device at the reactors are cooled walls. The fuel reactor at INNOCUOUS (10 MW plant) has no cooling walls. Perhaps in case of SUCCESS cooling walls for the fuel reactor are necessary depending on different Oxygen carriers (e.g. copper complexes) .

For bed material cooling a separate heat exchanger outside the reactors is foreseen.
This heat exchanger is necessary because the cooled walls in the air reactor cannot transfer the whole heat capacity for 100 % evaporation power. Therefore the bed material cooler is planned as evaporator in the steam cycle. The outlet temperature of flue gas from air reactor is controlled by the mass flow of oxygen carrier through the bed material cooler.

The design of bed material coolers for CLC operation is a very special item. For easier handling in SUCCESS It is suggested to take following parameters:
overall heat transfer coefficient: 300 - 450 W/m2K and temperature difference is taken as difference between bed material outlet temperature and boiling temperature of boiler water.

5.8 Figures for further efficiency calculations

5.8.1 Mechanical efficiency gear

etha m: 99,6%

5.8.2 Generator efficiency

etha G: 98,5%

5.8.3 Auxiliary power

etha Aux:estimated case by case

5.9 CO2 stream

For further usage of CO2 the purity of CO2 is a very important parameter. In the public document with reference “QGESS: Quality Guideline for Energy System Studies: CO2 Impurity Design Parameters, August 2013, NETL/DOE -341/011212” a recommendation for purity of CO2 is given.

Part of the document is exhibit2-1 “Gas stream condition”

Component	Unit (Max unless Otherwise noted)	Carbon Steel Pipeline		Enhanced Oil Recovery		Saline Reservoir Sequestration		Saline Reservoir CO_2 & H_2S Co-sequestration		Venting Concerns (See Section 3.0)
		Conceptual Design	Range in Literature	Conceptual Design	Range in Literature	Conceptual Design	Range in Literature	Conceptual Design	Range in Literature	
CO_2	vol% (Min)	95	90-99.8	95	90-99.8	95	90-99.8	95	20 – 99.8	Yes-IDLH 40,000 ppmv
H_2O	ppm_{wt}	300	20 - 650	300	20 - 650	300	20 - 650	300	20 - 650	
N_2	vol%	4	0.01 - 7	1	0.01 - 2	4	0.01 - 7	4	0.01 – 7	
O_2	vol%	4	0.01 – 4	0.01	0.001 – 1.3	4	0.01 – 4	4	0.01 – 4	
Ar	vol%	4	0.01 – 4	1	0.01 – 1	4	0.01 – 4	4	0.01 – 4	
CH_4	vol%	4	0.01 – 4	1	0.01 – 2	4	0.01 – 4	4	0.01 – 4	Yes- Asphyxiate, Explosive
H_2	vol%	4	0.01 - 4	1	0.01 – 1	4	0.01 – 4	4	0.02 – 4	Yes- Asphyxiate, Explosive
CO	ppm_v	35	10 - 5000	35	10 - 5000	35	10 - 5000	35	10 - 5000	Yes-IDLH 1,200 ppmv
H_2S	vol%	0.01	0.002 – 1.3	0.01	0.002 – 1.3	0.01	0.002 – 1.3	75	10 - 77	Yes-IDLH 100 ppmv
SO_2	ppm_v	100	10 - 50000	100	10 - 50000	100	10 - 50000	100	10 - 50000	Yes-IDLH 100 ppmv
NO_x	ppm_v	100	20 - 2500	100	20 - 2500	100	20 - 2500	100	20 - 2500	Yes-IDLH NO-100 ppmv, NO_2 - 200 ppmv

NH_3	ppm_v	50	0 - 50	50	0 - 50	50	0 - 50	50	0 - 50	Yes-IDLH 300 ppmv
COS	ppm_v	trace	trace	5	0 - 5	trace	trace	trace	trace	Lethal @ High Concentrations (>1,000 ppmv)
C_2H_6	vol%	1	0 - 1	1	0 - 1	1	0 - 1	1	0 - 1	Yes-Asphyxiant, Explosive
C_3+	vol%	<1	0 - 1	<1	0 - 1	<1	0 - 1	<1	0 - 1	
Part.	ppm_v	1	0 - 1	1	0 - 1	1	0 - 1	1	0 - 1	
HCl	ppm_v	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	Yes-IDLH 50 ppmv
HF	ppm_v	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	Yes-IDLH 30 ppmv
HCN	ppm_v	trace	trace	trace	trace	trace	trace	trace	trace	Yes-IDLH 50 ppmv
Hg	ppm_v	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	Yes-IDLH 2 mg/m^3 (organo)
Glycol	ppb_v	46	0 - 174	46	0 - 174	46	0 - 174	46	0 - 174	
MEA	ppm_v	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	MSDS Exp. Limits 3 ppmv, 6 mg/m^3
Selexol	ppm_v	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	

**Not enough information is available to determine the maximum allowable amount*

This spreadsheet from the before mentioned public document can be used for benchmarking the CO2 stream for usage of different OC.

As mentioned in the NETL-document further research is needed for better understanding of the impact of contaminants.

Non-condensables (N2, O2, Ar, CH4, H2) should be limited to reduce the amount of compression work; total non-condensables should be limited to less than 4 volume%

Further information on the CO2 stream can be found in the reference "CO2 Impurity Design Parameters, NETL, August 2013".

6 Economic assessment criteria

For calculation of CAPEX and OPEX only the main equipments have to be considered. This main equipments are summarised in the following lists.

CAPEX: prices for middle European market
engineering (basic and detail with drawings)
material and manufacturing
heat exchangers (Heating surfaces)
drum; vessels; reactors; cyclones; loop seals
firing equipment
steel structure – platforms
Piping, fittings (>DN 20)
fans; pumps; water treatment and storage
air/flue gas channels; stack; main expansion joints
insulation; lining;
field instruments; measuring and control equipment (hard/soft)
low tension unit; cabling
erection; commissioning; test run

OPEX:
fuel
manpower
Oxygen carrier
capital costs
water
electricity
spare and wear parts
chemicals such as those used for flue gas treatment

6.1 Reference year

Reference year could be 2013 (start of project)

6.2 Cost Indes

It is proposed to use the EPCCI Index

The cost indexes are used to adjust the process plant construction costs from one period to another. Indeed, historical data can be used in the cost-estimating methods.

Cost in year A = Cost in year B x Cost index in year A / Cost index in year B Although the cost indexes are defined in several ways, it consists generally of dimensionless composite indexes updated regularly and calculated with appropriate weighting factors to get the best estimate from several sub-indexes based on different prices of equipments (heat exchangers, tanks, pumps, compressors, etc.) and structures (construction, building, engineering and supervision). They do not usually take into account regional variations and are restricted to a particular region, generally including many of the EU countries.

The indexes available for process industries include CEPCI (Chemical Engineering Plant Cost Index), IC (Intrantec Chemical plant construction cost index), M&S (Marshall & Swift equipment cost index) and NF (Nelson-Ferrer refinery construction index). In the specific field of power generation, the EPCCI (European Power Capital Costs Index) defined by HIS CERA tracks the costs associated with the construction of a portfolio of power generation plants (coal, gas and wind) in Europe and indexed to year 2000 (next Figure 3).

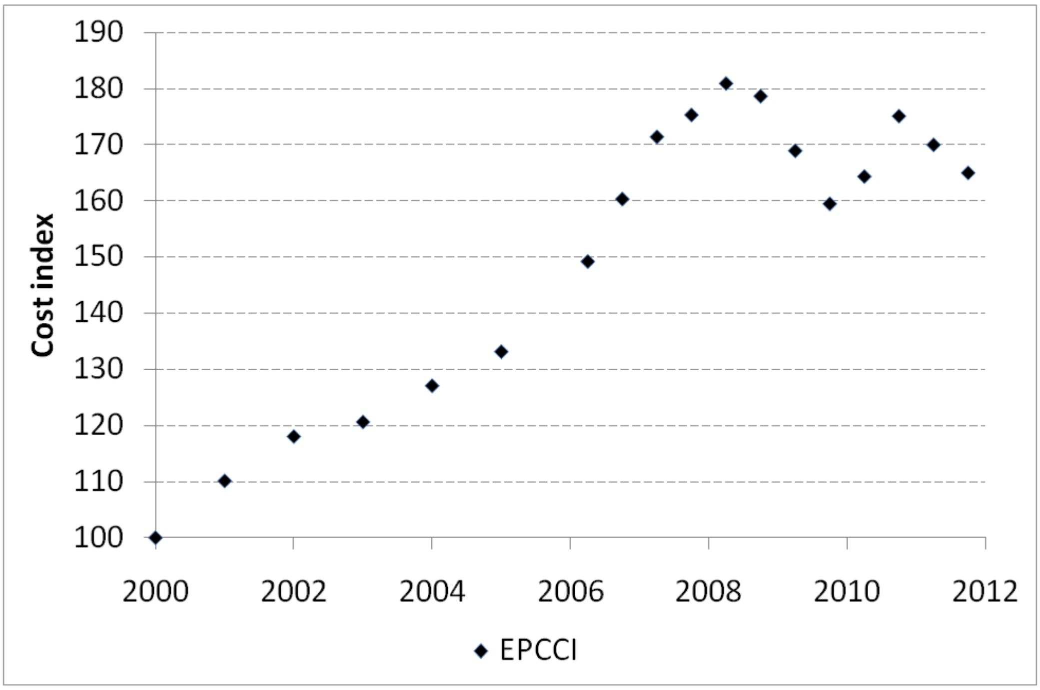


Figure 3. European Power Capital Cost Index (EPCCI) from 2000 to 2012

6.3 Annual allocation of finances

Year	allocation 3 years	allocation 4 years
1	40%	20%
2	30%	30%
3	30%	30%
4	-	20%

6.4 Financial parameters

Discounted cash flow rate	8%

If useful (other value than suggested), the rate should be accompagnied by:
Depreciation (year)
Residual Value
Tax Rate (%)
Inflation
% Debt
% Equity
Cost of Debt

6.5 Capital investment

The calculation of engineering, procurement and construction costs (EPC) shall be carried out in a bottom up approach.
Development should not be considered.
Indirect costs should be fixed according to following table

Indirect cost	percentage of EPC
yard improvement	1,5%
Service facilities	2%
Engineering/consultancy cost	4,5%
Building	4%
Miscellaneous	2%

6.6 Main operational parameters

Capacity factor in the first years of operation

First year	40%
Second year	65%
following years	85%

These values taken from CEASAR seem to be right for the operation performance of the first industrial CLC plants. For benchmarking it is suggested to take the following values assuming that well developed CLC plants have similar capacity factors than common plants.

First year	90%
following years	95%

Price for natural gas	€ 8 / GJ
price for electric power consumption	€ 0,1 /kWh
clean water (deionat)	€ 6/m3
cooling water	€ 0,4/m3
oxygen carrier	€ open

6.7 Main economic performance characteristics

Steam power output
Electric power output
CO_2 avoidance costs

6.8 Man power

For operating and maintenance a three shift surveillance is suggested.
Together with other necessary staff as well as considering weekly work time and holidays it is assumed that a total man power of 15 - 20 person have to be calculated to run a CLC boiler (without CO_2 compression)

6.9 Calculation of CO2 price

After calculation of all costs (Capex; Opex) and comparison of the different boiler types (CLC fired and common fired) a calculation of CO_2 price will be presented in terms of avoided CO_2.

7 Thermodynamic properties

7.1 Air

Properties according FDBR are recommended to be used.
In case of using other properties a comparison to FDBR should be made.

7.2 Flue gas

Properties according FDBR are recommended to be used.
In case of using other properties a comparison to FDBR should be made.

7.3 Water/Steam

International Association for Properties of water and steam (IAPWS- IF97) have to be used.
In case of using other properties a comparison to IAPWS-IF97 should be made.

8 Abbreviations

CCS	Carbon Capture and Storage
EBTF	European Benchmarking Task Force
EPC	Carbon Capture and Storage
FDBR	Fachverband Dampfkessel Behälter und Rohrleitungsbau
GTCC	Gas Turbine Combined Cycle
OC	Oxygen Carrier

9 List of symbols

$CO_{2,avoid}$	CO_2 avoidance rate	[-]
$CO_{2,capt}$	CO_2 capture rate	[-]
$\dot{m}_{CO_2}$	Mass flow of CO_2	[kg/s]
$\dot{n}$	Molar flow rate	[mol/s]
P_{th}	Thermal fuel power input (basis LHV)	[W]
y_{CO_2}	mole fraction of CO_2 in flue gas	[-]

Greek symbols:

ΔP_{th}	specific fuel consumption increase	[-]
$\Delta\eta$	efficiency penalty	[-]
η	net electric plant efficiency	[-]

Subscripts:

base	plant without carbon capture with equal electric output as plant with carbon capture
capt	captured part of CO_2
CC	plant with carbon capture
clean	after CO_2 capture unit
FG	flue gas
raw	before CO_2 capture unit
released	part of CO_2 released to the atmosphere
total	total CO_2 resulting from all fuel carbon in complete combustion