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Deliverable number:	D5.3
Deliverable title:	Studies on CLC-CCS deployment and infrastructure development
Deliverable description:	CLC technology is benchmarked with both CFB and NGCC technologies associated with solvent CO_2 capture considering two study cases: 1) steam and power production in refinery, and 2) power supply. The full CCS chain is then assessed considering offshore storage and different options for CO_2 transportation. Finally, a Life Cycle Assessment is provided including both environmental and health impacts.
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0 PREFACE

CHEERS conforms to the European Horizon 2020 Work Programme 2016 – 2017, 10. 'Secure, Clean and Efficient Energy', under the low-carbon energy initiative (*LCE-29-2017: CCS in Industry, including BioCCS)*. The ambition is to improve the efficacy of CO_2 capture in industry, and help ensuring sustainable, secure, and affordable energy.

The action involves a 2nd generation chemical-looping technology tested and verified at laboratory scale (150 kW_{th}). Within the framework of CHEERS, the core technology will be developed into a 3 MW_{th} system prototype for demonstration in an operational environment. This constitutes a major step towards large-scale decarbonisation of industry, offering a considerable potential for retrofitting industrial combustion processes.

The system prototype is based on a fundamentally new fuel-conversion process synthesised from prior research and development actions over more than a decade. The system will include heat recovery steam generation with CO_2 separation and purification, and it will comply with industrial standards, specifications, and safety regulations. Except for CO_2 compression work, the innovative concept can remove 96% of the CO_2 while eliminating capture losses to almost zero.

The CHEERS project is financed by the European Union's Horizon 2020 research and innovation programme under grant agreement No 764697, and co-funded by the Chinese Ministry of Science and Technology (MOST).

0.1 Disclaimer

1 EXECUTIVE SUMMARY

In addition to the demonstration of the CLC technology at MW scale, the CHEERS project aims at providing a techno-economic assessment of the process at industrial scale. The first deliverable D5.1 consisted in developing modelling tools to extrapolate the design at large scale. The second deliverable D5.2 reported the overall plant modelling with optimized efficiency to provide a whole set of data including heat &material balances and sizing. The present deliverable D5.3 deals with the CLC-CCS deployment and infrastructure development. It is composed of three complementary studies: First, the techno-economic assessment (TEA) of the CLC technology based on the technical design from D5.2 which includes a benchmark study in comparison with two reference cases and a sensitivity study. Second, an evaluation of a full CCS chain based on different scenarios allowing CO2 storage in the Northern Light facility. Third, a Life Cycle Assessment (LCA) including both environmental and health impacts in which the CLC technology is also benchmarked with the two reference cases.

As already explained in D5.2, two study cases are considered in the project to assess the CLC technology in different industrial applications:

1. **Refinery case** where both steam production and power supply are needed
2. **Power case** consisting in the production of electricity only.

In order to benchmark the CLC technology with the state of the art of CCS technology, two reference technologies are also considered:

- **NGCC**: Natural Gas Combined Cycle which is a mature technology used in refining and power supply industries
- **CFB**: Circulating Fluidized Bed boiler which is a reference technology for the combustion of petcoke.

The CFB case is associated with solvent-based CO_2 capture plant using a generic MEA. The NGCC reference case is considered in association with both MEA and an advanced PZ (piperazine)/AMP (amino-methyl-propanol) to provide a case representative to the current state of the art.

Considering the CLC case in the benchmark and the two reference cases without CO_2 capture needed to establish the CO_2 avoided cost, the TEA of 12 different plants are then provided in this deliverable.

Regarding the full CCS chain evaluation, the study case consists in performing the permanent storage of the CO2 in the Northern Light facility. All steps required from the CLC capture site to the storage site are considered including CO2 liquefaction, pipeline transportation and ship-based transportation. Several scenarios are assessed considering different assumptions for the CO2 compression during shipping and ship size.

Finally, a cradle-to-gate LCA is provided for the three technologies (CLC, CFB, NGCC) using SimaPro software (v9.3.0.3) in combination with EcoInvent v3.8 database. Cradle-to-gate means that the impacts due to the raw material extraction are included, but not the use of the produced electricity. Only the Power case is considered in this study to benchmark the CLC against CFB and NGCC.

The main conclusions of this deliverable are the following:

- For solid feedstock, like petcoke, the CLC is clearly competitive versus CFB with carbon capture thanks to higher energy efficiency and capture rate for both the cogeneration of steam and power in the refinery case, and in the power case.

- For the power case, CLC is slightly more expensive than the NGCC with carbon capture when using the reference natural gas and petcoke prices.
    - However, if the CLC power plant is built very near the CO_2 storage place, the CLC plant could compete with the NGCC with CCS if gas prices and petcoke prices become respectively higher and lower than considered in the base case evaluations.
    - However, in a case where the CO_2 needs to be transported and stored far away from the power plant, the competitiveness of CLC would be further reduced as less CO_2 needs to be transported in the NGCC pathway than in the CLC one.
- For the refinery case, the results emphasize that CLC is not a cost-efficient option compared to an NGCC with CO_2 capture for the reference natural gas and petcoke prices.
    - This conclusion is confirmed even when considering sensitivity in natural gas and petcoke prices, and when including CO_2 transport and storage cost.
    - Thus, unless petcoke is nearly free, gas prices increase significantly, and that CO_2 transport and storage cost are minimal, it is very unlikely that CLC would be cost-competitive with an NGCC with CO_2 capture in the refinery case.
- Based on LCA results, CLC reduces GHG emissions up to 43% compared to CFB thanks to better thermal efficiency and higher CO2 capture rate. NGCC presents the lowest impact on the environment, which is mainly due to the use of natural gas instead of petcoke.
- However, it is the most cost-efficient technology to burn petcoke. Thus, in a future scenario where burning petcoke without CO2 capture is not feasible (due to CO2 tax or policy regimes), CLC would be the best option to utilize this fuel – primarily in refineries to utilise this by-product.

2 DESCRIPTION OF THE UNITS

2.1 Study cases of industrial units

Two case studies related to respectively refining and power industries are considered in the scope of the CHEERS project:

Case 1: **Refinery**

Capacity: **100 t/h steam production and 50 MWe power supply**

Case 2: **Power**

Capacity: **200 MWe power supply**

The technology under study is the Chemical Looping Combustion (CLC) and is benchmarked against two different reference technologies for the energy production:

- NGCC: Natural Gas Combined Cycle
- CFB: Circulating Fluidized Bed (petcoke fired)

Table 2-1: Study cases

Case		Elec (MWe)	Steam (t/h)	Application	Design	Cost estimation
A1	CLC	50	100	Refinery	IFPEN/TOTAL	TOTAL
A2	CLC	200		Power	IFPEN/TOTAL	TOTAL
B1	NGCC + Amine	50	100	Refinery	SINTEF	SINTEF/TOTAL
B2	NGCC + Amine	200		Power	SINTEF	SINTEF/TOTAL
C1	CFB + Amine	50	100	Refinery	IFPEN/TOTAL	TOTAL/SINTEF
C2	CFB + Amine	200		Power	IFPEN/TOTAL	TOTAL/SINTEF

The industrial units under consideration are grass root plants.

The two reference technologies are considered for the following reasons:

- NGCC: This is the mature technology widely used in the refining industry as CHP source and in the power generation industry. A petcoke fired CLC process should be compared against this mature technology that it will replace.

- CFB (petcoke fired): This reference technology is included primarily to compare a potential alternate fluidized bed technology to CLC for burning petcoke in a future refinery or power plant. The focus here is to ensure that the same fuel is used for both the reference technology and the CLC.

2.2 Base case: CLC plant

The following Block diagram describe the CLC plant for production of electricity and, optionally, of steam for the refinery case.

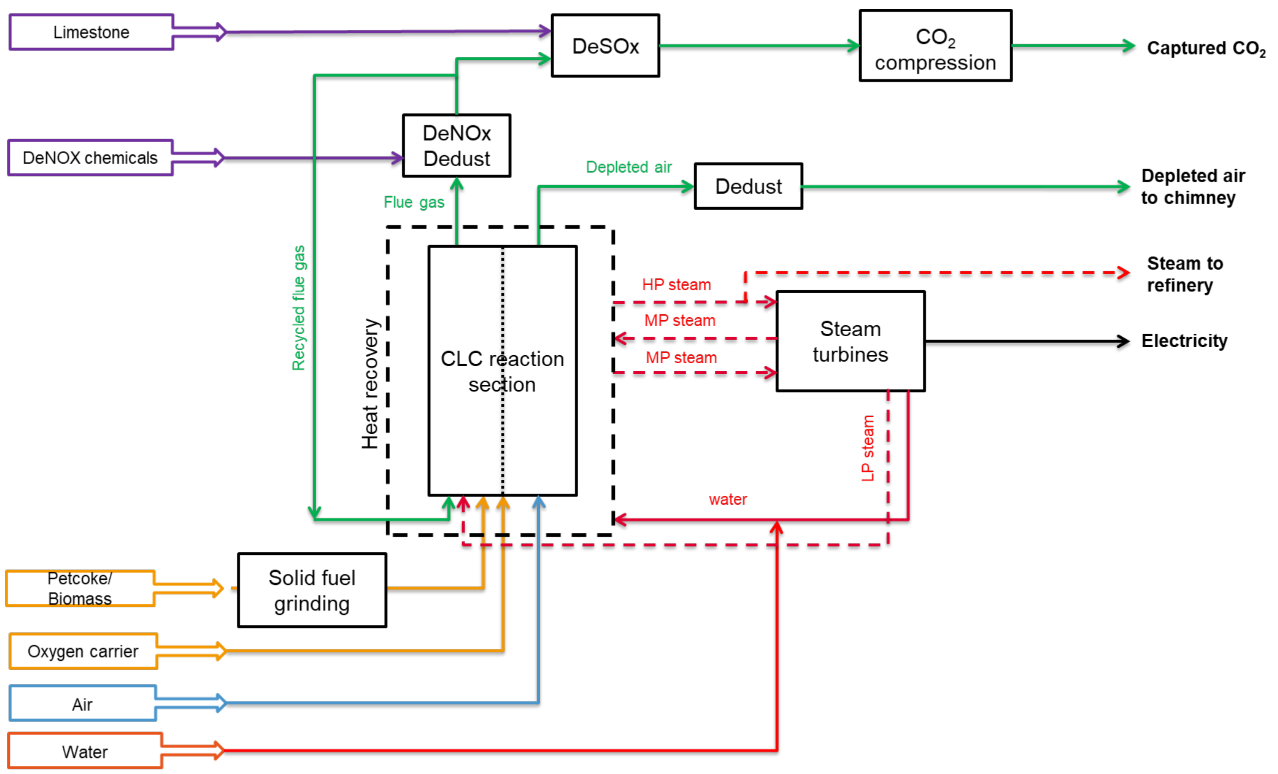

Figure 2-1: Block diagram of the CLC plant

The CLC reaction section provides heat from the combustion of solid fuel. In contrast to conventional combustion of fuel in the presence of air, CLC involves the use of an oxygen carrier that transfers oxygen from the air to the fuel, preventing direct contact between them. In the CLC system, the oxygen carrier particles are circulated between two reactors, an air and a fuel reactor.

Air is injected in the air reactor and the reoxidation of the oxygen carrier coming from the fuel reactor generates heat, which is transferred to the solid and to the Nitrogen-depleted air exiting the reactor. Depleted air is sent to the chimney after heat recovery and a dedust step.

Solid fuel is fed to the fuel reactor, and a mixture of steam and recycled flue gas is injected to fluidize the oxygen carrier particles. By contact with the fluidizing gas, the solid fuel is gasified and the produced gas is then oxidized (combusted) by contact with the oxygen carrier particles. The flue gas at the outlet of the fuel reactor is mainly composed of CO_2 and water, as well as NOx and SOx. The flue gas is therefore treated with deNOx, dedust and deSOx, prior to the CO_2 compression train, in order to meet CO_2 specification.

Heat is extracted from the CLC system by exchange with the solid inside the CLC reaction section and with the exhaust gases, i.e. depleted air and fuel reactor flue gas, in the convective zone of two dedicated back passes. This heat is transferred to a steam cycle, which converts heat into electricity through steam turbines, and optionally provides steam to the refinery.

2.3 NGCC reference case

The natural gas combined cycle (NGCC) reference model is based on the NGCC model in the public Deliverable D1.4.2 from the DECARBit project [1]. The gas turbine is equipped with a heat recovery steam generator (HRSG) and a steam turbine. A simplified process flow diagram (PFD) is shown in Figure 2-2. Before feeding the gas turbine combustor, natural gas is preheated up to 160°C by means of feedwater extracted from the intermediate pressure (IP) drum. The turbine inlet temperature (TIT) is kept the same as it would be without natural gas preheating, i.e. the fuel flow rate can be slightly reduced. Power is produced from both gas turbine and the steam cycle, while steam is produced in the steam cycle. An amine capture unit is used for capturing CO_2 from the exhaust of the Heat Recovery Steam Generator (HRSG). The captured CO_2 is further compressed to transportation pressure. The lower pressure (LP) steam is extracted for the regeneration of amine solvent.

The gas turbine chosen as reference case in CHEERS will be updated to reflect the electricity and steam requirement of the reference cases. However, all other parameters will be based on the public Deliverable D1.4.2 from the DECARBit project [1] as mentioned above.

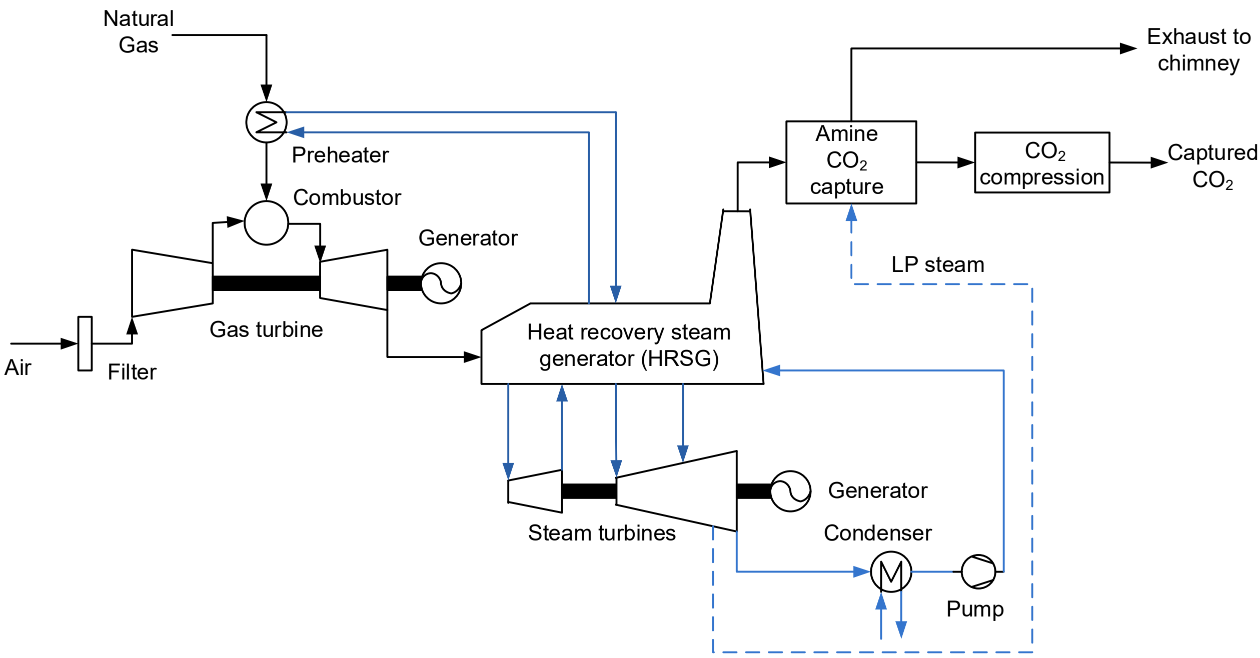

Figure 2-2: Process flow diagram of the Natural gas combine cycle reference case

2.4 CFB reference case

The following Block diagram illustrates the CFB plant reference case, i.e. a Circulating Fluidized Bed (CFB) boiler fired with petcoke and coupled to a CO2 amine post-combustion capture unit.

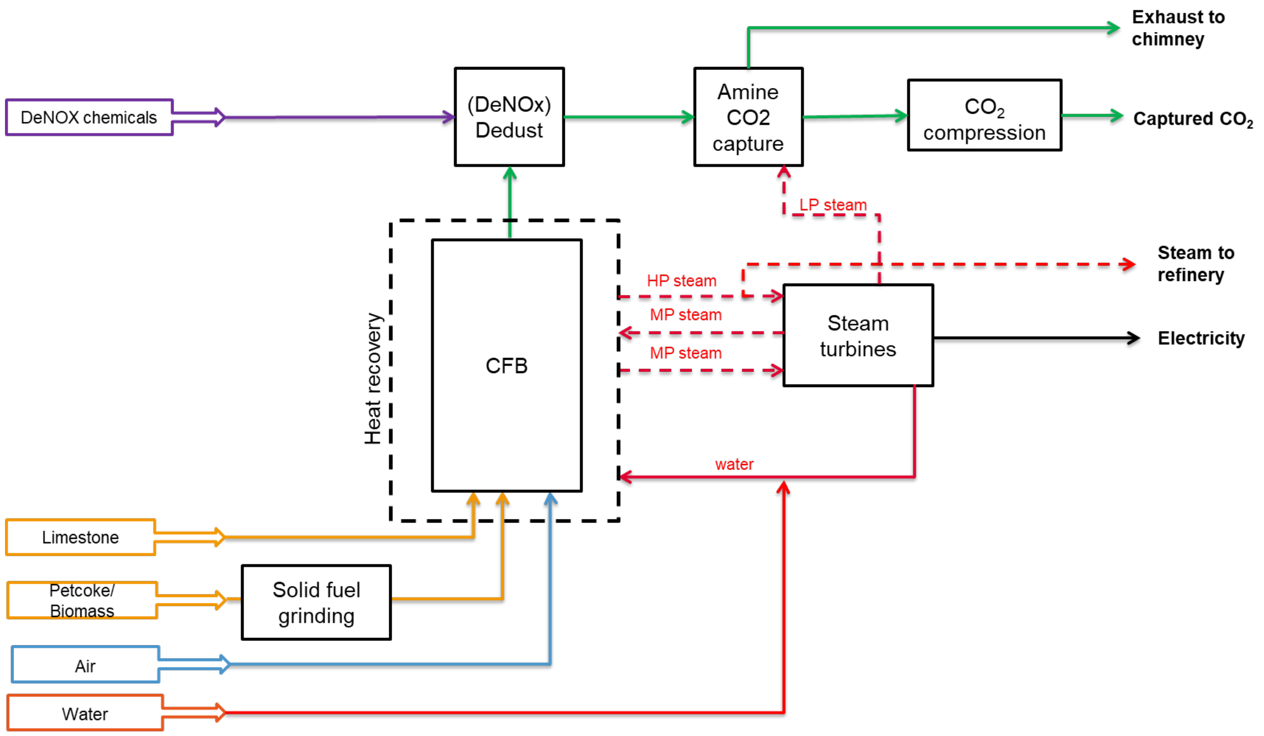

Figure 2-3: Block diagram of a Circulating Fluidized Bed with CO2 amine capture as reference case

In a CFB boiler the heat is provided by the combustion of a wide variety of solid fuels, including coals, petcoke or biomass. Low-cost limestone is injected into the furnace and acts as heat carrier as well as in situ sulfur capture, avoiding SOx in the flue gas. Air is fed to the CFB furnace and acts as fluidizing agent for both the solid particle species (limestone + solid fuel). Low temperature combustion in the CFB furnace (800-900°C) helps minimizing NOx formation.

The steam generation occurs inside the CFB furnace along water walls, and the produced steam is superheated in the radiative zone of the furnace or by the heat contained in the flue gas in the convective zone of the CFB back pass. Superheated steam drives the steam turbines to produce electricity. The intermediate pressure steam from the steam turbines train is reheated in the CFB back pass. The back pass also contains the economizer to preheat the boiler feed water. The flue gas at the back pass outlet is treated for deNOx if necessary and for dedust, prior to the CO_2 amine post-combustion capture unit and CO_2 compression train.

3 APPROACH FOR TECHNO-ECONOMICAL ASSESSMENT

3.1 Economic Assessment criteria

3.1.1 Key financial assumptions

- The project is assumed to be located in North-West Europe.
- The reference year for the cost is 2019.
- The evaluations are performed on a Nth-of-a-kind basis.
- Project evaluations are performed based on an economic lifetime of 25 years.
- The real discount rate and cost of capital assumed to be both equal to 8%[1].
- The plant is assumed to operate at 95% capacity (8300 h/y) except for the first year during with the plant is assumed to operate at 90% capacity.
- Decommissioning and remediation of the land at the end of the project is excluded. It is assumed that the residual value of the plant and the selling of the land should cover any cost related to the decommissioning of the plant.
- Inflation assumptions are not included. No allowance for escalation of fuel, raw materials, labour and other cost relative to each other is taken into account.
- Depreciation is not included. The calculation of cost Key Performance Indicators are calculated based on an EBITDA basis (Earnings Before Interest, Taxes, Depreciation and Amortisation).

3.1.2 Investment

Two approaches are considered in order to evaluate the Total Plant Cost (TPC): a Bottom-Up approach and a Top-Down approach [1-3].

3.1.2.1 The Bottom-Up approach

A Bottom-Up approach (BUA) is used to estimate the EPC costs for all the process units. A schematic overview of the BUA is given in Figure 3-1.

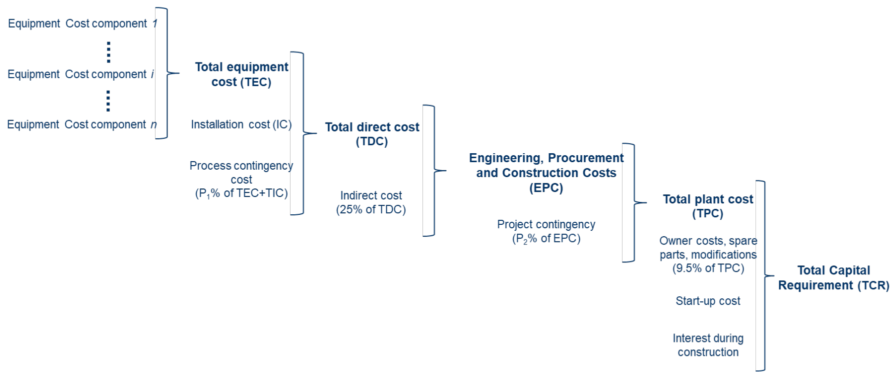

Figure 3-1: The Bottom-Up approach for estimation of total plant costs [3]

1 This real discount rate of 8% corresponds to a nominal discount rate of around 10% if an inflation rate of 2% is considered

The following cost elements are included:

- *Equipment Costs (EC)* – The Equipment Cost for each main basic equipment of the different processes can be estimated based on a step-count exponential costing method, using the dominant or a combination of parameters derived from mass and energy balance computations, combined with cost data obtained from equipment suppliers and/or other available data. The *Total Equipment Cost (TEC)* is the sum of all Equipment Costs in the plant.

- *Installation Costs (IC)* – The Installation Costs are estimated as additional expenses to integrate the individual equipment into the plant, such as costs for piping/valves, civil works, instrumentations, electrical installations, insulations, paintings, steel structures, erections and OSBL (outside battery limits).

- *Total Direct Costs (TDC)* – The Direct Costs is the sum of the Equipment Costs and the Installation Costs and shall also include the appropriate process contingency factor in order to reflect the differences in technology maturity of the different processed considered as shown in Table 3-1. It is worth noting that, within one process, different units might have different maturity level and thus process contingency factors.

  It is worth noting that although the direct cost of each unit shall be estimated, in some cases, certain units like storage and utilities productions facilities may be considered to be Outside battery limit (OSBL) units[2]. In such cases, the storage and utilities productions facilities cost may be estimated to represent 25% and 10% of the inside battery limit (ISBL)[3] units, although specific cost estimation shall be preferred as much as possible.

Table 3-1: Guidelines for process contingency cost [4]

Technology Status	**Process Contingency cost [% TDC without contingencies]**
New concept with limited data	40+
Concept with bench-scale data	30-70
Small pilot plant data	20-35
Full-sized modules have been operated	5-20
Process is used commercially	0-10

[2] The OSBL units includes the plant investment items that are required in addition to the main processing units within the battery limits.

[3] The ISBL units of a plant can be seen as the boundary over which raw materials, catalysts /chemicals, and utility supply streams are imported, and over which main products and byproducts are exported.

- *Engineering, Procurement and Construction Costs (EPC)* – The EPC cost is the sum of Total Direct Cost and Indirect Costs. The indirect costs are fixed to 25 % of the TDC and include the costs for the yard improvement, service facilities and engineering costs as well as the building and sundries.

3.1.2.2 The Top-Down approach

In some cases, a Top-Down approach may also be considered. In these cases, the EPC cost are directly estimated based on equipment supplier estimates for a complete process or unit. Calculation of total plant cost and total capital requirement then follow the same approach as the bottom-up approach.

3.1.2.3 Steps common to the Bottom-Up and Top-Down approaches

- *Total Plant Cost (TPC)* – The TPC is the sum of EPC cost and project contingency estimated following the AACE 16R-90 guidelines shown in Table 3-2.

Table 3-2: Guidelines for project contingency costs [4]

Estimate AACE Class*	Design effort	Project contingency cost (%-EPC)
Class 5/4	Simplified	30-50
Class 3	Preliminary	15-30
Class 3/2	Detailed	10-20
Class 1	Finalised	5-10

* Estimate class are defined in AACE (2011) as function of maturity level of definition

- *Total Capital Requirement (TCR)* – The TCR is the sum of total plant cost, the owner costs, spare parts, modifications, interest during construction and the start-up cost. The owner cost, spare parts, modifications are set as percentage of the TPC (7, 0.5 and 2% respectively) [1;2]. The interest during construction is calculated assuming that the construction costs are shared over a three-year construction period following a 40/30/30 allocation [1;2]. Finally, the start-up costs are evaluated based on the following considerations [5]:
    - 3 months of maintenance, operating and support labour
    - 1 month of materials, chemicals, consumables and disposal costs
    - 1.25 month of fuel costs

3.1.3 Operating costs

3.1.3.1 Fixed operating costs

The fixed operating costs, which include maintenance, insurance and labour costs, are estimated to be 4 % of the EPC cost.

3.1.3.2 Cost of key utilities, chemicals and raw materials

The variable operating costs include material utilities consumption such as petcoke, natural gas, process water, chemicals, solvent, etc. The costs of the main utilities and consumables are evaluated based on the process energy and mass balance and the costs presented in Table 3-3.

In the case of purchase or sell of electricity from/to the grid, a cost and CO_2 emission intensity of 62.3 €/MWh and 253 kgCO_2/MWh will be considered [2;6].

Table 3-3: Costs of main utilities, consumables and product (2019 reference year)

Utilities and consumables	Price		Range
Natural gas	6.2	€/GJ	3.2-9.3
Petcoke (4% sulphur)	100	€/t	50-150
Raw process water make-up	0.30	$/t	
Boiler feedwater (demin water)	0.52	€/t	
Cooling water	0.03	$/t	
Molecular sieve	6545	€/t	
Pure MEA solvent	1818	€/t	
Pure Piperazine	6000 (2013)	€/t	
Pure AMP	8000 (2013)	€/t	
Solvent sludge disposal	205	€/t	
DeSOx chemicals (calcium carbonate)	40	€/t	
DeNOx chemicals (ammonia)	300	€/t	
Oxygen carrier (Ilmenite)	500	€/t	145 -5000
Steam selling price (500°C – 100 bar)	23.43	$/t	HP steam

3.2 Key performance indicators

Key performance indicators (KPIs) are defined for comparative evaluation of the capture technologies, both with respect to CO_2 avoided and energy consumption (energy and environmental KPIs), and with respect to costs (economic KPIs).

3.2.1 Energy and environmental indicators

The *net electric efficiency* η is defined as follows:

$$\eta = \frac{W_{turbines} - W_{auxiliaries}}{P_{fuel}\ [MW_{LHV}]}$$

The *CO_2 capture ratio* (CCR) is a common KPI for CO_2 capture processes. It is defined as the CO_2 captured $\dot{m}_{\mathrm{CO2,capt}}$ divided by the CO_2 generated $\dot{m}_{\mathrm{CO2,gen}}$:

$$CCR = \frac{\dot{m}_{\mathrm{CO2,capt}}}{\dot{m}_{\mathrm{CO2,gen}}}$$

A minimum CO_2 capture ratio of 90% must be considered, but the optimal CO_2 capture ratio will be calculated as a function of the process technology.

The *CO_2 emission factor* in g CO_2/MWh evaluates the direct CO_2 emissions from the plant.

The *CO_2 avoided* evaluates the direct CO_2 emission reduction from the plant, taking the emissions related to the capture processes e.g. steam generation in addition to the emissions with the flue gas into account. It is defined as:

$$AC = \frac{e_{\mathrm{ref}} - e}{e_{\mathrm{ref}}}$$

where e_{ref} is specific emissions from the reference plant, and e is the specific emission from the plant with capture.

3.2.2 Economic indicators

While the SPECCA (Specific Primary Energy Consumption for CO_2 Avoided) is traditionally used to compare the increased equivalent fuel consumption to avoid the emission of CO_2, this index is however not suitable for the CHEERS project as multiple fuels with different costs are considered. Thus, here, a modified version of the SPECCA, called the "cost SPECCA" is proposed.

The cost-SPECCA (Specific Primary Energy Consumption Cost for CO_2 Avoided) index is defined by the following equation, quantifying the energy cost associated with the increased equivalent fuel consumption to avoid the emission of CO_2 the CHP or power plant.

$$Cost\ SPECCA \left[\frac{€}{t_{CO2}}\right] = \frac{HR_{CCS} - HR_{ref}}{e_{ref} - e_{CCS}} \cdot \ EC$$

Where HR_{ref} and HR_{CCS} are the heat rate of the plant with and without CCS respectively [$kJ_{LHV}/kW_{th}h$]

e_{ref} and e_{CCS} are the CO_2 emission rate [$tCO_2/kW_{th}h$]

EC is the primary energy cost [$€/kJ_{LHV}$]

3.2.2.1 Study cases delivering only power

The levelised cost of electricity [$€/MW_eh$] will be calculated as commonly defined in literature [7]. The levelised cost of electricity is calculated by dividing the annualised costs by the annual electrical output.

$$LCOE \left[\frac{€}{MW_e h}\right] = \frac{Annualised\ CAPEX + Annual\ OPEX\ [€]}{Annual\ electrical\ output\ [MW_e h]}$$

Cost of CO_2 avoided (CAC) is evaluated with the following equation, comparing the LCOE for cases producing only electricity and the equivalent specific emissions of the assessed energy plant.

$$CAC\ \left[\frac{€}{tCO_2, avoided}\right] = \frac{LCOE_{CCS} - LCOE_{ref}}{e_{ref} - e_{CCS}}$$

3.2.2.2 Study cases delivering both heat and power for refinery cases

Cost of CO_2 avoided (CAC): this is evaluated with the following equation, comparing the NPV of cost of the heat and power plant with and without CCS and the NPV of associated CO_2 emissions [8].

$$CAC\ \left[\frac{€}{tCO_2, avoided}\right] = \frac{NPV\ cost_{CCS} - NPV\ cost_{ref}}{NPV\ emissions_{ref} - NPV\ emissions_{CCS}}$$

Where $NPV\ cost_{ref}$ and $NPV\ cost_{CCS}$ are the net present value of cost of the heat and power plant with and without CCS respectively [M€].

Where $NPV\ emissions_{ref}$ and $NPV\ emissions_{CCS}$ are the net present value of CO_2 emissions in ton of the heat and power plant with and without CCS respectively [Mt_{CO2}].

4 CLC COMPARED TO CFB WITH SOLVENT-BASED CAPTURE AND TO CFB REFERENCE WITHOUT CAPTURE

4.1 Plant overall performance

The overall process performance indicators for the CLC case and the CFB reference case with and without CO_2 capture are given below in Table 4-1 and Table 4-2.

Table 4-1: Overall process performance indicators for the CLC plant

Results	Unit	Refinery	Power
Thermal power	MWth	265.4	522.3
Exported steam	MWth	92.0	
Gasification steam to FR production	MWth	7.9	15.7
Thermal power to steam cycle	MWth	242.8	477.7
Power produced	MWe	66.4	238.2
Auxiliaries consumption:	MWe	21.8	48.6
SC feedwater pump consumption	MWe	1.4	8.0
Fluid compression consumption	MWe	5.5	11.0
Air	MWe	3.8	7.7
Recycled flue gas	MWe	1.7	3.2
SCR and FGD consumption	MWe	0.2	0.4
CO_2 compression consumption	MWe	9.3	18.2
Net electric power	MWe	50.0	200.6
Gross electric efficiency	-	25.0%	45.6%
Auxiliaries electric contribution	-	-6.2% pts	-7.2% pts
Net electric efficiency	-	18.8%	38.4%
First-law efficiency	-	53.5%	

Table 4-2: Overall process performance indicators for the CFB plant with and without CO2 capture

		CFB without CO2 capture		CFB with CO2 capture	
Results	**Unit**	**Refinery**	**Power**	**Refinery**	**Power**
Thermal power	MWth	240.0	479.5	329.5	633.5
Exported steam	MWth	92.0		92.0	
Thermal power for CO2 regeneration	MWth			95.3	185.3
Thermal power to steam cycle	MWth	216.8	433.1	298.5	571.3
Power produced	MWe	55.8	216.4	73.4	250.9
Auxiliaries consumption:	MWe				
SC feedwater pump consumption	MWe	1.3	7.2	1.8	9.6
Fluid compression consumption	MWe	4.5	9.1	8.1	15.4
Air fan	MWe	2.1	4.3	2.9	5.6
Flue gas fan	MWe	2.4	4.8	5.2	9.8
CO_2 capture specific cons.	MWe			12.5	25.9
Net power	MWe	50.0	200.0	50.9	201.8
Gross electric efficiency	-	23.3%	45.1%	22.3%	39.6%
Auxiliaries contribution	-	-2.4%	-3.4%	-6.8%	-7.8%
Net electric efficiency	-	20.8%	41.7%	15.5%	31.9%
First-law efficiency	-	59.2%		43.4%	

4.2 Plant: equipment/units and sections

4.2.1 CFB Reference without capture and CFB with solvent-based capture: C1 and C2 case

The detailed cost of each equipment will not be given in this report. However, the cost of the main sub-systems constituting the CFB Reference case and the CFB with solvent-based capture plant will be given for benchmark purpose.

- CFB Section: CFB Reaction section, Air Supply section, Feed preparation section, Bottom solid discharge section
- Steam turbine generator and auxiliaries' section
- CO_2 Flue gas treatment section
- CO_2 capture section (for CFB with solvent-based capture plant)
- CO_2 compression section (for CFB with solvent-based capture plant)

4.2.2 CLC: A1 and A2 Case

The detailed cost of each equipment will not be given in this report. However, the cost of the main sub-systems constituting the CLC plant will be given for benchmark purpose.

- CLC Section: CLC Reaction section, Air Supply section, Oxygen carrier preparation section, Feed preparation section, Bottom solid discharge section
- Steam turbine generator and auxiliaries' section

- CO_2 Flue gas treatment section
- CO_2 compression section

4.2.2.1 Example of detailed equipment list for the CLC plant

For example, the layout of the CLC plant, including all the necessary units (ISBL and OSBL), is presented in the following plot plan.

For the CLC plant, 7 sections (S100 to S700) are considered inside the battery limit (ISBL). The table below gives the equipment list of these 7 sections.

Figure 4-1: Plot plan of the CLC plant

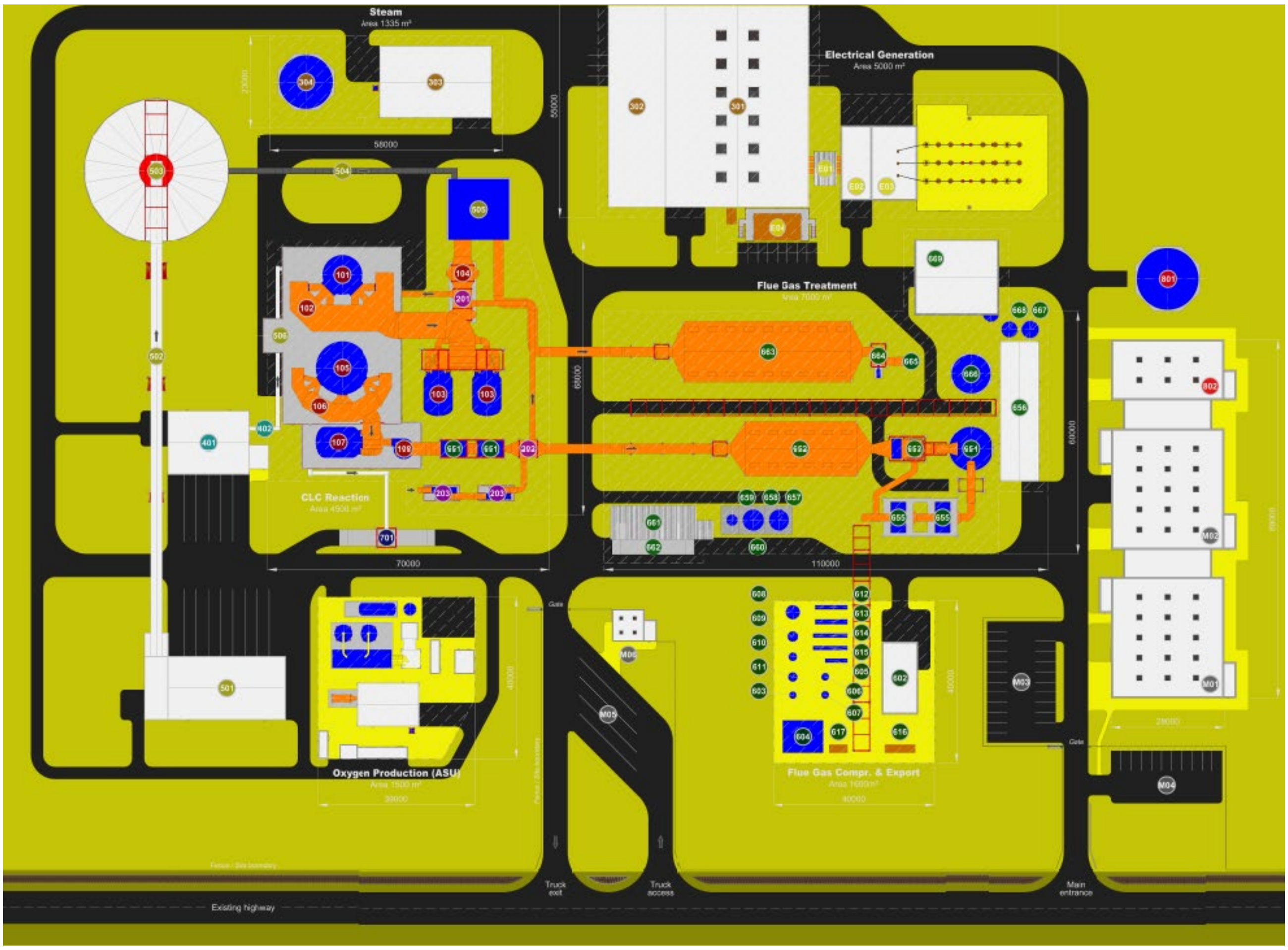

Figure 4-2: Equipment list of the CLC plant

Item	Tag	Description
CLC Reaction (S100)		
101	AR	Air reactor
102	AR-CY	Air reactor cyclones
103	HXARFG2/3	Air reactor BFW heaters
104	HXSTEAM	LP steam generator
105	FR	Fuel reactor / Carbon stripper
106	FR-CY1	Fuel reactor cyclones 1st stage
107	HXFRFG2	Fuel reactor BFW heater
108	FR-CY2	Fuel reactor cyclones 2nd stage
Air Supply (S200)		
201	HXAIR1	O2 depleted air stream/Air exch.
202	HXAIR2	ESP outlet air pre-heater
203	AIR COMPR	Combustion air blower
Steam (S300)		
301	TURB	Steam turbines
302	CONDENSE	Vacuum condenser
303	X-310	Auxiliary boiler package
304	T-320	Demineralized water tank
Ox Carrier Preparation (S400)		
401	X-401	Ox carrier unloading system
402	X-402	Ox carrier conveyor system
Feed Preparation (S500)		
501	/	Solid fuel unloading system
502	/	Solid fuel conveyor to silo
503	T-501	Solid fuel storage silo
504	X-502	Solid fuel conveyor to grinder
505	CRUSH	Solid fuel grinding machine
506	T-502	Fuel daily storage
Flue Gas Treatment & Compression (S600.1)		
601	HXGREC	Recycle CO2/O2 depl. air exch.
602	K-630	CO2 compressor package
603	C-630	CO2 drying column
604	X-630	TEG regeneration skid
605	C-631	CO2 direct contact cooler
606	P-630A/B	DCC circulation pump
607	E-630A/B	DCC quench water heat exch.
608	V-630	1st stage suction scrubber
609	V-631	2nd stage suction scrubber
610	V-632	3rd stage suction scrubber
611	V-633	4th stage suction scrubber
612	E-631	2nd stage suction cooler
613	E-632	3rd stage suction cooler
614	E-633	4th stage suction cooler
615	E-634	Discharge cooler
616	/	Electrical building
617	/	Electrical building

Item	Tag	Description
Flue Gas Treatment / Hamon Eqp (S600.2)		
CONFIDENTIAL		
Bottom Solid Discharge (S700)		
701	/	ASH handling equipment
Firefighting (S800)		
801	/	Fire water pumps building
802	/	Fire water storage tank
Electrical Generation		
E01	/	Generator cicuit breaker
E02	/	Auxiliary transformer
E03	/	Step-up transformer
E04	/	E-room
Miscellaneous		
M01	/	Control & administration building
M02	/	Workshop & store building
M03	/	Employee parking
M04	/	Visitor parking
M05	/	Truck site access parking
M06	/	Truck gate house

4.3 CFB without Carbon Capture / CFB with Carbon Capture / CLC - CAPEX

4.3.1 CAPEX Criteria

Table 4-3: CAPEX Criteria

CAPEX CRITERIA

Indirect cost	25%	of Total TDC Budget
Project Contingency	30%	of Total TDC Budget
Owner's cost	7%	of Total TPC Budget
Spare Parts	0,5%	of Total TPC Budget
Modifications	2,0%	of Total TPC Budget
Start up labor	25,0%	3 month of Fixed OPEX
Start up consumable	8,3%	1 month of consumables/disposal cost
Start up fuel	10%	1,25 month of consumptiion
CAPEX year	Q1 2019	

4.3.2 Power cases: 200 MWe

4.3.2.1 CFB Reference without capture

Table 4-4: CAPEX (M€) of the CFB Reference case without capture

CFB without capture - Ref case						
M€ By Section	**TEC** (1)	**IC** (2)	**Process Allowance** (3)	**TDC** (4)= ((1)+(2))*(1+(3))	**TPC** (5)= ((4)+ind Cost + Pj Ctgy)	**TCR**
CFB section	86	69	5%	163	264	536
Steam section	39	41	5%	84	136	
Flue gas treatment	15	12	5%	28	45	
Total	**140**	**122**		**275**	**446**	**536**

<u>Reminder:</u> TEC: Total Equipment Cost; IC: Installation Cost; TDC: Total Direct Cost; TPC: Total Plant Cost; TCR: Total Capital Requirement

For the current Techno-Economic Assessment, the process allowance affected to the sum of the TEC + IC was selected at 5% for mature technology such as Amine capture, Steam turbine section, NGCC, feedstock preparation section, Flue gas treatment and CO2 compression section. However, the process allowance for the CLC Reaction section was increased to 20%

Flue gas treatment consist of a De-NOx and ESP. De-Sox is included in the CFB section.

The TEC and IC data for CFB are provided by SOFRESID Engineering company (from SAIPEM) who delivered the TEA for CFB with and without capture for Power and Refinery cases.

The CFB data are provided by an Engineering software named PEACE and validated by comparisons with real CFB contractual offers done by SAIPEM.

4.3.2.2 CFB with capture: C2 case

Table 4-3: CAPEX (M€) of the CFB with sorbent-based capture: C2 Case

CFB with capture - C2 Case						
M€ By Section	**TEC** (1)	**IC** (2)	**Process Allowance** (3)	**TDC** (4)= ((1)+(2))*(1+(3))	**TPC** (5)= ((4)+ind Cost + Pj Ctgy)	**TCR**
CFB section	104	83	5%	196	319	847
Steam section	47	49	5%	101	164	
Flue gas treatment	18	14	5%	34	55	
CO2 capture unit	41	37	5%	81	132	
CO2 compression section	12	9	5%	22	35	
Total	**222**	**192**		**434**	**705**	**847**

The capture unit is based on MEA 30% solution absorption tower.

Flue gas treatment consist of a De-NOx and ESP (De-Sox included in CFB section)

CO_2 Compression target is 110 barg and 30 Deg C.

4.3.2.3 CLC: A2 Case

Table 4-4: CAPEX (M€) of the CLC: A2 Case

CLC - A2 Case						
M€ By Section	**TEC** (1)	**IC** (2)	**Process Allowance** (3)	**TDC** (4)= ((1)+(2))*(1+(3))	**TPC** (5)= ((4)+ind Cost + Pj Ctgy)	**TCR**
CLC Section	76	65	5%, (20% CLC reaction section)	162	264	720
Steam section	48	46	5%	99	160	
Flue gas treatment	28	50	5%	81	132	
CO2 compression section	15	10	5%	26	43	
Total	**166**	**172**		**369**	**599**	**720**

Flue gas treatment consists of a De-NOx, ESP, De-SOx and Wet ESP on the Fuel reactor side and ESP and dry De-SOx on Air reactor side

As detail above, the CLC Section is the sum of CLC Reaction section, Air Supply section, Oxygen carrier preparation section, Feed preparation section, Bottom solid discharge section. The 20% Process Allowance was only affected to the CLC Reaction section, 5% was used for the remaining elements which are mature technologies.

The TEC and IC data for CLC are provided by SOFRESID Engineering company (from SAIPEM) who delivered the TEA for CFB cases.

To be more confident in the equipment cost of this new design, several consultations had been launched for the different items of the CLC plant:

- CLC Air Reactor and Fuel Reactor construction and transport to western Europe place had been evaluated by CMP Arles boilermaker
- CLC Refractory installation had been evaluated by DAMRYS company
- CLC FGT had been evaluated by Esindus from HAMON group
- CLC Grinding section had been evaluated by POITTMILL company

4.3.3 Refinery cases: 50 MWe + 50 t/h HP Steam

4.3.3.1 CFB Reference without capture

Table 4-5: CAPEX (M€) of the CFB Reference case without capture

CFB without Capture - Ref Case						
M€ By Section	**TEC** (1)	**IC** (2)	**Process Allowance** (3)	**TDC** (4)= ((1)+(2))*(1+(3))	**TPC** (5)= ((4)+ind Cost + Pj Ctgy)	**TCR**
CFB section	41	33	5%	78	127	264
Steam section	20	20	5%	42	68	
Flue gas treatment	8	7	5%	15	25	
Total	**69**	**59**		**135**	**219**	**264**

4.3.3.2 CFB with capture: C1 case

Table 4-6: CAPEX (M€) of the CFB with sorbent-based capture: C1 Case

CFB with capture - C1 Case						
M€ By Section	**TEC** (1)	**IC** (2)	**Process Allowance** (3)	**TDC** (4)= ((1)+(2))*(1+(3))	**TPC** (5)= ((4)+ind Cost + Pj Ctgy)	**TCR**
CFB section	50	40	5%	94	153	449
Steam section	25	25	5%	52	85	
Flue gas treatment	10	8	5%	19	30	
CO2 capture unit	25	22	5%	49	80	
CO2 compression section	9	6	5%	16	26	
Total	**118**	**101**		**230**	**374**	**449**

4.3.3.3 CLC: A1 Case

Table 4-7: CAPEX (M€) of the CLC: A1 Case

CLC - A1 Case						
M€ By Section	**TEC** (1)	**IC** (2)	**Process Allowance** (3)	**TDC** (4)= ((1)+(2))*(1+(3))	**TPC** (5)= ((4)+ind Cost + Pj Ctgy)	**TCR**
CLC Section	44	38	5%, (20% CLC reaction	95	154	415
Steam section	25	25	5%	52	85	
Flue gas treatment	16	27	5%	46	74	
CO2 compression section	11	8	5%	19	32	
Total	**96**	**98**		**213**	**345**	**415**

4.4 CFB without Carbon Capture / CFB with Carbon Capture / CLC - OPEX

4.4.1 Power cases

Table 4-8: OPEX (M€) for the power cases

OPEX	UNIT	Ref case CFB	Case C2 CFB + carbon capture	Case A2 CLC
Fixed OPEX (4% TPC)	M€/year	**17,8**	**28,2**	**24,0**
Fuel cost - Petcoke	M€/year	**43,5**	**59,7**	**48,2**
Total Varialble OPEX	M€/year	**29,4**	**49,0**	**25,9**
Capture Solvent make-up	M€/year	-	7,8	-
Oxygen carrier	M€/year	-	-	5,3
CFB ash / CLC ESP Dust disposal	M€/year	19,7	27,0	5,3
Other variable OPEX	M€/year	9,6	14,2	15,2
Total	**M€/year**	**90,7**	**136,9**	**98,0**

The fixed OPEX cost is a ratio of the TPC. The fuel cost is linked to the energy needed for each case. The petcoke price is set at 100 €/t in this table. A sensitivity on the petcoke price is done in section 4.5.3.1 .

Regarding variable OPEX:

- Capture solvent is 30% solution MEA for the CFB with carbon capture unit.
- For the CLC case, oxygen carrier cost is based on 500 €/t price and 10 times inventory replacement per year. This is an average price between a natural base oxygen carrier that could be cheaper and a synthetic oxygen carrier that could be much more expensive. The oxygen carriers with lower price have generally a lower lifetime and unit inventory must be replaced more often. Sensitivity around the oxygen carrier price and the number of inventory replacement per year is done in section 4.5.3.2 .
- In units handling solids, one of the main OPEX item is the ashes/dust disposal cost. The main OPEX delta between CFB with carbon capture and CLC comes from the higher amount of solid handling in the CFB with carbon capture case compared to CLC. This difference is mainly the consequence of limestone injection directly in the CFB furnace for DeSOx purpose which generates a high amount of dust. For the CLC case, the gypsum from the DeSOx unit is produced downstream of the ESP and will be less affected by feed contaminants. It is then considered as sellable with just a very low price for transport cost. This solution is reducing the solid waste production of the CLC. Contrary to CLC, the limestone is injected in the CFB reactor upstream the solvent amine unit and the ratio $CaCO_3$/S (S is the sulphur content in the feed) must be high enough to have a low level of Sox at amine section inlet. The gypsum here with feed contaminant is considered as a waste.

4.4.2 Refinery case

Table 4-9: OPEX (M€) for the refinery cases

OPEX	Unit	Ref case CFB	Case C1 CFB + carbon capture	Case A1 CLC
Fixed OPEX (4% TPC)	M€/year	**8,8**	**15,0**	**13,8**
Fuel cost - Petcoke	M€/year	**21,8**	**29,6**	**25,1**
Total Varialble OPEX	M€/year	**14,2**	**24,7**	**13,7**
Capture Solvent make-up	M€/year	-	3,9	-
Oxygen carrier	M€/year	-	-	2,8
FR ESP & AR ESP Dust disposal	M€/year	10,0	13,8	3,5
Other variable OPEX	M€/year	4,2	7,0	7,4
Total	**M€/year**	**44,7**	**69,3**	**52,5**

4.5 Cost summary and economic indicators

4.5.1 Power cases

The calculated performances and economic indicators of the CLC cases are presented for the refinery and power cases in respectively Table 4-10 and Table 4-11.

Table 4-10: Cost summary and economic indicators for the power cases (without transport and storage costs)

POWER CASES : 200 MWe	UNIT	Ref case CFB	Case C2 CFB + MEA	Case A2 CLC
Case data				
Feed Thermal Energy	MW_{th}	480	659	532
Net electrical production	MW_e	200	200	200
HP Steam production	t/h	0	0	0
Net electric efficiency	%	41,7	30,4	37,6
CO2 capture ratio	%	0	90,0	97,5
Residual Emitted CO2	t/h	163,6	22,5	4,5
Captured CO2	t/h	-	202,2	176,5
Captured CO2	Mt/y	-	1,68	1,46
Total Plant Cost	M€	446	705	599
CAPEX - TCR	M€	536	847	720
Fixed OPEX	M€/y	17,8	28,2	24,0
Fuel cost	M€/y	43,5	59,7	48,2
Other variable OPEX	M€/y	29,4	49,0	25,9
Capture solvent/sorbent make-up*	M€/y	-	7,8	-
Oxygen Carrier*	M€/y	-	-	5,3
KPI				
Levelized Cost Of Electricity	€/Mweh	**85,0**	**130,5**	**99,8**
CO2 emission	kg CO2/MW_eh	817,9	112,3	22,6
CO2 captured	kg CO2/MW_eh	-	1011,1	882,2
CO2 avoided cost vs CFB wo CC	€/ton CO2 avoided	-	**64,5**	**18,6**
CO2 avoided cost vs NGCC wo CC	€/ton CO2 avoided	-	**250,5**	**97,4**
Cost SPECCA	€/t CO2	-	13,9	3,6
* Capture Solvent and Oxygen Carrier cost included in Other variable OPEX cost				

The LCOE of CFB with carbon capture unit is higher than the LCOE of CFB Ref case without capture because of the CAPEX needed for the amine unit capture and the higher energy demand for steam generation and capture solvent amine regeneration.

Due to its inherent carbon capture, the LCOE of the CLC case A2 slightly increases versus the LCOE of CFB without carbon capture but stays far below the LCOE of the CFB with carbon capture. For solid feedstock like petcoke, the CLC is clearly competitive versus CFB+Amine for the 200 MWe power case.

In this table, the CO_2 avoided cost for the CLC A2 case is quite low at 18.6 €/tCO_2 as it is compared with a CFB without capture unit, which emits a high amount of CO_2 to the atmosphere.

The CO_2 capture ratio is on the high side for the CLC unit. This ratio is reflecting the carbon stripper efficiency on the upper part of the fuel reactor. The higher the figure, the less unburned petcoke is sent to the air reactor and finally to the atmosphere as CO_2. A sensitivity study on this ratio is done in section 4.5.3.1 .

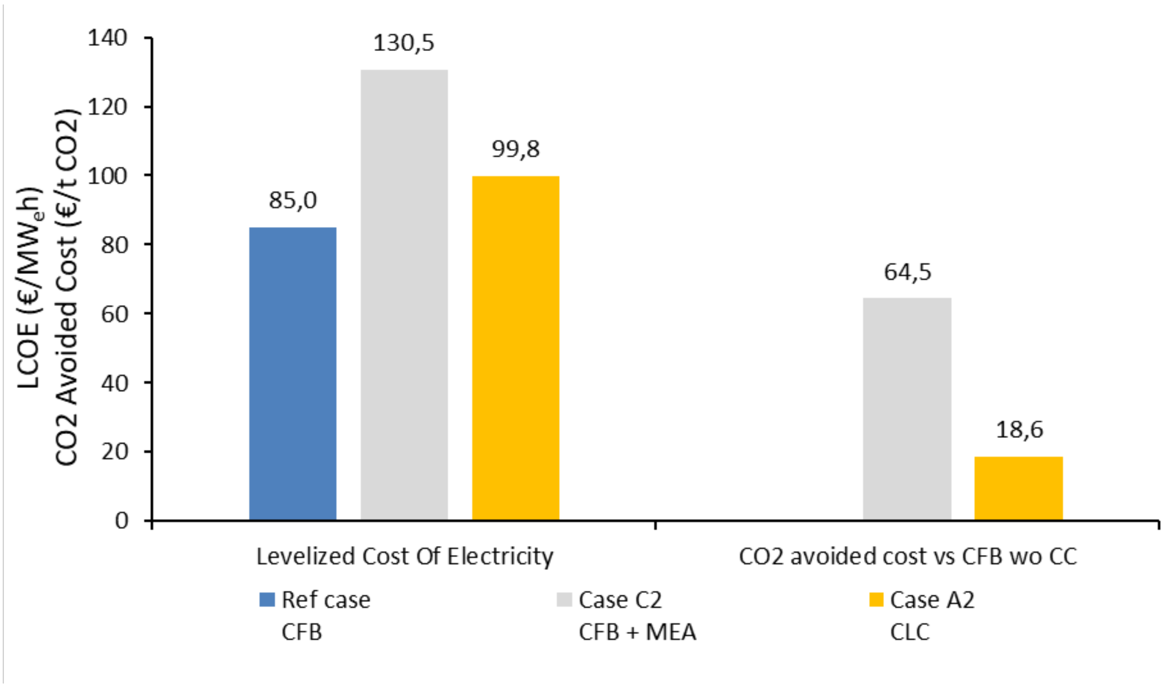

Figure 4-3: LCOE and CO_2 avoided cost for Power cases

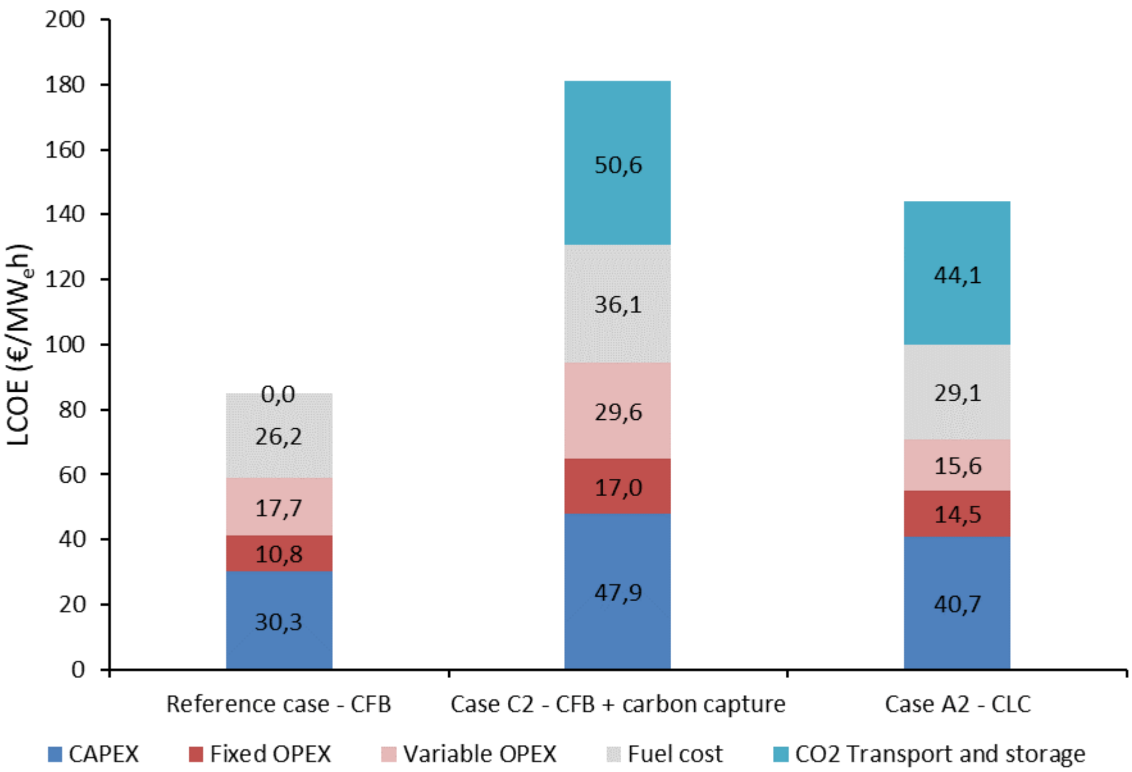

Figure 4-4: LCOE cost split for Power cases with 50 €/t transport and storage cost

Assuming a cost of 50 €/t for CO_2 transport and storage, the LCOE goes from 99.8 €/MW_eh to 144 €/MW_eh for the CLC case A2. The transport and storage cost has a similar impact on the two cases despite the better thermal efficiency of the CLC technology because the carbon capture ratio is respectively 90% for the CFB with carbon capture case and 97.5% for the CLC case.

A transport and storage cost sensitivity has been done for the power case in 4.5.3.4 section.

4.5.2 Refinery cases

Table 4-11: Cost summary and economic indicators for the refinery cases (without transport and storage costs)

REFINERY CASES : 50 MWe + 100 t/h Steam		**Refe case CFB**	**Case C1 CFB + MEA**	**Case A1 CLC**
Case data				
Feed Thermal Energy	MW_{th}	240	327	277
Net electrical production	MW_e	50	49,5	50
HP Steam production	t/h	100	100	100
CO2 capture ratio	%	0,0	90,0	97,5
Residual Emitted CO2	t/h	82,0	11,2	2,4
Captured CO2	t/h	-	100,5	91,8
Captured CO2	Mt/y	-	0,83	0,76
Total Plant Cost	M€	219	374	345
CAPEX - TCR	M€	264	449	415
Fixed OPEX	M€/y	8,8	15,0	13,8
Fuel cost	M€/y	21,8	29,6	25,1
Other variable OPEX	M€/y	14,2	24,7	13,7
Capture solvent/sorbent make-up*	M€/y	-	3,9	-
Oxygen Carrier*	M€/y	-	-	2,8
KPI				
NPV	M€	**741**	**1189**	**976**
CO2 Avoided Cost vs CFB wo CC **	€/ton CO2 avoided	-	71,5	33,3
CO2 emission	kg $CO2/MW_{th}h$	341,5	34,1	8,5
CO2 captured	kg $CO2/MW_{th}h$	-	307,3	331,8

* Capture Solvent, purchase/sale Electricity and Oxygen Carrier cost included in Other variable OPEX cost

** KPI calculated on NPV

In the refinery cases, the lower scaling effect and lower CAPEX is flattening the benefit of the CLC vs. CFB with capture. Consequently, the CLC CAC for the refinery case is nearly doubled the one for the power cases.

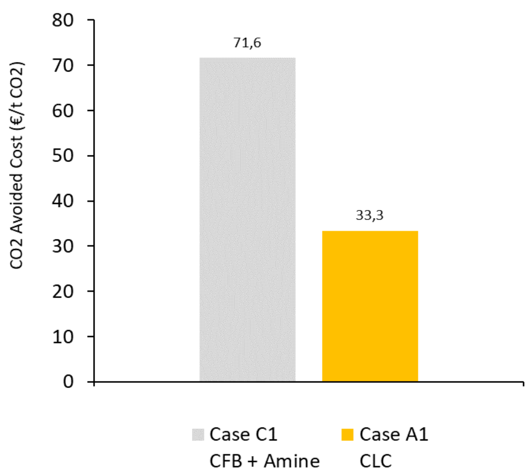

Figure 4-5: CO_2 avoided cost for Refinery cases

4.5.3 Sensitivity on case – Power cases 200 MWe

4.5.3.1 Petcoke price sensitivity

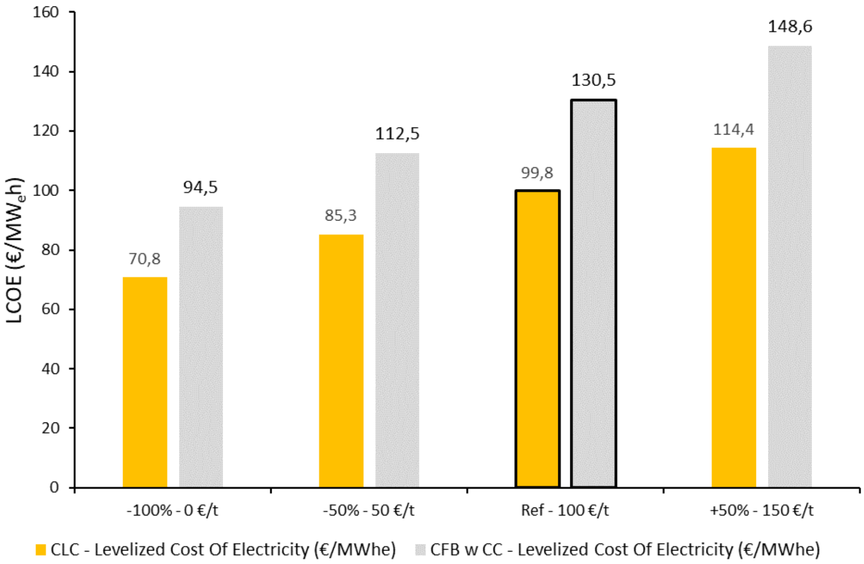

Figure 4-6: CLC Petcoke price LCOE sensitivity for Power cases

4.5.3.2 OC price / Lifetime sensitivity

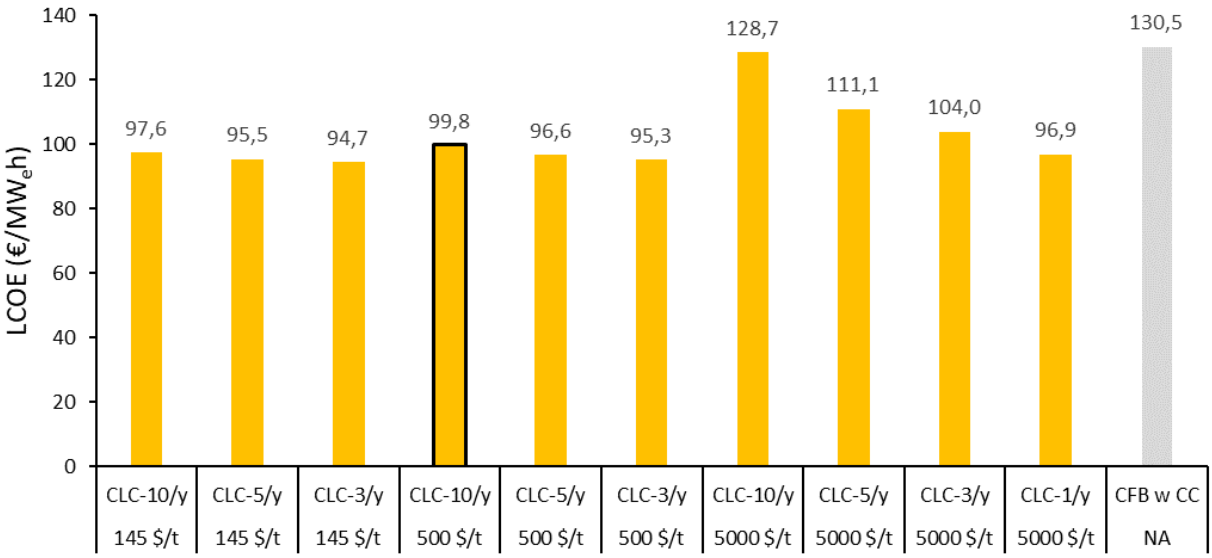

Figure 4-7: OC Price/Lifetime LCOE sensitivity for Power cases

The LCOE for the high price synthetic oxygen carrier is comparable to the lower price mineral oxygen carrier as soon as this synthetic oxygen carrier has a very good lifetime which requires to replace the inventory only once a year. It has to be noticed that the costs for cases with high inventory replacement (i.e. low life time) should be further assessed considering the environmental impact.

4.5.3.3 Solid waste disposal cost sensitivity

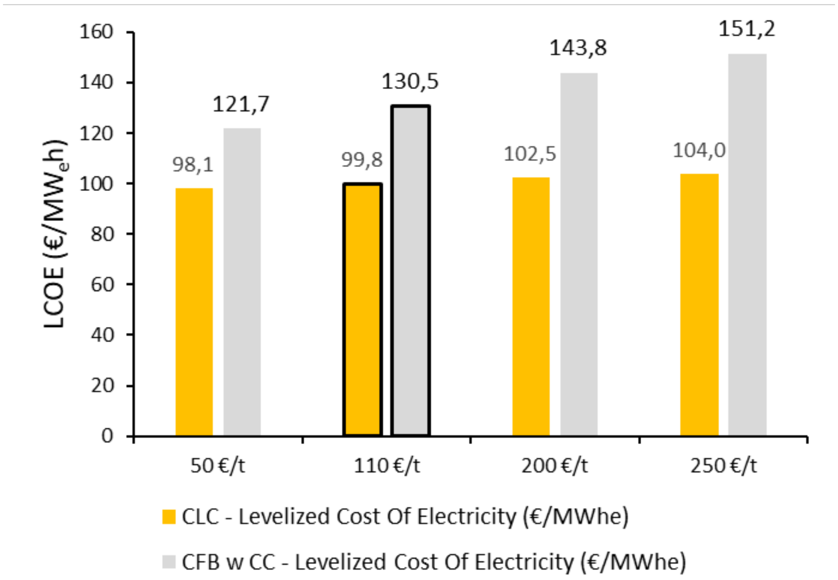

Figure 4-8: Solid waste disposal price LCOE sensitivity for Power cases

As already said in the OPEX section, the solid handling has a significant impact on the LCOE. Looking for recycling or a second life of this disposals must be looked at straight at the beginning of any CLC study.

For the CLC case, the gypsum from the DeSOx unit is produced downstream of the ESP and will be less affected by feed contaminants. It is then considered as sellable with just a very low price for transport cost. This solution is reducing the solid waste production of the CLC.

Contrary to CLC, the limestone is injected in the CFB reactor upstream the solvent amine unit and the ratio $CaCO_3/S$ (S is the sulphur content in the feed) must be high enough to have a low level of SOx at amine section inlet. The gypsum here with feed contaminant is considered as a waste.

This can explain the CLC / CFB with carbon capture differences for solid waste disposal sensitivity.

4.5.3.4 Transport and storage sensitivity

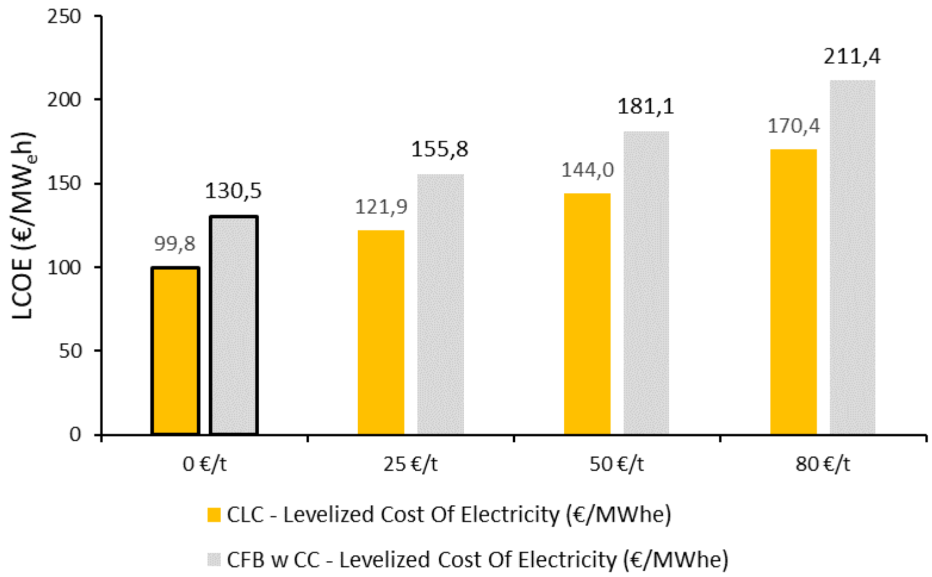

Figure 4-9: Transport and storage price LCOE sensitivity for Power cases

CFB with carbon capture and CLC case are handling about the same amount of CO_2, and transport and storage costs are affecting both cases significantly. This is pushing to build a CLC near a CO_2 network or near a potential storage place. This parameter will have lower impact on NGCC case as the amount of CO_2 produced is nearly half.

4.5.3.1 Carbon stripper efficiency in the Fuel Reactor

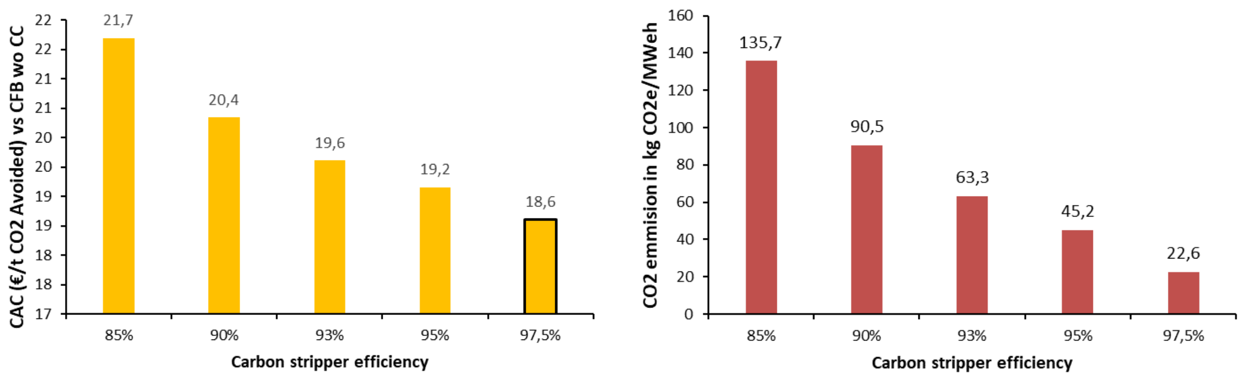

Figure 4-10: Carbon stripper efficiency CAC and CO2 emissions sensitivity for CLC Power cases

The CO_2 capture ratio is on the high side for the CLC unit. This ratio is reflecting the carbon stripper efficiency on the upper part of the fuel reactor. The higher the figure, the less unburned petcoke is sent to the air reactor and finally to atmosphere. In case of a poor carbon stripper efficiency of 90%, the CO_2 avoided cost could increase by 1.8 €/ tCO_2 avoided and the CO2 emission multiplied by a factor of about 4. The CAC at low carbon stripper efficiency could be furthermore increased if the flue gas treatment on the air reactor side must be improved (e.g. DeSOx unit).

5 NGCC WITH SOLVENT-BASED CAPTURE COMPARED TO NGCC REFERENCE

5.1 NGCC-CCS plant overall performance

The overall process performance indicators for the NGCC reference case with CO_2 capture is given below in Table 5-1. The cases included is the NGCC cases with MEA and PZ/AMP solvent-based CO_2 capture for the refinery and power cases. The refinery cases B1a and B1b, as well as the power case B2, are evaluated both with and without capture, to have a reference. The gas turbine exhaust in refinery cases B1a is not able to produce enough steam in the HRSG to cover both the refinery needs and the solvent regeneration in the capture plant. A separate gas boiler without CO_2 capture is therefore used to produce the steam for solvent regeneration in cases B1a. For further information on the differences between refinery case B1a and B1b, as well as details about case B2, please refer to Deliverable D5.2 CLC-CCS plant modelling.

Table 5-1: Overall process performance indicators for the NGCC plant with CO_2 capture

		NGCC with MEA CO_2 capture			NGCC with PZ/AMP CO_2 capture		
Results	**Unit**	**Refinery (B1a)**	**Refinery (B1b)**	**Power B2**	**Refinery (B1a)**	**Refinery (B1b)**	**Power B2**
Thermal power	MWth	195.4	347	454.2	190.0	347	454.2
Exported steam	MWth	92	92	0	92	92	0
Thermal power for CO_2 regeneration	MWth	30.7	70.2	91.0	27.1	64.1	82.6
GT power	MWe	50	119.4	163.9	50	119.4	163.9
ST power	MWe		13.4	66.6		14.9	69.4
Auxiliaries consumption:	MWe	4.4	11.2	16.8	5.0	12.7	15.9
SC pump consumption	MWe	0.5	0.7	1.2	0.5	0.8	1.3
CO_2 capture section	MWe	3.9	10.5	15.6	4.5	11.9	14.6
Net power	MWe	45.6	121.6	213.7	45.0	121.6	217.4
Gross electric efficiency	-	25.6%	38.3%	50.8%	26.3%	38.7%	51.4%
Net electric efficiency	-	23.3%	35.0%	47.0%	23.7%	35.0%	47.9%
First-law efficiency	-	70.4%	61.6%	46.0%	72.1%	61.6%	47.9%

5.2 NGCC-CCS plant : equipment/units and sections

The detailed cost of each equipment will not be given in this report. However, the cost of the main sub-systems constituting the NGCC and the NGCC-CCS plant will be given for benchmark purpose.

- NGCC plant: Gas Turbine, Generator and auxiliaries + HRSG, ducting and stack + Steam turbine generator and auxiliaries + Feed water and miscellaneous, BOP systems
- Solvent-based CO_2 capture section (for NGCC-CCS plant)
- CO_2 compression section (for NGCC-CCS plant)

5.3 NGCC plant CAPEX

The CAPEX calculation details for the different NGCC cases are summarised in Table 5-2 to Table 5-10.

Table 5-2: CAPEX (M€) of the B1a case without capture

M€ By Section	TEC (1)	IC (2)	Process Allowance (3)	TDC (4)= ((1)+(2))*(1+(3))	TPC (5)= ((4)+ind Cost + Pj Ctgy)	TCR
NGCC	41	28	5 %	72	118	140
Total	**41**	**28**		**72**	**118**	**140**

Table 5-3: CAPEX (M€) of the B1a case with MEA-based capture

M€ By Section	TEC (1)	IC (2)	Process Allowance (3)	TDC (4)= ((1)+(2))*(1+(3))	TPC (5)= ((4)+ind Cost + Pj Ctgy)	TCR
NGCC	41	28	5 %	72	118	208
CO2 capture	12	12	5 %	25	41	
CO2 conditioning	5	4	5 %	9	15	
Total	**59**	**43**		**107**	**174**	**208**

Table 5-4: CAPEX (M€) of the B1a case with AMP/PZ-based capture

M€ By Section	TEC (1)	IC (2)	Process Allowance (3)	TDC (4)= ((1)+(2))*(1+(3))	TPC (5)= ((4)+ind Cost + Pj Ctgy)	TCR
NGCC	42	29	5 %	74	120	208
CO2 capture	11	10	10 %	22	37	
CO2 conditioning	6	4	5 %	10	17	
Total	**58**	**43**		**107**	**174**	**208**

Table 5-5: CAPEX (M€) of the B1b case without capture

M€ By Section	TEC (1)	IC (2)	Process Allowance (3)	TDC (4)= ((1)+(2))*(1+(3))	TPC (5)= ((4)+ind Cost + Pj Ctgy)	TCR
NGCC	91	62	5 %	161	261	309
Total	**91**	**62**		**161**	**261**	**309**

Table 5-6: CAPEX (M€) of the B1b case with MEA-based capture

M€ By Section	TEC (1)	IC (2)	Process Allowance (3)	TDC (4)= ((1)+(2))*(1+(3))	TPC (5)= ((4)+ind Cost + Pj Ctgy)	TCR
NGCC	84	57	5 %	148	241	439
CO2 capture	33	30	5 %	66	107	
CO2 conditioning	8	5	5 %	14	22	
Total	**125**	**92**		**228**	**370**	**439**

Table 5-7: CAPEX (M€) of the B1b case with AMP/PZ-based capture

M€ By Section	TEC (1)	IC (2)	Process Allowance (3)	TDC (4)= ((1)+(2))*(1+(3))	TPC (5)= ((4)+ind Cost + Pj Ctgy)	TCR
NGCC	86	58	5 %	152	247	473
CO2 capture	38	34	10 %	79	129	
CO2 conditioning	8	5	5 %	14	22	
Total	**132**	**98**		**245**	**398**	**473**

Table 5-8: CAPEX (M€) of the B2 case without capture

M€ By Section	TEC (1)	IC (2)	Process Allowance (3)	TDC (4)= ((1)+(2))*(1+(3))	TPC (5)= ((4)+ind Cost + Pj Ctgy)	TCR
NGCC	127	86	5 %	224	364	432
Total	**127**	**86**		**224**	**364**	**432**

Table 5-9: CAPEX (M€) of the B2 case with MEA-based capture

M€ By Section	TEC (1)	IC (2)	Process Allowance (3)	TDC (4)= ((1)+(2))*(1+(3))	TPC (5)= ((4)+ind Cost + Pj Ctgy)	TCR
NGCC	119	81	5 %	210	341	
CO2 capture	40	36	5 %	80	129	589
CO2 conditioning	9	6	5 %	16	26	
Total	**168**	**123**		**305**	**496**	**589**

Table 5-10: CAPEX (M€) of the B2 case with AMP/PZ-based capture

M€ By Section	TEC (1)	IC (2)	Process Allowance (3)	TDC (4)= ((1)+(2))*(1+(3))	TPC (5)= ((4)+ind Cost + Pj Ctgy)	TCR
NGCC	122	83	5 %	215	350	
CO2 capture	41	37	10 %	85	138	611
CO2 conditioning	9	6	5 %	16	26	
Total	**171**	**126**		**316**	**513**	**611**

5.4 Operating cost

The OPEX calculation details for the different NGCC cases are summarised in Table 5-11 to Table 5-13.

Table 5-11: OPEX (M€/y) of the B1a case with and without capture

M€/y	No capture	MEA	AMP/PZ
Fixed OPEX	**3,62**	**5,35**	**5,37**
Fuel cost	**28,66**	**36,20**	**35,16**
Solvent make-up	**0,0**	**1,4**	**2,0**
Other variable OPEX	**0,48**	**0,72**	**0,63**
Cost from electricity purchase	**0,23**	**0,23**	**0,23**

Table 5-12: OPEX (M€/y) of the B1b case with and without capture

M€/y	No capture	MEA	AMP/PZ
Fixed OPEX	**8,03**	**11,39**	**12,27**
Fuel cost	**64,28**	**64,28**	**64,28**
Solvent make-up	**0,00**	**2,45**	**3,60**
Other variable OPEX	**1,07**	**1,32**	**1,15**
Revenues from electricity sale	**-51,55**	**-37,02**	**-37,80**

Table 5-13: OPEX (M€/y) of the B2 case with and without capture

M€/y	No capture	MEA	AMP/PZ
Fixed OPEX	**14,56**	**19,85**	**20,59**
Fuel cost	**84,11**	**84,11**	**84,11**
Solvent make-up	**0,0**	**1,0**	**2,0**
Other variable OPEX	**1,40**	**1,69**	**1,49**

5.5 Cost summary and economic indicators

The calculated performances and economic indicators of the NGCC cases are presented for the refinery and power cases in respectively Table 5-154 and Table 5-15.

While these numbers are mainly important as reference to understand the potential of CLC to reduce cost and emissions of low carbon heat and power production for the power and refinery cases, the following observations can be made:

- In the refinery cases, two levels of power production were considered: around 50MW (B1a case) and in the range of 150MW (B1b case). While the B1a case is set to satisfy the power requirement of the refinery, the B1b case result in a significant level of extra low-carbon power (beyond the 50MW required by the refinery) that could be sold on the power market. However, the current electricity prices do not allow to cover the production cost of this additional power. The B1b strategy thus does not appear to be preferable unless electricity prices become significantly higher.
- The new solvent (AMP/PZ) does not necessary lead to lower cost than MEA. In the B1a case, it is slightly better than MEA, while in the B1b and B2 cases it is slightly worse than MEA. Indeed, while this new solvent is slightly more energy efficient, it leads to higher investment cost than MEA due to the slower kinetics.

For comparison with CLC, the best solvent will be selected for each case.

Table 5-14: Techno-economic indicators of the NGCC with and without capture for the refinery cases (B1a and B1b) (without transport and storage costs)

REFINERY CASES		Ref Case - NGCC wo	Case B1a - NGCC+ MEA	Case B1a - NGCC+ AMP/PZ	Ref Case - NGCC wo	Case B1b - NGCC+ MEA	Case B1b - NGCC+ AMP/PZ
Case data							
Feed Thermal Energy	MWth	154,7	195,4	189,8	347,0	347,0	347,0
HP Steam production	t/h	100	100	100	100	100	100
CO2 capture ratio	%		71 %	73 %		90 %	90 %
Emitted CO2	t/h	32,0	11,7	10,6	71,8	7,2	7,2
CO2 captured	t/h	-	28,7	28,7	-	64,6	64,6
CO2 captured	Mt/y	-	0,301	0,293	-	0,536	0,536
Total Plant Cost	M€	118	174	174	261	370	399
CAPEX	M€	140	208	208	309	439	473
Fixed OPEX	M€/y	4	5	5	8	11	12
Fuel cost	M€/y	29	36	35	64	64	64
Other variable OPEX	M€/y	0,48	0,72	0,63	1,07	1,32	1,15
Capture solvent/sorbent make-up	M€/y	0	1,4	2	0	2	4
Oxygen Carrier	M€/y	-	-	-	-	-	-
Revenues/Cost from electricity sale/purchase	M€/y	0,2	2,3	2,4	-51,6	-37,0	-37,8
KPI							
NPV of costs	M€	492	698	694	542	892	937
CO2 avoided cost	€/ton CO2e avoided	-	114,6	106,6	-	49,4	55,7
Indicative Levelized Cost Of Thermal Output	$€/MW_{th}h$	36,1	51,2	50,9	44,4	59,8	61,9
CO2 avoided cost vs CFB wo CC	€/ton CO2e avoided	NA	45,9	44,0	NA	62,4	68,0
Cost SPECCA	€/tCO2	NA	63,4	57,3	NA	27,6	27,6

Table 5-15: Techno-economic indicators of the NGCC with and without capture for the power case (B2) (without transport and storage costs)

POWER CASES	UNIT	Ref Case - NGCC wo	Case B2 - NGCC+ MEA	Case B2 - NGCC+ AMP/PZ
Case data				
Feed Thermal Energy	MWth	454	454	454
Net electrical production	MWe	256	213,7	216
HP Steam production	t/h	0	0	0
Net electric efficiency	%	56,5 %	47,0 %	47,6 %
CO2 capture ratio	%	0	90 %	90 %
Emitted CO2	t/h	93,8	9,3	9,3
CO2 captured	t/h	-	84,5	84,5
CO2 captured	Mt/y	-	0,701	0,701
Total Plant Cost	M€	364	496	515
CAPEX	M€	432	589	611
Fixed OPEX	M€/y	15	20	21
Fuel cost	M€/y	84	84	84
Oxygen Carrier	M€/y			
Revenues/Cost from electricity sale/purchase	M€/y			
KPI				
Levelized Cost Of Electricity	€/MWeh	66,0	92,5	93,6
CO2 captured (kg CO2e/MW_eh)	kg CO2e/MWeh	NA	360	360
CO2 avoided cost vs CFB wo CC	€/ton CO2e avoided	NA	15,3	16,7
CO2 avoided cost vs NGCC wo CC	€/ton CO2e avoided	NA	80,3	83,8
Cost SPECCA	€/tCO2	NA	24,0	21,3

5.6 Sensitivity analyses

5.6.1 Natural gas price

As expected, the price of natural gas has a significant impact on the costs of the NGCC with solvent-based capture. While its impact on the CO_2 avoidance cost is less important than on the LCOE, this highlights the importance of the natural gas price for the comparison with the CLC process.

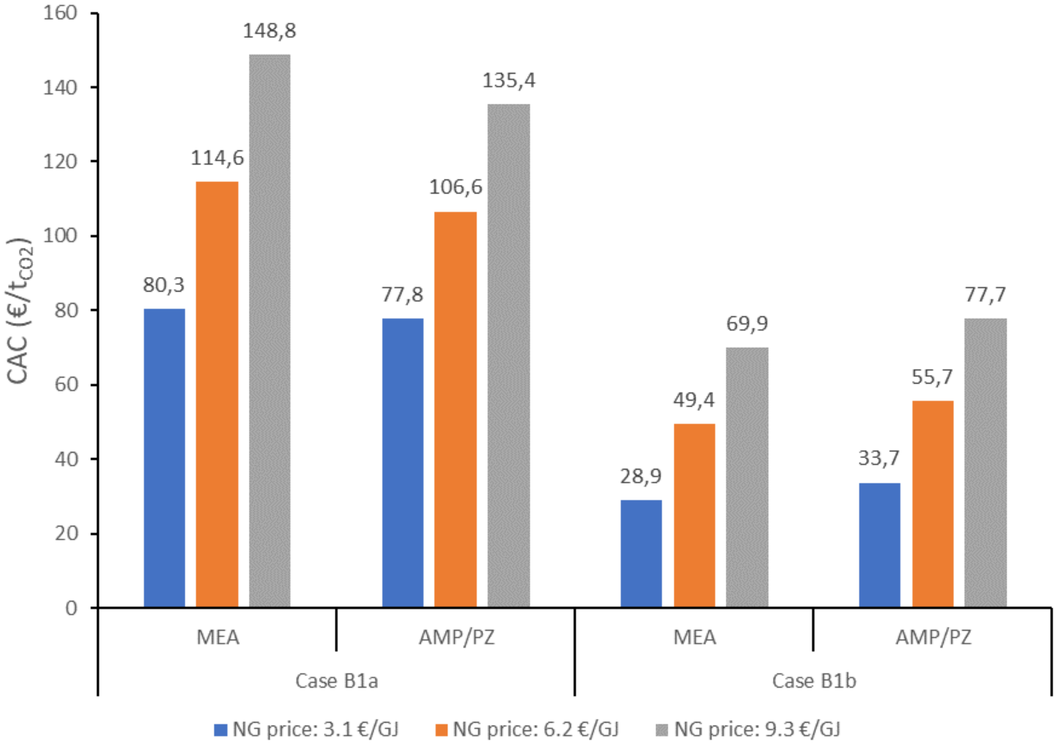

Figure 5-1: Impact of natural gas price on CO_2 avoided costs of the NGCC with MEA and AMP/PZ-based CO_2 capture in the B1a and B1b case vs NGCC wo CC.

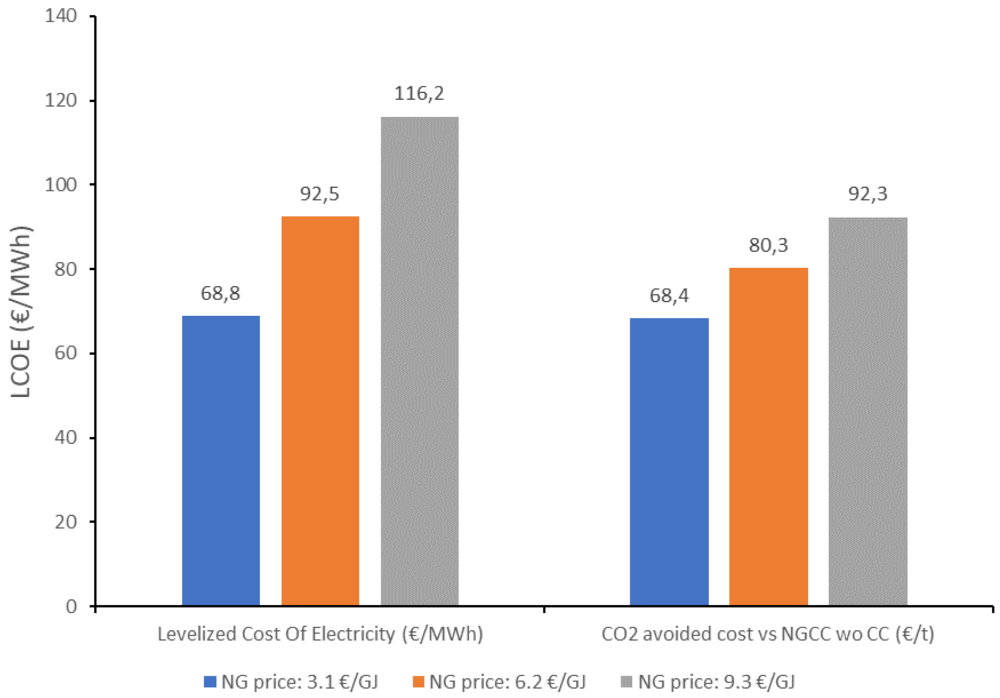

Figure 5-2: Impact of natural gas price on LCOE, and CO_2 avoided costs of the NGCC with MEA-based CO_2 capture in the B2 case

5.6.2 Transport and storage cost

As for the CLC, the levelized cost of electricity and CO_2 avoidance costs of the NGCC with solvent-based capture is significantly impacted by the cost of CO_2 transport and storage. However, as the amount of CO_2 captured per unit of power is around half of the one of CLC, the impact of CO2 transport and storage cost on the LCOE is less important than in the CLC case.

In any case, limiting the cost of transport and storage, by for example build a CLC near a CO_2 network or near a potential storage site, would be beneficial for comparison to the NGCC with CCS.

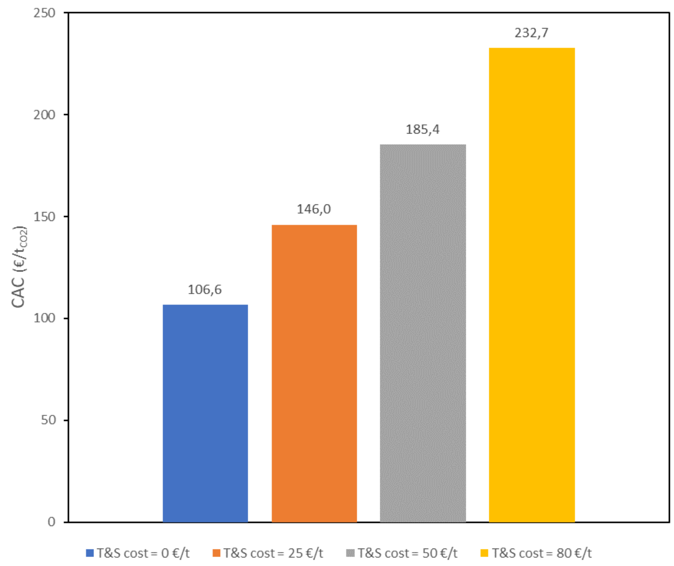

Figure 5-3: Impact of CO_2 transport and storage cost on CO_2 avoided costs of the NGCC with AMP/PZ-based CO_2 capture in the B1a case vs NGCC wo CC.

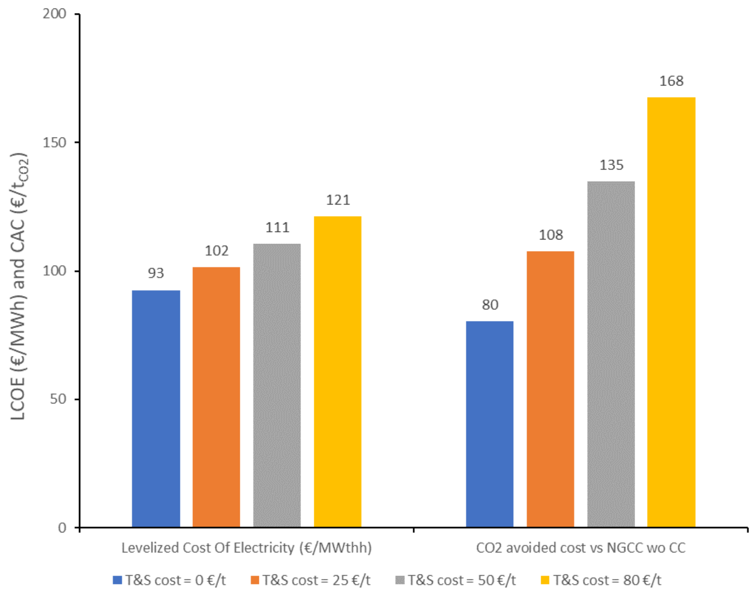

Figure 5-4: Impact of CO_2 transport and storage cost on LCOE, and CO_2 avoided costs of the NGCC with MEA-based CO_2 capture in the B2 case

6 CLC COMPARED TO NGCC WITH SOLVENT-BASED CAPTURE

6.1 Power cases

6.1.1 Power case comparison table

Comparing the technologies considered, CLC with the NGCC with solvent-based capture, is challenging as they do not consider the same fuels nor result in the same emissions level. However, the following effects can be observed:

- As shown in Table 6-1, low-carbon power production based on CLC result in a slightly higher LCOE than a NGCC with MEA-based capture (99.8 vs 92.5 €/MWh), however the CLC results in lower specific emissions (22.6 vs 40 kg_{CO2}/MWh)
- Compared to the unabated power production method using the same fuel (CFB), CLC does not result in a strong increase in LCOE (99.8 vs 85) thus resulting in a low CO_2 avoidance cost (18.6 €/t_{CO2}). However, the power production from a CFB is an expensive means of producing power compared to, for example, an NGCC (85 vs 66 €/MWh). Thus, when compared to a NGCC, CLC result in a quite higher CO2 avoidance cost than when compared to a CFB (97.3 vs 18.6 €/tCO_2).
- Similarly compared to CFB, a NGCC with MEA-based capture result in low increase in LCOE (92.5 vs 85 €/MWh) thus resulting in a low CO2 avoidance cost (9.7 €/t_{CO2}). However, for a NGCC with MEA-capture compared to a NGCC without capture, the LCOE increase is more important (92.5 vs 66 €/MWh) thus resulting in a CO_2 avoidance cost of 80 €/t_{CO2}.
- As the two low-carbon power production pathways (CLC and NGCC with MEA-based capture) do not consider the same type of fuel, the petcoke and natural gas prices can be expected to have a significant impact on performance and the comparison of these options. A sensitivity on the natural gas and petcoke price is provided in section 6.1.3. The above tables on techno-economic indicators does not take any transport and storage cost for the CO_2. Adding a transport and storage cost for the CO_2 will certainly push the balance toward the NGCC with capture case, as this case produces only half the CO_2 of the CLC amount. (See section 7.4).

Table 6-1: Cost summary and economic indicators for the power cases

POWER CASES : 200 MWe	UNIT	Ref case CFB	Case C2 CFB + MEA	Case A2 CLC	Ref Case NGCC	Case B2 - NGCC+ MEA
Case data						
Feed Thermal Energy	MW_{th}	480	659	532	454	454
Net electrical production	MW_e	200	200	200	256	214
HP Steam production	t/h	0	0	0	0	0
Net electric efficiency	%	41,7	30,4	37,6	56,5	47,0
CO2 capture ratio	%	0	90,0	97,5		90,0
Residual Emitted CO2	t/h	163,6	22,5	4,5	93,8	9,3
Captured CO2	t/h	-	202,2	176,5	-	84,5
Captured CO2	Mt/y	-	1,68	1,46	-	0,70
Total Plant Cost	M€	446	705	599	364	496
CAPEX - TCR	M€	536	847	720	432	589
Fixed OPEX	M€/y	17,8	28,2	24,0	15	20
Fuel cost	M€/y	43,5	59,7	48,2	84	84
Other variable OPEX	M€/y	29,4	49,0	25,9	1,4	5,0
Capture solvent/sorbent make-up*	M€/y	-	7,8	-	-	3,3
Oxygen Carrier*	M€/y	-	-	5,3	-	-
KPI						
Levelized Cost Of Electricity	€/Mweh	**85,0**	**130,5**	**99,8**	**66,0**	**92,5**
CO2 emission	kg CO_2/MW_eh	817,9	112,3	22,6	366,4	43,5
CO2 captured	kg CO_2/MW_eh	-	1011,1	882,2	-	394,9
CO2 avoided cost vs CFB wo CC	€/ton CO2 avoided	-	**64,5**	**18,6**	-	**9,6**
CO2 avoided cost vs NGCC wo CC	€/ton CO2 avoided	-	**254,0**	**98,5**	-	**82,1**
Cost SPECCA	€/t CO2	-	13,9	3,6	-	24

* Capture Solvent and Oxygen Carrier cost included in Other variable OPEX cost

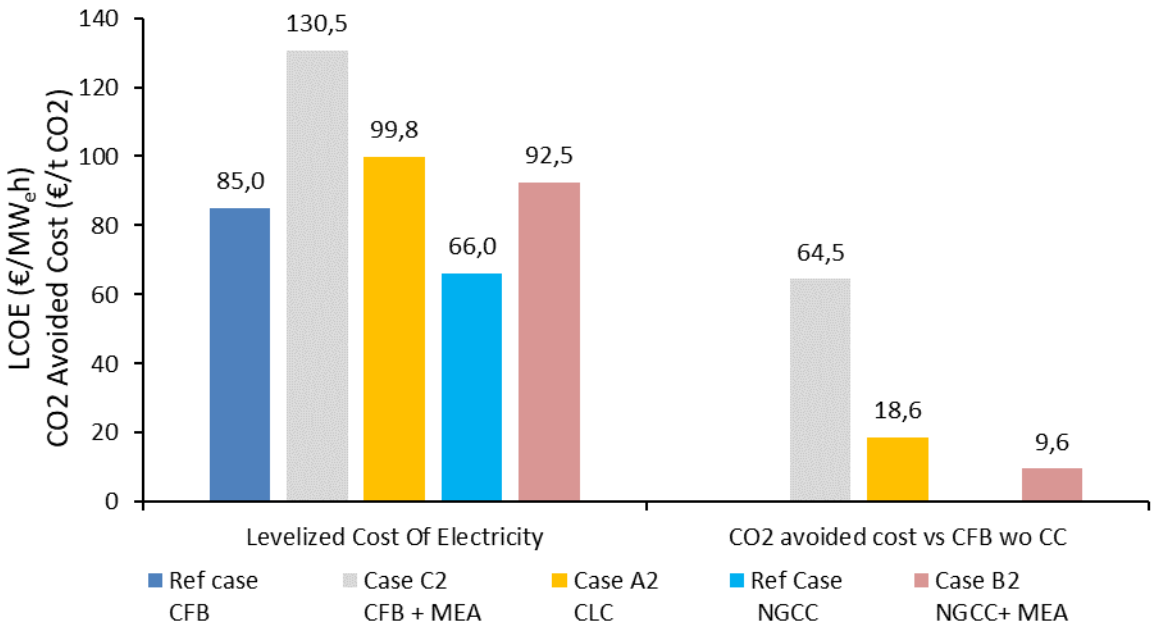

Figure 6-1: All cases LCOE and CO2 avoided cost for Power cases

6.1.2 CO_2 taxes price sensitivity on power cases LCOE

As the CLC and the NGCC with MEA-based capture does not result in the same levels of specific CO_2 emissions, considering a CO_2 tax is required to provide the most meaningfull technology comparison. The impact of such a tax on the LCOE of these two power production pathway is presented in Figure 6-2 considering also different fuel prices scenarios.

It can be observed from this figure that the slopes for CLC are less steep than the one of the NGCC with carbon capture. Indeed, the CLC unit is emitting less residual CO_2 than the NGCC unit with capture and is thus less sensitive to CO_2 taxes price.

It can also be observed that with CO_2 tax levels than can be expected in the near future (below 200 €/t), the NGCC with CO_2 capture is expected to be a cheaper option than CLC unless if gas prices are higher than the value assumed in the reference case, and/or petcoke price is decreased.

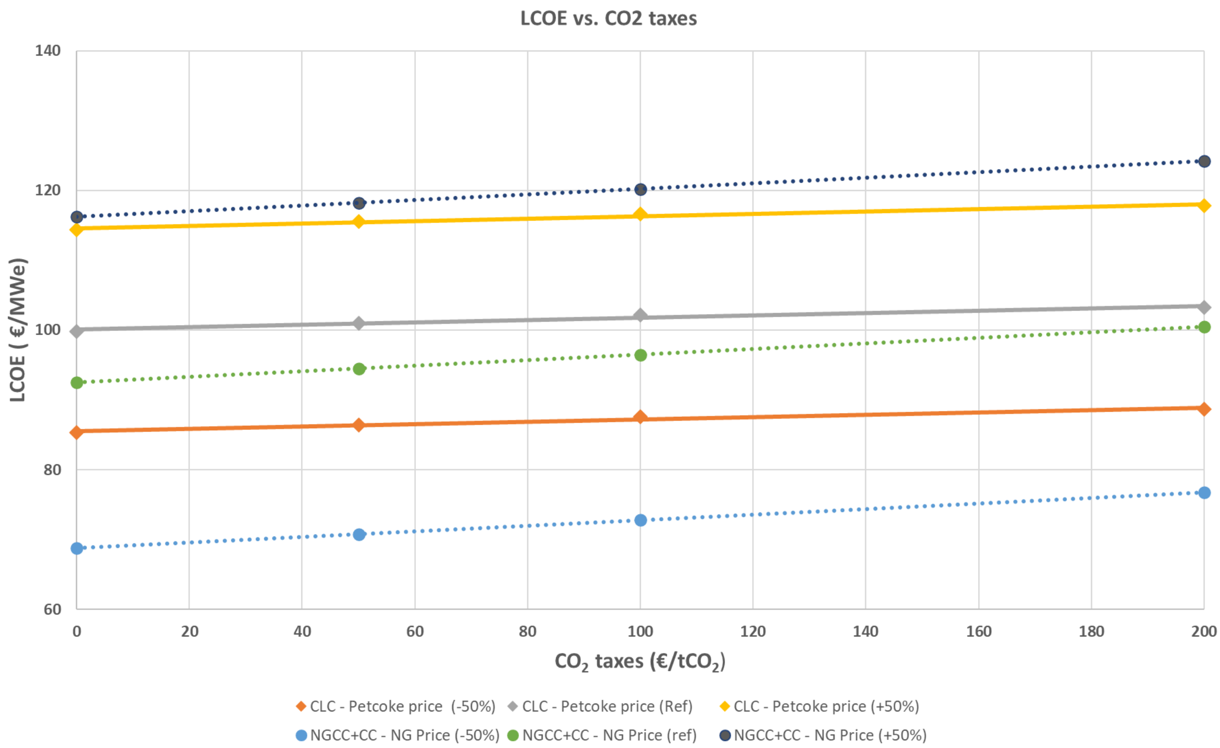

Figure 6-2: CO_2 taxes sensitivity on LCOE for Power cases at 0€/t Transport and storage cost

6.1.3 Feedstock price sensitivity for power cases

As can be seen above, fuel prices are critical for the comparison of CLC and NGCC with capture. It is important to better understand the impact of these on the comparison and when each technology can be considered cost competitive. In order to provide this understanding, we calculate the CO_2 switching price [9] that leads to an identical LCOE (including emissions cost) for the two options. The CO_2 switching price can be calculated as follow.

$$CO_2\ switching\ price\left[\frac{€}{t}\right] = \frac{LCOE\ CLC - LCOE\ NGCC\ with\ CC\ \ [€/MWh]}{Emmission\ CLC - Emmision\ NGCC\ with\ CC\ [CO_2/MWh]}$$

Figure 6-4 present the CO_2 switching price between these two technologies for different combinations of natural gas prices (Y-axis) and petcoke prices (X-axis). The average 0% being 100 €/t for petcoke price and 6.2 €/GJ for natural gas. Figure 6-4 excludes CO_2 transport and storage costs, while a similar figure is produced in section 7.4 taking into account the complete chain to provide the complete picture. The green cells represent the cases where CLC will be more competitive than NGCC with carbon capture even without CO_2 tax. The red cells represent the cases where NGCC with carbon capture will be more competitive than CLC unless the CO_2 price reaches at least 200€/t. The orange cells represent the cases where CLC could be better than NGCC with carbon capture for CO_2 prices that can be expected in a near future (i.e., switching price interval from zero up to 200 €/t).

With the reference gas and petcoke prices (2019 reference year), CLC cannot compete with the NGCC with carbon capture pathway.

Natural gas price	-100%	-90%	-80%	-70%	-60%	-50%	-40%	-30%	-20%	-10%	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
-50%	112	279	447	614	781	948	1115	1283	1450	1617	1784	1951	2119	2286	2453	2620	2787	2955	3122	3289	3456
-45%	-24	143	310	477	645	812	979	1146	1313	1481	1648	1815	1982	2149	2317	2484	2651	2818	2985	3153	3320
-40%	-160	7	174	341	508	676	843	1010	1177	1344	1512	1679	1846	2013	2180	2348	2515	2682	2849	3016	3184
-35%	-297	-129	38	205	372	539	707	874	1041	1208	1375	1543	1710	1877	2044	2211	2379	2546	2713	2880	3047
-30%	-433	-266	-99	69	236	403	570	737	905	1072	1239	1406	1574	1741	1908	2075	2242	2410	2577	2744	2911
-25%	-569	-402	-235	-68	100	267	434	601	768	936	1103	1270	1437	1604	1772	1939	2106	2273	2440	2608	2775
-20%	-705	-538	-371	-204	-37	131	298	465	632	799	967	1134	1301	1468	1635	1803	1970	2137	2304	2471	2639
-15%	-842	-674	-507	-340	-173	-6	162	329	496	663	830	998	1165	1332	1499	1666	1834	2001	2168	2335	2502
-10%	-978	-811	-644	-476	-309	-142	25	192	360	527	694	861	1028	1196	1363	1530	1697	1864	2032	2199	2366
-5%	-1114	-947	-780	-613	-445	-278	-111	56	223	391	558	725	892	1059	1227	1394	1561	1728	1895	2063	2230
0%	-1250	-1083	-916	-749	-582	-414	-247	-80	87	254	422	589	756	923	1090	1258	1425	1592	1759	1926	2094
5%	-1387	-1220	-1052	-885	-718	-551	-384	-216	-49	118	285	452	620	787	954	1121	1289	1456	1623	1790	1957
10%	-1523	-1356	-1189	-1021	-854	-687	-520	-353	-185	-18	149	316	483	651	818	985	1152	1319	1487	1654	1821
15%	-1659	-1492	-1325	-1158	-990	-823	-656	-489	-322	-154	13	180	347	514	682	849	1016	1183	1350	1518	1685
20%	-1796	-1628	-1461	-1294	-1127	-960	-792	-625	-458	-291	-123	44	211	378	545	713	880	1047	1214	1381	1549
25%	-1932	-1765	-1597	-1430	-1263	-1096	-929	-761	-594	-427	-260	-93	75	242	409	576	743	911	1078	1245	1412
30%	-2068	-1901	-1734	-1566	-1399	-1232	-1065	-898	-730	-563	-396	-229	-62	106	273	440	607	774	942	1109	1276
35%	-2204	-2037	-1870	-1703	-1535	-1368	-1201	-1034	-867	-699	-532	-365	-198	-31	137	304	471	638	805	973	1140
40%	-2341	-2173	-2006	-1839	-1672	-1505	-1337	-1170	-1003	-836	-669	-501	-334	-167	0	167	335	502	669	836	1003
45%	-2477	-2310	-2142	-1975	-1808	-1641	-1474	-1306	-1139	-972	-805	-638	-470	-303	-136	31	198	366	533	700	867
50%	-2613	-2446	-2279	-2111	-1944	-1777	-1610	-1443	-1275	-1108	-941	-774	-607	-439	-272	-105	62	229	397	564	731

Petcoke price

Figure 6-3: CO_2 switching price (€/t) for Power cases at 0€/t transport and storage cost

Note: the range for the sensitivity analysis of the NG price is set to +- 50% based on 2019 prices, which was a reasonable range in 2019. With the current uncertainty in the NG-market, primarily due to the war in Ukraine, it is impossible to estimate what a reasonable price range for NG will be for the years to come. It is worth to mention, however, that the currently suggested maximum EU-price for NG of 180€/MWh (=50 €/GJ), corresponds to an increase of 700% compared to the 2019 average. It is clear that the average NG will not be anywhere close to this, so this is just to put things in a perspective. Therefore, and in lack of a better estimate, we will stick with the original range of +- 50%.

6.2 Refinery case

6.2.1 Refinery case comparison table

Comparing the different technologies is a bit challenging as they do not consider the same fuels nor result in the same emissions level, and that two different products (steam and electricity) are produced. However, the following effect can be observed:

- CFB (without CCS) is not a good strategy to supply heat and power to the refinery even when not considering CO_2 emissions. Indeed, the net present value of cost of the CFB without capture is nearly 50% higher than the one of an NGCC without capture. Furthermore, the CFB without capture also emit more than 2.5 times the emissions of the NGCC without capture.
- Due to the inefficiency of the CFB without CCS, all the other alternatives result in low CO_2 avoidance cost in comparison. The CLC and CFB with MEA result in CO_2 avoidance cost of 33.3 and 71.5 €/t, while the NGCC with CO_2 capture even yield a negative CO_2 avoidance cost (-7.4€/t) as it has both lower cost and lower emissions than the CFB without capture.
- When compared to the reference NGCC, i.e., the most cost and emission efficient when CCS is not considered, a similar ranking is obtained. The NGCC with CCS is the most efficient low-carbon pathway, with a CO_2 avoidance cost of 106.6 €/t. Although better than the CFB with MEA (CO_2 avoidance cost of 378 €/t), CLC results in a CO_2 avoidance cost (184.62 €/t) that is less than twice the one of the NGCC with CO_2 capture.
- Compared to the power case, CLC performs worst vs. NGCC in the refinery case due to higher difference in CAPEX. The main reason for this lowered CAPEX in NGCC refinery case is that additionnal steam for MEA reboiler is produced by a simple low cost boiler whithout CO2 capture. On the contrary, in NGCC power case, the whole steam needed for power generation and MEA reboiler is produced by the steam cycle which decreases the difference in CAPEX between CLC and NGCC
- The above results thus emphasize that CLC is not a cost-efficient option to reduce emissions in the refinery case when compared with the most relevant reference, being NGCC with capture. However, as CLC residual CO_2 emissions represent a fifth of the ones of the NGCC with capture, it is worth understanding if future CO_2 tax levels could make CLC more cost efficient than NGCC with CO_2 capture. However, calculation of the CO_2 switching price between the two pathways (190 €/t) shows that it is very unlikely to be the case in the near future as it is far above the forecasted CO_2 price for the next decade.
- This conclusion is confirmed even when considering sensitivity to natural gas and petcoke prices. Adding a transport and storage cost for the CO_2 will certainly further push the balance towards the NGCC with capture, since this case produces only about half of the CO_2 of the CLC case amount.

Table 6-2: Cost summary and economic indicators for the refinery case

REFINERY CASES : 50 MWe + 100 t/h Steam		Refe case CFB	Case C1 CFB + MEA	Case A1 CLC	Ref Case NGCC	Case B1 - NGCC+ AMP/PZ
Case data						
Feed Thermal Energy	MW_{th}	240	327	277	154,7	189,8
Net electrical production	MW_e	50	49,5	50	49,6	45,3
HP Steam production	t/h	100	100	100	100,0	100,0
CO2 capture ratio	%	0,0	90,0	97,5	0,0	73,0
Residual Emitted CO2	t/h	82,0	11,2	2,4	32,0	10,6
Captured CO2	t/h	-	100,5	91,8	-	28,7
Captured CO2	Mt/y	-	0,83	0,76	-	0,29
Total Plant Cost	M€	219	374	345	118	174
CAPEX - TCR	M€	264	449	415	140	208
Fixed OPEX	M€/y	8,8	15,0	13,8	3,6	5,4
Fuel cost	M€/y	21,8	29,6	25,1	28,7	35,2
Other variable OPEX	M€/y	14,2	24,7	13,7	0,7	5,0
Capture solvent/sorbent make-up*	M€/y	-	3,9	-	-	2,0
Revenues/Cost from electricity sale/purchase*	M€/y	-	-	-	0,2	2,4
Oxygen Carrier*	M€/y	-	-	2,8	-	-
KPI						
NPV	M€	**741**	**1189**	**976**	**492**	**694**
CO2 Avoided Cost vs CFB wo CC **	€/ton CO2 avoided	-	71,5	33,3	-	**-7,4**
CO2 Avoided Cost vs NGCC wo CC **	€/ton CO2 avoided	-	378,1	184,6	-	**106,6**
CO2 emission	kg CO2/MW_{th}h	341,5	34,1	8,5	206,9	55,8
CO2 captured	kg CO2/MW_{th}h	-	307,3	331,8	-	151,2

* Capture Solvent, purchase/sale Electricity and Oxygen Carrier cost included in Other variable OPEX cost

** KPI calculated on NPV

6.2.2 Feedstock price sensitivity for refinery cases

Figure 6-8 is showing the similar trends as figure 6-4 (for power cases). However, the green window is now even smaller. Thus, unless petcoke becomes cheaper and gas prices increase significantly, it will be difficult for the CLC to be cost-competitive with an NGCC with CO_2 capture in the refinery case.

Natural gas price	Petcoke price: -100 %	-90 %	-80 %	-70 %	-60 %	-50 %	-40 %	-30 %	-20 %	-10 %
-50 %	277	314	351	388	424	461	498	535	572	609
-45 %	251	288	325	362	399	435	472	509	546	583
-40 %	225	262	299	336	373	410	446	483	520	557
-35 %	200	237	273	310	347	384	421	457	494	531
-30 %	174	211	248	284	321	358	395	432	468	505
-25 %	148	185	222	259	295	332	369	406	443	479
-20 %	122	159	196	233	270	306	343	380	417	454
-15 %	96	133	170	207	244	281	317	354	391	428
-10 %	71	107	144	181	218	255	292	328	365	402
-5 %	45	82	118	155	192	229	266	303	339	376
0 %	19	56	93	129	166	203	240	277	314	350
5 %	-7	30	67	104	140	177	214	251	288	325
10 %	-33	4	41	78	115	151	188	225	262	299
15 %	-59	-22	15	52	89	126	162	199	236	273
20 %	-84	-48	-11	26	63	100	137	173	210	247
25 %	-110	-73	-37	0	37	74	111	148	184	221
30 %	-136	-99	-62	-26	11	48	85	122	159	195
35 %	-162	-125	-88	-51	-15	22	59	96	133	170
40 %	-188	-151	-114	-77	-40	-4	33	70	107	144
45 %	-214	-177	-140	-103	-66	-29	7	44	81	118
50 %	-239	-203	-166	-129	-92	-55	-18	18	55	92

Natural gas price	Petcoke price: 0 %	10 %	20 %	30 %	40 %	50 %	60 %	70 %	80 %	90 %	100 %
-50 %	645	682	719	756	793	830	866	903	940	977	1014
-45 %	620	656	693	730	767	804	841	877	914	951	988
-40 %	594	631	667	704	741	778	815	852	888	925	962
-35 %	568	605	642	678	715	752	789	826	863	899	936
-30 %	542	579	616	653	689	726	763	800	837	874	910
-25 %	516	553	590	627	664	700	737	774	811	848	885
-20 %	490	527	564	601	638	675	711	748	785	822	859
-15 %	465	502	538	575	612	649	686	722	759	796	833
-10 %	439	476	513	549	586	623	660	697	733	770	807
-5 %	413	450	487	524	560	597	634	671	708	744	781
0 %	387	424	461	498	535	571	608	645	682	719	755
5 %	361	398	435	472	509	546	582	619	656	693	730
10 %	336	372	409	446	483	520	557	593	630	667	704
15 %	310	347	383	420	457	494	531	568	604	641	678
20 %	284	321	358	394	431	468	505	542	579	615	652
25 %	258	295	332	369	405	442	479	516	553	590	626
30 %	232	269	306	343	380	416	453	490	527	564	601
35 %	206	243	280	317	354	391	427	464	501	538	575
40 %	181	217	254	291	328	365	402	438	475	512	549
45 %	155	192	228	265	302	339	376	413	449	486	523
50 %	129	166	203	239	276	313	350	387	424	460	497

Figure 6-4: CO_2 switching price (€/t) for the refinery cases at 0€/t transport and storage cost

7 FULL CCS CHAIN EVALUATIONS AND COMPARISONS

7.1 Scenarios and methodology

The CO_2 being captured is here assumed to be transported to the Northern Light facility for permanent storage. As such the following steps are considered:

- Transport over 100 km via an onshore pipeline to reach shore;
- Liquefaction of the CO_2 prior to ship-based transportation
- Transport via ship to the Northern Light receiving terminal with a transport distance of 1180 km. This step also includes the buffer storage facilities at departing and receiving harbours,
- Reconditioning step to 200 bar post transportation
- Transport over 100 km via an offshore pipeline to reach the storage facility
- Storage in a deep saline aquifer.

While the first three steps are assumed to take place through dedicated infrastructure, the last three are assumed to be done by the infrastructure that would be developed as part of the second phase of the Northern Light Initiative (approximately 5 $MtCO_2$/y).

A simplified illustration of this chain is presented in Figure 7-1.

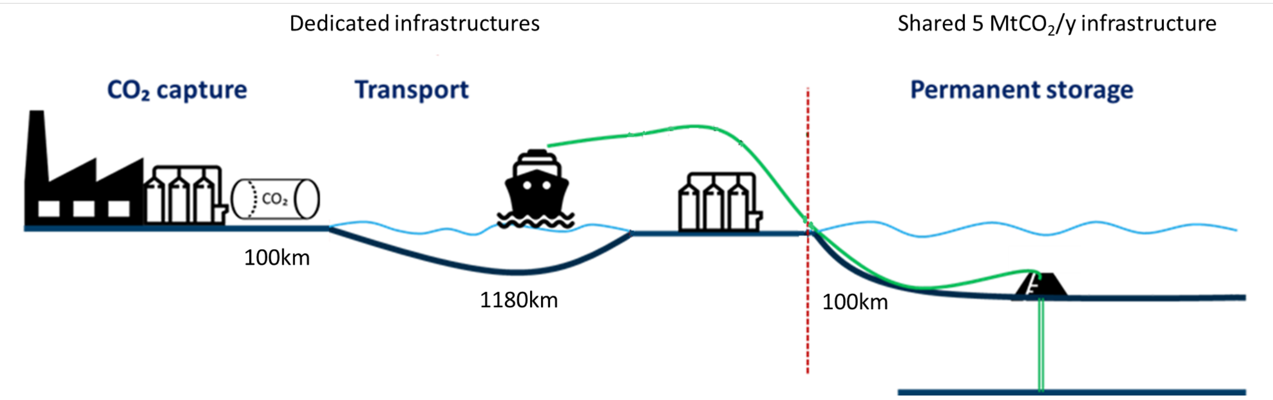

Figure 7-1: CCS chain considered

The chains are evaluated using the iCCS tool for techno-economic and environmental evaluation of CCS value chains developed by SINTEF Energy Research [10;11]. It is worth noting that a shipping fuel price of 374 €/t is assumed. [12]

For each of the power and refinery cases, 4 sub-scenarios are considered for both the CLC and NGCC combination by considering:

- Possible transport pressures for shipping of liquid CO_2: 15 and 7 barg.
- Possible ship size: 7500 m^3 as currently set by Northern Light or cost-optimal ship size.

It is worth noting that the results of the LCA study are not here taken into account.

7.2 Power case

While the complete CAPEX and OPEX breakdown by section of the chain are presented in Appendix A, the breakdown of LCOE and CO_2-intensity of the power cases for the different full-scale scenarios are presented in Table 7-1, Figure 7-2, and Figure 7-3.

The following observations can be made:

- As expected, transporting CO_2 at low-pressure and being able to optimise the ship size is the best strategy to transport the CO_2.
- With the best transport strategy, the complete LCOE of the two power options (CLC and NGCC with capture) is respectively 128 and 107 €/MWh.
- Since more CO_2 need to be transported and stored for the CLC case, including the cost of the full CCS chain increase the LCOE of the CLC scenario more than for the NGCC scenario. For the cost-optimal transport strategy, the increase in LCOE is 28.1 vs 14.7 €/MWh (CLC vs NGCC with capture).
- Similarly, CLC results in much more CO_2 emissions during the transport because of the significantly larger quantities of CO_2 that must be transported. While CLC lead to significantly lower emissions than the NGCC with CCS when looking only at the power plant with CCS, this gap is nearly closed (50 for CLC vs. 56.5 kg/MWh for NGCC with CO2 capture) when looking at the full chain for the cost-optimal strategy.
- Considering these elements, it is unlikely that with reference natural gas and petcoke prices, CLC can outperform NGCC with CCS when taking the full CCS chain into account. The impact of natural gas and petcoke prices on the full-chain comparison will be discussed in section 7.4.

Table 7-1: LCOE and CO_2-intensity of the power cases for the different full-chain scenarios.

		Refinery cases									
Shipping pressure (barg)		15 barg shipping				7 barg shipping				Cost-optimal strategy	
Ship size scenario		7500 m³ ships		Optimal ships size		7500 m³ ships		Optimal ships size			
Power and capture technology		NGCC + Solvent	CLC	NGCC + Solvent	CLC	NGCC + Solvent	CLC	NGCC + Solvent	CLC	NGCC + Solvent	CLC
LCOE (€/MWh)	Power + CO_2 capture	92,5	99,7	92,5	99,7	92,5	99,7	92,5	99,7	92,5	99,7
	Onshore pipeline	2,8	3,7	2,8	3,7	2,8	3,7	2,8	3,7	2,8	3,7
	Liquefaction	1,1	2,4	1,1	2,4	1,4	3,2	1,4	3,2	1,4	3,2
	Shipping	14,1	23,5	10,3	23,5	8,5	14,8	6,7	12,6	6,7	12,6
	Offshore pipeline	1,1	2,5	1,1	2,5	1,1	2,5	1,1	2,5	1,1	2,5
	Storage	2,7	6,1	2,7	6,1	2,7	6,1	2,7	6,1	2,7	6,1
	Sum	114	138	111	138	109	130	107	128	107,2	127,8
Residual emissions (kg/MWh)	Power + CO_2 capture	43,5	22,9	43,5	22,9	43,5	22,9	43,5	22,9	43,5	22,9
	Onshore pipeline	0,1	0,2	0,1	0,2	0,1	0,2	0,1	0,2	0,1	0,2
	Liquefaction	1,2	2,6	1,2	2,6	1,2	2,6	1,2	2,6	1,2	2,6
	Shipping	12,0	26,9	11,8	26,9	11,9	26,6	11,7	24,5	11,7	24,5
	Offshore pipeline	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	Storage	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	Sum	56,8	52,6	56,6	52,6	56,6	52,3	56,5	50,2	56,5	50,2

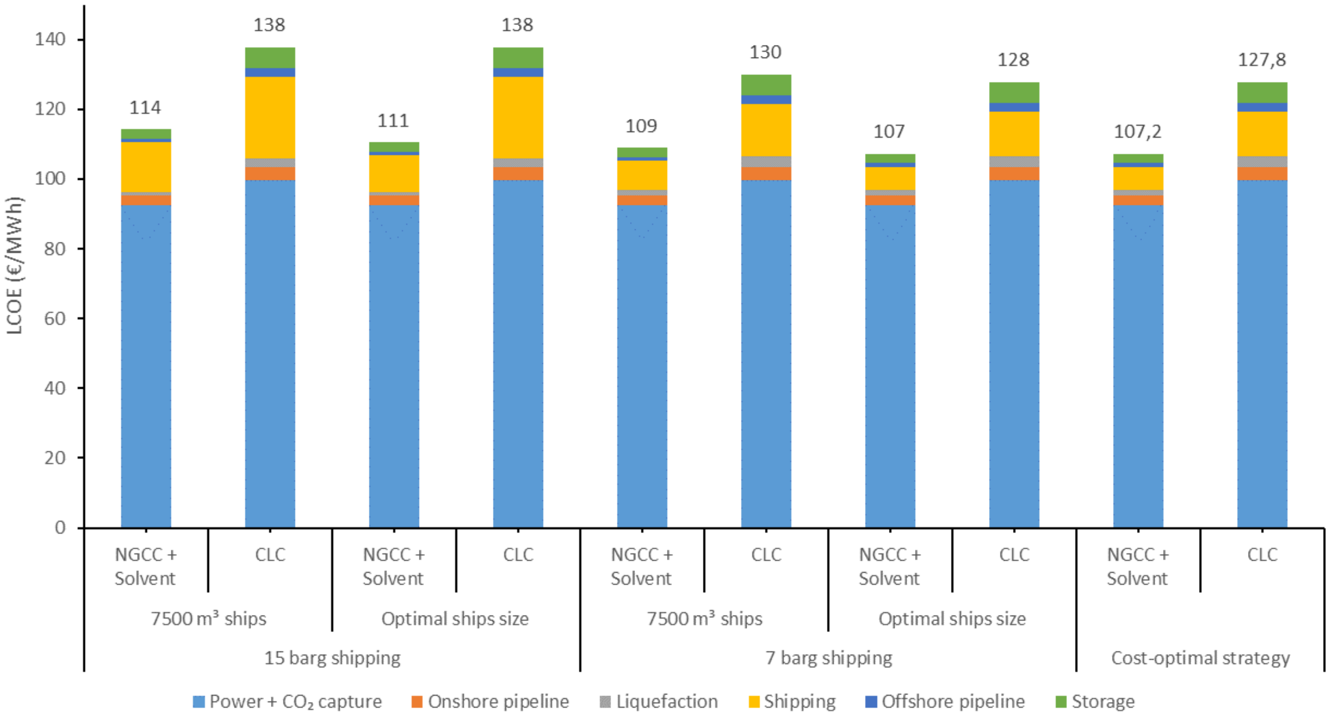

Figure 7-2: LCOE of the power cases for the different full-chain scenarios.

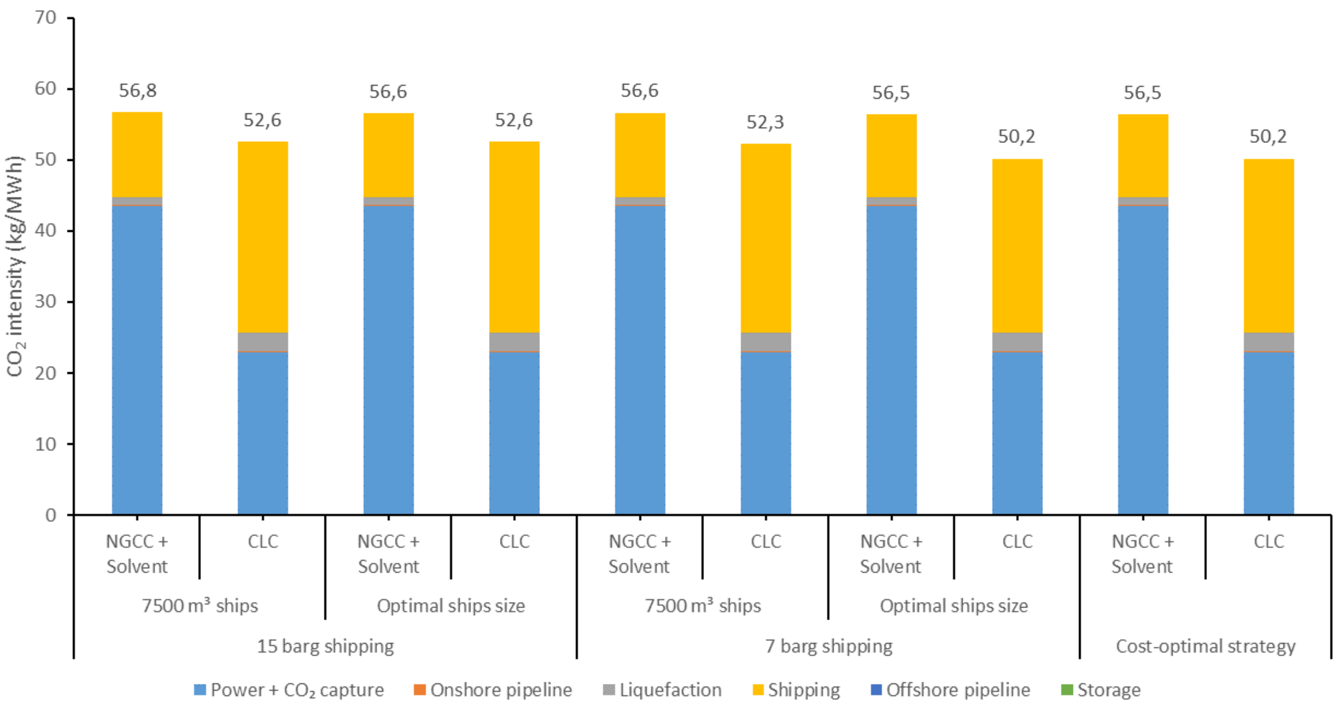

Figure 7-3: CO_2 intensity of the power cases for the different full-chain scenarios.

7.3 Refinery case

While the complete CAPEX and OPEX breakdown by section of the chain are presented in Appendix B, the breakdown of NPV of costs and residual CO_2 emissions of the refinery cases for the different full-scale scenarios are presented in Table 7-2, Figure 7-4, and Figure 7-5.

The following observations can be made:

- As expected, transporting CO_2 at low-pressure and being able to optimise the ship size is the best strategy to transport the CO_2.
- With the best transport strategy, the complete NPV of costs of the two refinery cases (CLC and NGCC with capture) is respectively 1265 and 843 M€.
- As more CO_2 needs to be transported and stored with the CLC, including the full CCS chain increase the NPV of CLC scenario more strongly than for the NGCC. For the cost-optimal transport strategy, the increase in NPV is 289 vs 150 M€ (CLC vs NGCC with capture).
- Similarly, CLC result in much more CO_2 emissions during the transport as a result of the significantly larger quantities of CO_2 that must be transported. While CLC led to residual emissions that were only one fifth of the NGCC with CCS ones, when looking only at the power plant with CCS, this gap is reduced to around 45% when looking at the full-chain (5.3 for CLC vs. 11.8 kg/MWh for NGCC with CO_2 capture for the cost-optimal strategy).
- Considering these elements, it is unlikely that with reference natural gas and petcoke prices, CLC can outperform NGCC with CCS when taking the full CCS chain into account. Even when considering the difference in residual emissions, a CO_2 emissions penalty of 735 €/tCO_2 would be required to make CLC cost competitive with the NGCC with CCS. The impact of natural gas and petcoke prices on the full-chain comparison will be discussed in section 7.4.

Table 7-2: NPV of costs and residual CO_2 emissions of the refinery cases for the different full-chain scenarios.

		Refinery cases									
Shipping pressure (barg)		15 barg shipping				7 barg shipping				Cost-optimal strategy	
Ship size scenario		7500 m³ ships		Optimal ships size		7500 m³ ships		Optimal ships size			
Power and capture technology		NGCC + Solvent	CLC	NGCC + Solvent	CLC	NGCC + Solvent	CLC	NGCC + Solvent	CLC	NGCC + Solvent	CLC
NPV of cost (M€$_{disc}$)	Power + CO_2 capture	693	976	693	976	693	976	693	976	693	976
	Onshore pipeline	38	52	38	52	38	52	38	52	38	52
	Liquefaction	8	22	8	22	11	29	11	29	11	29
	Shipping	144	271	117	271	85	164	70	130	70	130
	Offshore pipeline	9	22	9	22	9	22	9	22	9	22
	Storage	22	55	22	55	22	55	22	55	22	55
	Sum	913	1398	887	1398	857	1299	843	1265	843	1265
Residual emissions (t/h)	Power + CO_2 capture	10,57	2,33	10,57	2,33	10,57	2,33	10,57	2,33	10,57	2,33
	Onshore pipeline	0,02	0,01	0,02	0,01	0,02	0,01	0,02	0,01	0,02	0,01
	Liquefaction	0,10	0,26	0,10	0,26	0,10	0,26	0,10	0,26	0,10	0,26
	Shipping	1,07	2,74	1,08	2,74	1,06	2,72	1,08	2,67	1,08	2,67
	Offshore pipeline	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	Storage	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	Sum	11,8	5,4	11,8	5,4	11,8	5,3	11,8	5,3	11,8	5,3

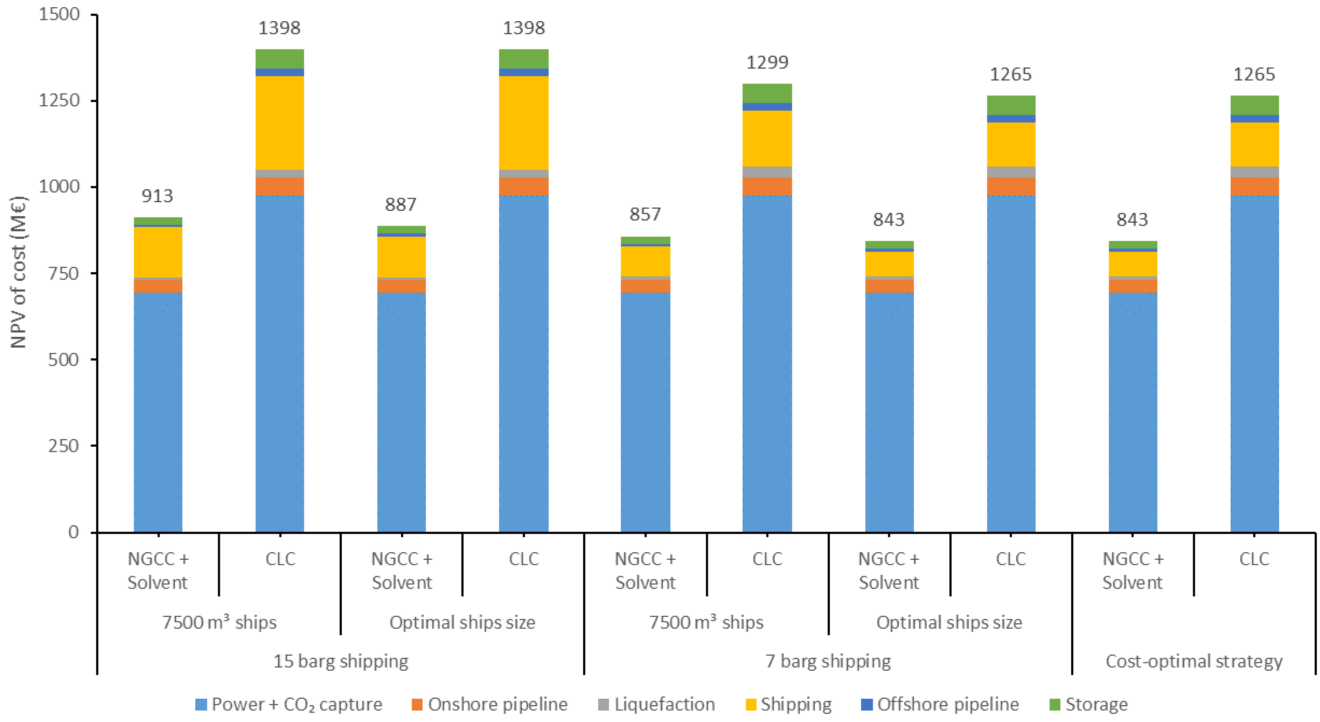

Figure 7-4: NPV of costs of the refinery cases for the different full-chain scenarios.

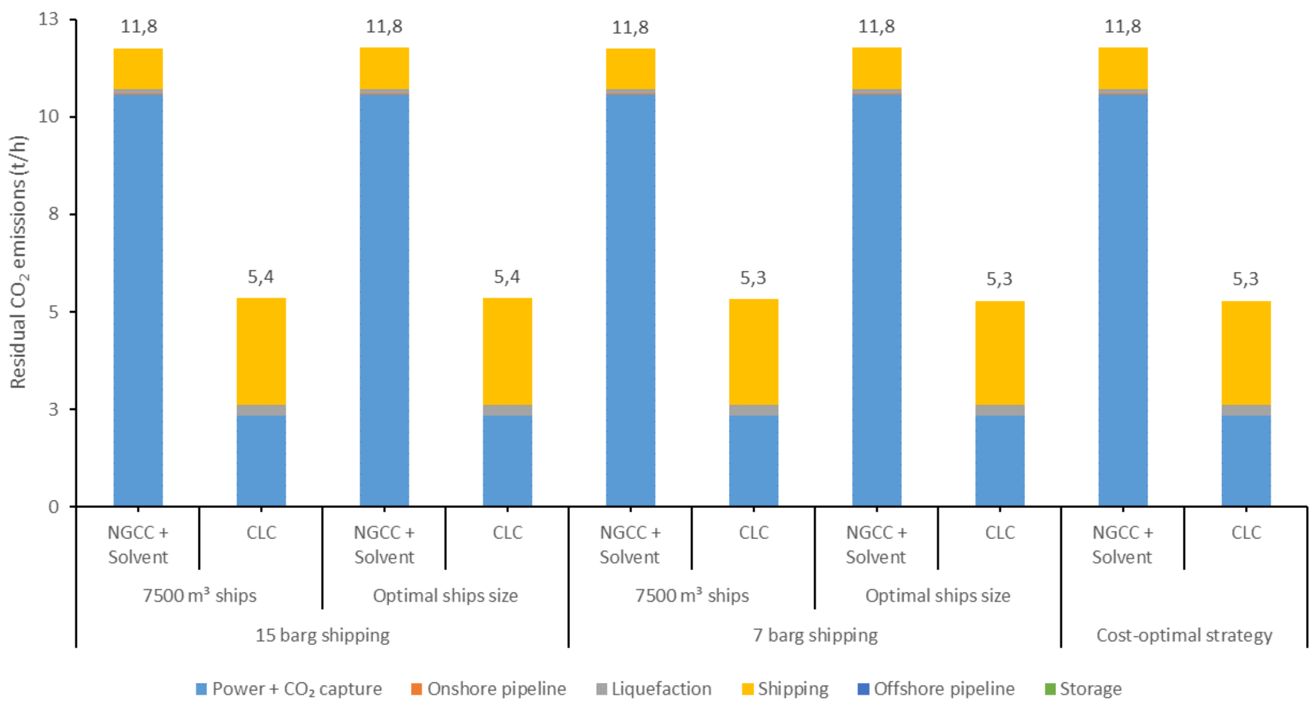

Figure 7-5: Residual CO_2 emissions of the refinery cases for the different full-chain scenarios.

7.4 Feedstock price sensitivity

Figure 7-6 and Figure 7-7 present the CO_2 switching price between CLC and NGCC with CO2 capture once the full CCS chain is included for the power and refinery cases for different natural gas and petcoke prices. Due to the higher amount of CO2 that must be transported and stored with the CLC concept, the area where CLC is cheaper than NGCC with CO2 capture (coloured in green) is reduced compared to when only the generation and capture plants are evaluated.

In the power cases, CLC could still be competitive if petcoke price were to decrease and the natural gas were to increase (compared to the reference price assumed).

In the refinery case, it is very unlikely that CLC could compete unless petcoke becomes nearly free, that natural gas price increase significantly, and that a CO2 penalty for CO_2 emissions higher than 200 €/t is put in place.

Natural gas price \ Petcoke price	-100 %	-90 %	-80 %	-70 %	-60 %	-50 %	-40 %	-30 %	-20 %	-10 %	0 %	10 %	20 %	30 %	40 %	50 %	60 %	70 %	80 %	90 %	100 %
-50 %	2453	2918	3384	3849	4314	4780	5245	5710	6175	6641	7106	7571	8036	8502	8967	9432	9898	10363	10828	11293	11759
-45 %	2074	2539	3005	3470	3935	4400	4866	5331	5796	6261	6727	7192	7657	8123	8588	9053	9518	9984	10449	10914	11380
-40 %	1695	2160	2625	3091	3556	4021	4486	4952	5417	5882	6348	6813	7278	7743	8209	8674	9139	9605	10070	10535	11000
-35 %	1316	1781	2246	2711	3177	3642	4107	4573	5038	5503	5968	6434	6899	7364	7830	8295	8760	9225	9691	10156	10621
-30 %	936	1402	1867	2332	2798	3263	3728	4193	4659	5124	5589	6055	6520	6985	7450	7916	8381	8846	9311	9777	10242
-25 %	557	1023	1488	1953	2418	2884	3349	3814	4280	4745	5210	5675	6141	6606	7071	7536	8002	8467	8932	9398	9863
-20 %	178	643	1109	1574	2039	2505	2970	3435	3900	4366	4831	5296	5761	6227	6692	7157	7623	8088	8553	9018	9484
-15 %	-201	264	729	1195	1660	2125	2591	3056	3521	3986	4452	4917	5382	5848	6313	6778	7243	7709	8174	8639	9104
-10 %	-580	-115	350	816	1281	1746	2211	2677	3142	3607	4073	4538	5003	5468	5934	6399	6864	7329	7795	8260	8725
-5 %	-959	-494	-29	436	902	1367	1832	2298	2763	3228	3693	4159	4624	5089	5554	6020	6485	6950	7416	7881	8346
0 %	-1339	-873	-408	57	523	988	1453	1918	2384	2849	3314	3779	4245	4710	5175	5641	6106	6571	7036	7502	7967
5 %	-1718	-1252	-787	-322	143	609	1074	1539	2004	2470	2935	3400	3866	4331	4796	5261	5727	6192	6657	7123	7588
10 %	-2097	-1632	-1166	-701	-236	229	695	1160	1625	2091	2556	3021	3486	3952	4417	4882	5348	5813	6278	6743	7209
15 %	-2476	-2011	-1546	-1080	-615	-150	316	781	1246	1711	2177	2642	3107	3573	4038	4503	4968	5434	5899	6364	6829
20 %	-2855	-2390	-1925	-1459	-994	-529	-64	402	867	1332	1798	2263	2728	3193	3659	4124	4589	5054	5520	5985	6450
25 %	-3234	-2769	-2304	-1839	-1373	-908	-443	23	488	953	1418	1884	2349	2814	3279	3745	4210	4675	5141	5606	6071
30 %	-3614	-3148	-2683	-2218	-1752	-1287	-822	-357	109	574	1039	1504	1970	2435	2900	3366	3831	4296	4761	5227	5692
35 %	-3993	-3527	-3062	-2597	-2132	-1666	-1201	-736	-271	195	660	1125	1591	2056	2521	2986	3452	3917	4382	4847	5313
40 %	-4372	-3907	-3441	-2976	-2511	-2046	-1580	-1115	-650	-184	281	746	1211	1677	2142	2607	3072	3538	4003	4468	4934
45 %	-4751	-4286	-3821	-3355	-2890	-2425	-1959	-1494	-1029	-564	-98	367	832	1297	1763	2228	2693	3159	3624	4089	4554
50 %	-5130	-4665	-4200	-3734	-3269	-2804	-2339	-1873	-1408	-943	-478	-12	453	918	1384	1849	2314	2779	3245	3710	4175

Figure 7-6: CO_2 switching price (€/t) for the power cases once the full CCS is included

Natural gas price \ Petcoke price	-100 %	-90 %	-80 %	-70 %	-60 %	-50 %	-40 %	-30 %	-20 %	-10 %	0 %	10 %	20 %	30 %	40 %	50 %	60 %	70 %	80 %	90 %	100 %
-50 %	594	640	687	733	780	827	873	920	967	1013	1060	1107	1153	1200	1247	1293	1340	1386	1433	1480	1526
-45 %	561	607	654	701	747	794	841	887	934	981	1027	1074	1121	1167	1214	1261	1307	1354	1400	1447	1494
-40 %	528	575	621	668	715	761	808	855	901	948	995	1041	1088	1135	1181	1228	1274	1321	1368	1414	1461
-35 %	495	542	589	635	682	729	775	822	869	915	962	1009	1055	1102	1148	1195	1242	1288	1335	1382	1428
-30 %	463	509	556	603	649	696	743	789	836	883	929	976	1022	1069	1116	1162	1209	1256	1302	1349	1396
-25 %	430	477	523	570	617	663	710	757	803	850	896	943	990	1036	1083	1130	1176	1223	1270	1316	1363
-20 %	397	444	491	537	584	631	677	724	770	817	864	910	957	1004	1050	1097	1144	1190	1237	1284	1330
-15 %	365	411	458	505	551	598	644	691	738	784	831	878	924	971	1018	1064	1111	1158	1204	1251	1297
-10 %	332	379	425	472	518	565	612	658	705	752	798	845	892	938	985	1032	1078	1125	1171	1218	1265
-5 %	299	346	392	439	486	532	579	626	672	719	766	812	859	906	952	999	1045	1092	1139	1185	1232
0 %	266	313	360	406	453	500	546	593	640	686	733	780	826	873	919	966	1013	1059	1106	1153	1199
5 %	234	280	327	374	420	467	514	560	607	654	700	747	793	840	887	933	980	1027	1073	1120	1167
10 %	201	248	294	341	388	434	481	528	574	621	668	714	761	807	854	901	947	994	1041	1087	1134
15 %	168	215	262	308	355	402	448	495	542	588	635	681	728	775	821	868	915	961	1008	1055	1101
20 %	136	182	229	276	322	369	416	462	509	555	602	649	695	742	789	835	882	929	975	1022	1069
25 %	103	150	196	243	290	336	383	429	476	523	569	616	663	709	756	803	849	896	943	989	1036
30 %	70	117	164	210	257	303	350	397	443	490	537	583	630	677	723	770	817	863	910	956	1003
35 %	38	84	131	177	224	271	317	364	411	457	504	551	597	644	691	737	784	830	877	924	970
40 %	5	51	98	145	191	238	285	331	378	425	471	518	565	611	658	704	751	798	844	891	938
45 %	-28	19	65	112	159	205	252	299	345	392	439	485	532	578	625	672	718	765	812	858	905
50 %	-61	-14	33	79	126	173	219	266	313	359	406	452	499	546	592	639	686	732	779	826	872

Figure 7-7: CO_2 switching price (€/t) for the refinery cases once the full CCS is included

8 LCA HYPOTHESIS AND RESULTS

8.1 Context and objective

This part of the report presents the results of the Life Cycle Assessment (LCA) of the Chemical Looping Combustion (CLC) process to assess its environmental performance against Natural Gas Combined Cycle (NGCC) and Circulating Fluidized Bed (CFB) processes both combined with CO2 capture unit based on Mono Ethanol Amine (MEA). All processes produce electricity (200MW).

8.2 Processes overview

8.2.1 CFB process

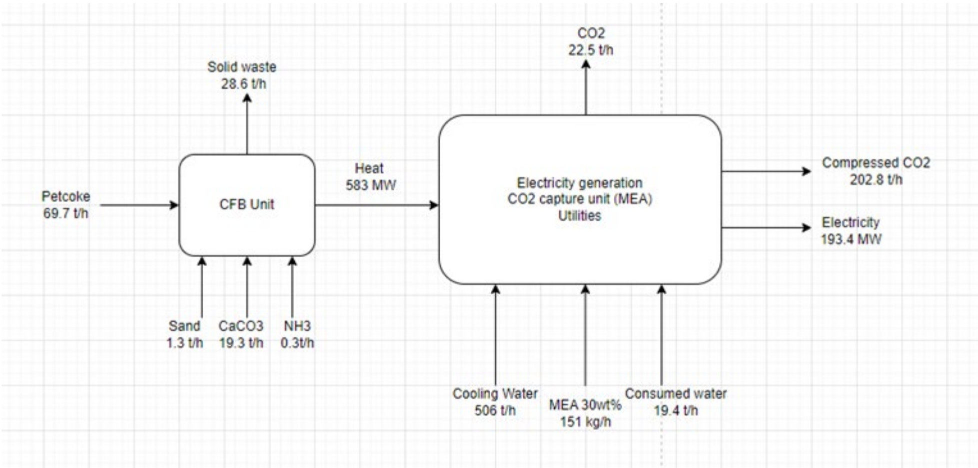

Figure 8-1: *Circulating Fluidized Bed process*

8.2.2 CLC process

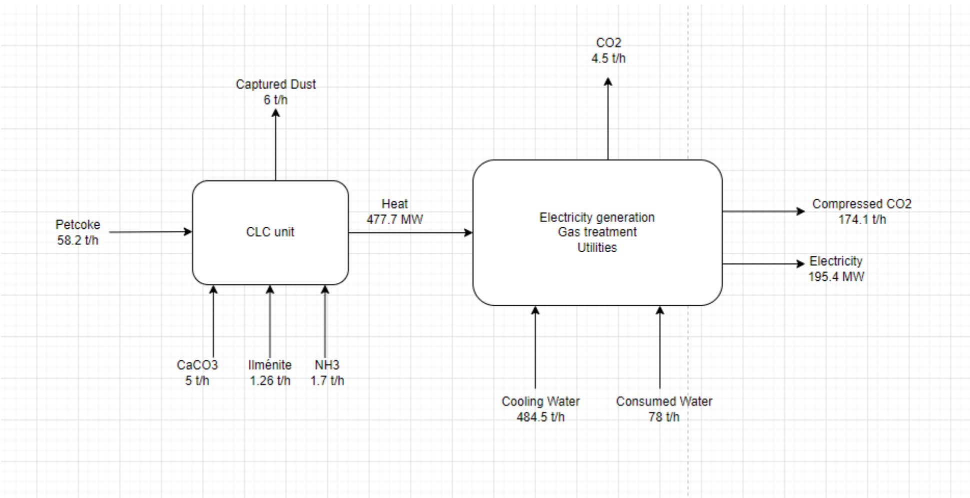

Figure 8-2: *Chemical Looping Combustion process*

8.2.3 NGCC process

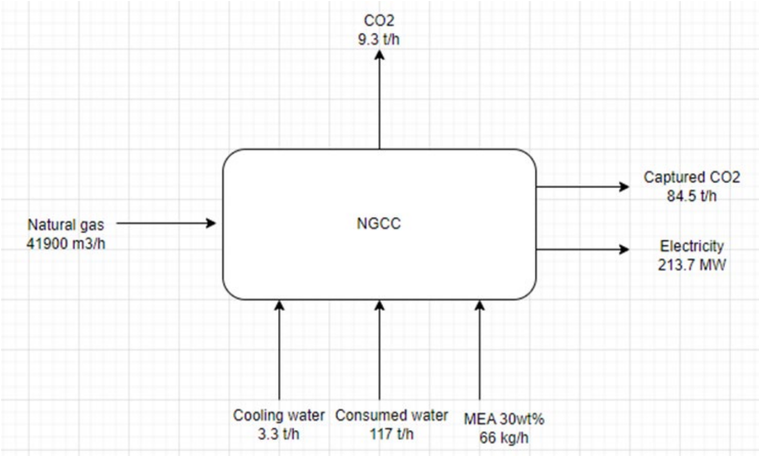

Figure 8-3: *Natural Gas Combined Cycle process*

8.3 LCA methodology

The analysis is cradle-to-gate meaning that it includes the impacts due to the raw material extraction, but it does not include the use of the produced electricity.

The functional unit is the production of 1 kWh electric power.

SimaPro software (v9.3.0.3) in combination with EcoInvent v3.8 database was used to assess the environmental performance of the processes. Impact World + methodology both Midpoint and Endpoint was used. Midpoint indicators focus on single environmental problem, such as climate change or acidification. Endpoint indicators show the environmental impact on higher aggregation levels, such as human health and ecosystem quality.

All processes are supposed to be based in Belgium and LCA inputs were chosen in consequence.

Three main limitations have been applied in the analysis:

- Both construction and decommissioning of plants have been excluded. It was shown in the literature [13] that they both have negligeable effects on environmental impacts when compared to the operating phase of the plant.
- Both transport and storage of compressed CO2 are not taken in account in this part of the study.
- The treatments of recovered dust and solid waste are not included in the LCA.

8.4 Assumptions

Main assumptions for the 3 different processes are presented in the Table 8-1.

Table 8-1: Process assumptions

	CLC	CFB+CCS	NGCC+CCS
Electric Power	200 MW		
	8283 h/yr		
Feed	Petroleum coke (35 MJ/kg) 58.2 t/h	Petroleum coke (35 MJ/kg) 69.7 t/h	Natural gas 41900 m^3/h
Other inputs	$CaCO_3$, 42171 t/yr NH_3, 14082 t/yr	Sand, 10768 t/yr $CaCO_3$, 159862 t/yr	
Catalyst	Ilménite, 54% TiO_2 10446 t/yr	X	X
CCS	X	MEA 30wt% solution in water, 4175 t/yr 1252.5 t/yr pure MEA + 2922.5 t/yr tap water	MEA 30wt% solution in water, 2361 t/yr 708.3 t/yr pure MEA + 1652.7 t/yr tap water
Cooling water	2% of total volume, from nature 484 t/h	2% of total volume, from nature 506 t/h	2% of total volume, from nature 3.3 t/h
Consumed water	78 t/h (tap water)	19 t/h (tap water)	117 t/h (tap water) + 10t/h purge steam
CO_2 emissions	4.5 t/h (97.5% capture rate)	22.5 t/h (90% capture rate)	9.3 t/h (90% capture rate)
Other emissions and waste	50000 t/yr captured dust	237000 t/yr solid waste	

8.5 Results and discussion

8.5.1 Impact on climate change

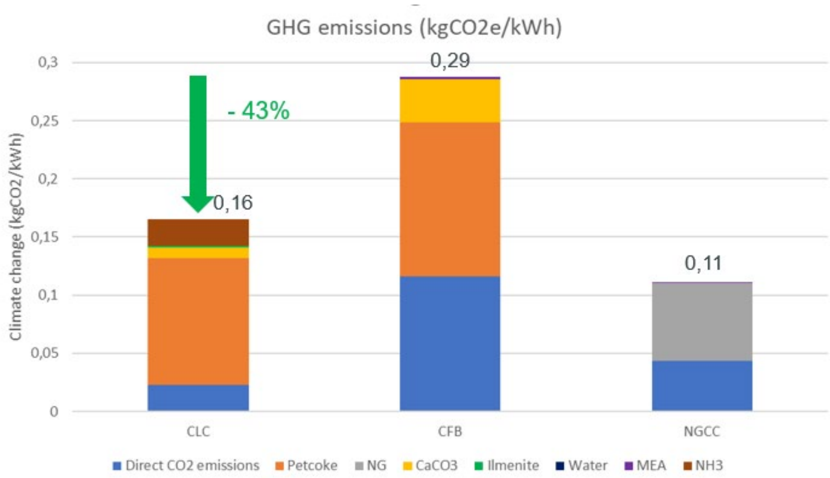

Figure 8-4: *Impact on climate change*

Figure 8-4 shows a reduction of GHG emissions by 43% with CLC when compared to CFB+CCS. Emissions are mainly due to the use of petcoke (66%) wile for CFB, emissions are due to petcoke (47%), $CaCO_3$ (13%) and direct process emissions (40%).

NGCC has the lowest GHG emissions.

8.5.2 Sensitivity study on CLC CO_2 capture rate

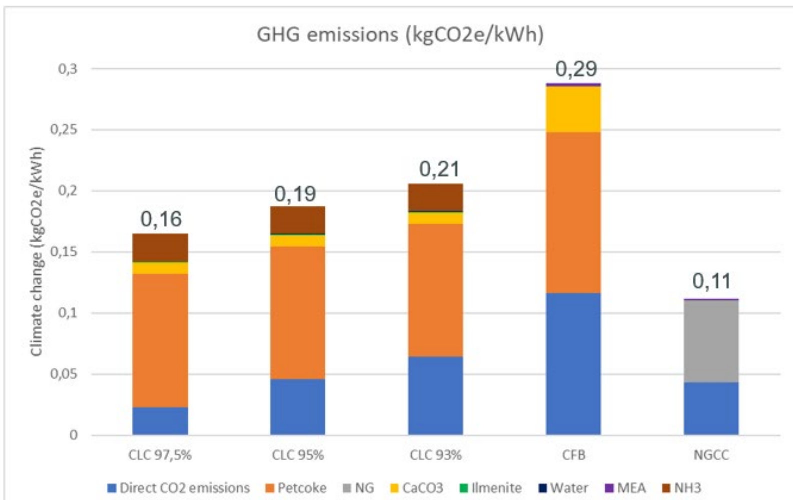

Figure 8-5: *Impact on climate considering various CO2 capture rate for the CLC process. No change in the CO_2 capture rate of CFB and NGCC.*

Figure 8-5 shows that CLC impact on climate change depends on its CO_2 capture rate. It is reduced by 43% compared to CFB when the CO_2 capture rate is 97.5%. This rate is cut to 29% when the CO_2 capture rate is 93%.

8.5.3 Other environmental impacts

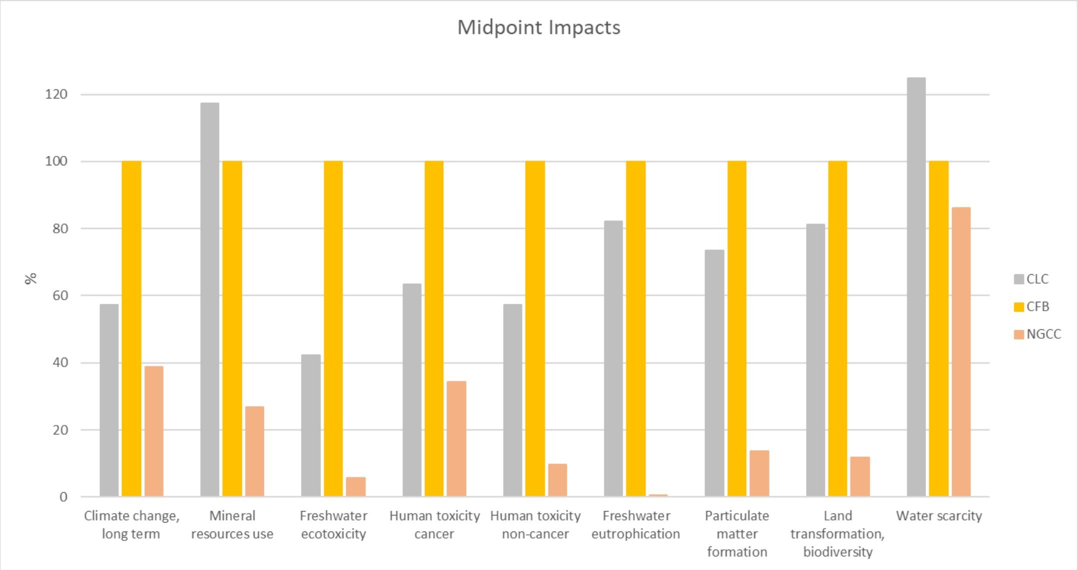

Figure 8-6: *Other environmental impacts*

Figure 8-6 shows that most environmental impacts are less damaged with CLC than with CFB: freshwater ecotoxicity, human toxicity, freshwater eutrophication, particulate matter formation and land transformation (biodiversity).

However, mineral resource use is increased with CLC as both ilmenite and $CaCO_3$ are used in this process. Water scarcity is also increased because of the use of ammonia, even if less water is used in the process.

In all cases, NGCC has the lowest impact on the environment.

8.5.4 Endpoint results

8.5.4.1 Impact on human health

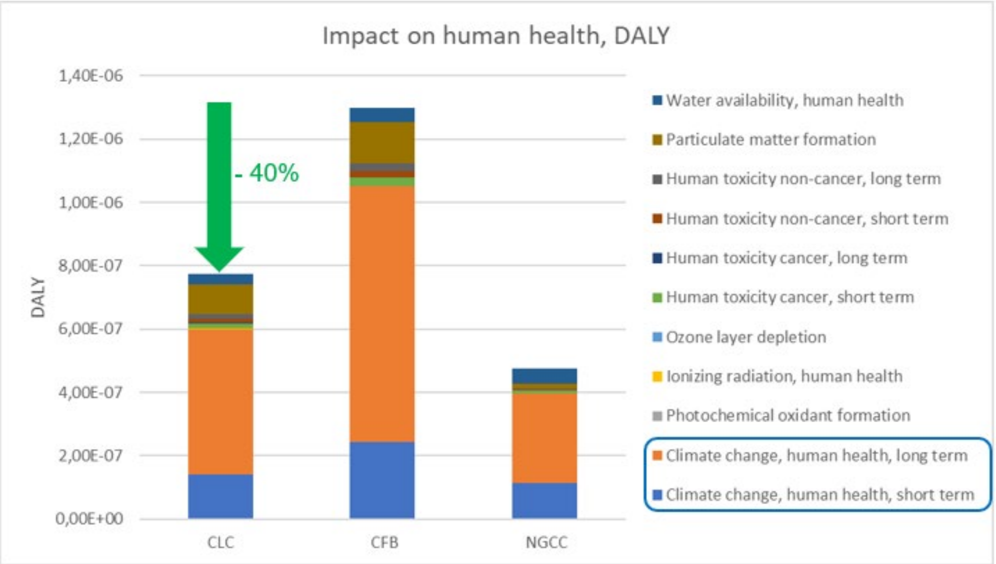

Figure 8-7: *Impact on human health*

Figure 8-7 shows that there is a reduction of impact on human health by 40% with CLC process compared to CFB. Damages are mainly related to GHG emissions (77% for CLC and 81% for CFB) due to the use (and extraction) of petcoke, which is also responsible for particulate matter formation.

NGCC has less impact on human health than CLC (-40%) and CFB (-65%).

8.5.4.2 Impact on ecosystem quality

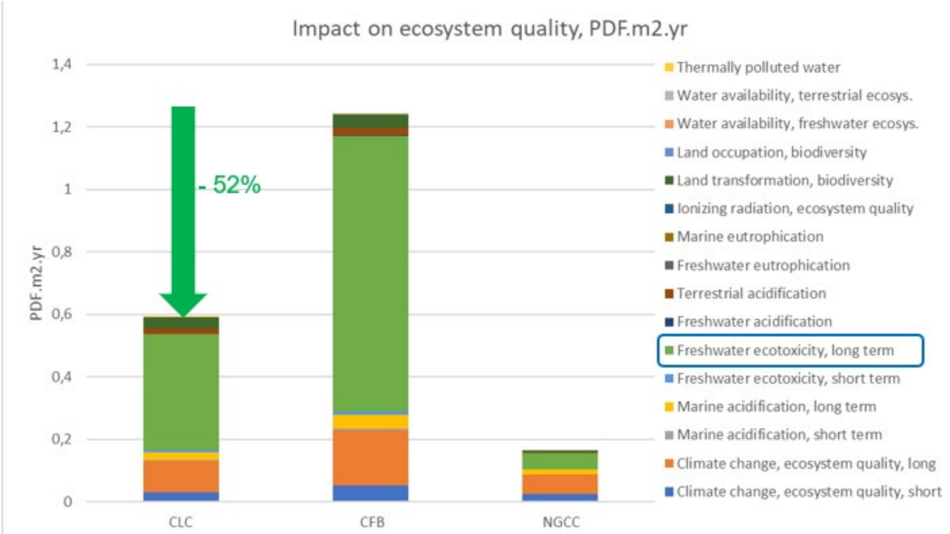

Figure 8-8: *Impact on ecosystem quality*

Figure 8-8 shows that there is a decrease of the impact on ecosystem quality by 52% with CLC process compared to CFB process. Freshwater ecotoxicity impact is less damaged as less $CaCO_3$ is used in the process.

NGCC has better results than CLC as neither petcoke nor $CaCO_3$ are used in the process.

8.6 LCA conclusions and perspectives

CLC process has reduced GHG emissions compared to CFB process. It can go up to 43% reduction when 97.5% CO_2 capture rate is applied to CLC process.

NGCC has the lowest impact on human health and ecosystem quality as this process does not need petcoke.

9 CONCLUSIONS

This deliverable is giving the conclusion of the Techno-Economic Assessments carried out in WP5 of the CHEERS project to benchmark the CLC against NGCC with carbon capture and CFB with carbon capture units at industrial scale. The main conclusions of this deliverable are the following:

- For solid feedstock like petcoke, the CLC is clearly competitive versus CFB with carbon capture for both the cogeneration in refinery case and the power case.
- For the Power case, CLC is slightly more expensive than the NGCC with carbon capture pathway with the reference natural gas and petcoke prices.
    - However, if the CLC power plant is built very near the CO_2 storage place, the CLC plant could compete with the NGCC with CCS if gas prices and petcoke prices become respectively higher and lower than considered in the base case evaluations.
    - However, in a case where the CO_2 needs to be transported and stored far away from the power plant, the competitiveness of CLC would be further reduced as less CO_2 needs to be transported in the NGCC pathway than in the CLC one.
- For the refinery case, the results emphasize that CLC is not a cost-efficient option compared to an NGCC with CO_2 capture for the reference natural gas and petcoke prices.
    - This conclusion is confirmed even when considering sensitivity in natural gas and petcoke prices and when including CO_2 transport and storage cost.
    - Thus, unless petcoke is nearly free, gas prices increase significantly, and that CO_2 transport and storage cost are minimal, it is very unlikely that CLC will be cost-competitive with an NGCC with CO_2 capture for the refinery case.
- Based on LCA results, CLC reduced GHG emissions up to 43% compared to CFB thanks to better thermal efficiency and higher CO_2 capture rate. NGCC presents the lowest impact on the environment, which is mainly due to the use of natural gas instead of petcoke.
- When benchmarking CLC burning petcoke against NGCC with CO_2 capture burning natural gas, the techno-economic results presented in this work show that the CLC is not competitive considering the assumptions made for petcoke and natural gas prices (2019 reference year).
- However, it is the most cost-efficient technology to burn petcoke. Thus, in a future scenario where burning petcoke without CO_2 capture is not feasible (due to CO_2 tax or policy regimes), CLC would be the best option to utilize this fuel – primarily in refineries to utilise this by-product.
- For the TEA of the CLC (and CFB) technology, we chose to focus only on petcoke fuel which is the hardiest feedstock in regards with combustion in FR. As perspectives, we could investigate other solid fuels as lignite or even biomass for which simpler design is expected making CLC more competitive against NGCC. For completeness, update of the TEA should be performed in later dedicated studies.

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A APPENDIX A: COSTS AND EMISSIONS OF THE POWER CASES WITH FULL CCS CHAIN

Table A-1: Costs of the power cases along the chain for the different scenarios considered.

		CLC				NGCC with CCS			
Net power output (MW)		200	200	200	200	214	214	214	214
Shipping pressure (barg)		15	15	7	7	15	15	7	7
Ship size scenario		7500 m3	Optimal	7500 m3	Optimal	7500 m3	Optimal	7500 m3	Optimal
Onshore pipeline diameter (in)		10,75	10,75	10,75	10,75	8,63	8,63	8,63	8,63
Ship size (m3)		7500	7500	7500	20000	7500	10000	7500	10000
Onshore pipeline diameter (in)		14,00	14,00	14,00	14,00	14,00	14,00	14,00	14,00
CO2 capture and conditioning	CAPEX (M€)	720	720	720	720	589	589	589	589
	Fixed OPEX (M€/y)	24,0	24,0	24,0	24,0	19,9	19,9	19,9	19,9
	Fuel cost (M€/y)	48,2	48,2	48,2	48,2	84,1	84,1	84,1	84,1
	Other variable OPEX (M€/y)	25,9	25,9	25,9	25,9	5,0	5,0	5,0	5,0
Extra-conditioning + onshore pipeline	CAPEX (M€)	55	55	55	55	44	44	44	44
	Fixed OPEX (M€/y)	0,9	0,9	0,9	0,9	0,7	0,7	0,7	0,7
	Electricity cost (M€/y)	0,1	0,1	0,1	0,1	0,0	0,0	0,0	0,0
	Other variable OPEX (M€/y)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Liquefaction	CAPEX (M€)	18	18	20	20	8	8	10	10
	Fixed OPEX (M€/y)	1,1	1,1	1,2	1,2	0,5	0,5	0,6	0,6
	Electricity cost (M€/y)	1,1	1,1	2,0	2,0	0,5	0,5	1,0	1,0
	Other variable OPEX (M€/y)	0,2	0,2	0,3	0,3	0,1	0,1	0,1	0,1
Shipping + reconditioning	CAPEX (M€)	215	215	115	91	147	100	78	55
	Fixed OPEX (M€/y)	10,6	10,6	5,6	4,6	7,4	5,1	3,9	2,8
	Fuel cost (M€/y)	4,5	4,5	4,4	4,1	2,1	2,1	2,1	2,1
	Electricity cost (M€/y)	0,5	0,5	0,5	0,5	0,2	0,2	0,2	0,2
	Other variable OPEX (M€/y)	3,2	3,2	3,2	3,2	1,5	1,5	1,5	1,5
Offshore pipeline	CAPEX (M€)	38	38	38	38	18	18	18	18
	Fixed OPEX (M€/y)	0,6	0,6	0,6	0,6	0,3	0,3	0,3	0,3
	Electricity cost (M€/y)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	Other variable OPEX (M€/y)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Storage	CAPEX (M€)	65	65	65	65	31	31	31	31
	Fixed OPEX (M€/y)	2,7	2,7	2,7	2,7	1,3	1,3	1,3	1,3
	Electricity cost (M€/y)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	Other variable OPEX (M€/y)	1,5	1,5	1,5	1,5	0,7	0,7	0,7	0,7

Table A-2: Residual CO_2 emissions of the power cases along the chain for the different scenarios considered.

		CLC				NGCC with CCS			
Net power output (MW)		200	200	200	200	214	214	214	214
Shipping pressure (barg)		15	15	7	7	15	15	7	7
Ship size scenario		7500 m3	Optimal	7500 m3	Optimal	7500 m3	Optimal	7500 m3	Optimal
Emitted CO2 (t/h)	CLC	4,58	4,58	4,58	4,58	9,30	9,30	9,30	9,30
	Onshore pipeline	0,04	0,04	0,04	0,04	0,02	0,02	0,02	0,02
	Liquefaction	0,52	0,52	0,52	0,52	0,25	0,25	0,25	0,25
	Shipping	5,37	5,37	5,32	4,90	2,56	2,52	2,53	2,49
	Offshore pipeline	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	Storage	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Total residual emissions (t/h)		10,51	10,51	10,46	10,04	12,13	12,09	12,10	12,06

B APPENDIX B: COSTS AND EMISSIONS OF THE REFINERY CASES WITH FULL CCS CHAIN

Table A-3: Costs of the refinery cases along the chain for the different scenarios considered.

		CLC				NGCC with CCS			
Shipping pressure (barg)		15	15	7	7	15	15	7	7
Ship size scenario		7500 m3	Optimal	7500 m3	Optimal	7500 m3	Optimal	7500 m3	Optimal
Onshore pipeline diameter (in)		8,63	8,63	8,63	8,63	5,56	5,56	5,56	5,56
Ship size (m3)		7500	7500	7500	10000	7500	5000	7500	5000
Offshore pipeline diameter (in)		14,00	14,00	14,00	14,00	14,00	14,00	14,00	14,00
	CAPEX (M€)	415	415	415	415	208	208	208	208
	Fixed OPEX (M€/y)	13,8	13,8	13,8	13,8	5,4	5,4	5,4	5,4
	Fuel cost (M€/y)	25,1	25,1	25,1	25,1	35,2	35,2	35,2	35,2
CO2 capture and conditioning	Other variable OPEX (M€/y)	13,7	13,7	13,7	13,7	4,9	4,9	4,9	4,9
	CAPEX (M€)	44	44	44	44	32	32	32	32
	Fixed OPEX (M€/y)	0,7	0,7	0,7	0,7	0,5	0,5	0,5	0,5
	Electricity cost (M€/y)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Extra-conditioning + onshore pipeline	Other variable OPEX (M€/y)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	CAPEX (M€)	9	9	10	10	4	4	4	4
	Fixed OPEX (M€/y)	0,5	0,5	0,6	0,6	0,2	0,2	0,2	0,2
	Electricity cost (M€/y)	0,5	0,5	1,0	1,0	0,2	0,2	0,4	0,4
Liquefaction	Other variable OPEX (M€/y)	0,1	0,1	0,1	0,1	0,0	0,0	0,1	0,1
	CAPEX (M€)	147	147	78	56	82	65	44	34
	Fixed OPEX (M€/y)	7,4	7,4	3,9	2,8	4,2	3,3	2,2	1,7
	Fuel cost (M€/y)	2,3	2,3	2,3	2,2	0,9	0,9	0,9	0,9
	Electricity cost (M€/y)	0,3	0,3	0,2	0,2	0,1	0,1	0,1	0,1
Shipping + reconditioning	Other variable OPEX (M€/y)	1,7	1,7	1,7	1,7	0,6	0,6	0,6	0,6
	CAPEX (M€)	19	19	19	19	7	7	7	7
	Fixed OPEX (M€/y)	0,3	0,3	0,3	0,3	0,1	0,1	0,1	0,1
	Electricity cost (M€/y)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Offshore pipeline	Other variable OPEX (M€/y)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	CAPEX (M€)	33	33	33	33	13	13	13	13
	Fixed OPEX (M€/y)	1,4	1,4	1,4	1,4	0,5	0,5	0,5	0,5
	Electricity cost (M€/y)	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Storage	Other variable OPEX (M€/y)	0,8	0,8	0,8	0,8	0,3	0,3	0,3	0,3

Table A-4: Residual CO_2 emissions of the refinery cases along the chain for the different scenarios considered.

		CLC				NGCC with CCS			
Shipping pressure (barg)		15	15	7	7	15	15	7	7
Ship size scenario		7500 m3	Optimal	7500 m3	Optimal	7500 m3	Optimal	7500 m3	Optimal
Emitted CO2 (t/h)	CLC	2,33	2,33	2,33	2,33	10,57	10,57	10,57	10,57
	Onshore pipeline	0,01	0,01	0,01	0,01	0,02	0,02	0,02	0,02
	Liquefaction	0,26	0,26	0,26	0,26	0,10	0,10	0,10	0,10
	Shipping	2,74	2,74	2,72	2,67	1,07	1,08	1,06	1,08
	Offshore pipeline	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	Storage	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Total residual emissions (t/h)		5,35	5,35	5,33	5,28	11,76	11,78	11,76	11,77