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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 CO₂ 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 CO₂ separation and purification, and it will comply with industrial standards, specifications, and safety regulations. Except for CO₂ compression work, the innovative concept can remove 96% of the CO₂ while eliminating capture losses to almost zero.

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0.1 Disclaimer

The sole responsibility of this publication lies with the authors. Neither the European Union nor the MOST is responsible for any use that may be made of the information contained herein.

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 CO₂ 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 CO₂ capture needed to establish the CO₂ 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 considering a shared transport infrastructure as a result of potential clustering. 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 Ecolnvent 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 CO₂ 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 CO₂ needs to be transported and stored far away from the power plant, the competitiveness of CLC would be further reduced as less CO₂ 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 CO₂ 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 CO₂ transport and storage cost.
 - Thus, unless petcoke is nearly free, gas prices increase significantly, and that CO₂ transport and storage cost are minimal, it is very unlikely that CLC would be cost-competitive with an NGCC with CO₂ 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.

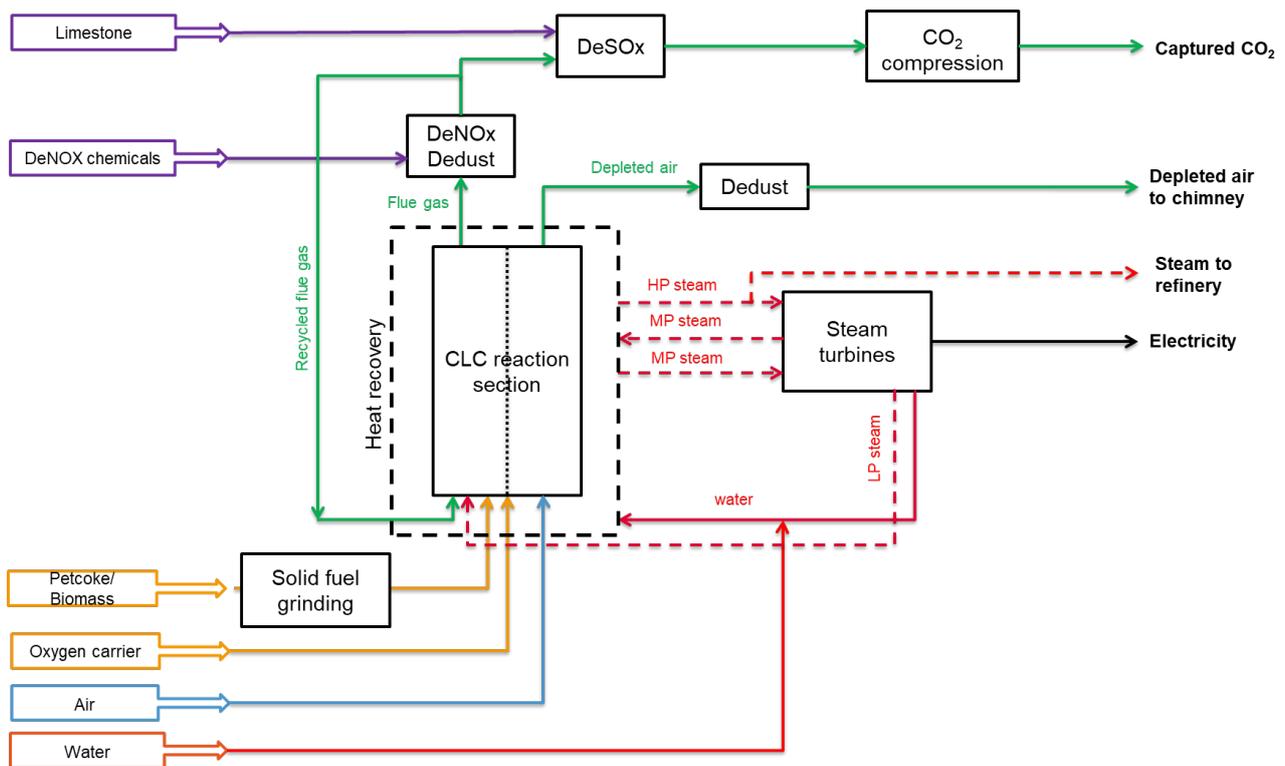


Figure 2-1: Block diagram of the CLC plant

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 CO₂ and water, as well as NO_x and SO_x. The flue gas is therefore treated with deNO_x, dedust and deSO_x, prior to the CO₂ compression train, in order to meet CO₂ 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 CO₂ from the exhaust of the Heat Recovery Steam Generator (HRSG). The captured CO₂ 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.

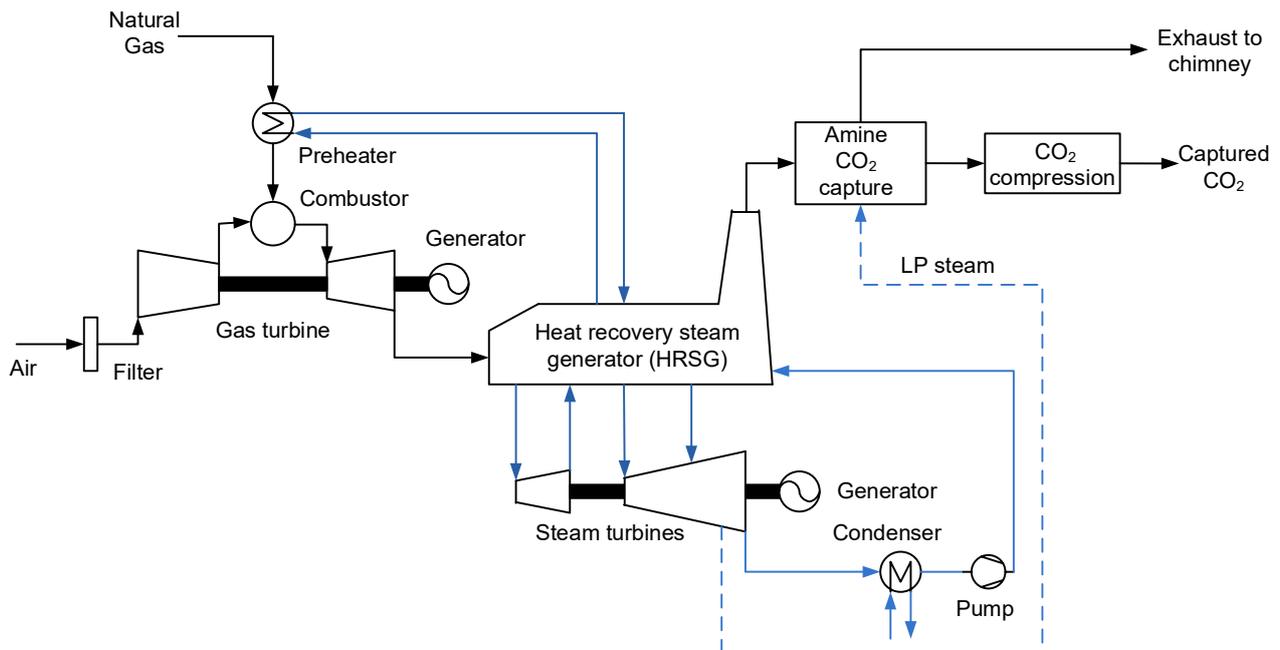


Figure 2-2: Process flow diagram of the Natural gas combine cycle reference case

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.

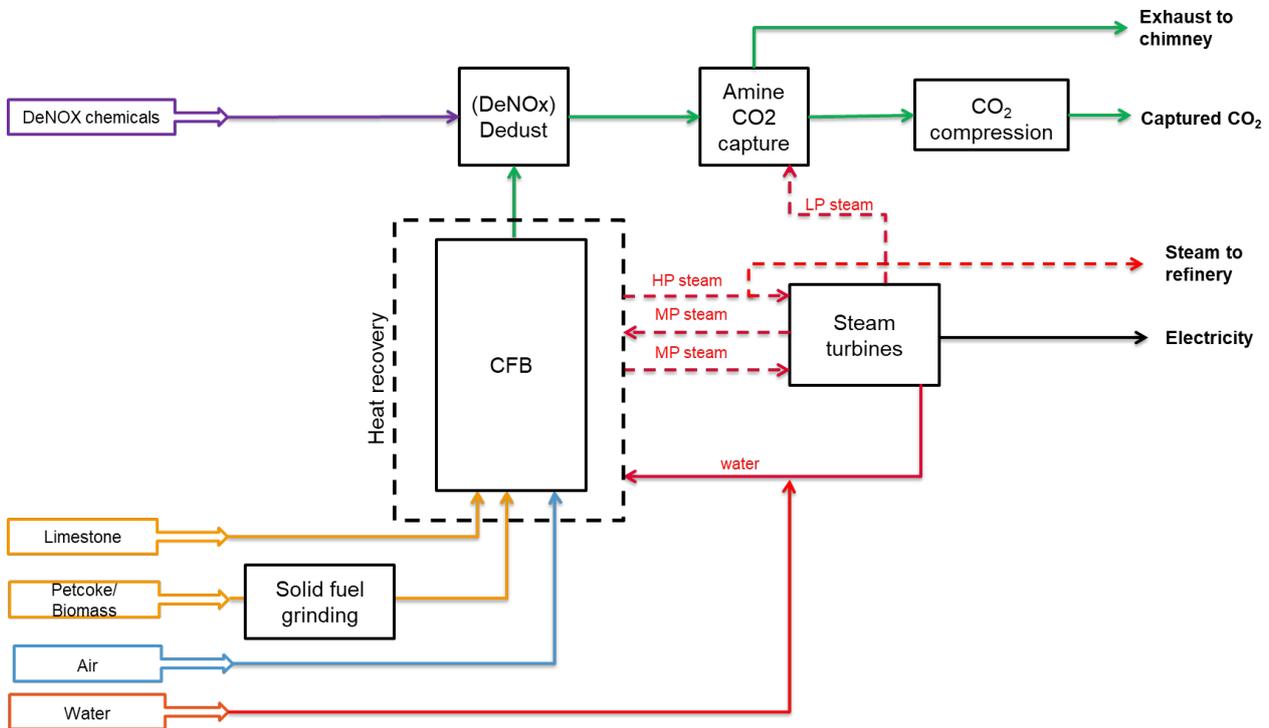


Figure 2-3: Block diagram of a Circulating Fluidized Bed with CO₂ amine capture as reference case

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 SO_x 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 NO_x 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 deNO_x if necessary and for dedust, prior to the CO₂ amine post-combustion capture unit and CO₂ 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.

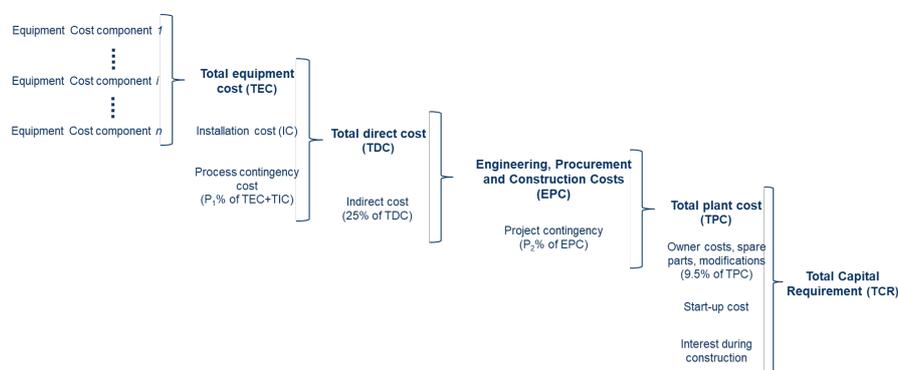


Figure 3-1: The Bottom-Up approach for estimation of total plant costs [3]

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 processes 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 production facilities may be considered to be Outside battery limit (OSBL) units². In such cases, the storage and utilities production 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 CO₂ emission intensity of 62.3 €/MWh and 253 kgCO₂/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 CO₂ 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 *CO₂ capture ratio* (CCR) is a common KPI for CO₂ capture processes. It is defined as the CO₂ captured $\dot{m}_{CO_2,capt}$ divided by the CO₂ generated $\dot{m}_{CO_2,gen}$:

$$CCR = \frac{\dot{m}_{CO_2,capt}}{\dot{m}_{CO_2,gen}}$$

A minimum CO₂ capture ratio of 90% must be considered, but the optimal CO₂ capture ratio will be calculated as a function of the process technology.

The *CO₂ emission factor* in g CO₂/MWh evaluates the direct CO₂ emissions from the plant.

The *CO₂ avoided* evaluates the direct CO₂ 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:

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

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 CO₂ Avoided) is traditionally used to compare the increased equivalent fuel consumption to avoid the emission of CO₂, 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 CO₂ Avoided) index is defined by the following equation, quantifying the energy cost associated with the increased equivalent fuel consumption to avoid the emission of CO₂ the CHP or power plant.

$$Cost\ SPECCA \left[\frac{\text{€}}{t_{CO_2}} \right] = \frac{HR_{CCS} - HR_{ref}}{e_{ref} - e_{CCS}} \cdot EC$$

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 CO₂ 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 [$€/MW_e h$] 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.

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

Cost of CO₂ 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.

$$CAC \left[\frac{\text{€}}{t_{CO_2, avoided}} \right] = \frac{LCOE_{CCS} - LCOE_{ref}}{e_{ref} - e_{CCS}}$$

3.2.2.2 Study cases delivering both heat and power for refinery cases

Cost of CO₂ 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 CO₂ emissions [8].

$$CAC \left[\frac{\text{€}}{t_{CO_2, avoided}} \right] = \frac{NPV\ cost_{CCS} - NPV\ cost_{ref}}{NPV\ emissions_{ref} - NPV\ emissions_{CCS}}$$

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 CO₂ 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 CO₂ 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

Results	Unit	CFB without CO ₂ capture		CFB with CO ₂ capture	
		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 CO ₂ 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
- CO₂ Flue gas treatment section
- CO₂ capture section (for CFB with solvent-based capture plant)
- CO₂ 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

- CO₂ Flue gas treatment section
- CO₂ 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	Item	Tag	Description
CLC Reaction (S100)			Flue Gas Treatment / Hamon Eqp (S600.2)		
101	AR	Air reactor	CONFIDENTIAL		
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)				Bottom Solid Discharge (S700)	
401	X-401	Ox carrier unloading system	701	/	ASH handling equipment
402	X-402	Ox carrier conveyor system			
Feed Preparation (S500)			Firefighting (S800)		
501	/	Solid fuel unloading system	301	/	Fire water pumps building
502	/	Solid fuel conveyor to silo	802	/	Fire water storage tank
503	T-501	Solid fuel storage silo			
504	X-502	Solid fuel conveyor to grinder	Electrical Generation		
505	CRUSH	Solid fuel grinding machine	E01	/	Generator circuit breaker
506	T-502	Fuel daily storage	E02	/	Auxiliary transformer
			E03	/	Step-up transformer
			E04	/	E-room
Flue Gas Treatment & Compression (S600.1)			Miscellaneous		
601	HXGREC	Recycle CO2/O2 depl. air exch.	M01	/	Control & administration building
602	K-630	CO2 compressor package	M02	/	Workshop & store building
603	C-630	CO2 drying column	M03	/	Employee parking
604	X-630	TEG regeneration skid	M04	/	Visitor parking
605	C-631	CO2 direct contact cooler	M05	/	Truck site access parking
606	P-630A/B	DCC circulation pump	M06	/	Truck gate house
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			

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 consumption
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

Reminder: 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 Ctg)	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)

CO₂ 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 Ctg)	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 Variable 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 Variable 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 _e h	817,9	112,3	22,6
CO2 captured	kg CO2/MW _e h	-	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 CO₂ avoided cost for the CLC A2 case is quite low at 18.6 €/tCO₂ as it is compared with a CFB without capture unit, which emits a high amount of CO₂ to the atmosphere.

The CO₂ 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 CO₂. A sensitivity study on this ratio is done in section 4.5.3.1 .

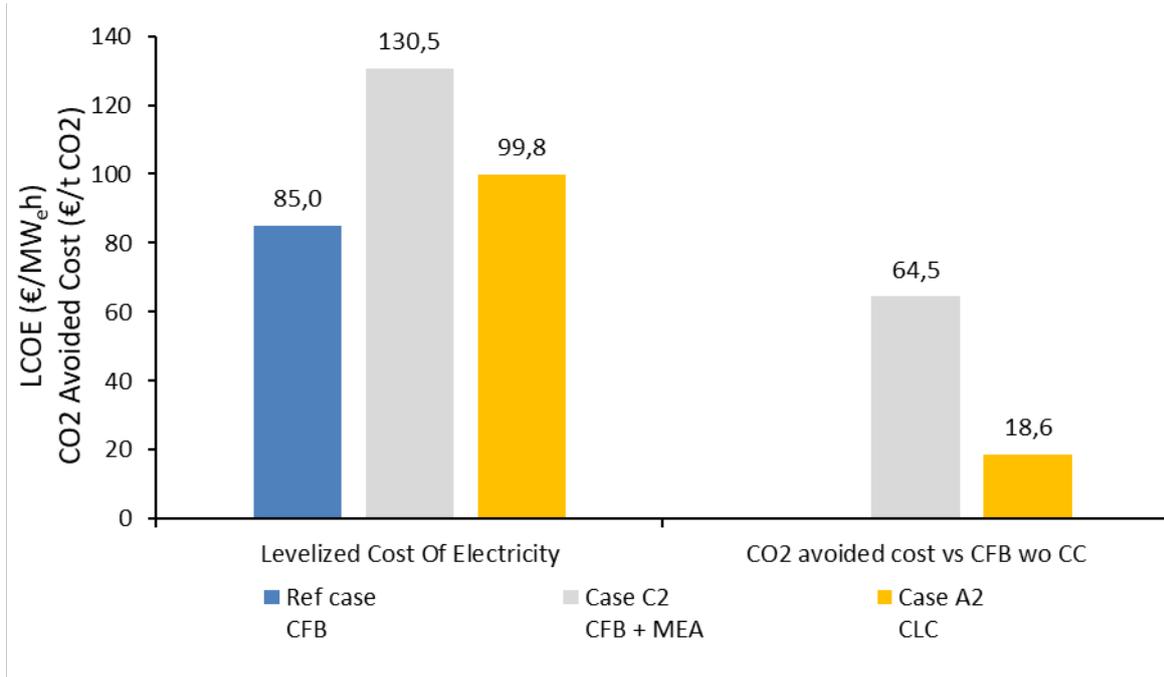


Figure 4-3: LCOE and CO₂ avoided cost for Power cases

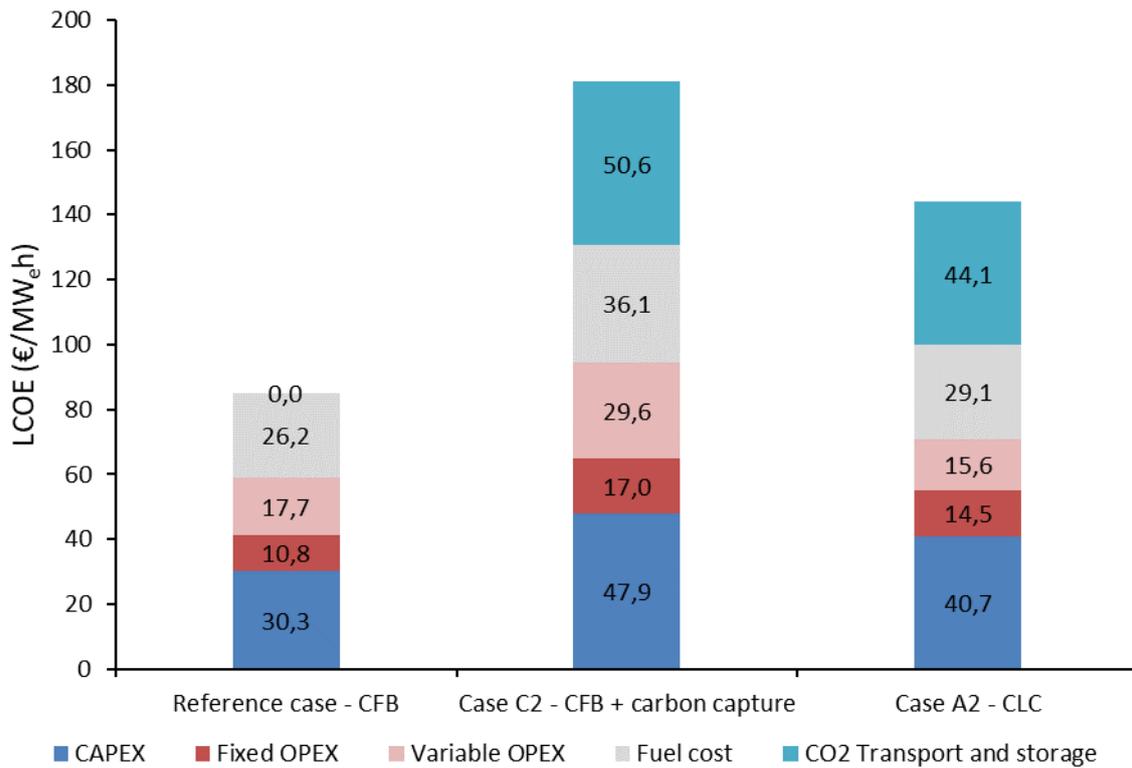


Figure 4-4: LCOE cost split for Power cases with 50 €/t transport and storage cost

Assuming a cost of 50 €/t for CO₂ 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
CO ₂ capture ratio	%	0,0	90,0	97,5
Residual Emitted CO ₂	t/h	82,0	11,2	2,4
Captured CO ₂	t/h	-	100,5	91,8
Captured CO ₂	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
CO ₂ Avoided Cost vs CFB wo CC **	€/ton CO ₂ avoided	-	71,5	33,3
CO ₂ emission	kg CO ₂ /MW _{th} h	341,5	34,1	8,5
CO ₂ captured	kg CO ₂ /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.

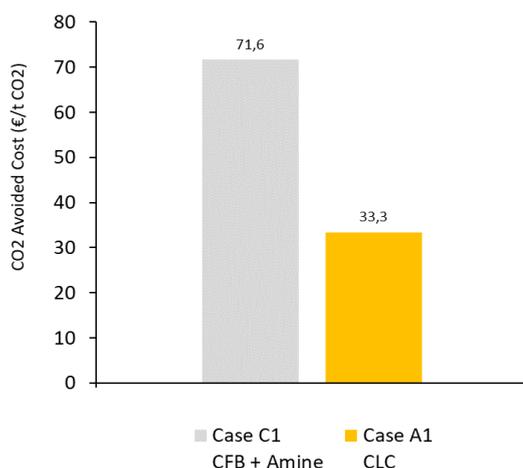


Figure 4-5: CO₂ avoided cost for Refinery cases

4.5.3 Sensitivity on case – Power cases 200 MWe

4.5.3.1 Petcoke price sensitivity

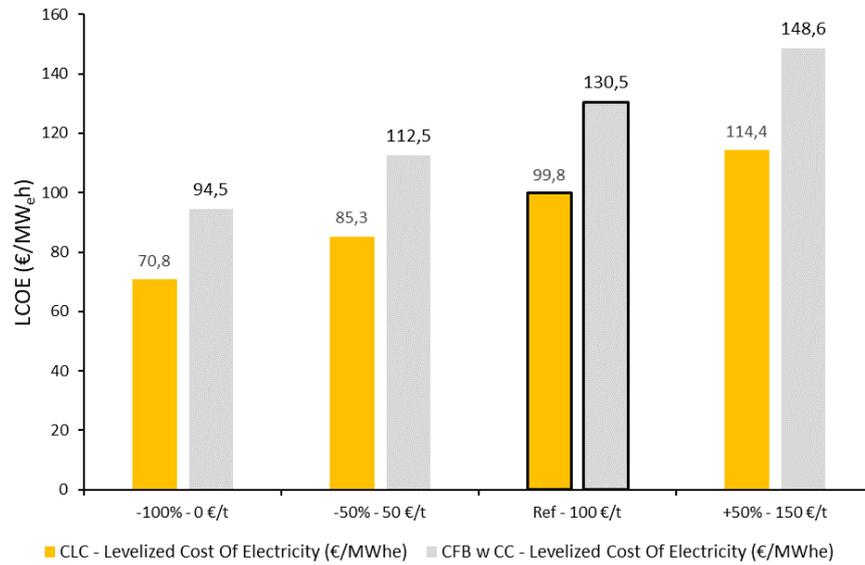


Figure 4-6: CLC Petcoke price LCOE sensitivity for Power cases

4.5.3.2 OC price / Lifetime sensitivity

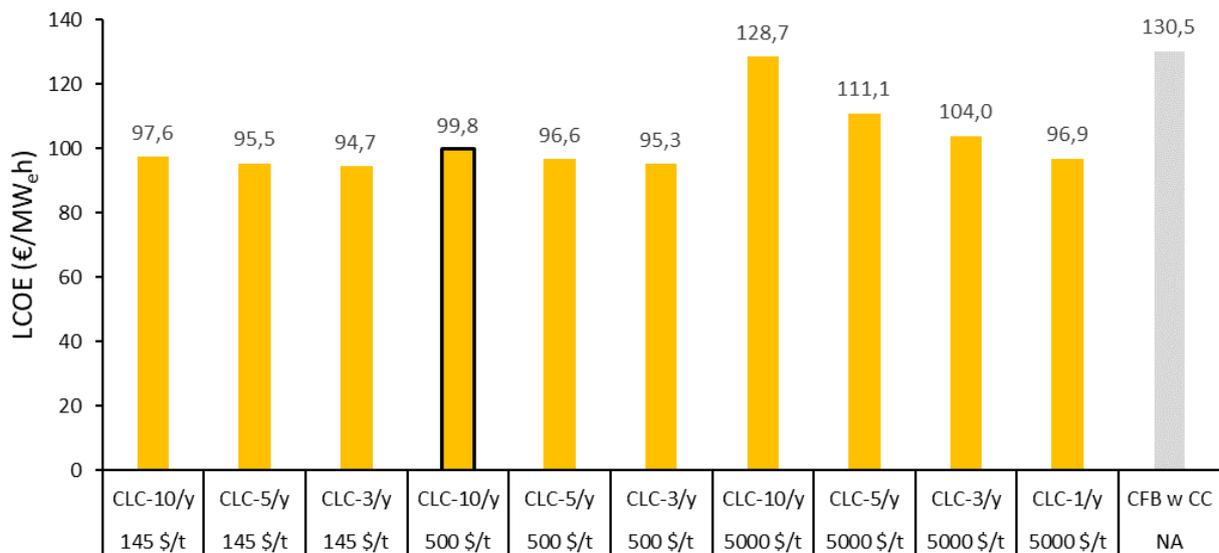


Figure 4-7: OC Price/Lifetime LCOE sensitivity for Power cases

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 lifetime) should be further assessed considering the environmental impact.

4.5.3.3 Solid waste disposal cost sensitivity

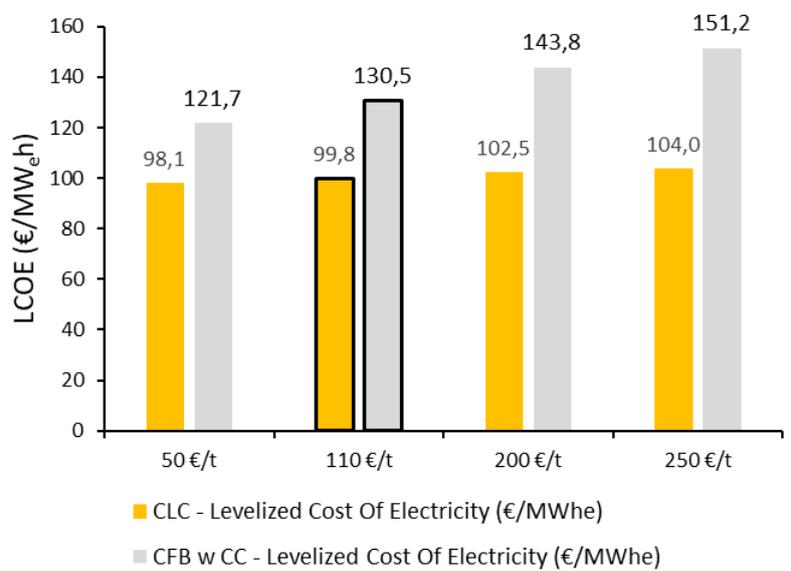


Figure 4-8: Solid waste disposal price LCOE sensitivity for Power cases

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

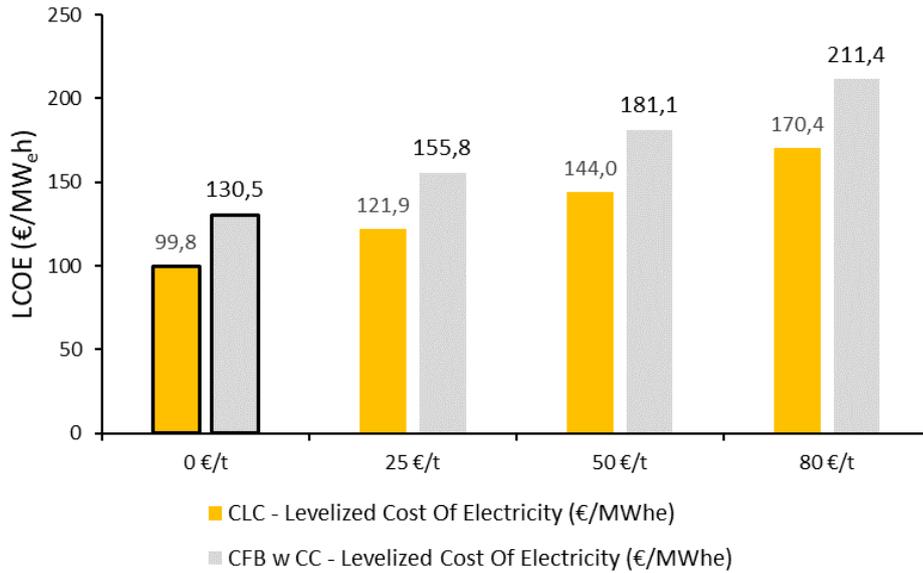


Figure 4-9: Transport and storage price LCOE sensitivity for Power cases

CFB with carbon capture and CLC case are handling about the same amount of CO₂, and transport and storage costs are affecting both cases significantly. This is pushing to build a CLC near a CO₂ network or near a potential storage place. This parameter will have lower impact on NGCC case as the amount of CO₂ produced is nearly half.

4.5.3.1 Carbon stripper efficiency in the Fuel Reactor

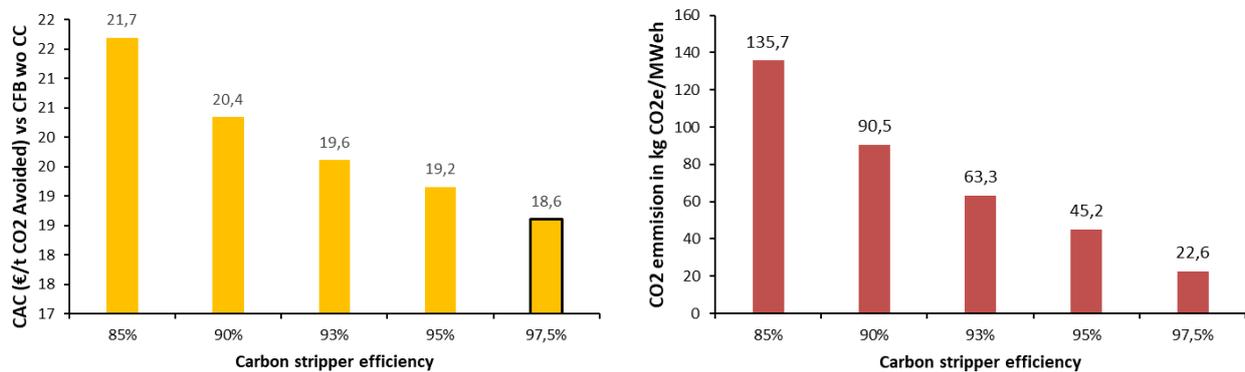


Figure 4-10: Carbon stripper efficiency CAC and CO₂ emissions sensitivity for CLC Power cases

The CO₂ 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 CO₂ avoided cost could increase by 1.8 €/ tCO₂ 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. DeSO_x 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 CO₂ capture is given below in Table 5-1. The cases included is the NGCC cases with MEA and PZ/AMP solvent-based CO₂ 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 CO₂ 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 CO₂ capture

Results	Unit	NGCC with MEA CO ₂ capture			NGCC with PZ/AMP CO ₂ capture		
		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 CO₂ capture section (for NGCC-CCS plant)
- CO₂ 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	589
CO2 capture	40	36	5 %	80	129	
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	611
CO2 capture	41	37	10 %	85	138	
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 _e h)	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 CO₂ 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.

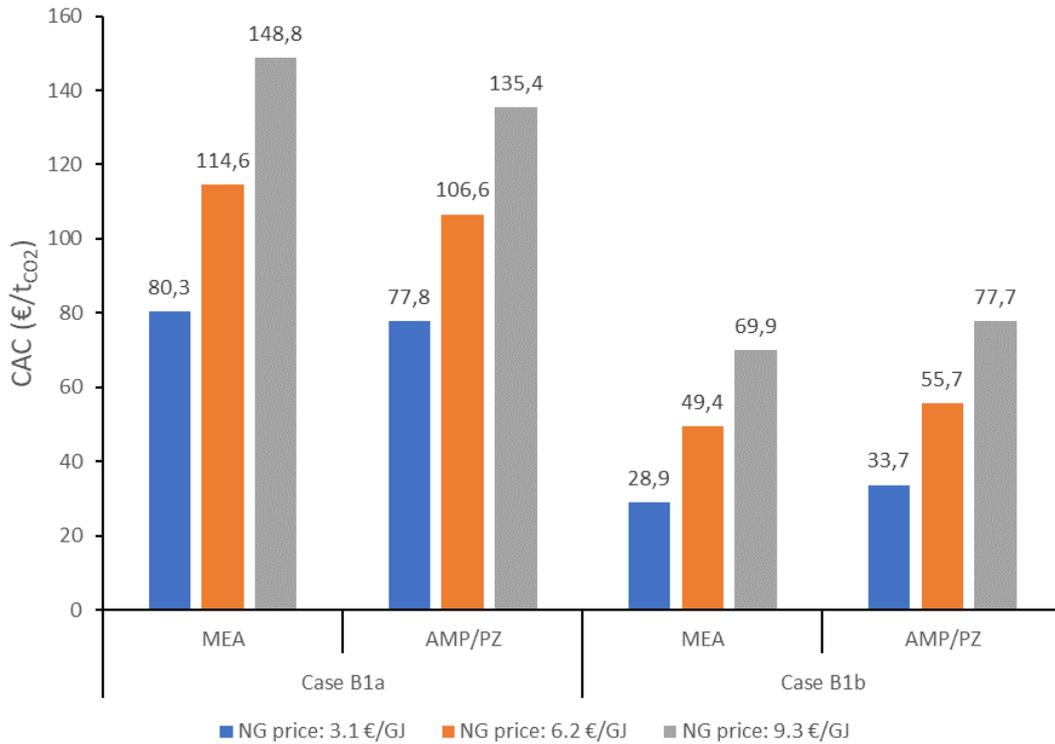


Figure 5-1: Impact of natural gas price on CO₂ avoided costs of the NGCC with MEA and AMP/PZ-based CO₂ capture in the B1a and B1b case vs NGCC wo CC.

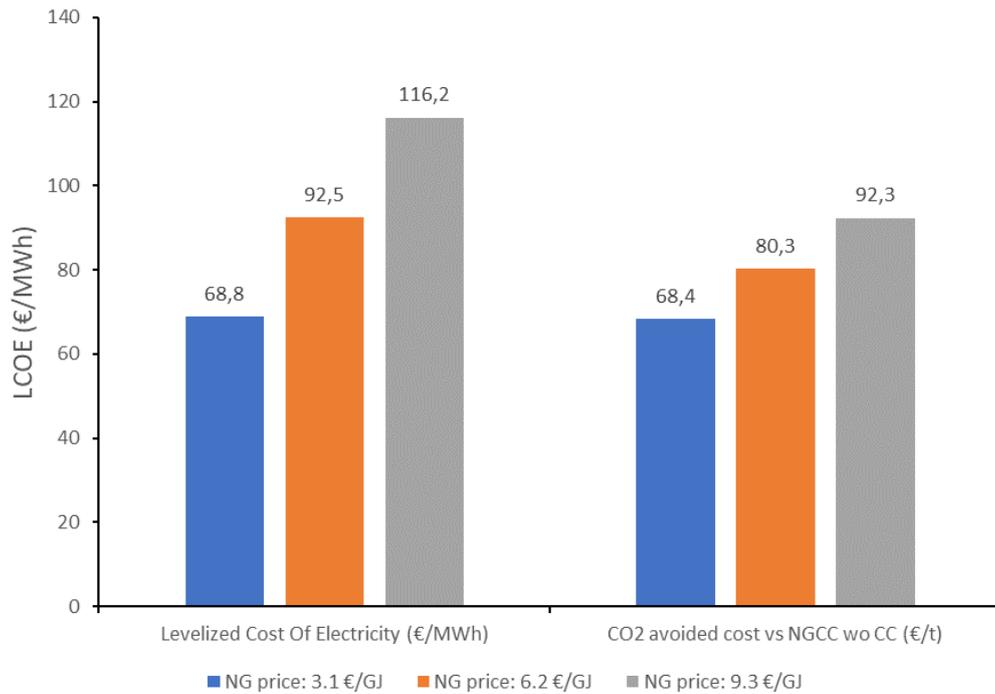


Figure 5-2: Impact of natural gas price on LCOE, and CO₂ avoided costs of the NGCC with MEA-based CO₂ capture in the B2 case

5.6.2 Transport and storage cost

As for the CLC, the levelized cost of electricity and CO₂ avoidance costs of the NGCC with solvent-based capture is significantly impacted by the cost of CO₂ transport and storage. However, as the amount of CO₂ 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 CO₂ network or near a potential storage site, would be beneficial for comparison to the NGCC with CCS.

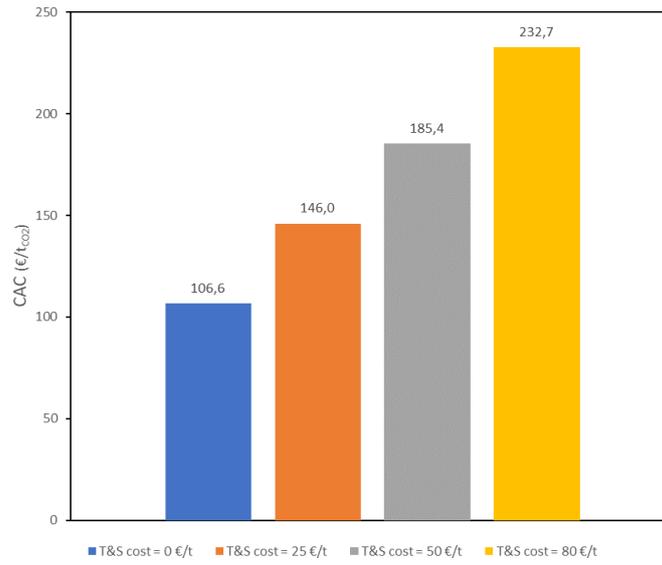


Figure 5-3: Impact of CO₂ transport and storage cost on CO₂ avoided costs of the NGCC with AMP/PZ-based CO₂ capture in the B1a case vs NGCC wo CC.

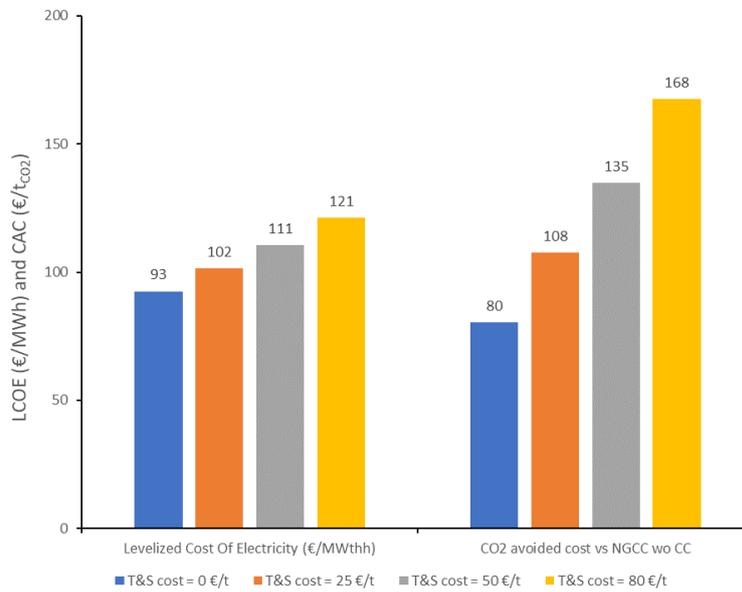


Figure 5-4: Impact of CO₂ transport and storage cost on LCOE, and CO₂ avoided costs of the NGCC with MEA-based CO₂ capture in the B2 case

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 CO₂ 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 €/t_{CO2}).
- 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 CO₂ 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 CO₂. Adding a transport and storage cost for the CO₂ will certainly push the balance toward the NGCC with capture case, as this case produces only half the CO₂ 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 CO2/MW _e h	817,9	112,3	22,6	366,4	43,5
CO2 captured	kg CO2/MW _e h	-	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

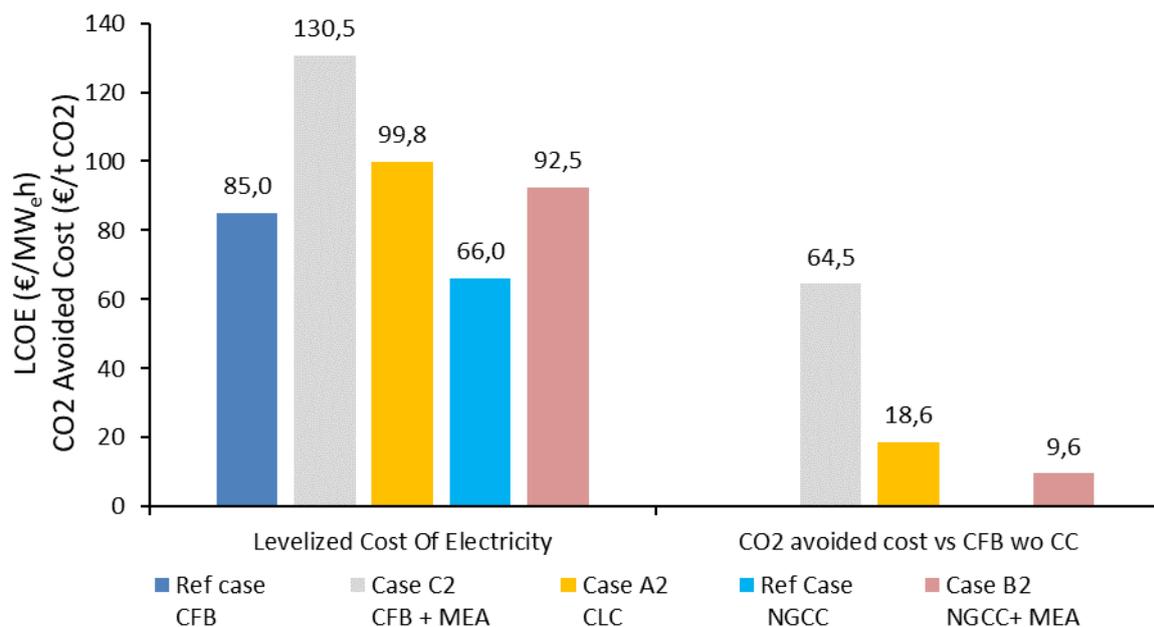


Figure 6-1: All cases LCOE and CO₂ avoided cost for Power cases

6.1.2 CO₂ 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 CO₂ emissions, considering a CO₂ tax is required to provide the most meaningful 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 CO₂ than the NGCC unit with capture and is thus less sensitive to CO₂ taxes price.

It can also be observed that with CO₂ tax levels than can be expected in the near future (below 200 €/t), the NGCC with CO₂ 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.

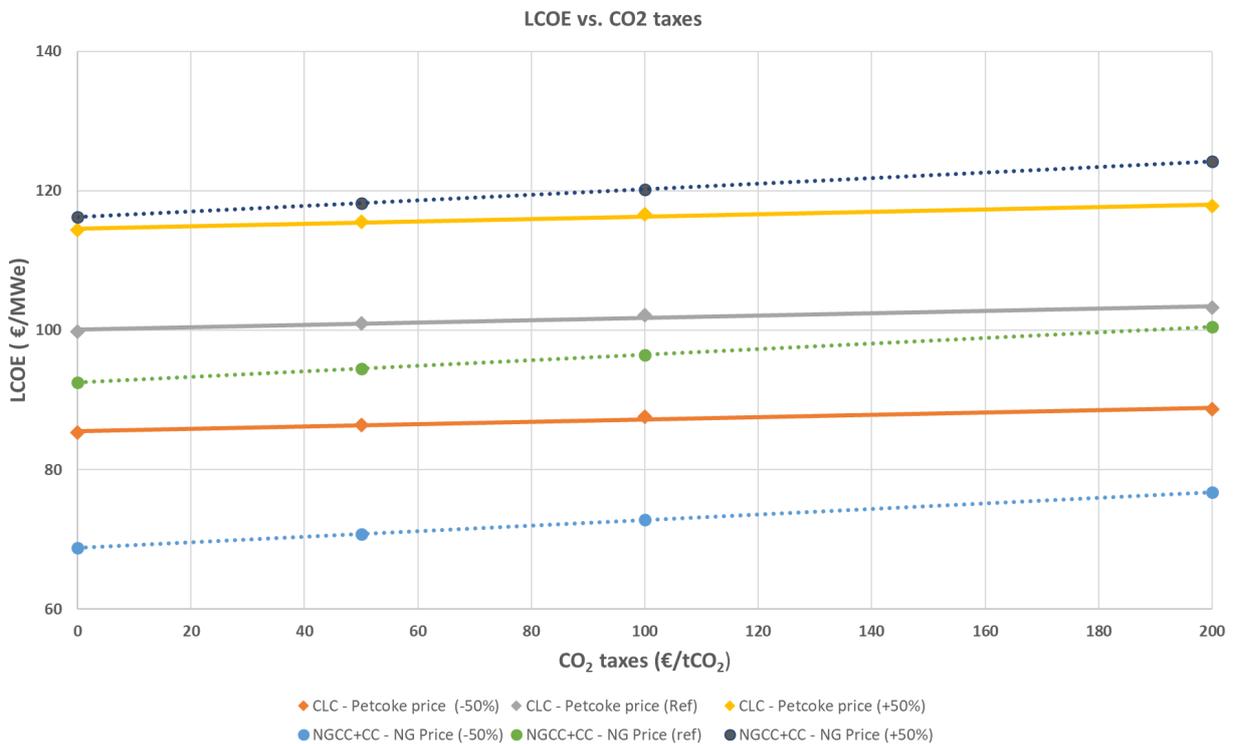


Figure 6-2: CO₂ taxes sensitivity on LCOE for Power cases at 0€/t Transport and storage cost

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 CO₂ switching price [9] that leads to an identical LCOE (including emissions cost) for the two options. The CO₂ switching price can be calculated as follow.

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

Figure 6-4 present the CO₂ 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 CO₂ 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 CO₂ tax. The red cells represent the cases where NGCC with carbon capture will be more competitive than CLC unless the CO₂ price reaches at least 200€/t. The orange cells represent the cases where CLC could be better than NGCC with carbon capture for CO₂ 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.

	-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
		-100%	-90%	-80%	-70%	-60%	-50%	-40%	-30%	-20%	-10%	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%

Figure 6-3: CO₂ 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 CO₂ 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 CO₂ avoidance cost in comparison. The CLC and CFB with MEA result in CO₂ avoidance cost of 33.3 and 71.5 €/t, while the NGCC with CO₂ capture even yield a negative CO₂ 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 CO₂ avoidance cost of 106.6 €/t. Although better than the CFB with MEA (CO₂ avoidance cost of 378 €/t), CLC results in a CO₂ avoidance cost (184.62 €/t) that is less than twice the one of the NGCC with CO₂ 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 additional steam for MEA reboiler is produced by a simple low cost boiler without 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 CO₂ emissions represent a fifth of the ones of the NGCC with capture, it is worth understanding if future CO₂ tax levels could make CLC more cost efficient than NGCC with CO₂ capture. However, calculation of the CO₂ 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 CO₂ 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 CO₂ will certainly further push the balance towards the NGCC with capture, since this case produces only about half of the CO₂ 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}	341,5	34,1	8,5	206,9	55,8
CO2 captured	kg CO2/MW _{th}	-	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 CO₂ capture in the refinery case.

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%
-50%	277	314	351	388	424	461	498	535	572	609	645	682	719	756	793	830	866	903	940	977	1014
-45%	251	288	325	362	399	435	472	509	546	583	620	656	693	730	767	804	841	877	914	951	988
-40%	225	262	299	336	373	410	446	483	520	557	594	631	667	704	741	778	815	852	888	925	962
-35%	200	237	273	310	347	384	421	457	494	531	568	605	642	678	715	752	789	826	863	899	936
-30%	174	211	248	284	321	358	395	432	468	505	542	579	616	653	689	726	763	800	837	874	910
-25%	148	185	222	259	295	332	369	406	443	479	516	553	590	627	664	700	737	774	811	848	885
-20%	122	159	196	233	270	306	343	380	417	454	490	527	564	601	638	675	711	748	785	822	859
-15%	96	133	170	207	244	281	317	354	391	428	465	502	538	575	612	649	686	722	759	796	833
-10%	71	107	144	181	218	255	292	328	365	402	439	476	513	549	586	623	660	697	733	770	807
-5%	45	82	118	155	192	229	266	303	339	376	413	450	487	524	560	597	634	671	708	744	781
0%	19	56	93	129	166	203	240	277	314	350	387	424	461	498	535	572	608	645	682	719	755
5%	-7	30	67	104	140	177	214	251	288	325	361	398	435	472	509	546	582	619	656	693	730
10%	-33	4	41	78	115	151	188	225	262	299	336	372	409	446	483	520	557	593	630	667	704
15%	-59	-22	15	52	89	126	162	199	236	273	310	347	383	420	457	494	531	568	604	641	678
20%	-84	-48	-11	26	63	100	137	173	210	247	284	321	358	394	431	468	505	542	579	615	652
25%	-110	-73	-37	0	37	74	111	148	184	221	258	295	332	369	405	442	479	516	553	590	626
30%	-136	-99	-62	-26	11	48	85	122	159	195	232	269	306	343	380	416	453	490	527	564	601
35%	-162	-125	-88	-51	-15	22	59	96	133	170	206	243	280	317	354	391	427	464	501	538	575
40%	-188	-151	-114	-77	-40	-4	33	70	107	144	181	217	254	291	328	365	402	438	475	512	549
45%	-214	-177	-140	-103	-66	-29	7	44	81	118	155	192	228	265	302	339	376	413	449	486	523
50%	-239	-203	-166	-129	-92	-55	-18	18	55	92	129	166	203	239	276	313	350	387	424	460	497

Figure 6-4: CO₂ switching price (€/t) for the refinery cases at 0€/t transport and storage cost

7 STRATEGIES FOR THE CLUSTERING AND DEPLOYMENT OF CLC-CCS - FULL CCS CHAIN EVALUATIONS AND COMPARISONS

7.1 Scenarios and methodology

The CO₂ 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 CO₂ 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 two steps are assumed to take place through dedicated infrastructure, the last four 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 MtCO₂/y). Considering a Belgium location, these numbers would also match clustering with some of the many in-development projects in the North-West European region⁴.

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

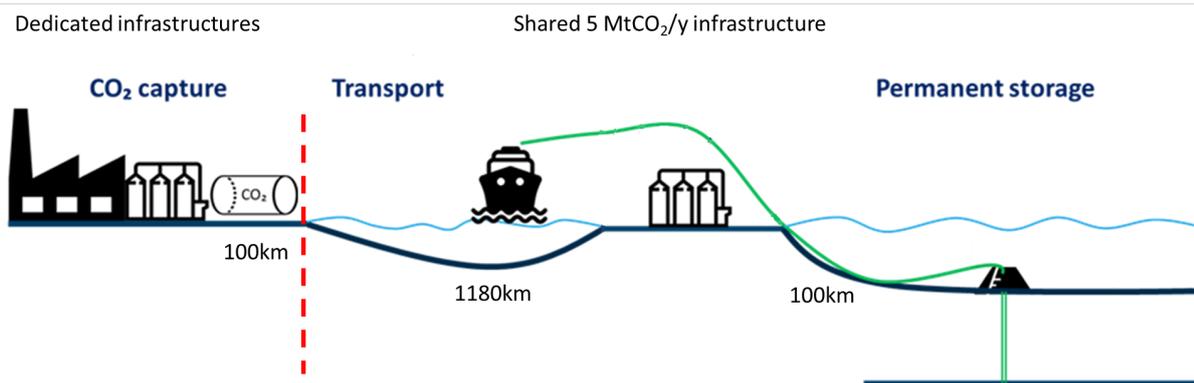


Figure 7-1: CCS chain considered

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]

⁴ IEA, CCUS Projects Database, IEA, Paris <https://www.iea.org/data-and-statistics/data-product/ccus-projects-database>.

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 CO₂: 15 and 7 barg.
- Possible ship size: 7500 m³ 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 CO₂-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 CO₂ at low-pressure and being able to optimise the ship size is the best strategy to transport the CO₂.
- With the best transport strategy, the complete LCOE of the two power options (CLC and NGCC with capture) is respectively 126 and 105 €/MWh.
- Since more CO₂ 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 26.4 vs 12.9 €/MWh (CLC vs NGCC with capture).
- Similarly, CLC results in much more CO₂ emissions during the transport because of the significantly larger quantities of CO₂ 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 (49 for CLC vs. 55 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 CO₂-intensity of the power cases for the different full-chain scenarios.

Shipping pressure (barg) Ship size scenario		Refinery cases									
		15 barg shipping				7 barg shipping				Cost-optimal strategy	
		7500 m ³ ships		Optimal ships size		7500 m ³ 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	9.8	22.0	8.5	19.1	5.8	13.1	4.8	10.9	4.8	10.9
	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	110	136	109	133	106	128	105	126	105.4	126.1
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	26.5	11.9	26.6	10.5	23.6	10.5	23.6
	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	52.2	56.6	52.3	55.3	49.4	55.3	49.4

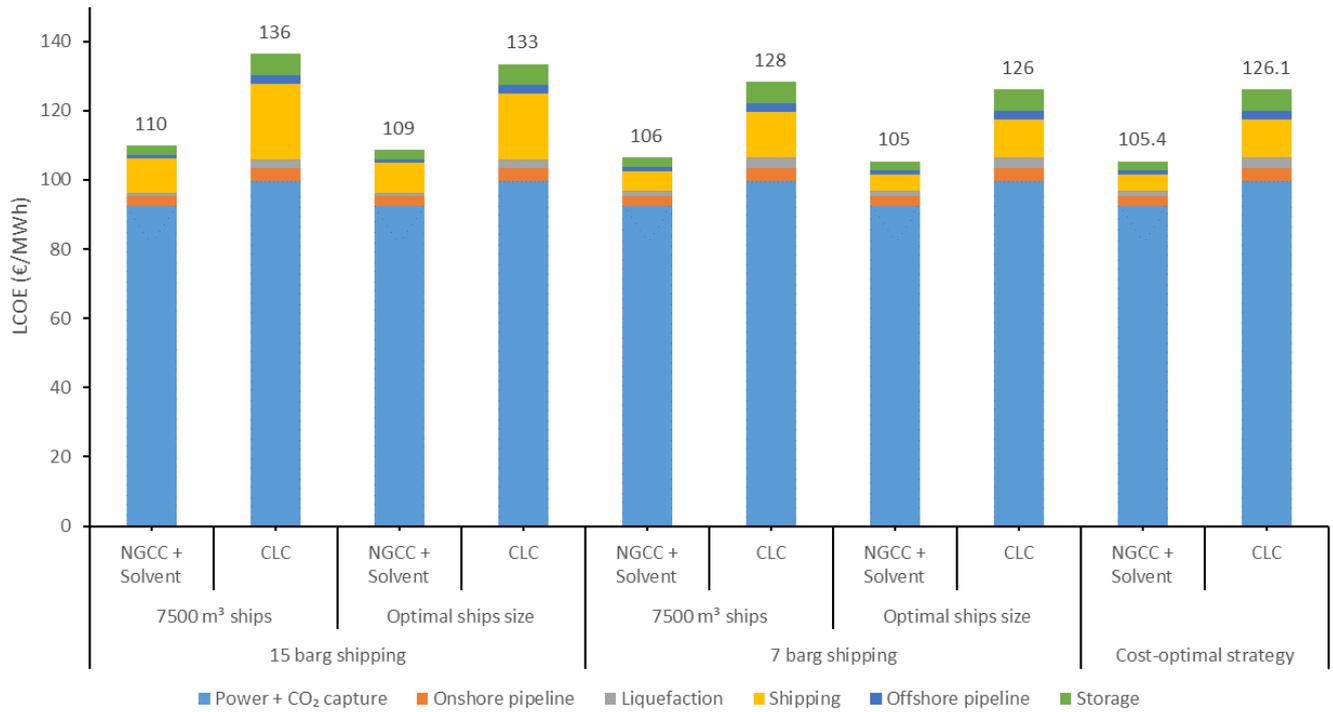


Figure 7-2: LCOE of the power cases for the different full-chain scenarios.

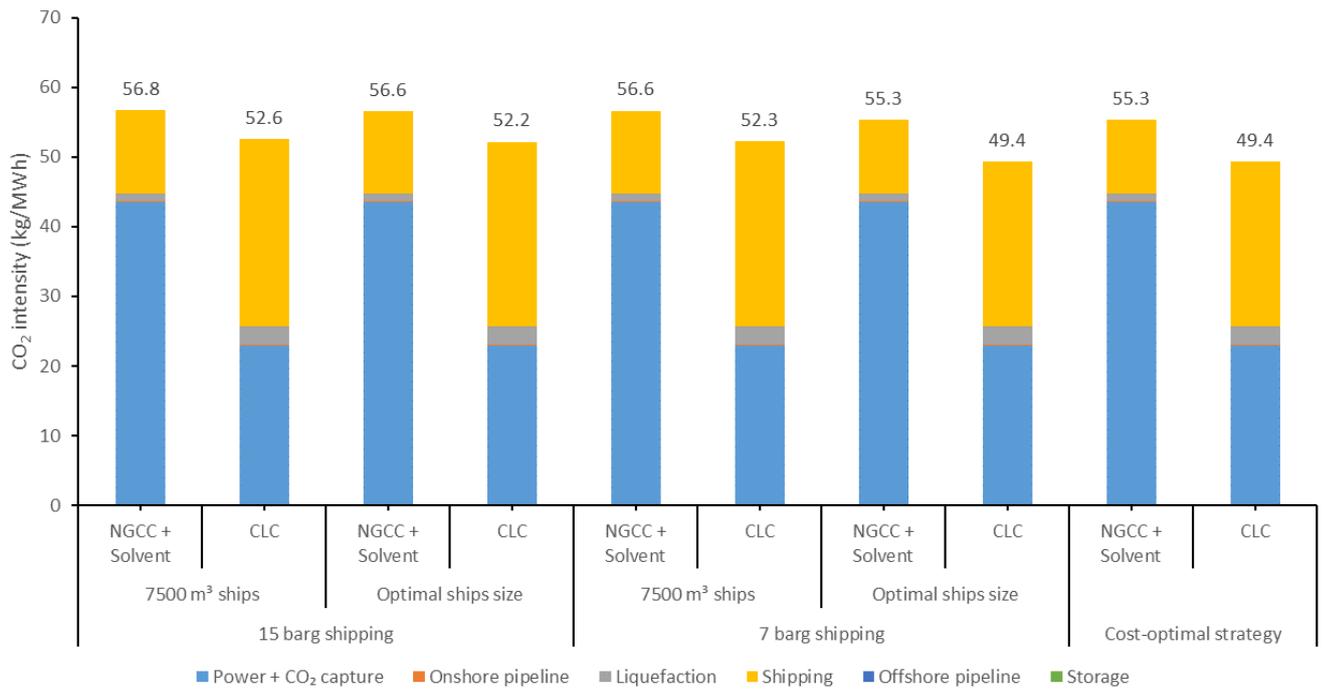


Figure 7-3: CO₂ intensity of the power cases for the different full-chain scenarios.

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 CO₂ 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 CO₂ at low-pressure and being able to optimise the ship size is the best strategy to transport the CO₂.
- With the best transport strategy, the complete NPV of costs of the two refinery cases (CLC and NGCC with capture) is respectively 1233 and 811 M€.
- As more CO₂ 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 257 vs 118 M€ (CLC vs NGCC with capture).
- Similarly, CLC result in much more CO₂ emissions during the transport as a result of the significantly larger quantities of CO₂ 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 for CLC vs. 11.6 kg/MWh for NGCC with CO₂ 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 CO₂ emissions penalty of 760 €/tCO₂ 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 CO₂ emissions of the refinery cases for the different full-chain scenarios.

Shipping pressure (barg)		Refinery cases									
		15 barg shipping				7 barg shipping				Cost-optimal strategy	
		7500 m ³ ships		Optimal ships size		7500 m ³ ships		Optimal ships size			
Ship size scenario		NGCC + Solvent	CLC	NGCC + Solvent	CLC	NGCC + Solvent	CLC	NGCC + Solvent	CLC	NGCC + Solvent	CLC
Power and capture technology		NGCC + Solvent	CLC	NGCC + Solvent	CLC	NGCC + Solvent	CLC	NGCC + Solvent	CLC	NGCC + Solvent	CLC
Power + CO ₂ capture	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	78	199	67	172	46	119	38	98	38	98
	Offshore pipeline	9	22	9	22	9	22	9	22	9	22
	Storage	22	55	22	55	22	55	22	55	22	55
	Sum	847	1326	837	1300	819	1254	811	1233	811	1233
NPV of cost (M€ _{disc})	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	1.06	2.70	1.06	2.72	0.94	2.41	0.94	2.41
	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	5.3	11.8	5.3	11.6	5.0	11.6	5.0
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	1.06	2.70	1.06	2.72	0.94	2.41	0.94	2.41
	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	5.3	11.8	5.3	11.6	5.0	11.6	5.0

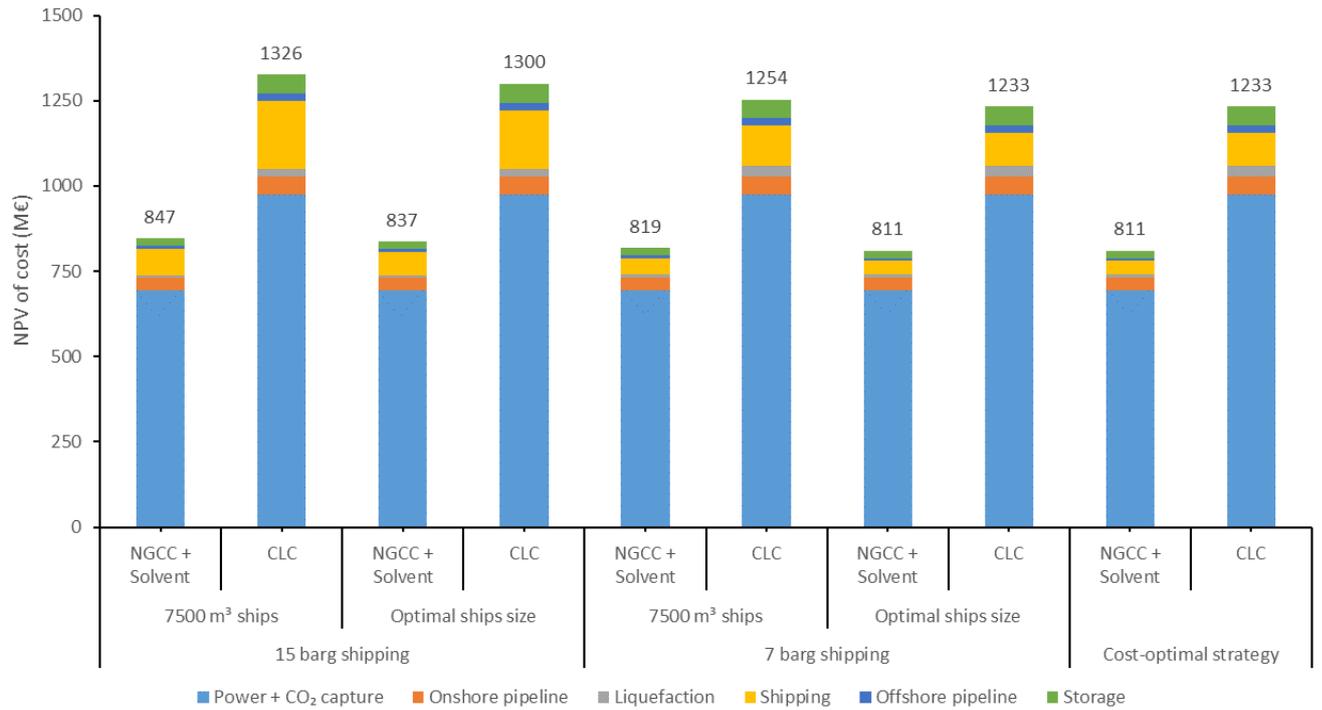


Figure 7-4: NPV of costs of the refinery cases for the different full-chain scenarios.

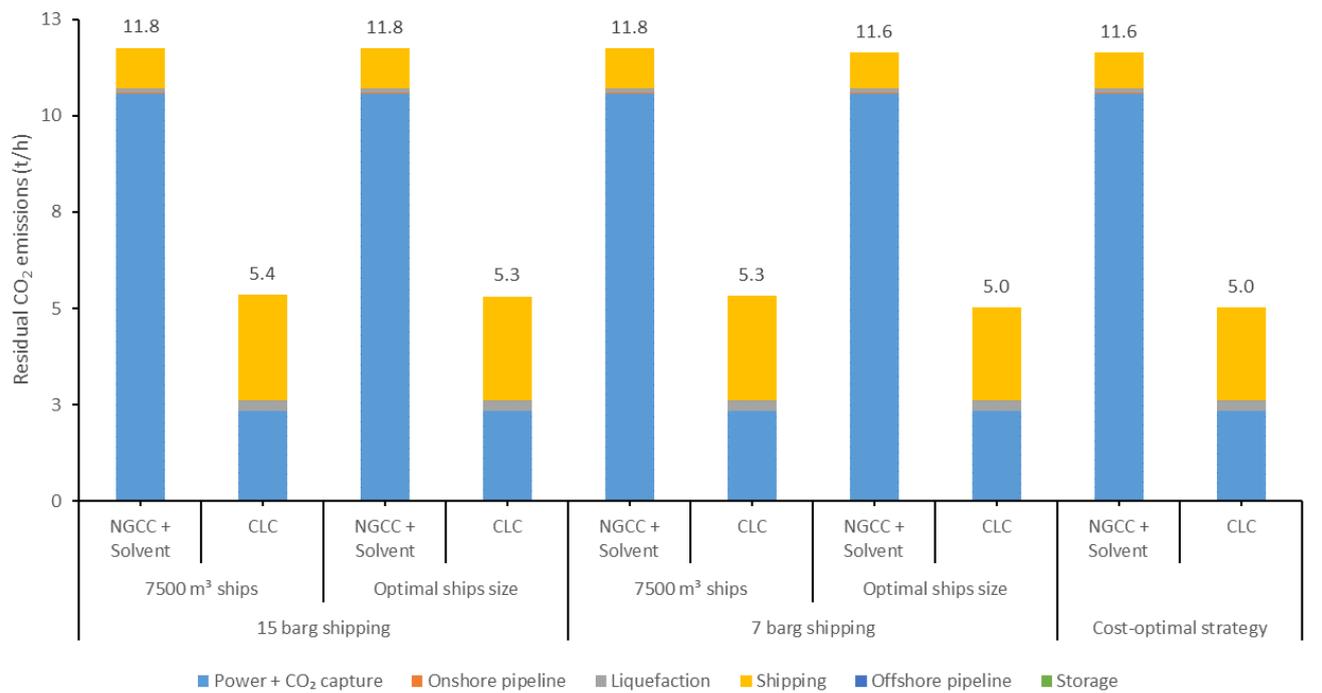


Figure 7-5: Residual CO₂ emissions of the refinery cases for the different full-chain scenarios.

7.4 Feedstock price sensitivity

Figure 7-6 and Figure 7-7 present the CO₂ 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 CO₂ emissions higher than 200 €/t is put in place.

Natural gas price	Petcoke price																				
	-50%	-45%	-40%	-35%	-30%	-25%	-20%	-15%	-10%	-5%	0%	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
-50%	2444	2909	3374	3839	4305	4770	5235	5700	6166	6631	7096	7562	8027	8492	8957	9423	9888	10353	10819	11284	11749
-45%	2064	2530	2995	3460	3925	4391	4856	5321	5787	6252	6717	7182	7648	8113	8578	9044	9509	9974	10439	10905	11370
-40%	1685	2150	2616	3081	3546	4012	4477	4942	5407	5873	6338	6803	7269	7734	8199	8664	9130	9595	10060	10525	10991
-35%	1306	1771	2237	2702	3167	3632	4098	4563	5028	5494	5959	6424	6889	7355	7820	8285	8750	9216	9681	10146	10612
-30%	927	1392	1857	2323	2788	3253	3719	4184	4649	5114	5580	6045	6510	6975	7441	7906	8371	8837	9302	9767	10232
-25%	548	1013	1478	1944	2409	2874	3339	3805	4270	4735	5200	5666	6131	6596	7062	7527	7992	8457	8923	9388	9853
-20%	169	634	1099	1564	2030	2495	2960	3425	3891	4356	4821	5287	5752	6217	6682	7148	7613	8078	8544	9009	9474
-15%	-211	255	720	1185	1650	2116	2581	3046	3512	3977	4442	4907	5373	5838	6303	6769	7234	7699	8164	8630	9095
-10%	-590	-125	341	806	1271	1737	2202	2667	3132	3598	4063	4528	4994	5459	5924	6389	6855	7320	7785	8250	8716
-5%	-969	-504	-38	427	892	1357	1822	2288	2753	3219	3684	4149	4614	5080	5545	6010	6475	6941	7406	7871	8337
0%	-1348	-883	-418	48	513	978	1443	1909	2374	2839	3305	3770	4235	4700	5166	5631	6096	6562	7027	7492	7957
5%	-1727	-1262	-797	332	134	599	1064	1530	1995	2460	2925	3391	3856	4321	4787	5252	5717	6182	6648	7113	7578
10%	-2107	-1641	-1176	-711	-245	220	685	1150	1616	2081	2546	3012	3477	3942	4407	4873	5338	5803	6268	6734	7199
15%	-2486	-2020	-1555	-1090	-625	-159	306	771	1237	1702	2167	2632	3098	3563	4028	4493	4959	5424	5889	6355	6820
20%	-2865	-2400	-1934	-1469	-1004	-538	-73	392	857	1323	1788	2253	2718	3184	3649	4114	4580	5045	5510	5975	6441
25%	-3244	-2779	-2313	-1848	-1383	-918	-452	13	478	943	1409	1874	2339	2805	3270	3735	4200	4666	5131	5596	6062
30%	-3623	-3158	-2693	-2227	-1762	-1297	-832	-366	99	564	1030	1495	1960	2425	2891	3356	3821	4287	4752	5217	5682
35%	-4002	-3537	-3072	-2607	-2141	-1676	-1211	-745	-280	185	650	1116	1581	2046	2512	2977	3442	3907	4373	4838	5303
40%	-4382	-3916	-3451	-2986	-2520	-2055	-1590	-1125	-659	-194	271	737	1202	1667	2132	2598	3063	3528	3993	4459	4924
45%	-4761	-4295	-3830	-3365	-2900	-2434	-1969	-1504	-1038	-573	-108	357	823	1288	1753	2218	2684	3149	3614	4080	4545
50%	-5140	-4675	-4209	-3744	-3279	-2814	-2348	-1883	-1418	-952	-487	-22	443	909	1374	1839	2305	2770	3235	3700	4166

Figure 7-6: CO₂ switching price (€/t) for the power cases once the full CCS is included

Natural gas price	Petcoke price																				
	-50%	-45%	-40%	-35%	-30%	-25%	-20%	-15%	-10%	-5%	0%	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
-50%	597	643	690	736	783	830	876	923	970	1016	1063	1110	1156	1203	1250	1296	1343	1389	1436	1483	1529
-45%	564	610	657	704	750	797	844	890	937	984	1030	1077	1124	1170	1217	1263	1310	1357	1403	1450	1497
-40%	531	578	624	671	718	764	811	858	904	951	998	1044	1091	1137	1184	1231	1277	1324	1371	1417	1464
-35%	498	545	592	638	685	732	778	825	872	918	965	1011	1058	1105	1151	1198	1245	1291	1338	1385	1431
-30%	466	512	559	606	652	699	746	792	839	885	932	979	1025	1072	1119	1165	1212	1259	1305	1352	1399
-25%	433	480	526	573	620	666	713	759	806	853	899	946	993	1039	1086	1133	1179	1226	1273	1319	1366
-20%	400	447	494	540	587	633	680	727	773	820	867	913	960	1007	1053	1100	1147	1193	1240	1287	1333
-15%	368	414	461	507	554	601	647	694	741	787	834	881	927	974	1021	1067	1114	1161	1207	1254	1300
-10%	335	381	428	475	521	568	615	661	708	755	801	848	895	941	988	1035	1081	1128	1174	1221	1268
-5%	302	349	395	442	489	535	582	629	675	722	769	815	862	909	955	1002	1048	1095	1142	1188	1235
0%	269	316	363	409	456	503	549	596	643	689	736	783	829	876	922	969	1016	1062	1109	1156	1202
5%	237	283	330	377	423	470	517	563	610	657	703	750	796	843	890	936	983	1030	1076	1123	1170
10%	204	251	297	344	391	437	484	531	577	624	670	717	764	810	857	904	950	997	1044	1090	1137
15%	171	218	265	311	358	405	451	498	544	591	638	684	731	778	824	871	918	964	1011	1058	1104
20%	139	185	232	279	325	372	418	465	512	558	605	652	698	745	792	838	885	932	978	1025	1071
25%	106	153	199	246	292	339	386	432	479	526	572	619	666	712	759	806	852	899	946	992	1039
30%	73	120	166	213	260	306	353	400	446	493	540	586	633	680	726	773	820	866	913	959	1006
35%	40	87	134	180	227	274	320	367	414	460	507	554	600	647	694	740	787	833	880	927	973
40%	8	54	101	148	194	241	288	334	381	428	474	521	568	614	661	707	754	801	847	894	941
45%	-25	22	68	115	162	208	255	302	348	395	442	488	535	581	628	675	721	768	815	861	908
50%	-58	-11	36	82	129	176	222	269	316	362	409	455	502	549	595	642	689	735	782	829	875

Figure 7-7: CO₂ 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

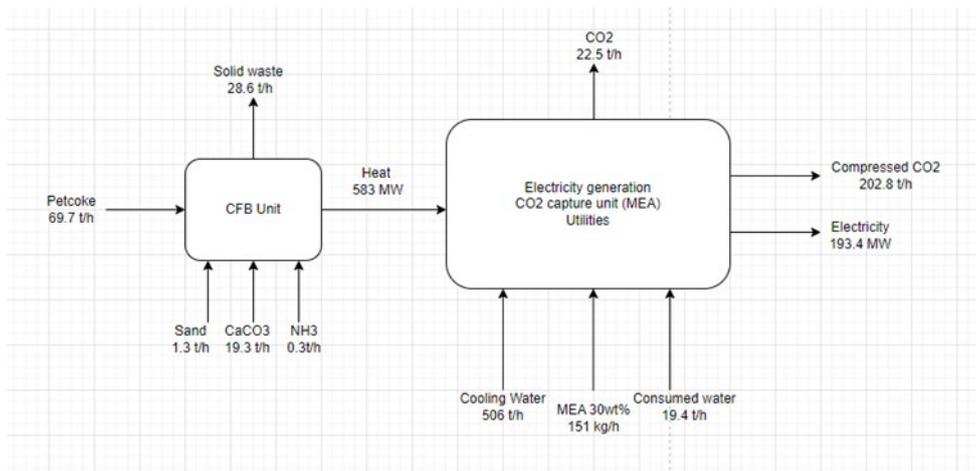


Figure 8-1: *Circulating Fluidized Bed process*

8.2.2 CLC process

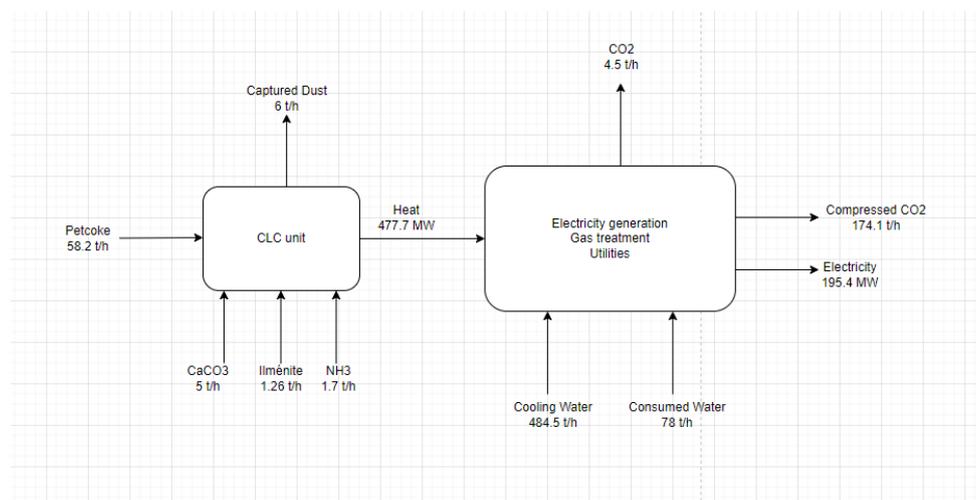


Figure 8-2: *Chemical Looping Combustion process*

8.2.3 NGCC process

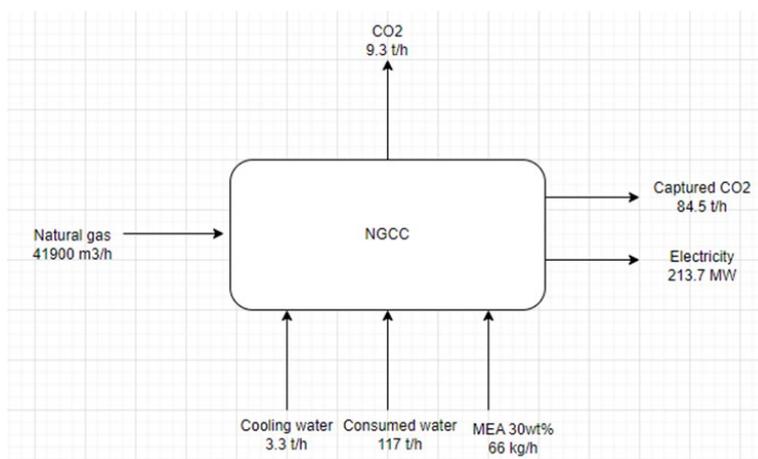


Figure 8-3: *Natural Gas Combined Cycle process*

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 negligible 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	Ilmenite, 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
CO₂ 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

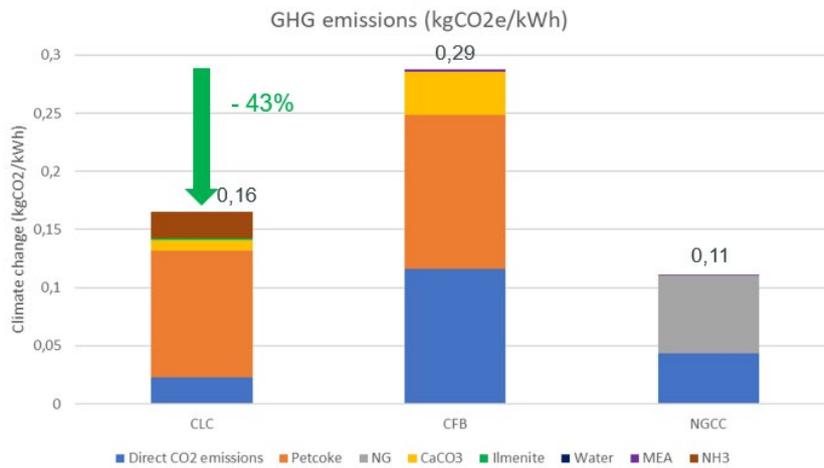


Figure 8-4: Impact on climate change

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%) while for CFB, emissions are due to petcoke (47%), CaCO₃ (13%) and direct process emissions (40%).

NGCC has the lowest GHG emissions.

8.5.2 Sensitivity study on CLC CO₂ capture rate

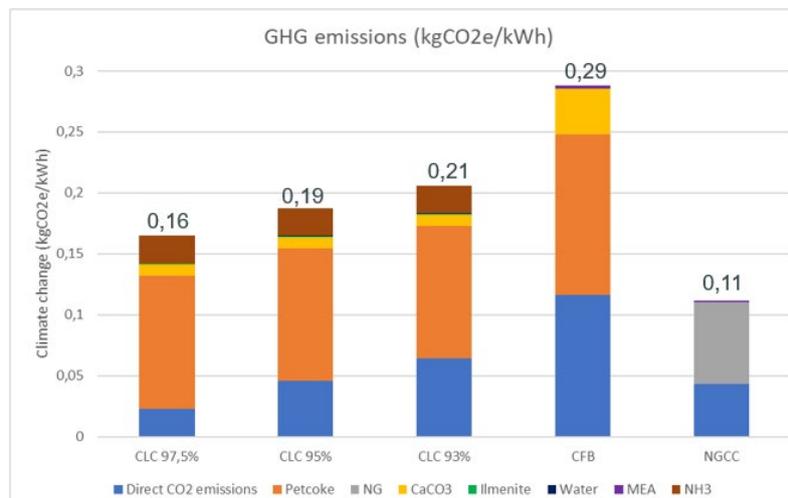


Figure 8-5: Impact on climate considering various CO₂ capture rate for the CLC process. No change in the CO₂ capture rate of CFB and NGCC.

Figure 8-5 shows that CLC impact on climate change depends on its CO₂ capture rate. It is reduced by 43% compared to CFB when the CO₂ capture rate is 97.5%. This rate is cut to 29% when the CO₂ capture rate is 93%.

8.5.3 Other environmental impacts

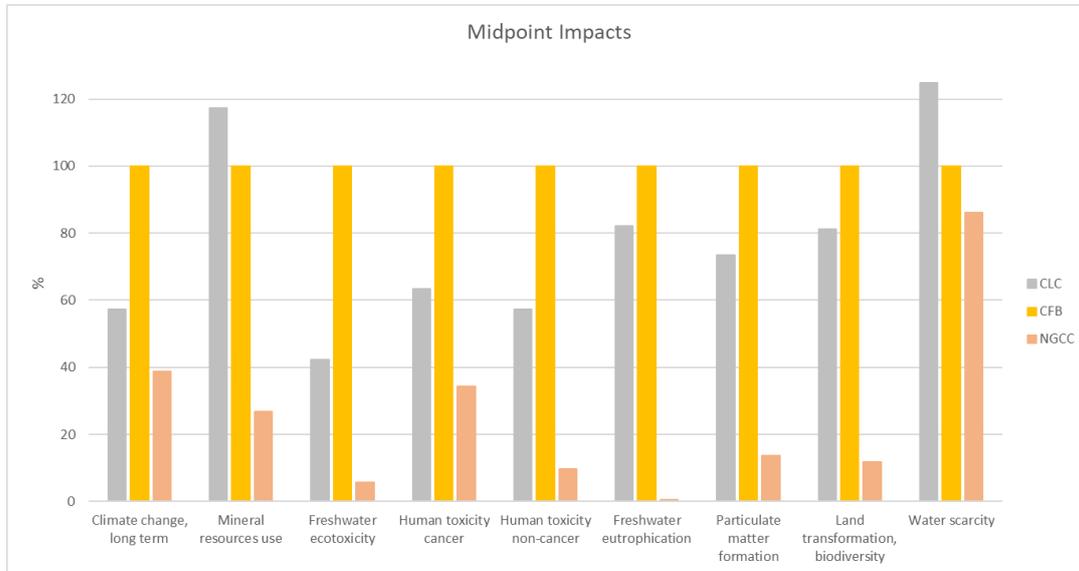


Figure 8-6: Other environmental impacts

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 CaCO₃ 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

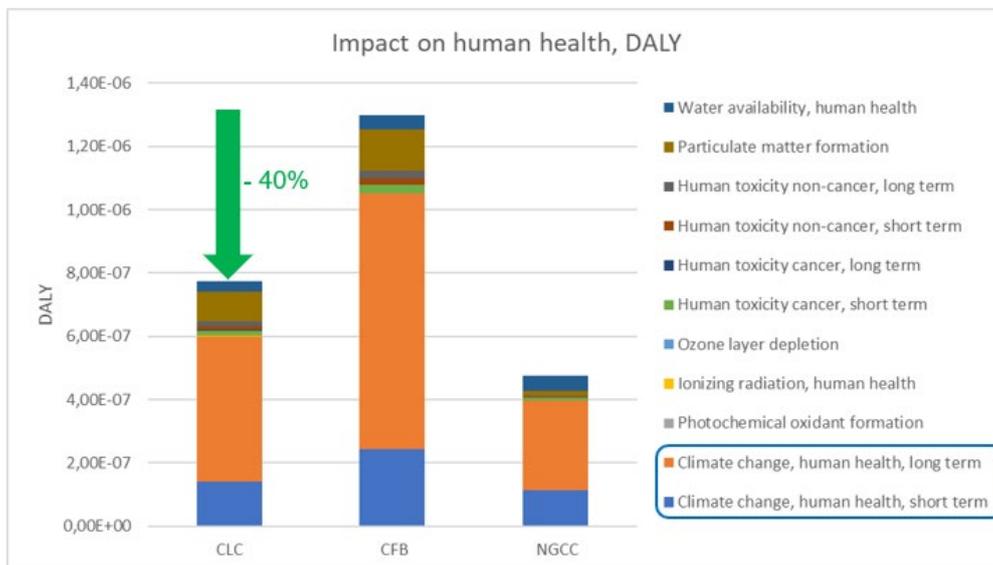


Figure 8-7: Impact on human health

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

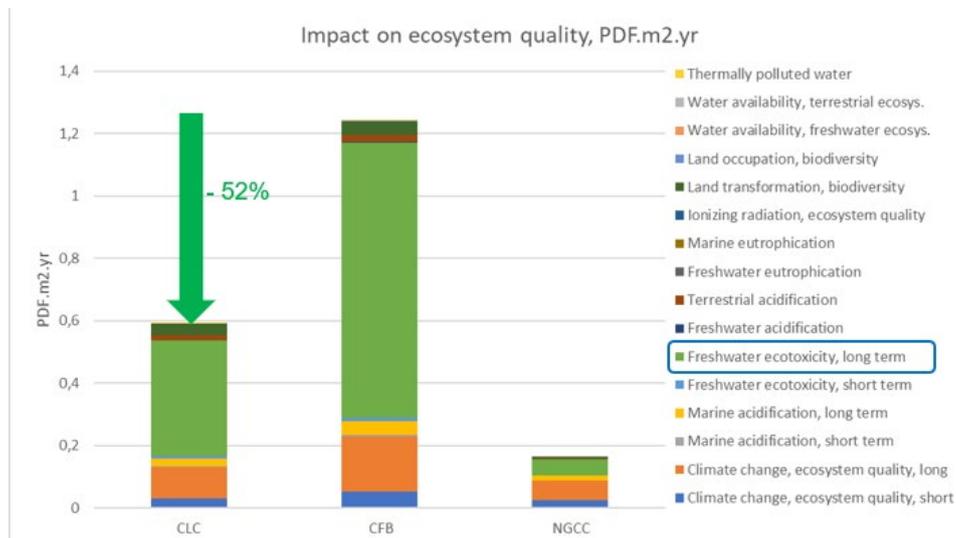


Figure 8-8: Impact on ecosystem quality

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 CaCO₃ is used in the process.

NGCC has better results than CLC as neither petcoke nor CaCO₃ 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% CO₂ 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 BUSINESS MODEL

Based on the detailed studies and the economic evaluations of the CLC unit, different business models for CLC in real industrial applications cases have been defined by the industrial partner. Two of the most promising applications are presented in the following.

9.1 First CLC business applications

The first business application case is a fossil fuelled CLC plant using petcoke to produce steam and electricity in refineries.

The industrial partner is looking at using petcoke produced from refineries with cocker unit. The business case with the refinery in Europe is penalised against a NGCC solution by the transport cost of captured CO₂, as described in the full chain CCS case in section 7. But refineries in USA that are already connected to a CO₂ transport network is much more competitive with a very low CO₂ transport cost due to benefits of the existing CO₂ network. However, petcoke CLC in USA will compete with NGCC where natural gas is affordable. This USA petcoke case is one of the best cases for the industrial partner and must be assessed more deeply with new unit integration cost in an existing refinery to be set as a viable CCS case.

In order to reach the targeted carbon capture and storage goals, it is clear that there is a need for a large number of CO₂ storage sites in Europe. Given that one or more of these sites are situated close to a refinery, this will minimize CO₂ transport costs, and therefore constitute a viable business case for petcoke-fuelled CLC.

Due to the increased geopolitical instability over the last years, the global cost of natural gas has increased since the reference year for the cost estimation (2019). Since Europe is a net importer of natural gas, its potentially sustained increased cost, together with a lower security of supply, will reduce the benefits of NGCC. This means that an updated TEA, accounting for these aspects, should be made before a decisive conclusion can be made whether NGCC or CLC with petcoke is the better option for future European refineries.

9.2 Second CLC business applications

The second business application case is a Biomass fuel CLC using biomass to produce steam and electricity.

The biomass fuelled CLC is opening the door to BECCS or to Biogenic CO₂ used for e-fuel production. It is foreseen that Biogenic CO₂ will eventually have a higher commercial price than fossil-based CO₂. This will favour biomass-fuelled CLC over NGCC. The biomass CLC case is, however, heavily dependent on the availability of biomass feedstock. An overview of potential supply to existing industrial sites in Europe and USA must therefore be obtained before any conclusion can be drawn regarding its applicability. This overview must consider both amount, cost, sustainability and seasonable variations.

10 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 CO₂ 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 CO₂ needs to be transported and stored far away from the power plant, the competitiveness of CLC would be further reduced as less CO₂ 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 CO₂ 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 CO₂ transport and storage cost.
 - Thus, unless petcoke is nearly free, gas prices increase significantly, and that CO₂ transport and storage cost are minimal, it is very unlikely that CLC will be cost-competitive with an NGCC with CO₂ 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 CO₂ 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 CO₂ 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 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.
- For the TEA of the CLC (and CFB) technology, we chose to focus only on petcoke fuel which is the hardest 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	10000	7500	25000	7500	10000	7500	25000
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€)	199	165	96	73	95	79	46	35
	Fixed OPEX (M€/y)	9.7	8.0	4.6	3.5	4.6	3.8	2.2	1.7
	Fuel cost (M€/y)	4.5	4.4	4.4	3.9	2.1	2.1	2.1	1.9
	Electricity cost (M€/y)	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2
Offshore pipeline	Other variable OPEX (M€/y)	3.2	3.2	3.2	3.2	1.5	1.5	1.5	1.5
	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
Storage	Other variable OPEX (M€/y)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	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
Storage	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 CO₂ 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 CO ₂ (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	5.30	5.32	4.73	2.56	2.52	2.53	2.25
	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	10.44	10.46	9.87	12.13	12.09	12.10	11.82

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				
	15	15	7	7	15	15	7	7	
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	10000	7500	25000	7500	5000	7500	5000	
Offshore 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€)	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
	Other variable OPEX (M€/y)	13.7	13.7	13.7	13.7	4.9	4.9	4.9	4.9
Extra-conditioning + onshore pipeline	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
	Other variable OPEX (M€/y)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Liquefaction	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
	Other variable OPEX (M€/y)	0.1	0.1	0.1	0.1	0.0	0.0	0.1	0.1
Shipping + reconditioning	CAPEX (M€)	101	84	49	37	40	33	19	15
	Fixed OPEX (M€/y)	4.9	4.1	2.3	1.8	1.9	1.6	0.9	0.7
	Fuel cost (M€/y)	2.3	2.2	2.3	2.0	0.9	0.9	0.9	0.8
	Electricity cost (M€/y)	0.3	0.3	0.2	0.2	0.1	0.1	0.1	0.1
Offshore pipeline	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
	Other variable OPEX (M€/y)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Storage	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
	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 CO₂ emissions of the refinery cases along the chain for the different scenarios considered.

	CLC				NGCC with CCS				
	15	15	7	7	15	15	7	7	
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 CO ₂ (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	2.70	2.72	2.41	1.07	1.06	1.06	0.94
	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	5.31	5.33	5.02	11.76	11.75	11.76	11.64	