Economic assessment of chemical looping oxygen production and chemical looping combustion in integrated gasification combined cycles

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Chemical looping promises significant reductions in the cost of CO_2 capture and storage (CCS) by enabling energy conversion with inherent separation of CO_2 at almost no energy penalty. This study evaluates the eco-nomic performance of a novel power plant configuration based on the principle of packed bed chemical looping. The new configuration, called COMPOSITE, integrates packed bed chemical looping combustion (PBCLC) and chemical looping oxygen production (CLOP) into an integrated gasification combined cycle (IGCC) power plant. The CLOP unit achieves air separation with minimal energy penalty and the PBCLC unit achieves fuel com-bustion with inherent CO_2 capture. The COMPOSITE configuration achieved a competitive CO_2 avoidance cost (CAC) of €45.8/ton relative to conventional IGCC with pre-combustion CO_2 capture with €58.4/ton. However, the improvement was minimal relative to a simpler configuration using an air separation unit (ASU) instead of the CLOP reactors, returning a CAC of €47.3/ton. The inclusion of hot gas clean-up further improved the CAC of the COMPOSITE configuration to €37.8/ton. Optimistic technology assumptions in the form of lower contingency costs and better CLOP reactor performance reduced the CAC to only €24.9/ton. Further analysis showed that these highly efficient chemical looping plants will be competitive with other low-carbon power plants (nuclear, wind and solar) in a technology-neutral climate policy framework consistent with a 2 °C global temperature rise. Economic attractiveness improves further in a high CO_2 tax scenario where large-scale deployment of CO_2 negative bio-CCS plants is required.

Abbreviations:
ASC, advanced supercritical;
ASU, air separation unit;
CAC, CO_2 avoidance cost;
CCS, CO_2 capture and storage;
CEPCI, chemical engineering plant cost index;
CGCU, coldgasclean-up;
CLOP, chemical looping oxygen production;
FOAK, first of a kind;
HGCU, hot gas clean-up;
IGCC, integrated gasification combined cycle;
LCOE, levelized cost of electricity;
O&M, operating and maintenance;
PBCLC, packed bed chemical looping combustion;
PV, photovoltaic;
SC-PC, supercritical pulverized coal;
TPC, total plant cost;
T&S, transport and storage

1. Introduction

CO_2 capture and storage (CCS) is broadly recognized as a vital climate change mitigation technology (IEA, 2016, 2017; IPCC, 2014). CCS is often the only viable solution for mitigating industrial emissions, can protect fossil fuel assets through retrofits, and can result in carbon-negative power production through bio-CCS. The latter option features prominently in 2 °C and "beyond 2 °C" scenarios from the IPCC and IEA. Most IPCC scenarios require zero emissions from the power sector by mid-century and deeply negative CO_2 emissions by the end of the century (CO_2 should be extracted from the atmosphere at a similar rate of current emissions) (IPCC, 2014). Without CCS, most model runs simply could not achieve the 450 ppm IPCC scenario.

Solid fuel CCS is therefore seen as a crucial future power sector technology: initially using coal as fuel followed by a gradual switch to biomass for achieving negative emissions. Given concerns about the limited rate of sustainable biomass production, energy conversion efficiency should be prioritized. In addition, the highly efficient CCS power plant should also have minimal local emissions to meet stringent legislation on local pollutants. The power plant configurations presented in this study aim to maximize efficiency and minimize local pollutants by relying on the integrated gasification combined cycle (IGCC) configuration.

Chemical looping combustion (CLC) technology has the potential to significantly reduce the energy penalty associated with CCS by achieving fuel conversion without direct contact between CO_2 and N_2.

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When using solid fuels, two pathways exist: solid fuel CLC where the fuel is fed directly to the CLC reactors (Lyngfelt, 2014; Lyngfelt and Leckner, 2015; Spinelli et al., 2016) and the IGCC pathway where solid fuel is externally gasified and cleaned before being fed to the CLC unit (Cloete et al., 2015; Spallina et al., 2014). Economic assessments of these concepts show similar performance with a CO_2 capture cost of about €20/ton (without transport and storage) relative to their re-spective benchmarks (Lyngfelt and Leckner, 2015; Mancuso et al., 2017). However, the IGCC configuration has potential for further effi-ciency increases via hot gas clean-up (Giuffrida et al., 2013, 2010) and the integration of a chemical looping oxygen production (CLOP) unit for more efficient air separation (Larring et al., 2016).

The potential of these options to increase power plant efficiency was recently assessed (Cloete et al., 2018), showing that the inclusion of hot gas clean-up and CLOP reactor technology can increase overall power plant efficiency beyond 45%. This study will investigate whether this very high CCS power plant efficiency can translate into significant economic benefits.

Furthermore, the study will assess the economic performance of such highly efficient solid fuel CCS power plants in various macro-economic scenarios consistent with a 2 °C climate change target. These include a high CO_2 price (€100/ton), a lower discount rate (4% instead of 8%), and widespread deployment of bio-CCS. The economic perfor-mance of the best performing CCS power plant is compared to other low-carbon power generation options (nuclear, wind and solar PV) in each scenario.

1.1. Power plant configurations

This study will compare the economic performance of seven plant configurations under several different macro-economic scenarios. The plant configurations are summarized in Table 1. Two benchmark cases without CCS are considered: an integrated gasification combined cycle (IGCC) plant and an advanced supercritical (ASC) pulverized coal plant. Performance of these benchmark power plants without CCS (cases 1 & 2) are taken from Franco et al. (2011).

The CCS plants considered in this study are all based on an IGCC configuration. The first case, 3a, is a conventional pre-combustion plant where syngas from the gasifier is shifted to H_2 and CO_2, CO_2 is re-moved, and H_2 is fed to the combined power cycle (Franco et al., 2011). The second CCS configuration, 3b, combusts the syngas in packed bed chemical looping combustion (PBCLC) reactors where CO_2 is inherently separated out (Spallina et al., 2014). This plant configuration brings a large efficiency advantage (3.6%-points higher), even though the inlet temperature of the combined cycle is relatively low (< 1200 °C) com-pared to the pre-combustion case (> 1400 °C). In addition, very high CO_2 avoidance is achieved, resulting in only a third of the specific CO_2 emissions of the pre-combustion plant.

Three different configurations of the novel COMPOSITE plant (Cloete et al., 2018) are assessed. The first option (4a) directly replaces the air separation unit (ASU) in the PBCLC plant with chemical looping oxygen production (CLOP) reactors. These reactors enable air separation with no direct energy penalty, but produce an O_2 stream that is strongly diluted by sweep gases (CO_2 and H_2O), thus requiring a larger gasifier and gas clean-up unit due to the larger stream of lower heating value syngas produced. Table 1 shows that this plant config-uration offers a further 2.8%-point efficiency advantage over the PBCLC ASU plant.

Table 1
Plant configurations considered in this study (Cloete et al., 2018; Franco et al., 2011; Spallina et al., 2014).

Case	Power plant	Capacity (MWe)	Specific emissions (kg/MWh)	Efficiency (% LHV)
1	IGCC w/o CCS	391.5	734.3	47.3
2	ASC w/o CCS	754.3	763.0	45.5
3a	IGCC pre-combustion	352.7	96.0	37.0
3b	IGCC PBCLC ASU	386.9	33.9	40.6
4a	COMPOSITE CGCU 18.4% O_2	414.1	52.9	43.4
4b	COMPOSITE HGCU 18.4% O_2	433.2	35.0	45.4
4c	COMPOSITE HGCU 14.4% O_2	432.2	40.4	45.3

A further efficiency benefit can be achieved by incorporating hot gas clean-up (HGCU) technology after the gasifier. This reduces the energy penalty associated with cooling the syngas produced by the gasifier all the way to 30 °C for conventional cold gas clean-up (CGCU). As shown in Table 1, a further 2%-point efficiency benefit is possible with this configuration (case 4b). It should be noted, however, that the other IGCC plants in this assessment can also achieve a similar benefit (e.g. Giuffrida et al. (2010)), so the comparison should focus on the COM-POSITE plant with CGCU.

Finally, a COMPOSITE plant configuration is considered with less optimal performance from the CLOP reactors, resulting in a lower O_2 concentration in the stream fed to the gasifier (case 4c). This does not strongly affect the plant efficiency, but further increases the capital costs of the gasifier and gas clean-up units. Given that the CLOP reactor technology is still in the lab-scale demonstration phase, it is valuable to consider a reasonable range of possible large-scale reactor perfor-mances.

For more details about each process layout, direct references to process flow diagrams and stream tables from the aforementioned re-ferences are provided in Table 2.

2. Methodology

2.1. Capital and operational cost estimates

The total capital cost estimates for the comparative power plants are based on numbers from the EU projects CESAR, CAESAR and DECARBit: "European best practice guidelines for assessment of CO_2 capture technologies" (Franco et al., 2011). There is not a significant difference between the current (2017/2018) Chemical Engineering Plant Cost Index (CEPCI) and the 2008 reference used in this report. Plant component cost data from Franco et al. (2011) will therefore be used directly in this study.

For the equipment purchase and installation cost, sizing for the benchmark IGCC plant with and without CO_2 capture is estimated based on the mass and energy balances using a bottom-up approach (BUA) for the required power plant size. This equipment cost break-down is also used for the other IGCC configurations investigated in this study, with appropriate scaling of the gasifier and gas clean-up unit costs with the syngas stream flowrate raised to the power of 2/3. In the cases with hot gas clean-up, gas clean-up equipment costs were as-sumed to be only 75% of the case with cold gas clean-up based on the capital cost estimates given in Table 6.4 of Nexant (2007). Only the reference case for the ASC plant is based on a top-down approach, based

Table 2
Direct references to process flow diagrams and stream tables for the plants assessed in this study.

Case	Power plant	Reference	Process flow diagram	Stream table
1	IGCC w/o CCS	Franco et al. (2011)	Figure 4.2.1.1	Table 4.2.2
2	ASC w/o CCS	Franco et al. (2011)	Figure 3.2.1	Table 3.2.2
3a	IGCC pre-combustion	Franco et al. (2011)	Figure 4.3.1.1	Table 4.3.2
3b	IGCC PBCLC ASU	Spallina et al. (2014)	Figure 4	Table 6
4	COMPOSITE HGCU	Cloete et al. (2018)	Figure 4	Table 10

on supplier estimates of the entire power plant.

The PBCLC and CLOP reactors were sized according to the flowrates specified in the power plant simulation study performed in this project (Cloete et al., 2018). Relatively high flowrates were specified to minimize the required reactor volume. This resulted in reactor pressure drops of up to 0.8 bar, which were taken into account in the power plant efficiency calculation.

Based on the flowrates employed in the aforementioned study (Cloete et al., 2018) and an assumed reactor height of 10 m, total reactor volumes of 1623 m^3 and 1843 m^3 were required respectively for the PBCLC and CLOP reactors in the COMPOSITE plants listed in Table 1. According to the reactor simulations in Cloete et al. (2018), the PBCLC reactors operate with 5 reactors in oxidation for every one reactor in reduction, while the CLOP reactors operate with 6 reactors in oxidation for every one reactor in reduction. When fixing the reactor height at 10 m, the PBCLC reactor cluster consists of 6 reactors with a diameter of 5.87 m, while the CLOP reactor cluster consists of 7 reactors with a diameter of 5.79 m.

It should be noted that such large pressurized reactors may be challenging to construct. If the number of reactors is doubled by halving the cross-sectional area and keeping the height at 10 m, the reactor investment cost outlined in Fig. 1 will increase by 17% for PBCLC and 10% for CLOP.

Reactor costs are split into four components: reactor vessel, refractory, switching valves and oxygen carrier. Reactor vessel costs are estimated based on Turton et al. (2008) and adjusted to 2017 Euros using a CEPCI ratio of 1.41 and an exchange rate of \$1.2/€. Refractory material was assumed to cost €10000/m^3, installed with a 1 m and 0.5 m thickness in the PBCLC and CLOP reactors respectively with installation costs equal to 50% of material costs. Valve costs were calculated based on the estimates of Hamers et al. (2014) for the PBCLC reactor, with half that estimate being used for the lower temperature CLOP reactor. Oxygen carrier costs were taken as €2500/ton for PBCLC and €10000/ton for CLOP. The CLOP oxygen carrier is more expensive because it contains more expensive raw materials.

The resulting reactor costs assumed in the following assessments are displayed in Fig. 1.

Finally, the COMPOSITE process also requires a syngas recycle blower to drive gases in a loop between the CLOP reactors, the gasifier and syngas cleaning units. This unit needs to increase the cleaned syngas stream pressure by about 2.5 bar with a power of about 6.5 MW. The total cost of large scale natural gas compressor station is about\$2000/kW (Rui et al., 2012), so this study will assume equipment purchase and installation costs of €10 million. Even though significant uncertainty is tied to this number, it only represents about 1% of total equipment costs and therefore cannot materially impact the overall cost assessment.

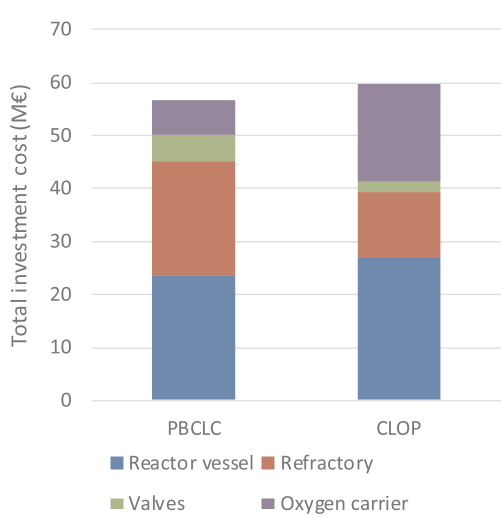

Fig. 1. Estimated total installed reactor costs.

Table 3
Equipment purchase and installation cost breakdown for the six different IGCC cases listed in Table 1 (M€).

	Case 1	Case 3a	Case 3b	Case 4a	Case 4b	Case 4c
Gasifier	162.0	180.0	180.0	218.4	218.4	257.3
Gas turbine	88.6	93.3	93.3	93.3	93.3	93.3
Steam turbine	55.0	52.0	52.0	52.0	52.0	52.0
Heat recovery steam generator	35.5	34.1	34.1	34.1	34.1	34.1
Low temperature heat removal	11.4	10.9	10.9	10.9	10.9	10.9
Cooling	40.6	39.0	39.0	39.0	39.0	39.0
Coal handling	49.5	53.9	53.9	53.9	53.9	53.9
Ash handling	16.0	17.4	17.4	17.4	17.4	17.4
Acid gas removal	19.8	32.8	32.8	39.7		
Gas clean-up	6.6	6.9	6.9	8.4		
Water treatment	19.2	34.2	34.2	41.5		
Claus burner	12.4	12.8	12.8	15.5		
Hot gas clean-up					78.9	92.9
Air separation unit	64.5	72.8	72.8			
CO2 compressor		30.0	30.0	30.0	30.0	30.0
Water-gas shift		21.1				
Selexol		45.0				
PBCLC			56.5	56.5	56.5	56.5
CLOP				59.8	59.8	59.8
Recycle blower				10.0	10.0	11.8
Indirect costs	81.3	103.1	101.7	109.3	105.6	113.3
Total	662.3	839.3	828.3	889.8	859.9	922.3
Owner's cost and contingency	198.7	251.8	248.5	267.0	258.0	276.7
Total plant cost (TPC)	861.0	1091.1	1076.9	1156.8	1117.8	1198.9
Specific TPC (€/kW)	2199.6	3093.2	2783.4	2793.6	2580.6	2774.0

A full breakdown of the equipment purchase and installation costs of all IGCC plants is given in Table 3. The top-down analysis of the ASC plant resulted in a total plant cost (TPC) of €1.456 billion (specific TPC of €1930/kW) (Franco et al., 2011).

The costs for Case 1 and 3a in Table 3 are taken directly from Franco et al. (2011). Modifications to certain plant components were then made to the costs of Case 3a as follows: The size of the gasifier and gas clean-up equipment was increased for the COMPOSITE cases because of the lower heating value of the produced syngas. An additional size in-crease was required for case 4c, where the lower O_2 content in the stream to the gasifier further reduced the syngas heating value. Fol-lowing Nexant (2007), the hot gas clean-up cost was taken as 75% of the combined cost of cold gas clean-up components (acid gas removal, gas clean-up, water treatment and Claus burner). PBCLC and CLOP reactor costs are taken from Fig. 1. The recycle blower is upscaled from Case 4b to Case 4c due to the lower syngas heating value. Table 3: Equipment purchase and installation cost breakdown for the six dif-ferent IGCC cases listed in Table 1 (M€).

For the IGCC plants, indirect costs of 14% are added to the equipment purchase and installation costs (Franco et al., 2011). This includes cost for service facilities, engineering costs, buildings, etc. An addi-tional contingency and owners cost of 15% is prescribed in Franco et al.(2011), but this number is doubled to 30% for the IGCC configurations in light of recent practical experience to calculate a more conservative TPC.

Fixed operating and maintenance costs of the IGCC and ASC plants are assumed to be 2.80% and 1.85% of TPC per year (Franco et al., 2011). Variable costs amount to €1.6/MWh for the ASC plant. A more detailed breakdown of operating and maintenance costs is given for the IGCC plants in Table 4. Replenishment costs for the PBCLC and CLOP oxygen carrier are calculated by assuming material lifetimes of 2 and 5 years respectively. The CLOP oxygen carrier is expected to last longer due to operation at significantly lower temperature as well as a lower rate and extent of conversion in each cycle. Given the uncertainty

Table 4
Operating and maintenance costs of the IGCC cases listed in Table 1 (k€/year).

	Case 1	Case 3a	Case 3b	Case 4a	Case 4b	Case 4c
Fixed costs						
Labour	9 873	11 796	11 642	12 506	12 085	12 962
Maintenance	14 810	18 767	18 522	19 897	19 227	20 622
Variable costs (85% availability)						
Fuel	55 957	63 938	63 938	63 938	63 938	63 938
Water	3 675	4 520	4 520	4 520	4 520	4 520
Selexol	100	1 115	1 115	1 115	1 115	1 115
Catalysts	180	300	300	300	300	300
Miscellaneous	1 450	2 600	2 600	2 600	2 600	2 600
CLC bed material			3 189	3 189	3 189	3 189
CLOP bed material				3 687	3 687	3 687
Total	86 045	103 037	105 826	111 752	110 660	112 932
Specific total (€/MWh)	29.5	39.2	36.7	36.2	34.3	35.1

involved in these material lifetime estimates, a sensitivity study is presented later (Fig. 4). The fuel cost (coal) is taken as €2.5/GJ.

2.2. Economic performance measures

The levelized cost of electricity (LCOE) and CO_2 avoidance costs (CAC) are the two primary economic performance indicators evaluated in this study. LCOE is determined via a discounted cash flow analysis over a 4-year construction period followed by a 25-year operating period. TPC is assumed to be distributed as follows over the 4-year construction period: 20% in year 1, 30% in year 2, 30% in year 3 and 20% in year 4. LCOE is calculated as the electricity price resulting in a zero discounted return on investment over this 29-year period. The plant utilization rate is set to 40% in the first operating year, 65% in the second year, and 85% thereafter (Franco et al., 2011). A discount rate of 8% is employed in the base case.

Data about LCOE and specific CO_2 emissions (E_{CO_2}) with and without CCS are used to calculate the CAC via Eq. (1). Here, LCOE has units of €/MWh and specific emissions has units of tonCO_2/MWh. CAC is calculated relative to both the IGCC and ASC plant without CO_2 capture.

$$CAC = \frac{LCOE_{CCS} - LCOE_{ref}}{E_{CO_2,ref} - E_{CO_2,CCS}} \quad (1)$$

3. Results and discussion

The economic performance of the different power plant configurations from Table 1 will be compared over a number of different macroeconomic scenarios:

1 A base case with no CO_2 tax
2 A CO_2 price consistent with a 2 °C global temperature rise
3 A low-interest rate scenario where the discount rate is halved
4 A case where biomass replaces coal to achieve negative CO_2 emissions

3.1. Base case

Figs. 2 and 3 and show the LCOE and CAC measures for all the plants considered in this study in the case where no cost is associated with emitting CO_2.

The significant cost increase imposed by all the plants with CCS is immediately evident from Fig. 2. Capital costs increase due to the additional process components required to achieve CO_2 capture as well as the lower plant efficiency. Fixed O&M increases because of the larger amount of capital to be maintained. Variable O&M increases due to the chemicals and oxygen carrier materials consumed by the CCS plants. Fuel costs increase due to the lower plant efficiency. Costs related to CO_2 transport and storage are also significant.

Overall, the addition of CCS increases the LCOE by 71% relative to the ASC plant when pre-combustion CO_2 capture is added. The use of PBCLC reactors can reduce this cost increase to 56–58%, although the COMPOSITE plant only brings a small economic benefit relative to the PBCLC ASU plant. In the case of COMPOSITE, the larger capital expenditures from a larger gasifier and gas clean-up unit almost cancel out the fuel cost and capital utilization benefits of higher efficiency. Costs associated with the CLOP reactor were almost identical to the ASU it replaced. The use of HGCU technology can further reduce the LCOE increase to only 46%, but poorer performance by the CLOP re-actor once again raises the cost increase to 53%.

These findings are better summarized by the CAC comparison presented in Fig. 3, where values range from €58.4/ton for the pre-combustion plant to €37.8/ton for the COMPOSITE plant with HGCU. These costs are significantly lower than estimates from a recent study (Mancuso et al., 2017), primarily due to lower IGCC capital and fixed O &M cost assumptions. When taken relative to the IGCC benchmark, the range is 27.7–49.2 €/ton, which is similar to the aforementioned study (Mancuso et al., 2017). This points to the uncertainty associated with IGCC power plant cost estimates. For example, IGCC capital cost estimates vary over a range of €1948/kW to €2650/kW in several recent studies (Gazzani et al., 2014; Irlam, 2017; Mancuso et al., 2017; Mansouri Majoumerd and Assadi, 2014; Rubin et al., 2015) ($1.2/€ exchange rate assumed). The cost assumed in this study (€2200/kW) falls close to the average of €2316/kW from these works.

Fig. 3 also displays data without CO_2 T&S costs for the case where various forms of productive CO_2 utilization can consume the CO_2 captured from these plants. This assumption lowers the CAC by a further 10–13 €/ton.

It should also be mentioned that, if the IGCC contingency cost is not doubled from the recommended 15% (Franco et al., 2011) to 30%, the LCOE of the best case reduces from 81.4 to 75.7 €/MWh, while the CAC reduces from 37.8 to 29.4 €/ton. In the most optimistic case, it can also be assumed that CLOP reactor performance can be improved to the point where upsizing of the gasifier and gas clean-up unit is not re-quired. The CLOP reactor will have to supply an O_2-rich stream con-taining about 25% oxygen, potentially with the aid of a mild pressure or temperature swing. In this best-case scenario, LCOE and CAC reduce to€72.6/MWh and €24.9/ton respectively.

Even though the plants with PBCLC and CLOP technologies outperform the conventional pre-combustion IGCC plant in this assessment, their cost estimations involve significant uncertainty. In particular, the cost and lifetime of the oxygen carrier material used in these process units is highly uncertain at present. A sensitivity analysis was therefore conducted where material lifetime was varied over a range of 0.25–2x the base value and material cost was varied over a range of 0.5–2x the base values.

As illustrated in Fig. 4, lower oxygen carrier lifetime and higher oxygen carrier costs result in significant increases in CAC from the COMPOSITE plant. In the worst-case scenarios, costs become similar to the pre-combustion case, illustrating that poor oxygen carrier performance can completely erode the large efficiency advantage offered by the COMPOSITE process. Direct demonstration of oxygen carrier longevity is therefore an important priority for justifying further scale-up of these process concepts.

Finally, a sensitivity analysis was completed regarding the other reactor costs (reactor vessel, refractory and valves). Fig. 5 shows that the attractiveness of the COMPOSITE configuration relative to the conventional pre-combustion configuration is sensitive to the reactor costs. If reactor costs double (100% greater) from the base case assumptions in Fig. 1, the economic benefit of the COMPOSITE plant is almost completely cancelled out. For the PBCLC ASU configuration, the sensitivity to reactor costs is less because no CLOP reactors are present. This configuration starts to outperform COMPOSITE when reactor costs

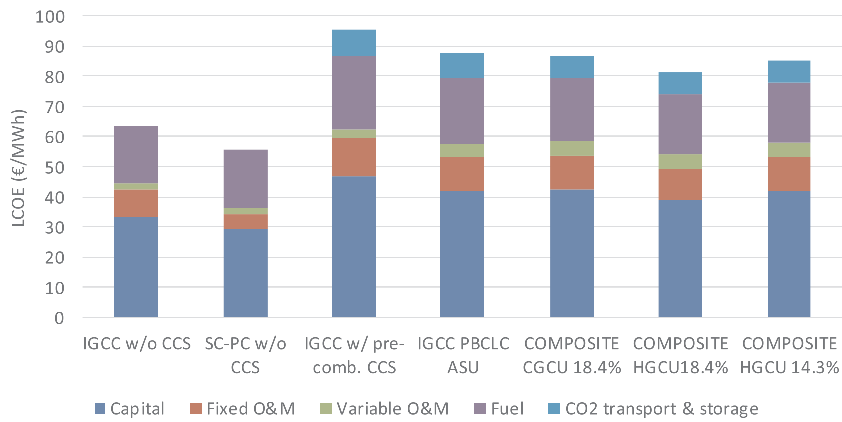

Fig. 2. Breakdown of LCOE of the different plant configurations listed in Table 1.

increase by 35% or more.

3.2. CO_2 price consistent with a 2 °C global temperature rise

It is obvious that CCS is not going to become a commercial reality without technology-neutral climate policies such as a CO_2 price. The International Energy Agency assumes that CO_2 prices in Europe rise from 20 $/ton in 2020 to 100 $/ton in 2030 and 140 $/ton in 2040 in their 2 °C scenario (IEA, 2016). Given that the power plant configurations evaluated in this work will not be commercially ready before 2030, a constant CO_2 price of €100/ton will be assumed over the life-time of the plant.

Fig. 6 clearly shows that all the CCS plants are more economically attractive than the plants without CO_2 capture in a policy scenario consistent with a 2 °C temperature rise. The plants relying on PBCLC and CLOP reactors widen their advantage over the conventional pre-combustion capture plant due to significantly lower specific emissions (Table 1). It is also noted that the PBCLC ASU plant now becomes more economical than the COMPOSITE CGCU plant due to its very low specific emissions. Emissions from the COMPOSITE plant are slightly higher because the CLOP reactors also result in a small amount of mixing of CO_2 and N_2.

Further perspective is given by a comparison to other low-carbon electricity options: nuclear power, onshore wind, offshore wind and solar PV. The cost assumptions for these technologies (relevant to Europe) are given in Table 5. Costs are based on the latest IEA assessment for plants commissioned in 2020 (IEA, 2015), but, given that the present work looks beyond the year 2030, significant further cost reductions are assumed for wind and solar power.

Construction time for nuclear plants is assumed to be 6 years, while a 1-year construction time is assumed for wind and solar technologies. LCOE is calculated over 25 years of operation for all technologies, although this assumption favours wind and solar generators that will generally have significantly shorter operating lifetimes than nuclear and CCS plants.

Like the carbon emissions from thermal plants, renewable wind and solar power also have a “hidden” cost that is not commonly included in LCOE calculations: their variable and non-dispatchable nature. According to a thorough review by Hirth et al. (2015), the cost associated with wind/solar variability and additional grid-related costs in the European market amounts to €25-35/MWh at a market share of 30–40%. This added cost includes three main components: profile costs (maintaining a fleet of backup dispatchable power plants operated at a lower utilization rate), grid-related costs (maintaining a more extensive transmission network with a lower utilization rate), and balancing costs (increased grid stability services due to imperfect forecasting). Added costs from wind and solar curtailment also start to increase rapidly when market share reaches 30–40%. Hence, an additional cost of €30/MWh is added to the LCOE of wind and solar generators.

As shown in Fig. 7, the COMPOSITE plant performs well in this comparison. Note that the integration costs of wind and solar power will continue to increase as more capacity is added (Hirth, 2015a, b). This cost increase is likely to negate any further cost declines beyond the values assumed in Table 5.

3.3. Low interest rate scenario

The developed world has entered a “new normal” of low benchmark interest rates. Factors such as globalization, aging populations, environmental constraints and slowing productivity growth suggest that

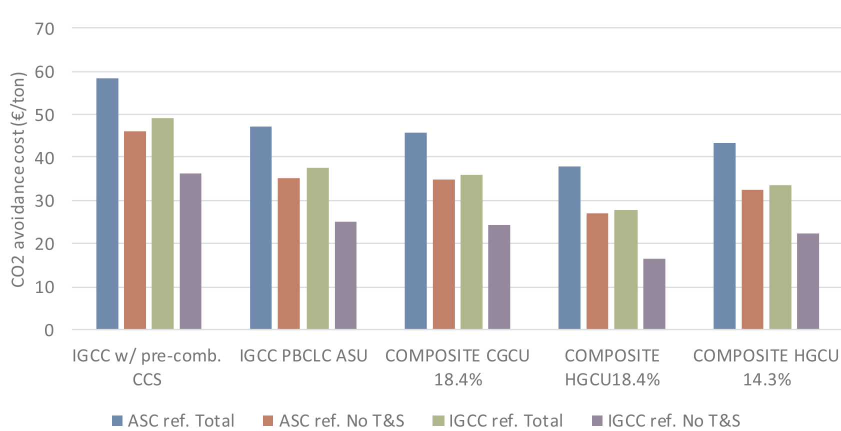

Fig. 3. Comparison of CAC with and without CO_2 transport and storage (T&S) for the different plant configurations listed in Table 1. CAC is expressed relative to both the ASC and IGCC plant configurations without CCS.

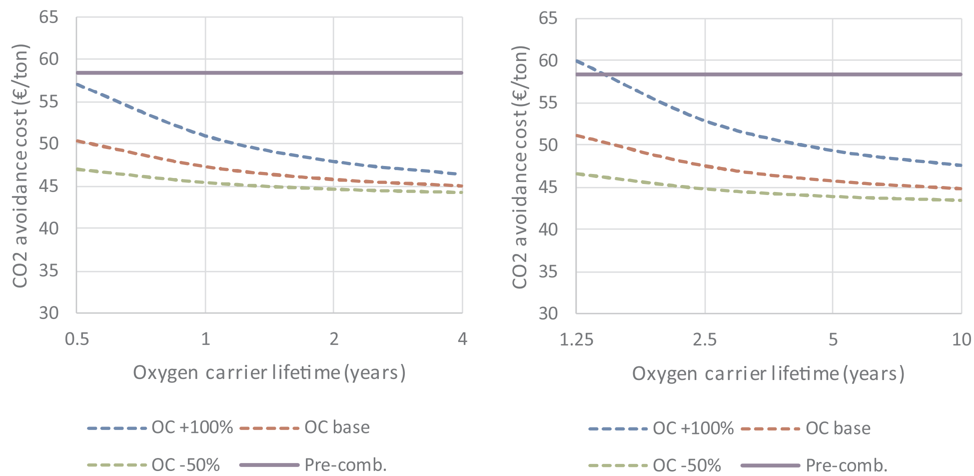

Fig. 4. The sensitivity of CAC to the cost and lifetime of the PBCLC oxygen carrier (left) and CLOP oxygen carrier (right) in the COMPOSITE CGCU case.

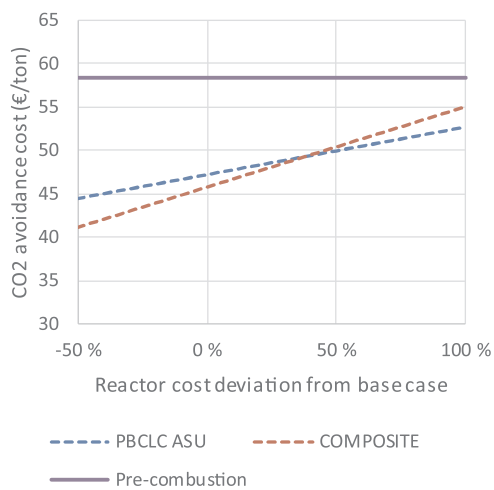

Fig. 5. The sensitivity of CAC to the cost of the reactor vessel, refractory and valves in the PBCLC ASU and COMPOSITE CGCU cases.

economic growth will be muted and benchmark interest rates will remain low relative to historic norms for the foreseeable future. In this environment, investors must take more risk to get a decent yield, implying that the electricity sector may get access to cheaper capital.

Improved climate change policy or targeted support mechanisms like feed-in tariffs can reduce interest rates further by lowering risk associated with low-carbon energy investments. Such favourable policy that guarantees investor returns can minimize the weighted average

Table 5
Low-carbon power plant cost assumptions.

Power plant	Capital cost (€/kWe)	O&M cost (€/MWh)	Fuel cost (€/MWh)	Capacity factor (%)
Nuclear	5000	13	9	90
Onshore wind	1400	15	–	30
Offshore wind	2800	25	–	45
Solar PV	800	15	–	15

cost of capital (WACC) as clearly illustrated by renewable energy deployment in Europe. For example, Kost et al. (2018) assumes real WACC in the range of 2.1–2.7% for utility PV, onshore wind and biogas facilities deployed in Germany. This low-cost financing scenario will therefore be explored via a reduction of the discount rate from 8% to 4%.

Figs. 8 and 9 show the effect of this assumption on the LCOE and CAC of the power plants evaluated in this study. Relative to Figs. 6, 8 shows a reduction in LCOE of around €15/MWh. Fig. 9 shows that CAC is now as low as €32.3/ton.

Given that the low-carbon power production options listed in Table 5 are more capital intensive than the CCS power plants, they benefit more from a reduction in the discount rate. Even so, Fig. 10 shows that the COMPOSITE power plant still compares favourably against other low-carbon electricity generators, especially wind and solar technologies where the constant integration cost now accounts for a larger share of the total cost.

It is important to note, however, that the low discount rate assumed in this section requires not only strong policy support, but also proven

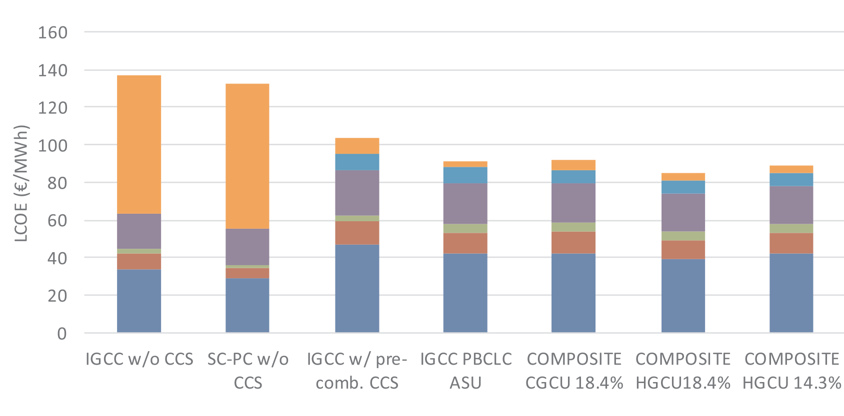

Fig. 6. Breakdown of LCOE for the different plant configurations assuming a CO_2 price of €100/ton.

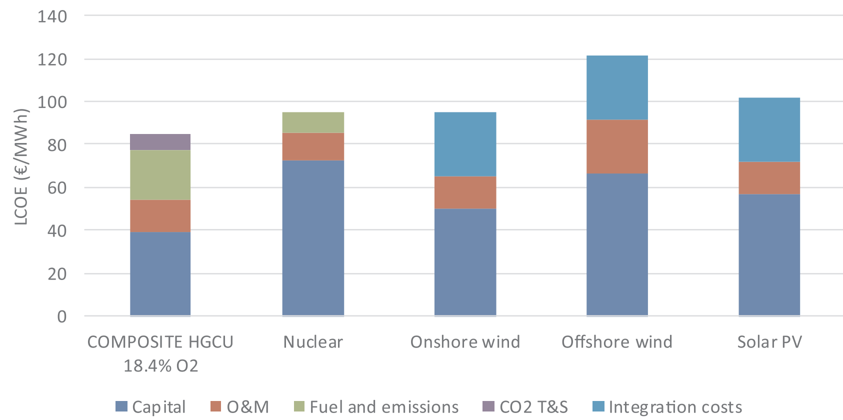

Fig. 7. Breakdown of LCOE for different low-carbon power plants in a future scenario with a CO_2 price of €100/ton and 30–40% of power production from variable wind and solar generators.

technical performance. First-of-a-kind (FOAK) plants are likely to face much higher discount rates due to the risks of poor performance or unforeseen costs in an unproven technology. Securing financing for FOAK plants at reasonable financing cost is expected to be an important challenge for the CCS plants evaluated in this study.

3.4. Bioenergy for negative CO_2 emissions

It is generally accepted that a lot of negative CO_2 electricity generation from bio – CCS will be required from mid-century if the world is to achieve the 2 °C global temperature rise goal (IEA, 2017; IPCC, 2014). Biomass, being much more expensive and supply-limited than coal, places more emphasis on power plant efficiency, highlighting the benefits of the COMPOSITE power plant configuration.

Interestingly, however, very high CO_2 prices (which would translate to a large CO_2 credit for carbon negative bio-CCS plants) can cause the effective fuel cost to become negative. Such a scenario, however, would also incentivise inefficient use of limited biomass resources and naturally will have to be prevented through targeted policy measures. As a simple illustration, the biomass price that would result in identical fuel and emissions costs to coal is shown in Fig. 11. Given that sizable quantities of biomass is available at less than €5/GJ (road side costs) in Europe (S2BIOM, 2018), it is clear that biomass will become attractive relative to coal even at moderate CO_2 prices.

It is well known that switching from coal to biomass for power production introduces several technical challenges, such as widely varying physical characteristics of different biomass fuels and the formation of tar compounds that can present severe fouling challenges in downstream pipelines (Sansaniwal et al., 2017). This study will assume that these challenges can be overcome and bio-fired power plant configurations perform identically to their coal-fired counterparts. For IGCC plants, this may entail the use of a fluidized bed gasifier, which shows good fuel flexibility although the tar problem persists (Sansaniwal et al., 2017). Such a gasifier was used in the COMPOSITE power plant modelling to handle the relatively low O_2 content of the incoming oxidant (Cloete et al., 2018), limiting the technical challenges involved in fuel switching. Thus, even though plant efficiency will be assumed identical to coal-fired plants, the cost of the gas clean-up section will be doubled to account for challenges with tar removal.

It will also be assumed that biomass has an identical CO_2 intensity (96 $kgCO_2/GJ$) to coal. This is a reasonable assumption, given the similar range of emissions factors reported by EPA (2018) for coal (88.6–98.5 kg/GJ) and solid biomass (89.1–112.3 kg/GJ). Furthermore, the assumption is made that biomass is not completely CO_2 neutral due to CO_2 emissions associated with growing, harvesting and distributing energy crops. Biomass is therefore assigned CO_2 emissions equivalent to 20% of coal (IPCC, 2014), which are emitted before the fuel is combusted in the power plant. As a result, the specific emissions in Table 1 are modified as shown in Table 6.

Biomass costs are assumed to be triple that of coal: €7.5/GJ. As mentioned earlier, substantial biomass capacity is available at lower costs in Europe, but transportation costs must be added and the market price will be higher than the cost price. It should also be mentioned that large plants such as those considered in this study may present significant logistical challenges regarding reliable biomass supply. Co-firing biomass with coal is a good strategy to overcome this potential challenge.

Fig. 12 shows the resulting breakdown of the LCOE of the different power plant configurations operating on biomass instead of coal. Clearly, the large CO_2 credit received by the bio-CCS plants strongly

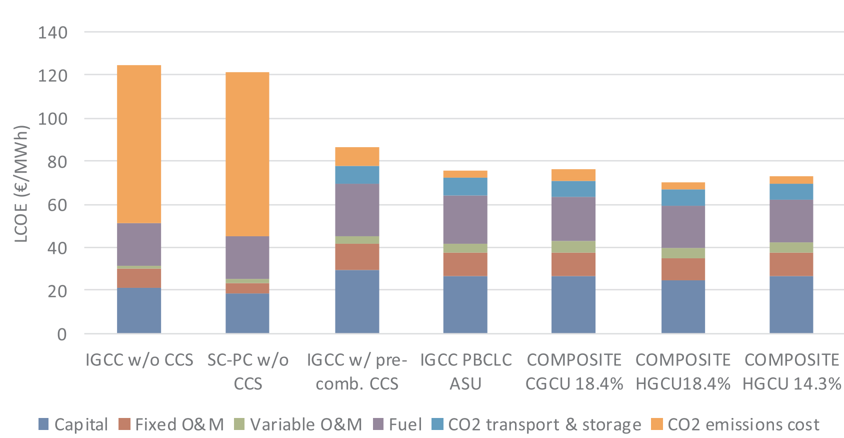

Fig. 8. Breakdown of LCOE for different plant configurations assuming a CO_2 price of €100/ton and a discount rate of 4%.

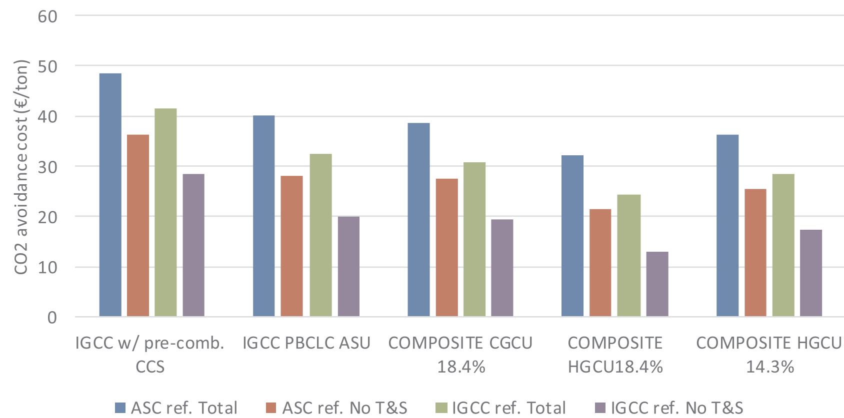

Fig. 9. Comparison of CAC for different power plants with CCS when the discount rate is set to 4%.

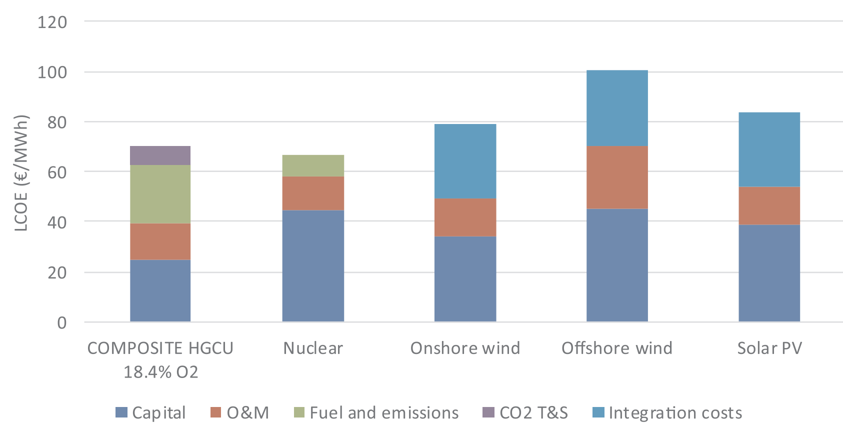

Fig. 10. Breakdown of LCOE for different low-carbon power plants in a future scenario with a CO_2 price of €100/ton, a discount rate of 4%, and 30–40% of power production from variable wind and solar generators.

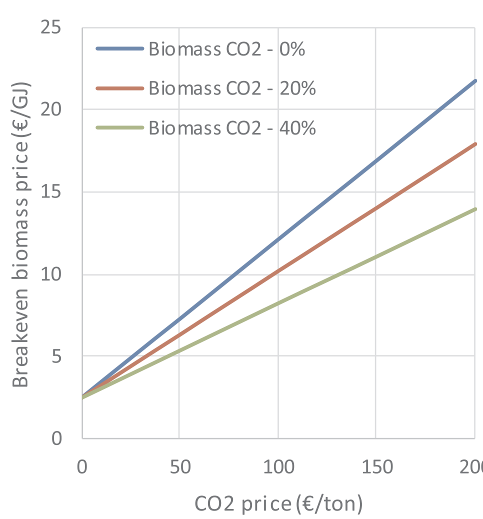

Fig. 11. Biomass price yielding identical fuel and emissions costs to coal (€2.5/GJ and 96 $kgCO_2$/GJ) under different assumptions for CO_2 price and biomass CO_2 intensity (percentage of coal CO_2 intensity).

reduces the LCOE. Relative to the coal plants shown in Fig. 6, the biomass plants in Fig. 12 reduce the LCOE of the CCS plants from 84.9 to 103.9 €/MWh to 68.5–85.4 €/MWh. This is the result of the large CO_2 credit almost completely cancelling out the high cost of biomass fuel.

When compared to other low-carbon alternatives, Fig. 13 shows that the bio-CCS plant is now the clear winner. As mentioned above, the combined fuel and emissions cost is almost zero because of the large emissions credit received by the negative emissions bio-CCS plant. However, this strong competitive position is dependent on moderate biomass fuel prices. If biomass prices increase to €10/GJ, the biomass plant returns roughly the same LCOE as the coal plant in Fig. 7. A further increase to €12.5/GJ will make the bio-CCS plant uncompetitive unless the CO_2 price is raised further beyond €100/ton. This sensitivity to fuel costs illustrates why promoting high efficiency to minimize fuel consumption in bio-CCS will be important not only for ecological reasons, but also for economic reasons.

Table 6
Plant configurations considered in this study with specific emissions from operation with biomass.

Power plant	Capacity (MWe)	Specific emissions (kg/MWh)	Efficiency (% LHV)
IGCC w/o CCS	391.5	146.9	47.3
ASC w/o CCS	754.3	152.6	45.5
IGCC pre-combustion	352.7	−655.2	37.0
IGCC PBCLC ASU	386.9	−651.0	40.6
COMPOSITE CGCU 18.4% O_2	414.1	−587.0	43.4
COMPOSITE HGCU 18.4% O_2	433.2	−576.7	45.4
COMPOSITE HGCU 14.4% O_2	432.2	−572.7	45.3

4. Discussion and conclusions

This study has illustrated how macro-economic scenarios can have a large impact on the economic attractiveness of promising new CCS power plant configurations. If climate science is correct and the world is forced to take the required actions limiting global temperature rise

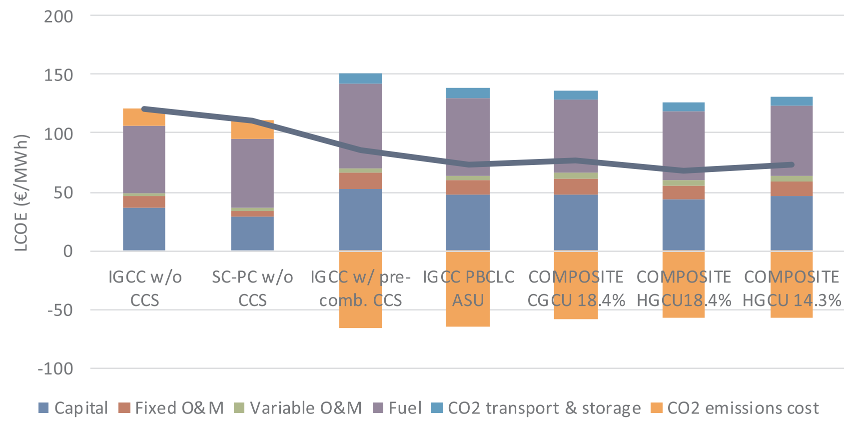

Fig. 12. Breakdown of LCOE (solid line) for different plant configurations running on biomass assuming a CO_2 price of €100/ton and a discount rate of 8%.

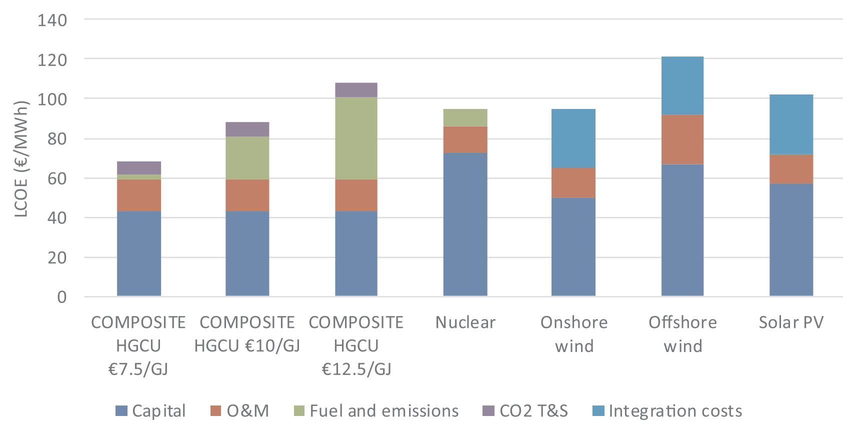

Fig. 13. Breakdown of LCOE for different low-carbon power plants in a future scenario with a CO_2 price of €100/ton, a discount rate of 8%, and 30–40% of power production from variable wind and solar generators. The COMPOSITE plant is assumed to run on biomass with fuel costs ranging from 7.5 to 12.5 €/GJ.

below 2 °C, technology-neutral climate policies and investment decisions favouring these CCS plants become increasingly likely.

In this scenario, CCS power plants are highly competitive with other low-carbon electricity generators. It should also be noted that the advanced CCS power plant configurations considered in this study will emit almost no SOx (due to pre-combustion gas clean-up), NOx (due to flameless combustion in the PBCLC reactors) or CO_2 (due to the highly efficient CO_2 separation in PBCLC reactors). The plants will also run on abundant locally produced solid fuels. As a result, these CCS plants will offer similar clean air and energy security benefits as other low-carbon electricity generators like nuclear, wind and solar power.

Regarding the different CCS power plant configurations considered in this study, the plants utilizing PBCLC reactors clearly outperformed the conventional pre-combustion plant. The economic advantage of these plants is dependent on relatively cheap oxygen carrier materials with long lifetimes. However, the benefits of adding the CLOP reactor in the COMPOSITE power plant configuration appear to be marginal. In this case, the larger gasifier and gas clean-up units required cancel out the savings from the higher power plant efficiency. The added complexity of the COMPOSITE power plant can thus not be justified economically, unless the CLOP reactor performance can be further improved to avoid the up-scaling of the gasifier and gas clean-up units. Aside from the added plant complexity, the addition of the CLOP unit will most likely reduce the load-following capability of the power plant, which can have significant economic ramifications in a future scenario with a high market share of variable and non-dispatchable wind and solar generators.

One scenario where the added efficiency of the COMPOSITE configuration can potentially justify the added complexity is a large-scale rollout of CO_2 negative bio-CCS plants. Given the limited technical potential of sustainable biomass production, this scenario is likely to reward the use of the most efficient energy conversion technology available.

The addition of hot gas clean-up technology was shown to have a significant positive impact on power plant economics. It should be noted that the economic benefits offered by this technology advancement directly apply to all CCS power plant configurations based on the IGCC concept.

In conclusion, the promising economic performance of the highly efficient IGCC-based CCS power plant configurations in this study merits further R&D investments. Specifically, hot gas clean-up technology and the inclusion of PBCLC reactors can significantly improve the efficiency and economics of an IGCC plant with CO_2 capture. Further scale-up and commercialization of these technologies are strongly recommended. Replacement of the ASU with CLOP reactors is seen as a lower priority unless the performance of the CLOP process (O_2 content in stream to gasifier) can be improved substantially.

Once these developments are complete, the plants evaluated in this study can form an important wedge in an "all of the above" technology-neutral climate change mitigation strategy. Highly efficient solid-fuel CCS power plants are likely to claim a central role in a possible future scenario where large investment in carbon negative power plants is required.

Acknowledgement

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