Low-Emission Natural Gas combined Cycle (NGCC) with Calcium Looping (CaL) Plant and Supercritical CO_2 Bottoming Cycle

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ABSTRACT
The natural gas combined cycle (NGCC) power plant has been a prominent technology for electrical power generation. Moreover, the relatively high efficiencies, low investment cost, and a low carbon-to-hydrogen ratio of natural gas compared to other fossil fuel sources have driven the attraction of NGCC plants for enhanced power generation. In addition to the need to increase power generation, there are environmental concerns over CO_2 emission from thermal power plants. Hence, recourse is taken to the development of efficient low-emission power generating systems.This work demonstrates a unique NGCC model using Aspen Plus®software integrated with the calcium looping (CaL) process for CO_2 capture. Also, the supercritical CO_2 cycle replaces the conventional steam Rankine cycle for the bottoming cycle, since sCO_2 would efficiently utilise the multiple high-grade heats emanating from the high-temperature CaL process. Furthermore, techno-economic assessment is presented, and the results show that the introduction of the recompression CO_2 cycle increased the power output from 440.6 MW to 480.3 MW. On the other hand, the plant's overnight cost was 1951.9 €/kW with CaL and 1029 €/kW without CaL. Hence, an increase of 61.6% and 27.2% relative to the reference plant with steam bottoming cycle, respectively. Also, the cost of CO_2 avoided was well feasible within the range project for a carbon tax by 2050.

Keywords: Carbon Capture, Natural gas combined cycle, Calcium looping,Economic analysis

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I. INTRODUCTION

1.1 Background to study

In view of a sustainable economic prospect, the world has to improve its energy supply by exploring a wide range of efficient energy sources. However, the increasing emission of CO_2 from several industrial operations remains a primary challenge to attaining this goal owing to strict policies regarding emission control. The rise in energy demand and the associated release of pollutants have left a major difficulty in attaining a reliable energy supply and environmental protection. Moreover, the International Energy Agency (IEA) stated that fossil fuels would probably remain the dominant source of energy in the nearest future (Sharifzadeh and Shah, 2015). Consequently, the emissions of CO_2 from power generation plants are becoming of significant environmental concern to the power sector where fossil fuel is predominantly utilised. The power sector is responsible for approximately 47% of the overall CO_2 emission, and CO_2 is a major greenhouse gas responsible for about 60% of global warming (Zaman and Lee, 2013). Without policies to prevent climate change, it is expected that global greenhouse gas emission in 2030 will rise by 25–90% above that of the year 2000, with the atmospheric concentration of CO_2 rising to 600-1550 ppm (Leung et al., 2014).

There are three fundamental ways to reduce CO_2 emission to the atmosphere energy-producing facilities, which are; the efficient use of energy facilities, by alternative fuels and energy sources with low or no carbon content, and by CO_2 capture and sequestration (CCS) (Zaman and Lee, 2013).The former two methods have been the likely practices in the power industry over the years, but the latter is increasingly becoming attractive as a significant amount of CO_2 emission could be averted. Thus, integrating carbon capture to existing fossil fuel facilities would be a major headway to achieving energy and environmental sustainability. Though, despite the awareness of theCCS technologies into various energy-producing infrastructures, there are some obstacles against the commercialisation of these technologies. Amongst these obstacles are the relatively mature state of current energy infrastructure and the fact that the current number of processes is much larger than the processes under construction. Thus, a little process retrofit should be required in improving energy efficiency and preventing emissions. Besides, the continuous incorporation of energy conversion processes with CCS technologies needs the latter to be as flexible as the former process (Sharifzadeh and Shah, 2015). Finally, to justify the process retrofit and overcome financial constraints, the energy consequences of the CCS process should be marginal.

Research efforts are continuously going on to assess the influence of several power plants combined with CCS configurations, in order to quantify the techno-economic value of emerging CCS technologies. Capturing CO_2 is probably the most cost-intensive stage in CCS technologies. It accounts for over 75% of the total cost of deploying the technology (Zaman and Lee, 2013). Over the years, there exists a range of separation techniques that have been commercial for CO_2 production, which has been utilised in industries like food processing and chemical manufacturing (Zaman and Lee, 2013). Nevertheless, the significant question remains, how viable is the technology on a large-scale power plant. Recent work has revealed that they are not cost-effective due to the need to separate other impurities, as well as the increased volume of flue gases to treat. For instance, the cost of electricity was expected to rise by roughly 80% and about 30% cut in generating capacity, when CCS was employed in a pulverised coal-fired power plant (Zaman and Lee, 2013). So, the suitable choice of technology to deploy is a function of the kind of power plant and the conditions of the gas stream to be treated, e.g., temperature, pressure and a targeted purity level of CO_2 concentration, economics, reliability, etc. (Zaman and Lee, 2013). The relatively high efficiencies, low investment cost and low carbon-to-hydrogen ratio of natural gas compared to coal has driven the attractiveness of NGCC when improved cycle efficiency is considered. However, the need to incorporate CCS technology to NGCC plants for environmental sustainability is likely to elevate the operating cost, based on the energy requirement and the fluctuating gas price. Therefore, it is worthwhile to resort to other means of compensating for these financial impacts while attempting to reduce the emission of CO_2 from power plants. Hence, alternative means of enhancing power produced is required, as well as a viable economic CO_2 capture process. Moreover, improving the plant's power output could be achieved by bottoming cycles for conventional NGCC plants (Wright and Anderson, 2017).

Li et al. (2017) conducted a comprehensive study on the current state of sCO_2 power cycle application to a range of industrial facilities such as nuclear, solar, geothermal, fuel cells, and waste heat utilisation. Conclusions were made concerning sCO_2 power cycle application to nuclear reactors and solar energy facilities. In the area of nuclear energy, it was attainable to experience high sCO_2 power cycle efficiency at a mild temperature of about 450-600 ^{o}C. And considering sCO_2 power application in solar energy facilities, special focus was on the effects of some major parameters on the cycle performance, the systems dynamic reaction of $sCO_{2,}$ and the automatic control system due to the variation of solar energy. Pagur and Joly (2015), carried out a comprehensive study on the feasibility of integrating a gas combined cycle with a suitable configuration of sCO_2 bottoming cycle options to enhance electricity generation, utilising a closed-loop bottoming cycle based on supercritical sCO_2 as working fluid. They emphasized that the diverse configuration of sCO_2 bottoming cycles has its unique way of heat utilisation and conversion to electric power.In conclusion, they stated that the simple recuperated cycle was the most suitable bottoming cycle configuration for small and medium-sized GTU.Moroz et al. (2015), furthered the work of Pagur and Joly (2015) to understand the extra power that could be delivered from a particular GTU when a sCO_2 bottoming cycle intricacy uses its heat. Results depicted that the composite cycle was 3.05 MW higher than what the present steam bottoming cycle produces. In the work of Le Moullec (2013), he explored the idea of retrofitting a coal-fired power plant with the sCO_2 Brayton cycle as well as integrating 90% post-combustion CO_2 capture technology. After carrying out a techno-economic assessment on the outlined power plant, it demonstrated a levelised cost of power reduction of 15%, and a 45% reduction in the cost of CO_2 avoided, without transport and storage capacity, comparedto a reference supercritical coal-terminated power plant outfitted with a standard CCS process.

On the other hand, the work of Hanak and Manovic (2016), proposed the use of a sCO_2 recompression cycle instead of steam in the bottoming cycle of a coal-fired combined cycle while retrofitting the system with a calcium looping (CaL) process for carbon capture. More improvements in the net efficiency of the retrofitted system were attained by adjusting the hardware and the turbine inlet conditions. As the capital cost of the sCO_2 cycle was up to 27% lower than that of the same steam cycle, this investigation demonstrates the feasibility of the recompression sCO_2 cycle application to CaL process. Conversely, Biliyok and Yeung (2013), showed that for a case of a 440 MW NGCC power plant integration with CO_2 capture and compression units designed for 90% capture level, the power output is seen to drop by 15%, whereas the need for cooling water rises by 33%by Erans et al. (2016). Although, the economic assessment of the entire system in their work was acceptable. Thus, it is wise to explore other means for enhancing and compensating for energy efficiency.

Furthermore, several studies such as; Angelino (1969), Moisseytsev and Sienicki (2009), Tobergte and Curtis (2013), Sarkar (2009), Bryant et al. (2011), Vitale Di Maio et al. (2015), Jeong et al. (2011),Dyreby et al. (2014), Cheang et al. (2015), Akbari and Mahmoudi (2014), Mecheri (2018) have justified the suitability of the alternative sCO_2 cycle layout. Despite the large-scale operation of NGCC power plants, there is no commercial-scale application of the proposed power plant in this study. Instead, a broad range of CO_2 capturing techniques and plant's efficiency improvement options have been applied to coal-fired power plants compared to NGCC on a commercial scale. Thus, an insight into the viability of an NGCC power with CO_2 capture while substituting the conventional bottoming steam Rankine cycle with sCO_2 cycle would certainly be a huge leap for electricity power generating applications. Besides, the bottoming steam cycle was substituted for sCO_2 to observe any improvement in plant efficiency or net power output while CO_2 capture was carried out by the CaL process.

The main aim of this work is to analyse the feasibility of the NGCC power plant with sCO_2thermodynamic bottoming cycles while adopting the calcium looping (CaL) process for CO_2 capture.Firstly, supercritical CO_2 as a working fluid for a bottoming cycle in place of steam for NGCC power plant is explored as compared to past studies where steam and coal plant is commonly used. Secondly, this work depicts the technological feasibility of the kind of power plant and a unique capture technique. Lastly, the economic implication of the system used in this study is highlighted as compared to other works. Thus, there are limited studies on the combination of the different power plants together.

II. NGCC MODEL DEVELOPMENT

Aspen Plus® was used to model the entire NGCC-CaL system from the gas turbine topping cycle to the capture process and down to the sCO_2 bottoming cycle. Thus, the three main sections of the retrofitted power plant are based on the standard design process from other studies. Although, some modification was required to enable a suitable process simulation in Aspen Plus®. The exhaust gas emanating from the natural gas turbine is channelled into the capture plant. Subsequently, the exhaust gas at about 580-600 ^oC undergoes a chemical reaction in the carbonator, extracting 90% of CO_2 before releasing a relatively hot clean gas at about 600 ^oC. Likewise, the reaction in the calciner involves a peak temperature of 600 ^oC, with the release of CO_2 gas to the storage unit. Consequently, high-grade from the calcium looping processing is recovered by the heat exchanger units to provide the heating requirement for the recompression CO_2 bottoming cycle. The sCO_2 cycle comprises the main and recompression compressors, the turbine, cooler, with the high and low-temperature recuperators. Notably, no air separation unit or CO_2 transport and storage units were modelled in this work. Although, the cost of the air separation unit would be estimated from other studies for economic analysis. Hence, the main aim here was simply to demonstrate the feasibility of the NGCC power plant integrated with the Calcium looping plant and a supercritical CO_2 bottoming cycle.

However, in benchmarking the reference power cycle to the model, the thermodynamic properties of the natural gas cycle were defined by the Peng Robinson (PR) cubic equation of state with the Boston-Mathias (BM) alpha function. As this property method is recommended for gas plant simulation in Aspen Plus®. Thus, to ensure a suitable simulation environment, it was vital to select in the model palette, the suitable blocks and streams to define each section of the entire system correctly.

The main input to the model consists of the natural gas and air components as given in Table 1, as well as CaO. Also, Table 2 shows the operating conditions for the NGCC topping cycle plant.

Table 1: Air and natural gas composition (Hanak and Manovic, 2017)

Air		Natural gas	
Component	**Mole fraction**	**Component**	**Mole fraction**
Nitrogen	0.773	Methane	0.8708
Oxygen	0.2074	Ethane	0.0077
Argon	0.0092	Propane	0.000999999
Carbon dioxide	0.0003	Iso-Butane	0.06
Water	0.0101	N-Butane	0.039
		Nitrogen	0.0147
		Carbon dioxide	0.0068

Table 2: Operating Conditions of NGCC Topping Cycle Power Plant (Biliyok and Yeung, 2013)

Description (Units)	Values
Fuel gas flow rate (kg/s)	15.69
Fuel temperature (C)	26.56
Turbine inlet Temperature (C)	1425
Ambient air temperature (C)	15
Air flow rate (kg/s)	686.61
Air to gas combustion ratio	43.76
Turbine isentropic efficiency	0.985
Turbine discharge pressure (bar)	1.013
Compressor efficiency (polytropic)	0.92723
Compressor discharge pressure (bar)	20.68

2.1. Gas Turbine

The gas turbine unit replicates the topping cycle of a 440 MW NGCC power plant modelled in GE's GateCycle™ turbine library software as illustrated in the work of Biliyok and Yeung, (2013). Thus, the natural gas turbine unit for this work is simulated. Table 3 highlighted the gas turbine performance indicators after running the simulation.

Table 3: Gas Turbine Performance Parameters(Biliyok and Yeung, 2013)

Description (Units)	Values
Gas turbine power output (MW)	591.51
Natural Gas turbine net power output (MW)	287.69
Outlet temperature (C)	580
Flue gas flow rate (kg/s)	702.3

2.2. Calcium Looping, (CaL) Process Model

Primarily, the CaL process was simplified to comprise two fluidised bed reactors (carbonator and Calciner) and two cyclones for separating the clean gas and CO_2 streams respectively. Originally, the carbonator (CARB) was modelled in Aspen Plus® by an RStoic block with the assumption of 90% sorbent conversion. Similarly, the calciner (CALC) was modelled using the RGibbs block that indicates the phase and chemical equilibrium using Gibbs' free energy under a given operating temperature (900 ^{o}C). Also, thermal input from the combustion of natural gas and oxygen is utilised for the calcination process. The integrated NGCC plant with the CAL system is shown in Fig. 1.

2.3. Process Model for sCO_2 Cycle

The model was developed based on a recompression sCO_2 cycle demonstrated in the work of Moisseytsev and Sienicki (2009), for a sodium-cooled fast reactor application but with slight modifications as shown in Fig 2. Unlike the reference model, the process model developed in this work utilised the high-grade heat from different heat sources of the CaL process and the fractional splitting of the working fluid between the compressor and recuperators to optimise the cycle's performance.

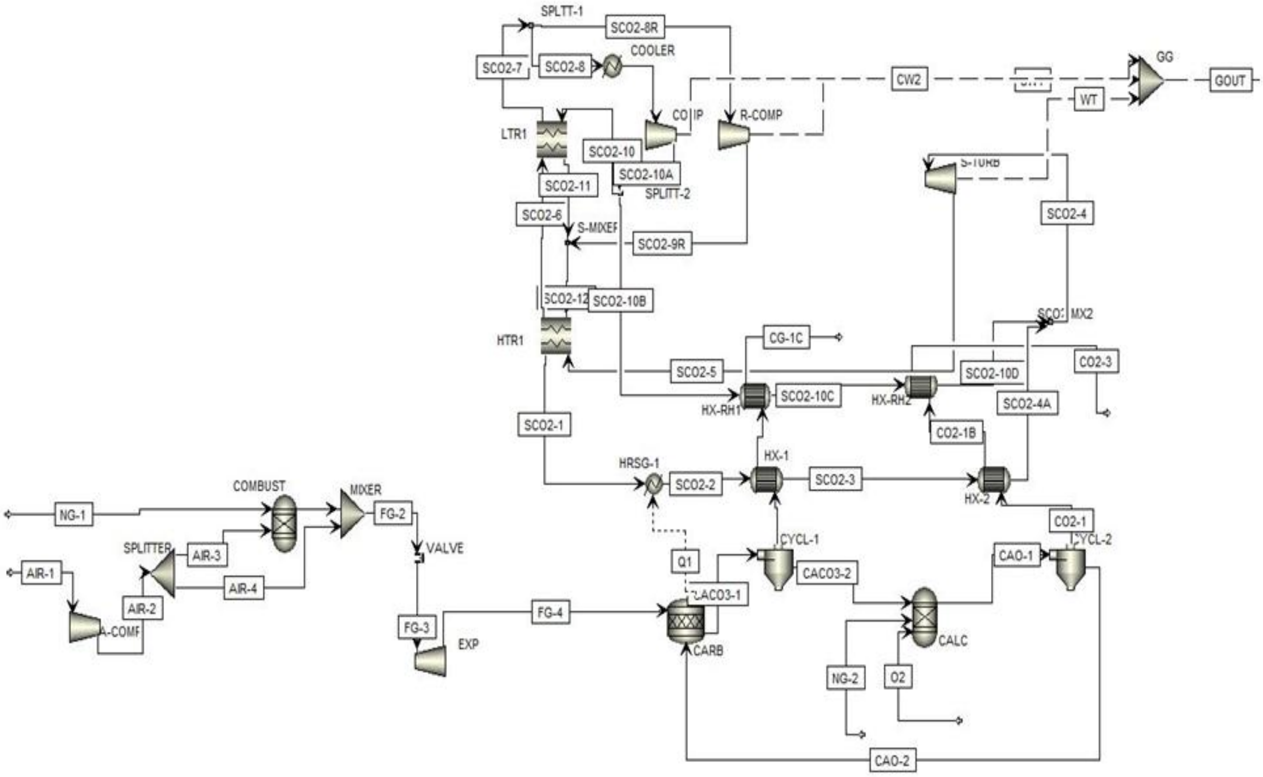

Fig. 1: Aspen plus Integrated NGCC plant with CaL

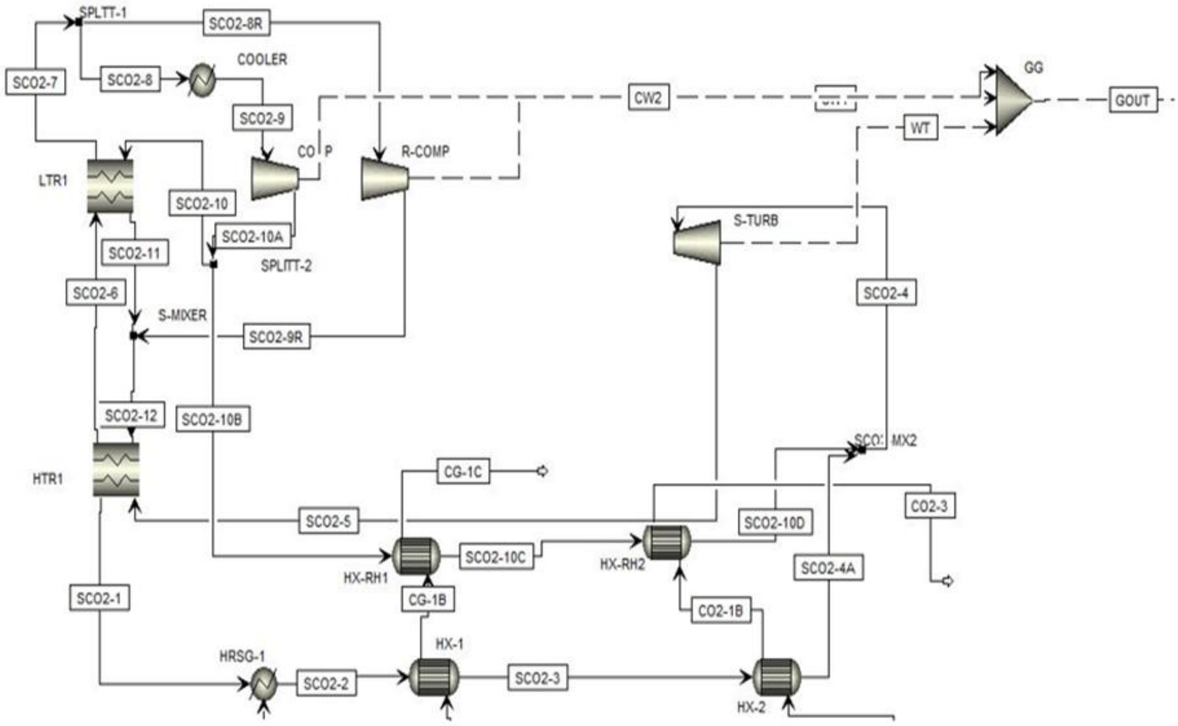

Fig. 2: Aspen sCO_2 cycle Model

2.4. Power Cycle Thermodynamic Performance Parameters

The process model demonstrated in this work has been developed in Aspen Plus® and also benchmarked against the reference 440 MW NGCC power plant model (Biliyok and Yeung, 2013). Likewise, the existing sCO_2 power cycle developed by Moisseytsev and Sienicki, (2009) and CaL process described by Hanak and Manovic, (2017) was adopted and modified in this work. Hence, the thermodynamic performance of the NGCC integrated with CaL process is evaluated using the main performance indicators commonly adopted for conventional thermodynamic cycles. Primarily, the net power output (W_{net}) and the net thermal efficiency (η_{th}) are considered, which are related in Eqn1. Additionally, the net efficiency penalty as defined in Eqn.2 is used to estimate the performance of the CaL process in this work against the reference power plant without a CO_2 capture plant. Finally, to recommend the model as a low emission power generating system, the environmental performance parameter was illustrated in Eqn.3 as the specific CO_2 emission (e_{CO2}) defined as the ratio of the rate of CO_2 discharge to the net power output.

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{fuel}} \quad \textbf{(1)}$$

$$EP = \eta_{th,ref} - \eta_{th,CALC} \quad \textbf{(2)}$$

$$e_{CO_2} = \frac{\dot{m}_{CO_2}}{\dot{W}_{net}} \quad \textbf{(3)}$$

III. ECONOMIC CONSIDERATIONS AND ESTIMATIONS

The economic appraisal of such a noble technology is a sensitive procedure that is carried out in several stages. Above all else, a few considerations must be noted to accurately predict and justify the financial implication under a real-life scenario. Such appraisal depends majorly on estimating the capital, operational, and maintenance expenditures, as well as fuel consumption. Likewise, consideration is given to the further utilization of the resources delivered, in addition to power and ecological benefits in this specific case. This methodology must be linked to both the reference and modelled plants, so an examination of the outcomes eventually results in a solid conclusion.

For this study, a reference power plant without CO_2 capture is first evaluated, then a similar procedure is carried out on the modelled power plant with CO_2 capture by CaL. Likewise, the NGCC power plant with sCO_2 bottoming cycle is compared to a reference plant with a conventional steam bottoming cycle. Thus, the specific goal here is to draw out solid feedback about the conceivable future for improved innovation. Additionally, studies such as Kuramochi et al. (2013); Erans et al. (2016); Akbari and Mahmoudi (2014); Diego et al. (2018); Mohajerani et al. (2018); Osagie et al. (2018) and Zhu *et al.*(2018)have considered the economic and environmental viability of such innovative efficient low-emission power plants.

3.1. Economic Parameters

The main economic parameters considered in this work are expressed in terms of the levelised cost of electricity (LCOE) and the cost of CO_2 avoided according to the expressions of Hanak and Manovic, (2017). Thus, this study targets to obtain credible values and justify the economic feasibility of the power plant from these expressions for the final recommendation. The following mathematical expressions are used to calculate the levelised cost of electricity given in Eqn 4:

$$LCOE = \frac{TPC \times FCF + FOM}{\dot{W}_{net} \times CF \times 8760hrs} + \frac{SFC}{\eta_{th}} + VOM \quad \textbf{(4)}$$

Where this parameter denotes the economic and thermodynamic performance indicators, such as total plant cost (TPC) (€), fixed charge factor (FCF), fixed operating and maintenance cost (FOM) (€), variable operating and maintenance cost (VOM) (€), net power output ($\dot{W}_{net}$) (MW), capacity factor (CF), specific fuel consumption (SFC) (g/KW_{el}h), and the net thermal efficiency (η_{th}).
Also, for the cost of CO_2 avoided, the expression is given as (Eqn 5):

$$Cost\ of\ CO2\ avoided\ (AC) = \frac{LCOE_{capture} - LCOE_{ref}}{e_{CO_2.ref} - e_{CO_2.capture}} \quad \textbf{(5)}$$

Where $LCOE_{ref}$ and $e_{CO_2.ref}$ are the levelised cost of electricity and CO_2 emission for the reference plant respectively.

3.2. Cost Estimation

The total capital requirement (TCR) or plant cost (TPC) of the low-emission power plant will be determined by first estimating the Engineering, Procurement, and Construction (EPC) cost. Cost scaling correlation to some reference power systems and equipment from literature are employed to determine an approximate cost of the modelled power plant with capture. Thus, a sequential cost approach is used to deduce the plant's EPC cost starting from the main units (Gas Turbine plant, sCO_2 power plant, and CaL unit) of the system to a globally integrated power plant with carbon capture. Therefore, the total equipment cost for the gas turbine and sCO_2 power plants will be estimated according to the expression in Eqn6 from Whitesides, (2012).

$$C = C_o \cdot \left[\frac{S}{S_o}\right]^{S_f} \cdot N \quad \textbf{(6)}$$

Where C is the total plant's equipment cost, C_o is the reference plant's equipment cost, S is the actual size of the scaling parameter and S_o is the reference size. A scaling factor *"S_f"* is used to adapt these plant costs; N stands for the number of plants or equipment.
For the CaL plant, the total equipment cost was approximated based on a bottom-up approach considering the cost of the carbonator calciner, heat exchangers, and fuel preparation system as the major cost factors. Eqns 7 to 11 were used to derive the overall equipment cost of the CaL plant.

$$C_{CaLC} = (1 + i_{P\&C}) \cdot (C_{Cal} + C_{Car} + C_{FS} + C_{HE}) \quad \textbf{(7)}$$

$$C_{Cal} = c_{Cal} \cdot \dot{Q}_{Cal}^{\ 0.67} \quad \textbf{(8)}$$

$$C_{Car} = c_{Car} \cdot \dot{Q}_{Car}^{\ 0.67} \quad \textbf{(9)}$$

$$C_{FP} = c_{FP} \cdot \dot{m}_F^{\ 0.24} \quad \textbf{(10)}$$

$$C_{HE} = 2546.9 \cdot A_{HE}^{\ 0.67} \cdot p_{HE}^{\ 0.28} [€] \quad \textbf{(11)}$$

Where ($i_{P\&C}$) is assumed to be 0.35, which represents the piping and integration cost. The c_{Car} and c_{Cal} represent the unit cost of the carbonator and calciner as determined (c_{Car} = 16 591 €/kW$^{0.67}$; c_{Cal} = 13 140 €/kW$^{0.67}$) according to the work of Criado, Arias and Abanades (2017) and the cost estimation was based on the heat flux $\dot{Q}$, in the reactors. The heat exchangers cost was a function of the area and operating pressures, while the cost of fuel preparation systems was assumed according toFout et al. (2015).A summary of all relevant costs and assumptions are given in Tables 4-7.

Table 4: Equipment cost for main units (US DOE, 2016)

Plant equipment	**Scaling parameter**	**Ref. cost (M€)**	**Ref. size S_o**	**Actual Plant size S**	**Scaling factor S_f**	**N**	**Cost (M€)**	**C**
GT unit	Net power output	133.51	237	287.69	0.67	1	152.02	
sCO_2 plant unit	Net power output	106.36	137.5	197.6	0.67	1	135.61	
Carb, Cal, H.EX, FPS	thermal input	-	-	-	-	-	134.65	
ASU and Cyclones	-	-	-	-	-	-	45.77	
TEC							468.05	

Table 5: Installation and delivery cost for main units (US DOE, 2016)

Installed Unit	**Equipment cost (EC) M€**	**Installation cost % over (EC)**	**M€**
GT plant	152.02	50	76.01
sCO_2 plant	135.61	50	67.80
CaL plant	134.64	30	40.39
ASU and Cyclones	45.77	35	16.02
Total Installation cost	-	-	200.23
Delivery cost (10% of TEC)	-	-	46.81

Table 6: Total plant cost for NGCC breakdown (US DOE, 2016)

Cost	Value
Total equipment cost (TEC) [M€]	468.05
Delivery and Install (D&I) [M€]	226.44
Direct cost (TEC+ D&I) [M€]	648.72
Indirect cost (14% of TEC) [M€]	90.82
EPC cost (DC+IDC) [M€]	739.54
Owner's & Contingency cost (15% of EPC) [M€]	110.93
Total Plant Cost (TPC) [M€]	850.47
Specific Plant Cost [€/kW]	1770.73

Table 7: Economic analysis assumptions (Hanak and Manovic, 2017)

Description	Value
Variable O&M cost	2% TPC
Fixed O&M cost	1% TPC
Fixed charge Factor (FCF)	10%
Gas price (€/GJ)	2.34
Project lifetime (years)	25
Project interest rate (%)	8.87
Capacity factor (%)	80
Carbon tax (€)	0.0

IV. THERMODYNAMIC AND ECONOMIC PERFORMANCES

4.1 Power Cycle Performance Analysis

The performance indicators of the NGCC power plant using the recompression sCO_2 cycle configuration for the bottoming cycle and with and without CaL plant have been summarised in Table 8.For similar natural gas turbine power output, the net power output of the combined cycle was shown to increase for the retrofitted NGCC-sCO_2 plant due to the introduction of recompression sCO_2 in place of the conventional steam system cycle. Hence, this improvement in power generated justifies the benefits of the supercritical CO_2 cycle as stated in the reports of Wright and Anderson (2017).

Table 8: Cycle Performance Indicators

Parameters	**Ref. NGCC (Steam) cycle only**	**Ref. NGCC (sCO_2) cycle only**	**NGCC (sCO_2) cycle with CaL**
NGCC system performance indicators			
Gas turbine power output (MW)	287.7	287.7	287.7
Total LHV thermal input (MW_{th})	738.3	934.8	1080.5
Power plant Net output (MW)	440.6	465.4	480.3
Net thermal efficiency ($\%_{LHV}$)	59.6	49.9	44.45
Integration performance indicators			
Efficiency penalty/gain($\%_{LHV\ points}$)	-	9.8	15.1
% Increase in gas consumption	-	21	32
CO_2 capture level (%)	-	-	90
Net Specific emission (kg CO_2/MWh)	354.5	323.9	32.52

Moreover, the high-grade heat streams from the CaL process was efficiently utilised for increasing the thermal condition of the sCO_2 working fluid of the bottoming cycle before entering the sCO_2 turbine at approximately 600 ^{0} C. Thus, the specified configuration (double heat recuperation, compression, and splitting of the working fluid), of the recompression sCO_2 cycle in this work improved its overall operating condition, thereby providing a better performance compared to the configuration of the recompression sCO_2 cycle in the study of Moisseytsev and Sienicki (2009) under similar operating condition. Therefore, justifying the selection of the sCO_2 recompression cycle against other possible sCO_2 cycle configuration. Notably, the net power output of the combined power plant with sCO_2 cycle was enhanced due to the reduction in parasitic load demand, where a smaller sized component was utilised compared to the steam cycle.

Furthermore, it can be deduced that the thermal input happened to increase by 38% for the NGCC-sCO_2 cycle with CaL compared to the reference system (NGCC plant only) due to the energy requirement by the CaL plant components. However, a net efficiency penalty of $15.1\%_{LHV}$ and $9.8\%_{LHV}$ relative to the reference NGCC plant was experienced for the NGCC-sCO_2 plants with and without CaL respectively. Consequently, this efficiency decrease for the retrofitted plant is because of the additional heat requirement utilised in the calcination process of the CaL plant. Notwithstanding the plant's efficiency due to the CaL process, the NGCC-sCO_2 plant with CaL plant is characterized by a low specific CO_2 emission of 32.52 (kg CO_2/KWh) relative to the power plants without CaL in Table 8. This entails that the proposed retrofitted power plant in this work has approximately 90% lower CO_2 specific emissions compared to the conventional NGCC power plant with CO_2 capture. Therefore, the environmental benefits of the retrofitted system are well achieved. However, it can be deduced that the value of specific CO_2 emission is a function of the CO_2 composition in the fuel, amount of gas consumed, and the net power output of the plant. Thus, it is vital to optimising the use of these factors to account for the environmental benefits of the system.

4.2 Economic Performance

4.2.1 Overnight cost, LCOE, and AC

Having illustrated the technical performance of the NGCC power with CaL process, it is vital to benchmark its economic performance indicators against that of the reference NGCC power plants without CO_2 capture. Hence, the LCOE and the cost of CO_2 avoided were the primary parameters used to evaluate the economic viability of the retrofitted power plant, as shown in Table9.

Table 9: Economic performance indicators

Parameters	**NGCC (steam)**	**NGCC (sCO_2)**	**NGCC (sCO_2) plant with**

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	plant only	plant only	CaL
Overnight Cost (OC) (€/kW)	749.0	1029.0	1951.9
Increase in (OC) (%)	-	27.2	61.6
LCOE (€/MWh)	29.5	36.2	53.8
CO_2 avoided (€/tCO_2)	-	-	60.3

From the result in Table 9, the specific capital cost of the NGCC-sCO_2 plant with CaL was estimated to be 1951.9 €/kW. This figure is slightly below the estimated value for the standard CaL retrofits scenario (2100 €/kW) in the study of Criado, Arias, and Abanades (2017). However, the specific capital cost of the plant is 27.2% and 61.6% respectively, higher than the reference NGCC plants without CO_2 capture. As well as 8.9% and 52% higher than the advanced NGCC plant with reduced operating cost with and without CCS respectively (936.9 €/kW) (1778 €/kW) (U.S. DOE, 2013; 2016). This implies that retrofitted power plants with CaL are always likely to involve an elevated capital cost compared to standalone plants due to the high cost of the CO_2 capture plant. Although, in the NGCC-sCO_2 cycle without CaL, the replacement of the steam cycle with sCO_2 cycle of more compact components did not result in lower specific capital cost as one would imagine it has the benefits of increased power output.

Furthermore, the LCOE associated with the NGCC-sCO_2 with CaL was estimated to be 53.8 (€/MWh) and the corresponding cost of CO_2 avoided (AC) was estimated as 60.3 (€/tCO_2). Meaning the LCOE and AC were a function of the total plant cost, plant's power capacity, and the degree of natural gas utilisation, respectively. Thus, for similar gas turbine operating conditions, the LCOE for the plant was 45.2% and 32.7%, respectively higher than that of the reference plants without CaL in this work. Yet, both the LCOE and AC respectively, for this study were approximately close to the values ranging for CaL retrofits (54.3-96 €/MWh; 28.9-58.3 €/tCO_2), chemical solvent scrubbing retrofits (65-75 €/MWh; 35-75 €/tCO_2) and chemical looping combustion (45-60 €/MWh; 16- 55 €/tCO_2) all highlighted in the study of Hanak and Manovic (2017). Besides, the projected figures for a carbon tax by 2050 is in the range 10-150 €/tCO_2 (EIA, 2010; UK DECC, 2014). Therefore, this implies that even with CO_2 emission control in view, the CaL process would still be economically feasible over the NGCC-sCO_2 plant in this study for carbon tax higher than 60.3 €/tCO_2 for a scenario of CO_2 utilisation. Although, this value is likely to be higher if the CO_2 transport and storage costs were considered.

4.2.2 Effect of Cost factors

To better comprehend the effects of varying cost factors, a cost designation for the COE cost for each scenario in this work is illustrated in the accompanying figures:

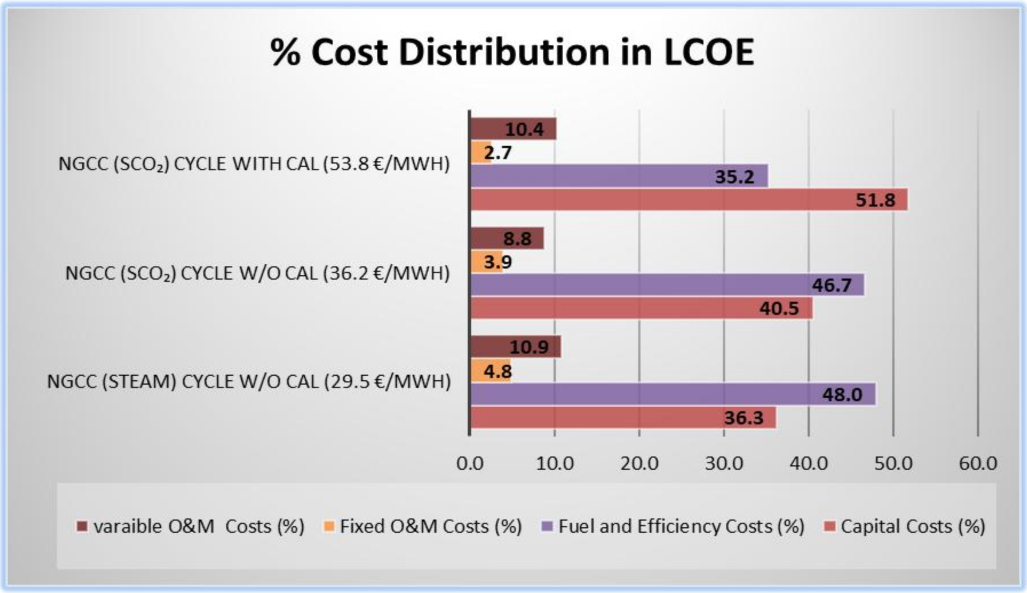

Figure 3: Percentage cost distribution in LCOE

Figure 3 clearly illustrates the contribution each cost factor has on the final LCOE for all power plant scenarios in the study. While the results obtained seem promising, the LCOE is observed to increase from 29.5 €/MWh for the NGCC-steam plant to 53.8 €/MWh for the NGCC-sCO_2 plant with CaL. Hence, the LCOE for the retrofitted plant was 45% greater than the LCOE for the NGCC-steam plant. However, the percentage increment in LCOE drops to 32.7% when the standalone NGCC plant used a sCO_2 bottoming in place of the steam Rankine cycle. Figure 3shows that the capital cost of the plant is the highest cost driver for the retrofitted plant. This can be understood due to extra capital cost incurred by integrating the CaL plant and the high-temperature recuperators of the sCO_2 cycle respectively, which conforms to the findings in some studies for NGCC retrofits with CO_2 capture plants (Biliyok and Yeung, 2013; Wright and Anderson, 2017). Also, a slight difference in the fixed was experienced. However, the fuel price remains the dominant cost driver to the final LCOE for the reference standalone NGCC plants, while the reverse case was experienced for the NGCC retrofit.

4.2.3 LCOE vs Natural Gas Price

It is reasonable to assume that the quantity of natural gas combusted in the calciner for the thermal requirement of the CaL process, would generate an increase in the LCOE than the reference standalone plants as shown in Figure 4.

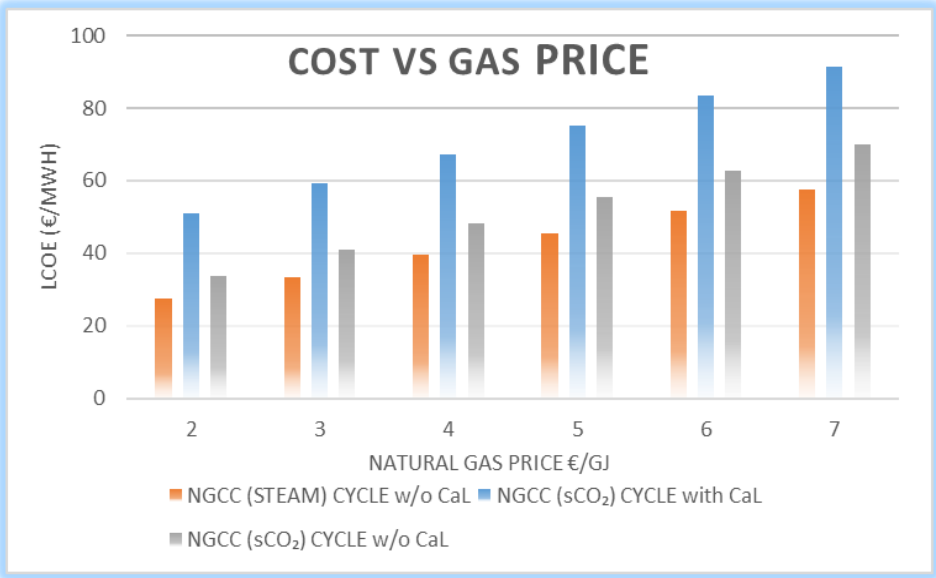

Figure 4:LCOE against natural gas price

Consequently, the entire system is sensitive to gas price as revealed in Figure 4. However, the LCOE remains higher with increasing gas price for both NGCC plants working on sCO_2 bottoming cycle with and without CaL plant due to the additional heating requirement. On the other hand, the increased power output from the sCO_2 compare would likely compensate for any fluctuating gas price.

4.2.4 Other cost indicators

Even though most studies have sectioned towards analysing the calcium looping process by evaluating the sorbent price, any possible fluctuation in sorbent price could likely affect the LCOE when considered on a global picture. In addition, it is worthwhile to consider looking into the cost of different system configurations with components optimisation in view. Moreover, a comprehensive study to consider varying costs for plant's components such as heat exchanger, piping materials, etc., would yield a more accurate prediction of the plant's projected cost.

V. CONCLUSION

This study proposed to establish that an NGCC plant retrofitted with CaL and sCO_2 bottoming cycle can be classified as an efficient and low-emission power generating system. Several conclusions were deduced from this work, which is outlined below;

Other studies as well as this work, reveals that the supercritical CO_2 thermodynamic power cycle is a prospective technology to displace steam in the bottoming cycle for gas turbines. Also, sCO_2 is a non-flammable, low cost, non-toxic, readily available, and stable working fluid.Also, sCO_2 high-density permits for the formation of a relatively compact power cycle, as well as a higher efficiency compared to the cycles such as the Helium Brayton cycle or steam Rankine cycle depending on the cycle's configuration. Hence, the recompression sCO_2 cycle configuration amongst other configurations was the most promising cycle configuration that integrates well to heat recovery systems such as the exhaust gas of gas turbine and high-grade heat from carbon capture plants.

A high fidelity 400 MW NGCC power plant has been adapted and modelled in Aspen Plus® to demonstrate the techno-economic performance of the proposed power plant. Results from simulations suitably replicate the reference gas turbine to enable a proper NGCC plant analysis. The introduction of the recompression CO_2 cycle considerably increased the power output from 440.6 MW to 480.3 MW. However, there was an efficient drop of 15.9%$_{LHV}$ point owing to the additional thermal requirement of the CaL plant base of the system design in this work. Thus, the optimisation of the design specification is likely to enhance plant efficiency.

At 90% CO_2 capture, and a 32% increase in gas consumption for the NGCC-sCO_2 cycle compared to the reference NGCC plant, the specific CO_2 is observed to drop significantly. On the other hand, the modelled plant overnight cost was 1951.9 €/kW with CaL and 1029 €/kW without CaL. Hence an increase of 61.6% and 27.2% relative to the reference plant with steam bottoming cycle. Consequently, a levelised cost of electricity of 60.3 €/MWh is obtained, which is close to values found in other literature for standard CO_2 capture retrofit. Moreover, the cost of CO_2 avoided was well feasible within the range project for a carbon tax by 2050.

Finally, a range of electricity power enhancement technologies are common in the energy industry, but the use of sCO_2 power cycle used in the work has proven to efficiency improve the power output from industrial power plants.

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