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Techno-economic comparison of optimized natural gas combined cycle power plants with CO_2 capture

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A B S T R A C T

Natural gas combined cycle (NGCC) power plants account for a large share of the global energy market. Although many alternative layouts of NGCC plants have already been addressed in the scientific literature, there are still relevant gaps of knowledge in comparative techno-economic performances of the previously proposed alternatives. This article presents a comprehensive comparative study of 19 alternative NGCC power plants with pre-combustion, post-combustion or oxy-fuel combustion CO_2 capture processes involving different choices of CO_2 absorbents and organic Rankine cycles for energy savings. The purpose of this study is to shed light on comparative techno-economic performances of power plants with different CO_2 capture strategies and various organic Rankine cycle configurations. First, performance of each alternative was optimized from a technical (equivalent work) standpoint. Then, the economic performance of each optimized alternative was evaluated. Based on the results within the sample of NGCC plants, using activated methyldiethanolamine could lead to better technical and economic performances than monoethanolamine in pre- and post-combustion capture systems. Moreover, the efficacy of organic Rankine cycles for enhancing the technical and economic performance of NGCC plants with CO_2 capture was shown, with a reduction of up to 1.39 years in the payback period for various process configurations.

1. Introduction

1.1. Introduction to natural gas combined cycle power plants with CO_2 capture

Within a context in which world energy demand is constantly increasing, natural gas power plants are getting increased shares of the world energy market [1,2]. However, a main issue associated with natural gas power plants is the release of large amounts of CO_2 in the process, thus contributing to global warming. Finding solutions for this issue has been the topic of numerous studies in the scientific literature (e.g. Refs. [3–6]). Considering process configuration, three main approaches can be utilized for CO_2 capture in natural gas combined cycle (NGCC) power plants: pre-combustion, post-combustion and oxy-fuel combustion CO_2 capture.

The pre-combustion approach involves hydrogen production from the natural gas feedstock and then CO_2 separation from the resulting stream before using it as the fuel for power generation [7]. This includes the use of a reformer where natural gas is converted into syngas ($CO + H_2$) according to Equations (1) and (2) [8–10]. Moreover, in the configuration proposed in some studies, a pre-reformer is added for converting heavier hydrocarbons according to Equations (3) and (4) in order to prevent the formation of coke in the primary reformer [8].

$$CH_4 + \frac{1}{2}\, O_2 \rightarrow CO + 2\, H_2 \tag{1}$$

$$CH_4 \; + H_2O \leftrightarrow CO + 3\, H_2 \tag{2}$$

$$C_xH_y + \; x\, H_2O \leftrightarrow x\; CO + \left(x + \frac{y}{2}\right) H_2 \tag{3}$$

$$CO + 3H_2 \; \leftrightarrow CH_4 + H_2O \tag{4}$$

The resultant stream is sent to water gas shift (WGS) reactors where Reaction (5) occurs [11,12], increasing hydrogen production.

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Nomenclature

Abbreviation

a-MDEA	Activated methyldiethanolamine
ASU	Air separation unit
BFW	Boiler feedwater
CLR	Chemical looping reforming
DEA	Diethanolamine
DGA	Diglycolamine
DIPA	Diisopropylamine
EGR	Exhaust gas recycling
EQW	Equivalent work
HP	High pressure
HRSG	Heat recovery steam generator
HT	High temperature
LP	Low pressure
LT	Low temperature
MDEA	Methyldiethanolamine
MEA	Monoethanolamine
MP	Medium pressure
NGCC	Natural gas combined cycle
O&M	Operation and maintenance
ORC	Organic Rankine cycle
PROAN	Process analyzer
PZ	Piperazine
TEA	Triethanolamine
WGS	Water gas shift
WHSV	Weight hourly space velocity

This process is usually implemented in two steps, known as high-temperature shift (HT shift) and low-temperature shift (LT shift) [13,14].

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{5}$$

The resulting stream is then cooled down to remove the water condensates before entering the CO_2 capture unit, typically based on chemical absorption. Different types of alkanolamines such as methyldiethanolamine (MDEA) [9,15] and monoethanolamine (MEA) [16] along with membrane contactors and ionic liquids [17,18] can be used for separating CO_2 from the fuel [19]. Many other absorbents such as piperazine (PZ) [20], diglycolamine (DGA) [21,22], diethanolamine (DEA) [23], diisopropylamine (DIPA) [24], triethanolamine (TEA) [25] and piperazine activated MDEA (a-MDEA) [26,27] have also been investigated for CO_2 capture.

The CO_2-free fuel is combusted to produce thermal energy which is converted into electricity in gas and steam turbines. Two schemes of this process based on different heat exchanger networks (changing the configuration of the BFW (boiler feedwater) heat exchangers and the pathway of the feed stream before entering the reformer, and using different configurations of the heat recovery steam generator (HRSG)) have been studied previously [8,9]. The processes based on pre-combustion require additional equipment for conversion of natural gas to syngas. However, these alternatives are evaluated in this study because of their versatility to switch to hydrogen or hydrogen/electricity plants. This is especially important due to the increasing interest in hydrogen, and because the economic comparison of pre-combustion alternatives has not yet been thoroughly studied in the scientific literature.

A second approach to CO_2 capture is its separation from the combustion flue gases (post-combustion CO_2 capture). In this scheme natural gas is fed as the fuel to the combustor, subsequently producing CO_2, water and heat due to natural gas combustion reactions. The resulting stream is mainly composed of N_2, water and CO_2. This stream passes through the gas turbine producing electricity and then enters the HRSG. The flue gases of the HRSG are then cooled down before entering the CO_2 capture unit, which is also typically based on chemical absorption. Several studies have previously described this kind of configuration [28–31].

In the oxy-fuel combustion approach, natural gas is also used as the fuel but the air components are separated in an air separation unit (ASU) producing N_2 and O_2. Only O_2 is pressurized and used as the fuel oxidizer. Besides, due to very high flame temperatures, a fraction of the flue gases is usually pressurized and recycled to be used as diluents. Steam-rich and CO_2-rich diluents have been investigated in the literature [32]. One of the characteristics of this approach is that the flue gas stream can have a purity >85 vol% CO_2 without an additional CO_2 capture unit. Similar configurations have been presented in other studies [33,34].

1.2. Motivation of the research study

Many studies have focused on improving specific aspects of the above-mentioned power plant processes. Some of them pay attention to the application of chemical looping reforming (CLR) of natural gas in the pre-combustion process and similarly for methanol production [13,35–37]. In this process, the reforming of methane is carried out in two reactors, known as air reactor and fuel reactor. Methane is oxidized by oxygen from an oxygen carrier (e.g., CuO and Mn_2O_3), which is constantly circulated between the two reactors.

The Organic Rankine Cycle (ORC) is similar to a Rankine cycle but, instead of water, an organic working fluid is used in the cycle. The effects of adding an organic Rankine cycle (ORC) on the performance of a post-combustion process and internal combustion engines have been investigated in previous studies [38,39]. Exhaust gas recycling (EGR) has also been explored in post-combustion processes in many other investigations [40–42].

Extracting steam from the HRSG to provide thermal energy for the CO_2 capture unit [8,31,43,44], CO_2 removal using advanced membrane technologies [2], the use of different diluents for the oxy-fuel process [32] and the application of process integration schemes [44–47] have also been investigated in the scientific literature. Furthermore, the comparison of various power production technologies [48], exergy and environmental analysis of power production processes [49–51], and health and emissions effects of switching from coal to natural gas power plants have been the topic of relevant investigations in this field [52–54].

Regarding the CO_2 capture process, MEA (a primary amine) and MDEA (a tertiary amine) are among the most common solvents for chemical absorption and their CO_2 capture performance has been explored in many studies [55–60]. MEA is known for its fast reaction rates, while MDEA is known for its higher acid gas loading [61] and lower regeneration energy [55,62]. Also, MDEA is selective towards absorption of H_2S [63] and, for the gases with high CO_2 content, usually a small fraction of primary or secondary amines are added to the solvent. In particular, piperazine (a secondary amine) has recently received significant attention for enhancing the performance of MDEA [58–60].

In other related publications, the comparison of different blade cooling schemes for gas turbines [64], energy and exergy analyses of closed-loop steam cooling of turbine blades [65] and the optimization of air-film cooling of blades using response surface methodology [66] were studied. Investigation of the possibility of enhancing efficiency of modern combined cycle power plants [67] and economic [68], thermodynamic [69] and environmental improvement [70] analyses of combined cycle power plants before and after addition of CO_2 capture have been the topic of other related publications. It was shown that integration of CO_2 capture would decrease the electrical efficiency of the power plant [68]. The loss of efficiency due to addition of MEA CO_2 capture unit was reported as 5.3–6.7% [68,70].

1.3. Novelty

Despite the extensive number of valuable studies published in the field of NGCC power plants, there are still some gaps that need to be filled. In this paper, a comprehensive comparative study was carried out among 19 alternatives of NGCC with three different types of carbon capture to shed light on the following gaps in the literature:

- Although two main pre-combustion configurations with different heat exchanger networks have been proposed by different researchers, there has not been any study comparing these configurations based on their technical and economic performances. One of the aims of this study is to compare these two configurations and their respective modifications by addition of ORCs and different CO_2 absorbents. More details about the differences of these two configurations are provided in Section 2.1 and Supplementary Material 1. To the best of our knowledge, this comparison has not been carried out in previously published articles.
- In the previously published studies, some ideas such as the addition of an ORC were proposed for improving the technical performance of the post-combustion process. In this research,

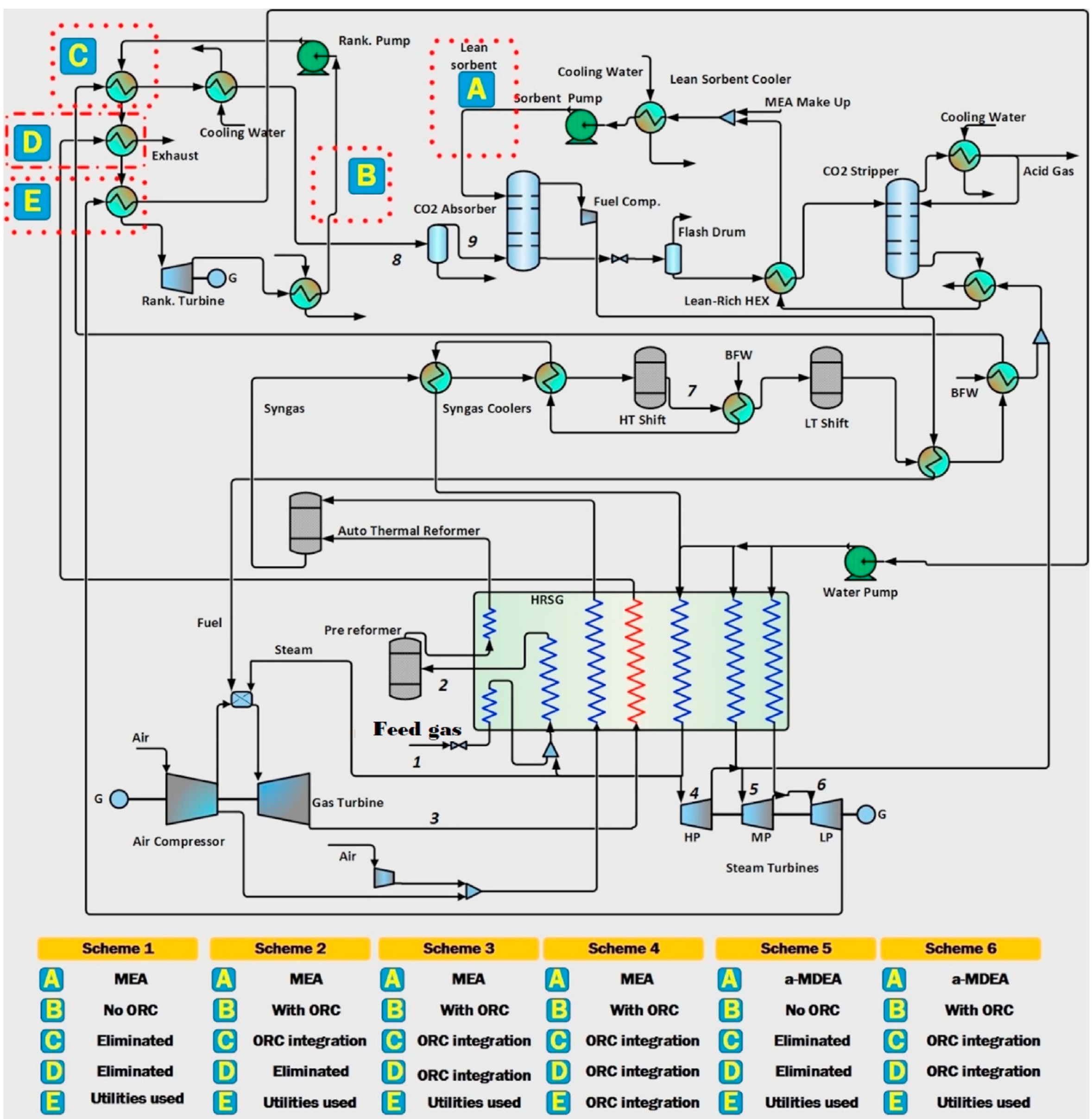

Fig. 1. Process flow diagram of an NGCC plant with pre-combustion CO_2 capture, heat integration scheme #1, and its alternative schemes.

not only those ideas are improved for further energy and costs savings on the post-combustion process, but they are also extended and developed for application in pre-combustion and oxy-fuel combustion processes. The authors could not find other published works describing the performances of the improved alternatives as presented in the current article.
- Most of the previous studies focus on improving the performance of a specific pre, post or oxy-fuel combustion process. This study does not focus on a single process. Instead, basic pre-combustion, post-combustion and oxy-fuel combustion processes were designed and optimized, and their enhanced configurations with heat recovery and heat integration ideas have also been investigated. Moreover, for pre-combustion and-post combustion processes, two different absorbents (MEA and piperazine-activated MDEA) were evaluated to shed light on the most promising CO_2 capture methods for each process.

2. Materials and methods

2.1. Brief process description of the designed alternatives

In this research, four basic NGCC plant configurations were simulated, optimized, economically evaluated and compared to each other:

I. NGCC power plant based on pre-combustion carbon capture and heat integration scheme #1 [8].

The process flow diagram of this basic configuration along with various modifications and operational options is shown in Fig. 1. Six different schemes were designed based on different CO_2 absorbents and types of ORC heat integration. Key features of each scheme can be seen in Fig. 1, based on specific choices regarding points A, B, C, D and E (Schemes 1–6).

II. NGCC power plant based on pre-combustion carbon capture and heat integration scheme #2 [9].

The main difference with respect to the previous basic configuration lies in the heat integration method: location of the BFW heat exchangers, feed stream pathway before entering the reformer, and streams involved in the HRSG [8,9]. A detailed description can be found in Supplementary Material 1. The corresponding process flow diagram is shown in Fig. 2. It contains six variations, representing Schemes 7–12.

III. NGCC power plant based on post-combustion carbon capture [28–31].

Another basic configuration was designed including post-combustion CO_2 capture. Fig. 3 shows the process flow diagram of the system with post-combustion capture and its variations based on different CO_2 absorbents and ORC types, representing Schemes 13–17.

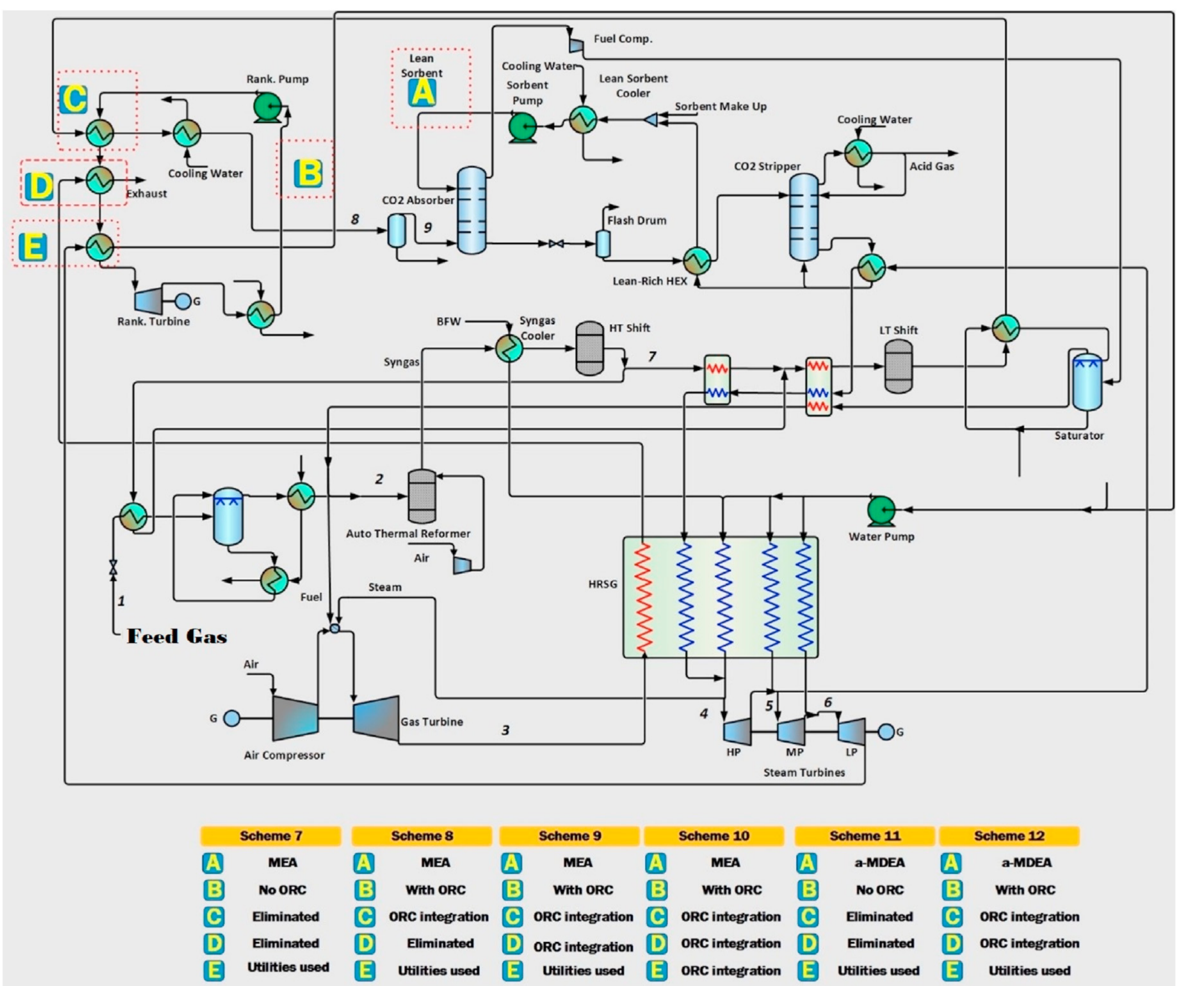

Fig. 2. Process flow diagram of an NGCC plant with pre-combustion CO_2 capture, heat integration scheme #2, and its alternative schemes.

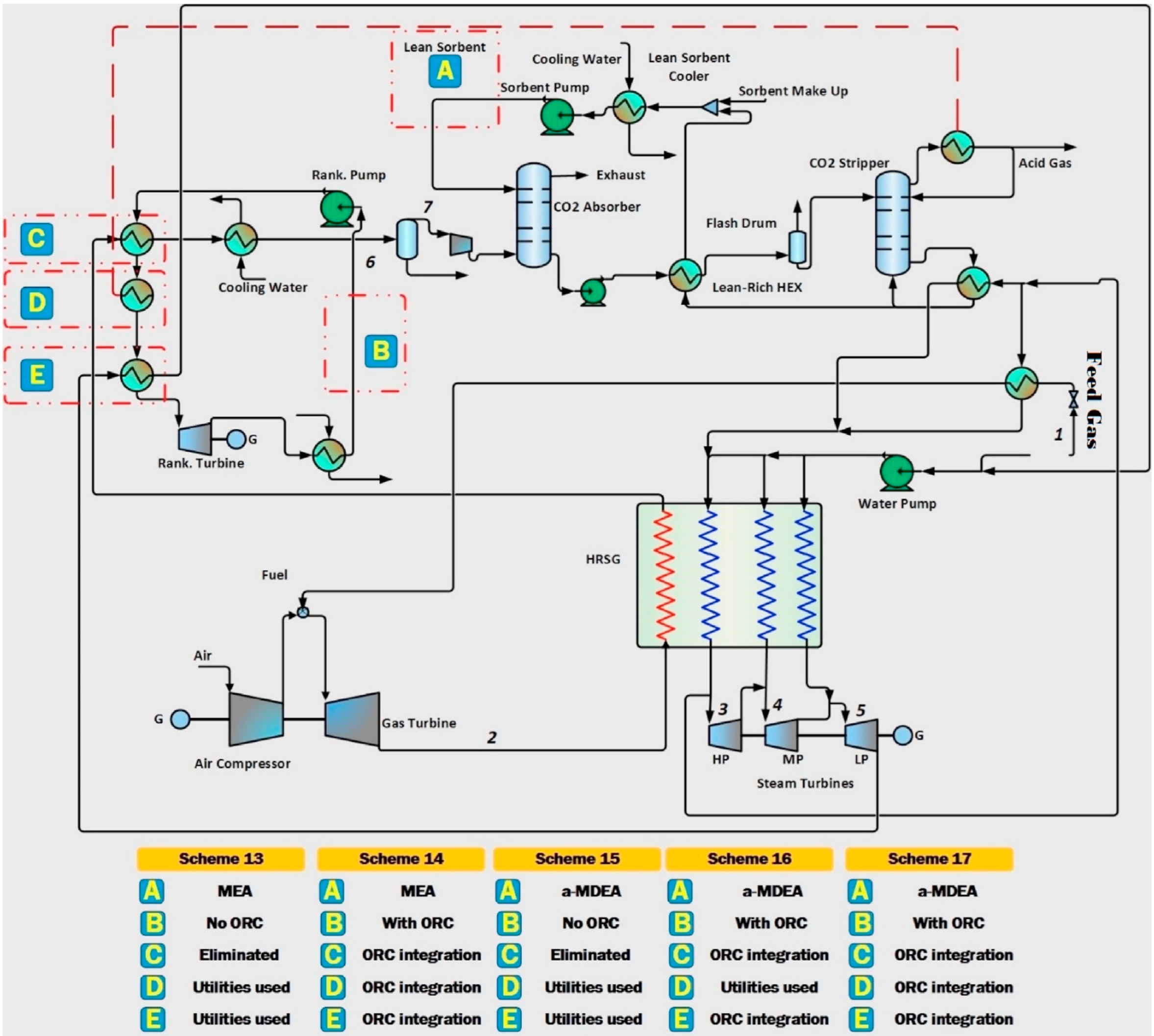

Fig. 3. Process flow diagram of an NGCC plant with post-combustion CO_2 capture, and its alternative schemes.

IV. NGCC plant based on oxy-fuel combustion carbon capture [33,34].

Two schemes were designed with oxy-fuel combustion capture based on CO_2 recirculation. The difference between these two schemes lies in the addition of ORC, as shown in Fig. 4 (Schemes 18 and 19).

Therefore, 4 basic schemes along with different modifications were designed based on the consideration of two different CO_2 absorbents (MEA and a-MDEA) and various ORC systems, leading to a total of 19 NGCC plant configurations. A detailed description of these 19 alternatives, including their individual process flow diagrams, are provided in Supplementary Material 1. All of the cases were designed based on the same feed specifications as reported by Nord et al. [8] and summarized in Table 1. It should be noted that a mixture of 61.96 mol% propane and 38.04 mol% ethane was used in this study instead of the C_{2+} component. The mole percentages were selected in such a way to yield the same stream molecular weight as presented in Ref. [8]. Every scheme was simulated using Aspen HYSYS® according to the technical specifications provided in Supplementary Material 1. Also, Supplementary Material 2 presents a comparison of the simulations carried out in this study with reference publications [8,71]. It was assumed that H-class gas turbines are available for the studied configurations.

2.2. Optimization method

MATLAB software was used to optimize the simulated alternatives. An overview of the optimization algorithm is shown in Fig. 5. The main optimizer is Fmincon with multiple initial values, to reduce the possibility of being trapped in local minimums. The equivalent work (*EQW*) of the whole process was used as the key feature within the objective function for the optimizer. As presented in Equation (6), this parameter is a combination of mechanical work and hot utilities produced/consumed in the process. This parameter has also been used as a key process feature in previous studies [72,73]. The coefficient 0.75 is considered as a nominal factor for second-law conversion efficiency of thermal streams. Based on this equation, the equipment where electricity is produced has positive EQW, and the equipment in which electricity is consumed has negative EQW. Therefore, the systems with higher EQW would be preferable.

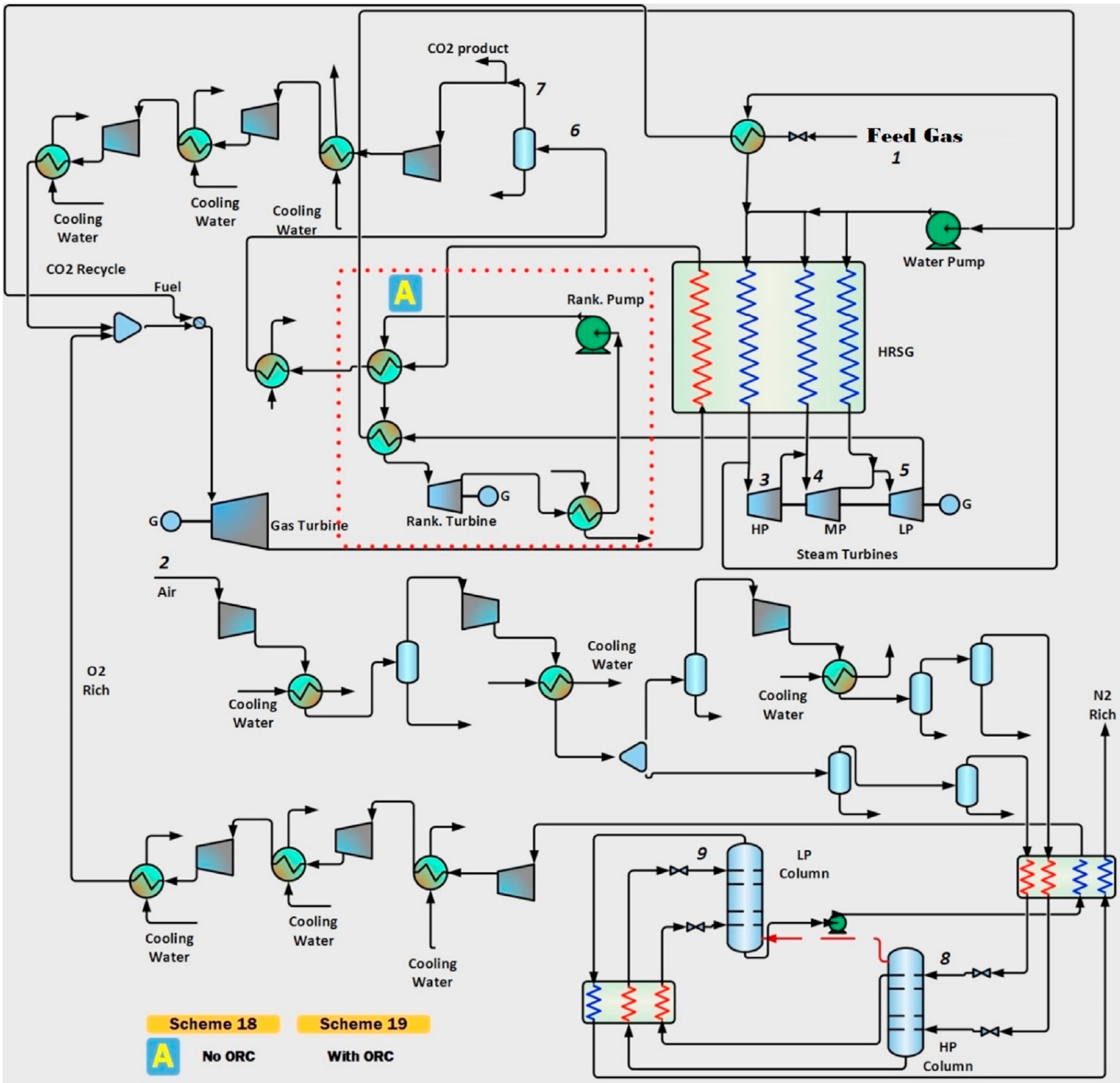

Fig. 4. Process flow diagram of an NGCC plant with oxy-fuel combustion CO_2 capture, and its alternative scheme.

Table 1
Feed gas specifications.

Parameter	Value	Component	Value
T (°C)	16.0	CH_4 (vol%)	79.84
P (bar)	31.00	C_{2+} (vol%)	16.72
Mass flow rate (kg/s)	19.0	CO_2 (vol%)	2.92
Molecular weight (kg/kmol)	20.73	N_2 (vol%)	0.51

$$EQW = -\sum\left(0.75 \times Qheating \times \left(\frac{Theat - Tsink}{Tsink}\right) + Wpump + Wcomp - Wturbine\right) \quad (6)$$

In Equation (6), *Qheating* is the energy consumed for heating a stream, *Theat* is the temperature of the hot utility used for heating up a cold stream, and *Tsink* is the average temperature (between inlet and outlet) of the cold stream. *Wpump* and *Wcomp* stand for the mechanical work required for the operation of pumps and compressors, respectively. *Wturbine* is the energy produced in expanders. It should be noted that *Theat* was determined based on the type of heating utility. A summary of the utilized heating and cooling utilities is presented in Table 2; the type of heating utilities was determined based on the maximum required cold stream temperature.

In this study, a software tool with user interface was developed to automate this method of optimization for other simulated processes as well. A screenshot of this software, which was named PROAN (short for Process Analyzer), is available in Supplementary Material 3. As a first step for optimization, the software gets the initial values of parameters from the user and applies them to the simulated process. Then, in order to make sure that the simulation has converged, the software rechecks convergence every 0.5 s. Once the simulation is converged, results of energy and material streams as well as equipment data are loaded into PROAN. Then, based on the type of equipment consuming/producing thermal or mechanical energy, the values of *Qheating*, *Theat*, *Tsink*, *Wpump*, *Wcomp*, *Wturbine* and *EQW* are calculated within PROAN, and using

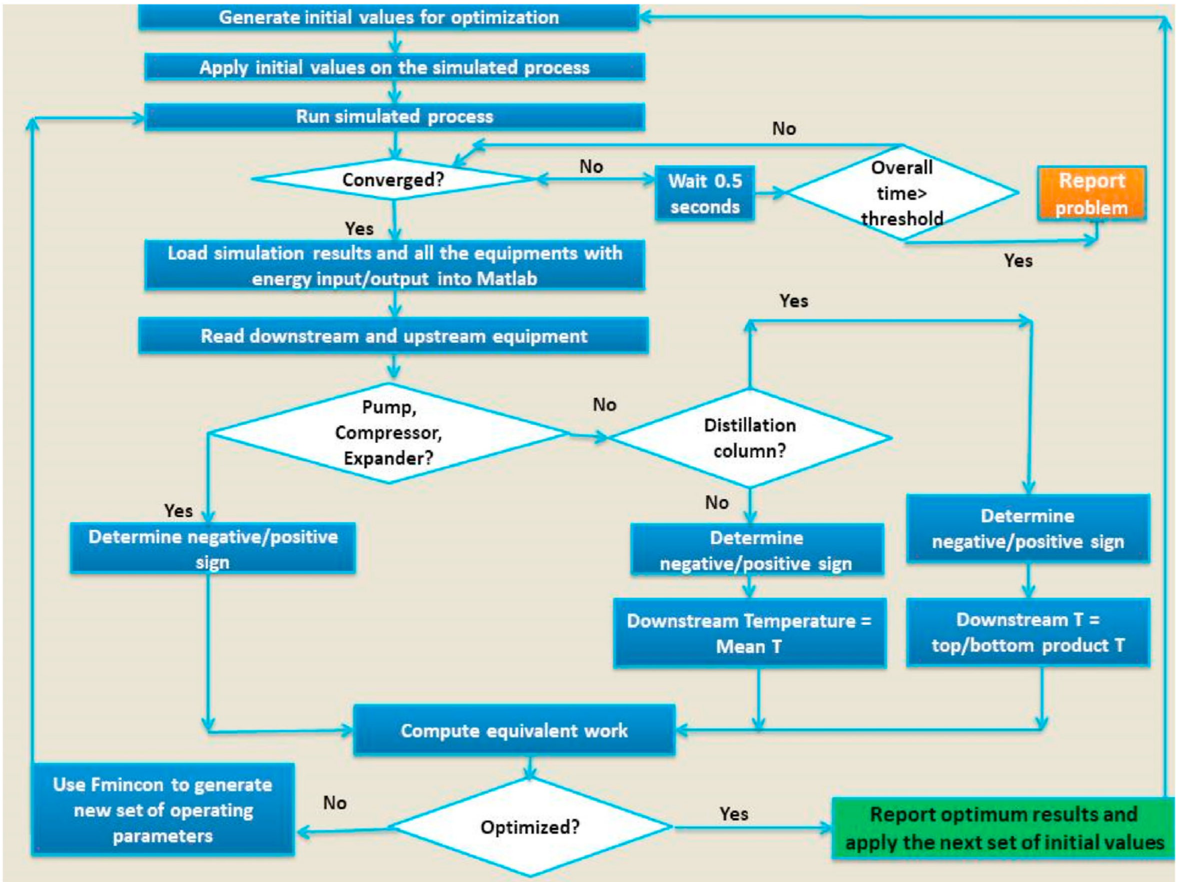

Fig. 5. Algorithm for optimization of the simulated processes.

Table 2
Heating utilities characteristics.

Type of utility	Utility temperature (°C)	Utility pressure (bar)	Maximum attainable cold stream temperature (°C)
Low-pressure (LP) steam	150	5	140
Medium-pressure (MP) steam	180	10	170
High-pressure (HP) steam	250	40	240

Fmincon this process is repeated multiple times to yield an optimum point. However, since the Fmincon optimizer is based on the gradient descent principle, the optimization of each process alternative was carried out with multiple initial values. One set of initial values and boundaries of each parameter is specified by the user. The rest of initial values for optimization are randomized within the boundaries of each parameter.

It should be noted that the algorithm in Fig. 5 was designed to read the simulation automatically. It only evaluates inputs/outputs of the process, while the interconnected/pinched energy streams in the process are discarded. After the optimization is completed, all the alternatives were economically evaluated to explore how the technically optimized processes would perform economically. Details of economic evaluations including the utilized correlations, equations used for calculation of the annual profit of the processes, and types of process utilities are presented in Supplementary Material 4.

3. Results and discussion

3.1. Technical optimization results

Before analysis of the results, it was necessary to make sure that the simulations carried out in this study are in accordance with the reference investigations. Comparison of the results obtained in this study with the previous ones is presented in Supplementary Material 2. The results show good accuracy of the simulation models developed in this study. The parameters obtained for the produced steam in the HP, MP and LP cycles of the four studied base cases are presented in Table 3.

The EQW results of the technically optimized processes are shown in Fig. 6. Data show that for the pre-combustion process with the heat integration strategy #1 or #2 and for the post-combustion process, the equivalent work of the schemes involving a-MDEA is higher than that of the corresponding schemes

Table 3
Parameters obtained for the produced steam in the four studied base-case scenarios.

Parameter	NGCC with post-combustion carbon capture	NGCC with pre-combustion carbon capture #1	NGCC with pre-combustion carbon capture #2	NGCC with oxy-fuel combustion carbon capture
Live steam temperature in HP cycle (°C)	540.0	568.0	450.6	590.0
Live steam pressure in HP cycle (bar)	85.5	86.8	85.0	85.0
Live steam temperature in MP cycle (°C)	194.6	215.0	301.2	223.8
Live steam pressure in MP cycle (bar)	8.5	9.3	9.7	10.4
Live steam temperature in LP cycle (°C)	118.5	116.6	112.8	131.4
Live steam pressure in LP cycle (bar)	1.9	1.7	1.5	2.8

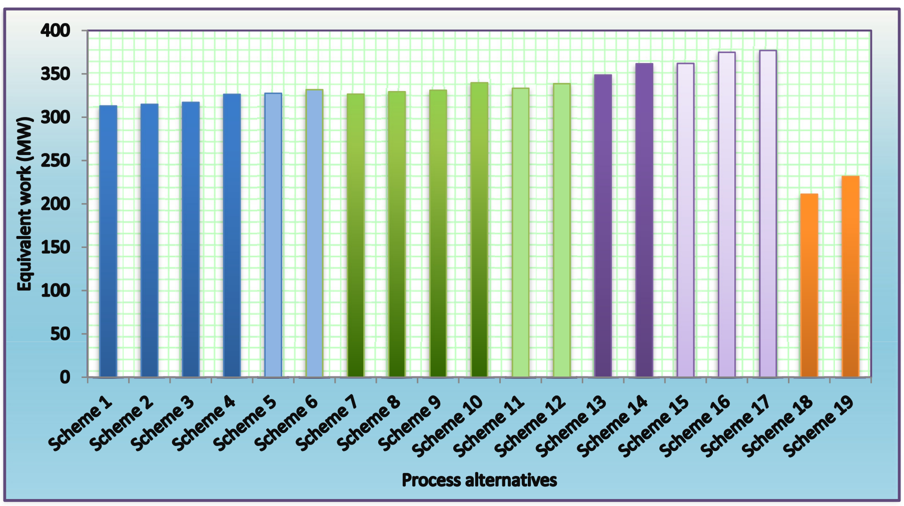

Fig. 6. Equivalent work of the 19 alternatives.

with MEA. For example, in the pre-combustion process with heat integration strategy #1, the a-MDEA scheme shows a 4.6% higher EQW, compared to the MEA scheme. Also, a difference of 2.0% was observed in pre-combustion processes based on a-MDEA and MEA and heat integration strategy #2. This is attributed to the fact that generally a-MDEA requires lower regeneration energy compared to MEA [61,62,74]. This lower regeneration energy results in lower reboiler duty for the stripper column of the CO_2 capture unit. This is very important because this reboiler is pinched with the steam cycle. For the schemes with larger reboiler duty, larger flow rates of steam are supplied, and therefore the power production in the steam cycle is reduced. The results also show that the second heat integration strategy for the pre-combustion NGCC power plants gives a better technical performance in terms of EQW than the heat integration strategy #1. The improvement is 4.4% for the MEA scheme and 3.4% for the a-MDEA scheme.

Furthermore, the results show that the addition of ORCs leads to higher EQW from pre-combustion, post-combustion and oxy-fuel combustion processes. In particular, the full ORC (implemented in Schemes 4, 10, 12 and 17) gives better results in terms of EQW.

The post-combustion scheme with a-MDEA absorbent and full ORC (Scheme 17) gives the best technical performance in terms of EQW (377 MW). On the other hand, the oxy-fuel combustion processes (Schemes 18 and 19) show the lowest EQW results, and a larger influence of ORC addition on the EQW performance of the process. This observation was attributed to the fact that a larger flow rate of the exhaust gases enters the ORC in this configuration. Lower net technical efficiency of the oxy-fuel process was also pointed out in previous studies [75]. This is linked to the ASU included in the system and the associated use of compressors.

Furthermore, the overall process efficiency (quantified as the ratio of EQW to the total thermal energy input) and the CO_2 captured and released in each of the schemes were evaluated (Fig. 7 and Fig. 8, respectively). In line with the EQW results, the selection of a-MDEA as the solvent, the addition of the full ORC and the choice for a post-combustion process (i.e., Scheme 17) would yield the highest overall efficiency (Fig. 7). The results in Fig. 8 show a similar CO_2 capture performance of the different pre- and post-combustion schemes (oxy-fuel configurations are not included in the figure because they involve a CO_2 purity of 85% in the exhaust gas without an additional CO_2 capture unit). Also, the electrical efficiency of the gas turbine and HRSG is presented in Fig. 7. Since there is a pinched reboiler in most of the alternatives, it was not possible to directly calculate this efficiency. Here, it was calculated based on the assumption that the supplied steam to that pinched reboiler is used in a steam turbine to generate more electricity. This produced electricity was then added to the gross electricity production in the turbines and divided by the total thermal energy input to calculate the efficiency. The maximum electrical efficiency (57.8%) was found in NGCC with post-combustion CO_2 capture according to Scheme 17. Close results were obtained for Schemes 16 and 14 as well. These observations show that the proposed configurations of ORC can lead to an enhanced electrical efficiency of these processes. It should also be noted that, in Schemes 18 and 19,

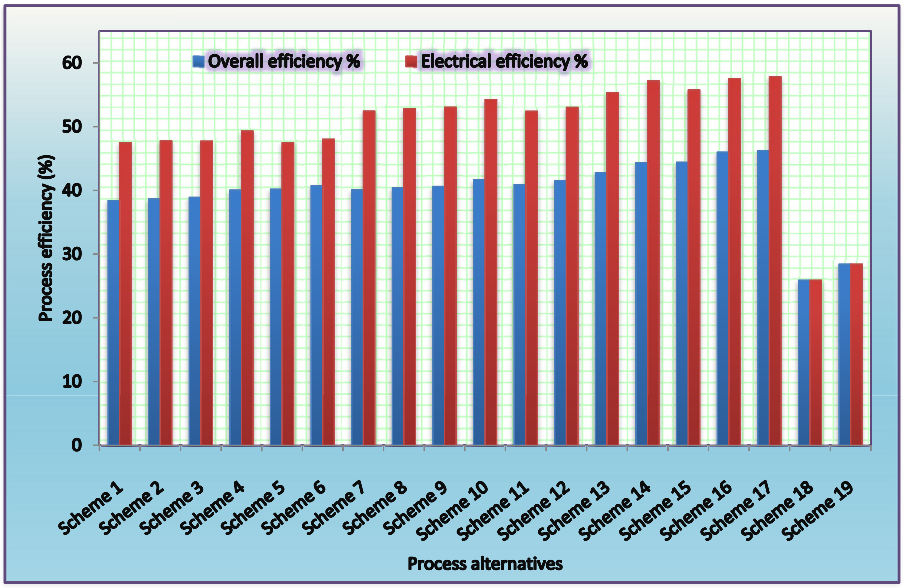

Fig. 7. Overall and electrical efficiencies the 19 alternatives.

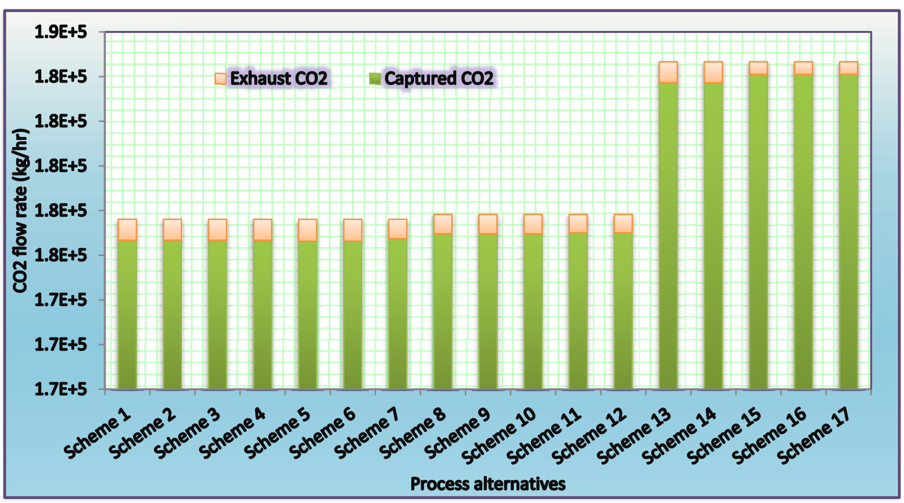

Fig. 8. Captured CO_2 and exhaust CO_2 in pre- and post-combustion alternatives.

the electrical efficiency values are the same as the overall process efficiency because, in these cases there is no amine CO_2 capture unit.

3.2. Economic evaluation results

The equipment costs of the 19 alternatives were calculated (Fig. 9). The results show that the post-combustion schemes involve the lowest equipment costs. This is due to the fact that, in the pre-combustion and oxy-fuel combustion schemes, additional equipment (autothermal reformer, WGS reactors, ASU, etc.) is required. The addition of ORCs was found to have a significant influence on the overall process equipment costs. This is mainly due to the addition of expensive turbines in ORCs.

The equipment cost per MW of equivalent work is also presented in Fig. 9. These results show that, although the overall equipment cost of the oxy-fuel schemes is comparable to that of the other schemes, their equipment cost per MW is much higher due to their lower EQW. The results also show that, on a MW basis, the addition of ORCs does not have significant influence on the pre- and post-combustion schemes. On the other hand, in the oxy-fuel configurations, the addition of ORCs was found to reduce the overall equipment cost per MW. The lowest equipment costs per MW were found for the schemes using a post-combustion process, with values around 1 million $/MW.

In order to calculate the payback period of the different strategies, product sales, operating labor costs, the natural gas purchase cost and other expenses were estimated. Energy sales are presented in Table 4, showing similar trends as observed for EQW. With 30.0 k$/hr, Scheme 17 (involving post-combustion, a-MDEA and full ORC) also shows the best performance under this aspect. The calculated O&M (operation and maintenance) costs are also presented in Table 4. It should be noted that the cost of the natural gas feed was 9.64 k$/h for all the alternatives, as all of them were designed based on the same feed specifications.

Annual profit results are presented in Fig. 10. Again, the best

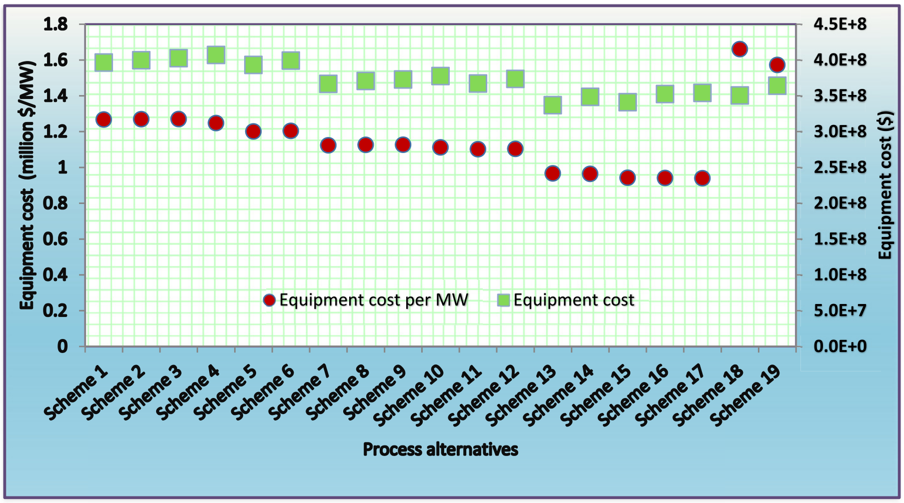

Fig. 9. Equipment cost for the 19 alternatives.

Table 4
O&M costs and product sales for the 19 alternatives.

	Fixed O&M cost $/yr	Variable O&M cost $/yr	Energy sales $/h
Scheme 1	4.04E+06	8.07E+06	2.63E+04
Scheme 2	4.06E+06	8.12E+06	2.65E+04
Scheme 3	4.09E+06	8.18E+06	2.66E+04
Scheme 4	4.21E+06	8.42E+06	2.74E+04
Scheme 5	4.23E+06	8.45E+06	2.69E+04
Scheme 6	4.28E+06	8.56E+06	2.72E+04
Scheme 7	4.22E+06	8.43E+06	2.72E+04
Scheme 8	4.25E+06	8.50E+06	2.74E+04
Scheme 9	4.27E+06	8.54E+06	2.75E+04
Scheme 10	4.39E+06	8.77E+06	2.82E+04
Scheme 11	4.30E+06	8.60E+06	2.78E+04
Scheme 12	4.37E+06	8.74E+06	2.82E+04
Scheme 13	4.50E+06	9.00E+06	2.77E+04
Scheme 14	4.67E+06	9.33E+06	2.88E+04
Scheme 15	4.67E+06	9.34E+06	2.88E+04
Scheme 16	4.84E+06	9.67E+06	2.99E+04
Scheme 17	4.87E+06	9.73E+06	3.00E+04
Scheme 18	2.73E+06	5.45E+06	1.65E+04
Scheme 19	2.99E+06	5.98E+06	1.82E+04

result was found for Scheme 17. As these are electricity production processes, the main reason for the superiority of this scheme is its higher EQW. On the other hand, the main reason for the comparatively low EQW and profit of the oxy-fuel schemes is the additional energy consuming equipment such as compressors in ASU and CO_2 recycling compressors. The results also show that for the pre-combustion schemes, the heat integration strategy #2 leads to a slightly better performance in energy and cost savings than the heat integration strategy #1.

The payback period for each of the 19 alternatives was calculated (Fig. 11). This analysis is especially important because it was shown that the addition of ORCs would increase the EQW and annual profit but adding expensive equipment to the processes. Thus, the calculation of the payback period of each alternative can help decision-making regarding the application of ORCs. In this sense, the results show that in all of the pre- and post-combustion schemes, the application of ORCs leads to a lower payback period. Taking into account that the ORCs only deal with a small section of the system, such an influence was deemed significant. For the oxy-fuel schemes, the economic impact of ORC addition was found to be even more significant, as shown in Fig. 11. Overall, it should be

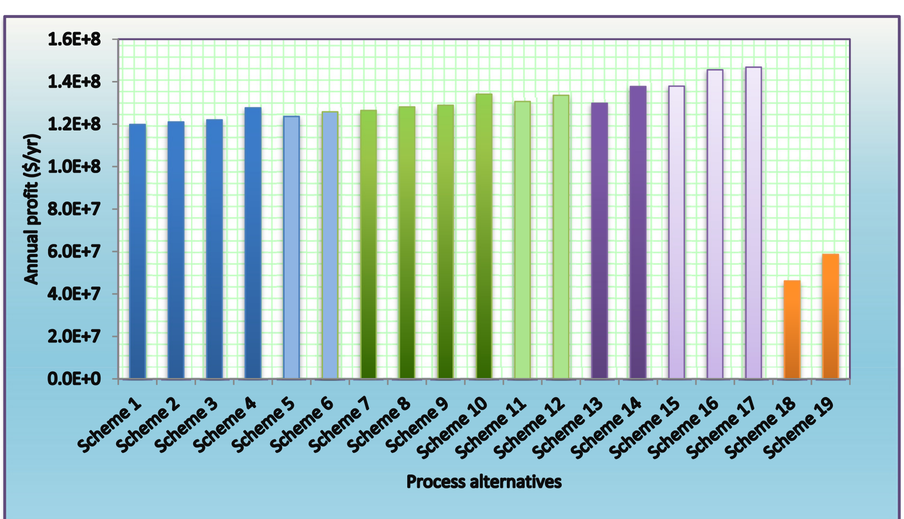

Fig. 10. Annual profit and energy sales of the 19 alternatives.

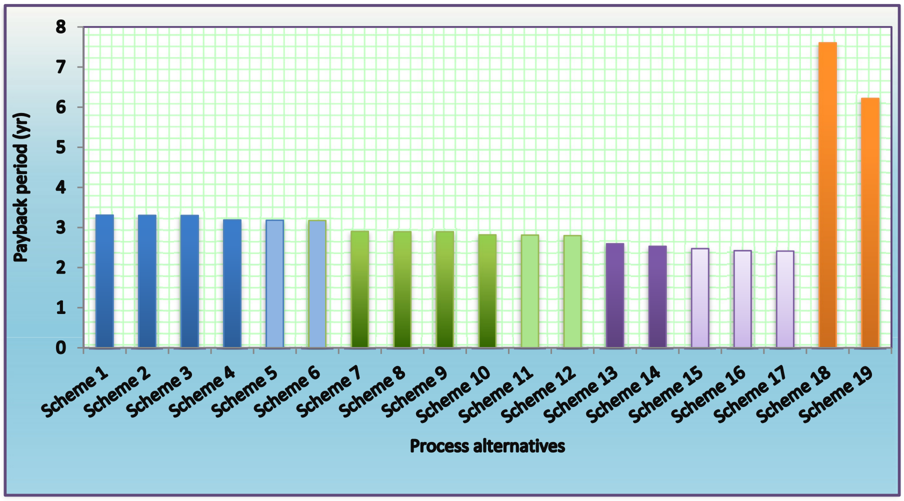

Fig. 11. Payback period for the 19 alternatives.

Table 5
Economic effects of the addition of ORC to different schemes.

Scheme	Change in annual profit ($/yr)	Change in annual profit (%)	Change in energy sales ($/h)	Change in equipment cost ($)	Change in payback period (yr)
2	1.2E+06	1.00	160.65	3.1E+06	−0.01
3	2.2E+06	1.82	296.04	6.0E+06	−0.01
4	7.8E+06	6.52	1052.84	1.0E+07	−0.12
6	2.2E+06	1.77	296.09	6.1E+06	−0.01
8	1.7E+06	1.33	225.87	3.9E+06	−0.01
9	2.4E+06	1.92	329.03	6.1E+06	−0.01
10	7.7E+06	6.08	1034.96	1.1E+07	−0.09
12	2.9E+06	2.24	396.06	6.5E+06	−0.01
14	7.9E+06	6.07	1059.25	1.2E+07	−0.06
16	7.7E+06	5.57	1033.59	1.1E+07	−0.05
17	8.9E+06	6.48	1200.96	1.3E+07	−0.06
19	1.2E+07	27.06	1675.77	1.4E+07	−1.39

stressed that the post-combustion schemes were found to involve the best payback periods within the full sample.

Finally, specific details on the influence of ORCs on the economic performance of the relevant schemes are presented in Table 5. The addition of ORC in these schemes was found to result in higher equipment costs compared to the base cases without ORCs, due to additional equipment such as expanders. However, at the same time, it yields higher energy sales and annual profit. In fact, in all of these schemes, the addition of ORC results in lower payback periods. Similar to the technical analysis of ORC addition, its economic effectiveness was also attributed to the different flow rates and temperatures of the streams entering ORCs.

3.3. Final remarks

Although the addition of ORCs to NGCC plants involves additional expensive equipment such as turbines, it was shown that it could lead to improved technical and economic performances. It was shown that the post-combustion scheme with ORC and using a-MDEA as the CO_2 absorbent exhibits the best technical and economic performance. However, it should be noted that these results were obtained based on a significant but limited number of process alternatives, and using EQW as the main parameter within the objective function of the optimizer. In order to obtain a more complete picture on this comparison, further research is required.

For instance, evaluation of other concepts such as EGR and the use of oxygen carriers in the reformers (CLR) are suggested as directions for future studies in this field. Furthermore, in order to obtain a complete sustainability perspective, environmental and social analyses of the proposed alternatives should also be addressed in the future.

4. Conclusions

Several configurations of natural gas power plants provided with pre-combustion, post-combustion or oxy-fuel combustion CO_2 capture were technically optimized and subsequently analyzed and compared under technical and economic aspects. The use of a-MDEA instead of MEA is concluded to lead to a better technical and economic performance in the schemes with pre- and post-combustion CO_2 capture. Furthermore, it is concluded that the addition of ORCs can successfully lead to energy and utility savings, being the higher equipment costs offset by higher annual profits and lower payback periods than those of the schemes without ORCs. In particular, the NGCC scheme involving post-combustion CO_2 capture with a-MDEA and full ORC integration arises as the strategy with the best technical and economic performance among the various alternatives (leading to EQW = 376.9 MW, energy sales = 30 k$/h, and annual profit = 161.6 M$/yr). Overall, the outcomes of this paper are expected to be useful to analysts and decision-makers concerned on the selection of promising NGCC alternatives. Nevertheless, further research is recommended to also explore the effect of economic and environmental optimization.

CRediT author statement

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Declaration of competing interest

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Appendix A. Supplementary data

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