Effect of the ambient conditions on gas turbine combined cycle power plants with post-combustion CO2 capture

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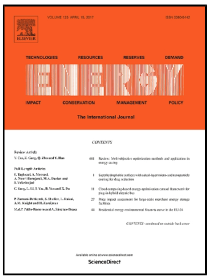

“Effect of the ambient conditions on gas turbine combined cycle power plants with post-combustion CO_2 capture”

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LP steam turbine capable to operate with capture off line but condenser with capture

"Effect of the ambient conditions on gas turbine combined cycle power plants with post-combustion CO_2 capture"

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Abstract

This paper evaluates the effect of ambient conditions on a natural gas combined cycle power plant (NGCC) with CO_2 capture and proposes design options for effective integration and off-design operation. In particular, the study assesses the effect of ambient temperature in the context of the electricity system in Mexico and proposes supplementary firing in the heat recovery steam generator to mitigate reduction in power output. For ambient temperature varying from -5 °C to 45 °C, a typical temperature variation in the north of Mexico, the efficiency of the NGCC with CO_2 capture reduces from 50.95% to 48.01% when the temperature increased from 15 °C (ISO design condition) to 45 °C, and reduces from 50.95 % to 50.78 % when the temperature decreased from 15 °C to -5 °C. The power generated decreases from 676.3MW at 15ºC to 530 MW at 45ºC. In order to compensate for the loss of output caused by seasonal changes in ambient temperature, supplementary firing in the heat recovery steam generator can be used to generate additional power and return the power output to 640 MW at 45ºC, at the expense of an increase in fuel costs and a drop in efficiency from 50.95 % to 43.46 %, without and with supplementary firing respectively.

Keywords: Ambient temperature, CO_2 capture, natural gas combined cycle, supplementary firing.

Nomenclature

CAPEX	Capital expenditure
CO_2	Carbon dioxide
GHG	Greenhouse gas
GT	Gas turbine
HRSG	Heat Recovery Steam Generator
IGV	Inlet guide vane
MEA	Monoethanolamine
NGCC	Natural gas combined cycle
EOR	Enhanced oil recovery
SOx	Sulfur oxide
LP	Low pressure
LCOE	Levelised cost of electricity

1. Introduction

The energy demand in Mexico is expected to grow by 56% between 2014 and 2029, driven mainly by expanding economic activity, a growing population, and rising standards of living [1, 2]. Low gas prices, lower capital costs, higher efficiency, and minimal SO_x emissions, have led to a significant increase in the number of NGCC plants being built. In the case of Mexico, projections show that natural gas will continue being the dominant source of energy until 2029, representing 45% of the total generation [2, 3]. Although NGCC power plants have a lower carbon intensity than coal plants, the large number of NGCC plants in Mexico causes large emissions of CO_2. A proportion of these plants will require CO_2 capture technologies to fulfill the greenhouse gas (GHG) emission targets set by the Climate Change Act, where the country is committed to reducing "its greenhouse emissions by 50% below 2000 levels by 2050" [1].

Off design operation of NGCC with CO_2 capture such as variation of ambient conditions and part-load operation, influences the cycle performance. The part-load performance of NGCC plants with carbon capture has been evaluated by Rezazadeh et al and Karimi et al [4, 5]. However, the effect of ambient conditions on a NGCC with CO_2 capture has not been evaluated. According to Arrieta et al and Kehlhofer et al [6, 7], pressure and relative humidity have minor influence on efficiency compared with ambient temperature, which is the predominant parameter and has the greatest influence on off-design operation. One characteristic of NGCC power plants is their flexibility to rapidly change power output according to electricity demand [8]. In the north of Mexico, the variations in electricity demand caused by the extreme weather condition, is more pronounce than in the south [2]. In the south of Mexico, there is no significant variation in demand due to the variation in temperature between summer and winter. However, in the north the demand varies due to the extreme variation in temperature. In summer the temperature reaches approximately 45°C and in winter it decreases to 5°C [2]. Figure 1 shows the variation of the ambient temperature in Nuevo Leon, Mexico in 2015, a state located in the north of Mexico. In addition, there are some areas where the ambient conditions are different from the rest of the country, for example in Mexico City the ambient pressure is around 0.758 bar, compared with Merida city where the pressure is at sea level 1.013 bar. In the case of the relative humidity, the north of Mexico is very dry around 30% compared with Merida City where it is around 80%. It is therefore necessary to ensure that the operation of options proposed to decarbonise the electricity market in Mexico operate adequately in the entire range of ambient conditions and do not impose a constraint on this flexibility.

1.1 Novelty

This article evaluates the effect of ambient conditions, such as ambient temperature, pressure and relative humidity on the performance of a NGCC with CO_2 capture and defines an optimum design for the capture plant.

Firstly, this article includes a quantitative analysis of the impact of ambient conditions on the power output, efficiency and cost of electricity of NGCC plants with post-combustion capture for regions in Mexico, where the ambient temperature varies extremely over the year from -5°C to 45 °C. The effect of ambient pressure and relative humidity on the design is also evaluated. According to Arrieta et al [6], the effect of the ambient pressure on the performance must be considered during the design, but once the plant is installed, the local pressure does not vary significantly.

Secondly, it provides insights into design guidelines for air-cooling technology applied to NGCC plants with post-combustion capture built in water deprived environments.

Thirdly, the article proposes supplementary firing - a widely used method involving rapidly increasing power output at the expense of efficiency - as an operating strategy to mitigate, under certain conditions, the loss of output of NGCC plants with post-combustion capture caused by extreme seasonal temperature variations.

1.2 Engineering aspects of operation of a NGCC at different ambient temperature

Because air density varies inversely with ambient temperature, the air mass flow rate entering in a typical machine of specific size and rotational speed is reduced on a hot day. The air temperature has a large influence on the power output and efficiency of a gas turbine, and this can be summarised as follows:

- A high ambient temperature reduces the density of the air. The air mass flow entering the gas turbine compressor therefore reduces. The power produced by the turbine is close to a linear function of air mass flow rate [7, 10]. The air/fuel mass ratio is kept constant as the air mass flow is reduced to prevent an increase in turbine inlet temperature and ensures effective blade cooling [11].
- The reduction in air mass flow rate reduces the pressure ratio of the cycle, since less pressure is needed to force the reduced mass flow through the fixed turbine nozzles, causing the outlet compressor pressure and the inlet pressure turbine to fall [7, 12].

- The reduction in the turbine pressure ratio raises the exhaust gas temperature for a fixed inlet turbine temperature. The magnitude of the exhaust temperature rise can be estimated for the adiabatic expansion equation 1 [12]:

  $$T_o = \frac{T_i}{(P_i/P_o)^x} \qquad \text{Equation 1}$$

  $$x = \eta_t \frac{(\gamma - 1)}{\gamma} \qquad \text{Equation 2}$$

  Where: T_o outlet turbine temperature, T_i inlet turbine temperature, P_o outlet turbine pressure, P_i inlet turbine pressure, η_t turbine efficiency, γ specific heat ratio of the combustion gases, x is the turbine exponent.
- The rise of exhaust gas temperature reduces the gas turbine efficiency [7], but is partially compensated by increased steam generation for the combined cycle.
- As the ambient temperature decreases, the temperature of the air used in the air-cooled condenser or the temperature of the cooling water used in the cooling tower is also reduced. This has a positive effect on the overall efficiency of the combined cycle plant [13].

2. Methodology

2.1 Natural gas combined cycle power plant

In order to determine the effect of the ambient conditions on the performance of a NGCC with CO_2 capture, a NGCC was simulated in Thermoflow™. Thermoflow™ is a software suite which mainly consists of the GT PRO, GT MASTER and Thermoflex software. GT PRO is a leading gas turbine and combined cycle modelling software used in the electricity generation industry. It utilises a database of gas turbines with mapped performance curves. The study is limited to an axial gas turbine with speed shaft of 3600 rpm, which operates under typical existing gas turbine conditions, described below

Implementation of the modelling methodology is as follows:

1. First, the NGCC is designed in GT PRO.
   - The configuration of the NGCC consists of two gas turbines, each one with a heat recovery steam generator (HRSG), and one steam turbine. Each gas turbine is a 7H.01 GE. The flue gas exiting the turbines flows into a HRSG where steam is generated at subcritical pressure and feeds a single reheat steam cycle, as shown in figure 2. Additional steam at low and intermediate pressures is generated in the HRSG in order to maximise the power output of the combined cycle.
   - **The gas turbine** is selected from a list of commercial machines available in GT PRO. The 7H.01 GE model is selected for the purpose of this study to represent realistic market conditions. The rest of the NGCC, such as the HRSG, air-condenser, steam turbine, and auxiliaries (pumps, fans, and coolers) are then designed automatically according to the gas turbine (GT) flue gas generation.

     Steam cycle: Based on the heat balance, it is calculated how much steam can be generated. The length and the number of tube rows required for the superheater, evaporator, economiser, and condenser as well as the number of tubes are also calculated. In addition, the size of the steam turbine inlet nozzle cross section to swallow the steam generated by the HRSG is calculated and it is also determined how large the ST exhaust annulus must be to effectively pass the volume of the exhaust seam into the condenser [14].
   - Since GT PRO has the information of the machines used, the ambient site conditions such as pressure, temperature, and relative humidity, are also needed, as well as the natural gas composition. Table 1 shows the standard condition [6, 15] and the natural gas composition taken to simulate the base case.
   - An air-cooling condenser is selected to condense the steam exiting the low pressure (LP) steam turbine by using ambient air. At design conditions, the condenser pressure should be at least 48 mbar, since a lower pressure would cause excessively high moisture contents causing erosion of the LP turbine last stage blades. The air cooler-condenser consists of 25 modules with a constant speed forced draft fans to circulate the ambient air. The amount of heat removed depends on the desired condenser pressure and is regulated by the number of fans in operation.
   - The size and capacity of the condenser is designed with CO_2 capture.

  - The LP steam turbine is sized for operation without extraction, in order to ensure continuity of operation if the capture plant were off line.
  - Capital expenditure (CAPEX) is calculated by using GT PRO linked to the PEACE software.

2. Once the design parameters are defined in GT PRO, these parameters are inserted in the GT Master Software.
   - For a Gas turbine, GT PRO gives to two options for evaluating the performance at off-design: 1. Manufacturer's guaranteed performance data (exhaust gas temperature, efficiency, power generated, vs compressor inlet temperature, as well as ambient condition, fuel type, inlet or exhaust flow, heat rate or efficiency, and steam/water injection data) or 2. Performance calculated from the model developed by Thermoflow. In this paper performance data from the manufacturer was selected [14].
   - With the size of the equipment fixed, the power plant performance over a range of ambient temperatures [5, 8] was determined. The HRSG is based on typical modelling principles, such as heat transfer fundamentals and relevant pressure drop. Two equations are needed to predict the behaviour of all heat exchangers in the HRSG and the condenser [16]. The first one is the energy balance between the streams, considering heat loss by radiation and convection from the HRSG. A simplified equation could be illustrated by Equations 3 and 4. The second equation is the heat transfer across the heat exchanger surface given by Equation 5 [17]. An iterative technique is necessary to simultaneously determine, for each heat exchanger, the rate of heat transfer and the inlet and exit gas and water/steam temperatures. This iterative technique must also include models for the resistance characteristics imposed upon the boiler boundaries by the pipes, control valves and steam turbine, at each pressure level [14].

     $$Q = m_v \left(h_{vout} - h_{vin}\right) \qquad \text{Equation 3}$$

     $$Q = m_g \left(h_{gout} - h_{gin}\right) \qquad \text{Equation 4}$$

     If a counter-flow exchanger is used, the heat transfer equation allows the calculation of the product of the overall heat-transfer coefficient *U* and the exchange surface A by means of a logarithmic mean temperature difference, as in Equation 5. U_DA is calculated at design condition and the new *UA* at part-load is calculated using the correlation shown in Equation 6.

     $$Q = UA\frac{\left(T_{gin} - T_{vout}\right) - \left(T_{gout} - T_{vin}\right)}{ln\left(\frac{T_{gin} - T_{vout}}{T_{gout} - T_{vin}}\right)} \qquad \text{Equation 5}$$

     The pressure drop in each will vary with mass flow and thermodynamic conditions.

   - Modules of the air condenser are switched off when the ambient temperature decreases below 15°C, in order to maintain an adequate condenser pressure and protect the LP turbine blades from excessive droplet impact.

   - The combined cycle is designed to operate with sliding pressure control. The temperature of superheated steam is controlled at around 585 ºC by a spray attemperator. The inlet guide vane (IGV) of the gas turbine compressor is held fully open (α=1) [18] for all the cases evaluated. This results in a constant air volume entering the compressor [6].

In all case studies, the operating strategy and the integration of the capture and compression system are based on the optimum alternatives from the state of the art; the capture plant and compressor are modelled in Aspen plus.

2.2 CO_2 capture plant and compressor unit

2.1.1 Capture Plant

All case studies are integrated with a standard CO_2 capture plant using 30% wt Monoethanolamine (MEA), as shown in Figure 2. The CO_2 capture plant is simulated in Aspen Plus® using a rate-based approach. The performance of the absorber is estimated to find the optimum parameters such as solvent lean loading, solvent rich loading, and the energy removed in the stripper overhead condenser, and the thermal energy consumption in the reboiler to achieve a 90% CO_2 capture rate [19]. The plant is optimised with an absorber packing height of 21 m. The cross flow heat exchanger area is taken from Gonzalez et al [20]. The methodology to optimise the design of the CO_2 capture plant is described as follows.

1. The lean solvent loading of the MEA solution is varied to find the minimum energy in the reboiler for a given CO_2 concentration in the flue gases.
2. While studying the effect of different lean loading on the CO_2 capture process, the stripper reboiler pressure is varied to change the values of the lean loading and the temperature was kept constant. The recommended temperature of the reboiler for MEA is 120 °C [21, 22, and 23]. At a given absorber height, the absorption solvent circulation rate is varied to achieve the targeted CO_2 removal capacity (90%). Flue gas enters the absorber at 44 °C and 1.13 bar; the outlet temperature of the overhead stripper condenser is 40 °C. The lean/rich solvent heat exchanger approach temperature is 10°C [20].
3. When the ambient temperature varies, the size of the absorber (height and diameter) is fixed in the model to reflect operation at off-design conditions. The stripper pressure and the reboiler temperature are maintained at design value.
4. The solvent flow to the absorber column is adjusted to maintain a capture level of 90%, so the liquid to flue gas ratio – often referred to as the L/G ratio - varies. In addition, steam extracted from the crossover of the combined cycle is maintained constant at 4 bar in all cases to overcome the pressure drop in the steam extraction pipe from the crossover to the desuperheater (heat exchanger before the reboiler shown in Figure 2) and to operate the reboiler with 3 bar of pressure on the steam side.

2.1.2 Compression System

Siemens [24] has presented three options to compress the CO_2:

1. Scenario A: Compression to subcritical conditions, liquefaction and pumping. The CO_2 is compressed to approximately 45 bar and is then condensed to approximately 0°C. A pump is then used to obtain the desired pressure [24].
2. Scenario B: Compression to supercritical conditions and pumping. The CO_2 is compressed to approximately 100 bar and is then condensed to approximately 20°C [24]. As in option A, a pump is used to obtain the desired pressure.
3. Scenario C: Compression to supercritical conditions. A compressor is used to directly obtain the desired pressure, as shown in Figure 3.

Although option A is characterized by the lowest compression power for CO_2, the condensation of CO_2 to a temperature of 0°C with refrigeration may not be suitable in warm countries such as Mexico, during part of the year at least. Therefore, it will represent an increment in capital and operating cost. The selection between scenario B and C mainly depends on the final pressure required. For very high discharge pressures, the final compression stages can be replaced by a pump (case B) to reduce power consumption, i.e., offshore pipeline. Very high discharge pressure is required with long pipelines, typically in the order of hundreds of kilometres, because it reduces the number of intermediate re-pressurisation locations along the pipeline.

In this paper, the onshore pipeline collection network is considered to be less than 100 kilometres, for evaluation purposes. It consists of relatively short pipelines without recompression, which is likely to be the case in Mexico given the geography of matching CO_2 sources with CO_2 sinks. Option C was therefore selected in this work. It consists of a gear-type centrifugal compressor with several stages to compress the CO_2 stream, as suggested by Siemens [25]. The number of stages depends on the pressure ratio. To compress CO_2 from 2 bar to 110 bar, i.e. with a pressure ratio of 55, six stages are needed [26]. For pressure ratios higher than 55, more compressor stages might be necessary. In this paper, the CO_2 is compressed from 1.9 bar to 150 bar for the purpose of enhanced oil recovery (EOR) [27]. The pressure ratio is around 80, therefore one more stage is needed. The configuration of the CO_2 compressor shown in Figure 3 is selected with two trains of a gear-type centrifugal compressor with seven stages and intercooling after each stage as it is designed for a nominal pressure ratio of 80 and a CO_2 temperature of 40 °C after the intercoolers based on [26] and [28]. The compressor system was simulated in Aspen Plus® and the performance curve used at off-design was taken from Liebenthal and Kather [26]

2.3 Operating strategy of the capture plant at off-design condition

In this study, steam extraction from the combined cycle for solvent regeneration occurs at constant pressure, when ambient conditions vary. This information is summarised in Table 2, including a conventional strategy of the NGCC.

3. Modelling methodology assessment

The output of the model is compared with information available in the literature, reporting the typical performance of a conventional NGCC (without capture) with air cooling [7]. The comparison of the model output, namely efficiency, power output, and condenser pressure of a conventional NGCC without capture at different ambient temperature, is shown in Figures 4, 5, 6. As can be seen in Figure 4, the variation of condenser pressure for temperature ranging from -5ºC to 45ºC is consistent between the two studies. It is worth noting that the condenser pressure of *this work* is for a NGCC without capture. The number of fans in the results presented in [7] is not specified. As can be seen in Figure 4, the pressure of the condenser from the literature from 15 °C to 45 °C is lower than the results presented in this paper. In this work the maximum number of fans 25 that was calculated to get the pressure in the condenser at design condition. However, it is possible to reduce the condenser pressure at ambient temperature from 15°C to 45 °C considering additional fans than the number of fans calculated at design condition at ISO condition, that could be the case in [7].

Since there is no available data, to the authors' knowledge, of the capture plant at different ambient temperature, simulation results of the capture plant model are compared with the work of Rezazadeh et al [4], reporting the performance of a capture process at part-load in Table 3. Rezazadeh et al presents part-load operation of the capture plant when the gas turbine is operated at part-load. Although, in this paper, the gas turbine operated at maximum output for the range of ambient conditions under consideration, the capture plant is exposed to similar changes in flue gas flow rates. One notable difference between the two studies is the reboiler temperature, due to the fact that the design of Rezazadeh et al extracts steam for solvent regeneration at a pressure of 2.5 bar, instead of 3 bar, as in this study.

4. Performance assessment

4.1 Optimisation of the CO_2 capture plant

The dimensions of the capture plant components are calculated and optimized by Gonzalez et al [20]. Figure 7 shows the results of the optimisation of the capture plant. The reboiler pressure is varied from 2 to 1.8 bar in order to find an optimum combination of pressure, lean loading, and solvent flow rate that minimises the reboiler duty. The lean loading minimising the specific reboiler energy is found at 0.275 kmolCO_2/kmol MEA which corresponds to a reboiler pressure of 1.9 bar. The optimum reboiler duty is 3.54 MJ/tonne CO_2 which corresponds to a pressure of 1.9 bar.

4.2 Effect of the ambient temperature on the NGCC performance with and without CO_2 capture

Figure 8 and Figure 9 show the variation with ambient temperature of two important parameters affecting the efficiency and power output of the steam cycle:

1. The exhaust gas temperature: when the ambient temperature increases, the exhaust gas temperature also increases, which is favourable for steam generation and power output of the combined cycle but detrimental to the output of the gas turbine
2. The condenser pressure: when the ambient temperature increases, the condenser pressure also increases, which has a negative effect on the steam cycle. The maximum number of fans, 25 in this case, is operating. As shown in Figure 9, the change of the specific volume of the air with ambient temperature also has an effect on the mass flow of air passing through the condenser

The effect of the combination of these two parameters on the steam cycle is not overly significant, being the pressure in the condenser the dominance effect.

The LP turbine is sized for operation without steam extraction, in order to ensure continuation of operation if the capture plant were to be by-passed and were off line. However, in this case, the condenser is designed for the steam flow corresponding to the operation of the capture plant, i.e. it is undersized when the capture plant is off. Figure 9 shows the impact of the condenser size on condenser pressure when the power plant operates with and without capture. With CO_2 capture, less steam flows to the condenser; thus the condenser pressure is lower with capture than without capture. Fewer modules are in operation at ambient temperature below 15°C compared to those required without CO_2 capture. In both cases, the condenser pressure increases as the ambient temperature increases. As a results of the increase in ambient temperature, the temperature of the air used in the air-cooled condenser is also increased, thereby reducing the capacity of the condenser.

At an ambient temperature above 15ºC, the negative effect on the gas turbine and the condenser pressure become the dominant effects on the efficiency, as can be seen in Figure 10.
The efficiency reduces marginally with and without CO_2 capture from 50.95% to 50.78%, and from 57.03% to 56.97%, respectively, when the ambient temperature reduces from 15 °C to -5 °C. However, when the ambient temperature increases from 15°C to 45°C the efficiency drops significantly from 50.95% to 48.0% with CO_2 capture and from 57.03% to 51.65% without capture. It is worth noting that, at higher ambient temperature, the difference between the efficiency with and without capture is lower than at lower an ambient temperature. At an ambient temperature higher than the design value, the flue gas flow rate reduces, as shown in Tables 4 and 5; this has a positive effect on CO_2 absorption in the CO_2 capture plant, due to an increase in residence time in the absorber column [19]. The CO_2 concentration in the exhaust gas is higher at lower ambient temperature, which has a marginally positive influence on the CO_2 capture plant. This conclusion is in agreement with [20].

Figure 11 compares the total power of a NGCC with and without CO_2 capture at different ambient temperatures without supplementary fire. Without CO_2 capture, when the ambient temperature reduces from 15°C to -5°C, the power output increases from 760 MW to 788 MW, and, with CO_2 capture, the power increases from 676 MW to 700 MW. However, when the ambient temperature increases from 15 °C to 45°C the power output reduces from 760 MW to 572 MW without capture, and from 676 MW to 530 MW with capture.

The key parameters for the NGCC with CO_2 capture are shown in Tables 4 and 5. The results show that the temperature of the flue gas that flows to the capture plant did not change significantly when the ambient temperature changed from -15 °C to 45 °C. The amount of the flue gas and the amount of CO_2 flowing to the capture plant reduces when the ambient temperature increases; however, since the equipment is sized for larger flows, the performance is not impaired.

4.3 Effect of the ambient pressure on the NGCC performance with and without CO_2 capture

The variation of the efficiency and the power at different ambient pressures is shown in Figures 12 and 13. It can be noted that the efficiency increases marginally when the ambient pressure varies from 1.013 bar to 0.7948 bar, which is in good agreement with Arrieta et al and Kehlhofer et al [6, 7]. Using the same gas turbine, the net power output reduces at lower ambient pressure because the amount of air reduces. This leads to the generation of smaller flow of exhaust gas and to the designing of smaller HRSG, steam turbines, and air condenser. When the capture plant is incorporated to the NGCC, at 1.013 bar the net power output reduces by 84 MW from 760 MW bar to 676 MW, and, at 0.7948 bar, the power reduces by 63 MW, from 628 MW to 565 MW. Our modelling results show that, unlike ambient temperature, the ambient pressure does not affect the condenser pressure as shown in Figure 14. This is one of the main reasons for maintaining the efficiency almost constant compared with the condenser pressure when the ambient temperature varies. Two options can be used to compensate the power at low ambient pressure: supplementary firing or designing the plant with a bigger GT.

The key parameters for the NGCC with CO_2 capture are shown in Tables 6 and 7. The CO_2 concentration in the exhaust gas did vary when the ambient pressure changed. The temperature of the flue gas that goes to the capture plant did not change significantly when the ambient pressure changed from 1.013 bar to 0.7948 bar.

4.4 Effect of the relative humidity on the NGCC performance with and without CO_2 capture

The relative humidity does not have effect on the power plant with and without capture, as can be seen in Figures 15 and 16. This statement is in agreement with [6, 7].

5. Supplementary firing in natural gas combined power plant with CO_2 capture

In order to compensate for the power loss caused by a rise in ambient temperature, mainly in the gas turbine, supplementary firing in the HRSG can be used to generate additional power in the steam turbine at the expense of efficiency, if increased revenue from additional electricity export is higher than the additional fuel costs. When the ambient temperature increased above the design condition (15°C) the power reduced as shown in Figure 11. Figure 17 shows the efficiency when supplementary firing is used to compensate the power output for the ambient temperatures of 25°C, 35 °C, and 45 °C. At an ambient temperature higher than the design condition, the efficiency penalty due to burning supplementary fuel is much higher than the benefit of increased CO_2 concentration in the flue gas with respect to the energy used in the capture process, as shown in table 8. It is clearly not sufficient to mitigate the drop in efficiency from supplementary firing, as can be seen in Figure 17; however, it can be justified in periods of high electricity demand. Figure 18 shows the power generated with and without supplementary firing. It is worth noting that when the ambient temperature rises to 45°C it is not possible to compensate the power loss in the gas turbine using supplementary firing in the HRSG. This is due to limitations imposed by the size of the steam turbine, the HRSG, and the pressure in the condenser. At 45°C, without supplementary firing, the net power is 530 MW. Using supplementary firing the net power generated increases to 620 MW compared with the power generated of 676 MW at 15°C.

In practice, the NGCC with CO_2 capture should be designed at the most frequent ambient temperature that can be identified from historical data. This would avoid the repeated use of supplementary firing to compensate the power loss caused by a rise in ambient temperature, although the ability to increase output may still be valuable during hotter days.

Another alternative to increase gas turbine power output is the use of fogging systems. This involves increasing the density of the air entering the gas turbine by evaporative cooling in the inlet air stream [29]. The inlet fogging system could be located upstream or downstream from the filter [30]. A fogging system applied in areas with relative humidity around 13% can increase it to 79 % - 94 % [31]. However, this is outside the scope of this study.

6. Comparison of cost of electricity

An economic study is carried out to compare the expected cost of electricity with and without capture at different ambient temperatures. Cost estimation is based on a methodology proposed in Rubin et al [32]. The sources of information are summarised as follow:

- Capital costs of the power plant, CO_2 capture, and compressor at ISO conditions are reported in Table 9. The sum of all equipment costs, together with the balance of plant (BOP), cooling water system, and installation costs is, as described by Rubin et al [32], the bare erected cost (BEC). Following the methodology, the BEC including indirect costs, engineering procurement and construction (EPC) costs, contingencies, and owner's costs gives the total capital requirement (TCR) for the power plant as well as for the capture plant and compression system.

  Capital cost of the NGCC was calculated using the commercial software PEACE™ from Thermoflow [14], most of the information pertaining to the equipment is provided by the manufactures.
  The sum of all equipment costs, together with the balance of plant (BOP), cooling water system, and installation costs includes:
  1. Specialized equipment which includes main items such as gas turbines, steam turbines, heat recovery boilers, condensers, chillers, etc.
  2. Other Equipment includes items such as pumps, cooling towers, heat exchangers, tanks.
  3. Civil which includes site Work, Excavation & Backfill, Concrete, Roads, Parking, Walkways
  4. Mechanical (on site transportation and rigging, equipment erection and assembly, piping, and steel)
  5. Electrical assembly and wiring
  6. Engineering and plant start-up

Capital costs of the MEA-based CO_2 capture and compression system for NGCC, shown in Table 9, are not calculated and are based on costs provided by some of the authors in Gonzalez et al, [20] who gave a detailed description of the sources of information.

- Operating costs of the power plant (O&M), the capture unit, compression, and transport are also based on [20] shown in Table 10 and Table 11.
- The CO_2 selling price for EOR and the gas price considered in this work are conservative at 20 \$/tCO_2 at below historical prices in Canada and the USA, and 3 \$/MMBTU (2.846 \$/GJ), above established prices at the time of writing.
- The total cost of the equipment, O&M, and the revenue for CO_2 selling are used to estimate the levelised cost of electricity (LCOE) which is calculated by annualizing the total capital cost and the total operating and maintenance costs and variable costs in \$/MWh using Equation 1.
  The net electricity produced and sold, the operating, maintenance and fuel costs are considered constant over the life of the plant based on constant dollars. Carbon prices are not included in this analysis. A simplified equation for these conditions is expressed by equation 1 reported by Rubin et al. [32].

$$LCOE = \frac{TCR \times FCF + FOM}{MW \times \mathrm{CF} \times 8760} + VOM + HR \times FC + TCO_2 \qquad \text{Equation 6}$$

$$FCF = \frac{\mathrm{r} \times (1+r)^T}{(1+\mathrm{r})^T - 1}$$

Where *TCR* is the total capital requirement, *FCF* fixed charge factor, *FOM* fixed *O&M* costs, *MW* net power output, *CF* capacity factor, *VOM* variable *O&M* costs, *HR* net power heat rate, *FC* fuel cost per unit of energy, and TCO_2 CO_2 transport cost. All of them in \$/MWh. *r* is the interest rate and *T* is the economic life of the plant (30 years in this study)

The sensitivity analysis is summarised in Figure 19 and for a difference ambient temperature the LCOE is estimated. At different ambient conditions, CAPEX and O&M were kept constant. The LCOE varied due to the reduction in efficiency at higher ambient temperature.

7. Conclusions

A comprehensive assessment shows the operation of NGCC plants with CO_2 capture is resilient to changes in ambient conditions, such as temperature, pressure and humidity. The results of the models developed in this study are in good agreement with available data in the literature, as shown in table 7 and Figures 14 to 16.

Although atmospheric pressure is an important parameter to define the generating capacity and to design a gas turbine, it has no impact on efficiency once the plant is installed. Nonetheless, atmospheric pressure does have a significant effect on power output, although this is not caused by the capture plant.

Similarly, the effect of relative humidity is not found to be significant.

The ambient temperature is an important variable that affects both the power generating capacity and the efficiency of the power plant, due to the effect on the air mass flow and pressure ratio of the gas turbine. The power decreases from 700 MW to 530 MW and the efficiency from 50.8% to 48% when the temperature increases to 45 °C for a plant designed for ISO conditions at 15ºC.

The ambient temperature also has an impact on the levelised cost of electricity from 52.58 \$/MWh to 64 \$/MWh when the ambient temperature increases from -5 °C to 45°C.

In the design of a NGCC plant with capture, the operating practices of the electricity market must be taken into consideration. It is proposed that the design include a low pressure steam turbine capable of operation with the capture plant by-passed, but that the condenser be designed when the capture plant is in operation. This approach gives the flexibility of operating the NGCC at full power even if the capture plant is off line, and allows the operation of the NGCC without the capture plant with a small penalty in efficiency due to a higher condenser pressure. An understanding of the performance of NGCC plants with CO_2 capture provides a good basis for defining relevant operating procedures. A flexible design also allows trade-offs between capture levels and electricity output by adjusting the carbon intensity of electricity generation under severe ambient conditions.

This could be a useful feature in the northern parts of Mexico where it might be possible to bring capture levels down to zero temporarily in extreme cases of high demand for electricity, e.g. for air conditioning, and extreme temperatures.

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Appendix

Thermoflow™ [14]

1. Steam properties used GT PRO, GT MASTER, STEAM PRO, STEAM MASTER, THERMOFLEX, and RE-MASTER is IFC-67. IFC-67: For many years, the industry standard for the calculation of steam properties was the IFC 1967 Formulation for Industrial Use. This was the basis of the ASME steam tables published between the late 1960's and the late 1990's. This formulation can be utilized for pressures up to 14,503 psia (1000 bar) and temperatures up to 1472 °F (800 °C).
2. The predominantly gas properties used is the ideal gas formulation. Exceptions are made in some cases. At low pressures, all components are treated as ideal gases, i.e. enthalpy and specific heat are functions of temperature alone. This underlying assumption results in reasonably accurate property estimations at moderate to high temperatures and low pressures. When temperature is low and/or the partial pressures of one or more components are relatively high, however, there are effects of pressure upon enthalpy not well-represented by these ideal gas relations. The program augments the ideal gas relations as necessary for:
    - Liquid water in equilibrium with the water vapour in the gas mixture,
    - Departure from ideal gas enthalpy and entropy of gases at moderate pressure,
    - Representation of the H_2O vapour with steam property functions, at moderate to high pressures,
    - Representation of N_2, O_2, and particularly CO_2 with the NIST property functions at low temperatures and high pressures.

   These effects are all negligible for air at ISO conditions [59 °F (15 °C), 60% relative humidity, at sea level] and for ordinary combustion product gases at atmospheric pressure so long as they are not cooled to near their dew point.

Aspen plus@

The amine solution system of the MEA-based carbon capture process, for the property method in the liquid phase, the ELECNRTL method calculated via non-ideal models is used for liquid phase material (such as, water, amine and hydramine) to absorb acid gas. ASPEN PLUS has a large built in databank of electrolyte reaction and interaction parameters for many electrolytes systems.

For gaseous phase parameters, Redlich-Kwong equation is selected.

Figures and caption

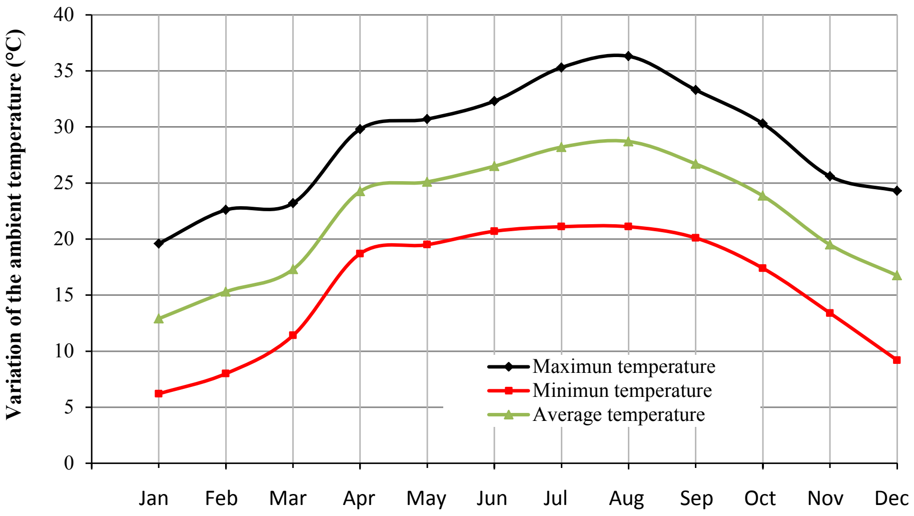

Figure 1. Maximum and minimum ambient temperature in Nuevo Leon state, Mexico during 2015 [9]

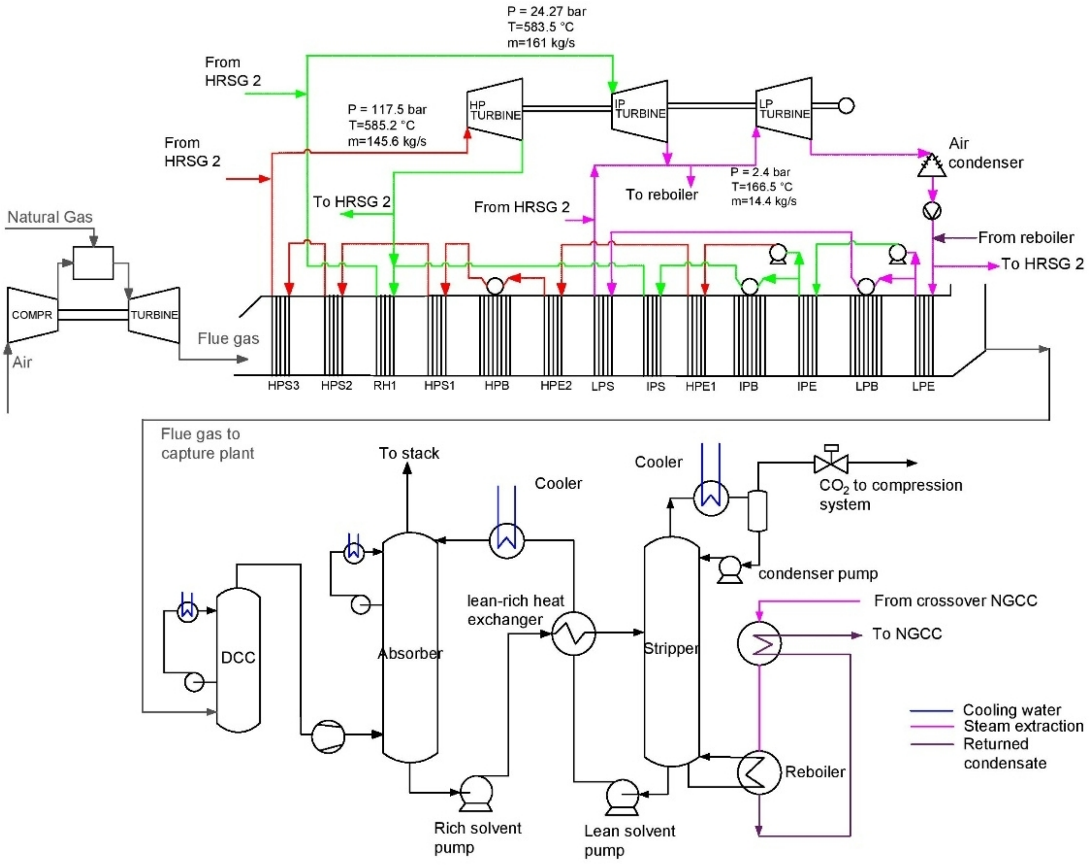

Figure 2. Schematic process flow diagram of the conventional natural gas combined cycle configuration with two 7H.01 GE gas turbine, two triple pressure HRSGs and one subcritical steam turbine with CO_2 capture

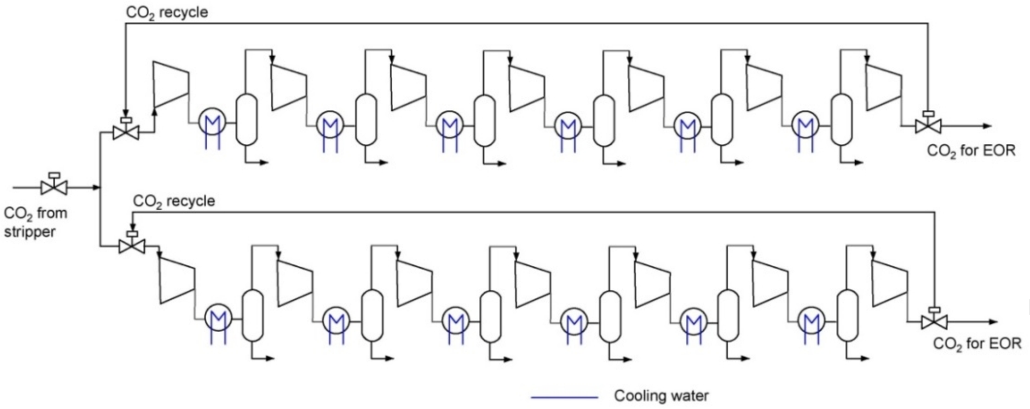

Figure 3. Schematic of CO_2 compressor trains with inlet guide vanes in the first stage and intercooling after each stage

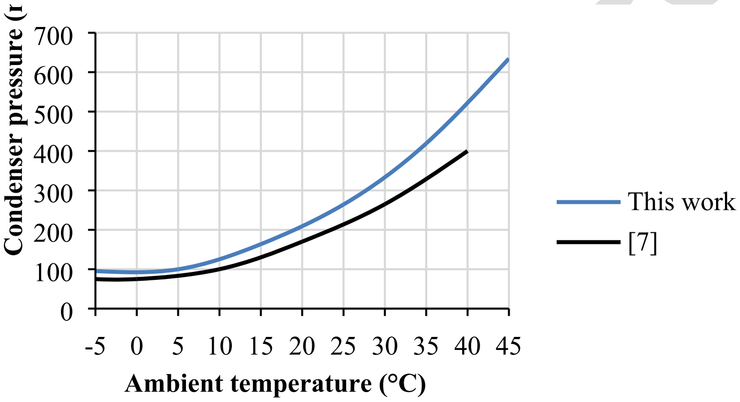

Figure 4. Comparison of the effect of the air temperature on the condenser pressure using air-cooled condenser with the literature. Without CO_2 capture

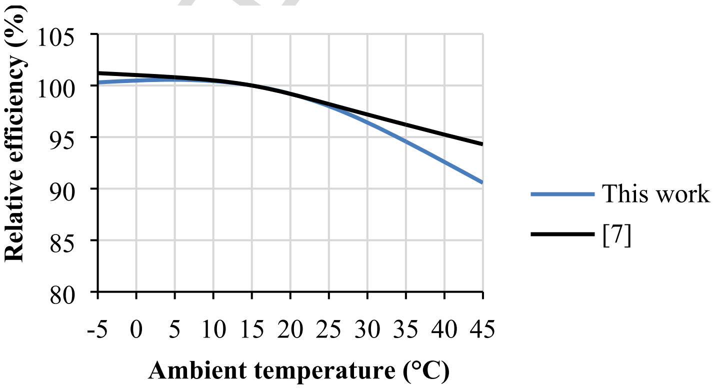

Figure 5. Comparison of the effect of the air temperature on the relative efficiency of a NGCC without CO_2 capture using air-cooled condenser with the literature

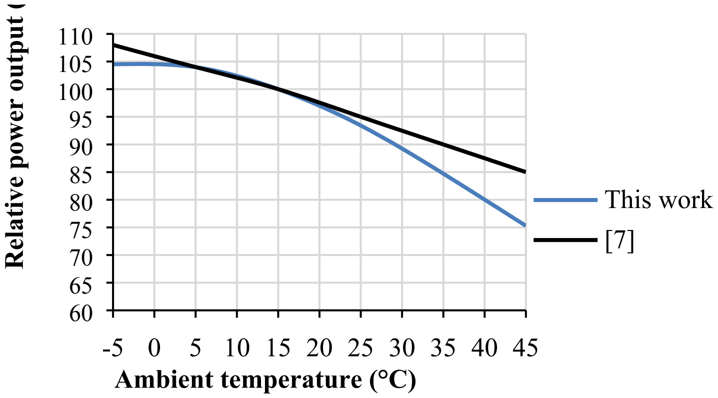

Figure 6. Comparison of the relative power output of a NGCC without capture

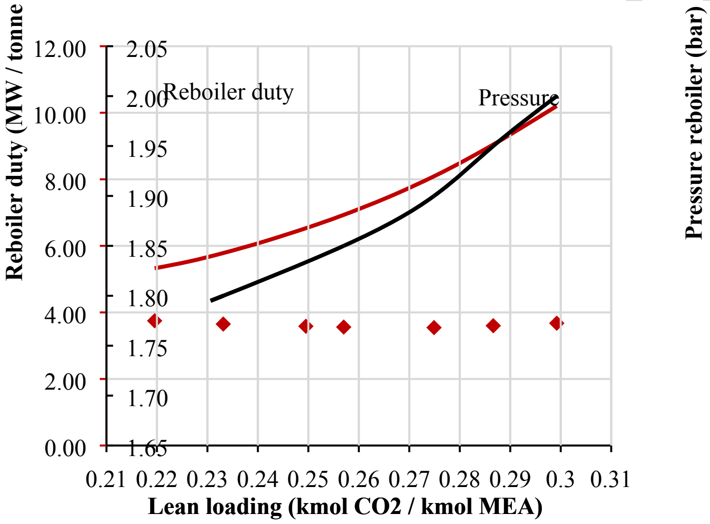

Figure 7. Optimisation of the energy in the reboiler for a natural gas combined cycle (NGCC) as a function of solvent lean loading, with CO_2 removal rate of 90% and stripper temperature of 120ºC. The CO_2 concentration in the flue gas is 4.24 mol% and the pressure is 1.9 bar

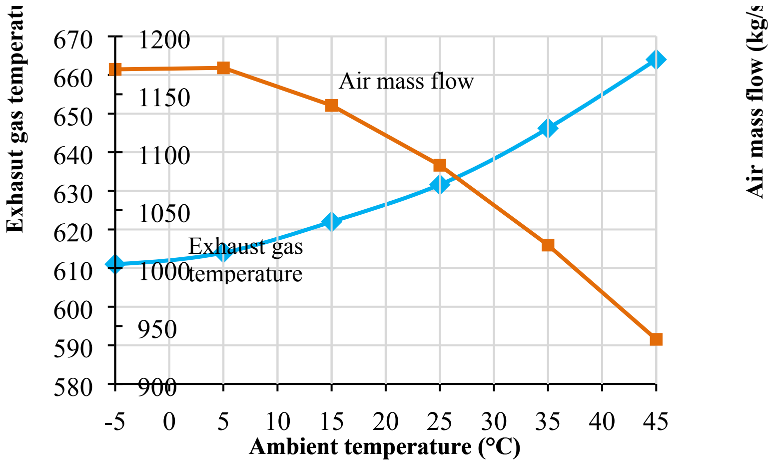

Figure 8. Variation of exhaust gas temperature and the air mass flow with the ambient temperature

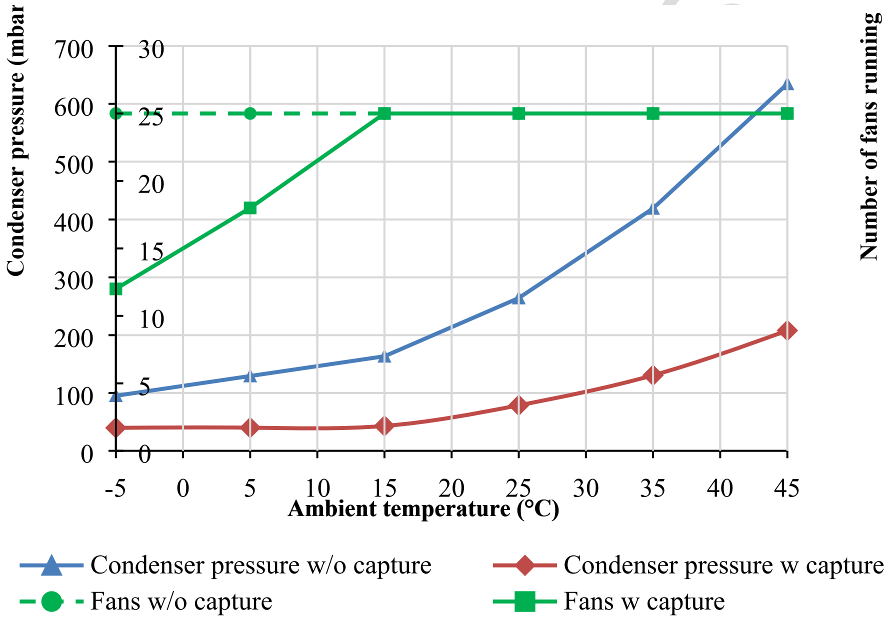

Figure 9. Variation of pressure in the air-cooling condenser with the ambient temperature with and without capture. Ambient pressure 1.013 bar and relative humidity 60%

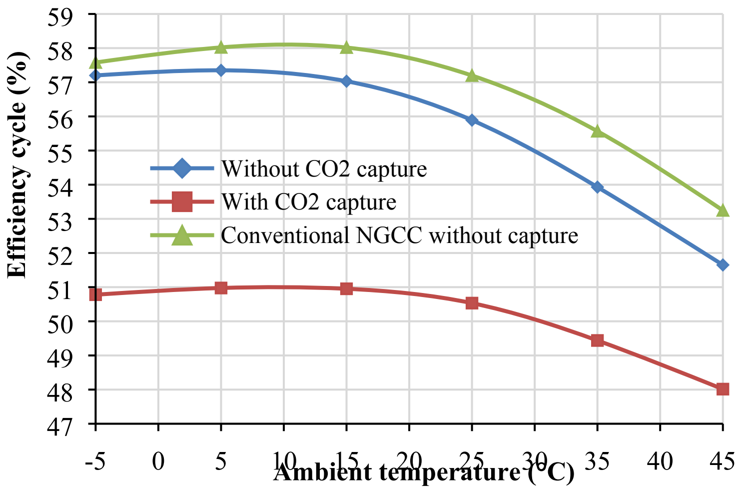

Figure 10. Variation of the efficiency with the ambient temperature of a combined cycle power plant with and without capture. Ambient pressure 1.013 bar and relative humidity 60%. The green curve represents a conventional NGCC designed to operate without capture. The red curve represents a NGCC operating with CO_2 capture, and the blue curve represents the same NGCC with the capture plant off line

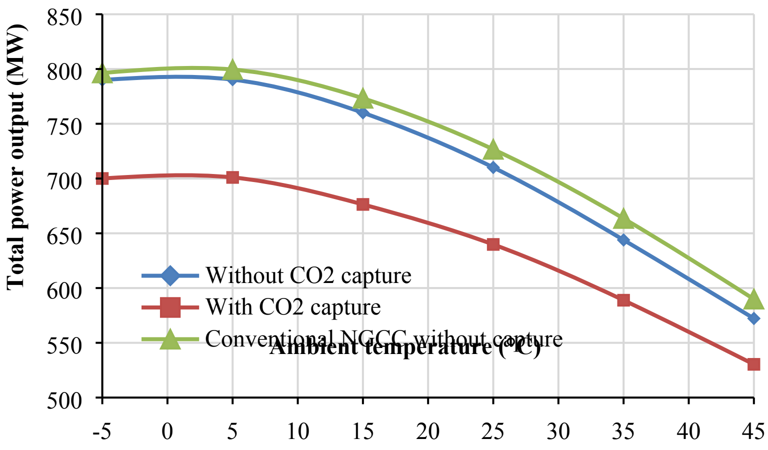

Figure 11. Variation of total power of a NGCC with and without capture at different ambient temperature. Ambient pressure 1.013 bar and relative humidity 60%. The green curve represents a conventional NGCC designed to operate without capture. The red curve represents a NGCC operating with CO_2 capture and the blue curve represents the same NGCC with the capture plant off line

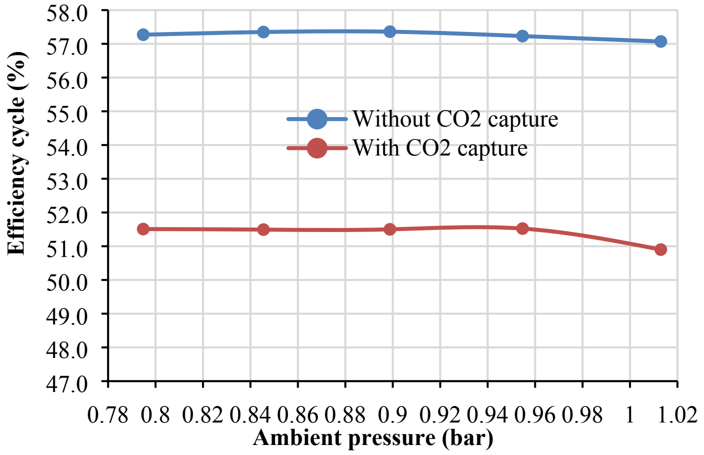

Figure 12. Variation of the efficiency with ambient pressure of a combined cycle power plant with and without capture. Ambient temperature 15°C and relative humidity 60%

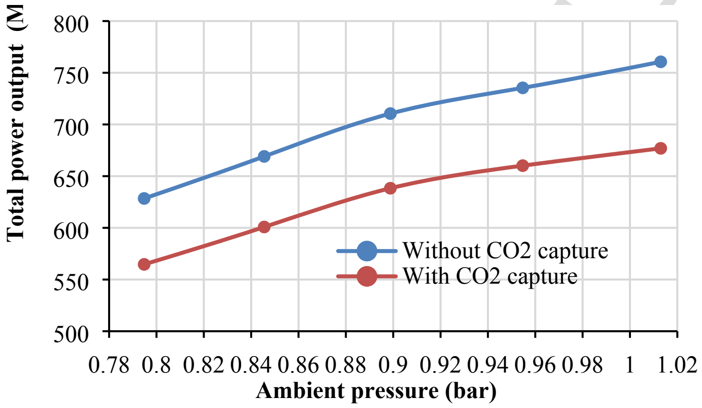

Figure 73. Variation of total power output of a NGCC with and without capture at different ambient pressure. Ambient temperature 15°C and relative humidity 60%

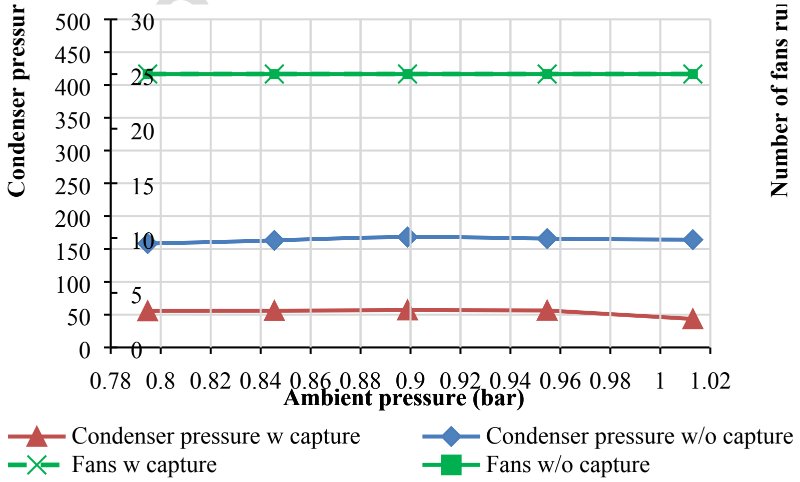

Figure 84. Variation of pressure in the air-cooling condenser with the ambient pressure with and without capture. Ambient temperature 15°C and relative humidity 60%

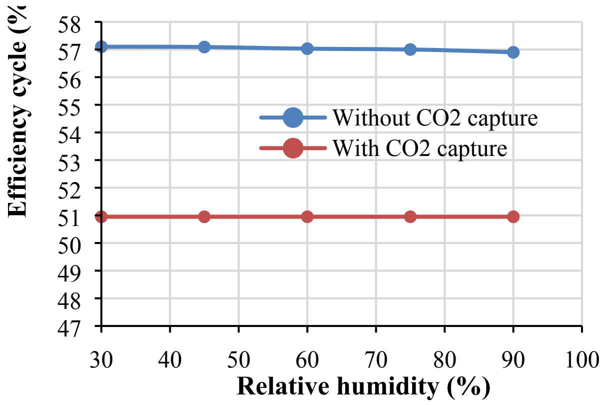

Figure 95. Variation of the efficiency with relative humidity of a combined cycle power plant with and without capture. Ambient temperature 15°C and ambient pressure 1.013 bar

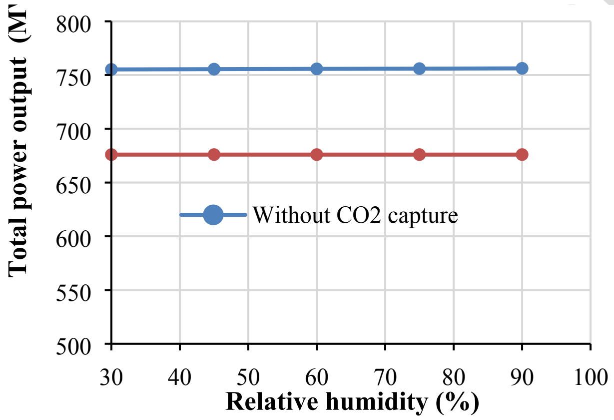

Figure 106. Variation of total power output of a NGCC with and without capture at different relative humidity. Ambient temperature 15°C and ambient pressure 1.013 bar

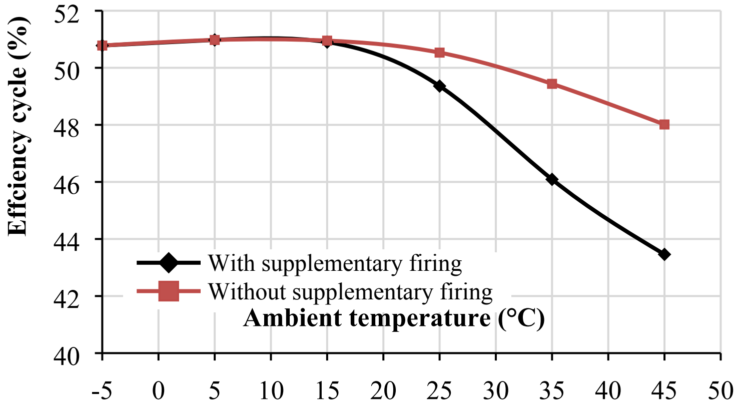

Figure 11. Variation of the efficiency with the ambient temperature of a combined cycle power plant with CO_2 capture: with and without supplementary firing

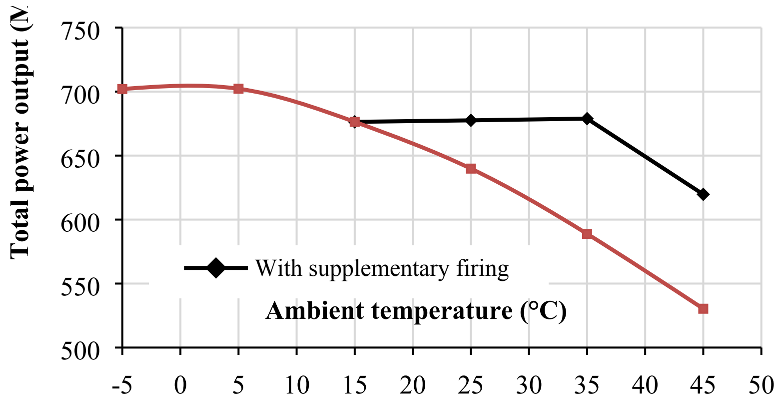

Figure 18. Net power output generated of the NGCC with CO_2 capture with and without supplementary firing

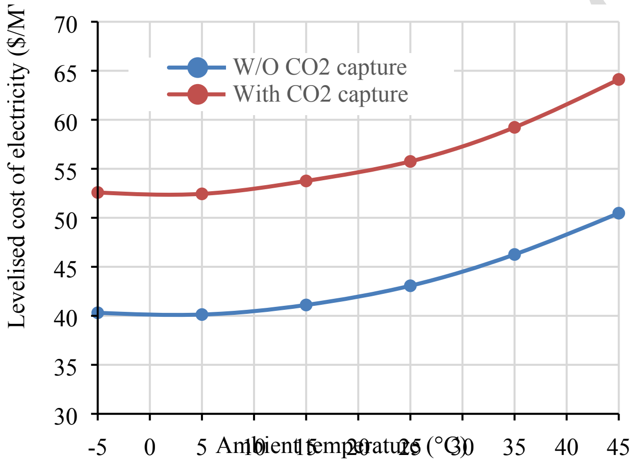

Figure 19. Levelised cost of electricity at different ambient temperature considering CO_2 selling price for EOR of 20\$/tCO_2 and gas price of 3 \$/MMBTU (2.8463 \$/GJ)

Tables and caption

Table 1. Ambient condition and natural gas composition

Pressure (bar)	1.013
Temperature (°C)	15
Relative humidity %	60
Natural gas composition	
N_2 (% mol)	5.308
CO_2 (% mol)	0.017
CH_4 (% mol)	85.95
Ethane (% mol)	8.342
Propane (% mol)	0.335
n-butane (% mol)	0.02
n-pentane (% mol)	0.02
Isobutane (% mol)	0.01

Table 2. Operating criteria for the power plant, CO_2 capture, and compressor unit when the ambient temperature changes

Parameter	**Criteria**
Gas turbine control	Fixed IGV
HRSG	With and without supplementary firing
Steam cycle (Pressure and temperature)	Subcritical
Steam cycle control	Sliding pressure
Steam extraction (integration strategy)	Fixed cross over pressure 4 bar
CO_2 capture plant	*Constant* stripper pressure and reboiler temperature, and variable L/G for all cases
CO_2 compressor	IGV and constant pressure ratio (P_{inlet} and P_{outlet} constant)

IGV = inlet Guide Vanes; HRSG = Heat Recovery Steam Generation; L/G = liquid to gas ratio in the absorber; NGCC= Natural Gas Combine Cycle; SSFCC= Sequential Supplementary Firing Combined Cycle

Table 3. Comparison of simulation results from Aspen Plus of the capture plant at part-load with Rezazadeh et al [4]

Reference	**Concept**	**Unit**					
[4]	Variation flue gas flow rate	%	100	94	89	82	75
This work	Variation flue gas flow rate	%	100	97	93	87	80
[4]	lean loading		0.21	0.21	0.21	0.21	0.21
This work	lean loading		0.275	0.275	0.275	0.275	0.275
[4]	Temperature reboiler	°C	117.2	117.2	117.2	117.2	117.2
This work	Temperature reboiler	°C	126	125	125	123	121
[4]	steam pressure	bar	2.5	2.5	2.5	2.5	2.5
This work	steam pressure	bar	3	3	3	3	3
[4]	L/G	Mass/mass	1	0.985	0.98	0.972	0.963
This work	L/G	Mol/mol	1.76	1.74	1.77	1.80	1.87
[4]	Reboiler duty	MW/tCO_2	3.64	3.65	3.66	3.70	3.70
This work	Reboiler duty	MW/tCO_2	3.539	3.541	3.544	3.545	3.548

Table 4. Summary of predicted results of a NGCC with CO_2 capture at different ambient temperature. Ambient pressure 1.013 bar and relative humidity 60%

Ambient temperature (°C)	**-5**	**5**	**15**	**25**	**35**	**45**
Gas turbine power output (MW)	570	569	546	514	472	424
Steam turbine power output (MW)	171	174	172	166	155	142
Net power output (MW)	700	701	676	640	589	530
Net efficiency (%)	50.78	50.98	50.95	50.53	49.44	48.01
Power consumption CO_2 compressor unit (MW)	25.1	25.3	24.4	23.2	21.8	20.2
Air mass flow (kg/s)	1141	1143	1111	1061	994	914
Natural gas mass flow (kg/s)	30.4	30.3	29.31	27.92	26.25	24.35
Air / fuel ratio	37.5	37.7	37.9	38.0	37.9	37.5
Compressor outlet pressure (bar)	22.21	22.27	21.61	20.66	19.38	17.87
Compressor outlet temperature (°C)	432	446	459	466	471	473
GT inlet temperature (°C)	1415	1420	1422	1423	1423	1420
Exhaust gas temperature (°C)	611	614	622	631.6	646.2	664
Pressure vapour cross-over (bar)	4.1	4.1	4.1	4.1	4.1	4.1
Temperature vapour cross-over (°C)	180	180	180	180	180	180
Number of fans in air condenser	12	18	25	25	25	25
Flue gas flow rate (kg/s)	1172	1173	1140	1089	1020	939
HP steam mass flow (kg/s)	146	147	146	145	143	140
HP steam temperature °C	581.5	584.1	585.2	585.2	585.2	585.2
HP steam pressure bar	116.4	117.8	117.5	116.2	114.5	112
IP steam mass flow (kg/s)	160.7	162.1	161.0	158.6	155.9	152.3
IP steam temperature °C	576.7	579.4	583.5	585.3	585.3	585
IP steam pressure bar	24.2	24.5	27.3	24	23.6	23
LP steam mass flow (kg/s)	15.7	15.5	14.4	12.9	10.8	8.7
LP steam temperature °C	166	166.8	166.5	168.2	170.2	173.2
Temperature of the flue gas to the capture plant °C	89.9	89.6	89.1	89.7	89.6	89.2

Table 5. Summary of predicted results of the CO_2 capture plant at different ambient temperature. Ambient pressure 1.013 bar and relative humidity 60%

Ambient temperature (°C)	**-5**	**5**	**15**	**25**	**35**	**45**
N_2 %	74.77	74.47	74.23	73.60	72.51	70.76
O_2 %	11.66	11.62	11.62	11.49	11.22	10.75
CO_2 %	4.30	4.27	4.24	4.22	4.21	4.21
H_2O %	8.38	8.74	9.02	9.81	11.19	13.43
Ar %	0.90	0.89	0.89	0.88	0.87	0.85
CO_2 mass flow to pipeline (kg/s)	70.5	70.7	68.3	64.9	61.1	56.6
Capture level (%)	90	90	90	90	90	90
Solvent energy of regeneration GJ/tonneCO_2	3.54	3.54	3.54	3.54	3.55	3.55
Steam extraction for capture plant (kg/s)	126.4	124.8	132	125.24	123.16	120.72
Number of absorber train	4	4	4	4	4	4
Liquid to gas molar ratio (L/G)	1.769	1.769	1.737	1.772	1.801	1.868
Lean loading	0.275	0.274	0.272	0.275	0.275	0.275
Absorber column diameter (m)	15.5	15.5	15.5	15.5	15.5	15.5
Absorber height (m)	21	21	21	21	21	21

Table 6. Summary of predicted results of a NGCC with CO_2 capture at different ambient pressure. Ambient temperature 15°C and relative humidity 60%

Ambient pressure (bar)	**0.7948**	**0.8455**	**0.8988**	**0.9547**	**1.013**
Gas turbine power output (MW)	449	478	508	526	546
Steam turbine power output (MW)	150.9	160	169	174	172
Net power output (MW)	565	601	638	660	676
Net efficiency (%)	51.51	51.49	51.50	51.52	50.95
Power consumption CO_2 compressor unit (MW)	24	26	27	28	29
Air mass flow (kg/s)	871	927	986	1047	1111
Natural gas mass flow (kg/s)	24.2	25.7	27.10	28.19	29.25
Air / fuel ratio	36.1	36.1	36.4	37.1	38.0
Exhaust gas temperature (°C)	647	646	646	633	622
GT inlet temperature (°C)	1465	1465	1461	1440	1421
Pressure vapour cross-over (bar)	4	4	4	4	4
Temperature vapour cross-over (°C)	185	187	188	186	180
Number of fans in air condenser	25	25	25	25	25
Flue gas flow rate (kg/s)	894	951	1011	1074	1139
Main steam mass flow (kg/s)	125	133	141	144	147
HP steam mass flow (kg/s)	147.3	144.1	141.0	133.4	125.5
HP steam temperature °C	585.2	585.2	585.2	585.2	585.3
HP steam pressure bar	119.7	117.2	115.0	108.8	108.8
IP steam mass flow (kg/s)	162.6	158.7	155.1	146.7	138.4
IP steam temperature °C	584.1	585.4	585.5	585.5	585.5
IP steam pressure bar	28.7	28	27.4	25.9	24.5
LP steam mass flow (kg/s)	13.1	12.0	11.0	10.6	10.3
LP steam temperature °C	187	186.8	186.4	184.0	181.4
Temperature of the flue gas entering the capture plant °C	82.47	83.35	84.36	86.30	89.11

Table 7. Summary of predicted results of the CO_2 capture plant at different ambient pressure. Ambient temperature 15°C and relative humidity 60%

Ambient pressure (bar)	**0.7948**	**0.8455**	**0.8988**	**0.9547**	**1.013**
N_2 %	73.61	73.68	73.77	73.90	74.03
O_2 %	11.05	11.08	11.14	11.37	11.58
CO_2 %	4.45	4.44	4.42	4.33	4.24
H_2O %	10.01	9.91	9.79	9.52	9.27
Ar %	0.88	0.88	0.89	0.89	0.89
CO_2 mass flow to pipeline (kg/s)	56.26	59.9651	63.427	65.7402	68.3
Capture level (%)	90	90	90	90	90
Solvent energy of regeneration GJ/tonneCO_2	3.56	3.54	3.55	3.54	3.54
Steam extraction for capture plant (kg/s)	92	98	104	108	132
Number of absorber trains	3	4	4	4	4
Liquid to gas molar ratio (L/G)	1.769	1.769	1.737	1.772	1.737
Solvent Lean loading (mol/mol)	0.275	0.274	0.272	0.275	0.272
Absorber column diameter (m)	15.5	15.5	15.5	15.5	15.5
Absorber height (m)	21	21	21	21	21

Table 8. Summary of key parameters of a NGCC with CO_2 capture and supplementary firing at ambient temperature higher than 15 °C

Ambient temperature (°C)	**25**	**35**	**45**
Gas turbine power output (MW)	514	472	424
Steam turbine power output (MW)	204	248	236
Net power output (MW)	678	679	620
Air mass flow (kg/s)	1061	994	914.2
Supplementary natural gas mass flow (kg/s)	2.4	6.2	7.1
Pressure condenser (bar)	0.113	0.311	0.545
N_2 %	73.4	72.0	70.34
O_2 %	10.8	9.7	9.44
CO_2 %	4.6	4.9	4.82
H_2O %	10.4	12.5	14.55
Ar %	0.88	0.9	0.84

Table 9. Estimated specific investment cost for natural gas combined cycle with CO_2 capture

Plant component	**Unit**	**With CO_2 capture**
Power plant		
Subtotal (main items power plant + balance of plant + cooling system) [14]	M$	376
Contractor's Soft & Miscellaneous Costs [14]	M$	81
Bare Erected Cost (BEC)	M$	457
Indirect cost [33]	M$	64
Engineering Procurement and Construction (EPC)	M$	521
Owner's costs & Miscellaneus cost [14]	M$	41
Total Capital Requirement (TCR) power plant	M$	562
Capture plant		
TCR capture plant [20]	M$	687
TCR CO_2 compression [20]	M$	49
Total cost (Power plant +CO_2 capture plant + compressor unit)	**M$**	**1298**

Table 10. Operating and maintenance cost (O&M) of the NGCC power plant and CO_2capture plant [20]

	Unit	**NGCC**	**NGCC with capture**
Power plant	M$		M$
Fixed O&M costs[a]	M$	13.3	11.6
Variable cost[a]	M$	17.6	15.4
CO_2 capture and compression			
Fixed O&M costs[b]	M$	NA	14.7
Variable cost[c]	M$	NA	10.9
Total	M$	30.9	52.6

[a] [34]

[b] 2% TCR CO_2 capture plant including compression [35]

[c] Solvent make up is estimated as 2.4 kg MEA/t CO_2 [36]

Table 11. Total cost of CO_2 transport [20]

	Unit	**NGCC**	**NGCC with capture**	**Subcritical SSFCC**
CO_2 transport[a]	M$	NA	7.0	8.2

[a] 3.65 \$/tCO_2 in 2011 dollar [37]