





# Modeling and Simulation of a Natural Gas and Alternative Fuels Combined Cycle Power Plant with Amine-Based CO<sub>2</sub> capture in Peru

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**Abstract** – This study evaluates alternative scenarios for reducing carbon dioxide emissions from the Ventanilla thermoelectric power plant in Lima, Peru, using the process simulation software ProMax 6.0. The scenarios involve blending hydrogen (0% and 15%) with natural gas (NG) as fuel and implementing CO<sub>2</sub> capture systems using monoethanolamine (MEA), 2-amino-2-methyl-1-propanol (AMP), and amine blends such as MEA/piperazine (PZ), MEA/methyldiethanolamine (MDEA), and MDEA/PZ. The study aimed to achieve CO<sub>2</sub> capture with a purity equal or higher than 99.8% to evaluate its commercialization potential. Additionally, an economic analysis was conducted to assess the profitability of the process, considering carbon taxes from Argentina (\$3.33 per ton CO<sub>2</sub>), Chile (\$5 per ton CO<sub>2</sub>), and Peru (\$5, \$10, or \$20 per ton CO<sub>2</sub> depending on the total emissions). A sensitivity analysis was also performed, taking into account the maximum and minimum dollar exchange rates observed in Peru over the past five years (4.134 soles and 3.434 soles respectively). And, hydrogen costs were evaluated based on their production pathways, with prices considered for green (\$1.3 per kg H<sub>2</sub>), blue (\$2.49 per kg H<sub>2</sub>), and gray (\$1.1 per kg H<sub>2</sub>). Among the alternative studied scenarios, the MDEA (40%) and PZ (10%) blend with 100% NG as fuel exhibited the best net profit margin of 43.91%, achieving 426.49 MW of net power generation and CO<sub>2</sub> emissions of 101.28 kgCO<sub>2</sub>/GJ. Moreover, vent gas with 99.8% CO<sub>2</sub> purity was obtained.

**Keywords**– Modeling and Simulation, NG Combined Cycle (NGCC), Carbon Capture, Amines, ProMax

## I. INTRODUCTION

Carbon dioxide emissions from the power industry represent 40% of the total emissions generated by all industries worldwide. In Peru, these emissions have increased by 337% since 1990 [1]. Although NG combined cycle power plants are more efficient than traditional fossil-fueled power plants, they still contribute to carbon dioxide emissions. In this context, previous studies have researched methods to reduce CO<sub>2</sub> emissions in NG combined cycle power plants, being the post-combustion capture with amine scrubbing one of the most studied due to its cost-effectiveness [2].

Ref. [3] determined 10% PZ and 40% MDEA blend as the most cost-effective option for carbon capture when compared to amine blends with MEA. Ref. [4] compared 15% MDEA/15% PZ and 25% MEA/5% PZ amine blends and found similar results, identifying the first one as the most efficient in CO<sub>2</sub> capture. Additionally, other studies highlighted 20% AMP/2-10% PZ blends as a promising alternative for post-combustion carbon capture [5]. Blends of NG and hydrogen as fuel are widely studied for combined cycle power plants, as the combustion of hydrogen with NG

lowers significantly the CO<sub>2</sub> content in the flue gas, this while still relying on existing infrastructure for power generation [6].

This study is centered on identifying the optimal scenario for reducing carbon dioxide emissions for the Ventanilla thermoelectric power plant, located in Lima, Peru. Additionally, it aims to capture carbon dioxide with a purity higher than 97%, to assess its potential commercialization. Scenarios involve the use of different amine blends for post-combustion CO<sub>2</sub> capture from the flue gas and blending NG with hydrogen as fuel. The compositions of the amine blends are obtained from [7, 8, 9], while the NG and hydrogen blend compositions are derived from [4]. The process simulations were conducted using ProMax 6.0, and the cost-effectiveness of each scenario is evaluated through a profit margin analysis. Additionally, the environmental impact of each scenario is assessed to determine its feasibility for large-scale implementation, considering both operational and economic factors.

## II. METHODOLOGY

### A. ProMax 6.0

ProMax 6.0 is a simulation software developed by Bryan Research & Engineering (BR&E), which is a useful tool for modeling chemical processes, and since its latest update has improvements for natural gas, refinery and CO<sub>2</sub> capture applications [10].

### B. General Simulation Details

The simulation of the complete process consists of two parts: Combined Cycle and CO<sub>2</sub> Capture Process. In the first part, information from [11] was used to model the Ventanilla Thermoelectric Power Plant and its corresponding streams, with the composition of dry NG from Camisea used as fuel, whose composition is described in Table 1.

TABLE I  
COMPOSITION OF DRY NG FROM CAMISEA IN THE COMBINED CYCLE

Compound	% molar
Methane (CH <sub>4</sub> )	88.05
Ethane(C <sub>2</sub> H <sub>6</sub> )	10.44
Nitrogen (N <sub>2</sub> )	1.07
Carbon Dioxide (CO <sub>2</sub> )	0.25
Propane (C <sub>3</sub> H <sub>8</sub> )	0.17
Butane (C <sub>4</sub> H <sub>10</sub> )	0.02

Adapted from [11]

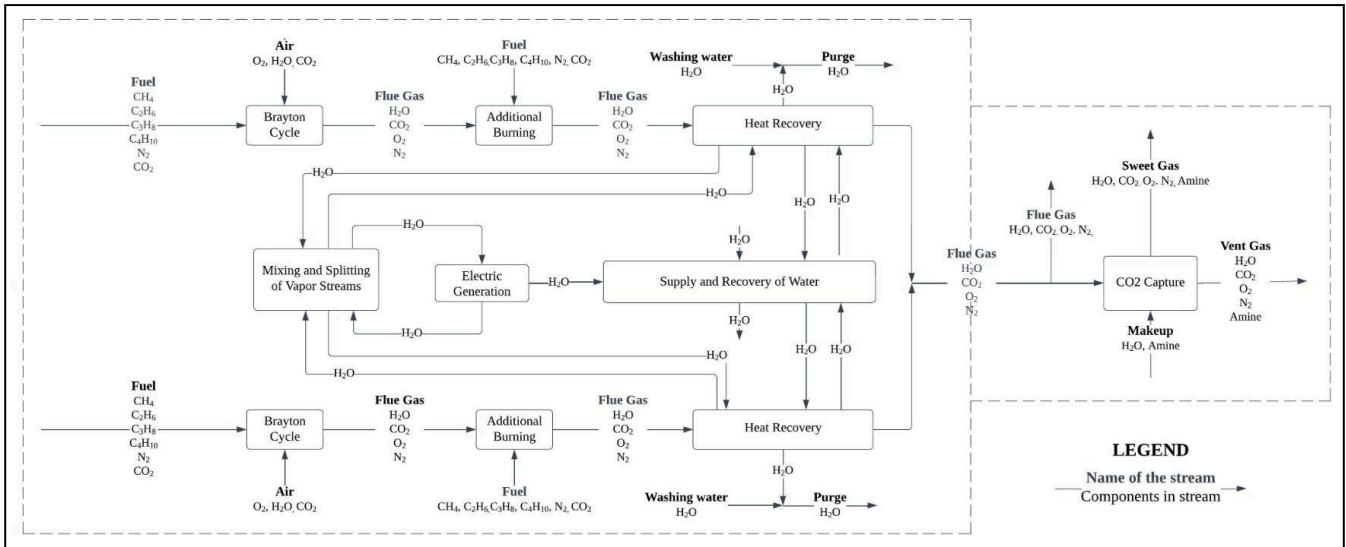


Fig. 1 Flow Diagram of the complete process.

The second part of the process corresponds to CO<sub>2</sub> capture using amines, with a model inspired by the one presented in [12], but modified to operate properly under the conditions of the flue gas from the Combined Cycle, also the aqueous amine flows are determined using the scenarios Tool available in ProMax 6.0.

Fig. 1 shows the flow diagram of the complete process to be modeled in ProMax 6.0.

### C. Thermodynamic Models

Due to the differences in the components used in each part of the simulation, two thermodynamic models were selected in alignment with the literature presented by [13]. The Combined Cycle employs the "Peng Robinson - Polar" model, as it is well-suited for systems with a predominance of water and steam. For CO<sub>2</sub> capture with amines, the "Amine Sweetening - Peng Robinson" model was chosen in accordance with previous studies that simulate amine sweetening processes using ProMax, ensuring alignment with established methodologies and accurate representation of the gas-liquid equilibrium in amine systems [14].

### D. Combined Cycle

NG and air are initially introduced into a burner, generating combustion gases that are directed to a gas turbine to generate power. The residual oxygen in the combustion gases is utilized in a secondary burner. Then, flue gas is routed to a series of heat exchangers, where its high temperature is used to evaporate water in the Rankine cycle. This process is carried out in duplicate and in parallel, as shown in Fig. 1. The Rankine cycle consists of three turbines operating at high, medium, and low pressure. Finally, a part of the lower-temperature flue gas is directed to the capture process, while the remainder is released into the atmosphere [11].

Additionally, scenarios are evaluated in which the fuel is a mixture of NG and hydrogen, aiming to reduce CO<sub>2</sub> emissions. The hydrogen percentages used in these scenarios are derived from [4] and are detailed in Table 2. Also, the percentages employed do not exceed the embrittlement limit [15]. For all scenarios, the system operates with a fixed inlet

volumetric flow rate of 1532.94 m<sup>3</sup>/h, ensuring consistency in the comparison.

TABLE 2  
COMPOSITION OF FUEL FOR COMBINED CYCLE

Scenario	Hydrogen (% mass)	NG (% mass)
1.1	0	100
1.2	15	85

Adapted from [4]

### E. CO<sub>2</sub> capture with amines

The CO<sub>2</sub> capture process begins with the conditioning of 17.52% mass of the combined cycle flue gas to the pressure and temperature required for the operation of the selected amines. This is achieved using a compressor and a heat exchanger, after which the gas enters the absorber. In this equipment, the flue gas is brought into contact with a lean amine stream, which selectively captures CO<sub>2</sub>, producing a flue gas stream with reduced CO<sub>2</sub> content that is released into the atmosphere.

The CO<sub>2</sub>-rich amine stream extracted from the bottom of the absorber is sent to a flash separator, where the light gaseous fraction, mainly composed of nitrogen, oxygen, and other non-condensable gases is released to the atmosphere. The remaining liquid phase, with low pressure, then passes through a heat exchanger, where it is preheated before entering the stripper. In the stripper, through the addition of heat provided by the reboiler, the CO<sub>2</sub> is desorbed from the amine solution. The desorber top stream is then partially condensed, drawing a vent gas stream rich in CO<sub>2</sub> and a condensate stream that is recycled for reuse in the system.

The regenerated amine solution, now with a low CO<sub>2</sub> content, is cooled through a heat exchanger, pumped and cooled again with an additional cooler before being recirculated back to the absorber. Additionally, a makeup flow is maintained to compensate for losses and ensure process efficiency.

Fig. 2 shows the block diagram of the CO<sub>2</sub> capture process.

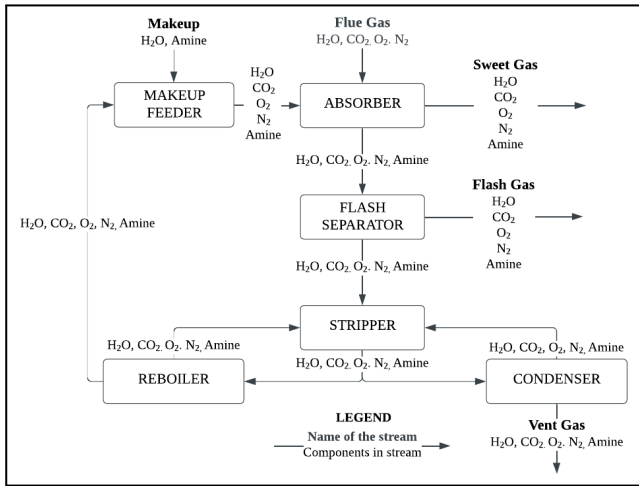


Fig. 2 Block Diagram of the CO<sub>2</sub> capture process.

In this case, scenarios employing different amines for CO<sub>2</sub> capture are evaluated, with their compositions obtained from [7, 9], as shown in Table 3. The parameters of interest for this analysis include CO<sub>2</sub> emissions per gigajoule of electricity produced, net power output, capture percentage, and CO<sub>2</sub> purity in the vent gas stream. The ProMax<sup>®</sup> scenarios tool is used with the objective of determining the lowest amine flow that results in the highest possible CO<sub>2</sub> capture.

TABLE 3  
AMINES FOR CO<sub>2</sub> CAPTURE

Scenario	Amines (% mass)
2.1	MEA (30%)
2.2	MEA (25%) and PZ (10%)
2.3	MEA (22.5%) and MDEA (15%)
2.4	AMP (30%)
2.5	MDEA (40%) and PZ (10%)

Adapted from [7, 9].

### E. Operational Profitability Analysis

The operational profitability of the base scenario, without CO<sub>2</sub> reduction alternatives, will be compared to various scenarios involving the use of hydrogen with NG as fuel and the implementation of CO<sub>2</sub> capture. The methodology for this type of analysis is derived from the approach outlined in [16].

For this analysis, the net utility and net sales are calculated, and the net profit margin is determined using Equation 1 as a percentage. Monetary values will be expressed in U.S. dollars, considering an exchange rate of 3.735 soles per US dollar [17].

$$\text{Net Profit Margin} = \frac{\text{Net Utility}}{\text{Net Sales}} \times 100\% \quad (1)$$

Net profit is calculated as the difference between sales revenue and total operating costs. These costs include both direct and indirect costs; however, this analysis focuses on the direct costs related to production, which are detailed in Table 4.

TABLE 4  
DIRECT COSTS

Direct Costs	Considerations
Raw Material	Market prices will be used
Services	Market prices will be used
Labor	10% of Total Cost
Supervision	15% of Total Cost
Maintenance	0.00212 USD/kWh [18]
Operational Supplies	15% of Maintenance
Laboratory Charges	10% of Labor
Patents and Royalties	2% of Total Cost

The maintenance cost when using hydrogen and natural gas blend is obtained from [19], considering a maintenance factor of +0.375%. For scenarios involving CO<sub>2</sub> capture with amines, an additional maintenance cost is included based on the annual amount of CO<sub>2</sub> captured, considering a rate of 0.00331 USD per ton of CO<sub>2</sub> captured [20].

Currently, there is no carbon tax in Peru; however, plans for its implementation are underway [21]. Therefore, the carbon taxes from Argentina (\$3.33 per ton CO<sub>2</sub>), Chile (\$5 per ton CO<sub>2</sub>), and the one proposed by [11] for Peru (\$5, \$10, or \$20 per ton CO<sub>2</sub> depending on the total emissions) are considered. Also, sales revenue includes the sale of captured CO<sub>2</sub>, considering a selling price of 0.416 dollars per kilogram of CO<sub>2</sub> [22].

The market prices of the raw material used in the process are detailed in Table 5, with the conversion from soles to dollars already applied.

TABLE 5  
COSTS OF RAW MATERIALS AND UTILITIES

Raw Material	Cost
Natural Gas	3.9139 USD/MMBTU [23].
Shaft Water	0.328 USD/m <sup>3</sup> [24, 25].
MEA	1.19 USD/kg [26].
MDEA	0.5 USD/kg [27].
PZ	0.101 USD/kg [28].
AMP	8 USD/kg [29].
Electricity	0.161 USD/kWh [30].
Steam at 50 psig	3 USD/1000 lb [2].
Process Air	0.03 USD/1000 ft <sup>3</sup> [31].
Demineralized Water	2.78 USD/1000 gal [32].
Hydrogen	1.3 USD/kg [33].

After identifying the scenario with the highest net profit margin, a sensitivity analysis will be carried out for both the hydrogen and non hydrogen version, in order to provide a more comprehensive economic evaluation. It considers the impact of the maximum (4.134 soles) and minimum (3.343 soles) exchange rates registered in Peru over the last five years [17], and the use of green (\$1.3 per kg H<sub>2</sub>), blue (\$2.49 per kg H<sub>2</sub>) and gray (\$1.1 per kg H<sub>2</sub>) hydrogen [33, 34].

## III. RESULTS

### A. Combined Cycle

Fig. 3 illustrates the combined cycle in its base scenario (without hydrogen), modeled and simulated in ProMax 6.0.

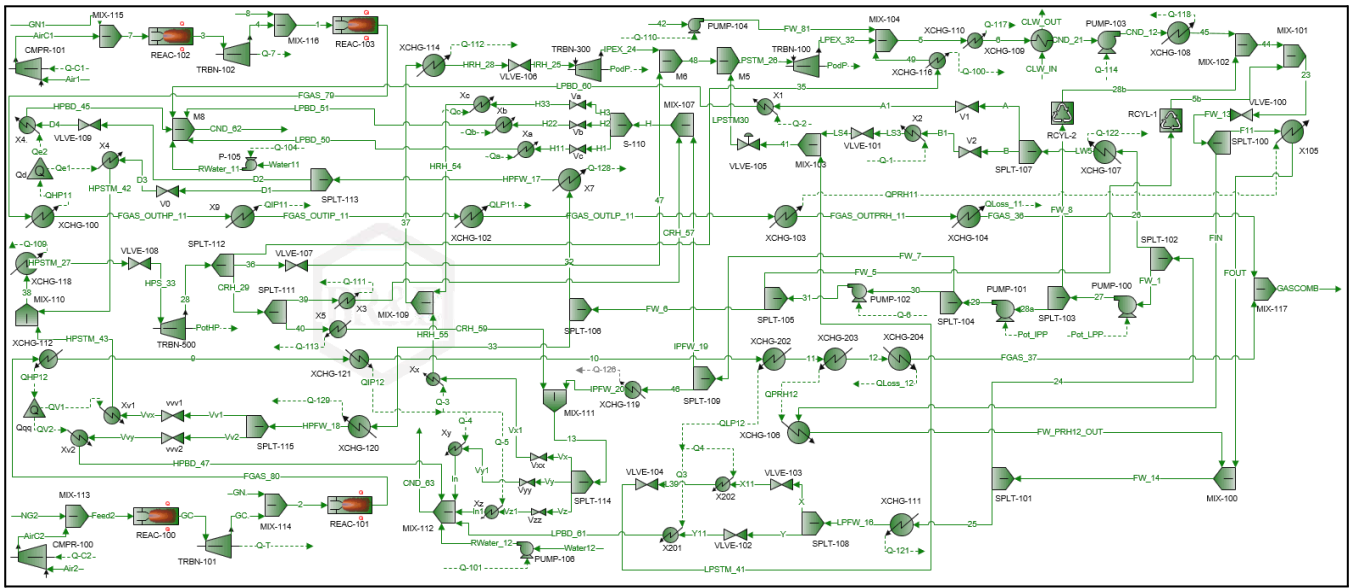


Fig. 3 Combined cycle simulation on ProMax 6.0.

The design is equivalent to that presented in Fig. 1, with the key difference that flowsheet connectors have been added on the right side to direct the specified percentages of flue gas to each CO<sub>2</sub> capture scenario. Table 6 below presents each one of the flows used in each scenario.

TABLE 6  
FLOW OF RAW MATERIALS

Scenario	1.1	1.2
Process Air (ft <sup>3</sup> /yr)	$8.44 \times 10^{11}$	$4.25 \times 10^{11}$
Hydrogen (kg/yr)	0.0	$3.84 \times 10^7$
NG (MMBTU/yr)	$1.61 \times 10^3$	$5.58 \times 10^8$
Shaft Water (m <sup>3</sup> /yr)	$1.67 \times 10^8$	$1.67 \times 10^8$
Demineralized Water (gal/yr)	$9.70 \times 10^8$	$9.70 \times 10^8$

Table 7 presents the key parameters to be analyzed, which are essential for evaluating the performance of the thermoelectric power plant and assessing the effectiveness of emission reduction strategies.

TABLE 7  
RESULTS FOR DIFFERENT SCENARIOS IN COMBINED CYCLE

Scenario	Net Power (MW)	Emissions (kg CO <sub>2</sub> /GJ)
1.1	487.10	107.54
1.2	336.20	86.96

### B. CO<sub>2</sub> capture scenarios

Fig. 4 illustrates the CO<sub>2</sub> capture system, modeled and simulated in ProMax 6.0, which is consistently applied across all evaluated scenarios. This system allows for the separation of CO<sub>2</sub> from flue gas using different amine-based solvents.

To analyze the effectiveness of each capture scenario, Table 8 presents the amine flows utilized in different cases. These values are essential for assessing the required solvent quantities and their impact on operational profitability analysis.

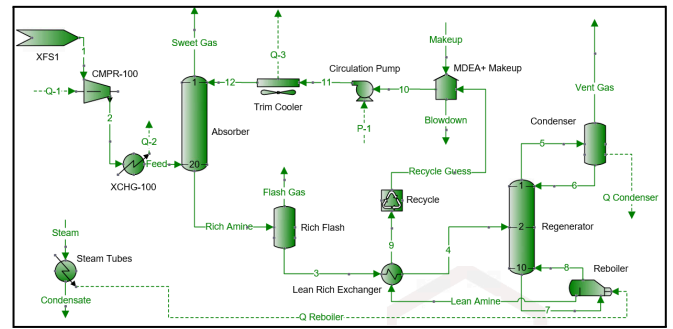


Fig. 4 CO<sub>2</sub> capture simulation on ProMax 6.0.

TABLE 8  
RESULTS FOR DIFFERENT SCENARIOS WITH CO<sub>2</sub> CAPTURE

Scenario	MEA (kg/yr)	MDEA (kg/yr)	PZ (kg/yr)	AMP (kg/yr)
2.1	$7.57 \times 10^7$	0.00	0.00	0.00
2.2	$6.25 \times 10^7$	0.00	$2.52 \times 10^7$	0.00
2.3	$6.23 \times 10^7$	$4.08 \times 10^7$	0.00	0.00
2.4	0.00	0.00	0.00	$7.09 \times 10^7$
2.5	0.00	$1.47 \times 10^8$	$3.72 \times 10^7$	0.00

A more detailed analysis of the system's overall performance, including net power, CO<sub>2</sub> emission rates and purity percentage, is presented in Table 9 and Table 10. This table integrates the different evaluated scenarios to provide a comprehensive overview of their implications.

TABLE 9  
RESULTS OF SCENARIOS WITH 0% HYDROGEN

Combined Cycle Scenario	1.1				
	2.1	2.2	2.3	2.4	2.5
CO <sub>2</sub> Capture Scenario	2.1	2.2	2.3	2.4	2.5
Net Power (MW)	426.5	426.5	426.5	426.6	426.5
Emissions (kg CO <sub>2</sub> /GJ)	101.9	101.8	101.9	106.9	101.3
CO <sub>2</sub> purity (%)	99.8	99.8	99.8	99.8	99.8

TABLE 10  
RESULTS OF SCENARIOS WITH 15% HYDROGEN

Combined Cycle Scenario	1.2				
	2.1	2.2	2.3	2.4	2.5
CO <sub>2</sub> Capture Scenario					
Net Power (MW)	289.5	289.5	289.5	289.5	289.5
Emissions (kg CO <sub>2</sub> /GJ)	84.1	84.4	76.8	79.8	83.3
CO <sub>2</sub> purity (%)	99.8	99.8	99.8	99.8	99.8

E. Operational Profitability Analysis

Table 11 illustrates the net profitability margin for every scenario evaluated without hydrogen, employing the same methodology as the one used for the base scenario.

TABLE 11  
NET PROFIT MARGIN OF ALL SCENARIOS WITHOUT HYDROGEN

Combined Cycle Scenario	1.1				
	2.1	2.2	2.3	2.4	2.5
CO <sub>2</sub> Capture Scenario					
Net Profit Margin no carbon taxes (%)	44.62	48.99	43.73	-107.37	51.76
Net Profit Margin for \$3.33 per ton CO <sub>2</sub> (%)	43.30	47.67	42.40	-108.85	50.45
Net Profit Margin for \$5 per ton CO <sub>2</sub> (%)	42.64	47.01	41.74	-109.59	49.80
Net Profit Margin for \$20 per ton CO <sub>2</sub> (%)	36.68	41.07	35.78	-116.23	43.91

Table 12 illustrates the net profitability margin for every scenario evaluated with 15% hydrogen, employing the same methodology as in Table 11.

TABLE 12  
NET PROFIT MARGIN OF ALL SCENARIOS WITH 15% HYDROGEN

Combined Cycle Scenario	1.2				
	2.1	2.2	2.3	2.4	2.5
CO <sub>2</sub> Capture Scenario					
Net Profit Margin no carbon taxes (%)	-5.93	-4.68	1.97	-217.53	10.01
Net Profit Margin for \$3.33 per ton CO <sub>2</sub> (%)	-7.07	-5.83	1.00	-218.57	8.88
Net Profit Margin for \$5 per ton CO <sub>2</sub> (%)	-7.65	-6.41	0.52	-219.09	8.32
Net Profit Margin for \$20 per ton CO <sub>2</sub> (%)	-12.81	-11.61	-3.80	-223.74	3.26

Table 13 and 14 shows the net profit margin for the minimum and maximum exchange rate values. The first one is calculated for the most profitable scenario, 2.5 (MDEA/PZ) without hydrogen (1.1), and for each of the proposed carbon taxes. The second one considers the three hydrogen types by production method and both the minimum and maximum exchange rates.

TABLE 13  
NET PROFIT MARGIN OF SCENARIO 2.5 WITH 0% HYDROGEN

Combined Cycle Scenario	1.1	
CO <sub>2</sub> Capture Scenario	2.5	
Net Profit Margin no carbon taxes (%)	Dollar for 4.134 soles	49.64%
	Dollar for 3.434 soles	53.43%
Net Profit Margin for \$3.33 per ton CO <sub>2</sub> (%)	Dollar for 4.134 soles	48.23%
	Dollar for 3.434 soles	52.20%
Net Profit Margin for \$5 per ton CO <sub>2</sub> (%)	Dollar for 4.134 soles	47.53%
	Dollar for 3.434 soles	51.59%
Net Profit Margin for \$20 per ton CO <sub>2</sub> (%)	Dollar for 4.134 soles	41.18%
	Dollar for 3.434 soles	46.07%

TABLE 14  
NET PROFIT MARGIN OF SCENARIOS 2.5 WITH 15% HYDROGEN

Combined Cycle Scenario	1.2		
CO <sub>2</sub> Capture Scenario	2.5		
Net Profit Margin no carbon taxes (%)	Green H2 for 1.3 USD/kg	Dollar for 4.134 soles	5.18%
		Dollar for 3.434 soles	13.80%
	Blue H2 for 2.49 USD/kg	Dollar for 4.134 soles	-17.07%
		Dollar for 3.434 soles	-5.42%
	Gray H2 for 1.1 USD/kg	Dollar for 4.134 soles	8.91%
		Dollar for 3.434 soles	17.03%
Net Profit Margin for \$3.33 per ton CO <sub>2</sub> (%)	Green H2 for 1.3 USD/kg	Dollar for 4.134 soles	3.96%
		Dollar for 3.434 soles	12.75%
	Blue H2 for 2.49 USD/kg	Dollar for 4.134 soles	-18.28%
		Dollar for 3.434 soles	-6.47%
	Gray H2 for 1.1 USD/kg	Dollar for 4.134 soles	7.70%
		Dollar for 3.434 soles	15.98%
Net Profit Margin for \$5 per ton CO <sub>2</sub> (%)	Green H2 for 1.3 USD/kg	Dollar for 4.134 soles	3.35%
		Dollar for 3.434 soles	12.22%
	Blue H2 for 2.49 USD/kg	Dollar for 4.134 soles	-18.89%
		Dollar for 3.434 soles	-7.00%
	Gray H2 for 1.1 USD/kg	Dollar for 4.134 soles	7.09%
		Dollar for 3.434 soles	15.45%
Net Profit Margin for \$20 per ton CO <sub>2</sub> (%)	Green H2 for 1.3 USD/kg	Dollar for 4.134 soles	-2.13%
		Dollar for 3.434 soles	7.49%
	Blue H2 for 2.49 USD/kg	Dollar for 4.134 soles	-24.37%
		Dollar for 3.434 soles	-11.73%
	Gray H2 for 1.1 USD/kg	Dollar for 4.134 soles	1.61%
		Dollar for 3.434 soles	10.72%

III. DISCUSSION

A reduction in net power from the baseline scenario is observed when using a fuel blend of 15% hydrogen and 85%

natural gas, decreasing from 487.1 MW to 336.2 MW. This reduction highlights the trade-off between lower carbon emissions and power output. Likewise, CO<sub>2</sub> emissions per GJ of energy produced decrease significantly, from 107.54 kg CO<sub>2</sub>/GJ in scenario 1.1 to 86.96 kg CO<sub>2</sub>/GJ in scenario 1.2, demonstrating the potential of hydrogen blending to mitigate emissions. However, this comes at the cost of reduced efficiency, which must be carefully considered when evaluating the feasibility of hydrogen integration.

For the base scenario with carbon capture, the net power remains constant at 425.5 MW across all CO<sub>2</sub> capture scenarios (2.1 to 2.5), indicating that the implementation of carbon capture technology reduces the net power output by the same magnitude compared to the baseline. CO<sub>2</sub> emissions show slight variations, ranging between 101.8 and 106.9 kg CO<sub>2</sub>/GJ, with scenario 2.4 exhibiting the highest emissions (106.9 kg CO<sub>2</sub>/GJ) and scenario 2.2 the lowest (101.8 kg CO<sub>2</sub>/GJ). These differences can be attributed to variations in capture efficiency and process conditions. Additionally, the captured CO<sub>2</sub> purity remains consistently high at 99.8% in all cases, ensuring its compliance with market requirements for potential commercialization. This high purity level is crucial for industries looking to utilize captured CO<sub>2</sub> in enhanced oil recovery, chemical synthesis, or other applications.

In the case of natural gas blending with hydrogen, the net power follows the same trend as the baseline scenario, decreasing to 289.5 MW and remaining constant across the different amines used. The scenario with the highest emissions was 2.2 (84.4 kg CO<sub>2</sub>/GJ), while the lowest-emission scenario was 2.3 (76.8 kg CO<sub>2</sub>/GJ). Additionally, the purity of the recovered CO<sub>2</sub> stream meets market distribution requirements, reaching 99.8%. This indicates that in the presence of hydrogen, MDEA/PZ is not the optimal amine combination; instead, MDEA/MEA proves to be the better choice. Therefore, from an environmental perspective, it represents the most suitable option.

For the baseline scenario without hydrogen blending (1.1), the net profitability without carbon taxes is positive for all capture scenarios except for scenario 2.4, where a significant loss of -107.37% is observed. This behavior indicates that while CO<sub>2</sub> capture can be profitable in some cases, the selection of the solvent and operating conditions play a key role in economic feasibility. In the case of scenario 2.5, the highest profitability is observed (51.76%), suggesting that this capture approach could be the most suitable from an economic perspective within this group.

In contrast, when hydrogen is blended with natural gas (1.2), overall profitability decreases significantly. Without CO<sub>2</sub> capture, profitability values are negative for most cases, suggesting that the reduction in system efficiency significantly impacts the economic viability of the process. Scenario 2.4 shows the largest loss at -217.53%, reinforcing the trend observed in scenario 1.1 regarding the lack of viability of this configuration.

When carbon taxes are introduced, it is observed that as the cost per ton of emitted CO<sub>2</sub> increases, the profitability of scenarios without capture decreases, while capture scenarios tend to be less affected. With a tax of \$3.33 per ton of CO<sub>2</sub>, capture scenarios maintain positive profitability margins in most cases, although the reduction is noticeable. With a tax

of \$5 per ton of CO<sub>2</sub>, capture scenarios continue to show better profitability margins compared to those without capture, reinforcing the importance of implementing emission mitigation strategies to avoid economic penalties.

CO<sub>2</sub> emissions exceeded 500000 tons in all evaluated scenarios; therefore, a maximum carbon tax of 20 USD per ton of CO<sub>2</sub> emitted is considered. For this case, losses become more pronounced in scenarios without capture; whereas capture scenarios, though affected, manage to maintain certain positive values—especially scenario 2.5 in case 1.1 and scenario 2.5 in case 1.2. This suggests that some capture configurations can become economically more attractive under high-tax schemes.

The use of hydrogen (scenario 1.2) introduces a profitability penalty compared to the exclusive use of natural gas (scenario 1.1). In all capture scenarios, profitability values in case 1.2 are lower, with some configurations even showing losses. This suggests that while hydrogen blending contributes to emission reduction, the loss of system efficiency negatively impacts profitability, making it less economically viable without additional incentives or improvements in process efficiency.

Additional insight was gained through a sensitivity analysis applied to the most profitable capture scenario in both configurations: with and without hydrogen blending. For scenario 2.5 without hydrogen (1.1), the net profit margin remained positive in all cases, with a notable increase when the dollar value decreased. In contrast, for the hydrogen-based configuration (1.2), profitability was strongly influenced by the type of hydrogen and exchange rate. While green and gray hydrogen allowed for positive margins under favorable conditions, blue hydrogen resulted in significant losses in all cases due to its high production cost. This cost is influenced by technological advancements, which are expected to lower costs over time, and the price of natural gas, which has shown an upward trend.

#### IV. CONCLUSIONS

This study evaluated different strategies to reduce CO<sub>2</sub> emissions from the Ventanilla thermoelectric power plant, focusing on fuel blending with hydrogen and CO<sub>2</sub> capture using various amine-based solvents. The analysis considered both environmental impact and economic viability to determine the most effective approach.

The implementation of CO<sub>2</sub> capture using amines proved to be an effective emission reduction strategy. Among the studied blends, the mixture of MDEA (40%) and PZ (10%) exhibited the best overall performance, achieving the highest net profit margin and the lowest CO<sub>2</sub> emissions per GJ of energy produced. The purity of the captured CO<sub>2</sub> also remained consistently high (99.8%), ensuring its suitability for commercialization.

Replacing 15% of natural gas with hydrogen led to a reduction in CO<sub>2</sub> emissions. However, the associated decrease in net power generation must be carefully considered when evaluating the feasibility of this approach. In these scenarios, the highest net profit margin obtained was 8.88%, corresponding to the MDEA (40%) and PZ (10%) amine blend. Despite its environmental benefits, hydrogen blending introduced economic challenges due to efficiency losses.

The economic analysis revealed that the MDEA (40%) and PZ (10%) blend provided the highest profitability for hydrogen and non hydrogen based scenarios, when incorporating carbon taxes from Argentina, Chile, and a proposed tax for Peru. This highlights the importance of considering regional tax policies when selecting carbon reduction strategies, as taxation can significantly influence the economic feasibility of CO<sub>2</sub> capture technologies.

The sensitivity analysis showed the high dependence between the dollar exchange rate in Peru and the type of hydrogen employed. The net profitability increased when the exchange rate was lower, reaching a maximum of 53.43% for the minimum exchange rate and employing gray hydrogen.

Finally, while both hydrogen blending and CO<sub>2</sub> capture contribute to emission reduction, they also result in efficiency losses that impact profitability. Therefore, establishing an optimal balance between environmental benefits and economic viability is crucial for the successful implementation of these strategies in the power generation sector.

#### REFERENCES

- [1] M. Crippa *et al.*, *CO<sub>2</sub> emissions of all world countries: JRC/IEA/PBL 2022 report*. Publications Office of the European Union, 2022. Accessed: Jan 11, 2025. [Online]. Available: <https://data.europa.eu/doi/10.2760/07904>
- [2] W. D. Seider, D. R. Lewin, J. D. Seader, S. Widagdo, R. Gani, and K. M. Ng, *Product and Process Design Principles: Synthesis, Analysis and Evaluation*. John Wiley & Sons, 2016.
- [3] W. Jiang, Y. Lin, C. Sun, Y. Sun, and Y. Zhu, "Comparative Review for Enhancing CO<sub>2</sub> Capture Efficiency with Mixed Amine Systems and Catalysts," *Molecules*, vol. 29, no. 19, Art. no. 19, Jan. 2024, doi: 10.3390/molecules29194618.
- [4] D. Piñera Villar, "Análisis de un ciclo de potencia que utiliza hidrógeno como combustible," M. S. Thesis, Universidad de Oviedo, Asturias, Spain, 2022. Available: <https://digibuo.uniovi.es/dspace/handle/10651/64412> [Accessed: Apr. 17, 2024]
- [5] A. A. Khan, GN. Halder, and A. K. Saha, "Experimental investigation on efficient carbon dioxide capture using piperazine (PZ) activated aqueous methyldiethanolamine (MDEA) solution in a packed column," *International Journal of Greenhouse Gas Control*, vol. 64, pp. 163–173, Sep. 2017, doi: 10.1016/j.ijggc.2017.07.016.
- [6] D. Pashchenko, "Hydrogen-rich gas as a fuel for the gas turbines: A pathway to lower CO<sub>2</sub> emission," *Renewable and Sustainable Energy Reviews*, vol. 173, p. 113117, Mar. 2023, doi: 10.1016/j.rser.2022.113117.
- [7] B. Aghel, S. Janati, S. Wongwises, and M. S. Shadloo, "Review on CO<sub>2</sub> capture by blended amine solutions," *International Journal of Greenhouse Gas Control*, vol. 119, p. 103715, Sep. 2022, doi: 10.1016/j.ijggc.2022.103715.
- [8] Q. Xie, A. Aroonwilas, and A. Veawab, "Measurement of Heat of CO<sub>2</sub> Absorption into 2-Amino-2-methyl-1-propanol (AMP)/Piperazine (PZ) Blends Using Differential Reaction Calorimeter," *Energy Procedia*, vol. 37, pp. 826–833, Jan. 2013, doi: 10.1016/j.egypro.2013.05.175.
- [9] X. Ding, H. Chen, J. Li, and T. Zhou, "Comparative techno-economic analysis of CO<sub>2</sub> capture processes using blended amines," *Carbon Capture Science & Technology*, vol. 9, p. 100136, Dec. 2023, doi: 10.1016/j.ccst.2023.100136.
- [10] "Bryan Research & Engineering, LLC." Accessed: May 01, 2025. [Online]. Available: <https://www.bre.com/Default.aspx>
- [11] P. Villanueva and D. Cristhian, "Economía verde y tributación: Análisis económico del impuesto al carbono en el Perú," 2024, Accessed: Jan 30, 2025. [Online]. Available: <https://hdl.handle.net/20.500.12640/3965>
- [12] X. Zeng *et al.*, "Combined pinch and exergy analysis for post-combustion carbon capture NGCC integrated with absorption heat transformer and flash evaporator," *Energy*, vol. 288, p. 129788, Feb. 2024, doi: 10.1016/j.energy.2023.129788.
- [13] E. C. Carlson, "Don't gamble with physical properties for simulations," *Chemical engineering progress*, vol. 92, no.10, pp. 35-46, 1996. Available: [http://utw10182.utweb.utexas.edu/eldridge/ChE473K/drop\\_folder/Don't%20Gamble%20With%20Physical%20Properties.pdf](http://utw10182.utweb.utexas.edu/eldridge/ChE473K/drop_folder/Don't%20Gamble%20With%20Physical%20Properties.pdf) [Accessed: Jan 06, 2025]
- [14] R. Hameidi and C. Srinivasakannan, "Simulation and optimization of amine sweetening process," *Petroleum and Coal*, vol. 60, no. 1, pp. 48–57, 2018.
- [15] H. Zhang *et al.*, "Research progress on corrosion and hydrogen embrittlement in hydrogen–natural gas pipeline transportation," *Natural Gas Industry B*, vol. 10, no. 6, pp. 570–582, Dec. 2023, doi: 10.1016/j.ngib.2023.11.001.
- [16] N. Tamayo, S. Castro, T. Patiño-Chiri, W. Ramos, and F. Tarazona-Vasquez, "Modeling and simulation of automotive urea production in Peru: 22nd LACCEI International Multi-Conference for Engineering, Education and Technology, LACCEI 2024," *Proceedings of the 22nd LACCEI International Multi-Conference for Engineering, Education and Technology*, 2024, doi: 10.18687/LACCEI2024.1.1.1428.
- [17] Superintendencia de Banca, Seguros y AFP (SBS), "Cotización de oferta y demanda y demanda tipo de cambio promedio ponderado," *Superintendencia de Banca, Seguros y AFP*. [Online]. Available: [https://www.sbs.gob.pe/app/pp/sistip\\_portal/paginas/publicacion/tipoc\\_ambipromedio.aspx](https://www.sbs.gob.pe/app/pp/sistip_portal/paginas/publicacion/tipoc_ambipromedio.aspx) [Accessed: Jan. 27, 2025]
- [18] "Frequently Asked Questions (FAQs) - U.S. Energy Information Administration (EIA)." Accessed: Feb 12, 2025. [Online]. Available: <https://www.eia.gov/tools/faqs/faq.php?id=19&t=8>
- [19] ETN Global, "Hydrogen Deployment in Centralised Power Generation: A Techno-Economic Case Study," ETN GLOBAL. Accessed: Feb 10, 2025. [Online]. Available: [https://etn\\_global/news-and-events/news/hydrogen-techno-economic-study/](https://etn_global/news-and-events/news/hydrogen-techno-economic-study/)
- [20] C. E. Webel, "Estudio técnico-económico para la obtención de CO<sub>2</sub> a partir de los gases de escape de los generadores de vapor de una central termoeléctrica," Thesis, 2014. Accessed: Jan 29, 2025. [Online]. Available: <http://saber.ucv.ve/handle/10872/6738>
- [21] "Cumplimiento de metas climáticas: costo del carbono," Desafíos PwC. Accessed: Feb 04, 2025. [Online]. Available: <https://desafios.pwc.com/cumplimiento-de-metas-climaticas-costo-del-carbono/>
- [22] "Veritrade | Importaciones y Exportaciones de DIÓXIDO DE CARBONO." Accessed: Feb 01, 2025. [Online]. Available: <https://www.veritrade.com/es/peru/importaciones-y-exportacion-es/dioxido-de-carbono/281121>
- [23] Organismo Supervisor de la Inversión en Energía y Minería (OSINERGMIN), "Informe Técnico que Sustenta la Fijación de Precios en Barra," *Organismo Supervisor de la Inversión en Energía y Minería*, April 2024. [Online]. Available: [https://www.google.com/url?q=https://www.osinergmin.gob.pe/Resoluciones/pdf/2024/Informe-Tecnico-210-2024-GRT.pdf&sa=D&source=docs&ust=1738516587397356&usq=AOvVaw16AsvGYfw\\_mKjCdJr-CnCl](https://www.google.com/url?q=https://www.osinergmin.gob.pe/Resoluciones/pdf/2024/Informe-Tecnico-210-2024-GRT.pdf&sa=D&source=docs&ust=1738516587397356&usq=AOvVaw16AsvGYfw_mKjCdJr-CnCl) [Accessed: Jan. 29, 2025]
- [24] Diario Oficial del Bicentenario: El Peruano, "Decreto Supremo que aprueba el valor de las retribuciones económicas por el uso del agua y por el vertimiento de aguas residuales tratadas a aplicarse en el año 2024," *Diario Oficial: El Peruano*, 2023. Accessed: Jan 30, 2025. [Online]. Available: [https://busquedas.elperuano.pe/api/visor\\_html/1726939-1](https://busquedas.elperuano.pe/api/visor_html/1726939-1)
- [25] Diario Oficial del Bicentenario: El Peruano, "Decreto Supremo que aprueba el valor de las retribuciones económicas por el uso del agua y por el vertimiento de aguas residuales tratadas a aplicarse en el año 2024 - DECRETO SUPREMO - N° 013-2023-MIDAGRI - DESARROLLO AGRARIO Y RIEGO." Accessed: May 02, 2025. [Online]. Available: <https://busquedas.elperuano.pe/dispositivo/NL/2246610-7>
- [26] Mike, "Monoethanolamine price index," businessanalytiq. Accessed: May 02, 2025. [Online]. Available: <https://businessanalytiq.com/procurementanalytics/index/monoethanolamine-price-index/>
- [27] "Precios de Metildietanolamina (MDEA)," QuimiNet. Accessed: Jan 31, 2025. [Online]. Available: <https://www.quiminet.com/productos/metildietanolamina-mdea-5205411059/precios.htm>
- [28] Imarc Group, "Piperazine Prices, News, Monitor, Analysis and Forecast." Accessed: Feb 01, 2025. [Online]. Available: <https://www.imarcgroup.com/piperazine-pricing-report>

- [29] E. Osagie, C. Biliyok, G. Di Lorenzo, D. P. Hanak, and V. Manovic, "Techno-economic evaluation of the 2-amino-2-methyl-1-propanol (AMP) process for CO<sub>2</sub> capture from natural gas combined cycle power plant," *International Journal of Greenhouse Gas Control*, vol. 70, pp. 45–56, Mar. 2018, doi: [10.1016/j.ijggc.2018.01.010](https://doi.org/10.1016/j.ijggc.2018.01.010).
- [30] "Perú precios de la electricidad, septiembre 2024," GlobalPetrolPrices.com. Accessed: May 02, 2025. [Online]. Available: [https://es.globalpetrolprices.com/Peru/electricity\\_prices/](https://es.globalpetrolprices.com/Peru/electricity_prices/)
- [31] U.S. Department of Energy: Energy Efficiency and Renewable Energy, "Determine the Cost of Compressed Air for Your Plant," *Department of Energy*, 2004. Accessed: Feb. 12, 2025. [Online]. Available: <https://www.energy.gov/eere/amo/articles/determine-cost-compressed-air-your-plant>
- [32] Water Innovations, "Operating Cost for WDI Deionized Water System," *waterinnovations.net*. Accessed: Feb 11, 2025. [Online]. [https://waterinnovations.net/wp-content/uploads/WDI-Ion-Exchange-System\\_Operating-Cost.pdf](https://waterinnovations.net/wp-content/uploads/WDI-Ion-Exchange-System_Operating-Cost.pdf)
- [33] "Potencial del Hidrógeno verde en el Perú archivos," H2 Perú. Accessed: Jan 23, 2025. [Online]. Available: <https://h2.pe/tag/potencial-hidrogeno-verde-peru/>
- [34] "Hydrogen prices to remain high for decades to come, analysts warn," Irish Examiner. Accessed: Jan 23, 2025. [Online]. Available: <https://www.irishexaminer.com/business/economy/arid-41546203.html>