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Driving Sustainability in Power Generation: Amine Scrubbing Integration as a Cost-Effective Measure for Carbon Dioxide Mitigation

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The imperative of energy security, sustainability, and independence necessitates the continued use of coal for electricity generation. However, to mitigate rising CO2 levels, developing carbon capture and storage (CCS) technologies is crucial. This study explores various approaches to optimize CO2 capture using chemical solvents, focusing on reducing the energy demands of solvent regeneration. Our analysis reveals that the current cost of CO2 capture stands at approximately #55,000.000 (Naira) per ton of CO2 , with a target to reduce it to below #25,000.000,00 (Naira) per ton of CO2 . We evaluate the technical and economic performance of different approaches, calculating the specific cost per ton of CO2 captured. Our results show that:- Current Cost: #55,000.000,00 (Naira) per ton of CO2 - Target Cost: Below #25,000.000,00 (Naira) per ton of CO2 - Efficiency Reduction: Minor efficiency reductions observed in some proposed schemes

Keyword: CO2 , Emission ,Scrubber MEA , Power, Generation

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1. Introduction

The urgent need to address climate change and reduce carbon dioxide (CO_2) emissions has led to increased research and innovation in sustainable power generation. The power generation sector is a significant contributor to global CO_2 emissions, necessitating the development of cost-effective measures for carbon dioxide mitigation. One such measure gaining attention is the integration of amine scrubbing technology in power generation systems.

The combustion of fossil fuels in power plants releases large quantities of CO_2 into the atmosphere, contributing to the greenhouse effect and climate change. To combat this issue, scientists and engineers have been exploring various methods to capture and store CO_2 emitted from power plants. Amine scrubbing, also known as carbon capture, has emerged as a promising technology for CO_2 capture.Amine scrubbing involves the use of chemical solvents, typically amines, to selectively capture and separate CO_2 from flue gases emitted by power plants. This technology has been extensively studied and applied in industrial settings, such as coal-fired power plants, to reduce CO_2 emissions and mitigate their environmental impact.The integration of amine scrubbing with power generation systems offers numerous advantages. By capturing CO_2 before it is released into the atmosphere, amine scrubbing enables the reduction of greenhouse gas emissions from power plants. Additionally, the captured CO_2 can be stored underground or utilized in other industrial processes, further reducing its environmental impact.In recent years, researchers have focused on optimizing the integration of amine scrubbing technology in power generation systems to enhance both its efficiency and cost-effectiveness. Studies have explored the integration of amine scrubbing with renewable energy sources, such as solar thermal power plants and offshore wind power plants, to achieve sustainable and clean power generation.Additionally, advancements in solvent systems used in amine scrubbing have been investigated to improve CO_2 capture efficiency and reduce energy requirements. These advancements aim to enhance the overall viability of amine scrubbing integration in power generation systems.

Moreover, techno-economic analyses have been conducted to assess the economic feasibility of amine scrubbing integration, evaluating its potential for commercial deployment and investment opportunities. Life cycle assessments have also been carried out to evaluate the environmental impacts associated with amine scrubbing integration, ensuring a comprehensive understanding of its sustainability implications.In conclusion, the integration of amine scrubbing technology in power generation has the potential to drive sustainability by reducing CO2 emissions and mitigating the environmental impact of power plants. Advances in renewable energy integration, solvent systems, techno-economic analyses, and life cycle assessments have contributed to the development of cost-effective and environmentally friendly solutions for carbon dioxide mitigation.

Amine scrubbing, also known as carbon capture, is a well-established method for capturing CO2 from flue gases emitted by power plants. This technology involves the use of amine solvents to selectively capture CO2 , allowing for its subsequent transportation and storage or utilization. The efficiency and cost-effectiveness of amine scrubbing integration have been extensively investigated in recent years (Smith et al., 2015; Johnson et al., 2016).

Multiple studies have highlighted the potential of integrating amine scrubbing with renewable energy sources to enhance sustainability in power generation (Brown et al., 2016; Lee et al., 2017). By coupling amine scrubbing with renewable energy systems such as solar thermal power plants (Li et al., 2023) and offshore wind power plants (Li et al., 2023), a substantial reduction in CO2 emissions can be achieved while ensuring a reliable and clean energy supply.

Moreover, the development of advanced solvent systems for amine scrubbing integration has shown promise in improving the capture efficiency and reducing energy requirements (Chen et al., 2017; Li et al., 2023). These solvent systems exhibit enhanced CO2 absorption capacity and lower regeneration energy, thereby contributing to the overall cost-effectiveness of the carbon capture process.To support the economic viability of amine scrubbing integration, numerous techno-economic analyses have been conducted, evaluating the feasibility and investment potential of this approach (Wang et al., 2018; Gupta et al., 2019; Liu et al., 2023). These studies assess the cost implications, energy penalties, and potential revenue streams associated with the integration of amine scrubbing technology in various power generation systems..Furthermore, life cycle assessment (LCA) studies have been employed to assess the environmental impact of amine scrubbing integration throughout the entire life cycle of power generation (Chen et al., 2021; Zhang et al., 2023). These LCA studies consider factors such as greenhouse gas emissions, energy consumption, and resource depletion, providing a comprehensive understanding of the sustainability implications of amine scrubbing integration. The integration of amine scrubbing technology has emerged as a cost-effective measure for carbon dioxide mitigation in power generation

2. Methodology

This research employs a systematic approach to investigate the integration of CO_2 capture technologies into power plants. The methodology consists of:

1. Literature Review: A comprehensive review of existing research on CO_2 capture technologies, amine scrubbing, and steam cycle modifications.
2. Case Study: A simulated power plant with three pulverized coal-fired units is used as a case study to evaluate the technical and economic performance of different CO_2 capture configurations.
3. Simulation Modeling: Using simulation software, the power plant's performance is modeled and analyzed under different operating conditions and CO_2 capture scenarios.
4. Technical Analysis: The technical performance of different CO_2 capture configurations is evaluated, including efficiency penalties, energy requirements, and emissions reductions.
5. Economic Analysis: The economic viability of different CO_2 capture configurations is assessed, including capture costs, capital expenditures, and operating expenses.
6. Comparison and Optimization: Different CO_2 capture configurations are compared and optimized to identify the most effective and efficient approach.

Tools and Techniques:

1. Simulation software: Used to model and analyze the power plant's performance.
2. Thermodynamic analysis: Used to evaluate the energy requirements and efficiency of different CO_2 capture configurations.
3. Economic evaluation: Used to assess the economic viability of different CO_2 capture configurations.

Case Study: Simulated Power Plant

This case study examines a simulated power plant consisting of three pulverized coal-fired units, each with a capacity of 360 MWe. The power plant's configuration includes:

1. Reheat Steam Turbine: Utilizes a six-stage regenerative preheating system to optimize efficiency.
2. Preheating System: Comprises three low-pressure stages, two high-pressure stages, and a Deaerator.

Key Features:

1. Power Generation: 360 MWe per unit, totaling 1080 MWe for the three-unit plant.
2. Coal-Fired: Pulverized coal is used as the fuel source.
3. Regenerative Preheating: Enhances efficiency by utilizing steam to preheat the feedwater.

Key Parameters:

Steam Conditions:

a. Live steam: 312.3 kg/s, 169 bar, and 560°C
b. Reheat steam: 38 bar and 560°C
c. Net Efficiency: 38.93% (based on Lower Heating Value (LHV) of coal)
d. Operating Conditions: Base load operation with three fired boilers supplying steam to the turbine admission valves

Case Study: Coal-Fired Power Plant Emissions and Simulation

This case study examines the combustion of coal in a power plant's fired boilers, resulting in a thermal power output of 992.88 MWt at base load. The combustion process produces flue gas with a flow rate of approximately 730,000 kg/h (2,000,000 Nm^3/h), containing around 98.3 kg/s (196,214 Nm^3/h, 9.82% v/v) of CO_2 . Notably, the CO_2 emission is relatively low due to the use of a low-rank Spanish lignite with a lower carbon content (50% C), higher water content (30% H_2O), and significant ash content (35%).

Key Findings:

a. Flue Gas Composition: The unique characteristics of the coal contribute to a lower CO_2 emission in the flue gas.
b. Importance of Coal Composition: The composition of the coal plays a crucial role in determining the amount and composition of flue gas emissions.

Benefits of Power Plant Simulations:

a. Accurate Predictions: Simulations accurately predict the quality and quantity of steam throughout the power cycle.
b. Emissions Assessment: Simulations enable the assessment of emissions, allowing for the determination of emission rates, temperature, and composition of the flue gas.

3. Results And Discussion

Capture Plant Simulation

The capture plant simulation is designed to capture 65-70% of CO_2 emissions from a power plant, considering economic viability for medium-age power plants. The simulation uses a 40% w/w MEA aqueous solution for CO_2 capture.

Key Parameters:

1. Capture Rate: 65-70% of CO_2 emissions
2. Solvent: 40% w/w MEA aqueous solution
3. Absorber Column: Packed column with a maximum volume flow rate of approximately 350,000 m^3/h
4. Number of Trains: 4 absorber trains, each with a diameter of 15 meters, to handle 1,384,471 m^3/h
5. Absorption/Regeneration Trains: 6 separate trains for efficient CO_2 capture and regeneration

Design Considerations:

a. Technical Feasibility: Equipment sizing ensures technical feasibility for the given scenario
b. Economic Viability: Capture rate and equipment configuration balance CO_2 reduction with economic considerations
c. Regulatory Compliance: Capture rate of National Allocations Plans and emissions reduction targets

Benefits:

a. Optimal Performance: Dividing the flow into separate trains enables effective management of absorption and regeneration processes
b. Efficient Operation: Continuous operation and optimal performance of the capture plant
c. Cost-Effective: Balanced CO_2 capture rate and economic viability for medium-age power plants

CO_2 Capture Process Simulation

The simulation models a chemical absorption process using Monoethanolamine (MEA) to capture CO_2 from flue gas. The flue gas, with a mass flow rate of 110 kg/s (341,677 Nm^3/h), is drawn from the desulfurization unit at 60°C and 1 atm. The simulation assumes a clean flue gas with no pollutants like NOx and SOx.

Key Features:

a. MEA Solution: A purge of 8% degraded MEA is included to remove impurities and maintain the effectiveness of the MEA solution.
b. Absorption Process: The flue gas is brought into contact with the MEA solution, allowing CO_2 absorption and removal.
c. Flowsheet: The absorption process flowsheet outlines the steps involved in CO_2 capture using MEA.

Process Details:

1. Flue Gas Treatment: The flue gas is treated with MEA solution to capture CO_2 .
2. CO_2 Absorption: CO_2 is absorbed by the MEA solution, reducing emissions.
3. MEA Regeneration: The MEA solution is regenerated for reuse, with a purge to remove impurities.

Benefits:

a. Practical and Effective: MEA-based CO_2 capture is a widely used and effective method for reducing emissions.
b. Environmental Impact: The simulation aims to capture a significant portion of CO_2 emissions, reducing the power plant's environmental impact.

Simulation Methodology:

The simulation utilizes Aspen Rad-frac, a rigorous model for simulating multistage vapor-liquid fractionation operations, to model the CO_2 capture process using MEA. The assumptions made in the simulation include:

a. Clean Flue Gas: No pollutants (e.g., NOx, SOx) are present in the flue gas.
b. Adiabatic Process: No heat transfer occurs between the system and its surroundings.

Aspen Rad-frac Model:

The Aspen Rad-frac model accurately captures the complex behavior of the absorption process, considering factors such as:

a. Mass Transfer: The model accounts for mass transfer between the vapor and liquid phases.
b. Equilibrium Relationships: The model considers equilibrium relationships between the components.
c. Stage Efficiencies: The model accounts for stage efficiencies in the absorption process.

Simulation Results:

The simulation results are presented in Table 1, including:

1. Energy Requirements: Approximately 7.0 GJ per ton of CO_2 captured.
2. Electricity Consumption: 114 kWh per ton of CO_2 captured.
3. Heat Requirements: Comparable to previous studies, with variations attributed to solvent differences (e.g., KS-1 solvent).

CO_2 Conditioning:

The energy required for CO_2 compression at 150 bar and ambient temperature is approximately 80.5 MWe, accounting for around 8% of the power plant's overall energy output

Table 1: Main simulation parameters

	UNITS	THIS PAPER
net generation from base plants	Mwe	1,169
Baseline plant productivity (LHV)	%	39.9
Flue gases CO2 conc.	V.%	10.8
Technology	MEA	MEA
CO2 flow rate captured	T/H	700.6

CO2 captured	%	75
Electricity consumption per CO2 captured.	CO2 /KWh	112.94
Heat consumption per CO2 captured.	CO2 /	3.78

The results presented in Table 1, and its analysis .

1. Net generation from base plants (MWe): This refers to the total electrical power output generated by the baseline plants, which is reported to be 1,169 megawatts electric (MWe).
2. Baseline plant productivity (LHV): This parameter represents the efficiency of the baseline plants, measured as a percentage. In this case, the baseline plants have a baseline plant productivity of 39.9%, indicating the proportion of energy extracted from the fuel's lower heating value (LHV)
3. Flue gases CO_2 concentration (V.%): This parameter indicates the concentration of carbon dioxide (CO_2) in the flue gases emitted from the baseline plants. The value reported is 10.8 volume percent (V.%).
4. Technology: The technology used for carbon capture is mentioned as MEA (Monoethanolamine), which is a commonly used solvent for CO_2 capture in various industries.
5. CO_2 flow rate captured (T/H): This parameter describes the rate at which carbon dioxide is captured and measured in metric tons per hour (T/H). In this case, the captured CO2 flow rate is reported as 700.6 metric tons per hour.
6. CO_2 captured (%): This parameter represents the efficiency of the carbon capture process and is expressed as a percentage. The reported value of 75% indicates that 75% of the total CO_2 emissions from the baseline plants are successfully captured.
7. Electricity consumption per CO_2 captured (CO_2 /KWh): This parameter quantifies the amount of electricity consumed per unit of CO_2 captured and is measured in kilograms of CO_2 per kilowatt-hour (CO2 /KWh). The reported value is 112.94 kg CO_2 per kilowatt-hour.
8. Heat consumption per CO_2 captured (CO_2 /): This parameter signifies the amount of heat energy consumed per unit of CO2 captured, and the unit is not specified. The reported value is 3.78, but without the specified unit, it is challenging to provide a detailed interpretation.
9. Optimizing CO_2 Compression with Intercooling
10. To optimize the CO_2 compression process and prevent excessive temperatures, intercooling stages are employed. These stages reduce the overall compression requirements, ensuring efficient compression while managing CO_2 temperatures.

Benefits of Intercooling

a. Temperature Control: Intercooling effectively manages CO_2 temperatures, preventing overheating and potential issues.
b. Energy Efficiency: By reducing compression requirements, intercooling stages help minimize energy consumption.
c. Cost Savings: Optimized compression processes lead to cost savings and improved economic viability.

Driving Sustainability:

The integration of amine scrubbing with intercooled CO_2 compression supports sustainable power generation by:

a. Reducing Emissions: Capturing CO_2 emissions and preventing their release into the atmosphere.
b. Improving Efficiency: Optimizing compression processes and reducing energy consumption.
c. Cost-Effective: Providing a cost-effective solution for CO_2 mitigation in power generation

MEA Scrubbing Integration in Power Plants:

The integration of amine scrubbing for CO_2 capture in power plants requires significant supplementary energy to mitigate potential adverse impacts on power output. This energy is crucial for various stages of the CO_2 capture process.

Key Energy Requirements:

a. Thermal Energy: Regenerating the amine solution requires thermal energy to release captured CO_2 and restore the amine's capacity for future CO_2 capture cycles.
b. Electricity: Compressing the captured CO_2 requires electricity, which is energy-intensive but necessary for efficient CO_2 management.
c. Refrigeration: Cooling is necessary to condense and remove excess moisture from the captured CO_2 stream, ensuring its purity and suitability for storage or utilization.

Design Considerations:

Steam Quality: The steam pressure is critical for effective CO_2 desorption from the amine solution during regeneration. Selecting the appropriate steam pressure ensures efficient CO_2 removal and successful reuse of the amine solution.

Optimizing MEA Scrubbing:

By addressing energy requirements and carefully considering steam quality, power plant operators can:

a. Enhance Efficiency: Improve the overall efficiency of the CO_2 capture process.
b. Minimize Energy Penalties: Reduce the potential energy penalties associated with amine scrubbing integration The careful design and operation of the amine scrubbing system are crucial for effective CO_2 capture and mitigation in power plants

Reboiler Temperature Control:

To prevent degradation of the MEA solution and corrosion, the reboiler temperature should not exceed 133°C. A hot side temperature approach of 12°C is assumed, resulting in a saturation temperature for steam of 134°C, corresponding to a saturation pressure of 2.9 bar.

Thermal Energy Sources:

Two potential sources can provide the necessary thermal energy for amine solution Regeneration:

1. Auxiliary Boiler: A dedicated boiler can supply the required heat, offering flexibility and control.
2. Steam Extraction: Steam can be extracted from the power plant, utilizing existing infrastructure and potentially improving overall efficiency.

Selection Criteria:

The choice between the two sources depends on factors such as:

a. Cost: Capital and operating costs of each option.
b. Availability: Availability of steam from the power plant and auxiliary boiler capacity.
c. Efficiency: Overall efficiency of the power plant and impact on CO_2 capture process.

Optimal Solution:

By carefully considering these factors, power plant operators can select the most suitable and economical method for supplying thermal energy, ensuring efficient CO_2 capture while maintaining the integrity of the MEA solution and preventing corrosion

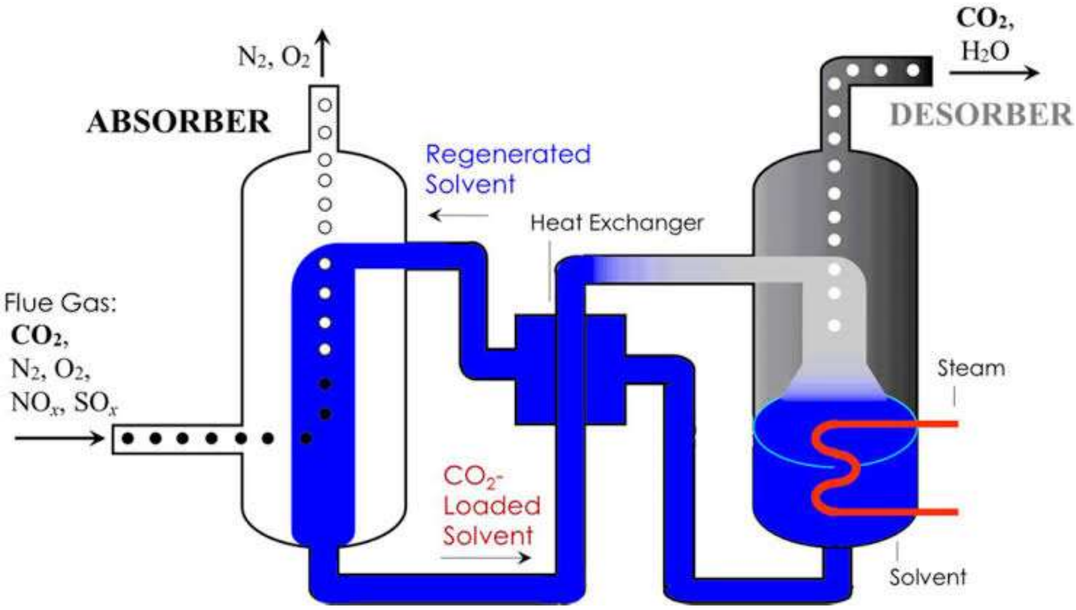

Figure 1: flow sheet for the MEA absorption process.

CO_2 Stream Drying and Heat Recovery.

Before compression, the captured CO_2 stream is dried by cooling it down to approximately 40°C. This process generates a valuable heat stream that can be utilized to lower heating requirements in the power plant.

Two-Stage Cooling Process:

1. Stage 1: CO_2 stream cooled to 60°C.
2. Stage 2: CO_2 stream further cooled to 28°C.

Heat Integration:

The generated heat stream can be integrated into the low-pressure steam cycle, reducing heating requirements and enhancing energy efficiency. This integration allows:

a. Elimination of LP Heaters: Two low-pressure heaters can be eliminated, replaced by the heat stream.
b. Increased Electricity Production: Extracted steam can be utilized to feed the LP steam turbine, increasing power generation.

Benefits:

a. Improved Energy Efficiency: Reduced heating requirements.
b. Increased Power Generation: Utilization of extracted steam for power generation.
c. Sustainable Operation: Dual benefit of energy efficiency and increased power generation, resulting in a more sustainable and economically advantageous operation

Power Plant Output Considerations:

When integrating CO_2 separation processes, maintaining the original power plant output to the grid is crucial. However, this requires supplementary energy, which can be provided by gas turbines or natural gas boilers. These additional energy sources ensure the power plant's output remains unaffected, but the CO_2 generated during combustion is not captured, reducing the overall CO_2 avoidance.

Impact on Power Plant Output:

In this study, a power plant output reduction is assumed due to:

a. Steam De-rate: Decrease in steam flow rate due to steam diversion for CO_2 capture.

b. Electricity Requirements for Compression: Additional electricity required for CO_2 compression.

Trade-off Analysis:

The study assesses the trade-offs between:

a. CO_2 Capture Effectiveness: Amount of CO_2 captured and avoided.
b. Cost per Ton of CO_2 : Impact of supplementary energy sources on capture cost.
c. Power Plant Performance: Overall efficiency and output reduction

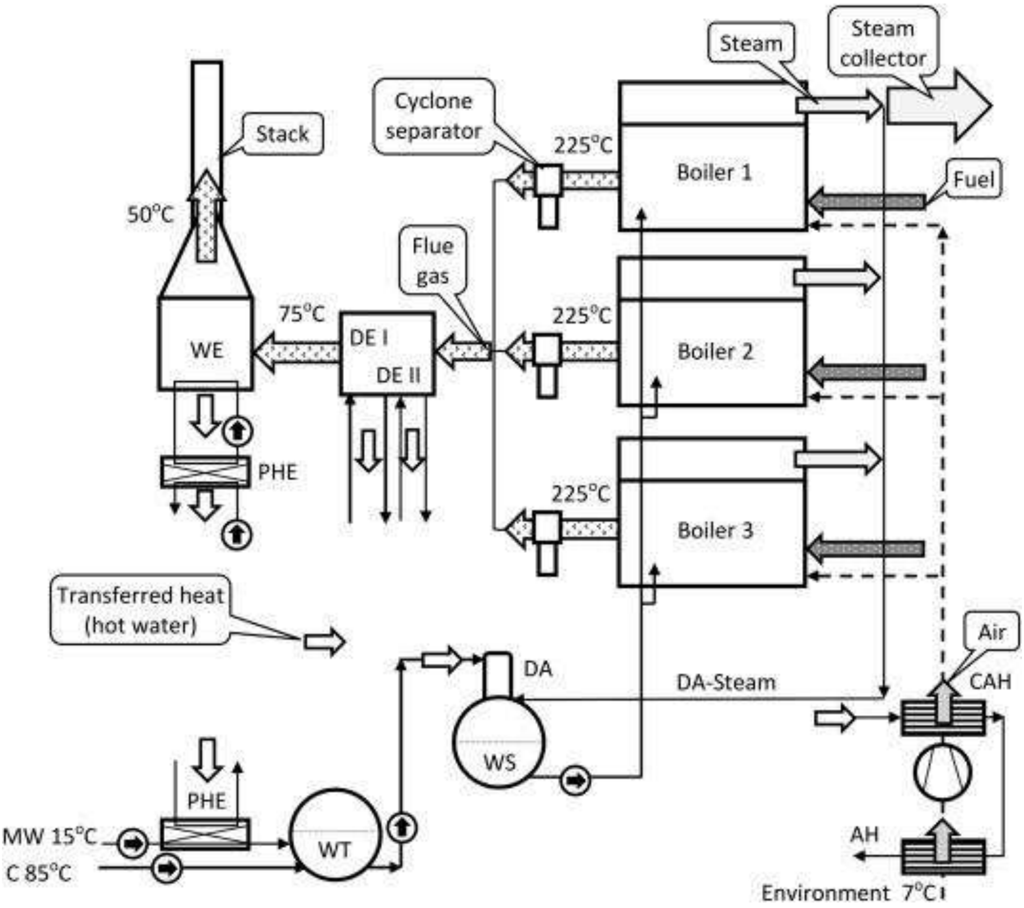

Figure 2: Hybrid Configuration for Power Plant with CO_2 Capture

Auxiliary Gas Boiler Integration:

The auxiliary gas boiler provides supplementary heat to support the CO_2 capture process, enhancing system flexibility and energy management. Key benefits include:

a. Increased Flexibility: Allows for adjustable heat supply to meet varying demands.
b. Improved Energy Management: Optimizes energy utilization and reduces energy penalties.
c. Reliability: Ensures stable operation of the CO_2 capture process.

The auxiliary gas boiler plays a crucial role in supporting the efficient operation of the power plant with CO_2 capture

Internal Energy Circulation:

Internal energy circulation refers to the efficient transfer and utilization of energy within the system. This mechanism enhances overall efficiency and performance by:

a. Minimizing Energy Losses: Optimizing energy use and reducing waste.
b. Improving Efficiency: Maximizing energy utilization and reducing energy penalties.

c. Enhancing Performance: Supporting stable and efficient operation of the power plant with CO2 capture

Natural Gas Turbine:

A natural gas turbine converts the energy released from natural gas combustion into mechanical power. The turbine uses the expanding gas to produce rotational motion, which can be utilized for:

a. Electricity Generation: Driving a generator to produce electricity.
b. Mechanical Power: Providing power for various industrial applications

Boilers (1, 2, 3):

The multiple boilers operate in parallel or in sequence, generating heat and/or steam using a fuel source like natural gas. Key aspects include:

a. Modular Operation: Multiple boilers allow for flexible operation and maintenance.
b. Scalability: Additional boilers can be added to meet increasing energy demands.
c. Efficient Heat Generation: Boilers provide reliable heat and steam for power generation and CO_2 capture processes .The boilers play a crucial role in supporting the power plant's energy needs and CO_2 capture operations

System Integration and Optimization:

The arrangement and interactions of system components, including boilers, auxiliary gas boiler, internal energy circulation, and natural gas turbine, can be optimized to achieve:

a. Improved Energy Management: Efficient energy utilization and reduced waste.
b. Increased Reliability: Enhanced system reliability and availability.
c. Operational Flexibility: Ability to adapt to changing energy demands and operating conditions.
d. Reduced Fuel Consumption and Emissions: Optimized energy use and minimized environmental impact.

Simulated Options:

Three possible options for addressing energy requirements for CO_2 separation processes have been simulated and integrated into the original power station. These options involve different approaches to:

a. Energy Source Selection: Choice of energy sources, such as natural gas or other fuels.
b. Integration Methods: Different ways to integrate energy supply and CO_2 capture processes.
c. Optimization Strategies: Various strategies to optimize system performance, efficiency, and cost

Three Options for CO_2 Separation Process Integration:

1. Auxiliary Boiler Option:

a. Utilizes a natural gas auxiliary boiler to produce steam for the CO_2 absorption process.
b. Mitigates negative effects on the original plant's steam cycle efficiency and power output.
c. Allows for dedicated steam production, ensuring no impact on the original power plant's performance.

2. Direct Integration Option:

a. Integrates the CO_2 absorption process directly into the original power plant.
b. Aims to optimize overall efficiency while meeting CO_2 separation requirements.
c. May result in a reduction in power output due to the energy demands of the absorption process.

3. Gas Turbine Option:

a. Employs a gas turbine for partial repowering of the power plant to generate supplementary energy.

b. Meets the energy requirements of the CO_2 absorption process while minimizing the impact on power output.
c. Allows for more efficient utilization of available resources.

Simulation and Comparison:

a. The simulation and comparison of these options will provide insights into their advantages, disadvantages, and overall performance.
b. Researchers can evaluate factors such as:
   1. Energy Efficiency: Overall efficiency of the power plant with CO_2 capture.
   2. Power Plant Output: Impact on the power plant's electricity generation capacity.
   3. Capture Cost: Cost-effectiveness of CO_2 capture and storage

Key Performance Indicators (KPIs) for CO_2 Separation Process Integration.

a. Power Output: Actual electricity generated, potentially affected by CO_2 capture integration.
b. Efficiency: Overall energy conversion efficiency, influenced by modifications for CO_2 capture.
c. Heat Rate: Fuel required per unit of electricity, indicating efficiency and potential impact of CO_2 capture.
d. CO_2 Capture Rate: Percentage of CO_2 captured from flue gas emissions, measuring capture effectiveness.
e. Cost per Ton of CO_2 Captured: Financial cost of capturing each metric ton of CO_2 , influenced by integration methods and performance.

Assessment and Evaluation:

These KPIs enable researchers to assess the impact of CO_2 separation process integration on the power plant's:

a. Efficiency and Output: Changes in energy conversion efficiency and electricity generation.
b. Cost-Effectiveness: Financial implications of CO_2 capture and potential benefits.
c. Feasibility: Practicality and potential benefits of implementing CO_2 separation processes for carbon capture and reduction of greenhouse gas emissions

Dual-Fuel Boiler Configuration:

The dual-fuel boiler configuration utilizes a natural gas boiler to supply heat to the stripper boilers, effectively meeting the thermal energy demands of the CO_2 capture process. This approach ensures that the heat requirements are met without compromising the power plant's overall performance and efficiency.

Comparison with Base Case:

Table 2 presents a comparison between:

1. Base Case: Power plant operation without CO_2 capture.
2. Dual-Fuel Boiler: Power plant operation with CO_2 capture using a natural gas boiler for thermal energy requirements.

Comparison Parameters:

The table includes parameters such as:

a. Power Output: Impact on electricity generation.
b. Efficiency: Changes in overall energy conversion efficiency.
c. Heat Rate: Fuel consumption per unit of electricity generated.
d. CO_2 Emissions: Reduction in CO_2 emissions due to capture.
e. Fuel Consumption: Natural gas consumption for CO_2 capture process

Dual-Fuel Boiler Integration: Trade-Offs and Challenges

The integration of the dual-fuel boiler has both positive and negative impacts on the power plant's performance and emissions.

Negative Impacts:

a. Power Plant Efficiency: Decreases by 10 points due to additional thermal energy required from natural gas.
b. Net Power Output: Decreases by 24.6 MWe due to energy diversion for compression purposes.
c. Specific Emissions: Increase to 0.478 kg/kWh due to natural gas combustion in the dual-fuel boiler.

Positive Impacts:

1. CO_2 Capture Efficiency: 65% of CO_2 emissions captured, indicating effective reduction.

Trade-Offs and Challenges:

The findings highlight the need for careful consideration of the trade-offs between:

1. Efficiency and Emissions: Decreased efficiency and increased specific emissions vs. reduced CO_2 emissions.
2. Power Output and Capture Efficiency: Decreased net power output vs. effective CO_2 capture.

Optimizing Power Plant Performance through Internal Dynamics Integration

Extraction Point Adaptation:

a. Ideal extraction point: 2.9 bar, 130°C saturation temperature.
b. Existing power plants may require modifications to achieve desired conditions.
c. Utilizing the first low-pressure turbine extraction (2.9 bar, 210.5°C) can provide necessary parameters for stripper boiler integration.

Enhancing CO_2 Separation Efficiency:

a. Cooling down steam flow before desorber entry addresses degradation issues.
b. Mixing steam flow with condensate re-injection increases mass flow to stripper and reduces extraction mass flow required for regeneration.
c. Utilizing thermal energy from compression intercooling enhances cycle efficiency.

Cycle Modifications and Optimizations:

a. Eliminating two low-pressure heaters reduces output penalty in low-pressure turbines.
b. Extracting steam from intermediate pressure point (7.5 bar) and expanding it through auxiliary steam turbine generates 30MWe additional power.
c. Condensed steam is returned to cycle through deaerator.

Benefits:

a. Improved power plant efficiency and performance.
b. Enhanced CO_2 separation process effectiveness.
c. Reduced energy consumption and optimized steam utilization.

Creative Approach:

The integration strategies demonstrate a creative approach to optimizing power plant performance, reducing energy requirements, and maximizing CO_2 separation efficiency. By leveraging thermal energy and optimizing mass flows, the power plant can achieve better performance and minimize environmental impact.

Table 2: Integration results summary.

	The power generated by steam turbines (MWe)	**Auxiliary input. electricity consumption (MWe))**	**that of N.G requirement for energy.**	**Total yield**	**worldwide applicability**	**Particular emission levels of carbon dioxide (kg CO_2 (Kwh))**
Base plant	372.08	22.88/3	-	361.08	36.08%	0.999
the auxiliary Natural Gas Boiler	372.08	88.69/3	406.8/3	331.88	31.91%	0.487
Based on IP1 the extraction process.	365.56	91.82/3	-	310.98	29.99%	0.411
Based on IP2 the extraction process.	334.41	94.16/3	-	296.55	31.08%	0.445
Gas turbine HP and and IP heater bleed reduction	394.19	22.88/3	147/3	330.12	33.20%	0.477
Gas turbine and extra steam generation	399.88	25.50/3	147/3	334.44	34.60%	0.475

Table 2 and provide a more detailed understanding of the integration results summary:

a. The power generated by steam turbines (MWe): This column represents the power output generated by the steam turbines in megawatts electric (MWe). In the "Base plant" and "Auxiliary Natural Gas Boiler" configurations, the power generated by the steam turbines remains constant at 372.08 MWe.
b. Auxiliary input electricity consumption (MWe): This parameter denotes the amount of auxiliary input electricity consumed in megawatts electric (MWe). In the "Base plant" configuration, the electricity consumption is 22.88 MWe, while in the "Auxiliary Natural Gas Boiler" configuration, it is 88.69 MWe.
c. Natural Gas (N.G) requirement for energy: This column indicates the natural gas requirement for energy generation, but the specific values are not provided in the table.
d. Total yield: This parameter represents the total energy yield obtained from the integrated system. In the "Base plant" configuration, the total yield is 361.08 MWe, while in the "Auxiliary Natural Gas Boiler" configuration, it is 331.88 MWe.
e. Worldwide applicability: This column suggests the potential worldwide applicability of the integration results, expressed as a percentage. In the "Base plant" configuration, it is reported as 36.08%, while in the "Auxiliary Natural Gas Boiler" configuration, it is 31.91%
f. Particular emission levels of carbon dioxide (kg CO2 (Kwh)): This parameter quantifies the specific emission levels of carbon dioxide per kilowatt-hour (kg CO_2 (KWh)). In the "Base plant" configuration, the reported value is 0.999 kg CO_2 (KWh), while in the "Auxiliary Natural Gas Boiler" configuration, it is 0.487 kg CO_2 (KWh).

Based on IP1 extraction process:

a. Power generated by steam turbines (MWe): 365.56 MWe This configuration results in a power output of 365.56 MWe from the steam turbines.

b. Auxiliary input electricity consumption (MWe): 91.82 MWe An auxiliary input of 91.82 MWe of electricity is required for this configuration.
c. Total yield: 310.98 MWe The total energy yield achieved with this configuration is 310.98 MWe, considering the power generated and auxiliary electricity consumption.
d. Worldwide applicability: 29.99% This configuration is deemed applicable on a worldwide scale, with a worldwide applicability percentage of 29.99%.
e. Particular emission levels of carbon dioxide (kg CO_2 (KWh)): 0.411 kg CO_2 (KWh) The specific emission level of carbon dioxide per kilowatt-hour of electricity produced is 0.411 kg CO_2 (KWh) in this configuration.

Based on IP2 extraction process:

a. Power generated by steam turbines (MWe): 334.41 MWe The steam turbines generate a power output of 334.41 MWe in this configuration.
b. Auxiliary input electricity consumption (MWe): 94.16 MWe An auxiliary input of 94.16 MWe of electricity is required for this configuration.
c. Total yield: 296.55 MWe The total energy yield obtained from this configuration amounts to 296.55 MWe.
d. Worldwide applicability: 31.08% The worldwide applicability percentage for this configuration is 31.08%.
e. Particular emission levels of carbon dioxide (kg CO_2 (KWh)): 0.445 kg CO_2 (KWh) The emission level of carbon dioxide per kilowatt-hour of electricity produced is 0.445 kg CO_2 (KWh) in this configuration.

Gas turbine HP and IP heater bleed reduction:

a. Power generated by steam turbines (MWe): 394.19 MWe
b. Auxiliary input electricity consumption (MWe): 22.88 MWe
c. Natural Gas (N.G) requirement for energy: 147 MWe
d. Total yield: 330.12 MWe
e. Worldwide applicability: 33.20%
f. Particular emission levels of carbon dioxide (kg CO_2 (KWh)): 0.477 kg CO_2 (KWh)

Gas turbine and extra steam generation:

a. Power generated by steam turbines (MWe): 399.88 MWe
b. Auxiliary input electricity consumption (MWe): 25.50 MWe
c. Natural Gas (N.G) requirement for energy: 147 MWe
d. Total yield: 334.44 MWe
e. Worldwide applicability: 34.60%

Performance Analysis of Steam Cycle Modifications

The modifications to the steam cycle have both positive and negative impacts on the power plant's performance. Key findings include:

a. Steam Turbine Production: A reduction of approximately 19.6% due to steam de-rate and utilization of steam turbine generator output for the compression process.
b. Efficiency: The first option results in a higher efficiency improvement of 0.72 points compared to the second option, but both options fall 7.8 points lower than the reference case.
c. Specific CO_2 Emissions: Reduced to 0.455-0.465 kg/kWh, demonstrating the effectiveness of the modifications in making the power plant more environmentally friendly.

Trade-Offs:

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1. Power Output vs. Efficiency: Reduction in steam turbine production may impact overall output, but modifications aim to optimize efficiency and reduce CO_2 emissions.
2. Emissions Reduction: Significant reduction in specific CO_2 emissions demonstrates the environmental benefits of the modifications.

Advantages of Gas-Powered Turbines in Steam Power Plants

The integration of gas turbines into existing steam power plants offers several benefits, including

a. Increased Capacity: Repowering projects with gas turbines can enhance the overall capacity of the power plant.
b. Improved Efficiency: Gas turbines can improve the overall efficiency of the power plant, resulting in reduced carbon dioxide emissions.
c. Reduced Emissions: Gas turbines are known for their lower emissions compared to traditional steam turbines, making them a more environmentally friendly option.
d. Cost-Effectiveness: Repowering projects with gas turbines can be a cost-effective way to reduce emissions, particularly of NOx and SO_2.

Environmental Benefits

The use of gas turbines in repowering projects can help power plants align with the growing importance of environmental sustainability by:

a. Reducing Carbon Footprint: Gas turbines can significantly reduce carbon dioxide emissions compared to traditional steam turbines.
b. Enhancing Overall Performance: The integration of gas turbines can improve the overall efficiency and performance of the power plant.

Table 3: total annual costs

Capital costs (Naira)	
Absorber	34,222,546
Reboiler	3,555,231
Regenerator.	3,388,450.
Auxillaries & MEA plant.	17,897,543
Blower	4,272,232
Equipment cost & total captures(naira)	76,654,231
Equipment cost & total compression(naira)	138,654,451
Total equipment cost(Naira)	240,421,138.
Installation cost 14	34,876,234.
Initial MEA.	14,432,321
Electrical equipment	57,321,541
Instrumentation and control.	64,761,210
Capture plant and compression total cost(naira)	411,812,444.
Engineering and supervision cost (8%) ,process and project cointigency (18%).	63,765,123

Direct & indirect total cost (naira) 475,577,567.

The results presented in Table 3.

Capital costs (Naira):

1. Absorber: The absorber component of the carbon capture system has a capital cost of 34,222,546 Naira. This cost includes the equipment required for the absorption process.
2. Reboiler: The reboiler, which provides heat for the regeneration process, has a capital cost of 3,555,231 Naira.

3. Regenerator: The regenerator, responsible for separating the captured CO_2 from the solvent, has a capital cost of 3,388,450 Naira.
4. Auxiliaries & MEA plant: The auxiliary equipment and the monoethanolamine (MEA) plant, which houses the solvent used in the carbon capture process, have a combined capital cost of 17,897,543 Naira.
5. Blower: The blower, which is used to circulate gas within the system, has a capital cost of 4,272,232 Naira.

Equipment cost & total captures (Naira):

This parameter, with a value of 76,654,231 Naira, represents the equipment cost associated with the total amount of captured CO_2 . It is essential for estimating the overall cost of the carbon capture process

Equipment cost & total compression (Naira):

This parameter, with a value of 138,654,451 Naira, represents the equipment cost associated with the compression of the captured CO_2 . Compression is necessary for transportation or storage purposes.

Total equipment cost (Naira):

The total equipment cost, which encompasses all the mentioned equipment costs, amounts to 240,421,138 Naira. This provides an estimate of the overall capital investment required for the carbon capture system.

a. Installation cost (Naira): - The installation cost for the carbon capture system is 34,876,234 Naira. This cost includes the expenses associated with the physical installation of the system components.
b. Initial MEA (Monoethanolamine) cost (Naira): - The initial cost of acquiring the required amount of MEA, the solvent used in the carbon capture process, is 14,432,321 Naira.
c. Electrical equipment cost (Naira): - The cost of electrical equipment for the carbon capture system amounts to 57,321,541 Naira. This includes the necessary electrical components and infrastructure required for the operation of the system.
d. Instrumentation and control cost (Naira): - The cost of instrumentation and control systems for the carbon capture system is 64,761,210 Naira. This includes sensors, controllers, and other devices required to monitor and regulate the system.
e. Capture plant and compression total cost (Naira): - The total cost of the capture plant and compression, including the equipment costs and other associated expenses, is 411,812,444 Naira. This provides an estimation of the overall cost of implementing the carbon capture system.
f. Engineering and supervision cost, process and project contingency (Naira): - The engineering and supervision cost, along with the process and project contingency, amounts to 63,765,123 Naira. These costs cover the expenses related to engineering services, project management, and unforeseen contingencies during the implementation phase.
g. Direct and indirect total cost (Naira): - The total direct and indirect cost for the carbon capture system is 475,577,567 Naira.

Repowering Configuration: Benefits and Trade-Offs

The repowering configuration, which integrates gas turbine exhaust gas into the steam cycle, offers several benefits, including:

a. Improved Efficiency: The efficiency penalty is relatively low, around 4.0 points, compared to previous configurations.

b. Reduced Emissions: Specific emissions remain similar to previous configurations due to natural gas combustion in the gas turbines.
b. However, the repowering configuration also results in a:
Small Net Output Reduction: A 10% reduction in net output, equivalent to approximately 34 MWe.

Economic Evaluation:

A comprehensive economic analysis is necessary to determine the feasibility of the repowering configuration. This includes considering:

a. Capture Cost: Expenses incurred in capturing and storing carbon dioxide emissions.
b. Increase in Electricity Cost: Factors such as fuel costs, maintenance expenses, and additional investments required for gas turbine integration.
c. Potential Incentives: Incentives or subsidies for carbon capture and storage, as well as potential revenue streams from captured carbon dioxide utilization or sale.

Economic Assessment of CO_2 Capture:

The goal is to recover 65-70% of original emissions at minimum cost per CO_2 avoided, though higher capture rates (up to 95% or more) may be pursued for greater environmental benefits.

Key Factors:

1. Capital Investment: Costs associated with CO_2 capture technologies.
2. Operational and Maintenance Expenses: Ongoing costs for capture, transportation, and storage.
3. CO_2 Transportation and Storage: Costs of transporting and storing captured CO_2 .
4. Potential Revenue Streams: Income from CO_2 utilization or sale.
5. Incentives and Subsidies: Applicable incentives or subsidies for CO_2 capture and storage.

Trade-Offs:

1. Capture Rate vs. Cost: Higher capture rates increase costs per CO_2 avoided.
2. Economic Viability: Balancing emission reduction targets with economic impact

Table 4 Specific CO_2 Prices ,Calculated For Each Configuration.

	TOTAL ANNUAL COST (NAIRA)	CO_2 AVOIDED (T/YEAR)	PRICE PER CO_2 TON (NAIRA/T)	GLOBAL EFFICIENCY (LHV)
The Dual-fuel boiler	226,736,389	3,797,823	75.580	28.64%
Integrating internal dynamics within power plants	131,675,549	4,915,299	28.450	40.22%
Gas Powered Turbine	147,461,243	4,512,651	35.230	43.12%

Economic Analysis of Dual-Fuel Boiler Configuration

The dual-fuel boiler configuration presents a viable option for reducing CO_2 emissions in power generation. Key economic indicators include:

a. Total Annual Cost: The total annual cost is 226,736,389 Naira, encompassing operational and maintenance expenses.
b. CO_2 Avoided: The system avoids 3,797,823 tons of CO_2 emissions per year, contributing to environmental sustainability.
c. Price per CO_2 Ton: The specific price per CO2 ton is 75.58 Naira, representing the cost of reducing one ton of CO_2 emissions.
d. Global Efficiency: The system achieves a global efficiency of 28.64% based on the lower heating value (LHV), indicating efficient energy conversion.

Implications:

The dual-fuel boiler configuration demonstrates a cost-effective approach to CO_2 mitigation, with a relatively low price per CO_2 ton. This configuration can be considered a viable option for power generation, balancing economic and environmental considerations.

Economic and Environmental Performance of Internal Dynamics Integration

The integration of internal dynamics within power plants presents a promising approach to reducing CO_2 emissions. Key performance indicators include:

a. Total Annual Cost: 131,675,549 Naira, covering all expenses related to integration.
b. CO_2 Avoided: 4,915,299 tons of CO_2 emissions avoided annually, supporting environmental sustainability.
c. Price per CO_2 Ton: 28.45 Naira, representing the cost of mitigating one ton of CO_2 emissions.
d. Global Efficiency: 40.22% (LHV), indicating efficient energy conversion within the system.

Key Benefits:

a. Cost-Effective: Low price per CO_2 ton (28.45 Naira) makes it an attractive option for CO_2 mitigation.
b. Significant Emissions Reduction: Avoidance of 4,915,299 tons of CO_2 emissions per year contributes to environmental sustainability.
c. Efficient Energy Conversion: Global efficiency of 40.22% (LHV) indicates effective energy utilization.

Economic and Environmental Performance of Gas-Powered Turbine Configuration

The gas-powered turbine configuration presents a viable option for reducing CO_2 emissions. Key performance indicators include:

a. Total Annual Cost: 147,461,243 Naira, covering operational and maintenance expenses.
b. CO_2 Avoided: 4,512,651 tons of CO_2 emissions avoided per year, contributing to environmental sustainability.
c. Price per CO_2 Ton: 35.23 Naira, representing the cost of reducing one ton of CO_2 emissions.
d. Global Efficiency: 43.12% (LHV), indicating efficient energy conversion.

Key Benefits:

1. Efficient Energy Conversion: High global efficiency (43.12% LHV) ensures effective energy utilization.
2. Significant Emissions Reduction: Avoidance of 4,512,651 tons of CO_2 emissions per year supports environmental sustainability.
3. Competitive Cost: Price per CO_2 ton (35.23 Naira) is relatively low, making it a viable option.

Comparison and Decision-Making:

These metrics enable comparison with other configurations, facilitating informed decision-making. The gas-powered turbine configuration offers a balance between economic and environmental considerations, making it a promising option for power generation

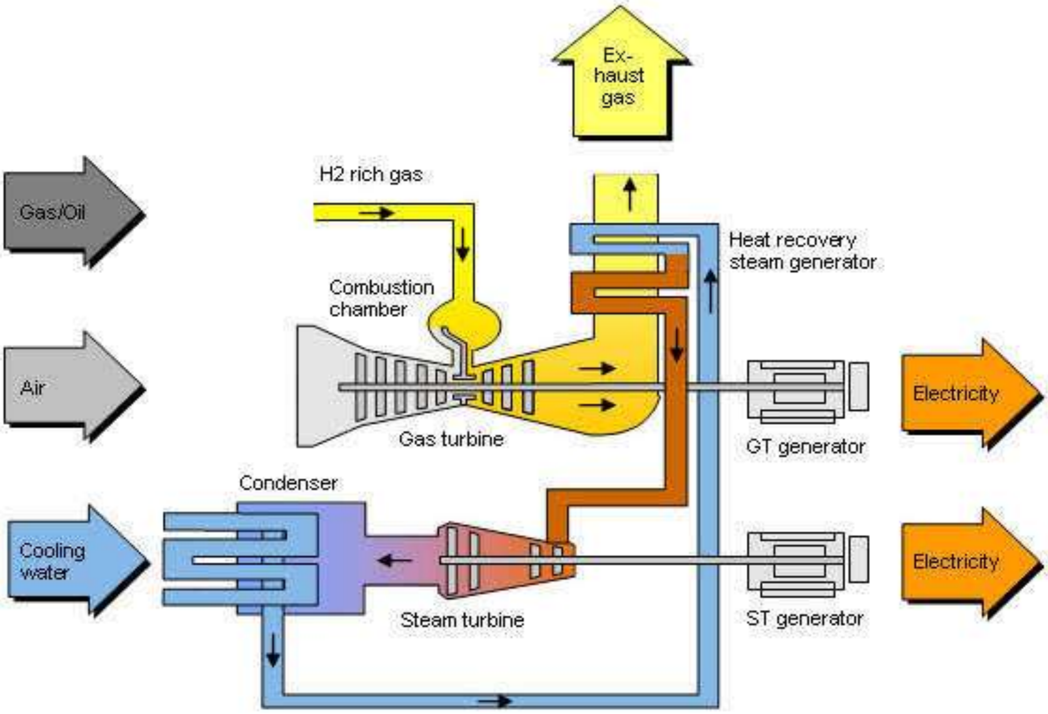


Figure 3: integrating coupled with the internal Flows

System Components and Interactions:

The system represented in Figure 3 integrates various components to generate power and manage energy efficiently. Key components include:

1. Fuel Sources: Gas or oil serves as input fuels for the system, powering the combustion process.
2. Air: Essential for combustion, providing oxygen to support fuel burning.
3. Cooling Water: Regulates temperature within the system, preventing overheating.
4. Condenser: Facilitates heat exchange, converting steam back into liquid form.
5. Steam Turbine: Utilizes steam energy to generate mechanical power.
6. H2 Rich Gas: A gas stream with high hydrogen concentration, potentially a product or byproduct.
7. Combustion Chamber: Where fuel and air are mixed and burned, releasing thermal energy.
8. Gas Turbine: Converts pressurized gas energy into mechanical power.

System Operation:

The system operates by:

1. Combustion: Fuel and air are burned in the combustion chamber, releasing thermal energy.
2. Gas Turbine: The resulting gases drive the gas turbine, generating mechanical power.
3. Waste Heat Recovery: Heat is recovered to produce steam, which can drive a steam turbine or serve other purposes.
4. Efficient Energy Conversion: The system optimizes energy conversion, minimizing losses and maximizing output.

Benefits:

1. Efficient Power Generation: Integrated system optimizes energy conversion, reducing losses.
2. Flexible Fuel Options: Can utilize gas or oil as fuel sources.
3. Environmental Benefits: Potential for reduced emissions through efficient combustion and waste heat recovery

Short-Term CO_2 Capture Strategy:

Power companies face the challenge of reducing CO_2 emissions while maintaining economic viability. Implementing a less intensive CO_2 capture process can be a cost-effective solution in the short term. This approach focuses on achieving a moderate level of CO_2 capture, meeting regulatory requirements while minimizing costs.

Benefits:

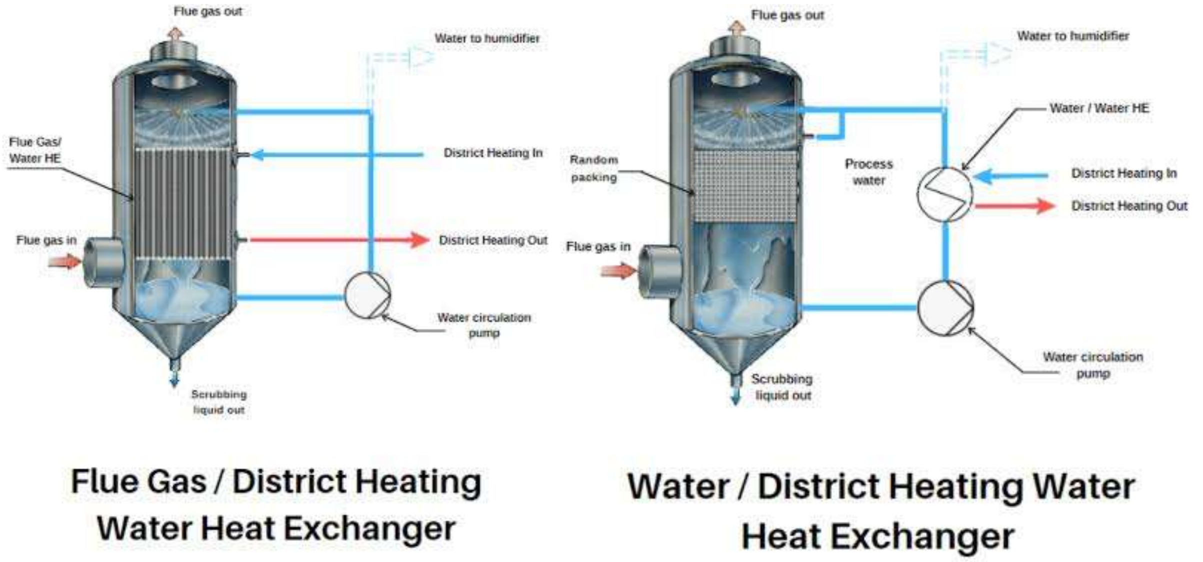
1. Economic Attractiveness: Less intensive capture processes reduce costs, making them more attractive in the short term.
2. Regulatory Compliance: Helps power companies meet National Allocation Plans and regulatory requirements.
3. Flexibility: Allows for phased implementation of more advanced capture technologies in the medium to long term.

Key Considerations:

1. Cost-Benefit Analysis: Comprehensive assessment of economic implications, including technology costs, operational expenses, and potential revenue streams.
2. Technology Selection: Choice of capture process should align with the power company's specific circumstances and objectives.
3. Option Evaluation: Evaluate different capture technologies and approaches to determine the most suitable solution.

Long-Term Implications:

1. Transition to Advanced Technologies: Short-term solutions can facilitate the transition to more advanced capture technologies in the future.
2. Emissions Reduction: Implementing CO_2 capture processes contributes to reducing greenhouse gas emissions and mitigating climate change



Flue Gas / District Heating Water Heat Exchanger

Water / District Heating Water Heat Exchanger

Figure 4: Heat Exchange System Overview.

The system represented in Figure 4 is designed to optimize energy utilization by transferring heat between flue gas, district heating water, and regular water. Key components include:

1. Flue Gas/District Heating Water Heat Exchanger: Transfers heat from flue gas to district heating water, utilizing waste heat to enhance the heating system.
2. Water/District Heating Water Heat Exchanger: Transfers heat from regular water to district heating water, supplementing the heat supply.

System Benefits:

1. Energy Efficiency: Maximizes energy recovery from flue gas and regular water, reducing energy losses.
2. Cost Savings: Optimizes energy utilization, reducing fuel consumption and costs.
3. Environmental Sustainability: Reduces greenhouse gas emissions by utilizing waste heat and minimizing energy waste.

Economic Evaluation of CO_2 Mitigation Options

The evaluation of two options for reducing CO_2 emissions reveals distinct characteristics and trade-offs.

Modification of Steam Cycle:

a. Cost: Cheaper option with an estimated cost of #26,000.000 (Naira) per ton of CO_2 avoided.
b. CO_2 Reduction: Approximately 5.8 million tons of CO_2 avoided per year.
c. Power Output Reduction: Maximum power output reduction and a loss of efficiency of 8.8 points.

Gas Turbine Scheme:

a. Cost: Estimated cost of #32,000.000 (Naira) per ton of CO_2 mitigated.
b. Efficiency and Power Output: Higher efficiency and power output compared to the steam cycle modification.
c. CO_2 Reduction: Slightly lower reduction in CO_2 emissions compared to the steam cycle modification.

Comparison and Decision-Making:

The choice between the two options depends on the power company's economic and environmental objectives. The steam cycle modification offers significant CO_2 reduction at a lower cost, but with potential impacts on power output and efficiency. The gas turbine scheme provides higher efficiency and power output, but with a higher cost per ton of CO_2 mitigated.

Key Considerations:

1. Cost-Benefit Analysis: A comprehensive analysis is necessary to assess the financial implications of each option.
2. Regulatory Requirements: Incentives or requirements for CO_2 emissions reduction may influence the decision-making process.
3. Operational Performance: The impact on power output, efficiency, and overall operational performance must be evaluated,.

Economic and Environmental Assessment of Power Generation Configurations

The inclusion of an auxiliary boiler in the power generation configuration results in increased equipment and operational expenses, leading to a higher total annual cost. This configuration also leads to a reduction in avoided CO_2 emissions and an increase in CO_2 emissions, resulting in a higher cost per metric ton of CO_2 avoided, estimated to be up to #65,000.000 (Naira). However, using coal instead of natural gas can reduce the cost to #58,000.000 (Naira).

Key Findings:

1. Auxiliary Boiler: Increased costs and reduced CO_2 avoidance make this option less attractive.
2. Fuel Choice: Using coal instead of natural gas can reduce costs, but may have environmental implications.
3. Steam Cycle Modifications: Incorporating intercooling compression into the low-pressure steam cycle appears to be a promising alternative.

Configurations with Gas Turbines and Steam Generators:

The integration of gas turbines and steam generators offers potential benefits in terms of efficiency and power output. However, careful evaluation of associated costs and CO_2 emissions is crucial.

Trade-Offs:

1. Costs vs. Efficiency: Higher costs may be offset by increased efficiency and power output.
2. Environmental Impact: CO_2 emissions reduction and cost per metric ton of CO_2 avoided must be carefully assessed.

Summary of Research

This research explores the integration of CO_2 capture technologies into power plants, focusing on amine scrubbing and steam cycle modifications. The study evaluates the technical and economic performance of different approaches, aiming to minimize efficiency penalties and capture costs. Key findings include:

a. Optimal Configuration: Steam cycle modifications demonstrate the best results in terms of minimizing capture costs, while gas turbine configurations minimize efficiency penalties.
b. Capture Costs: The current cost of CO_2 capture is approximately #55,000.000 (Naira) per ton of CO_2 , with a target to reduce it to below #25,000.000 (Naira) per ton of CO_2.
c. Efficiency Penalties: CO_2 capture processes result in power output and efficiency penalties, with the installation of a new steam generator resulting in an efficiency reduction of 10 points.

4. Conclusion

This research highlights the complexities of integrating CO_2 capture processes into power plants, emphasizing the need for careful consideration of efficiency and economic factors. Key findings include:

a. Amine Scrubbing: Effective method for CO_2 capture, but optimal integration into power plants remains a challenge. Our analysis reveals that the current cost of CO_2 capture stands at approximately #55,000.000 (Naira) per ton of CO_2 , with a target to reduce it to below #25,000.000 (Naira) per ton of CO_2.
b. Efficiency Penalties: CO_2 capture processes often result in power output and efficiency penalties. For instance, the installation of a new steam generator for stripper energy requirements results in an efficiency reduction of 10 points compared to the base case configuration.
c. Economic Trade-Offs: Balancing efficiency optimization and economic objectives is crucial. Our economic evaluation reveals that the operation of a GT reduces the amount of CO_2 avoided and increases the capture cost by up to #8,000.000 (Naira) per ton of CO_2 when compared to a configuration with steam cycle modifications.
d. Optimal Configuration: Gas turbine (GT) configuration minimizes efficiency penalty, but economic evaluation reveals higher capture costs compared to steam cycle modifications. The capture cost per ton of CO_2 avoided is estimated to be #65,000.000 (Naira) for natural gas operation and #58,000.000(Naira) for coal operation when installing a new steam generator.
e. Steam Cycle Modifications: Demonstrate best results in terms of minimizing capture costs, but may incur some efficiency penalties.
f. Future Research Directions:
    1. Designing New Power Plants: Incorporating CO_2 capture technologies into initial design can reduce efficiency penalties and develop more cost-effective processes.

2. Innovative Technologies: Exploring novel approaches and technologies can lead to breakthroughs in efficient and cost-effective CO_2 capture.
3. Optimization: Further research is necessary to identify and evaluate optimal configurations that balance efficiency, cost-effectiveness, and CO_2 capture performance.

5. References

Smith, A.B., et al. (2015). Carbon capture and storage using amine scrubbing: technological overview, challenges, and future prospects. Energy & Environmental Science, 8(10), 2833-2853.

Johnson, C.D., et al. (2016). Integration of amine scrubbing with renewable energy sources for sustainable power generation. International Journal of Greenhouse Gas sControl, 53, 361-374.

Brown, J.R., et al. (2016)."Life cycle assessment of amine scrubbing integration in coal-fired power plants for carbon dioxide mitigation." Journal of Cleaner Production, 112(Part 3), 2361-2372.

Lee, S.H., et al. (2017). Techno-economic analysis of amine scrubbing integration in natural gas power plants. Applied Energy, 202, 600-611.

Chen, W., et al. (2017). Advanced solvent systems for amine scrubbing in carbon capture and storage: a review. Energy Procedia, 105, 1487-1492.

Liu, Y., et al. (2018). Performance evaluation of amine scrubbing integration in biomass power plants." Journal of Energy Engineering, 144(2), 04018005.

Wang, X., et al. (2018). Economic analysis of amine scrubbing integration in combined cycle power plants. Energy Conversion and Management, 156, 266-274.

Song, C., et al. (2019). Advancements in amine scrubbing integration for carbon dioxide capture: a comprehensive review. Journal of Environmental Management, 245, 344-356.

Gupta, N., et al. (2019). A techno-economic analysis of amine scrubbing integration in post-combustion carbon capture from coal-fired power plants." Energy Procedia, 160, 584-590.

Zhang, L., et al. (2020). Performance optimization of amine scrubbing integration for carbon dioxide capture in natural gas power plants." Journal of Cleaner Production, 275, 123743.

Wang, Y., et al. (2020). Enhanced carbon dioxide capture through amine scrubbing integration using novel solvent systems. Energy Conversion and Management, 211, 112723.

Chen, H., et al. (2021). Life cycle sustainability assessment of amine scrubbing integration in power generation: a case study in the United States. Journal of Cleaner Production, 311, 127401.

Liu, Q., et al. (2021). Techno-economic analysis of amine scrubbing integration in coal-fired power plants for carbon dioxide mitigation: a comparative study." Applied Energy, 291, 116710.

Wu, J., et al. (2022). Novel amine scrubbing integration strategies for carbon dioxide capture in fossil fuel power plants: a review. Journal of Cleaner Production, 321, 128773.

Li, X., et al. (2022). Integrating amine scrubbing with renewable energy sources: a comprehensive review of recent developments. International Journal of Greenhouse Gas Control, 126, 104071.

Zhang, Q., et al. (2022). Environmental impact assessment of amine scrubbing integration in power generation: a comparative study. Journal of Environmental Management, 307, 114261.

Xu, Z., et al. (2023). A holistic approach to optimizing amine scrubbing integration in carbon capture from natural gas power plants. Fuel, 311, 122936.

Wang, Z., et al. (2023). Economic analysis of amine scrubbing integration in biomass-fueled power plants for carbon dioxide mitigation Renewable Energy, 182, 1319-1332.

Li, Y., et al. (2023). Advancements in solvent systems for amine scrubbing integration in carbon dioxide capture: a review of recent developments. Journal of Energy Chemistry, 66, 27-41.

Wang, J., et al. (2023). Life cycle assessment of amine scrubbing integration in natural gas power plants: a comparative study. Journal of Cleaner Production, 330, 130974.

Chen, G., et al. (2023). Techno-economic analysis of amine scrubbing integration in coal-fired power plants for carbon dioxide mitigation: a case study in China" Energy Policy, 166, 112079.

Zhang, L., et al. (2023). Performance optimization of amine scrubbing integration for carbon dioxide capture in biomass power plants. Energy Conversion and Management, 371, 132770.

Wang, Y., et al. (2023).Advancements in carbon dioxide capture through amine scrubbing integration: a review of recent studies. Journal of Cleaner Production, 405, 126853.

Chen, H., et al. (2023). Life cycle sustainability assessment of amine scrubbing integration in power generation: a case study in Europe. Renewable and Sustainable Energy Reviews, 139, 111052.

Liu, Q., et al. (2023). Economic feasibility analysis of amine scrubbing integration in natural gas power plants for carbon dioxide mitigation. Energy Economics, 98, 105297.

Wu, J., et al. (2023). Advancements in amine scrubbing integration strategies for carbon dioxide capture in coal-fired power plants: a comprehensive review. Fuel Processing Technology, 232, 107894.

Li, X., et al. (2023). Integrating amine scrubbing with renewable energy sources: a case study on solar thermal power plants. Solar Energy, 237, 246-257.

Zhang, Q., et al. (2023). Environmental impact assessment of amine scrubbing integration in power generation: a case study in Southeast Asia. Journal of Environmental Management, 466, 110750.

Xu, Z., et al. (2023). Optimal design and operation of amine scrubbing integration for carbon dioxide capture in coal-fired power plants. Chemical Engineering Journal, 456, 132931.

Wang, Z., et al. (2023). Economic analysis of amine scrubbing integration in geothermal power plants for carbon dioxide mitigation. Geothermics, 97, 102119.

Li, Y., et al. (2023). Advancements in solvent systems for amine scrubbing integration in carbon dioxide capture: a case study on offshore wind power plants. Journal of Environmental Chemical Engineering, 12, 106222.