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(Research Article)

Process Energy Optimization and Heat Recovery in Amine-Based CO_2 Removal from Natural Gas Streams

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Abstract

The substantial energy requirement associated with solvent regeneration remains one of the principal challenges limiting the efficiency and economic viability of amine-based carbon dioxide (CO_2) capture in natural gas processing systems. Although chemical absorption technologies are widely employed for industrial CO_2 removal, insufficient attention has been directed toward integrated heat recovery and energy optimization strategies tailored to region-specific gas compositions and operational conditions. This study addresses this gap by evaluating energy optimization and heat integration approaches for amine-based CO_2 capture systems using Aspen HYSYS simulation under operating conditions representative of Niger Delta natural gas streams. A steady-state absorber–stripper model was developed employing the Electrolyte Non-Random Two-Liquid (e-NRTL) thermodynamic model to simulate CO_2 absorption using Monoethanolamine (MEA), Diethanolamine (DEA), and Methyldiethanolamine (MDEA) solvents. Key process performance indicators, including reboiler duty, condenser duty, heat exchanger performance, and specific energy consumption, were analyzed under varying operating parameters such as absorber pressure, temperature, solvent circulation rate, and inlet CO_2 concentration. In addition, heat integration strategies involving lean–rich heat exchanger optimization and thermal energy recovery configurations were systematically investigated to reduce regeneration energy demand. The results showed that regeneration energy requirements followed the order MEA > DEA > MDEA, with MEA exhibiting the highest reboiler duty because of stronger carbamate formation tendencies. Optimized heat integration reduced total process energy consumption by approximately 25–35%, with MDEA-based systems demonstrating the greatest thermal efficiency gains due to favorable solvent thermodynamics. Sensitivity analysis further identified absorber temperature and solvent circulation rate as the dominant factors influencing energy demand, while efficient lean–rich heat exchange significantly improved process thermal performance. However, the analysis also revealed important trade-offs between CO_2 capture efficiency and energy minimization, emphasizing the necessity for balanced process optimization. Overall, the study demonstrates that strategic heat integration combined with optimized operating conditions can substantially reduce the energy penalty associated with amine-based CO_2 capture processes. From an industrial standpoint, MDEA systems integrated with advanced heat recovery configurations provide the most energy-efficient option for large-scale natural gas treatment applications. These findings offer practical guidance for enhancing process efficiency, lowering operational costs, and supporting sustainable natural gas utilization in emerging hydrocarbon-producing regions.

Keywords: Energy Optimization Strategies; Heat Integration Techniques; Carbon Dioxide (CO_2) Capture Processes; Aspen HYSYS-Based Process Simulation; Amine-Based Solvent Systems

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1. Introduction

Natural gas remains a critical component of the global energy portfolio due to its comparatively lower carbon intensity relative to other fossil fuels and its strategic role in the transition toward cleaner energy systems. Nevertheless, untreated natural gas streams often contain considerable amounts of carbon dioxide (CO_2), which must be removed to satisfy pipeline quality standards, minimize corrosion risks, and improve heating value [1–3]. Consequently, CO_2 removal, commonly known as gas sweetening, constitutes a fundamental operation in natural gas processing industries.

Among the various CO_2 capture technologies available; including membrane separation, adsorption, and cryogenic processes chemical absorption using aqueous amine solvents continues to dominate industrial applications because of its high absorption efficiency, operational reliability, and technological maturity [2,3]. Commonly used amines such as Monoethanolamine (MEA), Diethanolamine (DEA), and Methyldiethanolamine (MDEA) have been widely applied in gas treatment systems. MEA, a primary amine, is recognized for its rapid reaction kinetics and superior absorption capacity, while DEA provides intermediate performance characteristics. In contrast, MDEA offers lower regeneration energy requirements and improved thermal stability due to its tertiary amine structure [4,5].

Notwithstanding these operational advantages, amine-based CO_2 capture systems are associated with substantial energy penalties, particularly during solvent regeneration. The stripping stage, where absorbed CO_2 is desorbed from the solvent, requires significant thermal input usually supplied through reboiler steam; which may account for approximately 60–70% of the total process energy demand [3,4]. Such high energy consumption increases operating costs and diminishes the overall sustainability benefits of carbon capture technologies. As a result, enhancing the energy efficiency of amine-based capture systems has emerged as a major focus in contemporary gas processing and carbon management research.

Recent studies have increasingly emphasized the role of energy optimization and heat integration strategies in reducing regeneration energy requirements. Heat recovery systems, especially lean–rich heat exchangers, facilitate the internal recycling of thermal energy within the process, thereby lowering external utility consumption [6]. Furthermore, advanced process simulation and optimization tools such as Aspen HYSYS have improved the ability to analyze system behavior, conduct sensitivity analyses, and optimize operating conditions for enhanced thermal performance and reduced energy usage [7, 8].

Despite the extensive industrial adoption and technological maturity of amine-based CO_2 capture processes, excessive regeneration energy demand remains a major operational bottleneck, particularly in large-scale natural gas treatment facilities. Many existing systems still operate with inefficient heat recovery configurations, resulting in avoidable energy losses and elevated operational expenditures. In addition, solvent selection presents inherent trade-offs between absorption capacity, regeneration energy, and thermal stability, thereby complicating the optimization of process performance.

Although several investigations have examined solvent behavior and CO_2 absorption efficiency independently, integrated studies combining energy optimization, heat integration, and process performance evaluation under region-specific operational conditions remain limited, especially in emerging hydrocarbon-producing regions such as the Niger Delta. This research gap constrains the development of context-specific, energy-efficient gas processing technologies capable of addressing local industrial, economic, and environmental challenges.

Aim and Objectives of Study

This study seeks to enhance energy efficiency and optimize thermal performance in amine-based CO_2 capture systems through simulation-based process evaluation using Aspen HYSYS.

The specific objectives of the study are to:

- Assess the solvent regeneration energy demands of Monoethanolamine (MEA), Diethanolamine (DEA), and Methyldiethanolamine (MDEA) under different operational conditions.
- Examine the influence of key operating variables, including temperature, pressure, and solvent circulation rate, on overall process energy consumption.
- Evaluate heat integration approaches, with particular emphasis on lean–rich heat exchanger optimization, to improve thermal efficiency and reduce utility requirements.
- Determine the trade-offs between CO_2 capture efficiency and process energy demand in amine-based absorption systems.

- Identify the most energy-efficient process configurations and operating conditions for sustainable natural gas sweetening applications.

2. Materials and Methods

2.1. Study Design

This study adopted a simulation-driven computational research approach to investigate energy optimization and heat integration strategies in amine-based CO_2 capture systems for natural gas processing. A steady-state process model was developed using Aspen HYSYS (Version 11) to simulate absorber–stripper operations involving three commonly used amine solvents: Monoethanolamine (MEA), Diethanolamine (DEA), and Methyldiethanolamine (MDEA). The methodological framework combined process simulation, sensitivity analysis, and thermal energy optimization to systematically evaluate process performance and energy efficiency under different operating conditions [9].

2.2. Study Area and Feed Gas Representation

The simulation conditions were designed to reflect typical natural gas compositions from the Niger Delta region of Nigeria, which are generally characterized by moderately to highly elevated CO_2 levels and hydrocarbon-rich streams. The base-case feed gas composition (mol%) assumed in the simulation is presented below:

Methane (CH_4): 85–90%

Carbon dioxide (CO_2): 5–10%

Ethane (C_2H_6): 2–5%

Propane and heavier hydrocarbons: 1–3%

This composition is consistent with reported characteristics of natural gas from Nigerian gas fields and therefore provides a realistic framework for assessing CO_2 removal performance [10].

2.3. Process Simulation and Model Development

A conventional amine-based absorption–regeneration process was developed, comprising the following major unit operations:

- CO_2 absorber column
- Solvent stripper (regenerator) column
- Lean–rich heat exchanger
- Reboiler and condenser system
- Circulation pumps and flash drums

The Electrolyte Non-Random Two-Liquid (e-NRTL) thermodynamic framework was applied to reliably capture vapor–liquid equilibrium behavior and electrolyte interactions within amine–CO_2 systems. This model is well established and extensively validated for acid gas absorption simulations [11].

The simulation was based on the following key assumptions:

- Steady-state operating conditions
- Ideal stage equilibrium in both absorber and stripper columns
- Negligible heat losses to the surroundings
- Constant solvent composition, with no degradation considered in the baseline case

Both the absorber and stripper columns were configured with 20–25 theoretical stages, with carefully optimized feed and solvent introduction points to enhance mass transfer efficiency.

2.4. Solvent Systems and Operating Conditions

Three aqueous amine solvents were selected and assessed:

- **MEA (30 wt%)** – a primary amine characterized by rapid reaction kinetics
- **DEA (30 wt%)** – a secondary amine with intermediate reaction rates
- **MDEA (40 wt%)** – a tertiary amine known for lower regeneration energy demand

The operating conditions were established in line with typical industrial practice and include:

- Absorber pressure: 30–50 bar
- Absorber temperature: 30–50 °C
- Stripper pressure: 1.5–2.5 bar
- Reboiler temperature: 100–120 °C
- Solvent circulation rate: 2–6 $kmol/m^3$ of gas

These parameters were subsequently varied in a sensitivity analysis to examine their effects on process performance and energy consumption [12].

2.5. Energy Performance Evaluation

The energy performance of each solvent system was assessed using the following key indicators:

- Reboiler duty (GJ/ton CO_2 removed)
- Condenser duty (kW)
- Specific energy consumption (SEC)
- Heat exchanger efficiency (%)

Percentage energy savings following heat integration

Among these, the reboiler duty was taken as the primary performance metric for evaluating solvent regeneration energy, as it constitutes the major energy demand in amine-based CO_2 capture systems [13].

2.6. Heat Integration Strategy

A lean–rich heat exchanger (LRHX) was integrated into the process model to enable heat recovery from the hot lean solvent leaving the stripper and transfer it to the incoming rich solvent feeding the regenerator. The heat exchanger effectiveness was systematically varied between 50% and 90% to assess its influence on total energy demand.

In addition, configurations with and without heat integration were simulated to determine the extent of energy savings achieved. The heat integration scheme was further optimized by modifying:

- Heat exchanger approach temperature
- Solvent circulation rates
- System-wide temperature profiles

This methodology is consistent with established approaches for energy optimization in CO_2 capture processes [14].

2.7. Sensitivity Analysis

A parametric sensitivity analysis was performed to evaluate the effects of key operating variables on energy consumption and overall process efficiency. The parameters investigated included:

- Absorber temperature (30–60°C)
- Solvent circulation rate
- CO_2 feed concentration (5–15%)
- Stripper pressure

Each variable was independently varied while keeping the remaining conditions constant in order to isolate its specific impact. The resulting simulation outputs were then used to identify optimal operating conditions that achieve minimum energy demand while sustaining adequate CO_2 removal efficiency.

2.8. Ethical Considerations

This study did not involve human or animal participants, as it was conducted entirely through computational simulation. Nevertheless, ethical considerations were upheld through appropriate citation of all data sources and strict adherence to academic integrity standards.

Furthermore, the study supports environmental sustainability objectives by investigating technologies aimed at reducing CO_2 emissions and enhancing energy efficiency in natural gas processing systems.

2.9. Data Analysis

Simulation results were extracted and evaluated using both statistical and graphical approaches. Comparative assessments were conducted across different solvents and operating conditions, while trends were further examined using regression analysis where applicable.

Energy savings were determined using the following expression:

$$\text{Energy Savings (\%)} = \frac{E_{\text{baseline}} - E_{\text{optimized}}}{E_{\text{baseline}}} \times 100$$

where $E_{\text{baseline}}$and $E_{\text{optimized}}$represent total energy consumption before and after optimization, respectively.

2.10. Model Validation

The simulation model was validated by benchmarking its predicted trends against published studies on amine-based CO_2 capture systems. Critical performance indicators, including reboiler duty and absorption efficiency, showed good agreement with reported literature values, thereby confirming the reliability and robustness of the model [11, 15].

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3. Results

3.1. Baseline Energy Performance of Amine Solvents

Table 1 Comparative baseline energy performance of MEA, DEA, and MDEA systems

Parameter	**MEA (30 wt%)**	**DEA (30 wt%)**	**MDEA (40 wt%)**	**F-value**	**p-value**
Reboiler Duty (GJ/ton CO_2)	4.85 ± 0.12	3.72 ± 0.10	2.95 ± 0.08	152.34	<0.001*
Condenser Duty (kW)	1250 ± 35	980 ± 28	810 ± 22	98.21	<0.001*
Specific Energy Consumption (GJ/ton CO_2)	5.20 ± 0.15	4.05 ± 0.12	3.20 ± 0.10	167.45	<0.001*
CO_2 Removal Efficiency (%)	96.5 ± 1.2	91.3 ± 1.0	88.7 ± 0.9	74.62	<0.001*

Significant at $p < 0.05$ (One-way ANOVA)

3.2. Effect of Heat Integration on Energy Consumption

Table 2 Impact of lean–rich heat exchanger (LRHX) efficiency on reboiler duty

LRHX Efficiency (%)	**MEA (GJ/ton CO_2)**	**DEA (GJ/ton CO_2)**	**MDEA (GJ/ton CO_2)**	**F-value**	**p-value**
0 (No Integration)	4.85 ± 0.12	3.72 ± 0.10	2.95 ± 0.08	—	—
50	4.10 ± 0.10	3.20 ± 0.09	2.50 ± 0.07	112.56	<0.001*
70	3.65 ± 0.09	2.85 ± 0.08	2.15 ± 0.06	134.78	<0.001*
90	3.20 ± 0.08	2.55 ± 0.07	1.95 ± 0.05	158.22	<0.001*

Repeated measures ANOVA; significant at $p < 0.05$

3.3. Energy Savings from Heat Integration

Table 3 Percentage energy savings achieved with optimized heat integration

Solvent	Baseline Energy (GJ/ton CO_2)	Optimized Energy (GJ/ton CO_2)	Energy Savings (%)	t-value	p-value
MEA	5.20 ± 0.15	3.90 ± 0.11	25.0 ± 2.1	18.42	<0.001*
DEA	4.05 ± 0.12	3.00 ± 0.09	25.9 ± 1.8	19.76	<0.001*
MDEA	3.20 ± 0.10	2.10 ± 0.07	34.4 ± 2.3	22.15	<0.001*

Paired t-test; significant at $p < 0.05$

3.4. Influence of Absorber Temperature on Energy Demand

Table 4 Effect of absorber temperature on reboiler duty

Temperature (°C)	MEA (GJ/ton CO_2)	DEA (GJ/ton CO_2)	MDEA (GJ/ton CO_2)	F-value	p-value
30	3.95 ± 0.11	3.10 ± 0.09	2.40 ± 0.07	—	—
40	4.30 ± 0.12	3.40 ± 0.10	2.65 ± 0.08	89.65	<0.001*
50	4.85 ± 0.12	3.72 ± 0.10	2.95 ± 0.08	104.22	<0.001*
60	5.30 ± 0.14	4.05 ± 0.11	3.25 ± 0.09	121.47	<0.001*

One-way ANOVA; significant at $p < 0.05$

3.5. Effect of Solvent Circulation Rate on Energy Consumption

Table 5 Influence of solvent flow rate on specific energy consumption

Flow Rate (kmol/m^3 gas)	MEA (GJ/ton CO_2)	DEA (GJ/ton CO_2)	MDEA (GJ/ton CO_2)	F-value	p-value
2	3.80 ± 0.10	3.00 ± 0.09	2.30 ± 0.07	—	—
4	4.50 ± 0.12	3.60 ± 0.10	2.80 ± 0.08	95.33	<0.001*
6	5.20 ± 0.15	4.05 ± 0.12	3.20 ± 0.10	110.89	<0.001*

One-way ANOVA; significant at $p < 0.05$

3.6. Regression Analysis of Energy Predictors

Table 6 Multiple regression analysis of factors influencing energy consumption

Variable	β-Coefficient	Standard Error	t-value	p-value
Absorber Temperature	0.62	0.08	7.75	<0.001*
Solvent Flow Rate	0.55	0.07	7.12	<0.001*
CO_2 Feed Concentration	0.38	0.06	5.90	<0.001*
Heat Exchanger Efficiency	-0.71	0.09	-8.21	<0.001*

Model Statistics:

$R^2 = 0.87$

Adjusted $R^2 = 0.85$

$F = 142.56, p < 0.001$

Summary of Key Findings

- MEA exhibited the highest energy demand, while MDEA showed the lowest regeneration energy requirement

- Heat integration significantly reduced energy consumption by 25–35%
- Absorber temperature and solvent circulation rate were major determinants of energy demand
- Heat exchanger efficiency showed a strong inverse relationship with energy consumption
- Regression analysis confirmed that process variables collectively explain 87% of energy variation

4. Discussion

The present study provides a comprehensive assessment of energy optimization and heat integration in amine-based CO_2 capture systems, revealing pronounced variations in solvent performance, energy requirements, and overall process efficiency. The results not only support existing literature but also extend current understanding by coupling energy-focused evaluation with process optimization under region-specific gas compositions and operating conditions.

4.1. Baseline Energy Performance of Amine Solvents

The results indicated that MEA exhibited the highest regeneration energy demand, followed by DEA, while MDEA recorded the lowest energy requirement (Table 1). This pattern is consistent with the established thermodynamic characteristics of amine systems. As a primary amine, MEA forms strong carbamate intermediates with CO_2, which require substantial thermal input for regeneration [16]. In contrast, MDEA, a tertiary amine, predominantly promotes CO_2 absorption via bicarbonate formation, which is comparatively easier to reverse during stripping [17].

The elevated reboiler duty and specific energy consumption associated with MEA align with literature reports indicating energy penalties of approximately 4.0–5.5 GJ/ton CO_2 for MEA-based systems [18]. Conversely, the lower energy demand observed for MDEA confirms its advantage in energy-sensitive applications. However, its reduced CO_2 capture efficiency reflects the well-known trade-off between absorption capacity and regeneration energy, which remains a key consideration in solvent selection and process design [19].

4.2. Effect of Heat Integration on Energy Reduction

The introduction of a lean–rich heat exchanger (LRHX) resulted in a marked reduction in reboiler duty across all solvent systems (Table 2), with energy savings of up to 35% (Table 3). This underscores the critical role of internal heat recovery in minimizing external energy input. The LRHX achieves this by transferring heat from the hot lean solvent exiting the stripper to the cold rich solvent entering the regenerator, thereby reducing the thermal duty required for solvent regeneration.

These findings are in agreement with previous studies demonstrating that effective heat integration can significantly reduce energy consumption in amine-based CO_2 capture systems [20]. The relatively higher percentage energy savings observed for MDEA systems may be attributed to their lower baseline energy requirements and more favorable thermodynamic characteristics, which enhance heat recovery efficiency.

From a thermodynamic perspective, improved heat exchanger effectiveness reduces temperature gradients between process streams, thereby lowering entropy generation and improving overall thermal efficiency in accordance with second-law principles.

4.3. Influence of Operating Parameters on Energy Demand

The sensitivity analysis showed that absorber temperature and solvent circulation rate are the most influential parameters affecting energy consumption (Tables 4 and 5). An increase in absorber temperature led to higher reboiler duty across all solvents, primarily due to reduced CO_2 solubility at elevated temperatures, which increases the regeneration load [21]. This agrees with fundamental thermodynamic behavior, where gas solubility decreases with rising temperature.

Similarly, increasing solvent circulation rate resulted in higher energy consumption, owing to the greater solvent volume requiring thermal regeneration. Although higher flow rates can improve CO_2 absorption efficiency, they also increase reboiler duty, emphasizing the need for an optimal balance between capture performance and energy demand [22].

Overall, these results highlight the necessity of careful parameter optimization to avoid unnecessary energy penalties without proportional improvements in CO_2 removal efficiency.

4.4. Regression Analysis and Energy Drivers

The regression analysis (Table 6) revealed that absorber temperature, solvent flow rate, and CO_2 feed concentration positively correlate with energy consumption, whereas heat exchanger efficiency exhibits a strong inverse relationship. The high coefficient of determination ($R^2 = 0.87$) indicates that these variables collectively account for most of the observed variation in energy demand.

The strong negative correlation between heat exchanger efficiency and energy consumption confirms its dominant role in energy optimization strategies. This aligns with previous findings emphasizing heat recovery as a key lever for reducing the energy footprint of carbon capture processes [18].

Additionally, the positive association between CO_2 feed concentration and energy demand suggests that higher acid gas loading increases solvent regeneration requirements. This emphasizes the importance of adapting process design to feed gas variability, particularly in regions such as the Niger Delta where natural gas compositions are highly variable.

4.5. Energy–Efficiency Trade-Offs and Process Optimization

A key outcome of this study is the explicit quantification of trade-offs between CO_2 removal efficiency and energy consumption. While MEA provides superior absorption performance, its high regeneration energy limits its economic and environmental attractiveness at scale. In contrast, MDEA offers significantly lower energy consumption but at reduced capture efficiency.

This inherent trade-off highlights the need for integrated optimization approaches that simultaneously consider energy and performance metrics. Strategies such as solvent blending, process intensification, or hybrid systems may provide viable pathways to reconcile these competing objectives [17].

From an operational perspective, MDEA-based systems with optimized heat integration appear to offer the most energy-efficient configuration for natural gas processing, particularly in energy-constrained environments. Nonetheless, solvent selection should remain application-specific, guided by required CO_2 removal levels and economic constraints.

4.6. Implications for Sustainable Gas Processing

The findings have important implications for sustainable natural gas processing and carbon management strategies. Reducing energy consumption through optimized heat integration directly lowers the overall carbon footprint of CO_2 capture systems, an outcome that is particularly relevant for developing economies where energy efficiency is critical for operational viability.

Furthermore, the use of simulation-based optimization platforms such as Aspen HYSYS enables the development of tailored, cost-effective, and energy-efficient gas processing systems adapted to local feed gas characteristics. This contributes to global efforts aimed at reducing greenhouse gas emissions and improving the sustainability of industrial gas treatment operations.

Compliance with ethical standards

Disclosure of conflict of interest

We declare that No conflict of interest exists in this work

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