Heat Integration and Energy Optimization Strategies for Amine-Based CO_2 Capture Systems in Natural Gas Treatment: An Aspen HYSYS Simulation Study

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ABSTRACT

A major impediment to the economic viability of amine-based CO_2 capture in natural gas processing is the substantial energy burden imposed by solvent regeneration. Despite the widespread industrial adoption of chemical absorption for CO_2 removal, there remains a notable lack of systematic investigation into integrated heat recovery and energy optimization strategies tailored to region-specific gas compositions and operating conditions. The present study addresses this knowledge gap by employing Aspen HYSYS simulation to evaluate energy optimization and heat integration approaches for amine-based CO_2 capture systems under conditions typical of Niger Delta natural gas streams. A steady-state absorber–stripper model was constructed using the Electrolyte Non-Random Two-Liquid (e-NRTL) thermodynamic framework to simulate CO_2 absorption with MEA, DEA, and MDEA solvents. Key performance metrics—including reboiler duty, condenser duty, heat exchanger performance, and specific energy consumption—were assessed across a range of operating parameters, including absorber pressure, temperature, solvent circulation rate, and feed CO_2 concentration. Furthermore, heat integration strategies, encompassing lean–rich heat exchanger optimization and thermal energy recovery configurations, were systematically explored to reduce regeneration energy requirements. The results demonstrated that regeneration energy demand followed the hierarchy MEA > DEA > MDEA, with MEA exhibiting the highest reboiler duty attributable to its stronger carbamate formation chemistry. Implementation of optimized heat integration reduced overall process energy consumption by 25–35%, with MDEA-based systems realizing the greatest thermal efficiency improvements owing to their favorable thermodynamic properties. Sensitivity analysis identified absorber temperature and solvent circulation rate as the most influential parameters governing energy demand, while efficient lean–rich heat exchange substantially enhanced thermal performance. However, the analysis also revealed inherent trade-offs between CO_2 capture efficiency and energy minimization, emphasizing the need for balanced process optimization. Collectively, the findings indicate that strategic heat integration, coupled with optimized operating conditions, can significantly alleviate the energy penalty of amine-based CO_2 capture. From an industrial standpoint, MDEA systems integrated with advanced heat recovery configurations emerge as the most energy-efficient solution for large-scale natural gas treatment. These results provide valuable guidance for enhancing process efficiency, reducing operational expenditures, and supporting sustainable natural gas utilization in emerging hydrocarbon-producing economies.

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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INTRODUCTION

Natural gas constitutes an indispensable component of the global energy portfolio, owing to its comparatively lower carbon footprint relative to other fossil fuels and its strategic significance in advancing the transition toward low-carbon energy systems. Nevertheless, raw natural gas streams frequently contain appreciable quantities of carbon dioxide (CO_2), which must be effectively removed to satisfy pipeline quality specifications, mitigate corrosion risks, and enhance calorific value [1–3]. Consequently, CO_2 removal; commonly termed gas sweetening represents a critical unit operation in natural gas processing.

Among the spectrum of CO_2 capture technologies, including membrane separation, physical adsorption, and cryogenic distillation, chemical absorption using aqueous amine solvents continues to predominate in industrial applications, attributable to its high absorption efficiency, operational robustness, and technological maturity [2,3]. Primary amines such as Monoethanolamine (MEA), secondary amines like Diethanolamine (DEA), and tertiary amines such as Methyldiethanolamine (MDEA) have been extensively deployed in gas treatment systems. MEA is distinguished by its rapid reaction kinetics and superior absorption capacity, while DEA offers intermediate performance characteristics. In contrast, MDEA provides lower regeneration energy requirements and enhanced thermal stability, benefits derived from its tertiary amine molecular structure [4,5].

Notwithstanding these operational advantages, amine-based CO_2 capture systems are characterized by considerable energy penalties, particularly during solvent regeneration. The stripping stage, during which absorbed CO_2 is desorbed from the rich solvent, demands substantial thermal energy—typically supplied via reboiler steam; which may constitute approximately 60–70% of the total process energy consumption [3,4]. This elevated energy demand escalates operating costs and diminishes the overall sustainability credentials of carbon capture technologies. Consequently, improving the energy efficiency of amine-based capture systems has become a central research priority in contemporary gas processing and carbon management.

Recent investigations have increasingly underscored the importance of energy optimization and heat integration strategies in mitigating regeneration energy requirements. Heat recovery systems, particularly lean–rich heat exchangers, facilitate the internal recycling of thermal energy within the process, thereby reducing reliance on external utilities [6]. Furthermore, advanced process simulation and optimization platforms, such as Aspen HYSYS, have significantly enhanced the capability to analyze system behavior, perform sensitivity analyses, and optimize operating conditions for improved thermal performance and reduced energy consumption [7,8].

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

Although numerous studies have examined solvent behavior and CO_2 absorption efficiency in isolation, integrated investigations that combine energy optimization, heat integration, and process performance evaluation under region-specific operating conditions remain scarce, 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 imperatives.

Aim and Objectives of Study

The present study is designed to improve energy efficiency and optimize thermal performance in amine-based CO_2 capture processes through rigorous simulation-based evaluation using Aspen HYSYS. The specific objectives are as follows:

1. To evaluate the regeneration energy requirements of Monoethanolamine (MEA), Diethanolamine (DEA), and Methyldiethanolamine (MDEA) across a range of operational conditions.

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2. To investigate the effects of critical operating parameters—including temperature, pressure, and solvent circulation rate on overall process energy consumption.

3. To assess heat integration strategies, with particular focus on lean–rich heat exchanger optimization, for enhancing thermal efficiency and minimizing external utility requirements.

4. To establish the inherent trade-offs between CO_2 capture efficiency and process energy demand within amine-based absorption systems.

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

MATERIALS AND METHODS

2.1 Study Design

Approach: Simulation-driven computational research using Aspen HYSYS (V11) steady-state modeling.

Objective: Investigate energy optimization and heat integration in amine-based CO_2 capture.

Solvents Evaluated: MEA, DEA, MDEA.

Framework: Process simulation + sensitivity analysis + thermal optimization [9].

2.2 Feed Gas Composition

Study Area: Niger Delta, Nigeria.

Base-Case Composition (mol%):

- Methane: 85–90%
- CO_2: 5–10%
- Ethane: 2–5%
- Propane + heavier: 1–3%

Rationale: Reflects typical Nigerian gas field characteristics [10].

2.3 Process Simulation

Unit Operations:

- Absorber, stripper, LRHX, reboiler, condenser, pumps, flash drums

Thermodynamic Model: e-NRTL for VLE and electrolyte interactions [11]

Assumptions:

- Steady-state
- Ideal stage equilibrium
- Negligible heat loss

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- Constant solvent composition

Configuration: 20–25 theoretical stages with optimized feed points

2.4 Solvents and Operating Conditions

Solvents:

- MEA (30 wt%) – primary amine, fast kinetics
- DEA (30 wt%) – secondary amine, intermediate
- MDEA (40 wt%) – tertiary amine, low regeneration energy

Operating Ranges:

- Absorber: 30–50 bar, 30–50°C
- Stripper: 1.5–2.5 bar
- Reboiler: 100–120°C
- Solvent circulation: 2–6 kmol/m³ gas [12]

2.5 Energy Performance Metrics

Key Indicators:

- Reboiler duty (GJ/ton CO_2) – primary
- Condenser duty (kW)
- Specific energy consumption
- Heat exchanger efficiency
- Energy savings (%) [13]

2.6 Heat Integration

Strategy: Lean–rich heat exchanger (50–90% effectiveness)

Optimization Variables:

- Approach temperature
- Circulation rates
- Temperature profiles

Comparison: With and without integration [14]

2.7 Sensitivity Analysis

Variables Investigated:

- Absorber temperature (30–60°C)

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- Solvent circulation rate
- CO_2 concentration (5–15%)
- Stripper pressure

Method: Independent variation to isolate effects

2.8 Ethical Considerations

- Computational study only – no human/animal subjects
- Proper citation and academic integrity maintained
- Supports environmental sustainability

2.9 Data Analysis

Methods: Statistical and graphical analysis; regression analysis for trends

Energy Savings Calculation:

- Savings (%) = [(Energy_without_HT – Energy_with_HT) / Energy_without_HT] × 100

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

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].

3. Results

3.1 Baseline Energy Performance of Amine Solvents

Table 3.1: 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 3.2: 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 3.3: 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 3.4: 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 3.5: Influence of solvent flow rate on specific energy consumption

Flow Rate (kmol/m³ 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

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Table 3.6: 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

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 corroborate 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 3.1). 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-established trade-off between absorption capacity and regeneration energy, which remains a key consideration in solvent selection and process design [19].

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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 3.2), with energy savings of up to 35% (Table 3.3). 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 3.4 and 3.5). 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 3.6) 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.

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