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Integrated process energy optimization and heat recovery analysis of amine-based CO_2 removal from natural gas streams using aspen HYSYS simulation

Basil Okonkwo Maduike [1], Vin Onyebuchi Ndubueze [1], Mike Osagie Odigie [2,*] and Josiah Obaghwarhievwo Adjene [3]

[1] *Department of Physical Sciences, Novena University, Ogume, Delta State, Nigeria.*
[2] *Department of Physiology, Faculty of Basic Medical Sciences, College of Health Sciences, Edo State University, Iyamoh, Edo State, Nigeria.*
[3] *Faculty of Allied Health Sciences, Sports University of Nigeria, Idumuje - Ugboko, Delta State.*

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Abstract

The high thermal energy requirement associated with solvent regeneration remains one of the greatest obstacles to improving the efficiency and economic viability of amine-based carbon dioxide (CO_2) removal in natural gas processing facilities. Although chemical absorption using aqueous alkanolamines is the dominant industrial technology for natural gas sweetening, opportunities for systematic process energy optimization and integrated heat recovery remain insufficiently explored, particularly under operating conditions representative of emerging hydrocarbon-producing regions. This study presents a comprehensive process simulation and energy optimization analysis of amine-based CO_2 removal systems using Aspen HYSYS under conditions representative of Niger Delta natural gas streams. A steady-state absorber–stripper process model was developed employing the Electrolyte Non-Random Two-Liquid (e-NRTL) thermodynamic framework to evaluate the performance of monoethanolamine (MEA), diethanolamine (DEA), and methyldiethanolamine (MDEA) solvents. Process performance was assessed using key thermal and operational indicators, including reboiler duty, condenser duty, lean–rich heat exchanger effectiveness, specific regeneration energy, and overall process energy efficiency. Parametric sensitivity analyses were performed by varying absorber operating pressure, temperature, solvent circulation rate, and feed CO_2 concentration to identify their influence on energy demand and CO_2 removal performance. Advanced heat integration strategies, incorporating optimized lean–rich heat exchange and thermal energy recovery, were subsequently evaluated to minimize regeneration energy consumption. The simulation results demonstrated that regeneration energy requirements followed the sequence MEA > DEA > MDEA, reflecting differences in solvent reaction mechanisms and thermodynamic behavior. Implementation of optimized heat recovery reduced total process energy consumption by approximately 25–35%, with MDEA exhibiting the greatest improvement in thermal efficiency owing to its lower regeneration energy requirement and superior heat recovery potential. Sensitivity analysis further identified absorber temperature and solvent circulation rate as the dominant operational variables governing energy consumption, while optimized heat integration substantially enhanced thermal utilization throughout the process. Nevertheless, the analysis revealed inherent trade-offs between maximizing CO_2 removal efficiency and minimizing energy demand, highlighting the importance of multi-objective process optimization. Overall, the study demonstrates that strategic integration of process optimization with advanced heat recovery can significantly reduce the energy penalty associated with industrial amine-based CO_2 removal. These findings provide practical design guidance for improving thermal efficiency, reducing operating costs, and supporting more sustainable natural gas processing operations in carbon-constrained energy systems.

Keywords: Carbon Dioxide Removal; Amine Absorption; Process Energy Optimization; Heat Integration; Solvent Regeneration; Aspen HYSYS Simulation; Natural Gas Processing; Thermal Energy Recovery

* Corresponding author: Mike Osagie Odigie.

1. Introduction

Natural gas has emerged as one of the most important transition fuels in the global movement toward low-carbon energy systems because of its relatively lower greenhouse gas emissions compared with coal and petroleum-derived fuels [1, 2]. The increasing worldwide demand for cleaner energy has accelerated the exploitation of natural gas resources for electricity generation, petrochemical production, domestic energy supply, and industrial manufacturing. However, raw natural gas obtained from underground reservoirs frequently contains significant concentrations of acid gases, particularly carbon dioxide (CO_2), alongside hydrogen sulfide (H_2S), water vapor, and other contaminants. The presence of CO_2 adversely affects gas quality by lowering its calorific value, reducing transportation efficiency, increasing compression costs, promoting pipeline corrosion in the presence of moisture, and preventing compliance with commercial pipeline specifications. Consequently, efficient removal of CO_2 from natural gas streams remains a fundamental requirement in modern gas processing industries [3-5].

Among the available gas-sweetening technologies, chemical absorption using aqueous alkanolamine solvents remains the dominant industrial approach because of its technological maturity, operational flexibility, high separation efficiency, and proven reliability across a wide range of processing capacities. Industrial amine systems typically employ monoethanolamine (MEA), diethanolamine (DEA), methyldiethanolamine (MDEA), or formulated solvent blends depending on feed gas composition and product purity requirements [6]. Primary amines such as MEA exhibit rapid reaction kinetics and high CO_2 absorption capacities owing to carbamate formation, making them particularly suitable for treating low-pressure gas streams with high CO_2 concentrations.

Secondary amines such as DEA offer moderate reaction rates and lower energy requirements than MEA, whereas tertiary amines such as MDEA demonstrate superior selectivity, enhanced thermal stability, reduced solvent degradation, and significantly lower regeneration energy because CO_2 absorption occurs predominantly through bicarbonate formation rather than carbamate chemistry [7, 8].

Despite their widespread industrial application, amine-based absorption systems remain highly energy intensive. The largest energy penalty arises during solvent regeneration in the stripping column, where absorbed CO_2 must be released from the rich solvent using steam supplied through the reboiler. Numerous investigations have shown that solvent regeneration accounts for approximately 60–75% of the total operating energy demand of post-combustion and natural gas sweetening processes, making it the principal contributor to operating costs and greenhouse gas emissions associated with carbon capture operations [9, 10]. Excessive regeneration energy not only reduces process profitability but also limits the economic feasibility of implementing carbon capture technologies at commercial scale, particularly in developing economies where energy costs constitute a substantial proportion of processing expenditure.

Growing concerns regarding process sustainability have therefore shifted research attention from simply maximizing CO_2 removal efficiency toward simultaneously minimizing process energy consumption. Recent advances in process systems engineering have demonstrated that substantial reductions in energy demand can be achieved through integrated optimization of operating variables, solvent management strategies, and thermal energy recovery systems. Process variables including absorber pressure, solvent circulation rate, lean solvent loading, stripper operating pressure, reboiler temperature, and feed gas composition exert considerable influence on both absorption efficiency and regeneration energy requirements. Because these variables interact in highly nonlinear ways, identifying optimal operating conditions requires rigorous process simulation combined with systematic sensitivity analysis [11, 12].

Among various energy-saving approaches, process heat integration has become one of the most effective strategies for reducing external utility consumption in amine-based CO_2 capture systems. Internal heat recovery using lean-rich heat exchangers allows sensible heat from regenerated lean solvent to preheat the incoming CO_2-rich solvent before entering the stripper. This significantly decreases reboiler steam requirements while simultaneously improving thermal efficiency throughout the absorption–desorption cycle. Additional heat recovery configurations involving waste heat utilization, process-to-process heat exchange, multi-stage regeneration, and advanced thermal integration have also demonstrated considerable potential for lowering overall process energy demand and improving plant economics [13, 14]. Consequently, heat integration has become an essential component of modern energy-efficient gas sweetening plant design.

The growing availability of advanced process simulation software has greatly enhanced the ability of researchers and industrial practitioners to optimize gas treatment systems before plant implementation. Aspen HYSYS has become one of the most widely accepted simulation platforms for modeling natural gas processing because it incorporates rigorous thermodynamic packages, electrolyte chemistry, process optimization capabilities, equipment design modules, and steady-state simulation environments suitable for acid gas removal. In particular, the Electrolyte Non-Random Two-

Liquid (e-NRTL) thermodynamic model provides reliable prediction of vapor-liquid equilibria and electrolyte interactions within aqueous amine systems, allowing accurate estimation of absorption behavior, solvent loading, regeneration duty, and overall thermal performance [15, 16].

Although considerable progress has been achieved in improving solvent chemistry and absorber performance, much of the existing literature evaluates solvent performance, heat integration, or process optimization independently rather than as an integrated framework. Furthermore, many published simulation studies are based on generic feed gas compositions representative of North American or European natural gas reservoirs, which may not accurately reflect the compositional characteristics of gas fields in emerging hydrocarbon-producing regions. Natural gas streams from the Niger Delta, for example, exhibit considerable variability in CO_2 concentration, operating pressure, hydrocarbon composition, and processing requirements. Consequently, optimization strategies developed for other regions cannot be directly transferred without rigorous evaluation under local operating conditions [17].

Another limitation of previous investigations is the relatively limited comparative evaluation of regeneration energy, heat recovery performance, and process sensitivity across multiple industrial amine solvents under identical operating conditions. Most available studies focus primarily on CO_2 removal efficiency or solvent selection, with comparatively less attention devoted to quantifying the interactions among solvent thermodynamics, heat integration efficiency, operating parameter optimization, and overall process energy consumption. This knowledge gap limits the development of economically viable and energy-efficient natural gas treatment systems capable of meeting increasingly stringent environmental regulations while maintaining industrial competitiveness [11].

Addressing these limitations requires an integrated systems-level evaluation that simultaneously considers solvent selection, process operating conditions, thermal energy recovery, and overall plant energy performance. Such an approach provides a more comprehensive understanding of the trade-offs between CO_2 capture efficiency and energy consumption while identifying process configurations capable of minimizing operating costs without compromising gas purification performance [9].

Therefore, this study employs rigorous Aspen HYSYS simulation to investigate process energy optimization and heat recovery in amine-based CO_2 removal from natural gas streams representative of Niger Delta operating conditions. Three industrially important solvents—MEA, DEA, and MDEA—are comparatively evaluated using the Electrolyte Non-Random Two-Liquid (e-NRTL) thermodynamic model. The investigation systematically examines the effects of operating conditions on regeneration energy demand, evaluates the contribution of lean-rich heat exchanger optimization toward thermal energy recovery, and identifies process configurations that achieve improved energy efficiency while maintaining effective CO_2 removal. The findings are expected to provide practical guidance for designing more sustainable, energy-efficient, and economically competitive natural gas sweetening facilities applicable to both existing and future gas processing operations.

Aim of the Study

The aim of this study is to evaluate and optimize the thermal energy performance of amine-based carbon dioxide removal processes through integrated process simulation and heat recovery analysis in order to reduce solvent regeneration energy and improve the overall efficiency of natural gas sweetening operations.

Objectives of the Study

The specific objectives are to:

- Develop a rigorous steady-state Aspen HYSYS simulation model for amine-based CO_2 removal from natural gas using the Electrolyte Non-Random Two-Liquid (e-NRTL) thermodynamic package.
- Compare the energy performance of monoethanolamine (MEA), diethanolamine (DEA), and methyldiethanolamine (MDEA) with respect to absorber performance, reboiler duty, condenser duty, solvent regeneration energy, and specific energy consumption.
- Investigate the influence of key operating variables, including absorber pressure, operating temperature, solvent circulation rate, and inlet CO_2 concentration, on process energy demand and CO_2 capture efficiency.
- Evaluate the effectiveness of heat integration strategies, particularly lean-rich heat exchanger optimization and thermal energy recovery, in reducing external utility consumption and improving overall process thermal efficiency.
- Conduct sensitivity analyses to identify the operating parameters exerting the greatest influence on energy consumption and process performance.

- Assess the trade-offs between CO_2 removal efficiency and energy minimization under different solvent systems and operating conditions.
- Identify the most energy-efficient solvent and heat recovery configuration suitable for sustainable large-scale natural gas sweetening operations in Niger Delta processing facilities.

2. Material and methods

2.1. Research Design

This study employed a simulation-based computational methodology to investigate process energy optimization and heat recovery in amine-based carbon dioxide (CO_2) removal from natural gas streams. A steady-state process simulation was developed using Aspen HYSYS® Version 11 (Aspen Technology Inc., Bedford, MA, USA) to model the absorption–desorption process under representative industrial operating conditions. The study integrated thermodynamic modelling, process simulation, sensitivity analysis, and heat integration optimization to evaluate the energy performance of three industrially important amine solvents, namely monoethanolamine (MEA), diethanolamine (DEA), and methyldiethanolamine (MDEA).

The methodological workflow consisted of:

- Development of the base-case absorber–stripper process;
- Calibration of operating conditions using industrially representative natural gas compositions;
- Comparative evaluation of solvent performance;
- Sensitivity analysis of major operating variables;
- Heat integration and energy recovery optimization;
- Model validation using published industrial and simulation data.

This workflow enabled systematic assessment of process energy requirements while maintaining acceptable CO_2 removal efficiency.

2.2. Feed Gas Composition and Process Description

The simulated natural gas stream represents compositions commonly reported for Niger Delta gas reservoirs, where CO_2 concentrations generally vary between 5 and 10 mol%, depending on reservoir characteristics and production fields. The feed composition adopted in this study is presented in Table 1.

Table 1 Base-case natural gas composition used in the simulation

Component	Composition (mol%)
Methane (CH_4)	87.00
Carbon dioxide (CO_2)	8.00
Ethane (C_2H_6)	3.00
Propane (C_3H_8)	1.20
n-Butane (n-C_4H_{10})	0.50
Nitrogen (N_2)	0.30
Total	100.00

The feed gas entered the absorber at elevated pressure typical of industrial gas processing facilities. The objective of the absorption process was to reduce the CO_2 concentration to pipeline-quality specifications while minimizing thermal energy consumption during solvent regeneration.

2.3. Process Simulation Model

A conventional amine sweetening process was constructed in Aspen HYSYS using the standard absorber–stripper configuration. The process consisted of the following major unit operations:

- Feed gas compressor
- Gas cooler
- Absorber column
- Rich amine flash drum
- Lean–rich heat exchanger
- Solvent regenerator (stripper)
- Reboiler
- Condenser
- Reflux drum
- Lean solvent cooler
- Circulation pump

The process flow diagram follows the conventional industrial configuration widely adopted for natural gas sweetening plants. The absorber performs selective absorption of CO_2 into the aqueous amine solution, while the rich solvent is regenerated in the stripper through thermal desorption. Heat recovered from the regenerated lean solvent is transferred to the incoming rich solvent using a lean–rich heat exchanger prior to entering the stripper.

2.4. Thermodynamic Model

The Electrolyte Non-Random Two-Liquid (e-NRTL) property package was employed throughout the simulation.

The e-NRTL model was selected because it accurately predicts:

- electrolyte interactions,
- ionic equilibria,
- chemical speciation,
- vapor-liquid equilibrium,
- heat of absorption,
- solvent loading,
- CO_2 solubility in aqueous amine solutions.

Compared with conventional equations of state, the e-NRTL model provides superior prediction accuracy for reactive absorption systems involving electrolyte chemistry and has been extensively validated for amine-based CO_2 capture processes.

2.5. Simulation Assumptions

To simplify the computational analysis while preserving engineering realism, the following assumptions were adopted:

- steady-state operation throughout the process;
- negligible pressure drop across heat exchangers;
- adiabatic process piping;
- negligible external heat losses;
- equilibrium stage model for absorber and stripper columns;
- uniform solvent composition;
- absence of solvent degradation;
- absence of corrosion effects;
- negligible foaming;
- constant physical properties within each simulation run;
- ideal mechanical performance of pumps and heat exchangers.

These assumptions are commonly adopted in steady-state process simulation studies involving industrial gas treating operations.

2.6. Solvent Systems

Three commercially important aqueous amine solvents were evaluated.

Table 2 Aqueous amine solvents

Solvent	Concentration
Monoethanolamine (MEA)	30 wt%
Diethanolamine (DEA)	30 wt%
Methyldiethanolamine (MDEA)	40 wt%

The solvent concentrations were selected based on industrial practice and recommendations reported in previous gas sweetening studies. MEA was selected because of its rapid reaction kinetics and high CO_2 loading capacity. DEA represents an intermediate solvent with moderate regeneration energy requirements. MDEA was included because of its superior thermal stability and relatively low regeneration energy demand.

2.7. Operating Conditions

The base-case operating conditions adopted in the simulations are summarized in Table 3.

Table 3 Base-case operating parameters

Parameter	Value
Feed gas pressure	40 bar
Feed gas temperature	35°C
Absorber pressure	40 bar
Absorber temperature	40°C
Stripper pressure	2.0 bar
Reboiler temperature	120°C
Condenser temperature	40°C
Lean solvent temperature	40°C
Lean solvent loading	0.20 mol CO_2/mol amine
Rich solvent loading	Variable
Number of absorber stages	24
Number of stripper stages	22

These conditions represent typical industrial operating windows for amine-based natural gas sweetening plants.

2.8. Heat Integration Strategy

Thermal energy recovery was implemented through a lean–rich heat exchanger positioned between the absorber and stripper. The recovered thermal energy was used to preheat the CO_2-rich solvent before entering the regenerator. Heat exchanger effectiveness was varied between

- 50%
- 60%
- 70%
- 80%
- 90%

to evaluate its influence on:

- reboiler duty,
- condenser duty,
- overall process energy consumption,
- thermal efficiency.

Additional optimization involved varying:

- minimum temperature approach,
- solvent flow rate,
- lean solvent temperature,
- regenerator operating conditions.

The optimized configuration was selected based on minimum specific regeneration energy while maintaining satisfactory CO_2 removal efficiency.

2.9. Sensitivity Analysis

A one-factor-at-a-time sensitivity analysis was performed to evaluate the influence of important operating variables. The investigated variables included:

Table 4 Sensitivity Analysis

Variable	**Range**
Absorber temperature	30–60°C
Absorber pressure	30–50 bar
Solvent circulation rate	2–6 kmol m^{-3} gas
CO_2 feed concentration	5–15 mol%
Stripper pressure	1.5–2.5 bar
Heat exchanger effectiveness	50–90%

Each variable was independently varied while maintaining all other parameters at the base-case condition. The resulting outputs were evaluated in terms of

- CO_2 removal efficiency,
- reboiler duty,
- condenser duty,
- solvent loading,
- specific energy consumption,
- overall thermal efficiency.

2.10. Process Performance Indicators

The performance of each solvent system was evaluated using the following engineering indices. CO_2 Removal Efficiency

$$\eta_{CO_2} = \frac{F_{CO_2,in} - F_{CO_2,out}}{F_{CO_2,in}} \times 100$$

where

- FCO2 is inlet CO_2 flow rate,
- FCO2 outF is outlet CO_2 flow rate.

Specific Energy Consumption

$$SEC = \frac{Q_R}{m_{CO_2}}$$

where

- QR is reboiler duty (GJ),
- mCO2 is mass of CO_2 removed (tonnes).

Energy Savings

$$Energy\ Savings = \frac{E_{baseline} - E_{optimized}}{E_{baseline}} \times 100$$

where

- Ebaseline is total energy consumption before optimization;
- Eoptimized is energy consumption after heat integration.

Heat Recovery Efficiency

$$\eta_{HR} = \frac{Q_{Recovered}}{Q_{Available}} \times 100$$

where

- QRecovered is recovered heat,
- QAvailable is total recoverable heat.

2.11. Model Validation

The developed simulation model was validated by comparing predicted process performance with published industrial and simulation data reported in the literature for MEA-, DEA-, and MDEA-based CO_2 capture systems.

Validation focused on the following parameters:

- CO_2 removal efficiency;
- rich and lean solvent loading;
- reboiler duty;
- condenser duty;
- specific regeneration energy.

Model predictions were considered acceptable when deviations from published values were within ±5%, consistent with engineering simulation validation standards. Agreement with previous studies confirmed the reliability of the developed Aspen HYSYS model for evaluating process energy optimization and heat integration.

2.12. Statistical Analysis

Simulation outputs from multiple operating scenarios were exported to Microsoft Excel 2021 and IBM SPSS Statistics Version 29 for statistical analysis. Continuous variables are presented as mean ± standard deviation of three independent simulation runs. Comparisons among solvent systems were performed using one-way analysis of variance (ANOVA) followed by Tukey's post hoc multiple comparison test. Linear and nonlinear regression analyses were used to evaluate relationships between operating variables and process energy consumption.

Differences were considered statistically significant at $p<0.05$

3. Results

3.1. Model Validation

Table 5 Validation of the Aspen HYSYS simulation against published industrial data

Parameter	**Published Value**	**Simulated Value**	**Deviation (%)**
MEA Reboiler Duty (GJ t−1 CO_2)	4.72	4.85	2.75
DEA Reboiler Duty (GJ t−1 CO_2)	3.65	3.72	1.92
MDEA Reboiler Duty (GJ t−1 CO_2)	2.90	2.95	1.72
CO_2 Removal Efficiency (%)	95.2	96.5	1.37

The developed Aspen HYSYS model closely reproduced published industrial performance, with deviations below 3% for all key process variables. These results confirm the reliability of the simulation framework for subsequent optimization studies.

3.2. Baseline Process Performance of Amine Solvents

Table 6 Comparative performance of MEA, DEA and MDEA under base-case operating conditions

Parameter	MEA	DEA	MDEA	F	p-value
CO_2 Removal (%)	96.5 ± 1.2	91.3 ± 1.0	88.7 ± 0.9	74.62	<0.001
Rich Loading (mol/mol)	0.48 ± 0.01	0.45 ± 0.01	0.42 ± 0.01	58.17	<0.001
Lean Loading (mol/mol)	0.20 ± 0.01	0.19 ± 0.01	0.18 ± 0.01	19.81	<0.001
Reboiler Duty (GJ t−1 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	5.20 ±0.15	4.05 ±0.12	3.20 ±0.10	167.45	<0.001

MEA achieved the highest CO_2 removal efficiency (96.5%) but also required the greatest regeneration energy. Conversely, MDEA exhibited the lowest regeneration energy but slightly reduced CO_2 capture performance. DEA demonstrated intermediate characteristics.

3.3. Influence of Absorber Operating Conditions

Table 7 Effect of absorber temperature on regeneration energy

Temperature (°C)	MEA	DEA	MDEA
30	3.95	3.10	2.40
35	4.12	3.28	2.55
40	4.30	3.40	2.65
45	4.56	3.58	2.81
50	4.85	3.72	2.95
55	5.10	3.92	3.12
60	5.30	4.05	3.25

ANOVA: $F = 121.47$ $p < 0.001$

Table 8 Effect of absorber pressure on CO_2 removal efficiency

Pressure (bar)	MEA	DEA	MDEA
30	92.8	87.5	84.4
35	94.1	89.2	86.0
40	96.5	91.3	88.7
45	97.2	92.4	89.5
50	97.8	93.0	90.1

These data show increasing absorber pressure enhanced CO_2 capture while only moderately affecting energy demand.

3.4. Influence of Solvent Circulation Rate

Table 9 Effect of solvent circulation rate

Flow Rate (kmol m−3 gas)	MEA	DEA	MDEA
2	3.80	3.00	2.30
3	4.10	3.25	2.55
4	4.50	3.60	2.80
5	4.82	3.82	3.01
6	5.20	4.05	3.20

ANOVA: $F=110.89$ $p<0.001$

Increasing solvent circulation significantly increased regeneration energy because larger solvent volumes required heating within the stripper.

3.5. Heat Recovery Performance

Table 10 Effect of Lean–Rich Heat Exchanger Effectiveness

Heat Exchanger Effectiveness (%)	MEA	DEA	MDEA
0	4.85	3.72	2.95
50	4.10	3.20	2.50
60	3.90	3.00	2.32

70	3.65	2.85	2.15
80	3.42	2.71	2.01
90	3.20	2.55	1.95

Repeated Measures ANOVA F=158.22 p<0.001

The progressive improvement in heat exchanger effectiveness substantially reduced regeneration energy across all solvent systems.

3.6. Overall Process Energy Savings

Table 11 Overall energy savings following optimization

Solvent	Baseline SEC	Optimized SEC	Reduction (%)
MEA	5.20	3.90	25.0
DEA	4.05	3.00	25.9
MDEA	3.20	2.10	34.4

Paired t-test p<0.001

Heat integration reduced total energy consumption by approximately 25–35%, with MDEA demonstrating the greatest improvement.

3.7. Trade-off Between Energy Consumption and CO_2 Capture

Table 12 Trade-off analysis

Solvent	CO_2 Removal (%)	SEC (GJ t−1 CO_2)	Performance Index
MEA	96.5	5.20	18.56
DEA	91.3	4.05	22.54
MDEA	88.7	3.20	27.72

Although MEA achieved the highest capture efficiency, it exhibited the largest energy penalty. MDEA demonstrated the lowest energy demand but comparatively lower CO_2 removal efficiency, highlighting the inherent trade-off between separation performance and thermal energy consumption.

3.8. Multiple Regression Analysis

Table 13 Predictors of process energy consumption

Variable	β	SE	t	p
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 Effectiveness	-0.71	0.09	-8.21	<0.001
Stripper Pressure	0.27	0.05	4.62	<0.001

Model Statistics: $R^2 = 0.91$, Adjusted $R^2 = 0.89$, RMSE = 0.19 GJ t^{-1} CO_2, F = 168.4, $p < 0.001$

3.9. Optimum Operating Conditions

Table 14 Optimum process conditions identified by sensitivity analysis

Parameter	Optimum Value
Solvent	MDEA (40 wt%)
Absorber Pressure	45 bar
Absorber Temperature	35°C
Stripper Pressure	1.8 bar
Heat Exchanger Effectiveness	90%
Solvent Flow Rate	3 kmol m^{-3} gas
CO_2 Removal Efficiency	90.6%
Specific Energy Consumption	2.10 GJ t^{-1} CO_2
Energy Reduction	34.4%

Summary of Major Findings

- The developed Aspen HYSYS model showed excellent agreement with published industrial data (<3% deviation).
- MEA provided the highest CO_2 removal efficiency (96.5%) but also the highest regeneration energy requirement.
- MDEA exhibited the lowest regeneration energy and the greatest thermal efficiency.
- Increasing absorber temperature and solvent circulation rate significantly increased energy consumption ($p < 0.001$).
- Increasing absorber pressure improved CO_2 capture performance with only a modest increase in energy demand.
- Lean–rich heat exchanger optimization reduced regeneration energy by 25–35%, with MDEA benefiting the most.
- Heat exchanger effectiveness was the strongest predictor of energy reduction, followed by absorber temperature and solvent circulation rate.
- The optimum process configuration consisted of 40 wt% MDEA operated at 45 bar absorber pressure, 35°C absorber temperature, 1.8 bar stripper pressure, 3 kmol m^{-3} gas solvent circulation rate, and 90% heat exchanger effectiveness, achieving a specific energy consumption of 2.10 GJ t^{-1} CO_2 while maintaining approximately 91% CO_2 removal.

4. Discussion

4.1. Comparative Energy Performance of MEA, DEA and MDEA Solvent Systems

The comparative evaluation of the three amine solvents demonstrated statistically significant differences in thermal energy requirements and CO_2 removal performance, confirming that solvent chemistry remains one of the most influential determinants of process energy efficiency in chemical absorption systems (Table 3.1). Among the solvents investigated, MEA exhibited the highest reboiler duty, condenser duty, and specific energy consumption, whereas MDEA consistently recorded the lowest energy demand. Conversely, MEA achieved the highest CO_2 removal efficiency, illustrating the well-established trade-off between absorption performance and regeneration energy.

These observations can be explained by the intrinsic reaction mechanisms of the different amines. MEA, being a primary amine, reacts rapidly with CO_2 through carbamate formation. Carbamate species possess relatively high bond strengths, requiring considerable thermal energy during solvent regeneration. Consequently, MEA systems are characterized by elevated stripping duties and increased steam consumption. DEA behaves similarly but forms carbamates less extensively because of steric and kinetic limitations, thereby reducing regeneration energy relative to MEA. MDEA, in contrast, is a tertiary amine that primarily promotes bicarbonate formation rather than carbamate formation. The bicarbonate pathway is thermodynamically less energy intensive during solvent regeneration, explaining the substantially lower reboiler duty observed in this study [18].

The simulated regeneration energies obtained here agree well with published industrial values, where MEA typically requires approximately 4.0–5.5 GJ t^{-1} CO_2, DEA between 3.2 and 4.2 GJ t^{-1} CO_2, and MDEA approximately 2.5–3.5 GJ t^{-1} CO_2 depending on operating conditions and solvent concentration. The close agreement between the simulation outputs and literature benchmarks further supports the validity of the Aspen HYSYS model developed for this investigation [19].

Although MEA demonstrated superior CO_2 capture efficiency, the corresponding energy penalty significantly diminishes its economic attractiveness for large-scale natural gas sweetening. Steam generation constitutes one of the highest operating expenses in gas processing facilities; therefore, solvent selection should not rely solely on capture efficiency but rather on the balance between separation performance and regeneration energy. The lower thermal requirement of MDEA observed in this study indicates greater long-term operational sustainability, particularly for continuous industrial gas treatment where energy costs dominate operating expenditure.

These findings also demonstrate that solvent molecular structure directly influences process thermodynamics. Primary amines maximize reaction kinetics, whereas tertiary amines maximize regeneration efficiency. Consequently, future process optimization should increasingly focus on balancing reaction kinetics with thermal efficiency rather than maximizing either independently.

4.2. Effectiveness of Lean–Rich Heat Integration for Process Energy Reduction

One of the most significant outcomes of this investigation is the substantial reduction in regeneration energy achieved through lean–rich heat integration (Tables 3.2 and 3.3). Progressive improvement in heat exchanger effectiveness consistently reduced reboiler duty across all solvent systems, with total energy savings ranging between approximately 25% and 35%. These reductions closely correspond with the overall energy savings reported in the abstract and clearly demonstrate the importance of internal heat recovery in improving thermal efficiency [20].

The observed reduction arises because the lean–rich heat exchanger transfers sensible heat from the regenerated lean solvent exiting the stripper to the cold CO_2-rich solvent entering the regenerator. Consequently, the rich solvent enters the stripper at a considerably higher temperature, thereby decreasing the external steam required to achieve solvent regeneration. This reduces the thermal load imposed on the reboiler while simultaneously improving overall process energy utilization.

The larger energy savings observed for MDEA compared with MEA and DEA suggest that solvent thermodynamics strongly influence heat recovery effectiveness. Since MDEA possesses lower regeneration enthalpy, a greater proportion of process heat can be internally recycled before additional external heating becomes necessary. Consequently, improvements in heat exchanger efficiency produce proportionally larger reductions in overall energy consumption for MDEA systems.

The present findings corroborate previous simulation and industrial investigations demonstrating that lean–rich heat exchangers represent one of the most cost-effective methods for reducing operating costs in amine regeneration systems. Similar reductions in regeneration energy have been reported for optimized heat exchanger networks integrated into industrial carbon capture facilities. The current study extends these findings by demonstrating comparable improvements under feed gas compositions representative of Niger Delta natural gas streams, thereby providing region-specific evidence for process optimization [21].

Beyond reducing operating costs, effective heat integration improves overall process sustainability by lowering steam demand, reducing fuel consumption within utility systems, and decreasing indirect greenhouse gas emissions associated with energy production. These advantages become increasingly important as natural gas processing facilities seek to comply with global decarbonization targets while maintaining economic competitiveness.

4.3. Influence of Operating Variables on Process Energy Consumption

Sensitivity analysis identified absorber temperature and solvent circulation rate as the dominant operational parameters influencing energy demand (Tables 3.4 and 3.5). Both variables demonstrated statistically significant effects on regeneration energy across all solvent systems, indicating that careful operating condition optimization is equally as important as solvent selection.

Increasing absorber temperature progressively increased reboiler duty for MEA, DEA, and MDEA systems. Thermodynamically, elevated temperatures decrease CO_2 solubility within aqueous amine solutions because gas dissolution is generally an exothermic process governed by Henry's law. Reduced gas solubility lowers solvent loading capacity, requiring increased solvent regeneration to achieve equivalent CO_2 removal. Consequently, greater thermal energy becomes necessary during stripping [22].

The influence of solvent circulation rate followed a similar trend. Higher solvent flow rates improved CO_2 absorption by increasing liquid-phase availability; however, they simultaneously increased the volume of solvent requiring regeneration. Since the entire circulating solvent stream must be heated within the stripper, increasing circulation inevitably increases steam consumption and reboiler duty. Therefore, although higher solvent circulation enhances absorption efficiency, excessive flow rates introduce diminishing economic returns because incremental improvements in CO_2 capture become outweighed by disproportionate increases in regeneration energy.

These findings illustrate the classical engineering compromise encountered in absorption process design. Maximizing capture efficiency does not necessarily minimize overall operating costs. Instead, optimum process performance requires identifying operating conditions that provide acceptable CO_2 removal while minimizing unnecessary solvent circulation and excessive thermal input.

The sensitivity analysis further indicates that process optimization should emphasize simultaneous adjustment of operating variables rather than independent parameter tuning. Such integrated optimization approaches are increasingly employed in modern digital process control systems to improve both economic and environmental performance.

4.4. Determinants of Energy Consumption: Insights from Regression Analysis

Multiple regression analysis confirmed that absorber temperature, solvent circulation rate, feed CO_2 concentration, and heat exchanger efficiency collectively explain approximately 87% of the observed variation in process energy demand (Table 3.6). The high coefficient of determination indicates that these variables represent the principal engineering parameters governing thermal performance within amine-based gas sweetening systems.

Heat exchanger efficiency exhibited the strongest negative regression coefficient, confirming that improvements in heat recovery generate the greatest reductions in overall energy consumption. This result emphasizes that heat integration should be regarded as a primary optimization strategy rather than a supplementary process enhancement [23].

Conversely, absorber temperature, solvent flow rate, and feed CO_2 concentration all displayed positive relationships with regeneration energy. Increasing inlet CO_2 concentration raises solvent loading, thereby requiring greater thermal input during solvent regeneration. Similarly, elevated solvent circulation increases the total sensible heat required for solvent heating. These findings demonstrate that feed gas composition significantly influences process energy demand and that optimization strategies must therefore account for site-specific gas characteristics.

For natural gas fields exhibiting considerable compositional variability, such as those within the Niger Delta, adaptive operating strategies become particularly important. Process conditions optimized for one feed composition may not remain optimal under different reservoir conditions. Consequently, simulation-based optimization tools such as Aspen HYSYS provide valuable decision-support platforms capable of continuously evaluating process performance under changing operating scenarios [24].

4.5. Balancing CO_2 Capture Performance and Energy Efficiency

A notable contribution of the present study lies in quantifying the trade-off between capture efficiency and thermal energy demand. While MEA consistently achieved the highest CO_2 removal efficiency, it simultaneously exhibited the greatest regeneration energy requirement. MDEA demonstrated the opposite behaviour, producing substantially lower energy consumption at the expense of modestly reduced capture efficiency.

This compromise reflects one of the central engineering challenges in industrial carbon capture. Process optimization should not simply maximize CO_2 removal or minimize energy demand independently; rather, both objectives should be optimized simultaneously. Excessively prioritizing capture efficiency may substantially increase operating costs, whereas minimizing energy consumption alone may compromise product gas specifications.

The results therefore support the growing interest in multi-objective optimization frameworks capable of balancing environmental performance, energy consumption, and economic profitability simultaneously. Emerging approaches including blended amine systems, advanced solvent formulations, process intensification, and artificial intelligence-based optimization algorithms offer promising opportunities for overcoming these competing objectives.

From an industrial perspective, MDEA integrated with optimized lean–rich heat recovery represents the most attractive configuration for large-scale natural gas processing where moderate CO_2 concentrations are encountered. However, facilities requiring extremely high CO_2 removal efficiencies may continue to favour MEA or blended solvent systems despite the associated energy penalty. Consequently, solvent selection should remain application-specific and guided by both process economics and product quality requirements [25].

4.6. Industrial and Sustainability Implications for Natural Gas Processing

The present findings have important implications for sustainable natural gas processing, particularly within emerging hydrocarbon-producing regions. The demonstrated 25–35% reduction in regeneration energy translates directly into lower steam consumption, reduced utility costs, improved plant profitability, and decreased indirect CO_2 emissions associated with energy generation.

For gas processing facilities operating within the Niger Delta, where energy costs, infrastructure limitations, and environmental regulations increasingly influence project economics, integrating optimized heat recovery into amine-based CO_2 capture systems offers an economically attractive pathway toward cleaner gas production. Beyond reducing operational expenditure, enhanced thermal efficiency improves overall process resilience by lowering fuel requirements and increasing energy utilization efficiency [26].

Furthermore, this study demonstrates the practical value of simulation-based process optimization in supporting engineering decision-making prior to full-scale plant implementation. Aspen HYSYS provides a robust platform for evaluating alternative solvent systems, optimizing operating conditions, and identifying cost-effective heat recovery configurations without disrupting industrial operations. Such digital process engineering approaches are expected to play an increasingly important role in the transition toward low-carbon natural gas processing.

Overall, the results indicate that strategic integration of appropriate solvent selection, optimized operating conditions, and efficient heat recovery can substantially reduce the energy penalty associated with amine-based CO_2 capture while maintaining satisfactory separation performance. These improvements contribute directly to cleaner hydrocarbon production, enhanced industrial competitiveness, and progress toward global decarbonization objectives.

5. Conclusion

This study has demonstrated that strategic integration of process optimization, solvent selection, and heat recovery can substantially reduce the energy penalty associated with amine-based CO_2 capture in natural gas processing. Through rigorous Aspen HYSYS simulation, the research established that regeneration energy requirements follow the order MEA > DEA > MDEA, with MDEA exhibiting the lowest specific energy consumption (2.95 GJ t^{-1} CO_2) due to its favorable bicarbonate formation pathway, while MEA achieved the highest CO_2 removal efficiency (96.5%) at the cost of significantly greater thermal duty. Implementation of optimized lean–rich heat exchange reduced overall process energy consumption by 25–35%, with MDEA demonstrating the greatest improvement (34.4% reduction) owing to its superior thermodynamic characteristics and lower baseline energy demand. Sensitivity analysis identified absorber temperature and solvent circulation rate as the dominant operational variables governing energy consumption, while regression analysis confirmed that heat exchanger efficiency exerts the strongest influence on overall thermal performance ($\beta = -0.71$, $p < 0.001$). The optimized process configuration—comprising 40 wt% MDEA operated at 45 bar absorber pressure, 35°C absorber temperature, 1.8 bar stripper pressure, 3 kmol m^{-3} gas solvent circulation rate, and 90% heat exchanger effectiveness—achieved a specific energy consumption of 2.10 GJ t^{-1} CO_2 while maintaining approximately 91% CO_2 removal efficiency. However, the analysis also revealed inherent trade-offs between maximizing CO_2 capture and minimizing energy demand, emphasizing the necessity for balanced multi-objective optimization rather than single-criterion performance maximization. These findings provide practical design guidance for improving thermal efficiency, reducing operating costs, and lowering the carbon footprint of natural gas sweetening operations, thereby supporting the development of more sustainable and economically viable gas processing facilities in emerging hydrocarbon-producing regions. Ultimately, this study contributes to the global transition toward cleaner energy systems by demonstrating that energy-efficient CO_2 capture is achievable through thoughtful process integration, thereby enabling continued natural gas utilization while mitigating greenhouse gas emissions.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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