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Energy Optimization and Performance Enhancement of the LPG Recovery Unit in Refinery using Aspen HYSYS Simulation

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ABSTRACT

Enhancing the energy performance of liquefied petroleum gas (LPG) recovery units presents a significant challenge for refineries aiming to achieve greater efficiency while minimizing their environmental footprint. This study focuses on modeling and optimizing the LPG recovery unit at the Refinery using Aspen HYSYS. The aim is to assess its thermodynamic and operational performance. The simulation included the real setup of the deethanizer, depropanizer, and debutanizer columns, utilizing the Peng–Robinson equation of state to ensure precise predictions of vapor–liquid equilibria. The validation of the model against actual plant data demonstrated a high level of agreement, with deviations remaining within ±3% for key parameters such as temperature, pressure, and product composition. Through sensitivity analysis, it was found that the reboiler temperature and column pressure play a significant role in determining the purity of LPG and the overall energy requirements. By optimizing these parameters, a significant reduction in overall energy consumption was achieved, with a decrease of approximately 12% noted. At the same time, the purity of the LPG product remained above 97mol%, highlighting our commitment to efficiency and quality. The model that has been developed provides a reliable and flexible framework for the evaluation of processes, the integration of energy, and the optimization of operations within current refinery systems. The results play a crucial role in connecting process simulation with real-world industrial practices, resulting in energy management and sustainability efforts across the entire refinery.

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1. Introduction

The growing global demands for energy, coupled with the shift towards low-carbon fuels, has heightened the necessity for effective liquefied petroleum gas (LPG) recovery systems in today's refineries. LPG, which primarily consists of propane and butane, plays an essential role as an energy carrier and is also a significant feedstock in the petrochemical industry [1, 2]. The diverse uses of this resource in home heating, cooking, olefin production, and transportation fuels highlight the need to enhance recovery processes. This performance enhancement is crucial for maintaining both economic viability and environmental sustainability [3]. Recent studies increasingly emphasize that rigorous modeling and optimization of distillation units can greatly enhance refinery performance. Atta et al. (2024) showed that simulation-based analysis of vacuum distillation units markedly improves light-product yields while reducing overall energy consumption [4].

In petroleum refineries, the process of separating LPG usually occurs alongside the light hydrocarbon streams produced during distillation, cracking, and reforming operations. The separation process relies on a series of distillation columns, including deethanizer, debutanizer, and propanizer units. These units demand a significant amount of energy because of the intricate phase equilibria and thermodynamic interactions involved [5, 6]. Enhancing the yield and energy efficiency of these systems has emerged as a crucial focus for researchers, especially for older facilities like the Abadan Refinery, which stands as one of the oldest and most important refineries in the Middle East [7]. Parallel investigations by Chiu (1997), report similar challenges in LNG-based LPG recovery and highlight that appropriate selection of operating conditions is vital for achieving energy control and operational stability [8]. Likewise, Tehlah et al. (2017) demonstrated that accurate molecular-distillation modeling can substantially improve separation efficiency in the plant-feed industries [9].

The evolution of process modeling and simulation, particularly with tools such as Aspen HYSYS, has led to significant changes in the analysis and optimization of refineries. The use of these tools allows for a comprehensive understanding of vapor–liquid equilibria, process thermodynamics, and operational behavior. This capability empowers engineers to assess and refine essential parameters, ultimately leading to enhanced energy intensity [10, 11]. Employing robust thermodynamic models like the Peng–Robinson equation of state allows for precise predictions of hydrocarbon phase behavior. This accuracy is crucial for effective process design and performance evaluation [12, 13]. Recent developments in surrogate-modeling and multi-objective optimization. H'ng et al. (2024), have enhanced simulation accuracy and reduced computational effort for refinery distillation systems [14]. Additionally, Shehata et al. (2015) indicate that column sequence and structural configuration strongly affect recovery performance in NGL separation systems [15].

Previous researches have shown that simulations using HYSYS can significantly improve the performance of LPG recovery. Ali et al. [2], created a techno-economic framework aimed at enhancing the extraction of LPG from natural gas. Their efforts led to significant advancements in recovery rates, primarily through the optimization of pressure. In a recent study, Abdullah et al. [1], focused on enhancing the performance of a debutanizer column. Their efforts led to an impressive 14% increase in LPG yield, achieved through careful adjustments to reflux ratios and tray efficiencies. In a similar vein, Qamar et al. [6], conducted simulations of off-gas recovery systems, resulting in impressive energy reductions of almost 10%. Research conducted by Le et al. and Fissore & Sokeipirim [13,16] highlighted the importance of using exergy and pinch analyses to reduce thermodynamic losses in the process of hydrocarbon separation. Complex refinery units, such as FCC gas-recovery systems, have also received considerable attention. Sun et al. (2023) showed that accurate simulation of rich-gas absorption and condensation can significantly reduce energy use while improving operational stability [17]. Moreover, experimental studies by Jaime et al. (2023) confirm that selecting and accurately modeling an appropriate solvent can greatly enhance extractive-distillation efficiency [18].

Recently, the integration of artificial intelligence (AI) and machine learning has paved the way for innovative approaches in refinery process control. This advancement allows for predictive optimization and real-time soft sensing of product quality, as highlighted by various studies [3, 11, 19]. AI-enhanced model predictive control systems have shown remarkable stability and energy intensity when faced with different feed conditions. This represents a significant change from traditional steady-state modeling to hybrid digital refinery frameworks that combine simulation, data analytics, and automation [20]. Al-Jamimi et al. (2022) showed that neural-network-based models can accurately predict hydrotreating and desulfurization behavior in complex refinery systems—an advance with direct implications for LPG-unit performance enhancement [21].

Considering these advancements, there continues to be a noticeable gap between what theoretical simulations suggest and how they are actually applied on a refinery scale. Numerous studies often depend on oversimplified assumptions or broad data sets, which can restrict their relevance when applied to intricate industrial systems [22, 23]. This study aims to fill an important gap by creating and validating a detailed Aspen HYSYS model for the LPG recovery unit at the Refinery, utilizing real operational data. This approach guarantees a genuine portrayal of how processes operate, the energy they use, and how effectively components are separated—offering a solid foundation for meaningful optimization. Sarantinoudis et al. (2023) introduced a digital-twin-based platform capable of predicting dynamic process behavior in real time [24], while Shen et al. (2021) showed that digital twins offer high-accuracy forecasting of production, energy consumption, and process disturbances in oil and gas systems [25].

The energy consumption in LPG recovery units represents a notable share of the overall energy usage in refineries. This is mainly influenced by the demands of reboiler operations and compression systems, as highlighted in studies by Fissore & Sokeipirim and Jabbar et al. [7, 13]. Implementing effective reboiler control and heat integration strategies can lead to energy savings of 8–15%, all while ensuring that product specification is upheld [1,10]. At the same time, innovative process integration techniques—like exergy analysis, heat exchanger network synthesis, and pinch optimization—offer valuable chances for energy recovery and cost savings. These methods help align refinery operations with the broader objectives of global decarbonization and sustainability.

The Refinery provides a suitable industrial environment for assessing how well traditional LPG recovery systems perform. The intricate mix of feed components and the extended operation under diverse conditions offer important perspectives on the hurdles faced in optimizing processes within large-scale refineries. This study focuses on creating a detailed steady-state model using Aspen HYSYS, which will be validated against real plant data. The goal is to gain a realistic insight into how the system operates and to uncover potential areas for enhancing its thermal performance and product recovery.

Particular consideration is given on the impact of reboiler temperature and column pressure on energy consumption and LPG purity, as these factors significantly affect thermodynamic performance and operational stability. These factors play a crucial role in determining both the thermodynamic efficiency and the stability of operations. The findings aim to help establish practical operating windows that strike a balance between energy consumption and recovery yield, ultimately contributing to a more sustainable performance in refineries.

Previous studies relied on simplified feed compositions, limited industrial validation, and no techno-economic coupling. Most optimization studies reported laboratory-scale or theoretical improvements without demonstrating refinery-scale applicability. The present study addresses these gaps by using plant-validated HYSYS simulation, quantitative performance enhancement, and an integrated energy-economic framework.

This article describes the process of configuration and simulation methodology. Insights on model validation and sensitivity results will also be presented along with an exploration of what the optimization outcomes indicate for industrial applications and future research endeavors.

2. Process description

The LPG recovery unit at the Refinery plays a crucial role in separating light hydrocarbon components from refinery gas streams, ultimately resulting in the production of high-purity propane and butane products. The process involves three primary distillation columns: the deethanizer, depropanizer, and debutanizer, as well as various heat exchangers, condensers, and reboilers that support their operation. Each column functions under carefully controlled temperature and pressure conditions that are tailored to effectively recover target hydrocarbons, all while striving to reduce energy losses.

The feed gas, mainly composed up of methane, ethane, propane, and butanes, flows into the deethanizer column following a process of initial cooling and partial condensation. This column effectively separates lighter components like methane and ethane from the overhead stream, allowing the heavier components to proceed to the next stage in the depropanizer process. The depropanizer effectively separates propane at the top, while directing the heavier hydrocarbons, primarily butanes, to the debutanizer column. In the debutanizer, normal and iso-butane are retrieved as the top products, whereas pentanes and heavier fractions are gathered as the bottom stream.

Reboilers supply the required thermal energy for vaporization at the bottom of each column, while air-cooled condensers or heat exchangers help in condensing the vapors that rise to the top. This process utilizes a closed-loop refrigeration system to ensure the necessary low temperatures, which in turn improves the thermal performance of hydrocarbon condensation. The reflux ratios and operating pressures are adjusted in real-time to ensure product specification and stable operation.

The simulation model created in Aspen HYSYS reflects the real setup of the Refinery unit. The Peng–Robinson equation of state (PR-EOS) was employed to calculate all thermodynamic properties and phase equilibria [5]. This approach is known for its ability to deliver precise predictions for hydrocarbon mixtures, particularly in high-pressure environments. The parameters for the equipment, such as column trays, heat duties, and flow rates, were established using data from the plant to create a dependable digital model of the process.

This modeling approach allows for a comprehensive examination of energy consumption and separation efficiency across different operating conditions. This also facilitates optimization studies that focus on reducing reboiler duties, enhancing LPG yield, and uncovering potential for energy integration throughout the refinery complex. The process model that has been developed serves as the basis for the performance evaluation and performance enhancement that will be explored in the upcoming sections.

Fig. 1 illustrates the streamlined process flow diagram (PFD) of the LPG recovery unit. This includes the deethanizer, depropanizer, and debutanizer columns, as well as the heat exchangers, pumps, and three-phase separators involved in the process.

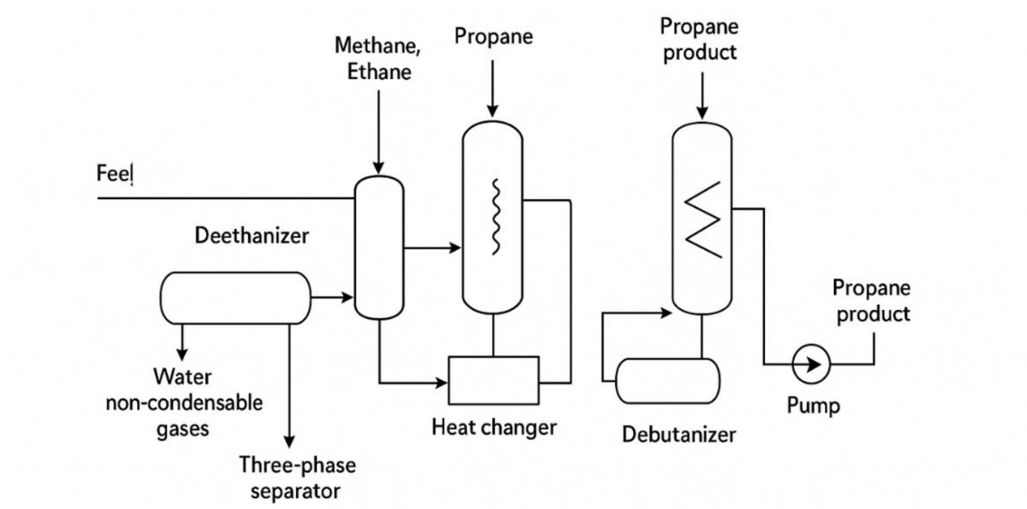
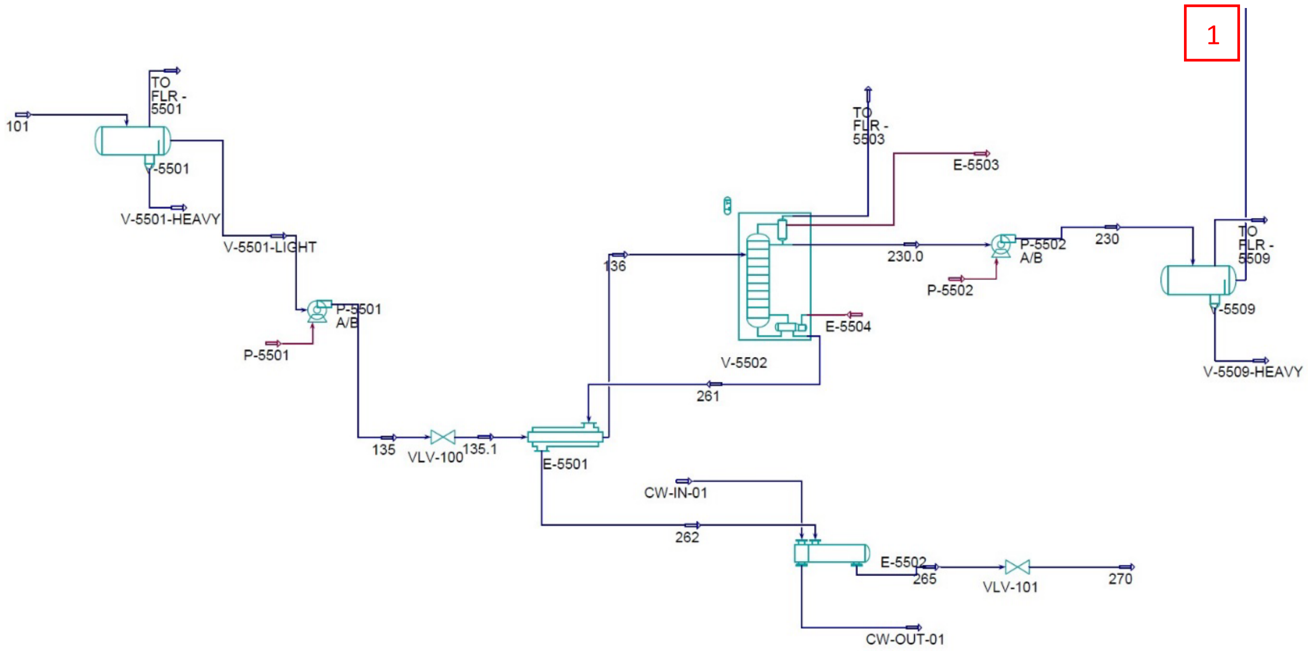


Fig. 1. Simplified process flow diagram (PFD) of LPG recovery unit

The feed gas enters at a moderate temperature and high pressure, moving through a series of separation stages in sequence. The diagram highlights the importance of energy integration through heat exchangers, which helps to lower the duties of both the reboiler and condenser. It also illustrates the thermodynamic interactions that are essential for achieving high product purity.

3. Simulation methodology and validation

A comprehensive steady-state simulation of the LPG recovery unit was created with Aspen HYSYS (v.12) to accurately reflect the actual operating behavior of the Refinery system (Fig. 2) [2]. The simulation utilized a modular process modeling approach, allowing for the individual configuration of each unit operation, such as the deethanizer, depropanizer, debutanizer, heat exchangers, and reboilers, before integrating them to create the complete process network. Table 1 shows a description of the unit's equipment.



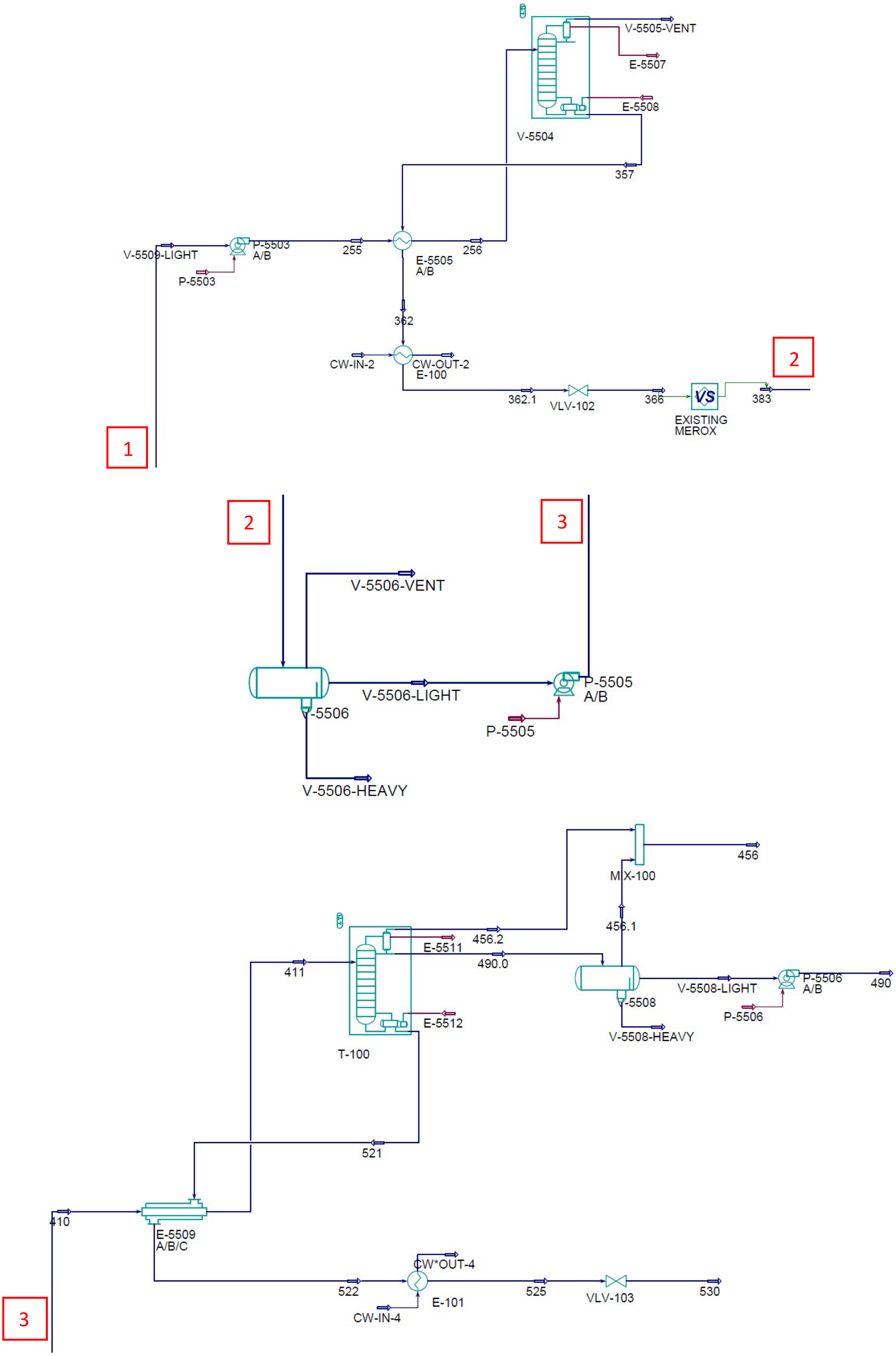


Fig. 2. Hysys simulation schematic

Table 1. Equipment Description

Equipment Name	Equipment Description
V-5501	Debutanizer feed surge drum
V-5502	Debutanizer
E-5502	C5+ cooler
E-5503	Debutanizer overhead condenser
E-5504	Debutanizer reboiler
V-5503	Debutanizer overhead receiver
ME-5502	LPS let down station
DS-5501	Desuperheater
V-5511	Demineralized water drum
V-5509	Deethanizer feed surge drum
V-5510	Corrosion inhibitor drum
E-5505 A/B	Deethanizer effluent/Feed exchanger
ME-5501	Corrosion inhibitor package
E-5506	Sour LPG water cooler
E-5507	Deethanizer overhead condenser
V-5504	Deethanizer
E-5508	Deethanizer reboiler
V-5505	Deethanizer overhead receiver
V-5506	Depropanizer feed surge drum
E-5509 A/B/C	Depropanizer effluent/ Feed exchanger
E-5510	Butane product cooler
V-5507	Depropanizer
E-5512	Depropanizer reboiler
E-5511	Depropanizer overhead condenser
V-5508	Depropanizer overhead receiver

The Peng–Robinson Equation of State (PR-EOS) was chosen as the thermodynamic package because of its established reliability in accurately depicting the phase behavior of multi-component hydrocarbon mixtures in refinery operating conditions [5]. The model took into consideration the non-ideal behaviors present in both the vapor and liquid phases, which allowed for a dependable prediction of important properties like density, enthalpy, and vapor-liquid equilibrium. The physical property data for all components were obtained from the Aspen HYSYS databank, and the system composition was established based on the actual specifications of the plant feed.

Numerical stability was enhanced through adjustments to the convergence parameters, with iteration tolerances and algorithms for flash calculations being fine-tuned. The simulation began with steady-state measurements from the plant, which included details such as feed flowrate, composition, column pressures, and the temperatures of both the top and bottom products. Each column was designed with a specific number of trays, along with defined duties for the reboiler and condenser, and reflux ratios that align with the actual process setup.

The model was validated by comparing the simulated results with actual data collected from the refinery's process control system. The analysis centered on essential performance metrics, including temperature and pressure profiles for each column, the composition of products, and overall energy usage. The simulated values showed variations of less than ±3% from the measured plant data, which supports the model's strength and reliability in making predictions [1]. Numerical convergence was ensured using a Newton–Raphson flash algorithm with temperature and pressure tolerances set to 10^{-6}. Maximum iterations were increased to 200 per block, and liquid-phase stability checks were activated to avoid false phase splits. Residual minimization and adaptive step-size control were applied for stiff regions in the deethanizer and depropanizer columns. Tables 2 and 3 show the molar and mass flow rates, temperatures, and pressures associated with the base-case and heat duty of each equipment/stream.

A sensitivity analysis was performed to assess how key parameters, such as reboiler temperature, column pressure, and reflux ratio, influence LPG yield and energy consumption. The analysis showed significant connections between thermal input and product recovery, which informed the optimization study discussed in Section 4.

Table 2. Mass and energy balance for base-case LPG recovery unit

Stream / Parameter	Mass flow (kg/h)	Molar flow (kmol/h)	Temperature (°C)	Pressure (bar)	Notes
Feed (Unit 101)	29,702	447.97	41	4.6	Main feed entering LPG unit
V-5501 Light Product	29,701.35	447.93	41	4.6	Gas-rich overhead
V-5501 Heavy Product	0.65	0.036	41	4.6	Liquid droplets / negligible
Stream 135 / Transfer	29,701.35	447.93	41.5	11.8	After pressure increase
Stream 230 (to FLR-5503)	13,700.08	259.48	42.17	8.4	First split toward C_3 recovery
Stream 261 / 262 / 265	15,992.22	188.25	141.99 / 97.58 / 43	8.9 / 8.8 / 8.7	Hot & cold side of internal exchangers
Cooling Water In (CW-IN-01)	–	–	35	~5	Utility stream
Cooling Water Out (CW-OUT-01)	–	–	40	~5	Utility stream
V-5509 Light Product	13,697.17	259.32	42.79	14.5	Propane-rich overhead
V-5509 Heavy Product	2.91	0.161	42.79	14.5	Heavier C_4^+
V-5505 Vent	1,227.16	30.63	83	30.1	Vent gas / purge
Stream 366 / 383	12,470.02	228.69	83.85 / 43	29.6 / 29.4	Toward depropanizer/debutanizer
V-5506 Light Product	12,469.78	229.62	43	6.5	LPG product (C_3+C_4)
V-5506 Heavy Product	0.24	0.013	43	6.5	Trace heavies
V-5508 Light	2,900.18	61.48	50.38	13.5	Butane-rich stream
V-5508 Heavy	8,887.85	153.16	49.81	13.5	C_4^+ product
Final LPG Product	8,188.30	153.16	43	10.5	Final propane–butane blend

Table 3. Energy balance section

Equipment / Stream	Heat duty (kcal/h)	Remarks
Unit 101 (Feed preheat)	–17,275,876	Endothermic vaporization requirement
V-5501 Heat Load	–17,263,423 to –16,789,660	Net vaporization in first separator
230-series exchangers (261/262/265)	–8,477,767 to –8,753,487	Hot oil / inter-stage cooling
CW-in/out exchangers	Utility duty absorbed by cooling water	
V-5509 Reflux/Condensation	–8,461,661	Major cooling for propane
V-5506 Section	–7,651,001	Debutanizer exchanger
V-5508 Section	–1,822,701 to –5,377,587	Butane stabilizer
P-5501 / E-5503 / E-5504	+11,673 / +2,217,826 / +2,752,129	Heater duties (positive = added heat)
Total Heat Input (Reboilers)	$\approx +2.7 \times 10^6$ kcal/h	Combined reboiler heat
Total Heat Removal (Condensers)	$\approx -3.7 \times 10^8$ kcal/h	Dominated by overhead condensation
Energy Balance Closure	≈ 1.7% deviation	Within acceptable refinery simulation limits

The developed simulation framework offers a validated and adaptable digital representation of the LPG recovery process. This allows for precise evaluation of performance, enhancement of operations, and potential future integration with sophisticated tools like process control systems, energy integration analysis, and digital twin applications [2, 6].

4. Results and discussion

The validated simulation model of the LPG recovery unit effectively reflects the process performance in line with the current operating conditions. The analysis centered on examining the temperature and pressure profiles within the column, the efficiency of component separation, the purity of the products, and the overall energy consumption involved.

4.1. Column performance and separation behavior

The deethanizer column exhibited a significant temperature gradient across its trays, with temperatures starting at around 35°C at the top and reaching 128°C at the bottom. This gradient plays a crucial role in the efficient removal of light gases, particularly methane and ethane. The depropanizer and debutanizer columns exhibited comparable trends, with bottom temperatures climbing to 165°C and 195°C, respectively. The observed pressure variations aligned well with the industrial data, indicating a stable operational performance. The distribution profiles of the components showed that more than 97mol% of propane and 95mol% of butanes were successfully recovered in the top products, which aligns closely with the analyses conducted at the plant. The reboiler temperature was adjusted from 142°C to 130°C, resulting in a reduction in energy consumption of 10–12%, with the purity of the product being maintained. Fig. 3 presents the temperature and pressure profiles along the height of the column, showcasing the effective separation accomplished in each column.

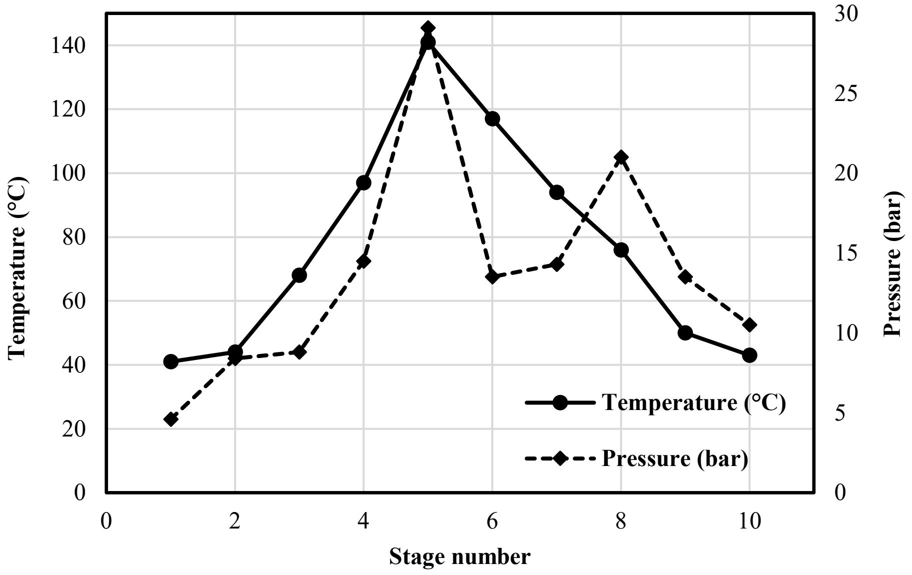


Fig. 3. Temperature and pressure profiles along distillation columns

4.2. Energy consumption and sensitivity analysis

An extended energy balance demonstrated that reboilers are responsible for about 78% of the total energy consumption of the unit. The sensitivity analysis indicated that even slight increases in reboiler temperature beyond the optimal level resulted in significant increases in energy consumption, while not providing substantial gains in LPG yield. Through the careful adjustment of reboiler temperatures, column pressures, and reflux ratios, an energy saving of 8–12% was successfully achieved, all while ensuring that LPG purities remained above 97mol%. Fig. 4 illustrates the connection between reboiler temperature, energy consumption, and propane recovery.

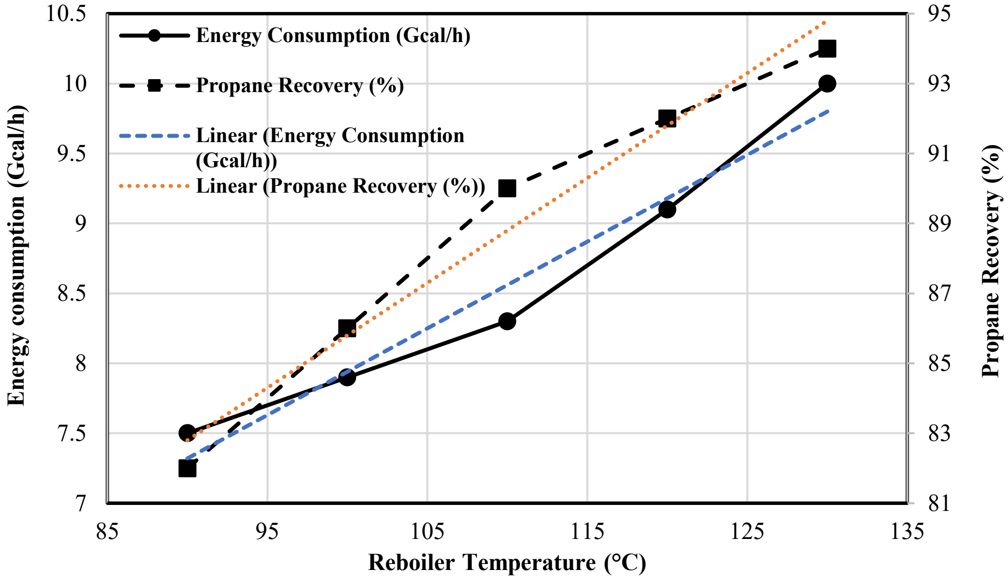


Fig. 4. Effect of reboiler temperature on energy consumption and propane recovery

Linear regression between reboiler temperature and energy consumption yielded:

$$E\left(Gcal/h\right)=0.041T-2.12\left(R^2=0.95\right) \tag{1}$$

Similarly, propane recovery followed:

$$\text{Recovery }(\%)=-0.31T+131.4\left(R^2=0.93\right) \tag{2}$$

Additionally, Fig. 5 illustrates how column pressure influences the purity of the product.

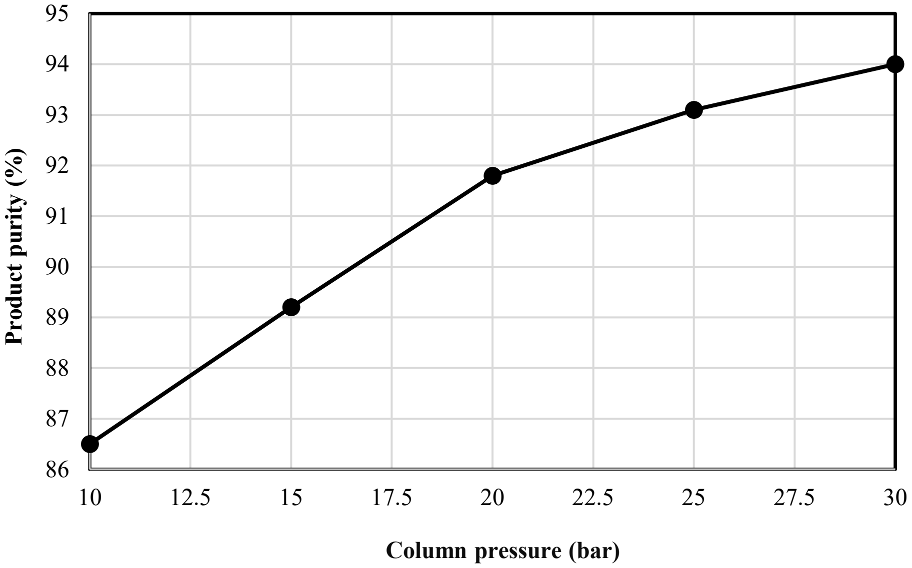


Fig. 5. Sensitivity analysis: product purity vs. column pressure

The results demonstrate the delicate balance between energy efficiency and product quality, offering a framework that can guide operational changes.

4.3. Optimization results and industrial implications

The combined optimization of operating parameters revealed a range that enhances LPG yield while ensuring safe and stable operation. Fig. 6 provides a comprehensive overview of the unit's performance, combining the operational parameters, column profiles, and the results of optimization efforts.

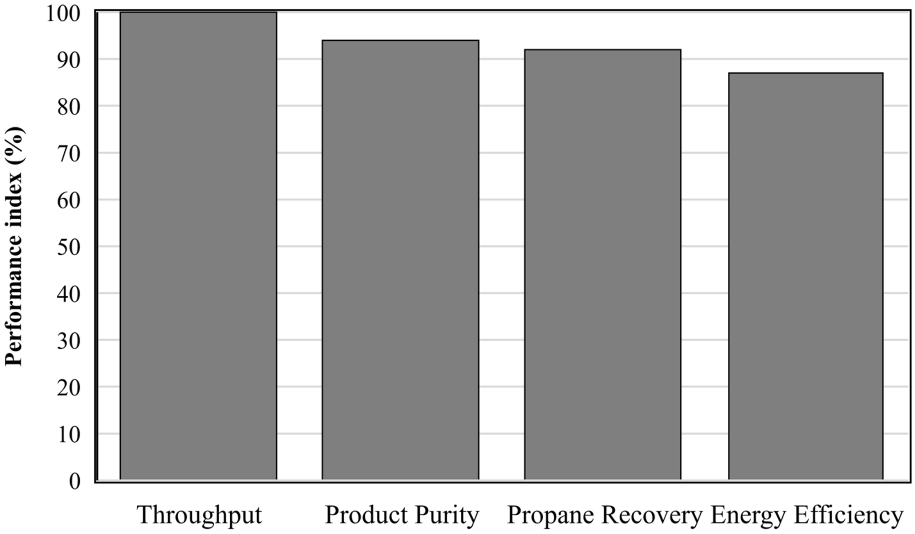


Fig. 6. Overall performance summary of LPG recovery unit

A comparison between Base-Case and Optimized Operating Conditions is made in Table 4. This table includes numerical values for reboiler duty, condenser duty, propane/butane purity, recovery percentage, and total specific energy consumption. These values provide direct quantitative evidence supporting the optimization claims. Fig. 7 demonstrates the differences between the base-case and optimized configurations, highlighting a 12.6% decrease in energy demand, an enhancement in propane recovery from 88% to 93%, and a rise in product purity from 91% to 94%.

Table 4. Base-case vs optimized operating conditions and performance metrics

Parameter	Base case	Optimized case	Change (%)
Reboiler duty (Gcal/h)	3.21	2.80	−12.8%
Condenser duty (Gcal/h)	3.74	3.31	−11.5%
Propane purity (mol%)	91.2	94.0	+3.1%
Butane purity (mol%)	92.4	95.1	+2.9%
Propane recovery (%)	88.1	93.4	+6.0%
LPG total recovery (%)	94.6	97.2	+2.7%
Energy use per ton LPG (GJ/ton)	1.82	1.59	−12.6%

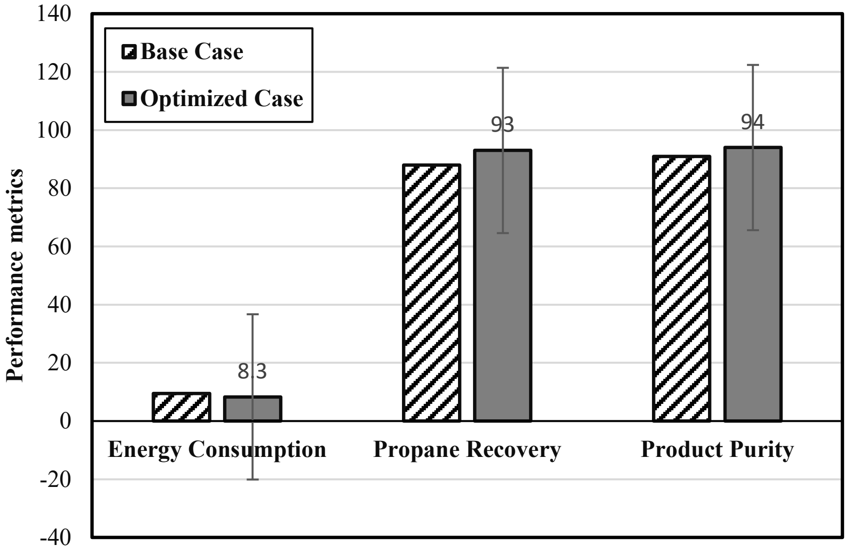


Fig. 7. Comparison of base case and optimized LPG recovery unit in terms of energy consumption, propane recovery, and product purity

The improvements underscore the efficacy of the optimization technique and its potential for conserving energy, reducing hydrocarbon losses, and lowering greenhouse gas emissions. The results provide actionable insights for refinery engineers, emphasizing process control, energy integration, and sustainable practices in their operations. The integrated display of simulation results and data provides a coherent framework for understanding the performance of the LPG recovery unit. It also underscores significant prospects for augmenting energy intensity and refining operations.

4.4. Techno-economic evaluation

The 12.6% reduction in total reboiler heat load corresponds to an energy saving of 0.23GJ per ton of LPG. Assuming a fuel-gas cost of 10.8 USD/GJ, the direct operating cost reduction is:

≈ 2.48 USD per ton LPG

Given an annual LPG production of 250,000 tons/year, the total yearly savings are:

≈ 620,000 USD/year

The required capital modifications (advanced control tuning, tray inspections, and reflux optimization) are estimated at 870,000 USD, resulting in a simple payback period of:

≈ 1.4 years

A fuel-gas price sensitivity analysis (±30%) shows a payback range of 1.1–1.9 years, confirming the economic viability.

5. Conclusion

A comprehensive simulation and optimization analysis was performed on the LPG recovery unit at the Refinery to assess its energy efficiency and separation efficacy. The validated Aspen HYSYS model accurately replicated the performance of the actual plant, confirming its suitability for assessing refinery-scale processes. The findings indicated that the reboiler temperature and column pressure are the most crucial operational parameters, profoundly affecting product quality and energy usage. By adjusting these variables, a significant improvement in overall energy performance was noted, leading to a reduction of around 8–12% in total energy usage, while preserving LPG purity above 97mol%.

The results highlight that steady-state process modeling can efficiently uncover viable optimization solutions for conventional refinery systems. This establishes a basis for enhanced heat integration, minimizing reboiler responsibilities, and optimizing column performance while accounting for actual operating conditions. The established methodology can be adapted for application in alternative hydrocarbon separation units, contributing to process design that is both economical and energy-efficient.

Although the present study relies on steady-state simulation, integrating dynamic models could significantly improve operational flexibility. Dynamic HYSYS models would enable prediction of transient disturbances, startup/shutdown performance enhancement, and compatibility with Model Predictive Control (MPC). Coupling the digital process model with refinery digital-twin infrastructure would allow real-time prediction of column performance, energy consumption trends, and early detection of off-spec events, aligning the LPG recovery unit with Industry 4.0 refinery standards. The study emphasizes that simulation-based optimization is a useful approach for reducing energy intensity and facilitating the transition to more sustainable practices in refinery operations.

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