Journal of Petroleum Science and Technology 14(3): 43, 2024, Pages 41-49
DOI: 10.22078/jpst.2025.5539.1952

Journal of Petroleum Science and Technology

Research Paper

https://jpst.ripi.ir/

Energy Efficiency and Cost-effectiveness Analysis on Flare Gas Recovery Consumption Sources at Industrial Gas Processing Plant

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Abstract
Flared gas recovery (FGR) plays a crucial role in controlling greenhouse-gas emissions and improving energy-efficiency in industrial gas plants. Every year, significant amounts of valuable gases are lost through flaring, leading to both environmental/economic consequences. Moreover, developing an effective and cost-efficient strategy for flare gas recovery remains a major challenge, requiring a careful balance between technical feasibility and financial viability. This study introduces a new approach to flare gas recovery by investigating two alternative utilization scenarios in a large-scale gas refinery. Furthermore, unlike conventional studies focusing primarily on economic feasibility, this research comprehensively integrates exergy analysis to evaluate energy and financial performance. This study analyzes all potential consumption sources of recovered flare gas and evaluates the feasibility and efficiency of two major effective scenarios. In the first scenario, recovered flare gases are compressed to 70 bar and injected into the gas sweetening unit, achieving an exergy-efficiency of over 69%. In the second scenario, recovered gases are redirected to existing compressors in the gas condensate stabilization unit, yielding a calculated exergy efficiency exceeding 78%. A detailed economic evaluation, considering both capital and operating expenditures, reveals that the overall flare gas recovery system has a return on investment of 17 months. Scenario one requires 24 months to break even, whereas scenario two achieves profitability in just 11 months. Ultimately, findings demonstrate that directing recovered flare gases to compressors of gas condensate stabilization unit provides most efficient and optimal utilization of these gases. Also, this research presents a viable solution for reducing emissions, minimizing waste, and maximizing both energy and financial resources in gas processing plants.

Keywords: Exergy Analysis, Economic Evaluation, Flare Gas Recovery, Gas Refinery, Greenhouse Gas.

Introduction
The global increase in population and improved living standards has led to a rise in greenhouse gas emissions. Large amounts of co-produced gas are being flared to meet the demand for oil and gas, causing environmental harm and wasting valuable energy resources. Moreover, this practice has sparked controversial debates due to its dual impact on the environment and the petroleum industry [1]. In addition, flares are designed to safely eliminate waste gases from industrial plant operations, including the discharge of flammable waste gases from refinery activities. Furthermore, these gases are collected and sent to a flare system for secure disposal. Moreover, according to a report from the Global Gas Flaring Reduction Partnership by the World Bank, it has been estimated that approximately 150 billion cubic meters of natural gas are burned annually globally. In addition, this represents approximately 25% of the total annual natural gas consumption in the United States [2]. In 2021, more than half of the gas flaring worldwide was attributed to the five countries: Russia, Iraq, Iran, the United States, and Algeria. Additionally, this practice represents a significant economic loss, especially considering the current high natural gas prices. It is estimated that this wastefulness amounts to a staggering USD 55 billion annually [3]. Gas flares burn in open flames, releasing carbon dioxide, methane, sulfur dioxide, and other pollutants into the atmosphere, leading to climate change, air pollution, and public health issues. Moreover, the inefficiency of flare systems results in a conversion rate of less than 97%, releasing a significant amount of methane into the atmosphere without being fully burned. This methane, known for its potent greenhouse effect, contributes more than 20 times the impact of carbon dioxide on global warming [4]. Furthermore, gas flaring continues to be prevalent in various regions globally,

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Received 2024-09-10, Received in revised form 2025-02-03, Accepted 2025-02-09, Available online 2025-08-16

particularly in developing countries with weak or ineffective regulations [5]. In 2019, flaring activities resulted in the release of approximately 400 million tons of CO_2 emissions [6]. These initiatives align with the Tokyo and Paris Protocols, which emphasize the need for international collaboration to mitigate climate change's destructive effects. By implementing these measures, we aim to effectively reduce gas flaring emissions, promote sustainable development, and safeguard the environment for future generations. The International Energy Agency has set a goal of eliminating routine flaring by 2030 as part of its Sustainable Development Scenario, which strives to lower greenhouse gas emissions and combat global warming [7]. However, achieving this target will require significant investments in infrastructure and technology, along with strong government policy and regulatory support.

Iran holds a prominent status as a major global producer and exporter of natural gas, accompanied by substantial oil reserves. It is worth noting, nonetheless, that the practice of gas flaring within Iran's oil and gas industry emerges as a significant environmental quandary, actively contributing to detrimental air pollution levels and the emission of greenhouse gases [8]. According to the World Bank's Global Gas Flaring Reduction Partnership, a significant amount of gas was flared in Iran in 2019, reaching approximately 16.7 billion cubic meters [9]. To address this issue, the South Pars Gas Complex, which manages the major gas project in Iran's Persian Gulf region, has undertaken a five-year initiative to reduce gas flaring in the largest shared gas reservoir with Qatar. The objective of this initiative is to completely eliminate all flaring activities at the South Pars site by March 2020, thereby preventing the burning of up to 400 million cubic meters of associated petroleum gases on an annual basis. In addition to mitigating environmental concerns, this sustainable development plan is projected to augment natural gas production from South Pars by an annual increment of 400 million cubic meters, leading to an estimated $80 million in year. Notably, the South Pars gas field has emerged as the primary source of gas flaring in Iran, accounting for approximately 70% of the total volume of flared gas [10] . As a prominent global oil and gas producer, Iran carries a considerable carbon footprint attributed to flaring. However, Iran is actively taking steps to mitigate this impact. In recent years, the country has introduced several initiatives to enhance energy efficiency and reduce emissions within the oil and gas sector. For instance, the National Iranian Oil Company has committed to achieving zero routine gas flaring by 2025. To realize this goal, substantial investments have been made in constructing flare gas recovery systems across multiple production sites [11]. The growing recognition of the significance of environmental and economic factors has resulted in a heightened adoption of flare gas recovery systems aimed at reclaiming gases expelled through flare header systems, repurposing them for alternative applications. Technological advancements in this domain have facilitated substantial reductions in the quantity of discharged gases within refineries, accomplished through the implementation of gas compression and recovery systems [12]. Moreover, utilizing the FGR system offers the notable advantage of mitigating the undesirable consequences of continuous flaring. Implementing this innovative system substantially reduces smoke, heat, noise, and emissions, thereby bestowing significant environmental and community benefits. Also, the FGR system encompasses fundamental processes encompassing the recovery of flare gases from the header, the compression of these gases using compressors, and the subsequent separation of entrained liquids in a separator. Once separated, the remaining gas undergoes treatment to eliminate contaminants such as H2S, rendering it suitable for use as a fuel gas. The design of these systems incorporates various considerations, including capacity, pressure, temperature, material selection, and safety measures, to ensure their effective and safe operation [13]. The choice of compressor technology significantly influences the design of Flare Gas Recovery (FGR) systems, with implications for initial cost, physical dimensions, and operational and maintenance expenses. Gas refineries typically employ either liquid ring compressors or reciprocating compressors to compress gases to construct FGR units. Notably, using liquid ring compressors offers a substantial advantage wherein the gas undergoes cooling through heat transfer with water inside the compressor during the compression process. Fig. 1 illustrates the schematic process of the flare gas recovery system. In addition, an alternative option to water for separating hydrogen sulfide from flare gases is the utilization of amine. On the contrary, reciprocating compressors are easily accessible for procurement and offer spare parts, repair, and maintenance services. However, it is crucial to acknowledge that reciprocating compressors have the potential to explode if the temperature surpasses the allowable limit [14].

Materials and Methods

Objective

The South Pars gas processing complexes are the prominent refineries in southern Iran, characterized by their massive scale. These complexes are closely linked to Qatar's North Field, regarded as an extension of it, boasting a vast capacity of 10.2 trillion standard cubic meters. The initial discovery of the field dates back to 1988, and current estimations suggest a minimum natural gas volume of 3.4 trillion standard cubic meters, potentially even greater [15]. According to Rahimpour et al. (2012), the current daily burn rate within this network of flares is estimated to be a staggering 365 million cubic feet of gas. These statistics underline the vast magnitude of industrial operations in the area and underscore the urgent necessity for implementing sustainable measures to alleviate the environmental consequences [16]. Tables 1 and 2 present a comprehensive analysis of the constituents and state of typical flaring. This data serves as a foundation for simulating and optimizing the retrieval system for flare gas. Maintaining a favorable backpressure in the flare header to avert air infiltration and potential explosions is crucial, emphasizing the necessity of effectively utilizing these gases. A gas processing facility that operates efficiently and safely depends on the optimal utilization of these gases to maximize production output while minimizing adverse impacts on the environment [17].

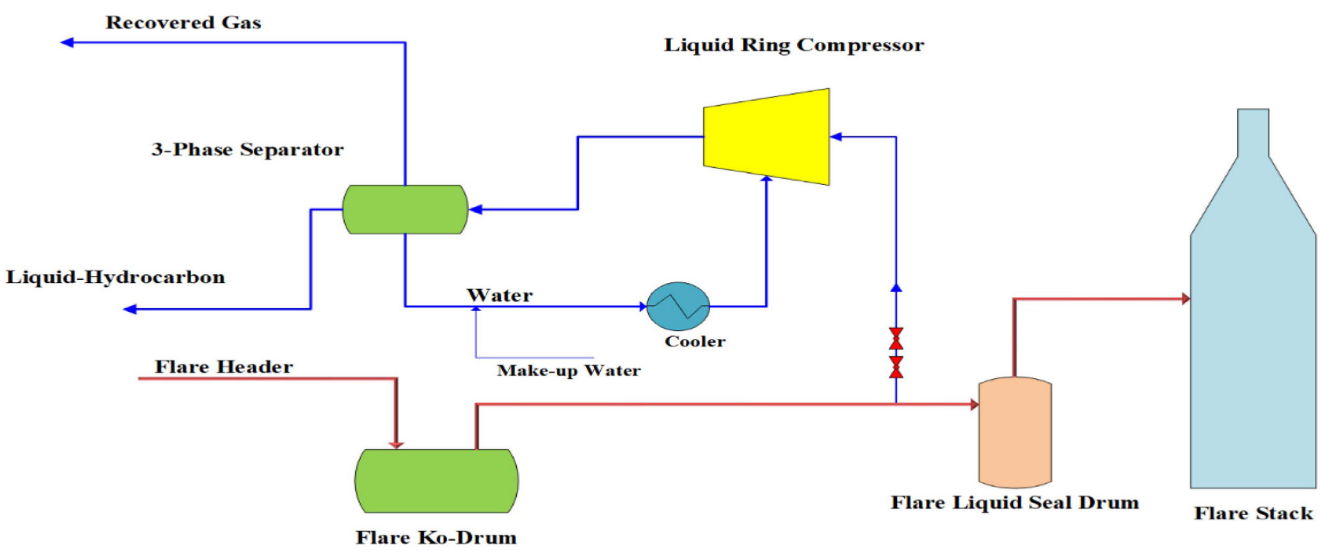

Fig. 1 Flare gas recovery system Schematic.

Table 1 Composition of gathered flare gas [16].

Component	Mole fraction
Methane	0.8527
Ethane	0.0543
Propane	0.0199
Nitrogen	0.0355
CO_2	0.0192
i-Butane	0.0036
n-Butane	0.0057
i-Pentane	0.0018
n-Pentane	0.0016
H_2O	0.0005
H_2S	0.0052

Table 2 Conditions of Flaring [17]

Conditions	Value
Temperature (C)	34.19
Pressure	305
Mass flow (kg/h)	29000
Molar enthalpy (kJ/kgmol)	-7.981e + 004

At the South Pars gas processing plant, different types of flare networks are categorized based on their pressure levels: high-pressure, medium-pressure, and low-pressure flare headers [18]. Moreover, the design of the flare gas recovery system is influenced by the origin of the consumed gas, as different gas compositions require specific treatment procedures. Furthermore, various methods can be employed, including converting the retrieved gas into Gas to Liquid, liquefying it as natural gas (LNG), or utilizing it for power generation through gas-to-wire systems. Moreover, the gas sweetening unit is utilized to eliminate sour components. To effectively manage consumption sources, a viable approach is to reinject the recovered gas into the gas processing facility. The existing gas sweetening unit is the most suitable option for reinjecting the recovered gas [16]. Two scenarios exist for reinjecting the recovered flare gas at the gas processing plant.

First Scenario

In the first scenario, the recovered gas from the flare gas recovery system is directly directed towards the gas sweetening unit. Nevertheless, considering that the gas must reach a pressure of 70 barg to align with the sweetening process requirements, including a compressor station becomes imperative to elevate the gas pressure. In the first scenario, the recovered gas from the flare gas recovery system is directly directed towards the gas sweetening unit. Nevertheless, considering that the gas must reach a pressure of 70 barg to align with the sweetening process requirements, including a compressor station becomes imperative to elevate the gas pressure. In the first scenario, the recovered gas undergoes compression stages at the compressor station to reach the required pressure of 70 barg. Subsequently, the compressed gas is directed into the gas sweetening unit while maintaining a temperature of 40 degrees Celsius at the increased pressure. This enables the gas to effectively undergo the necessary sweetening process within the unit. Following this approach, the recovered flare gas can be efficiently injected into the gas sweetening unit, ensuring its proper treatment and utilization within the overall gas processing plant. Fig. 2 depicts the process block diagram of this scenario.

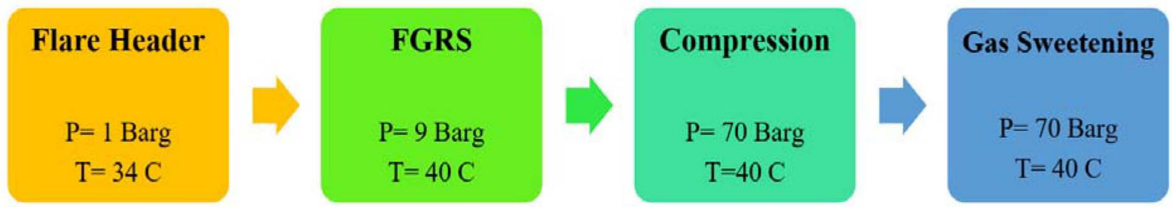

Fig. 2 Process Block Diagram of First Scenario.

First Scenario Technical Challenges

Implementing the first scenario—compressing recovered flare gas to 70 barg for injection into the gas sweetening unit- involves several technical hurdles. One of the biggest challenges is the high energy demand required for multi-stage reciprocating compressors to reach the target pressure. These compressors must operate continuously under significant stress, increasing the likelihood of mechanical failures and frequent maintenance. Compression generates a large amount of heat, making intermediate cooling systems essential to keep gas temperatures at 40°C. In addition, excessive heat could damage equipment without proper cooling or, in extreme cases, pose explosion risks if temperatures exceed safe limits [18]. Another key challenge is smoothly integrating the compressed flare gas into the existing gas sweetening unit. Also, the injected gas must meet strict pressure, temperature, and purity standards to prevent disruptions in the sweetening process. Fluctuations in gas composition, particularly varying levels of sulfur compounds like H_2S, could overload the absorption columns, reducing efficiency and driving up operational costs. Retrofitting the system to handle the additional gas flow may require modifications to piping, control systems, and safety protocols, all of which must align with the plant's operational constraints, while ensuring compliance with environmental and safety regulations. Successfully addressing these challenges requires careful engineering, advanced process control strategies, and well-thought-out contingency plans to manage potential system upsets or emergency shutdowns.

Second Scenario

In the second scenario, the recovered gas from the flare gas recovery system follows an alternative path. It is introduced directly into an established compression station called the off-gas compressor. The off-gas compressor station's primary responsibility is compressing the volatile gas from the condensate stabilization unit. Under normal circumstances, the gas derived from the upper section of the condensate stabilizer tower is directed through the off-gas compressor station. The gas undergoes a pressure increase within this station to reach 70 barg. Once the desired pressure level is attained, the gas enters the gas sweetening unit, which undergoes further processing. In the gas processing plant, the recovered gas from the flare gas recovery system is channeled towards the initial stage of the off-gas compressor after recovery. In this first stage, the gas is maintained at a pressure of 9 barg and a temperature of 40 degrees Celsius. By implementing this secondary scenario, the recovered gas is smoothly integrated into the current compression system of the plant, specifically within the off-gas compressor station. This strategic approach enhances resource utilization and promotes overall efficiency. Fig. 3 Shows the process block diagram of the second scenario. Moreover, the primary assessment of this scenario initially suggests its advantages in minimizing both capital and operational expenditures. Furthermore, this paper utilizes a comprehensive approach to examine the flare gas recovery system meticulously. Also, this involves conducting simulations and exergy analysis for two distinct scenarios. Ultimately, an economic evaluation is carried out to determine the feasibility and long-term sustainability of implementing the proposed system.

Second Scenario Technical Challenges

The second scenario, while economically advantageous due to its reliance on existing infrastructure, introduces technical challenges tied to integrating flare gas into the off-gas compressor station. A key issue arises from the inherent variability in flare gas composition and flow rates, which can disrupt the compressor's operational stability. Initially engineered for steady-state gas from the condensate stabilization unit, the off-gas compressor may struggle to handle fluctuating flare gas inputs, leading to surging, overheating, or incomplete compression during sudden volume spikes. Additionally, the combined load of flare gas and condensate-derived gas could exceed the compressor's design capacity, necessitating upgrades to critical components such as seals, valves, and cooling systems to prevent mechanical failures. Furthermore, synchronizing the flare gas recovery system with the compressor's control logic requires advanced automation to adjust pressure, temperature, and flow rates dynamically. Inadequate control strategies might result in pressure imbalances between the flare header and compressor inlet, increasing the risk of backflow or system downtime.

Energy Efficiency

Energy analysis plays a crucial role in the gas refinery sector due to the significant impact of energy consumption on costs and productivity across various processes within the industry [19]. Moreover, this analytical approach enables refinery management to identify areas of strength and weakness in energy consumption and initiate necessary improvements. In particular, the concept of exergy, which refers to the maximum amount of work attainable from an ideal system given a specific energy input, holds utmost importance. Furthermore, exergy efficiency serves as a vital parameter for assessing the overall efficiency of a process, taking into account the available equipment and its corresponding energy consumption. Also, the exergy efficiency is determined by calculating the ratio of output exergy to input exergy within the system, thus serving as an indicator of the system's energy efficiency [20]. In addition, the presented equations illustrate the calculation methodology for determining the exergy efficiency of an open process system [21].

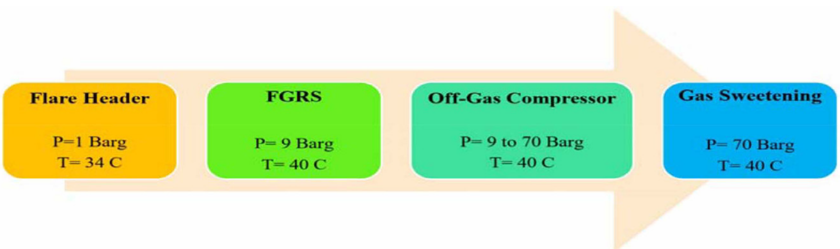

Fig. 3 The Second Scenario Block Flow Diagram.

$$\Delta E=\Delta H - T^*\Delta S \quad (1)$$

$$\text{Exergy Efficiency} = (\text{output exergy})/(\text{input stream exergy}) \quad (2)$$

$$\text{Output Exergy} = \text{output stream exergy} + \text{Compressor power} \quad (3)$$

$$\text{Input Exergy} = \text{Input exergy} + \text{Cooler Duty} \quad (4)$$ [21]

ΔE = Change in exergy (kJ)
ΔH = Change in enthalpy (kJ)
T = Temperature (K)
ΔS = Change in entropy (kJ/K)
Among the various factors influencing the utilization of recovered gases, the performance analysis and efficiency of scenarios in the energy sector are of particular significance. The exergy efficiency calculations for each scenario offer a means for analyzing and selecting the most suitable option for the consumption of recovered flare gases. The initial step involves simulation to initiate exergy studies and assess energy and duty associated with streams and equipment. Subsequently, these parameters are utilized to perform the exergy analysis.

Results and Discussion

FGR Exergy Analysis

The data presented in Table 1 and Table 2 elucidate the extent of gas flaring under normal conditions, encompassing information on quantity, gas composition, and operational parameters. Emitted gases are systematically collected and channeled into a flare gas recovery system, where a vertical suction drum separates liquid components from the gas. It is crucial to recognize that flare gas recovery systems, tailored for typical flare loads, may inadequately address emergency flare loads due to varying flare rates. These systems should align with local regulations, consider refinery throughput and operating modes, and be sized for dynamic load variations. Achieving over 90% annual flare load recovery necessitates designing compression facilities to handle 2 to 3 times the average normal flare load, with specific considerations for facilities like chemical plants with less variable flare rates [6]. The Peng-Robinson model is commonly employed for the determination of thermodynamic parameters such as enthalpy, entropy, phase equilibrium, and duty. In the case of the flare gas recovery system, an analysis is performed by conducting a simulation to assess the system's energy and mass balances. Moreover, this involves gathering relevant data pertaining to the energy of streams and equipment. Subsequently, the system's exergy efficiency is calculated. Fig. 4 presents the comprehensive energy balance derived from the steady-state simulation of the FGR system.

$$\text{Exergy Efficiency} = (13+1870+1972)/(2210+1854+1917)*100 = 64.45\,\% \quad (5)$$

Using the simulation data, the exergy efficiency of the FGR system is calculated, yielding a value of 64.45%. As determined in this analysis, the exergy efficiency of a flare gas recovery system accounts for numerous factors, including the type of compressor used, its efficiency and compression ratio, and the temperature of the gases exiting the compressor and intermediate coolers. This information is critical in assessing the energy efficiency of the FGR system and holds significant importance. Notably, the exergy efficiency directly impacts the system's costs and overall efficiency. Hence, enhancing and optimizing the factors that influence this value can contribute to an improved overall efficiency of the FGR system.

First Scenario Exergy Analysis

In the first scenario, the objective is to raise the pressure of gases extracted from the flare network utilizing reciprocating compressors, from 9 to 70 bar. The exergy efficiency of this particular scenario is calculated by employing the simulation-based exergy scenario and the acquired data. As per the calculations, the exergy efficiency for scenario one amounts to 69.01%. Fig. 5 illustrates the block diagram depicting the energy balance in the first scenario of recovered gas from the flare header. This exergy efficiency value is employed as a comprehensive macro index when assessing the energy efficiency within the first scenario, subsequently reflecting energy utilization and system performance. The aforementioned percentage indicates a substantial conversion of the input energy into productive and functional work output.

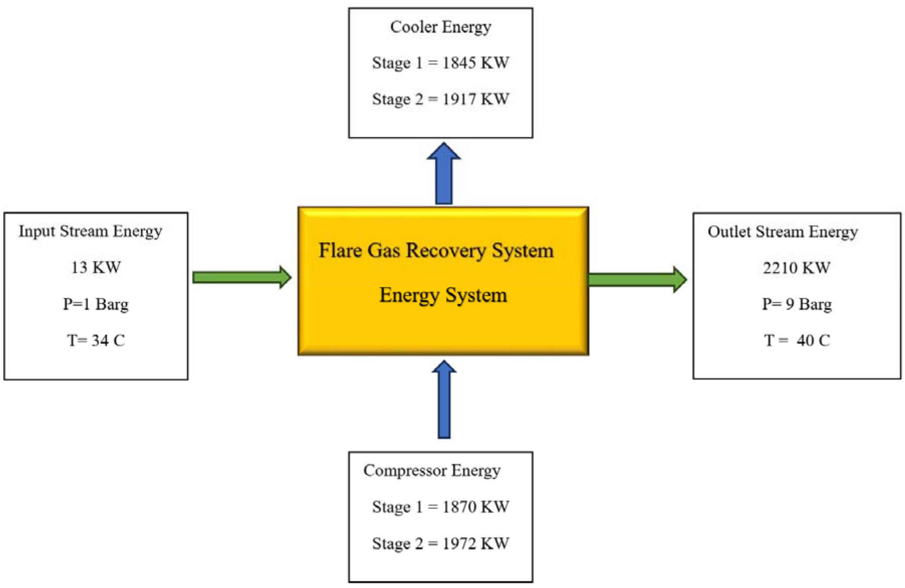

Fig. 4 FGRS Energy Balance.

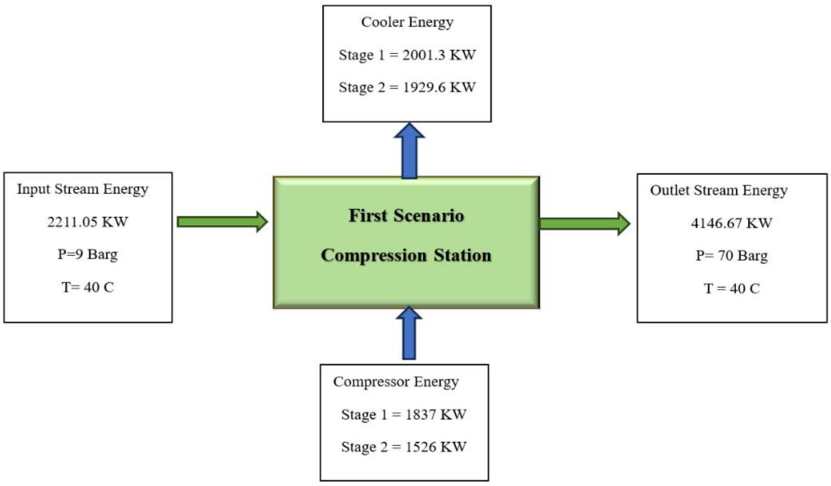

Fig. 5 Energy Balance on First Scenario of Recovered gas.

$$\text{Exergy Efficiency} = (2211.05+1837+1526) \,/\, (4146.67+2001.3+1929.6) \; *100 = 69.01\ \% \tag{6}$$

Second Scenario Exergy Analysis

The gas condensate stabilization unit is crucial in the gas refinery structure, primarily dedicated to stabilizing and processing the extracted gas condensate from the refining process. Its function encompasses creating suitable conditions for subsequent processes, achieved through removing gases from heavy components and mixtures of gas condensates. A second scenario involves the injection of recovered flare gases into this unit's off-gas compressors. Following recovery by the Flare Gas Recovery (FGR) system at a pressure of 9 bar, the flare gases are introduced into the first stage of the Off-Gas compressors, where their pressure is subsequently increased to 70 bar, before being directed to the gas sweetening unit of the refinery. Moreover, reciprocating compressors are utilized in this scenario, incorporating intermediate coolers to maintain a consistent temperature throughout the compression process. Based on the assessment of exergy flows, energy input from the compressors, and energy output from the coolers, the calculated exergy efficiency for this process amounts to 78.59%. Fig. 6 presents the block diagram illustrating the energy balance in the second scenario, where recovered gas from the flare header is injected into the Off-Gas compressor.

$$\text{Exergy Efficiency} = (2211.05+797.2+2213.7+2913.5) \,/\, (5569.7+2528+2254) = 78.59\% \tag{7}$$

A high exergy efficiency is a paramount indicator of productivity and effectiveness within the system, reflecting the amount of energy successfully converted into a useful and usable form throughout the process. By enhancing exergy efficiency, energy availability for useful work increases while reducing energy losses. Consequently, this improves the overall performance and productivity of the process, lowers costs, and contributes to mitigating adverse environmental impacts.

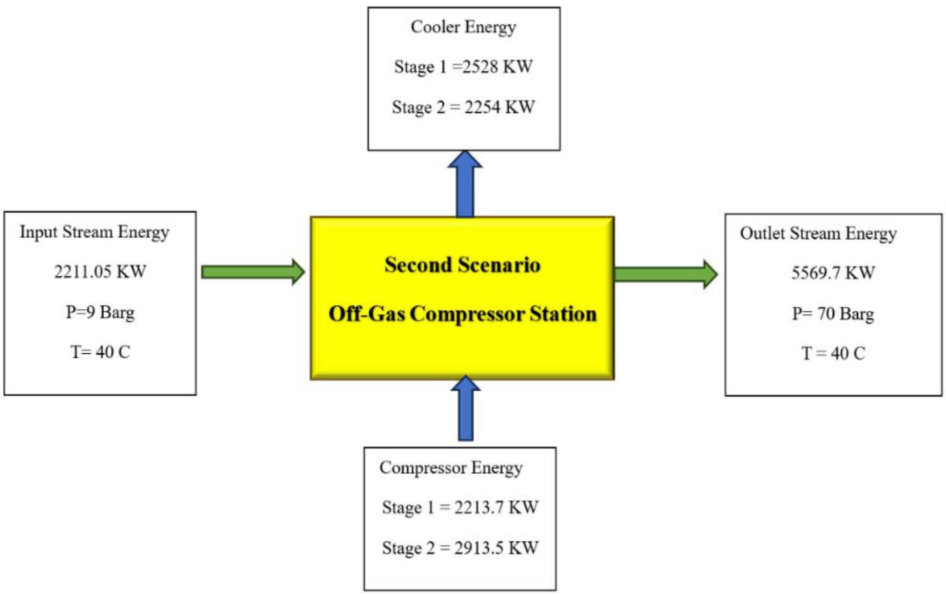

Fig. 6 Energy Balance on Second Scenario of Recovered gas.

The exergy analysis reinforces these findings, highlighting the importance of key operational factors such as compressor choice, efficiency, and thermal management. In the first scenario, the system achieves an exergy efficiency of 64.45%, while the second scenario surpasses it with an outstanding efficiency of 78.59%. This demonstrates how optimizing the recovery system can greatly reduce energy losses and enhance overall process performance. Fig. 7 presents the economic evolution data for both the flare gas recovery system and its consumption scenarios, offering a detailed comparison of the financial benefits achieved through improved efficiency.

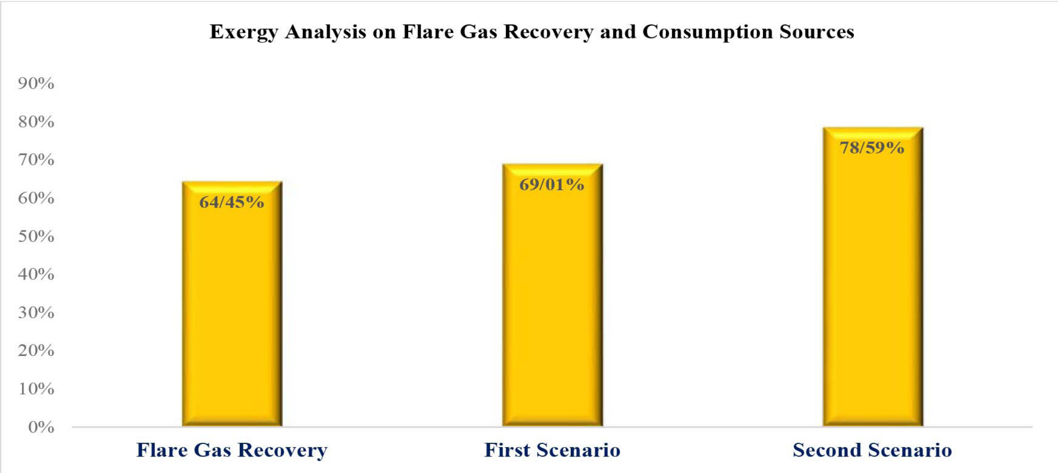

Fig. 7 Energy Analysis Data on Flare Gas Recovery Consumption Sources.

Cost-Effective Analysis

The economic evaluation of flare gas recovery systems and their associated consumption sources focuses on determining the rate of return on investment. This evaluation assesses the financial viability of implementing such systems by considering various factors, including capital costs, operational expenses, and projected revenue generated from the recovered gas. Moreover, by quantifying the potential economic benefits, such as reduced fuel consumption and the sale of recovered gas, this evaluation provides valuable insights into the feasibility and profitability of investing in flare gas recovery systems. Additionally, it aids decision-making for industry participants, allowing them to prioritize investments based on the projected return on investment and optimize their operational practices to enhance sustainability and financial performance. Notably, a comprehensive survey carried out by John Zink, a renowned provider of combustion equipment and environmental systems, underscores that initiatives leveraging the FGR system to reclaim gases vented to the burner manifest a comparatively concise return on investment timeframe. On average, these projects achieve a rate of return within the span of 14 to 16 months, thereby demonstrating a significantly swifter recoupment period in contrast to analogous endeavors witnessed within the industry [10]. This study focuses on conducting economic analyses by simulating two scenarios, named scenario one and scenario two. In addition, the simulations employ software to model the recovery process of flare gases, considering relevant data concerning process equipment and energy consumption. Furthermore, this comprehensive evaluation allows for the assessment of economic factors. Following the simulations, calculations are performed to determine the project's fixed costs, operational costs, and return on investment rate, using equations 8 to 9 as referenced in the academic literature.

Capital Cost=∑(Cost of Equipment+Construction Costs+Other Initial Costs) (8)

Operating Cost=∑(Utility Costs+Labor Costs+Maintenance Costs+Other Recurring Expenses) (9)

Utility Cost=Power (kW)×Operating Hours/Year×Electricity Price ($/kWh) (10)

“Revenue=Recovered Gas (kg/h)×Hours/Year×Calorific Value×Gas Price (11)

Net Profit=Revenue-OPEX (12)

Rate of Return (Months)=(CAPEX/Net Profit)×12 (13)

To establish the selling price of gas, it is necessary to calculate its heat capacity. The simulation data reveals that the projected gas selling price in 2024 is estimated at 2.7 USD/MMBtu. Additionally, the calorific value of the recovered flare gases is determined to be 0.04 MMBtu/kg [5]. Taking into account the recovered flare gas quantity of 27,800 kg per hour and taking into consideration the prevailing global gas prices, the revenue from its sale is expected to exceed 23 million dollars. Furthermore, it is standard practice for a refinery unit to operate for approximately 330 days annually, adhering to established refinery design standards. However, it should be noted that a provision of 36 days is allocated for major repair activities. The economic evaluation of the flare gas recovery system compared two scenarios, the first scenario and the second scenario. The evaluation took into account various cost factors such as capital cost, operating cost, utility cost, equipment cost, and installation cost. According to the calculations, the second scenario revealed a rate of return of 11 months. This means that the project will start generating profit and benefits after this period. Considering its cost-effectiveness, the second scenario emerged as the optimal choice for consumption. This scenario considers the existence of an already established compressor station, which impacts both capital and operating expenditures. Ultimately, based on these considerations, the second scenario is recommended as the best selection for consumption. Table. 3 presents valuable data on the economic evaluation of various scenarios regarding the recovered flare gas consumption sources.

Table 3 Economic Evaluation on Flare Gas Recovery Consumption Sources.

Item	FGR System	First Scenario	Second Scenario
Capital Cost ($)	11.545.000	7.334.000	2.070.000
Operating Cost ($)	5.089.000	4.503.000	1.778.000
Utility Cost ($)	2.931.000	2.955.000	1.250.000
Equipment Cost ($)	6.307.000	3.021.000	840.000
Installation Cost ($)	7.387.000	3.830.000	500.000
Rate of Return (Months)	17	24	11

Among the two scenarios analyzed, directing recovered gases to the compressors in the gas condensate unit offers the best financial return, achieving a payback period of just 11 months, half the 24 months required in the alternative scenario. This demonstrates the economic value of repurposing flare gases, transforming waste into a valuable asset. Fig. 8 shows the exergy evolution data for the flare gas recovery system and consumption scenarios, highlighting the optimized gas utilization approach's superior efficiency and economic benefits. Moreover, these results support the implementation of flare gas recovery as an effective solution for improving the industry's energy efficiency and financial outcomes.

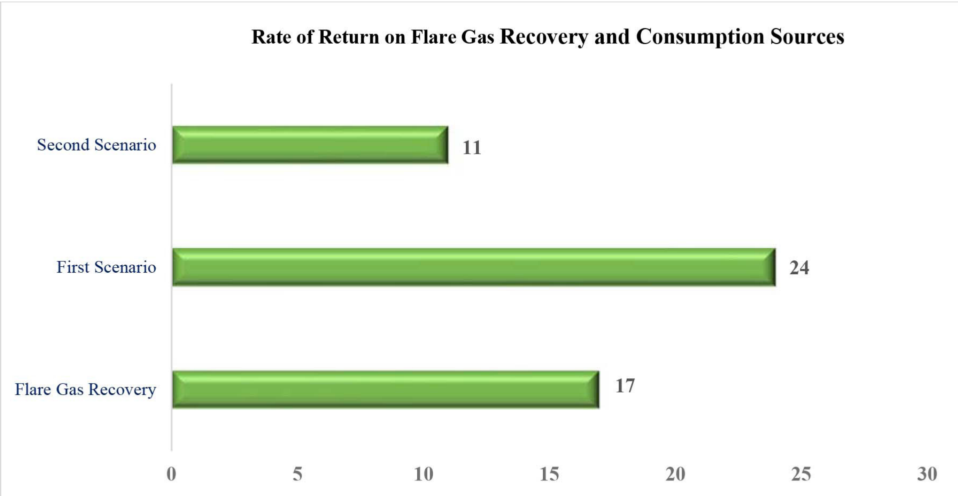

Fig. 8 Economic Evaluation Data on Flare Gas Recovery Consumption Sources.

Conclusions

This study presents a novel approach to flare gas recovery by integrating exergy analysis with economic evaluation, providing a comprehensive framework for optimizing energy utilization in gas processing plants. The findings reveal that injecting recovered flare gases into the compressors of the gas condensate stabilization unit is the most effective strategy, maximizing both energy efficiency and economic gains. This approach not only minimizes energy losses but also enhances the overall sustainability of the process. From an economic standpoint, the benefits are significant, with projected earnings exceeding $23 million from selling recovered flare gases. Among the two scenarios analyzed, directing the recovered gases to the compressors in the gas condensate unit offers the best return, achieving a payback period of just 11 months—less than half of the 24 months required in the first scenario. These results highlight the financial viability of repurposing flare gases, turning what was once waste into a valuable economic asset.

The exergy analysis further supports these conclusions, demonstrating the critical role of key operational parameters such as compressor selection, efficiency, and thermal optimization. Ultimately, it is found out that the first scenario achieves an exergy efficiency of 64.45%, while the second scenario significantly outperforms it, reaching an impressive 78.59%. Moreover, an optimized recovery system can substantially reduce energy losses and improve overall process performance. Also, by bridging technical innovation with economic feasibility, this research contributes to sustainable industrial practices, offering a scalable solution for reducing greenhouse gas emissions and maximizing resource efficiency in the gas processing industry.

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