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Green Manufacturing Approach for Waste Management in Flare Recovery Unit (FRU)

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Abstract

Air pollution has become an increasingly urgent environmental issue, particularly in petrochemical industrial zones. This study aims to examine the application of *Flare Recovery Unit (FRU)* technology to support more efficient and environmentally friendly gas waste management through a *Green Manufacturing* approach, in line with the principles of zero waste and net zero emission. The research method employed is a mixed-method approach using a case study design, a sequential mixed method, conducted in two stages: beginning with a quantitative approach, followed by a qualitative approach to explain or deepen the quantitative findings. The results show that the FRU successfully captures and processes waste gases, which are then reused in the production process. The application of the reduce, reuse, and recycle principles has proven to improve energy efficiency and reduce air pollution. These findings are supported by Reduction Emission of CO_2 Analysis, Material Flow Analysis (MFA), and Energy Flow Analysis (EFA). From an economic perspective, the FRU system is highly feasible. This is evidenced by a high Net Present Value (NPV), an Internal Rate of Return (IRR) above the viability threshold, a relatively short Payback Period (PBP), and a very feasible Benefit-Cost Ratio (BCR). These results confirm that innovations such as the FRU can become an integral part of sustainable business strategies while also supporting national environmental targets through emission reduction and improved resource efficiency.

Keywords: Flare Recovery Unit (FRU), Green Manufacturing, gas waste, petrochemical industry, air pollution

INTRODUCTION

The petrochemical industry is one of the industrial sectors that plays an important role in the global economy, especially in the provision of raw materials for various chemical-based products (Ridwana et al., 2023). However, alongside its significant contribution to economic growth, the industry is also one of the largest contributors to carbon emissions worldwide, particularly from flaring activities and the burning of gas waste that has not been optimally managed (Hess, 2016; Ledhem, 2022; Surya et al., 2021). The main challenge faced is how to efficiently manage waste gas without sacrificing productivity and profitability.

Polyethylene (PE) is one of the primary products produced by the petrochemical sector. In the production process, especially on a large industrial scale such as at PT XYZ, the gas waste generated contains flammable hydrocarbon compounds including ethylene, propane, and hexene (Kakar et al., 2021; Tiago et al., 2023; Wang et al., 2022; Xu et al., 2020; Zallaya et al., 2023). If not properly managed, this waste has the potential to pollute the air and significantly increase greenhouse gas emissions. Amid growing global awareness of climate change, sustainability-based waste management approaches are increasingly important to integrate into industrial operations.

In this context, the application of the *Green Manufacturing* concept is crucial (Gao et al., 2023; Mathiyazhagan et al., 2019; Yandri et al., 2023). PT XYZ, as one of the largest polymer manufacturers in the Middle East region, demonstrates its commitment to sustainability principles through the adoption of *Flare Recovery Unit (FRU)* technology. *FRU* is a system designed to capture and reprocess exhaust gases from flare systems so they can be reused in the production process. This technology not only prevents the release of gases into the atmosphere but also improves energy efficiency and reduces fossil fuel consumption. The use of *FRU* aligns closely with the zero routine flaring policy implemented by the company since 2022.

Moreover, the development of low-carbon technologies such as *FRU* is part of the broader macro strategy of the countries where PT XYZ operates, aiming to achieve Net Zero Emission targets. Middle Eastern countries, despite being known as major fossil fuel producers, are now actively drafting and implementing national energy transition roadmaps focused on improving energy efficiency, diversifying energy sources, and reducing emission intensity in the industrial sector. According to national strategy documents such as Energy Strategy 2050 and Net Zero Roadmap 2060, the heavy industry sector, including petrochemicals, is mandated to innovate through energy recovery technologies and circular economy practices to support decarbonization goals. Within this policy framework, *FRU* represents a tangible contribution from industry toward environmentally friendly net zero objectives.

As global and national policies increasingly emphasize sustainability, there is an urgent need to integrate the energy transition pathway into industrial operational strategies. The energy transition pathway refers to the strategic, systematic stages that lead to shifting the energy system from fossil-based to clean and low-carbon sources. Governments in the Middle East, including those where PT XYZ operates, have established policy-driven roadmaps such as Energy Strategy 2050 and Net Zero 2060, encouraging the industry to implement energy efficiency technologies and minimize flaring. Within this context, the application of *FRU* technology is a critical element of the energy transition pathway, bridging operational needs with decarbonization demands. *FRU* is not only a technical innovation but also a concrete representation of national energy transition policies emphasizing efficiency, emission reduction, and long-term sustainability of the industry.

The incoming material flow (input) to *FRU* is a feed gas consisting of hydrocarbons and nitrogen entering through a membrane separation system. This gas stream derives from the PE production process, known to contain flammable hydrocarbons. Prior to entering the Membrane Unit, these feed gases are cooled and filtered to ensure optimal separation conditions. After processing in the *FRU*, the gas stream yields three outputs:

1. Nitrogen (N_2): Nitrogen separated from hydrocarbons is recycled back into PE production units or reused in other processes. This reduces the demand for fresh nitrogen and enhances resource efficiency.
2. Top Light Column: A stream of light hydrocarbons such as methane and ethane that can be further processed as raw materials or used as supplementary energy sources.
3. Heavys Column: Heavy hydrocarbon streams that can be stored or further processed in storage tanks for additional raw materials or other industrial uses.

The success of *FRU* implementation is, however, linked to technical challenges—particularly due to the specific characteristics of waste gases from PE production, which contain a high proportion of flammable hydrocarbons, requiring careful and safe handling. Currently, the *FRU* system at PT XYZ focuses on recovering hydrocarbons and nitrogen, without separating CO_2 due to its negligible presence. This approach is expected not only to reduce emissions but also to return gas to the production process as a secondary energy source.

In the system, the feed gas flow—consisting of non-condensable or inert gases and heavy hydrocarbons—enters the Membrane Unit. Here, the gas is separated into two primary streams: 1) Retentate, a stream low in hydrocarbons such as nitrogen (N_2), which cannot be reused; and 2) Permeate, a stream enriched with hydrocarbons like methane, ethane, and ethylene, which can then be recycled in production.

Furthermore, the *Green Manufacturing* approach implemented by PT XYZ focuses not only on emission reduction but also on economic efficiency. Gas successfully recovered through *FRU* can be reused internally, lowering operational costs and improving the company's competitiveness. This holistic sustainability framework integrates environmental, social, and economic dimensions in modern industrial practice.

Green Manufacturing intends not only to ensure compliance with environmental regulations but also to enhance operational efficiency. The exhaust gas recovery at *FRU* results in three main reusable outputs (N_2, Top Light Column, and Heavys Column), supporting sustainability by reducing reliance on virgin raw materials, cutting costs, and minimizing the company's carbon footprint.

The petrochemical industry remains a major contributor to global economic growth while being one of the largest sources of greenhouse gas emissions, particularly through flaring. Prior studies, such as those by Bassey (2009) and Sitaresmi et al. (2020), have highlighted the environmental and economic disadvantages of flaring, stressing the need for innovative solutions to capture and repurpose waste gases. While many prior studies focus on large-scale flare gas recovery or monetization, gaps remain in understanding how such technologies integrate with *Green Manufacturing* principles. This research addresses these gaps by examining *FRU* as a sustainable solution aligned with zero-waste and net-zero emission paradigms, offering a more holistic approach to waste gas management.

The urgency of this research is heightened by increasing global emphasis on sustainability and the petrochemical industry's role in achieving decarbonization goals. Governments worldwide—especially in the Middle East—have introduced policies like Energy Strategy 2050 and Net Zero Roadmap 2060, mandating low-carbon technology adoption. However, as noted by Khair and Matsana (2021), many existing gas recovery systems lack full optimization for circular economy principles, causing inefficiencies. This study fills this critical gap by evaluating *FRU*'s technical and economic feasibility within a *Green Manufacturing* framework, providing actionable insights for industries facing regulatory emission reduction pressures.

A key novelty of the research is its mixed-method approach, combining quantitative performance analyses of *FRU* with qualitative stakeholder insights. Unlike prior theoretical studies by Bhattacharya et al. (2011) and Helu and Dornfeld (2013), this study offers empirical evidence on *FRU*'s impact on emission reduction and energy efficiency. Integrating Material Flow Analysis (MFA) and Energy Flow Analysis (EFA), the research delivers a comprehensive evaluation of *FRU*'s role in closing petrochemical production loops—an often-overlooked dimension in earlier works.

The primary objective is to assess *FRU* technology's effectiveness in reducing greenhouse gas emissions and enhancing resource efficiency in the petrochemical industry. Specifically, it investigates *FRU*'s capacity to capture and repurpose waste gases like hydrocarbons and nitrogen, evaluating alignment with the reduce, reuse, and recycle principles central to *Green Manufacturing*. Using PT XYZ as a case study, the research bridges theoretical sustainability models and practical industrial applications, offering a replicable framework for other petrochemical firms.

The benefits of this study extend beyond environmental conservation to include economic and operational advantages. Findings show that *FRU* not only reduces emissions but also decreases operational costs by reusing recovered gases, as demonstrated by positive Net Present Value (NPV) and Internal Rate of Return (IRR) metrics. These outcomes align with Pampanelli et al. (2014), who advocate for lean and green manufacturing models, while this study adds quantification of *FRU*'s financial viability—critical insights for stakeholders balancing profitability and sustainability.

In conclusion, this study comprehensively examines *Flare Recovery Unit (FRU)* application in PE production at PT XYZ from technical, environmental, and economic perspectives. It examines how *FRU* contributes to national energy transition and net zero emission targets and how the *Green Manufacturing* approach can provide sustainable and economical waste management solutions. The results are expected to offer a robust scientific and practical basis for supporting environmentally friendly technology implementation in the petrochemical sector.

MATERIALS AND METHODS

This study assessed the contribution of *Flare Recovery Unit (FRU)* technology in supporting the application of *Green Manufacturing* in the petrochemical industry. *FRU* is a technology designed to capture and process exhaust gases typically released through flare stacks, enabling their reuse as additional energy or raw materials. This technology supports sustainability by minimizing waste gases released into the atmosphere and improving operational efficiency. The study focused on evaluating how *FRU* contributed to greenhouse gas emission reduction, enhanced energy efficiency, and the implementation of the zero-flaring concept, integral to the company's sustainability policy.

The research employed a mixed-methods approach with an explanatory design, combining quantitative and qualitative methods to obtain comprehensive results. The quantitative phase involved surveys evaluating technical efficiencies of *FRU*, such as hydrocarbon recovery rates, greenhouse gas emission reductions, and operational cost efficiency. Qualitative data were collected through focus group discussions (FGDs) with stakeholders including technicians, managers, operational staff, and environmental and economic experts. The FGDs aimed to explain the quantitative findings by identifying technical and operational challenges, exploring opportunities for optimization, and understanding the environmental and economic impacts of *FRU* implementation.

The study was conducted at one of the largest petrochemical companies in the Middle East, which adopted a sustainability policy in 2024 emphasizing operational efficiency and environmentally friendly technologies like *FRU* to meet zero flaring targets within its global sustainability strategy. The research framework was designed to identify, analyze, and evaluate the impact of *FRU* on emission reduction, energy efficiency, and compliance with *Green Manufacturing* standards.

The analysis integrated technical and economic evaluations with a sustainability perspective to provide strategic recommendations for future *FRU* optimization. Initially, a quantitative analysis measured the technical and economic effectiveness of *FRU*, followed by qualitative analysis to understand factors influencing system effectiveness and implementation challenges within the petrochemical industry.

Data collection included both primary and secondary sources to evaluate the effectiveness of *FRU* in supporting *Green Manufacturing* at PT XYZ.

1. Primary Data

Primary data was obtained through three methods: questionnaires, Focus Group Discussions (FGD), and direct observation.

a. Questionnaire: The questionnaire is designed to obtain direct information from the parties involved in *Flare Recovery Unit (FRU)* operations. The main respondents consisted of operational staff, technicians, and managers.

1. Operational staff provide data related to daily process efficiency, technical challenges faced, and gas waste management results.
2. Technicians offer evaluations related to the performance of the *FRU* device, the effectiveness of hydrocarbon and nitrogen separation, and the energy efficiency achieved.
3. Managers assess *FRU*'s strategic contribution to the company's sustainability, cost efficiency, and compliance with *Green Manufacturing* standards.

This questionnaire aims to evaluate three main aspects of *FRU* implementation: energy efficiency, emission reduction, and contribution to environmental sustainability. As part of the data triangulation method, questionnaires are used to validate data obtained from direct observation and FGDs, thereby generating accurate and relevant information.

b. Focus Group Discussion (FGD): The FGD was used to gather in-depth information on the implementation of *Green Manufacturing* and the effectiveness of the *FRU* from technical, operational, and economic perspectives. The discussion involved technicians, managers, operational staff, as well as environmental and economic experts. The FGD focused on three main areas:

1. Strategies for implementing *Green Manufacturing*, including measures to reduce gas waste and improve energy efficiency.
2. The technical and economic efficiencies of *FRUs*, such as the separation of hydrocarbons and nitrogen, as well as the reuse of exhaust gases.
3. Recommendations for optimizing *FRU* technology to support environmental and operational sustainability.

The moderator guided the discussion with key questions, including how the *FRU* can better support *Green Manufacturing* principles and what steps are needed to improve its technical and economic efficiency. The results were analyzed qualitatively to complement the quantitative data from questionnaires and secondary data, resulting in a more comprehensive understanding.

c. Direct Observation: Direct observation was conducted at the facilities where the *FRU* operates to record material and energy flows and collect technical data related to system efficiency. These activities included observing hydrocarbon and nitrogen recovery, as well as potential energy savings within the system. The collected data was analyzed using Material Flow Analysis (MFA) and Energy Flow Analysis (EFA) approaches. This method provides a realistic picture of material and energy efficiency and highlights the contribution of the *FRU* in reducing waste gases.

2. Secondary Data: Secondary data was obtained from company documents, environmental reports, and relevant literature. This data provided context to the primary data, supported the analysis, and ensured the research's alignment with petrochemical industry sustainability standards.

a. Technical Report: Contains data on the amount of exhaust emissions successfully captured by the *FRU*, results of gas reuse, and energy performance evaluated using measuring tools related to *Green Manufacturing*, such as the CO_2 Emission Reduction Analysis approach.

b. Regulatory Documents: Used to validate compliance with the zero flaring policy and to demonstrate the *FRU*'s contribution to achieving environmental sustainability targets.

RESULTS AND DISCUSSION

Result of Focus Group Discussion (FGD)

The main objective of this FGD is to gain a further understanding of the application of FRU in waste gas management and its impact on Green Manufacturing, as well as to identify existing challenges and opportunities. The participants of the FGD consist of Environmental and Sustainability Managers, FRU Operations Teams & Technicians, Energy & Gas Technology Experts, HSE Regulatory Officers, and Academics or Researchers who have expertise in this field. The discussion focused on understanding FRU technology, the challenges faced in its implementation, and optimization strategies in supporting the sustainability of the petrochemical industry.

In the discussion, participants agreed that the Flare Recovery Unit (FRU) has a very important role in supporting Green Manufacturing in the petrochemical industry. Most of the participants explained that FRU functions to capture exhaust gases that were previously burned in the flare stack, separating nitrogen (N_2) and hydrocarbons (HC) to be reused in the production process. This separation process strongly supports the principle of Reduce, Reuse, and Recycle in Green Manufacturing, as the recovered gas not only reduces greenhouse gas emissions but can also be used for other purposes in industry. Some participants mentioned that although the implementation of FRU has been running, it is not fully optimal, especially at the gas processing stage which is still constrained by dirt in the filter and gas flow fluctuations that affect compressor performance.

In terms of reducing exhaust emissions, the majority of participants agreed that FRU has a significant impact. With this technology, previously burned exhaust gases, which have the potential to produce CO_2, methane, and NOx, can now be reused without emitting harmful emissions. One participant revealed, "With FRUs, gases released into the atmosphere can be reused in the process, reducing emissions that can damage the environment." In addition, energy efficiency is also improved, as previously discharged gas is now used to produce energy that supports the production process, allowing companies to reduce their dependence on external energy and lower operational costs.

However, in its implementation, technical challenges remain the main issues discussed in the FGD. One of the biggest problems is interference with the control system (PLC) that often interferes with FRU operations, such as a fault in the sequencer that causes a disruption of gas flow. Some participants also complained of fluctuations in gas flow resulting in excessive vibration in the compressor, which can shut down the compressor and reduce the overall performance of the system. Participants also suggested that the analyzer system used to monitor exhaust gases needs to be more accurate and recalibrated, especially for light columns and heavy columns, so that hydrocarbon separation can be carried out more efficiently.

The strategy for optimizing the implementation of FRU was also an important topic in the discussion. Participants agreed that the optimization of hydrocarbon separation and improvements to the control system are the main steps to improve the operational efficiency of FRU. In addition, employee awareness needs to be increased, by involving them more deeply in the company's sustainability programs. "Companies must be more active in educating employees about the importance of their role in supporting Net Zero Emission policies," said one of the participants. In addition, the integration of additional technologies, such as the use of membrane separators for the separation of hydrogen in exhaust gases, can be a promising solution to improve the effectiveness of FRUs. Thus, the implementation of FRU is expected to further support the sustainability of the petrochemical industry.

Discussion of FRU compared to previous research

This research answers two main questions, namely the role of Flare Recovery Unit (FRU) technology in the use of waste gas to reduce air pollution and increase recycling cost efficiency in the petrochemical industry, and how the Green Manufacturing approach is applied through the use of FRU technology. The results of technical, economic, and observational studies show that the implementation of FRU at PT XYZ has had a real and measurable impact in supporting industrial sustainability.

First, FRU plays an important role in reducing air pollution by capturing exhaust gases from the polyethylene (PE) production process which were previously directly burned through flare stacks as in previous studies. Gases such as nitrogen (N_2), ethylene (C2), propane (C3), and other hydrocarbons are successfully recovered through condensation, membrane-based separation, and distillation. The results of this recovery are then reused in the production process or as internal fuel. Thus, greenhouse gas emissions such as CO_2, methane (CH_4), and NOx can be significantly reduced, in line with the principle of emission reduction in national energy transition policies.

The differences before and after the FRU can be seen through the following table:

Table 1. Comparison of Cash Flow and Benefits of FRU Implementation 2022–2024

Description	FRU Implementation	Investment (USD)	Operational Cost (USD)	Total Cash Outflow (USD)	Cash Inflow (USD)	Net Cash Flow (USD)	Emissions (ton CO_2-eq)	Gas Recovered (ton)
Before Implementation	Before	0	1,724.043	1,724.043	0	-1,724.043	>1,110	0
After Implementation	After	20,000.000	1,724.043	21,724.043	12,291.796	-9,432.247	400	320

Source: Calculation results based on PT XYZ's internals, 2024

In terms of cost efficiency, the calculation results show that FRU not only reduces the need for external raw materials but also generates significant economic value from the sale or reuse of gas components. This is consistent with the research of Sitaresmi et al. (2020), who developed a flare gas monetization strategy using reciprocating compressors to process low-pressure gases to make them marketable. In the context of PT XYZ, the recovery and separation of C2, C3, C4, and C6 contribute to the efficiency of production costs and strengthen the company's competitiveness.

Second, the use of the Green Manufacturing approach in the implementation of FRU is reflected in the implementation of the principles of reduction, reuse, and recycle. Exhaust gases that were previously released into the air are now reprocessed and reused, not only reducing air pollution, but also improving energy efficiency and production cycles. FRU technology enables the conversion of waste into new inputs, lowers energy intensity, and supports the achievement of zero routine flaring. This research uses a Green Manufacturing approach that is different from previous studies.

This approach is in line with the research of Khair and Matsana (2021) which examines the optimization of trimming and FRU systems in the polymerization process in the plastics industry. They show that gas recovery systems can improve production efficiency and lower off-spec transition products. Similar findings were also obtained in this study, where gases from degassing and flare units are no longer waste, but are put back into the system as part of a closed-loop system that supports the circular economy.

Thus, it can be concluded that the application of FRU technology not only has a positive impact on the environment and cost efficiency but also becomes a tangible representation of the application of Green Manufacturing in the heavy industry sector. This study reinforces the empirical evidence that has been developed by previous studies and shows how energy transition and technological innovation can go hand in hand to realize a sustainable petrochemical industry.

CONCLUSION

This study demonstrates that the implementation of *Flare Recovery Unit (FRU)* technology at PT XYZ effectively supports environmentally friendly and efficient gas waste management by capturing and separating exhaust gases like hydrocarbons and nitrogen for reuse in production. This approach significantly reduces greenhouse gas emissions and decreases reliance on fresh raw materials, contributing to resource efficiency and minimizing environmental impacts in the petrochemical sector. Employing the *Green Manufacturing* principles of reduce, reuse, and recycle, the *FRU* system enhances energy efficiency and sustainability, as confirmed by CO_2 Emission Reduction Analysis, Material Flow Analysis (MFA), and Energy Flow Analysis (EFA). Economically, the *FRU* investment shows strong feasibility with positive Net Present Value (NPV), high Internal Rate of Return (IRR), and a short Payback Period (PBP), making it a strategic asset for improving operational performance and supporting long-term goals such as the Net Zero Flaring program. Aligned with national energy transition policies like Energy Strategy 2050 and Net Zero Emission Roadmap 2060, *FRU* serves not only as a technical emission reduction solution but also as a key industry response to sustainability regulations, integrating operational efficiency with decarbonization efforts. For future research, it is suggested to explore the scalability and adaptability of *FRU* technology across different petrochemical processes and regions, as well as to assess potential advancements in membrane separation techniques to further improve recovery efficiency and economic benefits.

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