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Utilization of Flare Gas for Energy Generation as a Sustainable Approach in the global Oil and Gas Sector

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Abstract- The global oil and gas sector is facing growing pressure to minimize environmental footprint and optimize resource efficiency. Gas flaring, a century old issue in oil and gas production, is a cause of colossal energy wastage and contributes to the greenhouse gas burden. This review covers the use of flare gas for power generation as a viable alternative to conventional flaring. The study is founded upon historical context analysis, environmental impact, and economic cost of gas flaring in consideration of technological innovation in flare gas recovery, including gas-to-power conversion, gas-to-liquid (GTL) fuel production, and compressed or liquefied natural gas (CNG/LNG) applications. Comparative global case study analysis of the Middle East, Africa, and Southeast Asia determines best practice and its advantages to emission reduction, energy security, and economic development. Evidence has proven that flaring can be minimized by as much as 840 tons a day in some instances and provide strong economic returns with projects achieving over $10 billion of revenue impact. Flare gas recovery technology is faced with, technical complexity, huge capital investment, and policy uncertainty. This study calls for policy interventions, economic incentives, and strategic investment to reinforce flare gas recovery projects. By incorporating flare gas utilization into conventional energy planning, oil and gas firms can enhance sustainability, operational efficiency, and the achievement of global climate goals.

Indexed Terms- Flare Gas Utilization; Gas-to-Power Conversion; CO_2 Emissions Reduction; Gas-to-Liquid Technology; Sustainable Energy.

I. INTRODUCTION

1.1 Background

Gas flaring, the controlled burning of excess natural gas during oil and gas extraction, has long been a significant environmental and economic challenge in the global energy sector. Initially adopted as a necessary practice due to limited infrastructure, market demand, and economic feasibility, flaring has become a controversial issue as the world shifts toward sustainable energy solutions [1]. The practice is particularly prevalent in oil-rich countries such as Russia, Nigeria, Iran, Iraq, Venezuela, and the United States, where large volumes of associated gas, natural gas found alongside crude oil are flared due to inadequate processing and transportation infrastructure [2]. The World Bank's Global Gas Flaring Tracker Report (2023) estimates that about 140 billion cubic meters (bcm) of natural gas are flared annually worldwide [3]. This volume of gas could generate 750 terawatt-hours (TWh) of electricity, enough to power the entire African continent for a year [4]. Instead, this valuable energy resource is burned off, releasing over 300 million tons of carbon dioxide (CO_2) and other harmful pollutants into the atmosphere [5]. The economic cost of this waste is staggering, with estimates suggesting that global flare gas has a market value of approximately $30 billion per year (IEA, 2024) [6]. Historically, gas flaring was considered a necessary byproduct of oil production due to technical and economic constraints. In remote locations or offshore oil fields where pipeline infrastructure is unavailable, storing or transporting associated gas can be prohibitively expensive. Additionally, fluctuating market prices for natural gas have made it difficult for some producers to justify investment in gas processing and utilization facilities. However, recent advancements in flare gas recovery (FGR) technologies and increasing regulatory pressure have created viable alternatives to gas flaring, allowing oil companies to capture, process, and repurpose flare gas for energy generation [7]The move from gas flaring to flare gas utilization is in line with global climate goals, including the Paris Agreement (2015), which focuses on limiting the increase in global temperatures by reducing greenhouse gas (GHG) emissions. 2. [9] The United Nations' Sustainable Development Goals (SDGs), particularly: a. Goal 7 (Affordable and Clean Energy) – Promoting access to reliable and sustainable energy. b. Goal 13 (Climate Action) – Reducing carbon emissions and mitigating climate change. 3. [10] The World Bank's Zero Routine Flaring by 2030 Initiative, which encourages oil-producing nations to phase out routine gas flaring and adopt sustainable energy solutions. Given the economic, environmental, and regulatory imperatives, flare gas utilization is emerging as a critical solution for reducing emissions, improving energy security, and enhancing economic efficiency in oil and gas.

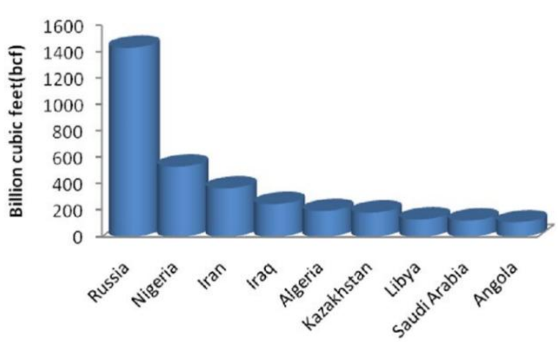

Figure 1 : Gas Flaring by Country [11].

1.2 The Need for Sustainable Flare Gas Utilization

The global energy sector is under increasing pressure to reduce carbon emissions and transition toward cleaner energy solutions. Flare gas utilization presents a unique opportunity to bridge the gap between fossil fuels and renewable energy, offering an immediate, cost-effective means of reducing emissions while maximizing the value of existing energy resources. The need for sustainable flare gas utilization can be understood through four key dimensions: environmental impact, economic benefits, regulatory frameworks, and technological advancements.

1.2.1 Environmental Impact of Gas Flaring

Gas flaring significantly contributes to air pollution and climate change by emitting harmful gases and particulate matter into the atmosphere. One of the primary environmental concerns associated with gas flaring is the release of greenhouse gases. Carbon dioxide (CO_2) is the dominant byproduct of flaring, while incomplete combustion results in the emission of methane (CH_4), a highly potent greenhouse gas with a global warming potential (GWP) that is 80 times greater than CO_2 over a 20-year period (IPCC, 2023). Estimates indicate that gas flaring is responsible for approximately 1.2 gigatons of CO_2 equivalent emissions annually, ranking it among the largest industrial sources of greenhouse gas emissions. Air Pollution and Health Hazards [13] : Gas flaring releases toxic pollutants such as nitrogen oxides (NO_x), sulfur oxides (SO_x), volatile organic compounds (VOCs), and black carbon (soot). These pollutants contribute to: Respiratory diseases, including asthma and bronchitis; Increased cancer risks due to prolonged exposure to carcinogenic hydrocarbons; Acid rain formation, which affects soil and water quality. A case study from Nigeria's Niger Delta region, one of the most heavily flared areas globally revealed that communities living near flare sites experience significantly higher rates of respiratory illnesses and reduced life expectancy [14]. By capturing and utilizing flare gas, these health risks can be mitigated, improving overall air quality and public health.

1.2.2 Economic Benefits of Flare Gas Utilization

The economic impact of gas flaring extends beyond lost energy potential. By investing in flare gas recovery systems, oil companies can; (i) [15] Monetize Flare Gas. Instead of burning associated gas as waste, companies can convert it into marketable energy products, including: Electricity through gas-to-power (GTP) systems; Synthetic fuels via gas-to-liquid (GTL) processes; Liquefied natural gas (LNG) or compressed natural gas (CNG) for industrial and transport applications. Capturing just 30% of flared gas worldwide could generate enough electricity to power hundreds of millions of households, boosting energy access in developing regions. (ii) [16] Reduce Operational Costs: Oil extraction and refining operations require significant energy inputs, often supplied by diesel generators or imported natural gas. Utilizing flare gas for onsite power generation can cut fuel costs and improve energy security. In offshore drilling, integrating flare gas recovery with enhanced oil recovery (EOR) techniques can further increase production efficiency. (iii) [17] Create New Revenue Streams: Countries such as Norway, Canada, and Saudi Arabia have successfully implemented carbon credit trading and tax incentives to encourage flare gas utilization. Oil companies that invest in flare gas recovery can benefit from Carbon trading markets, earning credits for reducing emissions; Government subsidies for deploying clean energy technologies; Public-private partnerships, securing funding for gas utilization projects.

1.2.3 Regulatory and Policy Drivers [18]

Many governments and international organizations have implemented strict regulations and policies to curb gas flaring. These include: The World Bank's Zero Routine Flaring by 2030 Initiative, which encourages countries to adopt mandatory flare reduction policies; The European Union's Carbon Pricing Mechanism, which penalizes excessive GHG emissions; Nigeria's Gas Flare Commercialization Program (NGFCP), which promotes third-party investments in flare gas utilization projects; Saudi Arabia's Master Gas System, which captures and repurposes over 99% of associated gas for domestic energy use. Companies failing to comply with these regulations face heavy fines, legal restrictions, and reputational damage, making flare gas utilization a necessary step toward regulatory compliance.

1.2.4 Technological Advancements Enabling Flare Gas Utilization [19]

Innovations in flare gas recovery and processing technologies have made it increasingly viable to capture and utilize flare gas. Key advancements include: Modular Gas-to-Power Systems, allowing onsite electricity generation from flare gas. Small-Scale GTL and LNG Plants, enabling portable conversion of flare gas into liquid fuels. AI and IoT-Based Flare Monitoring, optimizing flare gas recovery efficiency. With continued research and investment, flare gas utilization technologies are becoming more cost-effective and scalable, paving the way for a more sustainable oil and gas industry.

1.3 Objectives of the Study

This study aims to: Analyze the current state of gas flaring and its global implications, Examine existing and emerging flare gas recovery technologies, Evaluate case studies of successful flare gas utilization projects, Identify challenges and propose strategies for large-scale implementation. By addressing these objectives, this research will highlight practical pathways for integrating flare gas utilization into mainstream energy systems, contributing to both economic and environmental sustainability.

II. LITERATURE REVIEW

2.1 Overview of Gas Flaring and Its Implications

2.1.1 Definition and History of Gas Flaring

Gas flaring refers to the controlled burning of excess natural gas associated with oil extraction. It occurs when infrastructure for gas capture, processing, or transportation is unavailable or economically unfeasible. The practice dates back to the early 20th century when large-scale oil production began, particularly in regions such as the United States, Russia, and the Middle East. Initially, flaring was a safety measure to prevent gas build-up and explosions, but as production increased, it became a routine method of disposing of associated gas [20]. Over the decades, technological advancements have provided alternative solutions such as gas reinjection, gas-to-power (GTP) conversion, gas-to-liquid (GTL) synthesis, and liquefied natural gas (LNG) processing [21]. However, in many developing oil-producing nations, especially those lacking gas utilization infrastructure, flaring remains widespread. Historical analysis shows that global flaring peaked in the 1980s, reaching over 150 billion cubic meters (bcm) annually, but has since declined due to regulatory pressure and technological improvements. However, flaring levels remain high in regions with weak enforcement mechanisms, such as Nigeria, Venezuela, and Iraq [22].

2.1.2 Impact of Gas Flaring

(i) Climate Change and Air Pollution

Flaring contributes to climate change by releasing carbon dioxide (CO_2), methane (CH_4), nitrogen oxides (NO_x), and black carbon (soot) into the atmosphere [23]. Methane, which is often released due to incomplete combustion, has a global warming potential (GWP) 80 times greater than CO_2 over a 20-year period [24]. Estimates show that gas flaring is responsible for 1.2 gigatons of CO_2 equivalent emissions annually, making it one of the most significant industrial contributors to climate change. Beyond GHG emissions, gas flaring releases toxic pollutants that cause acid rain, respiratory diseases, and ecosystem degradation. Research conducted in Nigeria's Niger Delta by [25] revealed that communities near flare sites experience higher cases of asthma, lung infections, and cancer, underscoring the need for urgent mitigation.

(ii) Economic Losses from Flared Gas

Gas flaring represents a significant economic loss. According to the International Energy Agency [26], the 145 bcm of gas flared annually has a market value of approximately $30 billion. If captured and utilized, this gas could: Generate over 750 terawatt-hours (TWh) of electricity enough to power Africa for an entire year; Be converted into LNG or CNG, expanding the global gas supply; Be monetized through carbon credit trading, allowing companies to offset emissions. In contrast, countries like Norway and Saudi Arabia, which have adopted strict flare gas utilization policies, have successfully eliminated routine flaring while increasing economic efficiency.

2.2 Flare Gas Utilization Technologies

2.2.1 Gas-to-Power (GTP) Conversion

Gas-to-power conversion involves using flare gas to generate electricity through gas turbines, internal combustion engines, or microturbines. Modular gas-to-power systems have been successfully deployed in remote oilfields to provide off-grid power generation [27]. A study by [28] highlights that GTP systems can operate at efficiencies exceeding 40%, making them a cost-effective solution for oil producers. Case studies in Alberta, Canada, and the Permian Basin, USA, show that GTP projects can reduce flaring by up to 70% while providing stable electricity to local communities [29]. Despite these benefits, challenges remain, including: Capital-intensive investment in gas processing equipment; Operational difficulties in fluctuating gas flow conditions; Regulatory hurdles for integrating GTP into national grids.

2.2.2 Gas-to-Liquid (GTL) Technology

Gas-to-liquid (GTL) technology converts flare gas into synthetic fuels such as diesel, gasoline, and naphtha. The process involves: Gasification, which involves converting methane into synthesis gas (CO and H_2). Fischer-Tropsch Synthesis involves catalytic conversion into liquid hydrocarbons. Refining which involves separation into different fuel products [30]. Shell's Pearl GTL plant in Qatar is the largest GTL facility globally, processing over 140,000 barrels of GTL products daily. Similarly, Nigeria's Escravos GTL plant has successfully utilized flare gas to produce clean-burning synthetic diesel [31]. Advantages of GTL technology include: Elimination of sulfur and nitrogen oxides from fuels, reducing emissions, Production of high-quality synthetic fuels, compatible with existing infrastructure, Potential for decentralized deployment in oil-rich regions [32]. However, GTL is energy-intensive and capital-intensive, requiring high initial investment costs.

2.2.3 LNG and CNG Technologies.

LNG and CNG technologies offer viable alternatives for transporting and utilizing flare gas. LNG involves cooling gas to -162°C, while CNG compresses gas to high pressures (3000-4000 psi) for storage and transportation [33]. Countries such as Norway, the UAE, and Australia have successfully deployed floating LNG (FLNG) plants to capture flare gas offshore [34]. Case studies show that FLNG can reduce offshore flaring by up to 90% while providing exportable LNG [35]. Key challenges include: High costs associated with LNG liquefaction and regasification; Infrastructure requirements for LNG terminals and CNG refueling stations; Transportation logistics for remote oilfields [36].

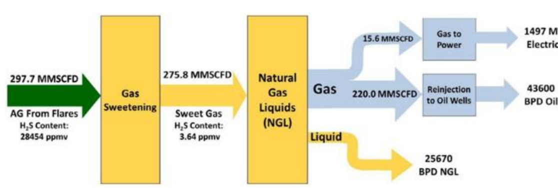

Figure 2: Sankey Diagram of the optimal flare gas recovery system [37].

2.3 Regulatory and Policy Frameworks for Flare Gas Utilization

2.3.1 Global Regulatory Initiatives [38]

Governments and international organizations have implemented strict regulations to curb gas flaring. Some notable policies include: World Bank's Zero Routine Flaring by 2030 Initiative – Encouraging oil producers to eliminate routine flaring; European Union's Carbon Pricing Mechanism – Imposing financial penalties for excessive GHG emissions; United States Environmental Protection Agency (EPA) Regulations – Requiring mandatory flare gas recovery in certain fields.

2.3.2 National Policies and Case Studies

(i) Norway [39]

Norway has one of the world's most stringent anti-flaring policies. By integrating flare gas recovery with enhanced oil recovery (EOR), Norway has reduced flaring to less than 1% of total gas production.

(ii) Nigeria [40]

Nigeria's Gas Flare Commercialization Program (NGFCP) seeks to auction flare gas to third-party investors for energy projects. However, implementation challenges, corruption, and infrastructure deficits have hindered progress.

(iii) Saudi Arabia [41]

Saudi Arabia's Master Gas System captures over 99% of associated gas, converting it into LNG and petrochemical feedstocks. The initiative has saved over $10 billion annually in lost gas revenues.

Table 1.0: Review of relevant literatures

Paper References	Objectives	Results	Findings	Practical Implications
[42]	The study aims to explore innovative technologies for converting flare gas into valuable energy resources, particularly focusing on minimizing flare gas emissions at the Skikda gas refinery.	It investigates various technologies like liquefied natural gas (LNG), compressed natural gas (CNG), and gas-to-liquid (GTL) technologies, with a focus on using gas turbines for electricity generation, which is considered the most commercially viable and economically attractive method for reducing flare gas emissions.	The study found that using flare gas to generate electricity through turbines significantly reduces harmful emissions while providing substantial economic benefits. This approach underscores the potential for sustainable energy generation at gas refineries. The most effective configuration identified in the study is a system with two turbines operating in series. When using flare gas with an interior diameter of 0.0889 m, this setup provides the highest annual profit with	The study concluded that converting flare gas into electricity with gas turbines is the most commercially viable and economically appealing method, significantly reducing harmful emissions and providing notable economic benefits. This finding highlights the potential for refineries to adopt innovative technologies that improve both environmental impact and profitability. The study's results suggest that a system with two turbines

			moderate capital investment.	operating in series, utilizing flare gas with a specific interior diameter, can yield the highest annual profit with moderate capital investment. This configuration offers a practical solution for gas refineries to effectively manage flare gas emissions while generating sustainable energy, addressing both economic and environmental concerns.
[43]	The primary objective of the study is to assess and implement the latest technologies to reduce flare gas emissions in the upstream oil and gas industry, focusing on Flare Gas Recovery methods. The study demonstrates the economic feasibility of converting flare gas into electrical energy, highlighting its benefits over other technologies and its potential to support zero flaring initiatives while contributing to environmental sustainability.	The implementation of Flare Gas Recovery technology in the upstream oil and gas industry has been shown to be economically feasible, with a Net Present Value (NPV) of IDR 48.82 billion, an Internal Rate of Return (IRR) of 23.03%, a Benefit-Cost Ratio (BCR) of 1.14, and a payback period of only 4.27 years. The project demonstrates a competitive and sustainable energy production cost, with a Levelized Cost of Electricity (CoE) of IDR 285.98/kWh and a Life Cycle Cost (LCC) of IDR 400.37 billion, supporting zero flaring initiatives while significantly reducing flare gas emissions.	The study concluded that Flare Gas Recovery to Electricity technology is the optimal solution for promoting zero flaring initiatives, as it substantially reduces flare gas emissions while offering high economic and environmental value.	From an economic standpoint, the project shows strong feasibility, with an NPV of IDR 48.82 billion, an IRR of 23.03%, and a payback period of just 4.27 years. This indicates that Flare Gas Recovery to Electricity technology is a viable option for companies looking to improve profitability while adhering to environmental regulations.
[44]	The main objective of the research is to	A case study demonstrated that the	The ULEB was proven to reduce harmful	The successful case study showed that the

	introduce a cutting-edge ultra-low emission burner (ULEB) that eliminates gas flaring in oil fields, thus contributing to global zero-flaring goals and promoting sustainability within the oil and gas industry. The study aims to demonstrate the burner's effectiveness in drastically reducing harmful emissions such as NOx and CO by over 90%, while ensuring high adaptability to various operational conditions and causing minimal disruption to existing workflows in oil field operations.	ULEB effectively reduced CO2e emissions from 1440 metric tons (venting) to 158 metric tons per day, highlighting its potential to enhance energy efficiency and promote sustainable energy practices within the oil and gas sector.	emissions, including NOx and CO, by over 90%, making it an essential tool for aligning oil field operations with environmental regulations and sustainability objectives, thus supporting the global zero-flaring movement.	ULEB could transform previously wasted flare gas into energy, decreasing CO2e emissions from 1440 metric tons to 158 metric tons per day. This demonstrates its ability to improve operational efficiency while minimizing disruptions to existing workflows.
[45]	The research focuses on designing a specialized Flare Gas Recovery Unit (FGRU) to capture and repurpose flared gases such as Methane and LPG, preventing hydrocarbon emissions and addressing the environmental risks associated with flaring. The study aims to optimize recovery processes to maximize the extraction of valuable products like sales gas and LPG for energy use, while also conducting economic and environmental	The research emphasizes the development of specialized Flare Gas Recovery Units (FGRUs) that efficiently capture and repurpose flared gases such as Methane and LPG, thereby reducing hydrocarbon emissions and minimizing the environmental risks linked to flaring in industrial settings. Economic and environmental analyses show that adopting FGRUs could bring substantial advantages, including the maximization of valuable product extraction (like	Economic and environmental assessments reveal the significant benefits of implementing FGRUs in Egypt, where routine flaring contributes to greenhouse gas emissions. The use of FGRUs promotes sustainable industrial practices that maximize resource utilization, boost economic returns, and minimize environmental impact. The research stresses the importance of Flare Gas Recovery Units (FGRUs) in industrial operations to capture and repurpose flared	By optimizing recovery processes and employing liquid ring compressors for gas compression, the study supports the idea of enhancing economic returns by extracting valuable products like sales gas and LPG, thereby promoting sustainable industrial practices and improving resource utilization.

	analyses to demonstrate the benefits of adopting FGRUs, particularly in Egypt, where flaring significantly contributes to greenhouse gas emissions.	sales gas and LPG) for energy use, while also reducing greenhouse gas emissions in Egypt, where regular flaring is a major environmental concern.	gases such as Methane and LPG, helping mitigate greenhouse gas emissions in Egypt.	
[46]	The research aims to create a self-sustaining, net-negative multigeneration system that transforms flare gas into hydrogen, while using captured CO_2 for enhanced oil recovery (EOR), thus tackling both energy waste and the greenhouse gas emissions linked to gas flaring. The study offers a thorough global comparison of three methods for converting flare gas into hydrogen, examining the influence of CO_2 emission policies and assessing the economic feasibility and carbon reduction potential of autothermal reforming processes, with and without the integration of CO_2 capture and EOR.	The research concluded that the autothermal reforming with CO_2 capture and enhanced oil recovery (AACPE) method is a promising strategy for carbon reduction. It generates hydrogen at a cost of $1.31 per kilogram, with a greenhouse gas emission rate of 3.09 $kgCO_2$ per kg of H_2, and achieves a CO_2 capture rate of 72%.	The adoption of the AACPE system in fossil fuel-rich areas, particularly within the Organization of the Petroleum Exporting Countries-plus (OPEC+), could reduce carbon emissions by up to 138.72 million tons annually.	The AACPE system would produce 12.62 million tons of hydrogen each year at a cost of $0.94 per kilogram of H_2, contributing to mitigating climate change.
[47]	The primary aim of this research is to develop Carbon Capture and Utilization (CCUS) technology that captures flare gas, a	The synthesis of CNTs from flare gas yielded a purity of around 95% for Multi-Walled CNTs, with diameters ranging from 30-50 nm, comparable to commercial-grade CNT	The project demonstrated an effective method for converting flare gases, typically a source of greenhouse gas emissions, into high-	The CNTs synthesized have been applied in energy storage technologies, particularly supercapacitors,

	hydrocarbon source contributing to greenhouse gas emissions, and converts it into value-added products, particularly high-quality Carbon Nanotubes (CNTs). The project also focuses on applying the synthesized CNTs in energy storage applications, especially by coating them onto the electrodes of supercapacitors, and benchmarking their performance against commercial supercapacitors in terms of energy density, power, and cycling capability.	products. This was achieved using a Fluidized Bed Chemical Vapor Deposition (FBCVD) reactor, designed for mobile deployment to capture flare gas. The CNTs produced were successfully applied in energy storage applications, specifically as coatings for supercapacitor electrodes. Performance tests indicated that the CNTs-based supercapacitor demonstrated competitive energy density, power, and cycling performance when compared to commercial supercapacitors.	purity CNTs using a mobile reactor unit. This method supports sustainability by reducing GHG emissions and generating valuable products for advanced applications.	improving performance metrics such as energy density, power, and cycling ability. This suggests that CNTs can enhance current energy storage systems, contributing to more efficient energy solutions.
[48]	This study seeks to assess both new and existing technologies for minimizing gas flaring in Nigeria, emphasizing their practicality, efficiency, and environmental effects. The technologies examined include gas re-injection, flare gas recovery systems, and liquefied natural gas (LNG) projects. The research explores challenges related to reducing flaring volumes, particularly in terms of regulatory enforcement, economic viability, and technological	The assessment found that although there has been some progress in decreasing gas flaring volumes in Nigeria, substantial challenges persist, particularly regarding regulatory enforcement, economic feasibility, and the adoption of advanced technologies. The study emphasizes the importance of stronger policy frameworks, greater investment in sustainable technologies, and improved international cooperation to reach the Zero Routine Flaring goal by 2030. It provides useful recommendations for	The paper stresses the importance of stronger policy frameworks and improved regulatory enforcement to effectively reduce gas flaring in Nigeria, proposing that more robust regulations and incentives could foster the adoption of advanced technologies and practices.	The research underscores the need for greater investment in sustainable technologies and international collaboration, suggesting that cooperation among stakeholders can drive the development and implementation of innovative solutions, such as gas-to-methanol conversion and carbon capture and storage, to reach the target of Zero Routine Flaring by 2030.

	execution, and provides recommendations to help enhance Nigeria's environmental sustainability and economic stability.	policymakers and industry stakeholders to enhance Nigeria's environmental sustainability and economic resilience.		
[49]	The paper highlights insights from Petroleum Development Oman's (PDO) largest flare recovery initiative, focusing on the design and execution of Atmospheric Flares and Gas Recovery systems to meet Zero-Routine Flaring objectives in the oil and gas industry. It examines various gas recovery technologies, concluding that the Rotary Vane Compressor is the most effective for handling challenges related to low flow rates and high-pressure ratios, and emphasizes its economic benefits in achieving zero routine flaring targets.	The project achieved zero-routine flaring by recovering nearly all routine flare gas using the Rotary Vane Compressor, which was the ideal solution for low flow rate and pressure conditions, reducing capital costs by 50% compared to initial projections. The Rotary Vane Compressor resolved key gas recovery issues, including eliminating emissions with a double seal system, cutting costs, and offering a standardized solution for future projects, underscoring the importance of innovative solutions for engineering challenges.	After evaluating over 15 gas recovery technologies, the study identified the Liquid Ring Compressor, Rotary Vane Compressor, and liquid educator as viable options, with the Rotary Vane Compressor emerging as the best choice due to its cost-effectiveness, minimal maintenance, and compatibility with zero routine flaring goals.	The successful use of the Rotary Vane Compressor in PDO's flare gas recovery project showcases a feasible method to achieve zero-routine flaring, recovering nearly all routine flare gas while significantly reducing capital and operational costs. This approach could be adapted for other oil and gas operations with similar challenges. The case study emphasizes the need for innovative engineering solutions and thorough feasibility assessments to overcome challenges in gas recovery systems. It offers valuable insights for future projects, including selecting technologies like the Rotary Vane Compressor, which provides higher efficiency, lower costs, and minimal maintenance, advancing sustainability goals in the sector.

[50]	The paper examines new and evolving business models in the oil and gas sector that support the transition to a low-carbon economy, focusing on balancing sustainability with profitability. It emphasizes the importance of diversifying energy portfolios by investing in renewable sources and improving operational efficiency with digital technologies, while highlighting the role of carbon capture, utilization, and storage (CCUS) in reducing environmental impacts.	The paper emphasizes the need for partnerships between oil and gas companies and renewable energy firms, as well as workforce reskilling to adapt to new industries. It also points out that regulatory frameworks are increasingly supporting green investments and low-carbon initiatives, which are critical for creating new revenue streams aligned with decarbonization goals.	The oil and gas sector is transitioning to a low-carbon economy by diversifying energy sources such as wind, solar, and hydrogen, and leveraging digital technologies like AI and IoT to enhance operational efficiency. This shift aims to maintain profitability while promoting sustainability, with innovative business models focused on reducing waste and emissions through resource optimization and collaboration between oil and gas and renewable energy companies.	The paper stresses the need for oil and gas companies to diversify into renewable energy sources like wind, solar, and hydrogen, aligning with global decarbonization goals while creating new revenue streams to ensure financial stability in a low-carbon economy. It highlights the role of digital technologies, such as AI and IoT, in enhancing operational efficiency, optimizing resources, reducing emissions, and shaping business models based on circular economy principles, fostering both innovation and sustainability.
[51]	The main goal of the research is to evaluate the potential benefits of installing flare gas recovery systems (FGRS) in gas oil separation plants (GOSPs) to reduce greenhouse gas (GHG) emissions and reduce the energy lost from flaring gases during oil extraction and refining. The study performs a quantitative analysis by comparing the amount of flared gases before and after the implementation of	The analysis showed a notable reduction in flared volumes following the implementation of FGRS in GOSPs, highlighting a decrease in wasted energy and GHG emissions when compared to conventional flaring methods. The study provides evidence from other industries that supports the positive outcomes of FGRS, showcasing their effectiveness in reducing CO2 and overall GHG emissions, promoting	The research highlights that implementing FGRS in GOSPs can substantially reduce GHG emissions by minimizing the amount of gas flared, thus contributing to environmental protection and sustainability.	FGRS not only reduces wasted energy but also allows for excess gas to be used as feedstock fuel, improving energy efficiency and enhancing power generation capabilities in GOSPs.

	FGRS, supporting the positive outcomes of using FGRS over conventional flaring methods, with evidence from other industry practices.	sustainability, and aiding power generation.		

2.4 Challenges and Limitations

Despite technological and regulatory progress, several challenges persist: High capital costs for gas recovery infrastructure; Regulatory gaps in enforcement and monitoring; Fluctuations in global natural gas prices, affecting investment feasibility; Technical challenges in processing low-BTU gas mixtures. Addressing these challenges requires public-private partnerships, policy incentives, and advancements in gas processing efficiency.

2.5 Summary of Key Findings

1. Gas flaring remains a major environmental and economic challenge, with over 140 bcm of gas wasted annually.
2. Flare gas utilization technologies (GTP, GTL, LNG, CNG) offer viable solutions, but cost and infrastructure remain key barriers.
3. Countries with strong regulatory frameworks (e.g., Norway, Saudi Arabia) have successfully minimized flaring, while others (e.g., Nigeria) face implementation challenges.
4. Public and private sector collaboration is critical for scaling up flare gas utilization projects.

III. DISCUSSION

The integration of Solid Oxide Fuel Cells (SOFCs) into natural gas processing plants has been explored as a solution to reduce emissions and generate electricity from flare gas. [52] demonstrated that by redirecting 70% of flare gas to SOFCs, a plant processing two billion standard cubic feet of natural gas daily could reduce CO_2-equivalent emissions from 263 tons to 101 tons per day, while also producing 20 MW of electricity. Similarly, [53] evaluated four power generation scenarios for flare gas recovery, including the Reciprocating Internal Combustion Engine Cycle, Combined Gas Turbine Cycle, and Solid Oxide Fuel Cell/Gas Turbine Cycle. Their findings showed that the Combined Gas Turbine Cycle provided the most economically advantageous scenario and offered better flexibility with varying gas compositions. In Nigeria, the potential for reducing CO_2 emissions through alternative uses of flare gas has been explored. A study [54] highlighted that converting flared gas into compressed natural gas (CNG) could be used as an alternative fuel for the Lagos Bus Rapid Transit system, thus reducing greenhouse gas emissions. These studies collectively highlight the effectiveness of various technologies in utilizing flare gas for energy generation, each offering distinct advantages and challenges. The following table provides a comparative summary of significant flare gas utilization projects, outlining their key parameters and results.

Table 2.0: Comparative Analysis of Flare Gas Utilization Projects

Project Location	Technology Employed	Flare Gas Utilized	Power Generation Capacity	CO_2 Emissions Reduction	Economic Impact
Malampaya Gas Field, Philippines [55]	Gas-to-Power Conversion	Not specified	3,200 MW	Displacement of over 1.35 million kg of CO_2 per hour	Generated over $10 billion in government revenues as of 2018

Project Location	Technology Employed	Flare Gas Utilized	Power Generation Capacity	CO_2 Emissions Reduction	Economic Impact
Saqala Field, Kurdistan [56]	Gas-to-Power Conversion	40 million standard cubic feet per day (MMscfd)	165 MW	Reduction of 840 tons of CO_2 per day	Enhanced local grid stability and reduced power costs
Undisclosed Location, Middle East [57]	Gas Treatment and NGL Production	40 MMscfd	180 MW	Reduction of 840 tons of CO_2 per day	Enabled maximization of oil production and provided stable power to the local grid
Undisclosed Location, Africa [58]	Centralized Power Station Utilizing Flare Gas	Not specified	10 MW (scalable to 15 MW)	Annual reduction of 52,348.5 tons of CO_2	Annual savings of approximately $25 million USD

3.2 Key Findings

- Environmental Impact: Utilizing flare gas for power generation significantly reduces CO_2 emissions. For instance, the projects in Kurdistan and the Middle East each reported a reduction of 840 tons of CO_2 per day.
- Economic Benefits: Flare gas utilization projects can lead to substantial economic gains. The Malampaya Gas Field project generated over $10 billion in government revenues by 2018, while the African project reported annual savings of approximately $25 million USD.
- Energy Production: Converting flare gas into electricity contributes to significant power generation capacities, ranging from 10 MW in Africa to 3,200 MW in the Philippines, thereby enhancing energy security and supporting local grids.

3.3 Challenges and Considerations

- Technical Complexity: Implementing flare gas utilization projects involves complex engineering, including gas treatment and infrastructure development, which require specialized expertise.
- Capital Investment: Significant upfront capital is necessary for the development of infrastructure and technology deployment, which may pose financial challenges, especially in developing regions.
- Regulatory Frameworks: The success of such projects often depends on supportive regulatory environments and policies that encourage investment and provide clear guidelines for implementation.

CONCLUSION

The findings from this review highlight the considerable environmental and economic advantages of utilizing flare gas as a practical alternative to routine gas flaring. The analysis of various global projects demonstrates that technologies such as gas-to-power conversion, GTL synthesis, and LNG applications can successfully convert waste gas into valuable energy, reducing carbon emissions and improving energy security. Notably, projects in Kurdistan and the Middle East have achieved daily CO_2 emission reductions of up to 840 tons, while large-scale implementations such as the Malampaya Gas Field have generated substantial economic returns exceeding $10 billion. These successes highlight the potential for replicating similar initiatives in other oil-producing regions. However, widespread adoption remains constrained by financial, technical, and regulatory challenges. Overcoming these barriers requires collaborative efforts between governments, private sector investors, and technology developers to facilitate policy frameworks, financial incentives, and infrastructure investments. Moving forward, integrating flare gas recovery technologies into broader energy transition strategies will be crucial in achieving sustainability goals while maximizing the economic value of associated gas. By addressing these challenges, the oil and gas industry can make significant strides in emissions reduction, energy efficiency, and resource optimization, paving the way for a more sustainable and resilient energy future.

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