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Assessing Gas Flaring Mitigation Technologies in Nigeria: A Review of Existing Solutions and Future Trends

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Abstract:

Gas flaring remains a critical global issue with significant economic and environmental impacts. Despite ongoing efforts, Nigeria remains one of the top ten countries for gas flaring. This research assesses both advanced and existing technologies aimed at mitigating gas flaring in Nigeria, focusing on their viability, effectiveness, and environmental implications.

The evaluation begins with gas reinjection techniques, which involve redirecting flared gas back into reservoirs to enhance oil recovery and reduce emissions. It also covers flare gas recovery systems that capture and repurpose flared gas for energy production or other beneficial uses. Additionally, the potential of liquefied natural gas (LNG) projects to minimize flaring and monetize associated gas is explored.

Furthermore, the study examines innovative approaches such as gas-to-methanol (GTM) conversion, which transforms flared gas into methanol, a valuable chemical feedstock. The review also considers advanced methods like carbon capture and storage (CCS), which can absorb carbon emissions from flaring and mitigate its environmental impact.

The assessment includes the integration of renewable energy sources as a sustainable alternative to fossil fuel-based energy generation to reduce reliance on flaring.

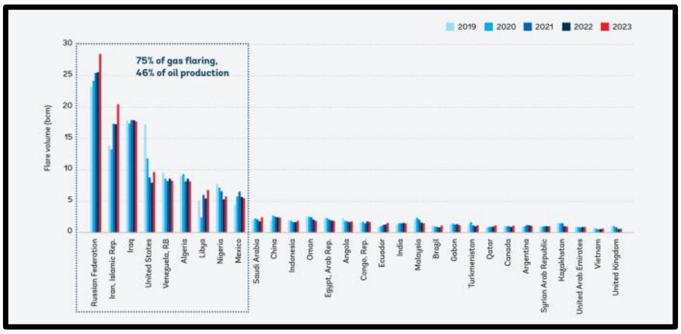
Findings reveal that while progress has been made in reducing flaring volumes, challenges persist, particularly in regulatory enforcement, economic feasibility, and technological adoption. The review highlights the need for improved policy frameworks, increased investment in sustainable technologies, and international cooperation to achieve Zero Routine Flaring by 2030. This study provides valuable insights and recommendations for policymakers and industry stakeholders to enhance Nigeria's environmental sustainability and economic resilience.

Keywords: Gas flaring, Nigeria, mitigation technologies, environmental impact, sustainability, carbon capture, renewable energy.

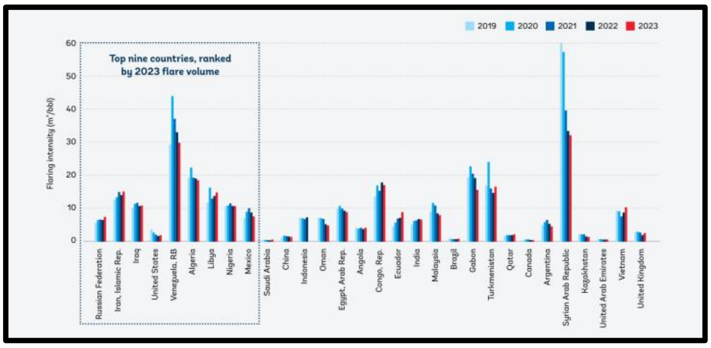
1. Introduction

For years, Nigeria has been struggling to break free from the 'oil curse', where oil has proven more of a curse than a blessing [66]. This highlights the persistent challenges Nigeria faces in managing its oil wealth, particularly with regard to gas flaring. Gas flaring is the controlled combustion of excess associated natural gas produced during the extraction, processing, and refining of oil and gas, as well as other related activities [ANG][9]. In 2023, global gas flaring increased by 9 billion cubic meters (bcm) to reach 148 bcm, the highest level since 2019. This marks a reversal from the decline observed between

2021 and 2022, indicating that efforts to reduce gas flaring have not been sustainable, with urgent action needed to achieve Zero Routine Flaring by 2030 [36]. Due to the Covid-19 pandemic, the menace dropped significantly to 7 billion cubic meters in 2020, dropping further to 6.5 billion cubic meters in 2021, before resting at 5.3 billion cubic meters in 2022[73]. Gas flaring has been an issue since oil extraction began over 160 years ago and has persisted in Nigeria since oil production started in the 1950s. Nigeria remains among the top 10 countries for gas flaring despite ongoing efforts to curb the practice [2][3]. Since 1979, Nigeria has technically banned gas flaring. But because of multiple extensions to the deadlines for this prohibition to take effect, Nigeria continues to be a major gas flarer [4]. Nigeria is the world's top flarer of gas, with the majority coming from the Niger Delta. Approximately 12 million tons of methane are discharged into the atmosphere annually for the Rivers, Bayelsa, and Delta States [5]. The National Environmental, Economic and Development Study [NEEDS] on Climate Change in Nigeria estimates that the environmental cost of gas flaring is N28.8 billion [US$94 million] per year [6].



[Fig 1] Flare volumes in the top 30 flaring countries, in order of 2023 flare volume with the top 9 flaring countries indicated, 2019–23 [36]



[Fig 2] Flaring intensity in the top 30 flaring countries from 2019 to 2023 in order of 2023 flare volume, with the top 9 flaring countries indicated [36]

The Department of Petroleum Resources reports that Nigeria has 1,481 active wells and 159 oil fields. With an estimated 37 billion barrels, Nigeria has the second-largest proven crude oil reserves in Africa, after Libya. Over the past 15 years, Nigeria has reduced gas flaring by 70%, though it remains among the top seven flaring nations. Between 2012 and 2021, Nigeria reduced flaring by 31% and increased flare intensity by 10%. Additionally, daily oil production has remained nearly constant at around 1.4 million barrels [9].

To effectively manage and utilize the collected gas, diverse gas utilization strategies require various technological setups and often complex arrangements of suitable infrastructure. These strategies are:

1. Gas Re-Injection Process [GRP]
2. Liquified Natural Gas [LNG] Projects
3. Flare Gas Recovery Systems
4. Compressed Natural Gas [CNG] [9]

Since 1969, the Nigerian government has undertaken several attempts to lower gas flaring. These include the Environmental Impact Assessment Act [EIAA] of 1992, the National Environmental Standards and Regulation Act of 2007, the Associated Gas Reinjection Act of 1979, and the revised Petroleum Act Decree of 1973. An important milestone in the endeavor to decrease gas flaring was the Nigerian government's 2002 membership in the Global Gas Flaring Reduction [GGFR].

Since associated natural gas significantly contributes to global gas flaring, the primary objective of the Global Gas Flaring Reduction Partnership (GGFR) is to assist nations and oil and gas companies in increasing the use of this resource to reduce global gas flaring. To achieve this, the GGFR, in collaboration with the World Bank and partner nations, launched the Zero Routine Flaring 2030 project, aiming to eliminate routine gas flaring by 2030 [9].

In 2016, the Nigerian government introduced the Nigerian Gas Flare Commercialization Program (NGFCP). The NGFCP aims to end gas flaring through technically and financially viable gas utilization projects developed by qualified external investors. The government also established the "Flare Gas (Prevention of Waste and Pollution) Regulations 2018" to provide a legal framework for the NGFCP [50]. In 2024, TotalEnergies became the first Nigerian E&P company to end routine gas flaring across its operations. This milestone supports Nigeria's broader efforts under the Global Gas Flaring Reduction Partnership and the Zero Routine Flaring by 2030 initiative[71]

1.1 Purpose

Growing up in Nigeria, I have been keenly aware of the oil and gas industry's prominence in our economy and the pollution it generates. The persistent environmental degradation and health issues reported by communities near flaring sites like the Niger Delta: oil spills are common throughout the area, as a consequence of pipeline corrosion, poor maintenance of infrastructure and spills or leaks at the well heads [7] and thousands of people who live in the Niger delta are being exposed to oil contamination near their homes, farm lands, fishing grounds and in their drinking water and foods [8], has caused my determination to understand the root causes and explore potential solutions.The purpose of this review paper is to critically evaluate the current technologies and emerging trends for mitigating gas flaring in Nigeria. By assessing the effectiveness, feasibility, and environmental impact of various solutions, the paper aims to ensure technical and economic feasibility while achieving positive environmental outcomes through reduced routine gas flaring. This work aspires to contribute to a future where community health and well-being are safeguarded, and the environment is preserved for future generations.

1.2 Scope

The percentage of gas flared in Nigeria has been decreasing since 2002, reaching 10% in 2018. However, the country remains among the top 10 gas-flaring nations, flaring 7.4 billion cubic feet in 2018 [see graph 1.2 and 2.0]. This accounted for 6.9% of the gas flared by the top 10 gas-flaring countries that year [6]. The Niger Delta region, which includes Rivers, Akwa Ibom, Bayelsa, and Imo states, is the center of Nigeria's oil and gas industry. Gas flaring has been a persistent issue in this region since the start of commercial crude oil extraction, with 10% to 40% of associated gas being flared into the atmosphere [67, 68].

This review paper will cover the following areas:

- **Overview of Gas Flaring and Its Impact in Nigeria**: Introduction to gas flaring, its causes, and specific environmental and health impacts in Nigeria
- **Current Technologies for Gas Flaring Mitigation**: Examination of existing technologies such as gas re-injection and flare gas recovery systems.
- **Emerging Trends and Innovations**: Exploration of new and developing technologies, including carbon capture and storage and renewable energy integration.
- **Evaluation of Technologies**: Assessment of the effectiveness, feasibility, and environmental impact of the various technologies.
- **Challenges and Barriers**: Discussion of technical, economic, and regulatory challenges in adopting these technologies in Nigeria.
- **Future Directions and Recommendations**: Suggestions for further research, policy changes, and best practices to enhance gas flaring mitigation efforts in Nigeria.

2. Discussion

2.1 Current Technologies for Gas Flaring Mitigation

2.1.1 Gas Re-Injection:

Gas re-injection involves pumping natural gas back into an underground reservoir, typically one containing both natural gas and crude oil, to sequester gas that cannot be exported or to increase the reservoir's pressure, enhancing crude oil flow [13]. This method is used to boost oil production after primary recovery methods become ineffective due to decreased reservoir energy, helping to delay the decline in oil production and maximize extraction [11].

Gas re-injection serves multiple purposes: reducing normal flaring, maintaining pressure, enhancing oil recovery (EOR), and storing gas for future use when markets are more developed. However, it is often not cost-effective due to high expenses and limited additional oil reserves. It is particularly useful when the cost of gas processing and export equipment is prohibitive, making the investment in processing or export facilities uneconomical [12][10].

Usage In Nigeria: Enhanced oil recovery and storage

Limitations in Nigeria: Limited to onsite use, economic unattractiveness to investors and limitation to certain type of reservoirs

Projects In Nigeria: In 2024, Nigeria has advanced several gas reinjection projects aimed at reducing gas flaring and optimizing gas utilization. TotalEnergies, in partnership with NNPC, is investing heavily in projects such as a new gas processing facility at the Ubeta onshore field, which will process 350 million cubic feet of gas per day. This is part of a larger $550 million investment in Nigeria’s gas sector

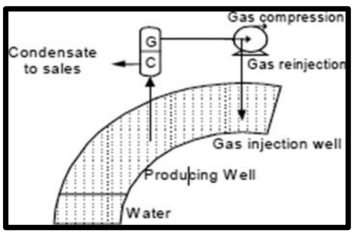


Fig.2. Typical gas re-injection process [14]

2.1.2 Flare Gas Recovery Systems:

This system collects flare gasses and reroutes them into manufacturing processes for reuse as fuel gas [15]. Instead of being discharged into the atmosphere, the gasses are captured and utilized [16]. During recovery, gas from the flare knock-out vessel is extracted and compressed, often using liquid ring compressors, making the gasses safe for reuse [17]. Reintegrating recovered gasses into the facility's fuel gas system reduces reliance on external energy sources.

Environmentally, these systems lower greenhouse gas emissions, helping combat air pollution and climate change. Financially, flare gas recovery systems (FGRS) significantly benefit the oil, gas, chemical, and petrochemical sectors by reducing operational costs and environmental impact [18]. In Nigeria, establishing an FGRS requires a capital investment of about $500 million but yields a post-tax profit margin increase of approximately $1.5 billion. This profitability results from reduced greenhouse gas emissions and refinery waste [19].

2.1.3 Liquefied Natural Gas [LNG] Projects:

To produce liquefied natural gas (LNG), natural gas is cooled to -162 °C at atmospheric pressure, reducing its volume by 600 times and facilitating storage and long-distance transport [9][20]. The LNG industry includes gas resource development, liquefaction plants, transportation, receiving terminals, and customer distribution through power plants or municipal gas companies [21].

LNG is a greener, more sustainable option as it emits fewer carbon dioxide, sulfur dioxide, and nitrogen oxides compared to traditional fossil fuels. The EU's carbon tax makes LNG more attractive, and its energy efficiency, 3-5% higher than oil-fired products, contributes to sustainability. LNG's broad distribution network and significant reserves make it a competitive energy choice, emitting 40% less CO_2 than coal and 30% less than oil [9][22].

The global LNG market was valued at USD 109.48 billion in 2021 and is projected to grow at a compound annual growth rate (CAGR) of 8.1% from 2022 to 2030. Global LNG demand is expected to reach approximately 700 million tonnes per year by 2040, a 90% increase from 2021 levels [25]. **Usage In Nigeria:** Approximately 40% of Nigeria's annual domestic cooking gas or LPG consumption needs, as well as LNG sales or exports, are currently met by Nigeria LNG. The petrochemical, fertilizer, and home utility sectors, as well as domestic power generation, place additional pressures on the use of NLNG.

Limitations in Nigeria: Insufficient progress is being made to acquire small to medium-sized LNG plants in order to boost output and improve supply variability of ANG.

Projects In Nigeria: The Bonny Island Nigeria LNG [NLNG] facility started operating in 1999. A cooperative venture involving Shell Gas, Total, Eni, and the Nigerian National Petroleum Corporation [NNPC] operates this facility. It is expanding to add a seventh train, which would bring the capacity to 30 mtpa by 2024. Currently, it has six active LNG processing units with a total capacity of 22 million tonnes per annum [mtpa]. [24, 25].

2.1.4. Gas to methanol [GTM]

Natural gas can be converted into methanol using GTM (gas-to-methanol) technology, which can then be used as a fuel, chemical feedstock, or for other industrial applications. This technology helps utilize natural gas more efficiently and reduces gas flaring. The process typically involves steam-reforming natural gas to produce synthesis gas, which is then converted into methanol and water vapor in a catalyst-equipped reactor [26]. Methanol, also known as methyl alcohol, is a colorless liquid with a distinctive odor and high octane rating, making it a potential clean-burning fuel. Converting CO_2 to methanol is a promising method for reducing CO_2 emissions [27]. The main technologies for large-scale methanol production are coal-to-methanol and natural gas-to-methanol processes [28].

In the natural gas-to-methanol process, natural gas is pre-reformed and reformed to produce syngas, which is adjusted to the necessary carbon-hydrogen ratio (1:2) [28]. The chemical process involves three steps: steam reforming to convert natural gas into synthesis gas, synthesizing methanol from the syngas, and distillation [29][30]. This conversion is a dual-benefit strategy for addressing gas flaring issues, turning waste into revenue and promoting sustainable environmental practices [31].

The global methanol market was valued at USD 30.7 billion in 2021 and is projected to grow at a compound annual growth rate (CAGR) of 3.4%, reaching USD 41.48 billion by 2030. Over 90% of the world's methanol production relies on natural gas feedstock, the most common feedstock in the industry [32].

Projects In Nigeria: Nigeria is actively using Gas to Methanol [GTM] technology. The Nigerian Energy Dialogue has partnered with the Federal Ministry of Science, Technology, and Innovation to promote methanol fuel production technology. This initiative includes converting gas to methanol and subsequently to hydrogen fuel cells, which can be used across various sectors including transportation and household energy. Projects like the Brass Methanol Plant are part of this effort to create a cleaner, more sustainable energy landscape in Nigeria [33, 34, 35]

2.2 Emerging Technologies & Trends

2.2.1 Carbon Capture Storage

Carbon Capture and Storage (CCS) is a technology designed to reduce CO_2 emissions from industrial processes and power generation. It involves capturing carbon dioxide at its emission source, transporting it to a storage site, and then injecting it deep underground into geological formations for long-term storage [37,38].

Potential Benefits:

1. Emissions Reduction: The primary benefit of carbon capture is its ability to significantly reduce CO_2 emissions from industrial activities, helping companies meet emission targets and regulatory requirements [57]
2. Climate Change Mitigation: By capturing and storing CO_2, the oil and gas industry can contribute to global efforts to mitigate climate change, transitioning towards a low-carbon future [57].
3. Resource Optimization: Carbon capture technology allows for the extraction of additional oil and gas reserves through enhanced oil recovery [EOR] techniques, maximizing resource utilization while reducing emissions [57].
4. Economic Opportunities: Implementing carbon capture projects can create new economic opportunities, such as job creation, infrastructure development, and fostering a market for carbon capture and storage services [57].

Potential Challenges:

1. 1. High costs associated with capturing, transporting, and storing CO_2 [42].
2. Requires substantial infrastructure investments [42 43].
3. Potential risks related to CO_2 leakage from storage sites [44].
4. Regulatory and public acceptance issues [45].
5. In countries like Nigeria, large-scale carbon capture projects are difficult to implement due to the country's limited industrialization. Industrial plants are often dispersed and too far apart, making it

challenging to aggregate CO_2 for efficient capture and storage.

Future Prospects In Nigeria:

1. Nigeria has significant potential for CCS due to its extensive oil and gas industry [44].
2. The Niger Delta region, with its existing oil fields, could serve as potential CO_2 storage sites [45].
3. Integration with Enhanced Oil Recovery [EOR] could make CCS more economically viable in Nigeria [46].
4. Government policies and international collaborations could drive the adoption and development of CCS technologies [47].
5. Research and pilot projects are needed to demonstrate the feasibility and safety of CCS in the Nigerian context [48].

Recommendations:

1. Develop a Comprehensive Regulatory Framework: Establish clear standards and provide financial incentives to support the deployment of CCS technology, ensuring it aligns with Nigeria's emission reduction goals.
2. Utilize Existing Infrastructure: Leverage existing oil fields in the Niger Delta for CO_2 storage and Enhanced Oil Recovery [EOR], optimizing resource use and economic viability.
3. Foster Government and International Collaboration: Encourage public-private partnerships and seek international support to share expertise, technology, and resources, driving the adoption of CCS in Nigeria.
4. Market Development: Foster the development of a market for CCS services, encouraging local companies to participate and benefit from the emerging CCS industry
5. Combine Flare Gas Recovery Systems with CCS: Integrate flare gas recovery systems with CCS technologies to address both flare gas emissions and CO_2 capture, enhancing overall emission reductions and economic efficiency.

2.2.2 Renewable Energy Integration

Renewable energy integration uses sources like solar, wind, and hydroelectric power to meet energy needs in oil and gas operations, reducing gas flaring and its environmental impact [37][38].

For example, in the Netherlands, wind power supplies about 15% of electricity, with wind capacity growing by 18.2% in 2021 to 7.8 GW [69]. In 2024, China will lead in hydroelectric power, adding 24 GW in 2022, accounting for nearly 75% of global growth that year. The Three Gorges Dam, the largest hydroelectric dam with 22.5 GW capacity, significantly contributes to China's hydroelectric output [70][71].

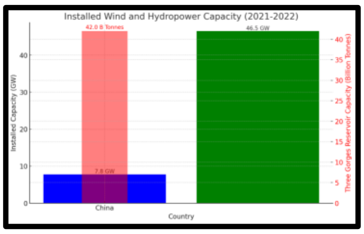


Fig.3. Contributions of wind power in the Netherlands and hydropower in China

Blue Bar: Represents the installed wind power capacity of the Netherlands in 2021 (7.8 GW).

Green Bar: Represents the total hydropower capacity added by China in 2022, including the Three Gorges Dam (24 GW added + 22.5 GW from the dam).

Red Bar: Represents the water capacity of the Three Gorges Reservoir (42 billion tonnes).

Potential Benefits:

1. Reduces greenhouse gas emissions by decreasing reliance on fossil fuels for energy production, directly impacting the amount of gas flared [39].
2. Enhances energy security by diversifying the energy mix and reducing dependence on flared gas as an energy source [40].
3. Promotes economic development through the creation of green jobs and investments in renewable energy infrastructure [41].

Potential Challenges:

1. Intermittency and variability of renewable energy sources can affect grid stability and reliability, which may complicate their use in continuous oil and gas operations [42].
2. High initial costs for renewable energy infrastructure and technology [43].
3. Requires significant upgrades to the existing grid infrastructure to accommodate distributed energy resources [44].
4. Policy and regulatory barriers that can hinder the deployment of renewable energy projects [45].

Future Prospects In Nigeria:

1. Nigeria has abundant renewable energy resources, particularly solar and wind, which can be harnessed to offset energy needs in oil and gas operations, thus reducing gas flaring [46].
2. The Nigerian government has initiated several policies and programs to promote renewable energy development, such as the Renewable Energy Master Plan and the Rural Electrification Agency's initiatives [47].
3. International collaborations and investments from development partners can help accelerate the deployment of renewable energy technologies in Nigeria [48].
4. Continued research and development are needed to address the technical and economic challenges associated with renewable energy integration in the context of reducing gas flaring [49]. 5. In 2016, Nigeria signed power purchase agreements (PPAs) worth US$2.5 billion with 14 independent power producers (IPPs) to build a total 1,125 megawatts of installed solar capacity for the national grid. [72]

Recommendations:

1. Upgrade and Expand Grid Infrastructure: Invest in upgrading the electrical grid to handle the variable nature of renewable energy sources, ensuring stability and reliability. Implement smart grid technologies to enhance grid management, improve efficiency, and facilitate the integration of distributed energy resources.
2. Foster Local Manufacturing and Supply Chains: Implement policies to encourage local manufacturing of renewable energy components and development of supply chains. Leverage the renewable energy sector to create jobs and stimulate economic growth in local communities.
3. Integrate Renewable Energy with Other Sectors: Promote the integration of renewable energy with other sectors, such as agriculture and industry, to enhance overall sustainability and efficiency. Encourage the development of hybrid systems that combine renewable energy with conventional power sources for greater reliability
4. Ensure Financial Mechanisms and Support: Improve access to finance for renewable energy projects through grants, loans, and investment from both domestic and international sources.

2.2.3 Advanced Monitoring and Detection Technologies

Advanced monitoring and detection technologies play a crucial role in mitigating gas flaring by providing real-time data and analytics to optimize gas recovery processes and reduce emissions. These technologies include satellite monitoring, drone surveillance, and advanced metering systems .

Potential Benefits:

Accurate Measurement and Reporting: Advanced metering systems can provide precise data on gas flaring volumes, enabling better regulatory compliance and accurate reporting [50].

Real-Time Monitoring: Satellite and drone technologies offer real-time surveillance, allowing for immediate detection and response to gas flaring incidents, thereby minimizing environmental impact [51].

Data-Driven Decision Making: The integration of AI and machine learning in monitoring systems can help predict flaring events and optimize gas recovery operations, leading to more efficient resource utilization [50, 51].

Potential Challenges:

High Implementation Costs: The initial investment in advanced monitoring technologies can be substantial, posing a financial challenge for some operators [50]

Technical Complexity: The deployment and maintenance of sophisticated monitoring systems require specialized expertise, which may not be readily available in all regions.

Data Privacy and Security: Handling large volumes of data from monitoring systems raises concerns about data security and privacy, necessitating robust cybersecurity measures.

Projects In Nigeria:

NGFCP Initiatives: The Nigerian Gas Flare Commercialization Program [NGFCP] aims to utilize advanced technologies to reduce gas flaring through commercially sustainable projects developed by third-party investors [51].

NUPRC Metering System: The Nigerian Upstream Petroleum Regulatory Commission [NUPRC] has implemented a metering system that significantly reduced gas flaring from over 40% to below 7% in Nigeria's oil and gas industry [50].

NOSDRA's Efforts: The Nigerian Oil Spill Detection and Response Agency [NOSDRA] emphasizes the need for effective monetization of gas resources to further reduce flaring and improve revenue generation [50]

Recommendations:

Invest in Infrastructure and Technology Development: Upgrade existing infrastructure to support the integration of advanced monitoring systems, including high-speed internet and IoT networks. Allocate funding for research and development to drive innovation in monitoring and detection technologies, making them more accurate, efficient, and cost-effective.

Enhance Workforce Skills and Training: Develop specialized education and training programs to equip the workforce with the necessary skills to operate and maintain advanced monitoring systems. Introduce certification courses for professionals to ensure they have the expertise needed to implement and manage these technologies effectively.

Promote Data Integration and Interoperability: Develop standardized data protocols and interoperability frameworks to ensure seamless integration of different monitoring and detection systems. Create centralized platforms for data collection, analysis, and reporting to enhance decision-making and coordination across various sectors.

Support Pilot Projects and Demonstrations: Launch pilot programs to test and demonstrate the effectiveness of advanced monitoring and detection technologies in real-world scenarios. Develop feedback mechanisms to gather insights from pilot projects, refining and improving technologies before wide-scale deployment.

2.3. Comparison & Evaluation

2.3.1 Gas Re-Injection and **Carbon Capture and Storage** both aim to mitigate the environmental impact of gas flaring but differ in their approach and effectiveness. Gas re-injection involves injecting associated gas back into reservoirs to maintain pressure and enhance oil recovery, thus reducing gas flaring and lowering greenhouse gas emissions. While it is effective in reducing emissions and enhancing oil recovery, it involves high capital and operational costs and requires suitable reservoir conditions [13]. In contrast, Carbon Capture and Storage (CCS) captures CO2 emissions from gas flaring and stores them underground. It is highly effective in reducing greenhouse gas emissions and mitigating climate change. However, it also involves high costs for technology implementation and infrastructure, along with regulatory and safety considerations [30].

2.3.2 Flare Gas Recovery Systems and **Renewable Energy Integration** offer different methods for addressing gas flaring. Flare gas recovery systems capture and process flare gas for reuse, converting it into fuel or feedstock and thus reducing the volume of gas flared. This system is effective in waste gas conversion but comes with high installation and maintenance costs, and technical complexities [15]. Renewable energy integration involves using sources like solar and wind to reduce reliance on gas flaring. This method reduces overall emissions by replacing fossil fuels with renewable energy, promotes sustainable practices, and diversifies the energy supply. However, it requires high initial investments and is dependent on suitable geographic and climatic conditions [9].

Comparison Summary:

Effectiveness: Current technologies like gas re-injection, flare gas recovery systems, and LNG projects are proven and widely implemented but often come with high costs and infrastructure requirements. Emerging technologies like CCS, renewable energy integration, and advanced monitoring offer innovative solutions with potentially greater long-term benefits but face challenges in terms of high initial investments and technical complexities.

Environmental Impact: Emerging technologies generally provide more significant reductions in greenhouse gas emissions and promote sustainability compared to current technologies, which are more focused on immediate economic benefits and practical gas utilization.

Economic Viability: Current technologies tend to offer immediate economic returns through the sale of recovered gas or enhanced oil recovery. In contrast, emerging technologies may require substantial initial investment but offer long-term economic and environmental benefits.

2.4 Case Studies

The Nigerian government launched the **Decade of Gas Initiative** in 2021 to transform Nigeria into a gas-powered economy by focusing on the development of its vast natural gas resources. The initiative aims to harness natural gas for power generation, industrial development, and cleaner energy transitions, driving economic growth while reducing the country's carbon footprint. The following programs are part of the broader strategic framework of the Decade of Gas Initiative.

1. **Nigeria Gas Flare Commercialisation Programme [NGFCP]**

The Nigerian Gas Flare Commercialization Programme (NGFCP) is a key initiative by the Nigerian government to reduce gas flaring by commercializing flare gas. It aims to attract investment, utilize flare gas for beneficial purposes, and reduce environmental pollution while generating economic benefits. The program has seen significant investor interest and is actively implementing flare gas capture projects [52][53].

The NGFCP was reintroduced in 2022 to align with Nigeria's Energy Transition Plan and address evolving industry and socio-economic conditions. This updated program reflects changes in gas flaring dynamics and operational realities since its initial launch by the Ministry of Petroleum Resources and the Department of Petroleum Resources [53].

2. The National Gas Expansion Programme [NGEP]

The National Gas Expansion Programme (NGEP), launched in December 2020, aims to transition from LPG to CNG for cooking, power, and small industries, and promote CNG for transportation. The NGEP includes a N250 billion intervention facility managed by the Central Bank of Nigeria to attract private investment, boost infrastructure, expand gas-based industries, and create jobs [54].

3. The Gas Flare Tracker

The gas flare tracker is a cutting-edge technology for monitoring and reporting flaring activity across Nigeria. It provides real-time data, enhancing accountability and transparency, and helps regulatory agencies enforce anti-flaring policies. By pinpointing high flaring areas and prompting swift actions, it supports efforts to reduce gas flaring [55].

4. Nigerian Gas Transportation Network Code [NGTNC]

The NGTNC is a contractual framework that provides open and competitive access to Nigeria's gas transportation infrastructure. Established to optimize the use of Nigeria's gas resources, it ensures secure and efficient natural gas transportation through a structured network. The framework aims to promote gas monetization and commercialization, reducing flaring by offering reliable transportation to consumers and markets [56].

2.5. Challenges & Barriers

2.5.1. Carbon Capture Storage

Technical Challenges:

1. Scaling up carbon capture technologies to industrial levels and deploying them across diverse operational environments requires extensive research, testing, and collaboration [57].
2. Identifying suitable sites for CO2 storage and ensuring long-term stability and containment poses logistical and technical challenges [57].

Economic & Financial Barriers:

1. One of the primary challenges is the high cost associated with implementing carbon capture technologies, operational expenses, and infrastructure development [57]. Nigeria’s current 2024 estimated GDP is $2498.58 [in billions] in comparison to Norway’s 2024 estimated GDP, $574.08 [in billions] [87]; Norway is an active implementer of CCS technologies to mitigate gas flaring.
2. Carbon capture processes often require significant energy, which may offset the environmental benefits and increase operational costs [57].

Regulatory & Policy Issues:

1. Uncertainty surrounding regulatory frameworks and policies related to carbon capture can hinder investment and project development [57].
2. Public perception and acceptance of carbon capture technologies, including concerns about safety,

environmental impact, and long-term efficacy, remain significant challenges [57].

2.5.2. Renewable Energy Integration

Technical Challenges:

1. To transfer power from production locations to consumption areas, renewable energy needs the right locations and infrastructure. Because existing infrastructure frequently favors centralized fossil fuel facilities rather than decentralized renewable sources, finding suitable locations and constructing essential transmission connections can be difficult and expensive [58].
2. Significant technical obstacles must be overcome in order to integrate renewable energy into the current grid, which was built for steady fossil fuel power. Modern grid management and energy storage technologies are necessary to provide a steady supply of electricity due to the intermittent nature of renewable energy sources like solar and wind [59].

Economic & Financial Barriers:

1. There are large upfront expenses associated with the construction and installation of renewable energy facilities, such as wind and solar farms. Due to their low maintenance requirements and free fuel [sun and wind], they are affordable to operate, although the initial outlay may put some people off [58]
2. As fossil fuel companies frequently receive large subsidies, renewable energy finds it challenging to compete on price. Furthermore, financial markets have become reliant on fossil fuel investments, making it difficult to reallocate funds to renewable energy sources [60].
3. In developing countries, like Nigeria, there are limited incentives for companies to invest in renewable energy. Unlike in many Western countries where incentives and subsidies make renewable energy projects profitable, investors often find fewer opportunities for financial returns, hindering the growth of renewable energy in such regions.

Regulatory & Policy Issues:

1. Regulations that are ambiguous or inconsistent may discourage investment in renewable energy. Long-term, stable policies are required by policymakers in order to inspire investor confidence in the future of the renewable energy markets [61].
2. There is a large disparity in the countries' readiness to switch to renewable energy. Maintaining a balance between energy security, accessibility, and environmental sustainability is a major challenge for major emitters such as the US, China, India, and Russia. To develop an inclusive, sustainable, and secure energy system, the public and private sectors must work together in concert for the transition to be effective [59].

2.5.3. Advanced Monitoring & Detection Technologies

Technical Challenges:

1. Implementing advanced monitoring and detection technologies involves significant technical challenges due to the complexity of integrating various systems and ensuring interoperability between new and existing infrastructure [62, 63]. For instance, smart grid technologies require sophisticated integration to ensure reliable and secure data flow across all components.
2. As these technologies often deal with sensitive data, ensuring robust cybersecurity measures is critical. There are significant challenges in protecting data from cyber threats, particularly in sectors such as fintech, digital health, and intelligent transportation systems [64]

Economic & Financial Barriers:

1. The deployment of advanced monitoring and detection technologies can be prohibitively expensive due to the high initial capital investment required for the hardware, software, and infrastructure needed

[63]. For example, upgrading to a fully functional smart grid involves substantial investment in smart meters, communication networks, and data management systems [62]
2. The economic viability of these technologies is often questioned due to the uncertainty in the return on investment. The benefits, while potentially significant in the long run, are not immediately apparent, which can deter investors and stakeholders [63, 65]

Regulatory & Policy Issues:

1. The regulatory environment for advanced monitoring and detection technologies is rapidly evolving. Regulations such as the EU AI Act and the NIST AI Risk Management Framework aim to address the risks associated with these technologies but also create a complex compliance landscape that businesses must navigate [66].
2. Adhering to the myriad of regulatory requirements across different jurisdictions can be costly and time-consuming for companies. Ensuring compliance with regulations like the SEC's cybersecurity requirements for public companies or the EU's Digital Operational Resilience Act [DORA] requires significant resources and ongoing monitoring [64, 67].

2.6. Future Directions & Recommendations

2.6.1 Research & Development

1. Artificial Intelligence and Machine Learning Applications:

Predictive Maintenance and Optimization: Develop AI and machine learning models to predict equipment failures and optimize the operation of gas flaring mitigation systems, enhancing efficiency and reducing downtime.

Real-time Monitoring and Adaptive Control Systems: Implement AI-driven real-time monitoring systems that can adaptively control flaring processes, ensuring optimal performance and minimizing emissions.

2. Blockchain for Carbon Credits and Emission Tracking:

Transparent Emission Monitoring Systems: Develop blockchain-based platforms to transparently track and report gas flaring emissions, facilitating better regulatory compliance and enabling oil companies to earn carbon credits for reducing emissions.

Incentive Programs for Emission Reductions: Create blockchain-enabled incentive programs that reward oil companies and stakeholders for adopting innovative gas flaring mitigation technologies and reducing their carbon footprint.

3. Advanced Materials for Gas Capture and Conversion:

Nanomaterials for Gas Adsorption: Explore the development of novel nanomaterials with high surface area and selective adsorption properties to capture and store flare gasses more effectively.

Catalysts for Low-Temperature Gas Conversion: Research new catalytic materials that enable the conversion of flare gasses into liquid fuels or chemicals at lower temperatures and pressures, making the process more energy-efficient and cost-effective.

4. Hydrogen Production and Utilisation:

Flare Gas to Hydrogen [F2H] Technologies: Investigate innovative processes to convert flare gas into hydrogen, which can be used as a clean energy source. This could involve reforming flare gas or using advanced electrochemical methods.

Hydrogen Fuel Cells for Remote Operations: Research the integration of hydrogen fuel cells in oil and gas operations, especially in remote areas, to utilize flare gas as a hydrogen source for clean, on-site power generation.

2.6.2. Policy Recommendations

1. Enhanced Financial Support for Infrastructure Development

Green Bonds and Climate Funds: Introduce green bonds or leverage international climate funds to finance the development of infrastructure needed for gas flaring mitigation, such as gas pipelines, LNG facilities, and gas processing plants.

Low-Interest Loans and Grants: Provide low-interest loans and grants to oil and gas companies for upgrading their facilities to reduce gas flaring.

2. Enhancing Market Mechanisms and Economic Incentives

Carbon Trading and Credits: Establish a national carbon trading system where companies can earn credits for reducing emissions through gas flaring mitigation. These credits can be traded, providing an economic incentive to invest in flaring reduction technologies.

Subsidies for Cleaner Technologies: Provide subsidies or financial incentives for companies adopting cleaner technologies, such as microturbines, fuel cells, and other advanced gas utilization systems.

3. Promoting Community Engagement and Benefits

Community Development Agreements [CDAs]: Mandate oil and gas companies to enter into CDAs with local communities, ensuring that a portion of the benefits from gas utilization projects is directed towards community development projects, such as schools, healthcare facilities, and clean water supply.

Local Employment and Training Programs: Encourage companies to hire locally and provide training programs for community members, enabling them to participate in and benefit from gas flaring mitigation projects.

3. Conclusion

This review examines various technologies and strategies for mitigating gas flaring in Nigeria, evaluating their effectiveness, cost feasibility, and environmental impact. Established methods like gas re-injection, flare gas recovery systems, and LNG projects are effective but costly and infrastructure-intensive. Emerging technologies such as Carbon Capture and Storage (CCS), renewable energy integration, and advanced monitoring systems offer promising long-term benefits but face high initial costs and technical challenges.

Case studies, particularly the Nigeria Gas Flare Commercialization Programme (NGFCP), demonstrate successful implementations and the potential for scaling these technologies. The NGFCP has shown promise in reducing flaring through flare gas commercialization, attracting investment, and generating environmental and economic benefits.

Nigeria's approach to gas flaring is evolving with increased regulatory pressure, advancing technologies, growing investment in sustainable energy, and collaborative efforts among stakeholders.

In conclusion, continued innovation and investment in emerging technologies are essential for significant long-term benefits.

Future research should focus on improving catalyst performance, optimizing reaction processes, integrating AI and blockchain for better control and transparency, and supporting policy frameworks to drive sustainable practices in the oil and gas industry.

For decades, Nigeria has battled the oil curse, where vast resources have brought more harm than good. To transform this curse into a boon, it is imperative to take bold, transformative actions to turn what has long been a curse into a powerful engine for progress and a true blessing for its people.

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