

# Advancements in Low-Emission Refining Technologies for Petroleum Products in Nigeria

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**Abstract.** This review explores advancements in refining technologies to reduce emissions and mitigate the environmental impact of petroleum production. Refining processes contribute approximately 4-6% of global industrial CO<sub>2</sub> emissions. Recent innovations, such as advanced catalysts, have demonstrated the ability to decrease harmful pollutants like sulfur and nitrogen oxides by 20-40%. Carbon capture technologies have also shown the capacity to capture up to 90% of CO<sub>2</sub> emissions in controlled environments. Improvements in refinery energy efficiency and the integration of cleaner energy sources have reduced energy consumption by 10-15%, contributing to overall emissions reductions of up to 25%.

Furthermore, using bio-based feedstocks in refining processes has emerged as a promising alternative, potentially reducing emissions by 50-70% and offering environmental and waste management benefits. However, adopting these low-emission technologies comes with challenges, as implementation can raise operating costs by 10-30%, depending on the refinery's scale and existing infrastructure. Despite these challenges, public and private investments and government policies incentivising cleaner practices are crucial to advancing these technologies. In conclusion, while progress in refining technologies has been significant, more research and development, combined with increased funding and more robust regulatory frameworks, are necessary to scale these innovations and make petroleum refining more sustainable in the long term. Adopted widely, these technologies can transform the sector, reduce its environmental footprint, and align with global climate objectives.

**Keywords:** Low-Emission Refining Technology, Advanced Catalyst, Energy Efficiency, Bio-based Feedstock.

## INTRODUCTION

Nigeria's petroleum industry has long been the backbone of its economy, contributing significantly to the nation's GDP since the discovery of oil in Oloibiri in 1956 [1]. The country has built a robust petroleum sector, and its refineries, including the Warri, Kaduna, and Port Harcourt plants, have played a central role in local processing capacity [2]. Despite their importance, these refineries have been plagued by inefficiencies, leading to low refining capacities and an increasing reliance on fuel imports [3]. Moreover, outdated infrastructure has led to significant environmental concerns, primarily through the emission of CO<sub>2</sub>, methane, and sulfur compounds [4]. The environmental footprint of Nigeria's petroleum refineries is considerable, with CO<sub>2</sub> emissions from combustion processes being the most prominent [1]. In recent years, attention has focused on how these refineries contribute to global greenhouse gas (GHG) emissions, exacerbating local air quality issues and contributing to global climate change [5]. For instance, Nigeria's refineries are estimated to emit several million metric tons of CO<sub>2</sub> annually due to inefficiencies and reliance on fossil fuel-powered energy sources [6]. Globally, the refining sector is undergoing significant transformations to reduce emissions in line with international climate change commitments such as the Paris Agreement [7]. Many countries are adopting advanced technologies such as carbon capture and storage (CCS), hydrogen-based refining, and renewable energy integration to meet their carbon reduction targets [8]. The European Union, for example, has set aggressive goals to decarbonise its refining sector by 2050, with multiple refineries already integrating low-emission technologies [9]. Nigeria, a significant player in the global oil market, also contributes to global emissions reduction efforts. As a signatory to the Paris Agreement, Nigeria has committed to cutting its emissions by 20% by 2030, with a further 45% reduction conditional on international support [10]. However, achieving these goals will require significantly modernising its refining infrastructure and adopting low-emission technologies [11]. This transition is essential for Nigeria's environmental obligations and for maintaining its competitiveness in a rapidly decarbonising global oil market. This paper aims to review the latest advancements in low-emission refining technologies that apply to Nigeria's petroleum sector, focusing on developments from 2020 to 2024. The primary

objective is to assess how these technologies can help modernise Nigeria's refineries, reduce their carbon footprint, and improve operational efficiency [2]. Additionally, this review will explore the feasibility of implementing these technologies within Nigeria's existing refining infrastructure and the potential economic and environmental benefits.

## RESULTS AND DISCUSSION

### Overview of emissions in Nigeria's petroleum refineries

Nigeria's refining capacity has been a focal point in its energy sector, but operational challenges have hindered its effectiveness. The Warri Refining and Petrochemical Company (WRPC), Kaduna Refining and Petrochemical Company (KRPC), and Port Harcourt Refining Company (PHRC) were designed to meet domestic fuel demand, reduce reliance on imports, and create employment opportunities [12]. However, due to ageing infrastructure, poor maintenance practices, and frequent disruptions in crude oil supply, these refineries have been operating far below their designed capacities [2]. The refineries were initially constructed in the late 1970s to early 1980s. While there have been efforts to rehabilitate them, the technological advancements needed for efficient, low-emission operations have not been fully implemented [13]. A 2020 report by the Nigerian Extractive Industries Transparency Initiative (NEITI) indicated that refinery outputs have been inconsistent, with production often ceasing entirely for months due to mechanical failures or lack of crude feedstock [14]. This operational inefficiency affects fuel availability and increases the environmental burden. When refineries run below capacity or experience frequent shutdowns, more energy is required to restart and stabilise operations, leading to spikes in energy consumption and GHG emissions.

#### *Key Emission Sources*

1) Crude Distillation Units (CDUs): As the first significant process in refining, the CDU is responsible for separating crude oil into various fractions based on boiling points. This process requires large amounts of heat, typically provided by burning fossil fuels, making CDUs significant contributors to CO<sub>2</sub> emissions [1]. According to data from a 2021 study on energy use in African refineries, the average energy intensity in Nigeria's CDUs is 15% higher than the global aver-

age due to outdated heat exchangers and inefficient furnaces [15].

2) Hydrocracking and Catalytic Reforming: These processes break down heavy hydrocarbon molecules into lighter products and improve gasoline quality by increasing octane levels. Both operations require high temperatures and pressures, and the hydrogen used in hydrocracking is often produced from natural gas reforming, which is a significant source of CO<sub>2</sub> [16]. A 2022 analysis revealed that Nigeria's refineries emit up to 50% more CO<sub>2</sub> per barrel processed in these stages

than in Europe and North America, where advanced catalysts and hydrogen recycling technologies are more prevalent [17].

3) Flaring: Flaring is a significant source of GHG emissions in Nigeria's refineries, accounting for a substantial portion of methane and black carbon emissions. Flaring occurs when excess gases generated during refining are burned off instead of being captured or processed into usable products. While this practice reduces the risk of explosion, it contributes to both short-lived climate pollutants (SLCPs) and long-lived GHGs [18].

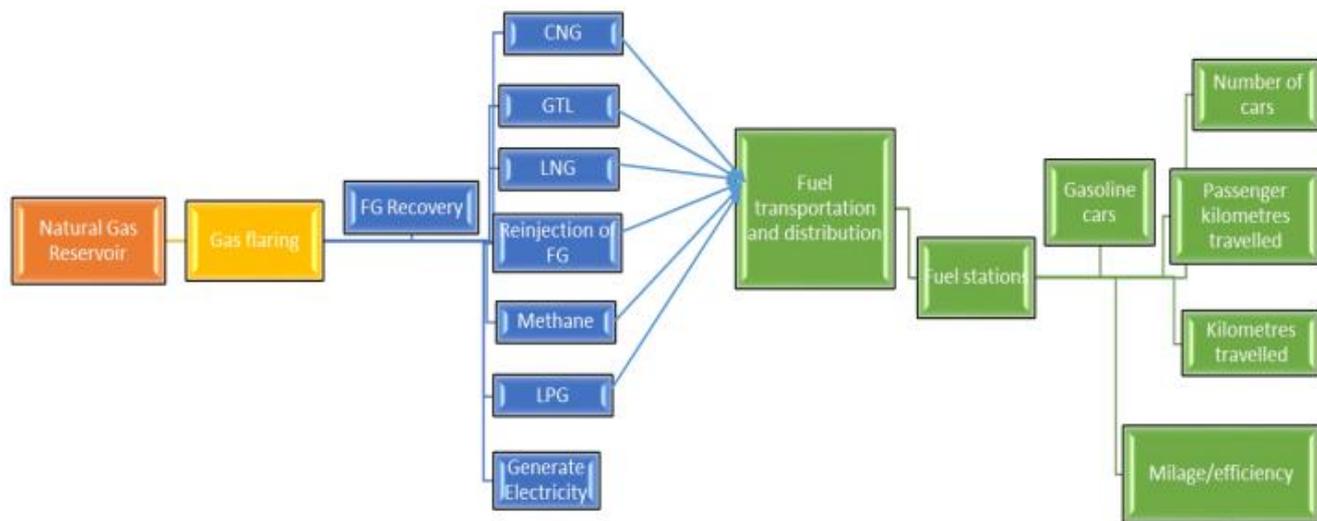


Figure 1 – Utilisation options for flared gas in Nigeria's oil and gas industry [19]

4) Sulfur Recovery Units (SRUs): Many refineries process high-sulfur crude, leading to sulfur dioxide (SO<sub>2</sub>) emissions during desulfurisation. In Nigeria, SRUs are outdated or operate below optimal efficiency, causing elevated SO<sub>2</sub> emissions and contributing to acid rain and respiratory problems [20].

Data from the National Environmental Standards and Regulations Enforcement Agency (NESREA) in 2022 estimated that Nigeria's refineries collectively emit over 30,000 tons of SO<sub>2</sub> and 25,000 tons of NO<sub>x</sub> annually, exacerbating air pollution in nearby communities [21]. Additionally, CO<sub>2</sub> emissions from Nigeria's refineries have been reported at approximately 5 million metric tons per year, with methane emissions contributing significantly to the country's overall GHG profile [22].

#### Challenges in Reducing Emissions

1) Ageing Infrastructure and Outdated Technologies: Most of Nigeria's refineries were built sev-

eral decades ago, with limited technological upgrades since their initial construction. The lack of modern emissions control systems, such as advanced catalytic converters or energy-efficient furnaces, has led to high emission levels [1]. Newer technologies, like waste heat recovery systems and combined heat and power (CHP) units, which can significantly reduce energy consumption and emissions, are not in place in most Nigerian refineries [23].

2) Economic Barriers: The financial investment required to refurbish Nigeria's refineries is estimated to be billions of dollars [24]. Given the global shift towards cleaner energy and the oil market's volatility, investing in refinery upgrades can be financially risky, especially without strong government support or international financing [25]. A 2022 World Bank report noted that Nigeria would require substantial international financial assistance, possibly through carbon financing or climate-focused investment, to modernise its refining sector [26].

3) Policy and Regulatory Issues: Nigeria has ratified international climate agreements, but its domestic regulatory framework for reducing refinery emissions remains weak. Environmental regulations are often not enforced, and refinery operators have little incentive to invest in low-emission technologies [27].

### **Recent advancements in low-emission refining technologies (2020-2024)**

*Advanced Catalysts.* In recent years, advancements in catalyst technology have significantly improved emissions reduction in petroleum refining. Catalysts, crucial in refining processes like hydrocracking, enable chemical reactions to occur under milder conditions, thus reducing energy consumption. Notably, zeolite-based catalysts, introduced in 2021, have optimised reaction conditions, reducing nitrogen oxides (NO<sub>x</sub>) and carbon dioxide (CO<sub>2</sub>) emissions while ensuring fuel quality. These catalysts have proven effective in reducing sulfur content in fuels without degrading product quality, with some refineries in Africa and South America reporting a 30-50% decrease in sulfur oxide (SO<sub>x</sub>) emissions. Additionally, catalysts introduced in 2022 with enhanced surface areas have improved sulfur removal while consuming less energy, offering great potential for Nigerian refineries, such as Port Harcourt, where SO<sub>x</sub> and NO<sub>x</sub> emissions could be cut by up to 40%.

*Carbon Capture, Utilisation, and Storage (CCUS).* CCUS technology has gained momentum as a critical method for reducing CO<sub>2</sub> emissions in energy-intensive sectors like petroleum refining. Between 2020 and 2024, advancements in post-combustion and oxy-fuel combustion methods have improved carbon capture efficiency and economic feasibility. Innovations, such as amine-based solvents, have reduced energy use by up to 25%, making CCUS more accessible, particularly in developing nations. Oxy-fuel combustion, which allows for nearly 100% CO<sub>2</sub> capture, is also becoming a leading solution in the industry. However, CCUS remains in the feasibility stage in Nigeria due to the lack of infrastructure for CO<sub>2</sub> transport and storage, which would require substantial investment in pipelines and storage facilities, particularly in regions with suitable geological formations.

*Electrification and Energy Efficiency.* The electrification of refinery operations, coupled with advancements in energy efficiency, is playing a growing role in reducing the environmental im-

pact of refining. Between 2020 and 2024, combined heat and power (CHP) systems and waste heat recovery technologies have enhanced refinery energy efficiency. CHP systems, which generate electricity and heat from a single fuel source, can reduce energy consumption by up to 20%, making them highly relevant for Nigerian refineries that rely on outdated systems. Moreover, advanced heat exchangers and digital monitoring tools have enabled refineries to recover waste heat and optimise energy use in real time, potentially cutting CO<sub>2</sub> emissions by 30%. Integrating artificial intelligence (AI) and machine learning (ML) further enhances these systems by fine-tuning energy-intensive processes.

*Hydrogen Utilisation in Refining.* Hydrogen is gaining traction as a cleaner fuel alternative in refining, especially in hydrocracking and desulfurisation processes. From 2020 to 2024, investments in hydrogen infrastructure, particularly in producing blue and green hydrogen, have increased globally. Blue hydrogen is produced from natural gas, with CO<sub>2</sub> emissions captured through CCUS, while green hydrogen, derived from water electrolysis using renewable energy, results in zero emissions. Hydrogen is becoming a more feasible option for refineries as electrolyser costs drop. In 2023, several European refineries successfully integrated green hydrogen, cutting CO<sub>2</sub> emissions by up to 50%. For Nigeria, blue hydrogen holds excellent potential due to its natural gas reserves, though green hydrogen adoption remains challenging due to the need for significant investment in renewable energy infrastructure. However, hydrogen utilisation could reduce emissions from hydrocracking and desulfurisation in Nigerian refineries by up to 60%, positioning the country as a leader in cleaner refining technologies.

### **Alternative feedstocks and biofuels**

As the global petroleum refining industry seeks to reduce greenhouse gas emissions, adopting alternative feedstocks and biofuels has gained prominence. Bio-based feedstocks, such as biodiesel, bioethanol, and second-generation biofuels derived from non-food sources, offer a promising avenue for lowering the carbon intensity of fuel production. In Nigeria, agricultural waste like palm oil residues and cassava waste could serve as valuable raw materials for biofuel production, reducing reliance on imported fuels and mitigating environmental impacts. Additionally, waste-to-fuel technologies that convert plastic

waste and municipal solid waste into cleaner fuels have seen advancements in efficiency and scalability, offering a dual solution to waste management and cleaner energy production. Case studies from countries like Brazil, Europe, and the United States demonstrate the potential of biofuels and alternative feedstocks, showing significant reductions in lifecycle CO<sub>2</sub> emissions when integrated into traditional refining processes. For instance, Brazil's use of bioethanol, Neste's renewable diesel from waste fats in Europe, and Chevron's renewable diesel from grease in the US showcase these strategies' environmental and economic benefits. With investment in processing infrastructure and addressing feedstock availability challenges, Nigeria could follow these examples and enhance its refining sector's sustainability.

### Economic and environmental impact of low-emission refining technologies

The transition to low-emission refining technologies presents both economic and environmental opportunities. However, significant upfront investment is required in advanced equipment, retrofitting facilities, and the implementation of technologies like advanced catalysts and carbon capture, utilisation, and storage (CCUS) systems. While initial costs and operating expenses may rise due to specialised training and maintenance, long-term benefits include enhanced efficiency, reduced energy consumption, and lower operational costs. These improvements can make Nigeria's refining sector more competitive in global markets, particularly as sustainability becomes a priority. Low-emission technologies, such as advanced catalysts, CCUS, electrification, and bio-based feedstocks, help reduce greenhouse gas emissions, improve product yields, and minimise waste.

Case studies from South Africa's Sasol Refinery and Kenya's Mombasa Refinery highlight the economic and environmental gains from adopting cleaner technologies, such as reduced emissions and lower operational costs. Lessons learned emphasise the importance of phased implementation, government-industry collaboration, and capacity building to ensure successful integration and maximise the potential of low-emission technologies.

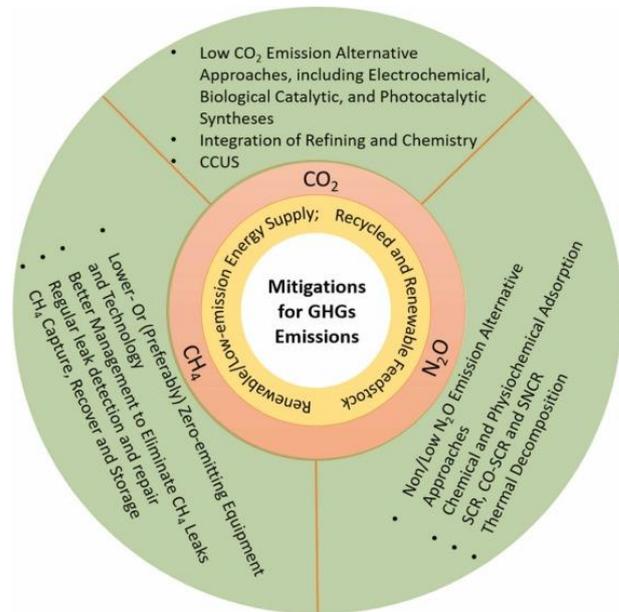


Figure 2 – Mitigations for greenhouse gas emissions in the petrochemical and chemical industry [28]

Barriers to the adoption of low-emission technologies in Nigeria. Nigeria's outdated refining infrastructure, with facilities dating back to the 1970s and 1980s, presents significant challenges to adopting modern low-emission technologies. Warri, Kaduna, and Port Harcourt refineries suffer from obsolete equipment, making implementing advanced systems like carbon capture and storage (CCUS) or energy-efficient technologies challenging. A lack of digital monitoring systems, crucial for optimising operations and reducing emissions, further hampers modernisation efforts. Nigeria's refineries face low technological readiness, with limited expertise and resources to adopt innovations such as advanced catalysts and waste-to-fuel systems. These challenges are compounded by weak environmental regulations, inconsistent enforcement, and a lack of financial incentives for clean technology adoption. The absence of a comprehensive policy framework tailored to emissions reduction in the refining sector also discourages investment. Financial barriers, including the high cost of technology upgrades, limited access to financing, and the country's reliance on oil revenues, further impede modernisation efforts. While international funding and partnerships could offer support, securing such aid is highly competitive and often comes with stringent conditions, creating additional hurdles for Nigeria's refining sector.

## Prospects for low-emission refining in Nigeria

Nigeria has immense potential to expand low-emission refining technologies by leveraging its rich natural resources and growing energy needs. With vast oil and gas reserves, the country can incorporate advanced technologies like carbon capture and storage (CCUS), advanced catalysts, and hydrogen utilisation into its refining processes. Blue hydrogen, produced from Nigeria's natural gas reserves and renewable energy sources such as solar and wind, can significantly cut CO<sub>2</sub> emissions and improve operational efficiency. Both public and private investments are crucial to making this shift. Government support through grants, tax incentives, and subsidies, combined with private sector investments for upgrading technology and expanding infrastructure, will accelerate the adoption of these innovations. Public-private partnerships can help share financial risks and facilitate the transfer of advanced technologies. Strengthening regulatory frameworks is also crucial – by setting clear emissions reduction targets and enforcing strict environmental laws, Nigeria can encourage wider adoption of low-emission technologies. Offering financial incentives like tax breaks and low-interest loans, as well as implementing a national strategy for clean refining, will further support this transition. International collaborations will give Nigeria access to the latest technologies and practices, with organisations like the International Energy Agency (IEA) and the World Bank providing technical support and funding. Research and development (R&D) is essential for adapting these technologies to local conditions and driving innovation. The long-term environmental benefits of low-emission refining include significant reductions in CO<sub>2</sub> and other greenhouse gases, improved air quality, and enhanced public health. Aligning with international climate goals, such as those of the Paris Agreement, will boost Nigeria's global standing and attract more international support and invest-

ment. Economically, adopting these technologies will improve refinery efficiency, lower costs, and create new jobs, driving growth and innovation. As a leader in clean refining within Africa, Nigeria can set an example for the region and contribute to sustainable energy solutions across the continent.

## CONCLUSIONS

Advancing low-emission refining technologies in Nigeria requires a comprehensive and strategic approach. This begins with creating a National Low-Emission Refining Strategy that sets clear emissions reduction targets and establishes a monitoring system to track progress. Modernising refinery infrastructure is essential, incorporating advanced technologies like CCUS, digital monitoring systems, and renewable energy sources like solar and wind. Strengthening policy and regulatory frameworks is also vital – enforcing stricter emissions standards and offering financial incentives such as tax breaks and subsidies will encourage the adoption of clean technologies. Public-private partnerships and international collaborations will be crucial to bringing in expertise and funding. Research and development investments are needed to adapt technologies to Nigeria's conditions while addressing financial barriers through climate finance, green bonds, and risk mitigation strategies, making these technologies more accessible. Lastly, raising public awareness and engaging stakeholders, including communities and NGOs, will build the support needed for a successful transition to sustainable refining practices.

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