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National Centre for Energy and Environment, Energy Commission of Nigeria, University of Benin:
ISSN 2504-9593
DOI: 10.5281/zenodo.19182956
https://ijree.com/index.php/publications/article/view/45
Int. J. Renew. Energ & Environ Vol.4 (1), pp 297-307(2026)

SOURCE CHARACTERISATION OF CO_2 EMISSIONS IN PETROLEUM REFINERIES IN PORT HARCOURT: RELEVANCE FOR CARBON CAPTURE AND STORAGE

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Abstract
This study assessed the sources, operational drivers, and feasibility of implementing carbon capture and storage (CCS) at the refinery. Data were collected from 18 staff members, including engineers, environmental officers, operations managers, and maintenance personnel, through structured questionnaires and semi-structured interviews, supplemented by secondary reports. Respondents estimated annual CO_2 emissions between 1–5 million tonnes, with the fluid catalytic cracking (FCC) unit (29.8%), fired heaters/boilers (27.2%), and steam methane reforming (SMR, 19.1%) identified as the primary contributors. Reported CO_2 concentrations in flue gases ranged from 5–15%, with FCC and SMR units exhibiting 8–12% and 12–15%, respectively, indicating suitability for post-combustion capture technologies. Energy consumption was concentrated in FCC (120–150 MW/day), boilers (80–100 MW/day), and SMR units (60–70 MW/day), further highlighting their role as major emission drivers. Capacity utilization post-2024 rehabilitation was 53.3% for the New Plant and 41.7% for the Old Plant, reflecting underutilization and operational instability. While 44% of staff demonstrated familiarity with CCS and identified existing natural gas pipelines and compression infrastructure as adaptable for CO_2 transport, 56% had limited or no knowledge, indicating gaps in technical readiness. The study concludes that targeted CCS implementation at high-emission units is technically feasible, but successful deployment requires enhanced monitoring systems, workforce training, and infrastructural assessment. These findings provide critical insights for policymakers and refinery management in Nigeria and contribute to strategies for emissions reduction in oil and gas operations in emerging economies.
Keywords: Port Harcourt Refinery, CO_2 emissions, Carbon capture and storage, Fluid catalytic cracking, Nigeria, CCS feasibility

1. Introduction

Petroleum refining remains one of the most energy-intensive and carbon-emitting industrial activities globally, owing to its reliance on fossil fuel combustion, hydrogen production, and high-temperature process units. As countries pursue pathways toward net-zero emissions under the Paris Agreement, refineries have emerged as critical targets for greenhouse gas mitigation, particularly carbon dioxide (CO_2), which constitutes the dominant share of refinery emissions (IPCC, 2023; International Energy Agency, 2024). Identifying and quantifying the major sources of CO_2 within refinery systems is a foundational step for designing effective decarbonization strategies, including the deployment of carbon capture and storage (CCS) technologies. Globally, the oil and gas sector is a major source of energy-related CO_2 emissions, with petroleum refining contributing significantly through fuel combustion in heaters, boilers, and furnaces, as well as emissions from hydrogen production, fluid catalytic cracking (FCC) units, and routine flaring (International Energy Agency, 2023; Intergovernmental Panel on Climate Change, 2022).Studies have shown that stationary combustion sources typically dominate refinery emission profiles, followed by process-related emissions and fugitive releases. The persistence of these emission sources, combined with growing demand for refined petroleum products, presents a major challenge to achieving deep emission reductions without targeted technological interventions. In Nigeria, the challenge is particularly pronounced. As Africa's largest oil producer, Nigeria has committed to achieving net-zero greenhouse gas emissions by 2060**,** in line with its obligations under the Paris Agreement (Adebayo *et al.,* 2022; Ogunleye *et al.,* 2023). However, the petroleum refining sector continues to rely on ageing infrastructure characterised by low energy efficiency and high carbon intensity. The Port Harcourt Refining Complex, one of the country's most significant refining hubs, plays a central role in meeting domestic fuel demand but is also a major point source of CO_2 emissions. Emissions arise primarily from crude distillation units, reforming units, hydrogen plants, utility systems, and gas flaring associated with both routine operations and process upsets. Beyond national climate commitments, the local environmental impacts of refinery emissions are serious. Port Harcourt and nearby communities in the Niger Delta face ongoing air quality issues caused by industrial activities, mainly oil refining and gas flaring, which increase health risks such as respiratory and heart problems (Ede & Edokpa, 2017; Ana *et al.,* 2019; Nwankwo *et al.,* 2021). Without a clear understanding of where emissions occur within refinery processes, efforts to reduce them are scattered and ineffective, hindering Nigeria's progress to upgrade its refining industry according to global standards. Against this background, identifying the significant sources of CO_2 emissions in petroleum refineries in Port Harcourt is both timely and essential. Source-level characterisation provides the empirical basis for evaluating the technical suitability and economic feasibility of CCS integration, enabling prioritisation of high-emission units for capture and informing infrastructure planning. Moreover, such analysis supports evidence-based policymaking, strengthens Nigeria's position in attracting international climate finance, and aligns refinery operations with emerging carbon-constrained trade regimes. By systematically examining CO_2 emission sources within Port Harcourt's refineries, this study contributes to the broader discourse on industrial decarbonisation in developing, oil-dependent economies.

2.0 Literature Review

Petroleum refining is widely recognised as one of the most carbon-intensive industrial activities due to its heavy reliance on fossil fuel combustion, high-temperature processing, and hydrogen-dependent upgrading operations. Recent global assessments indicate that the refining sector contributes approximately 6–7% of total industrial carbon dioxide (CO_2) emissions, with emissions largely concentrated in a limited number of energy-intensive process units rather than being evenly distributed across refinery operations (IEA, 2024; IPCC, 2023). This concentration of emissions at identifiable point sources distinguishes refineries from many other sectors and makes them particularly suitable for detailed source characterisation and targeted mitigation strategies such as carbon capture and storage (CCS). As international climate policy increasingly focuses on deep emission reductions from hard-to-abate sectors, understanding the origin, magnitude, and characteristics of refinery CO_2 emissions has become a central theme in the literature. Existing studies consistently classify refinery CO_2 emissions into three interrelated categories: combustion-related emissions, process emissions, and utility-associated emissions. Combustion emissions arise from the burning of refinery fuel gas, fuel oil, petroleum coke, or natural gas in furnaces and boilers used across primary and secondary processing units. These emissions dominate in crude distillation and thermal treatment processes, where large quantities of heat are required to separate and transform hydrocarbon fractions. Process emissions, by contrast, originate directly from chemical reactions that release CO_2 as a reaction product, most notably in fluid catalytic cracking (FCC) units and hydrogen production systems based on steam methane reforming (SMR). Utility-associated emissions stem from combined heat and power (CHP) plants and auxiliary boilers that supply electricity and steam to support refinery-wide operations (Leung et al., 2014; IEA, 2024). Collectively, these emission categories account for more than 80% of total refinery CO_2 output, highlighting the importance of unit-level emission profiling in decarbonisation planning.

Among all refinery process units, the FCC unit is consistently identified in the literature as the single largest source of CO_2 emissions. The FCC process upgrades heavy hydrocarbon fractions into lighter, more valuable products by cracking long-chain molecules over a catalyst at high temperatures. During operation, coke accumulates on the catalyst surface and must be periodically burned off in a regenerator, releasing substantial volumes of CO_2-rich flue gas. Recent studies estimate that FCC units contribute between 30% and 40% of total refinery CO_2 emissions, with flue gas CO_2 concentrations typically ranging from 10% to 20% depending on feedstock quality, operating severity, and regeneration mode (IEA, 2024; IPCC, 2023). These relatively high concentrations, combined with the continuous and central role of FCC operations, make FCC regenerators among the most technically and economically attractive targets for post-combustion carbon capture. In addition to FCC units, crude distillation units (CDUs) represent a major source of refinery emissions due to the extensive combustion required to preheat crude oil before atmospheric separation. CDUs form the backbone of refinery operations and operate continuously, consuming large quantities of fuel to maintain temperatures typically between 350°C and 400°C. Although the CO_2 concentration in CDU furnace flue gases is comparatively low, generally between 3% and 5%, their sheer scale and sustained operation result in significant cumulative emissions, often accounting for 20–30% of total refinery CO_2 output (Leung et al., 2014; IEA, 2024). The literature therefore recognises CDUs as important contributors to refinery emissions, particularly in older facilities where energy efficiency is lower, and fuel consumption per barrel of crude processed is higher. Hydrogen production through steam methane reforming constitutes another critical emission source in modern refineries, particularly as fuel quality regulations increasingly require deep desulphurisation of transport fuels. In SMR units, natural gas reacts with steam at high temperatures to produce hydrogen and carbon monoxide, followed by the water–gas shift reaction that converts carbon monoxide to CO_2 while generating additional hydrogen. This process results in CO_2 emissions that are fundamentally different from those of combustion-based units, as they often produce high-purity CO_2 streams with concentrations ranging from 20% to 30% (IEA, 2023). Although SMR units typically contribute a smaller share of total refinery emissions, generally around 10–15%, their favourable gas composition significantly reduces capture complexity and energy penalties. Consequently, the literature frequently identifies SMR units as low-hanging opportunities for early CCS deployment in refinery settings.

Utility systems, particularly combined heat and power plants, further add to the refinery emission profile by supplying electricity and steam to multiple process units. CHP plants are integral to refinery operations, especially in regions with unreliable grid electricity, and they typically operate continuously to meet base energy demand. Emissions from CHP systems usually contain CO_2 concentrations in the range of 5–10% and can account for approximately 20–25% of total refinery emissions (Rivas-Gómez & González-Garay, 2022; IEA, 2024). While these emissions are more diffuse than those from FCC or SMR units, their steady operating conditions and centralised exhaust points enhance their suitability for post-combustion capture when integrated into refinery-wide decarbonisation strategies. By contrast, secondary units such as hydrotreating and catalytic reforming generally contribute a smaller fraction, often less than 10%, of total emissions, as their primary reactions do not directly release CO_2 and emissions are mainly associated with auxiliary heating and hydrogen consumption (IEA, 2024). Beyond emission volumes, recent literature increasingly emphasises the importance of CO_2 concentration, pressure, temperature, and temporal stability in determining the feasibility and cost of carbon capture. High-concentration and high-purity streams significantly reduce solvent regeneration energy requirements and equipment size, thereby lowering capture costs (IEA, 2023; IPCC, 2023). Consequently, studies advocate for a source-prioritisation approach in which capture efforts initially target FCC regenerators and SMR units before expanding to lower-concentration sources such as CDU furnaces and CHP stacks. This phased strategy is particularly relevant in developing-country contexts, where capital constraints and infrastructure limitations necessitate careful prioritisation of mitigation investments. While the global literature on refinery emissions and CCS deployment is extensive, studies focusing on developing economies, especially sub-Saharan Africa, remain comparatively scarce. In Nigeria, research on refinery emissions has historically concentrated on air pollution, gas flaring, and operational inefficiencies, with limited attention given to systematic CO_2 source characterisation at the unit level (Oyekan & Adewumi, 2020; Dike, 2020). This gap is significant because Nigerian refineries are characterised by ageing infrastructure, intermittent operation, and higher energy intensity than many modern facilities, factors that can substantially influence emission profiles and capture feasibility. The Port Harcourt Refinery Complex, with a combined installed capacity of 210,000 barrels per day, is one of the largest and most strategically important refining hubs in Nigeria. Available studies suggest that its emission structure broadly mirrors global refinery patterns, with FCC units, CDUs, SMR units, and CHP plants accounting for the majority of CO_2 emissions (Okafor & Okeke, 2019; IEA, 2024). However, the absence of detailed, site-specific emission inventories limits the ability to design optimised CCS systems that reflect local operating conditions, fuel mixes, and infrastructure constraints. This limitation persists despite growing recognition of the Niger Delta's substantial geological CO_2 storage potential in depleted oil and gas reservoirs and deep saline aquifers, which positions the region as a promising candidate for CCS deployment (IPCC, 2023; IFC, 2025). Recent CCS scholarship underscores that detailed source characterisation is a prerequisite for credible techno-economic assessment, policy formulation, and investment mobilisation. Capture costs, integration challenges, and long-term performance are all highly sensitive to emission source characteristics, including gas composition and operational variability (IEA, 2023). In the Nigerian context, robust emission profiling is also essential for accessing international climate finance, attracting technology partnerships, and aligning industrial operations with national commitments under the Paris Agreement and Nigeria's 2060 net-zero target. Overall, the reviewed literature demonstrates that although global understanding of refinery CO_2 emission sources and capture opportunities is well established, empirical evidence from Nigerian refineries, particularly the Port Harcourt Refinery, remains limited and fragmented. This gap highlights the need for comprehensive, unit-level source characterisation to support informed decision-making on carbon capture deployment and to advance refinery decarbonisation strategies within Nigeria's unique economic, infrastructural, and policy context.

3.0 Methodology

This study adopts an integrated methodological approach to examine carbon dioxide (CO_2) emission sources and conditions relevant to carbon capture and storage (CCS) at the Port Harcourt Refinery, considering technical, geological, environmental, and socio-institutional dimensions. The Port Harcourt Refinery occupies approximately 1,200 hectares and is located about 25 km south-east of Port Harcourt, Rivers State. It is strategically connected to Nigeria's petroleum supply network, receiving crude oil via pipelines from the Bonny terminal and distributing refined products nationwide. Although the refinery employs fewer than 500 permanent staff, it plays a significant socio-economic role in surrounding communities through indirect employment and service-related activities.

Technically, the refinery comprises atmospheric and vacuum distillation units, fluid catalytic cracking (FCC) systems, reforming units, and hydrotreating facilities. The primary sources of carbon dioxide (CO_2) emissions are process heaters, boilers, and the FCC regenerator, which together account for approximately 70% of total plant emissions. These units, therefore, form the core focus of the CCS feasibility assessment. Geologically, the refinery is located within the Niger Delta Basin, which is widely regarded as favourable for CCS deployment due to the presence of extensive sedimentary formations, depleted hydrocarbon reservoirs, and deep saline aquifers. The Agbada Formation has been identified as particularly suitable for long-term CO_2 storage, owing to its favourable porosity, permeability, and caprock integrity (Nigerian CO_2 Storage Atlas, 2022). These formations lie within 50–100 km of the refinery, offering potential for short-distance CO_2 transportation. The broader socio-political context of the Niger Delta also informs the methodological framework. The region has a history of environmental degradation and socio-economic marginalisation linked to oil and gas activities, resulting in community distrust of industrial projects. Consequently, social acceptance and stakeholder engagement are critical factors in evaluating CCS feasibility. At the same time, the concentration of oil and gas infrastructure and technical expertise in the region presents opportunities for integrated CCS deployment. Climate change risks such as flooding and sea-level rise further highlight the urgency of adopting emission reduction measures such as CCS.

3.2 Research Design

A mixed-methods research design was adopted, using a convergent parallel approach as described by Creswell and Plano Clark (2018). Quantitative and qualitative data were collected concurrently, analysed separately, and integrated at the interpretation stage. This design enables a balanced assessment of technical feasibility and stakeholder perceptions while enhancing the validity of the findings through data triangulation.

3.3 Sampling Techniques

Purposive sampling was used to select key informants for semi-structured interviews, including refinery engineers, managers, and regulatory officials with relevant technical or policy expertise. For the questionnaire survey, stratified sampling was employed to capture perspectives from three stakeholder groups: refinery staff, regulators, and host communities. A total of 130 questionnaires were administered, comprising 20 to refinery staff, 10 to regulatory officials from NUPRC, NESREA, and the Federal Ministry of Environment, and 100 to residents of surrounding communities in Alesa-Eleme and Port Harcourt.

3.4 Data Collection Methods

Data were collected through structured questionnaires, semi-structured interviews, and secondary sources. The questionnaires included Likert-scale items assessing awareness, perceived feasibility, and environmental and economic implications of CCS, alongside open-ended questions for detailed responses. Semi-structured interviews were conducted to explore technical, institutional, and policy-related issues in greater depth (Kvale & Brinkmann, 2015). Secondary data were obtained from technical reports, environmental impact assessments, policy documents, and peer-reviewed literature, including publications from the International Energy Agency and the British Geological Survey (IEA, 2024; BGS, 2020).

3.5 Analytical Methods

Quantitative data were analysed using descriptive statistics, including frequencies, percentages, and mean scores, with cross-tabulations used to compare responses across stakeholder groups. Correlation analysis was applied to examine relationships between key variables, and statistical analysis was conducted using SPSS (Fowler, 2014). Qualitative data from interviews and open-ended responses were analysed thematically through systematic coding to identify recurring themes related to technical feasibility, regulatory readiness, and social acceptance. Findings from both datasets were integrated using the convergent parallel approach to provide a comprehensive feasibility assessment.

3.6 Ethical Considerations

The study adhered to established ethical standards for research involving human participants. Informed consent was obtained from all respondents, participation was voluntary, and confidentiality and anonymity were assured through data anonymisation and secure storage. Engagement with participants was conducted with cultural sensitivity, particularly within host communities. Access to participants was obtained through appropriate institutional approvals from NNPC, PHRC, and the Federal Ministry of Environment, ensuring compliance with academic and institutional ethical requirements.

4. Results and Discussion

4.1 Overview of CO_2 Emission Sources

The Port Harcourt Refinery is a significant point source of carbon dioxide (CO_2) emissions in Nigeria. This study assessed operational units, emission intensity, flue gas characteristics, and infrastructural factors relevant to carbon capture and storage (CCS). Data were collected from refinery engineers, environmental officers, operations managers, and maintenance personnel directly involved in refinery processes. The findings provide an integrated perspective on CO_2 emission distribution, operational constraints, and opportunities for CCS deployment.

4.2 Operational Profile of Respondents

The professional distribution of respondents ensures that emission estimates reflect operational realities. Table 1 summarises the roles, experience, and plant coverage.

Variable	Category	Frequency (%)
Professional Role	Process Engineers	33.3
	Environmental Officers	22.2
	Operations Managers	16.7
	Maintenance Engineers	16.7
	Other	11.1
Years of Experience	< 5 years	22.2
	5–10 years	38.9
	10–20 years	11.1
	> 20 years	27.8
Plant Coverage	New Plant	44.4
	Old Plant	27.8
	Both Plants	27.8

Table 1: Professional Roles, Experience, and Plant Coverage Respondents

4.3 Estimated Annual CO_2 Emissions

Respondents estimated refinery CO_2 emissions based on operational data and environmental reporting practices. As summarised in Table 2, most estimates align with global benchmarks for similar refineries (IEA, 2024).

Table 2. Estimated Annual CO_2 Emissions ($MtCO_2$/year).

Estimated Emissions	Frequency (%)
<1	11.1
1–3	33.3
3–5	22.2
>5	11.1
Not sure	22.2

The variation in responses highlights gaps in access to consolidated emissions inventories, which may constrain CCS system design and assessment.

4.4 Major CO_2 Emission Sources

Table 3 presents refinery units ranked by CO_2 contribution. FCC and fired heaters/boilers are the primary sources, accounting for over 50% of emissions.

Estimated Emissions ($MtCO_2$/year)	Frequency (%)
< 1	11.1
1–3	33.3
3–5	22.2
> 5	11.1
Not sure	22.2

Table 3. Major CO_2 Emission Sources

4.5 CO_2 Concentration in Flue Gases CO_2 concentration is critical for capture feasibility. Table 4 summarises typical ranges for major units.

Unit	CO_2 Concentration (%)	CCS Suitability
FCC	8–12	High
Fired Heaters/Boilers	6–10	Moderate–High
SMR	12–20	Very High
CDU	<6	Moderate

Table 4. Typical CO_2 Concentrations in Flue Gases

Reported ranges suggest that post-combustion capture, particularly amine-based absorption, is technically feasible for key emission sources.

4.6 Energy Intensity and Operational Drivers

Energy-intensive units are also major contributors to emissions (Table 5). Operational inefficiencies further exacerbate CO_2 output.

Unit	Energy Intensity	Emission Implication
FCC	Very High	Major CO_2 source
Boilers/Heaters	High	Continuous emissions
SMR	High	Process-related CO_2
CDU	Moderate	Indirect emissions

Table 5. Energy Intensity and Emission Drivers

4.7 Implications for CCS Deployment
Findings indicate that CO_2 emissions are concentrated in a few high-intensity units, facilitating targeted CCS deployment. Concentration levels in flue gas units are within technically viable ranges for commercial capture systems. However, barriers include limited continuous emissions monitoring, low CCS awareness among staff, and uncertainty regarding existing compression and pipeline infrastructure. Successful CCS implementation will require infrastructural upgrades, staff training, and detailed site-specific engineering assessments.

5.0 Discussion of Findings
The results of this study provide a comprehensive characterisation of CO_2 emissions at the Port Harcourt Refinery, highlighting both technical opportunities and operational challenges for the deployment of carbon capture and storage (CCS). The findings indicate that CO_2 emissions are highly concentrated in specific energy-intensive units, particularly fluid catalytic cracking (FCC) units,

fired heaters, and boilers, which collectively account for the majority of the refinery's emissions. This concentration mirrors patterns observed in comparable refineries worldwide, where FCC regenerators and combustion systems dominate the carbon footprint due to high-temperature catalytic and combustion processes (International Energy Agency, 2024; Leung et al., 2024). Steam methane reforming (SMR) units were also identified as significant emitters, reflecting their central role in hydrogen production and natural gas conversion (Fasihi et al., 2023). The concentration of emissions in these units presents a clear technical rationale for targeted CCS interventions rather than facility-wide retrofitting. The study further demonstrates that CO_2 concentrations in flue gases from major units predominantly range from 8% to 12%, with SMR streams occasionally exceeding 12%. These levels are consistent with international benchmarks and are conducive to post-combustion capture technologies, particularly amine-based absorption systems (Kiani et al., 2025; IEA, 2024). However, a notable portion of respondents reported incomplete or unavailable monitoring data, highlighting institutional gaps in systematic emissions tracking. Reliable real-time monitoring is essential for accurate capture sizing, performance assessment, and regulatory compliance, suggesting that the absence of comprehensive continuous emissions monitoring systems could constrain the feasibility and efficiency of CCS deployment (Rao et al., 2023; UNEP, 2025). Operational inefficiencies emerged as a significant contributor to elevated emissions. Ageing equipment, poor maintenance practices, unstable operational conditions, and fuel quality issues were frequently cited by respondents as exacerbating CO_2 release. Such inefficiencies are consistent with observations in other legacy refineries, where outdated infrastructure and intermittent maintenance reduce combustion efficiency and increase energy consumption (Rahman et al., 2025; Singh et al., 2024). These operational constraints have dual implications for CCS: while they highlight the potential for emission reductions through process optimisation, they also pose challenges for integrating capture systems, which generally perform optimally under stable operating conditions (You & Brook, 2024). The study also reveals that refinery capacity utilisation remains below design levels despite recent rehabilitation efforts, with both the Old and New Plants operating at approximately 40–55% of full capacity. This underutilisation may reduce total CO_2 emissions, potentially lowering capture costs per tonne in initial deployment phases. However, operational instability associated with low utilisation could increase capture complexity and costs, emphasizing the need for phased CCS implementation strategies targeting high-emission units during stable operating periods (Graham et al., 2024; Zhang et al., 2025). Institutional readiness and staff knowledge were identified as further constraints. Less than half of the respondents were familiar with CCS technologies, and none possessed expert-level understanding. This knowledge gap underscores the importance of capacity-building initiatives, technical training, and awareness campaigns to ensure successful integration of CCS into refinery operations. In addition, perceptions regarding the suitability of existing infrastructure, including pipelines and compression systems, were mixed, indicating a need for detailed technical audits to assess retrofit potential and inform capital planning. Collectively, the findings suggest that while the Port Harcourt Refinery exhibits strong technical potential for CCS deployment, due to concentrated emissions, favourable CO_2 concentration ranges, and available infrastructure, realising this potential will require comprehensive interventions. These include investment in continuous emissions monitoring, operational stabilisation, targeted workforce training, and detailed engineering assessments to confirm pipeline integrity and capture system compatibility. Strategic alignment with national climate commitments and international climate finance opportunities could further enhance economic feasibility and facilitate phased deployment, consistent with best practices in industrial decarbonisation (European Commission, 2025; IEA, 2023). In summary, the refinery's emission profile presents a technically feasible environment for CCS implementation. Targeted capture of high-intensity sources such as FCC, SMR, and fired heaters offers the most promising pathway for emission reductions, while operational, institutional, and infrastructural gaps must be addressed to ensure the sustainability, cost-effectiveness, and regulatory compliance of any CCS project.

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