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# WASTE-TO-ENERGY POTENTIAL AND ENVIRONMENTAL BURDEN OF GAS FLARING IN THE NIGER DELTA: A TWELVE-YEAR KERNEL DENSITY ANALYSIS

**Morufu Olalekan Raimi[1*], Nimisingha Jacob Amakama[2], and Akayinaboderi Augustus Eli[3]**

[1]Niger-Delta Institute for Emerging and Re-Emerging Infectious Diseases, Federal University Otuoke, Nigeria
[2]Laboratory for the Science of Risks (LSR), Institut Mines-Telecom Mines Ales, France
[3]Department of Environmental Management and Toxicology, Federal University Otuoke, Nigeria
[*]***Corresponding Author Email:*** *raimimo@fuotuoke.edu.ng*

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## Introduction

Gas flaring, the controlled combustion of associated natural gas during petroleum extraction, is a major environmental, climate, and resource-efficiency concern in oil-producing regions. Nigeria remains a major gas-flaring country, with the Niger Delta accounting for most national petroleum production and associated flaring (Kwen *et al.,* 2024; Raimi *et al.,* 2024; 2025; Keme-Iderikumo *et al.,* 2025; Akayinaboderi *et al.,* 2025). The region supports large populations whose livelihoods depend substantially on fisheries, agriculture, and other ecosystem services, creating important environmental-health implications where petroleum infrastructure overlaps with communities and sensitive ecosystems. Despite extensive discussion of gas flaring in the Niger Delta, much of the evidence has focused on descriptive trends, environmental consequences, and regulatory concerns, with comparatively limited statistical characterization of the distributional properties of flaring volumes. This is important because flaring observations can be highly skewed and influenced by extreme values, conditions under which conventional parametric summaries may inadequately represent the underlying distribution. Kernel density estimation (KDE), a non-parametric approach that does not require specification of a normal distribution, provides a useful framework for characterizing skewness, modality, and the influence of extreme observations. This study applied KDE to twelve years of satellite-derived gas-flaring data to characterize the statistical structure and magnitude of flaring in the Niger Delta and to quantify associated energy-recovery potential. The study aimed to characterize gas-flaring dynamics in the Niger Delta Region of Nigeria from 2012 to 2023 using non-parametric statistical methods. Specifically, it sought to: (i) characterize the distribution,

skewness, modality, and extreme-value behaviour of annual flared volumes; (ii) describe the spatial and field-type distribution of recorded flaring and examine its regulatory implications; and (iii) estimate the electricity-generation potential represented by the gas flared during the study period and discuss its environmental and public-health significance in relation to published evidence.

## Methodology

Flaring data for 2012-2023 were obtained from the World Bank Global Gas Flaring Tracker. The dataset comprised annual records of flare events, field type, flare location, and flared volume, reported in million cubic metres (MCM). Descriptive statistics, including counts, means, standard deviations, skewness, and kurtosis, were calculated for each year. Flare volumes were categorized as small (0–50 MCM), medium (>50–500 MCM), and large (>500 MCM). One-dimensional Gaussian KDE was subsequently applied to annual flare-volume distributions to examine their modality, concentration, and tail behaviour. Bandwidth selection was based on an asymptotic mean integrated squared error (AMISE) criterion. All numerical analyses and graphical outputs were generated using Mathematica version 12. For energy-recovery estimates, the cumulative flared volume was converted to electricity-generation potential assuming combined-cycle gas-turbine efficiencies of 40%, 50% and 60%, using a standard natural-gas energy-content conversion. Published peer-reviewed evidence on environmental and health consequences of gas flaring in the Niger Delta was synthesized to contextualize the quantitative findings.

## Results

Across the twelve years, 2,076 flare events were recorded, corresponding to a cumulative flared volume of 89,454.40 MCM (89.45 bcm). Of these events, 1,246 (60.02%) occurred onshore and 830 (39.98%) offshore. Oil fields accounted for 1,913 events and 82,430.76 MCM (82.43 bcm), compared with 123 events and 5,300.04 MCM (5.30 bcm) for gas fields and 40 events and 1,723.59 MCM (1.72 bcm) for LNG facilities. Annual flared volume declined from 9,622.37 MCM in 2012 to 5,578.61 MCM in 2023, although the pattern was not monotonic. Flare-event frequency did not consistently track annual flared volume: the highest number of events occurred in 2020 (195), whereas the largest annual volume occurred in 2012. This demonstrates that event counts alone do not adequately describe the magnitude of gas flaring. All annual distributions were positively skewed, with skewness values ranging from 1.845 to 4.004, and displayed substantial tail behaviour, with reported kurtosis values ranging from 5.964 to 327.499. KDE consistently identified unimodal, right-skewed distributions concentrated predominantly within the small-flare category, while a relatively small number of larger observations contributed disproportionately to aggregate flared volume. The largest individual flare volume was 550.62 MCM, recorded from an offshore oil field in 2018. These findings demonstrate the value of distribution-sensitive statistical analysis for distinguishing the frequency of flare events from their volumetric significance. The cumulative 89.45 bcm of gas flared during 2012–2023 represents substantial unrealized energy potential. Assuming a natural-gas energy content of approximately 10.55 kWh per $m^3$, the flared gas corresponds to approximately 377.5 TWh of electricity at 40% CCGT efficiency, 471.9 TWh at 50% efficiency, and 566.2 TWh at 60% efficiency. These estimates illustrate the scale of energy potentially recoverable through gas capture and utilization, although actual recoverable electricity would depend on gas composition, collection efficiency, processing losses, infrastructure availability and plant performance. The results also indicate that regulatory monitoring based solely on the number of flare events could obscure substantial volumetric emissions; volume-based monitoring is therefore more informative for assessing the magnitude of flaring. However, the present dataset does not independently establish legal non-compliance for individual facilities, and the observed extreme values should be interpreted as evidence of substantial flaring intensity rather than direct proof of regulatory violations.

## Conclusion

Gas flaring in the Niger Delta from 2012 to 2023 exhibited a strongly right-skewed, heavy-tailed and predominantly unimodal distribution, with relatively frequent small events coexisting with

fewer high-volume observations. KDE provided a distribution-sensitive description of this structure and demonstrated why event frequency alone is insufficient for representing flaring magnitude. Although aggregate flaring volumes declined over the study period, substantial quantities of natural gas continued to be combusted, representing significant unrealized energy potential. The findings support the use of satellite-informed, volume-based monitoring alongside conventional event reporting and provide a quantitative basis for strengthening gas-utilization and emissions-reduction strategies. Regulatory and industry interventions should prioritize accurate, transparent, and independently verifiable measurement of flared volumes, with satellite observations integrated with facility-level reporting and inspection. Gas-capture, processing, transportation and utilization infrastructure should be expanded where technically and economically feasible to create viable alternatives to routine flaring. Regulatory enforcement should be supported by measurable facility-level thresholds, transparent reporting, independent verification and proportionate sanctions, while recognizing that statistical evidence of extreme flaring does not by itself establish legal non-compliance. Investment in gas-to-power and other productive gas-utilization pathways should be accompanied by improvements in transmission, distribution and local energy infrastructure. Public-health and environmental monitoring should also be strengthened around petroleum-producing communities to characterize exposure and health consequences associated with persistent flaring.

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