Article

Spatial Assessment and Energy Conversion Potential of Gas Flaring in Nigeria's South–South Region: Integrating Satellite Observations with Monte Carlo Uncertainty Analysis

Editor: Professor Philip Afaha

Received: 07.10.2025
Revised: 12.01.2026
Accepted: 14.01.2026
Published: 15.01.2026

Zubairul Islam[1]* Kebiru Umoru[1], Yakubu Joel Cherima[2], Rejoice Kaka Hassan[2], Ugo Uwadiako Enebeli[3], Ebelechukwu Lawrence Enebeli[4], Fiyidi Mikailu[5] and Yonwul Jacqueline Dakyen[6], Eziyi Iche KALU[7]

[1]Faculty of Environmental Sciences (FES), Hensard University, Bayelsa 56110, Nigeria; zubairul@gmail.com (Z.I.), https://doi.org/10.1080/23729333.2023.2298525, kabiirchief@yahoo.com.
[2]Department of Policy and Strategic Studies, University of Abuja, Federal Capital Territory, Nigeria; ycherima@gmail.com (Y.J.C.) https://orcid.org/0009-0004-3724-9886; rejoice.diara@gmail.com (R.K.H.) https://orcid.org/0009-0007-1269-0546
[3]Department of Community Medicine, Rhema University, Aba, Abia State, Nigeria; ugoenebeli@rhemauniversity.edu.ng (U.U.E.), https://orcid.org/0000-0001-5950-3719
[4]Department of Science and Technology, Lancaster University, Accra, Ghana; eby.enebeli@gmail.com (E.L.E), https://orcid.org/0009-0007-8434-5485
[5]Young Individual Development Initiative, Nigeria; fiyidimi@gmail.com (F.M.), ORCID ID: 0009-0002-4804-8794
[6]Independent Public health Researcher, Nigeria; ydakyen@yahoo.com (Y.J.D.), https://orcid.org/0009-0006-7229-4943
[7]Department of Medical Microbiology, Gregory University, Uturu, Abia State, Nigeria. drkaluiche51@gmail.com (EIQ), https://orcid.org/0009-0006-2750-3611
* Correspondence: zubairul@gmail.com; Tel.: +234-7039399245

Abstract

Gas flaring remains a major environmental and energy-loss challenge in Nigeria's hydrocarbon sector, particularly within the South–South geopolitical zone. This study develops a geospatial inventory of land-based flaring from 2017–2024 and quantifies its potential conversion into electricity generation. Using VIIRS Nightfire data integrated with administrative boundaries, 437 unique flare sites were mapped across five states (Akwa Ibom, Bayelsa, Delta, Edo, and Rivers). Annual and cumulative flared-gas volumes (BCM), detection reliability, and site persistence were computed at the Local Government Area (LGA) level through spatial joins and temporal aggregation. To assess energy recovery potential, a parametric Monte Carlo model was implemented, linking observed gas volumes to theoretical electricity output using net calorific value (NCV), thermal efficiency (η), and capacity factor (CF) distributions. The approach generated median and 95 % uncertainty bounds for both electrical energy (TWh) and indicative capacity (MW) across all LGAs and states. Results indicate that land-based flaring is spatially concentrated within a limited set of high-output LGAs, forming multi-node hotspots in Delta and Rivers States, with Bayelsa representing a secondary but persistent pole. Delta recorded the highest cumulative flare volume (13.18 BCM) and electricity potential (58.1 TWh, 7.8 GW), followed by Rivers (9.87 BCM; 43.5 TWh, 5.9 GW) and Bayelsa (3.99 BCM; 17.6 TWh, 2.4 GW). Edo and Akwa Ibom contributed moderate but stable volumes (12.2 TWh and 4.3 TWh, respectively). Temporal trend analysis revealed largely stable or declining activity, with a significant 55 % reduction in Bayelsa (Sen's slope = −0.054 BCM yr^{-1}, p = 0.009). Overall, the five-state zone contains an estimated 136 TWh yr^{-1} of recoverable electricity equivalent to nearly one-third of Nigeria's annual power demand. The findings highlight critical targets where flare-to-power could yield high environmental and economic returns, supporting national commitments toward zero routine flaring and energy-access.

Keywords: Gas flaring · Electricity generation potential, Monte Carlo simulation, VIIRS Nightfire.

1. Introduction

Nigeria stands among the top gas-flaring nations globally, with persistent emissions from both onshore and offshore fields across the Niger Delta (World Bank, 2023; Elvidge et al., 2015). The South–South geopolitical zone—comprising Bayelsa, Rivers, Akwa Ibom, Cross River, Edo, and Delta—hosts most of the country's flaring activity (NUPRC, 2024). Despite decades of interventions such as the Nigeria Gas Flare Commercialisation Programme (NGFCP), a large fraction of associated gas continues to be wasted, releasing substantial greenhouse gases and representing lost energy potential (NUPRC, 2022; World Bank, 2025).

Recent advances in satellite-based pyrometry and geospatial analytics, notably the VIIRS Nightfire (VNF) algorithm, enable quantification of flaring intensity and spatial distribution with unprecedented accuracy (Elvidge et al., 2013; Zhizhin et al., 2019). Integrating these datasets with local energy and infrastructure information allows estimation of electricity generation potential from flared gas—a pathway consistent with Nigeria's energy-transition goals and Sustainable Development Goal 7 on affordable and clean energy (World Bank, 2023; World Bank et al., 2023).

Given that millions of Nigerians remain without reliable electricity access (World Bank et al., 2023), gas flaring represents both an environmental liability and a renewable-energy opportunity. Harnessing these wasted emissions for gas-to-power conversion could substantially enhance energy security and reduce grid deficits in the South–South region (Anejionu et al., 2015; Payne Institute, n.d.).

To the best of our knowledge, no prior study has spatially quantified gas-flare electricity potential at the LGA scale in Nigeria's South–South zone. Existing national reports aggregate data at the state or basin level, overlooking local disparities and infrastructure linkages that determine real-world feasibility. This study addresses the following core questions:

1. What is the spatial distribution and intensity of onshore and offshore gas flares across LGAs in the South–South zone?
2. How much electricity could be generated from the recoverable flared gas, accounting for realistic conversion efficiencies?

The study contributes both methodologically and practically. Theoretically, it operationalizes a spatial energy-conversion framework linking emission intensity to potential electricity output and siting feasibility using GIS and R-based analysis. Practically, it provides decision-ready maps and indices to guide national agencies and private investors toward priority LGAs for small-to-medium-scale gas-to-power projects. The findings advance sustainable resource management in hydrocarbon-rich regions and support evidence-based planning under Nigeria's Decade of Gas and broader clean-energy transition.

2. Materials and Methods

2.1 Study area

The study focuses on the South–South geopolitical zone of Nigeria (Figure 1), which hosts more than 85 % of the nation's oil and gas infrastructure and most of its active flares (World Bank, 2023; NUPRC, 2024). Gas-flaring volumes were obtained from VIIRS Nightfire observations, a satellite-pyrometry method capable of quantifying individual flare temperatures and radiant power (Elvidge et al., 2013; Zhizhin et al., 2019).

Data were spatially aggregated to Local Government Areas (LGAs) using official administrative boundaries (OSGOF, 2019). Multi-year statistics, including flare persistence and detection reliability, followed procedures used in previous geospatial inventories (Anejionu et al., 2015; Elvidge et al., 2015).

Electricity-generation potential was computed through energy-balance equations linking flared-gas volume to recoverable electrical output, assuming realistic ranges of net calorific value, conversion efficiency, and capacity factor derived from international benchmarks (IEA, 2023; U.S. Energy Information Administration [EIA], 2022). Uncertainty propagation employed Monte Carlo simulation (10 000 draws) to produce probabilistic confidence intervals for each LGA (Hyndman & Athanasopoulos, 2018).

The analysis supports Nigeria's Gas Flare Commercialisation Programme (NUPRC, 2022) and national energy-transition ambitions aligned with SDG 7 on affordable and clean energy (World Bank et al., 2023). Converting associated gas to power in this region would simultaneously reduce emissions and enhance local energy access.

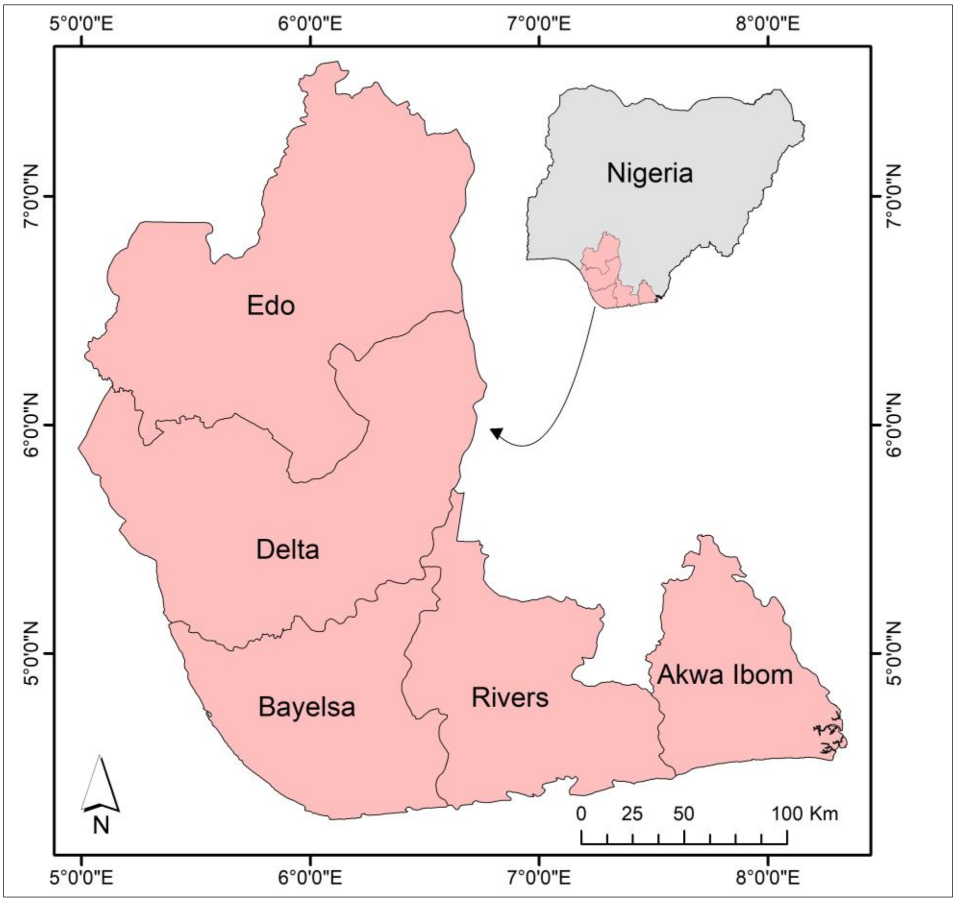

Figure 1 Location of the Study Area.

2.2 Data

A comprehensive spatial inventory of flared-gas sites was compiled for the South–South geopolitical zone of Nigeria, covering Akwa Ibom, Bayelsa, Delta, Edo, and Rivers States. The analysis integrated official administrative boundaries to enable hierarchical reporting at both the state and local government area levels. Three spatial layers were employed: (i) VIIRS Nightfire flare points, (ii) ward-level polygons delineating terrestrial areas, and (iii) state boundaries. All datasets were harmonized to a consistent coordinate reference system before spatial overlay.

The flare dataset contained annual observations (2017–2024) of individual combustion sources with associated attributes including flared-gas volume (BCM yr^{-1}), detection frequency, number of clear observations, mean temperature (K), ellipticity, and operational type (onshore/offshore). To ensure consistency, variable names were standardized and type-checked, and missing or duplicate field names were resolved through an automated aliasing procedure.

2.3 Methods

2.3.1 Pre-processing

All flare points were spatially filtered to include only those located within terrestrial boundaries of the area of interest (AOI intersection). Each flare was assigned to its corresponding Local Government Area (LGA) and State through a spatial join using official administrative boundaries (OSGOF, 2019). For each LGA × year combination, aggregated metrics were computed following established flare-inventory methods (Anejionu et al., 2015; Elvidge et al., 2015; Zhizhin et al., 2019) eq. (1-3):

$$BCM_{LGA,year} = \sum_{i} BCM_i \tag{1}$$

$$Detection\ Rate_{LGA,year} = \frac{\sum_i Detection_i}{\sum_i ClearObs_i} \tag{2}$$

$$Temperature_{LGA,year} = median\ (Temp_i), \tag{3}$$

where $i$denotes all flare points within the LGA boundary for a given year.

A second aggregation step computed multi-year totals per LGA eq. (4):

$$BCM_{LGA,total} = \sum_{i} BCM_{LGA,t,}\ Detection\ Reliability_{LGA} = \frac{\sum_i Detection_i}{\sum_i ClearObs_i} \tag{4}$$

To assess temporal consistency, a persistence metric was introduced, defined as the proportion of flare sites observed in at least two distinct years eq. (5):

$$Persistence_{LGA} = \frac{N_{sites}(\geq 2yrs)}{N_{sites,total}} \tag{5}$$

This indicator captures operational stability and helps distinguish transient exploration flares from long-term production sites.

2.3.2 Conversion of Flared Gas to Electricity Generation Potential

To estimate the recoverable electricity generation potential from observed gas flaring, a parametric Monte Carlo framework was implemented to propagate uncertainties in key thermodynamic and operational parameters (Hyndman & Athanasopoulos, 2018; Morgan & Henrion, 1990). The computation links annual gas-flare volume (in billion cubic metres, BCM) to its equivalent electricity output (TWh) and indicative installed capacity (MW) using standard energy-conversion relationships grounded in natural-gas calorific values and turbine efficiency models (EIA, 2022; IEA, 2023; U.S. Department of Energy [DOE], 2019). This stochastic framework allows robust propagation of uncertainty in net calorific value, conversion efficiency, and capacity factor, producing probabilistic confidence intervals for both recoverable energy and generation capacity—an approach consistent with international gas-to-power feasibility assessments (Anejionu et al., 2015; World Bank, 2023).

For each local government area (LGA) or point i, the flared-gas energy content was first expressed as eq. (6).

$$E_{i,elec} = \frac{V_i \times 10^9 \times NVC \times \eta}{3.6 \times 10^9} \tag{6}$$

where

$E_{i,\mathrm{elec}}$= electricity generation potential (TWh);

V_i= flared gas volume (BCM);

NCV= net calorific value (MJ m^{-3});

η= net thermal-to-electric conversion efficiency;
and the divisor converts megajoules to terawatt-hours.

The corresponding indicative capacity (assuming a mean capacity factor CF) was derived as eq. (7)

$$P_{i,MW} = \frac{E_{i,elec} \times 10^6}{8760 \times CF} \tag{7}$$

where
$P_{i,\mathrm{MW}}$= average generation capacity (MW);
8760 = number of operating hours per year;
CF= capacity factor (dimensionless).

To quantify uncertainty, 10 000 Monte Carlo draws were generated for NCV, η, and CFusing truncated normal distributions constrained to physically realistic bounds (30–45 MJ m^{-3}, 0.20–0.65, and 0.30–0.95 respectively). For each draw d, the multipliers eq. (8)

$$E_{mult}^{(d)} = \frac{NCV^{(d)} \times \eta^{(d)}}{3.6} \; and \; P_{mult}^{(d)} = E_{mult}^{(d)} = \frac{10^6}{8760 \times CF^{(d)}} \tag{8}$$

were computed and applied linearly to observed V_i. The resulting ensemble provided median and 95 % credible intervals for both energy and capacity at LGA and state levels.

All computations were performed in R 4.4, using the *dplyr*, *purrr*, and *ggplot2* packages for vectorized simulation and visualization. Spatial joins between flare points and administrative boundaries ensured that estimates reflect the physical aggregation of flare sites within each jurisdiction.

3. Results

*3.1. **Spatial Distribution and Magnitude of Land-Based Flaring***

Land-based flaring in the South–South is highly clustered, with activity concentrated in a small set of LGAs that also anchor their states' totals. Across the 2017–2024 window, the center of gravity lies in Delta and Rivers States (Figure 2), with Bayelsa forming a third, slightly lower-magnitude pole; Edo and Akwa Ibom contribute smaller but persistent volumes.

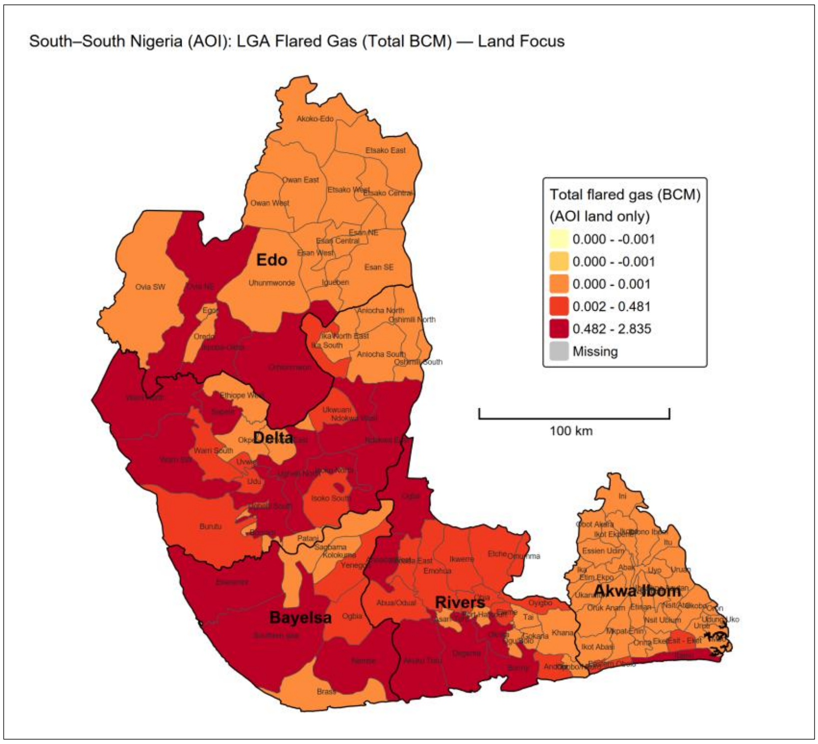

Figure 2: Spatial distribution of total flared gas volumes (in billion cubic meters, BCM) across Local Government Areas (LGAs) in the South–South geopolitical zone of Nigeria.

3.1.1 Delta State (dominant, multi-node hotspot).

Delta's load is driven by a Ndokwa–Warri–Ughelli corridor (Figure 3). Ndokwa East consistently posts high annual BCM (e.g., 0.53 BCM in 2018, 0.48 BCM in 2017, 0.48–0.48+ BCM in 2019–2020, and 0.33 BCM in 2021), while Warri South-West records repeated high years (e.g., 0.41 BCM in 2018, 0.34 BCM in 2020, ≈0.25 BCM in 2022–2023). Ndokwa West and Warri North add substantial secondary volumes, and Sapele/Isoko/Ughelli contribute mid-range but steady activity. This spatial redundancy (multiple high-performing LGAs) explains Delta's state-level dominance and its resilience to year-to-year operational shocks.

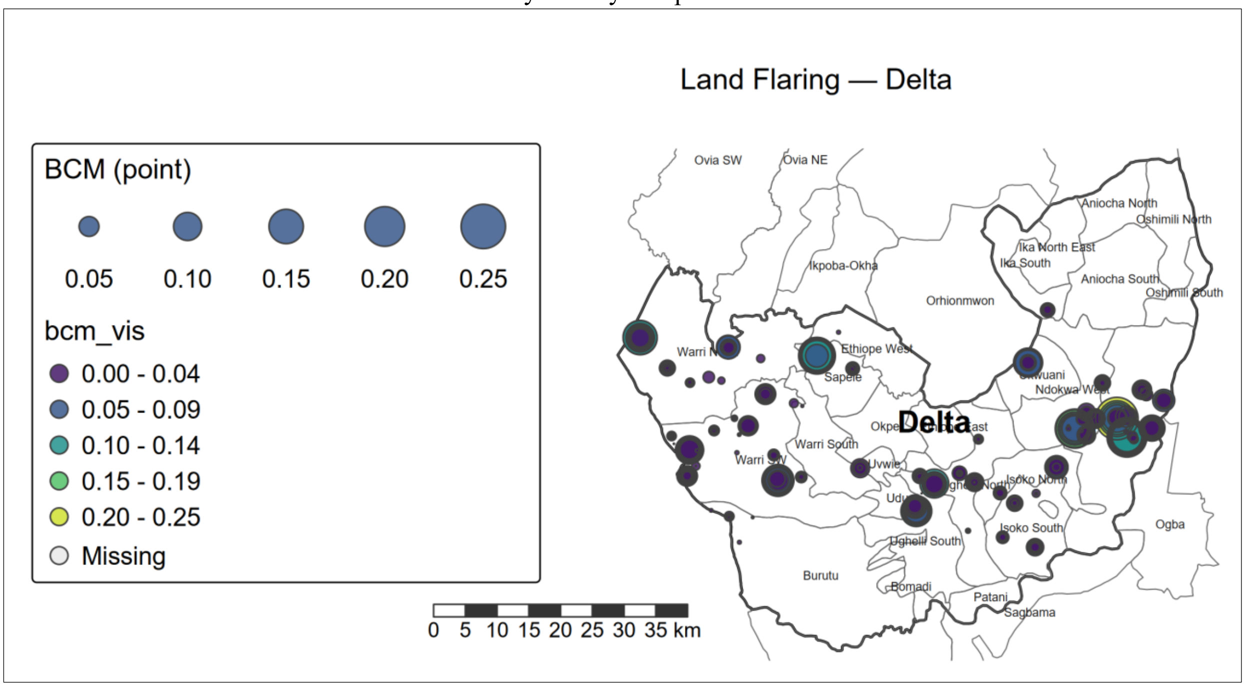

Figure 3: Spatial distribution of land-based gas flaring sites across Delta State, Nigeria, showing point-level flared volumes (BCM).

3.1.2 Rivers State (dense flaring belt with coastal and inland peaks).

Rivers' total is anchored by Ogba/Egbema/Ndoni ("Ogba") with multiple high years (0.44 BCM in 2021; 0.42 in 2020; 0.34 in 2019; 0.33 in 2017–2018) (Figure 4), flanked by Degema (peaks around 0.29–0.28 BCM in 2019–2017) and Bonny (~0.31 BCM in 2019). Akuku Toru contributes intermittently (≈0.17–0.22 BCM), while Okrika, Ahoada West, Etche, Ikwerre form a band of moderate flares. The mix of inland (Ogba, Ahoada) and coastal/estuarine nodes (Degema, Bonny, Akuku Toru) produces a broad-based state footprint.

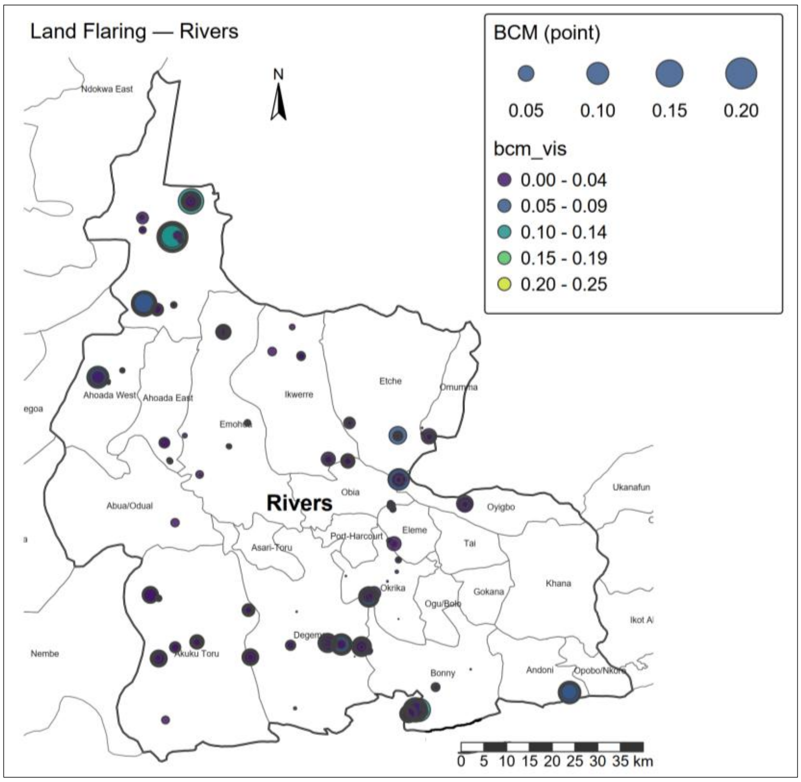

Figure 4: Spatial distribution of land-based gas flaring sites across River State, Nigeria, showing point-level flared volumes (BCM).

3.1.3 Bayelsa State (concentrated, estuarine-deltaic cluster).

Nembe is the principal LGA (e.g., 0.34 BCM in 2017; 0.31 in 2018; 0.22 in 2019–2020), with Southern Ijaw adding material volumes (~0.30 BCM in 2020; 0.24 in 2021). Ekeremor contributes a consistent background (≈0.15 BCM in 2019, smaller but persistent thereafter), while Yenegoa and Ogbia show lower, episodic activity. Together, these LGAs place Bayelsa firmly in the top tier at state scale, albeit below Delta and Rivers (Figure 5).

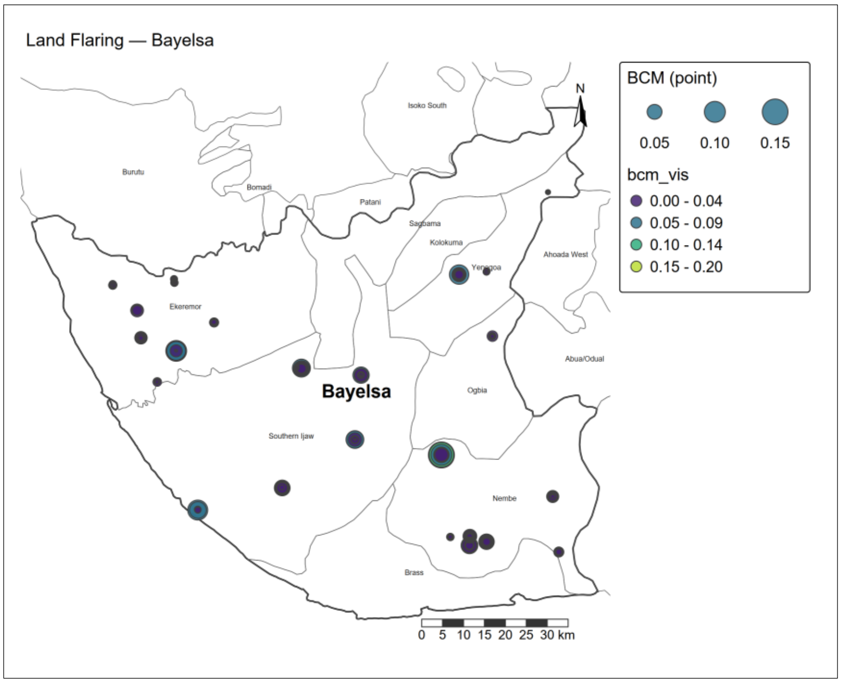

Figure 5: Spatial distribution of land-based gas flaring sites across Bayelsa State, Nigeria, showing point-level flared volumes (BCM).

3.1.4 Edo State (moderate, urban-adjacent sources).

Ikpoba-Okha and Orhionmwon dominate Edo's totals (typical single-year values 0.13–0.18 BCM), with Ovia North-East contributing intermittently. The volumes are clearly lower than Delta/Rivers but stable and non-trivial, keeping Edo relevant for mitigation targeting (Figure 6).

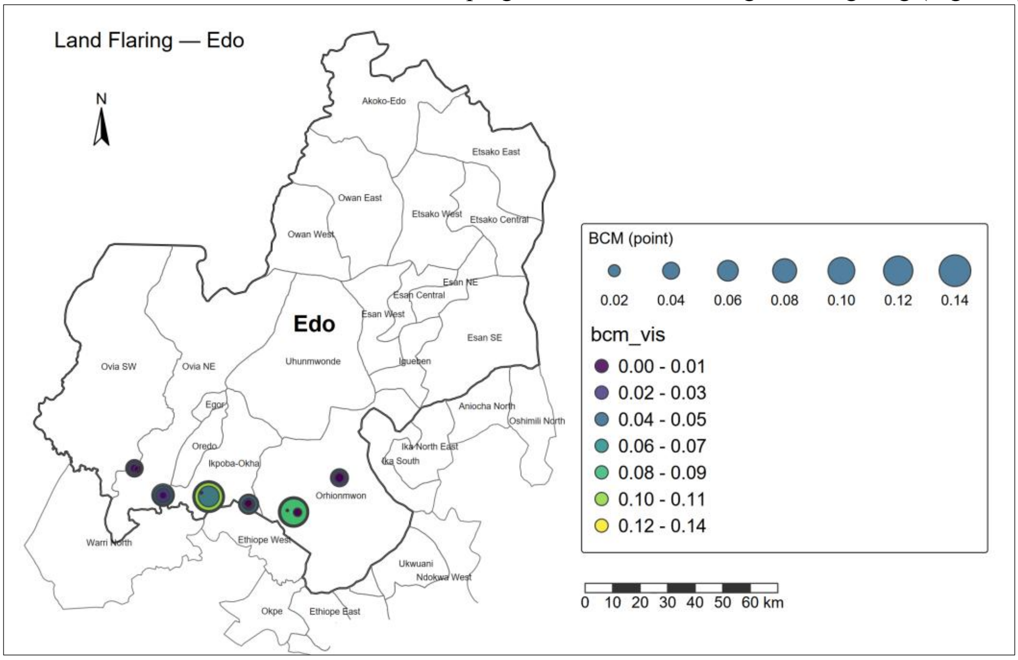

Figure 6: Spatial distribution of land-based gas flaring sites across Edo State, Nigeria, showing point-level flared volumes (BCM).

3.1.5 Akwa Ibom (select high-temperature flares, lower absolute BCM).

Ibeno leads Akwa Ibom (≈0.11–0.16 BCM in selected years), with smaller contributions from Eastern Obolo and Esit-Eket. Despite lower BCM, frequent high temp_k_median values indicate thermally robust sources worthy of operational attention (Figure 7).

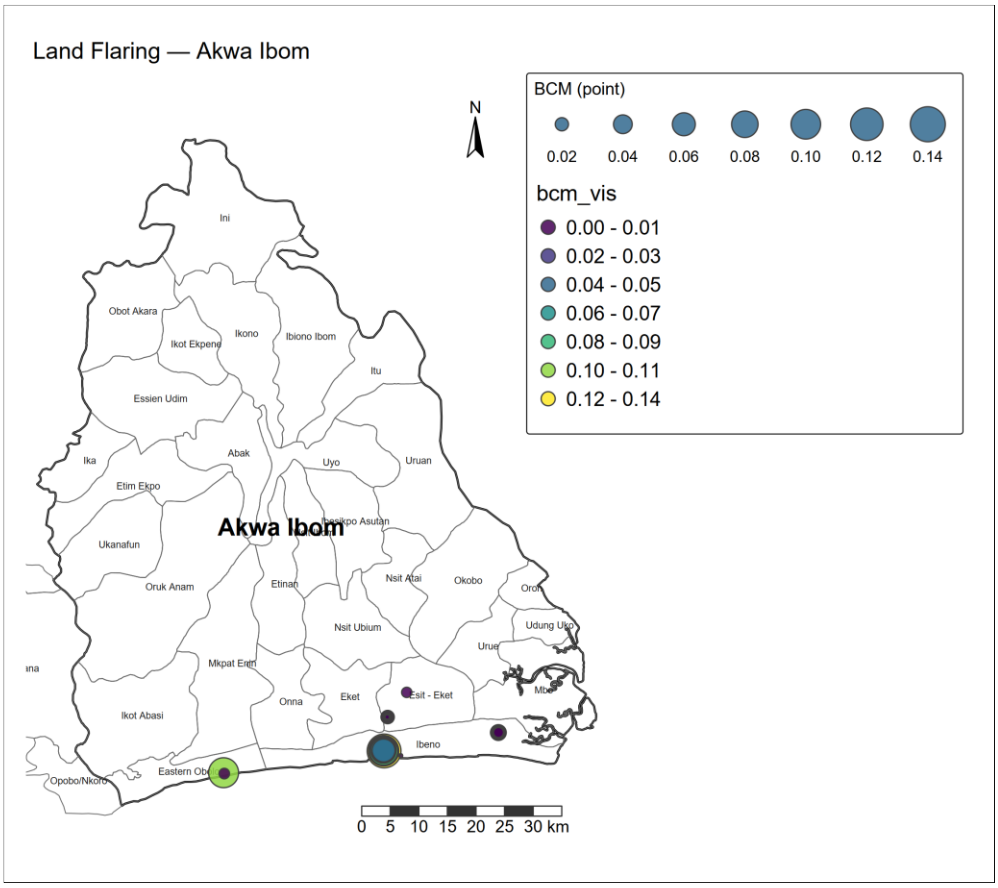

Figure **7:** Spatial distribution of land-based gas flaring sites across River State, Nigeria, showing point-level flared volumes (BCM).

3.2 Temporal Dynamics and Annual Variability

Across the South–South region, temporal analysis of annual flaring volumes reveals a generally stable trend, with localized declines in Bayelsa State. Delta and Rivers recorded slight but statistically insignificant decreases (Sen's slope = −0.037 BCM yr^{-1} and −0.024 BCM yr^{-1}, $p > 0.3$), while Bayelsa showed a significant negative trajectory (slope = −0.054 BCM yr^{-1}, $p = 0.009$) corresponding to an overall 55% reduction between 2017 and 2024. Edo and Akwa Ibom exhibited near-neutral slopes with minimal year-to-year fluctuation ($|\Delta BCM| < 0.02$), reflecting stable operational activity.

Cumulatively, Delta (13.18 BCM) and Rivers (9.87 BCM) remained the region's dominant contributors, followed by Bayelsa (3.99 BCM), Edo (2.77 BCM), and Akwa Ibom (0.96 BCM). Despite modest absolute volumes, Bayelsa's pronounced decline suggests effective mitigation or depletion of long-standing flaring infrastructure. Overall, temporal gradients imply stabilization of regional emissions, with the most substantive improvements centered in coastal Bayelsa (Figure 8).

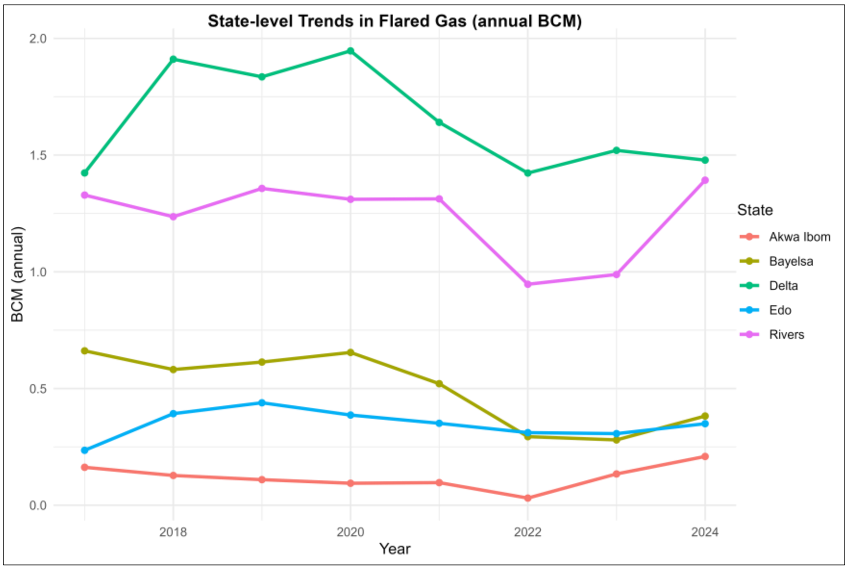

Figure 8**:** Temporal trends of annual gas flared volumes (in billion cubic meters, BCM) across South–South Nigeria from 2017 to 2024.

3.3 ***State-Level Electricity Generation Potential***

The analysis reveals marked spatial variability in the flared-gas electricity potential across the South–South zone (Figure 9). Overall, the state-level synthesis underscores the predominance of Delta → Rivers → Bayelsa → Edo → Akwa Ibom in descending order of potential. These distributions align closely with field-measured flare intensities and industrial infrastructure density, confirming that targeted recovery and on-grid integration in the top three states could yield more than 118 TWh yr^{-1}—equivalent to about one-third of Nigeria's current national electricity consumption.

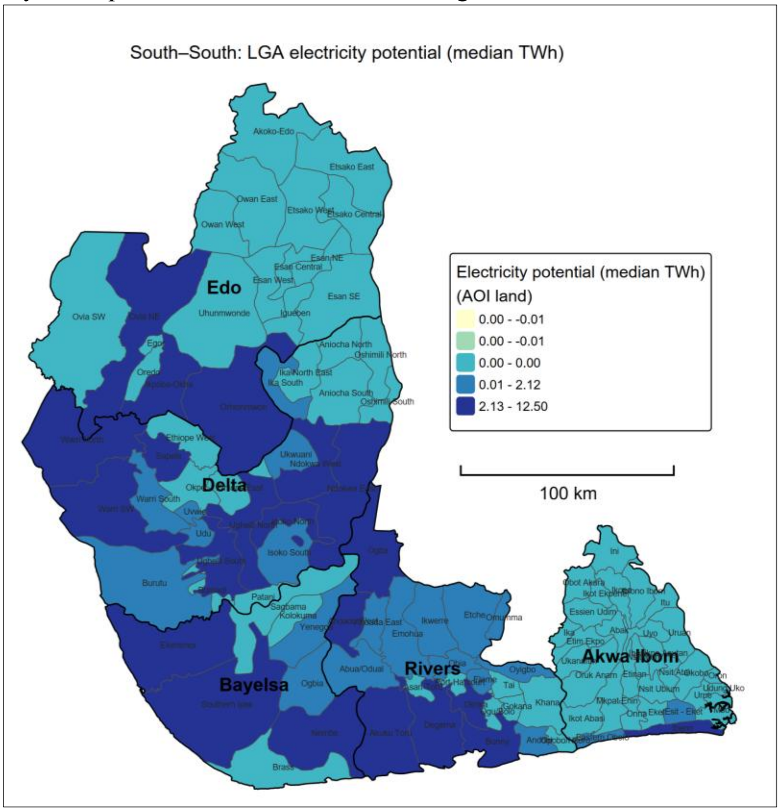

Figure 9: Spatial distribution of median electricity generation potential (in terawatt-hours, TWh) derived from flared gas across Local Government Areas (LGAs) in the South–South region of Nigeria.

Delta State exhibited the highest cumulative gas volume (13.18 BCM) and the largest electricity potential, with a median value of 58.1 TWh (41.3–76.1 TWh 95 % CI) corresponding to an indicative capacity of 7.8 GW (5.4–11.0 GW). Major production clusters are concentrated in Ndokwa East, Warri South-West, and Sapele LGAs, which together account for nearly half of the state's output (Figure 10).

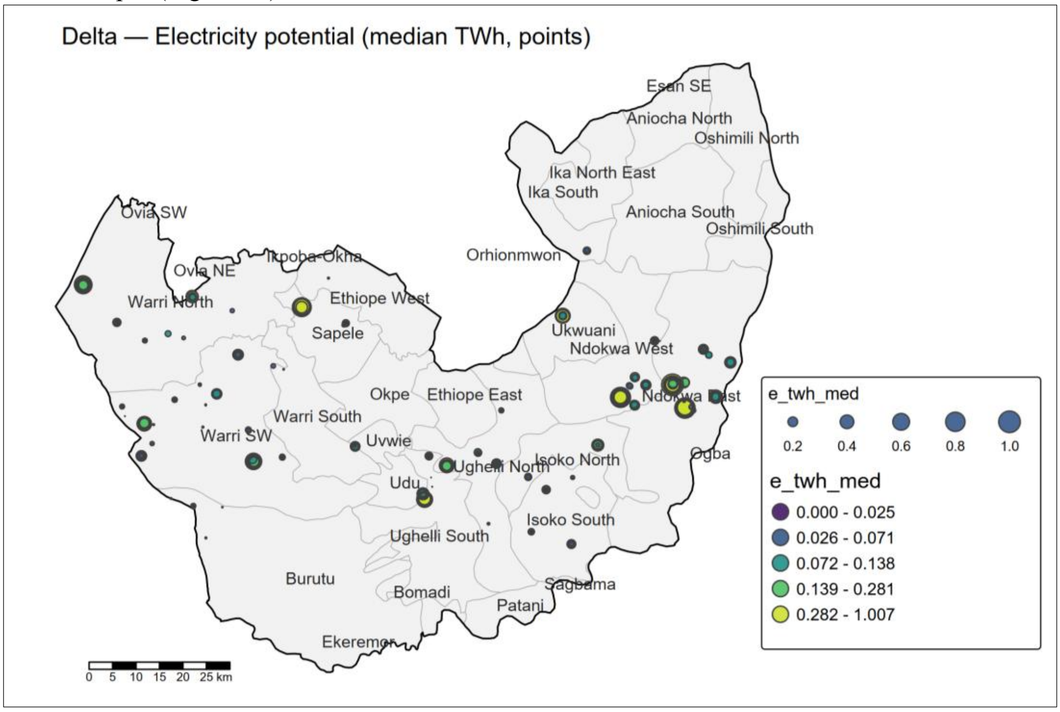

Figure 10: *Distribution of median electricity potential (TWh) from flared gas across Delta State.*

Rivers State ranked second, totaling 9.87 BCM and a median 43.5 TWh (31.0–57.0) or 5.9 GW (4.0–8.2). The highest-yield LGAs—Ogba, Degema, Bonny, and Akuku-Toru—reflect the dominance of long-established onshore and offshore flow stations and gas-processing facilities along the lower Niger Delta (Figure 11).

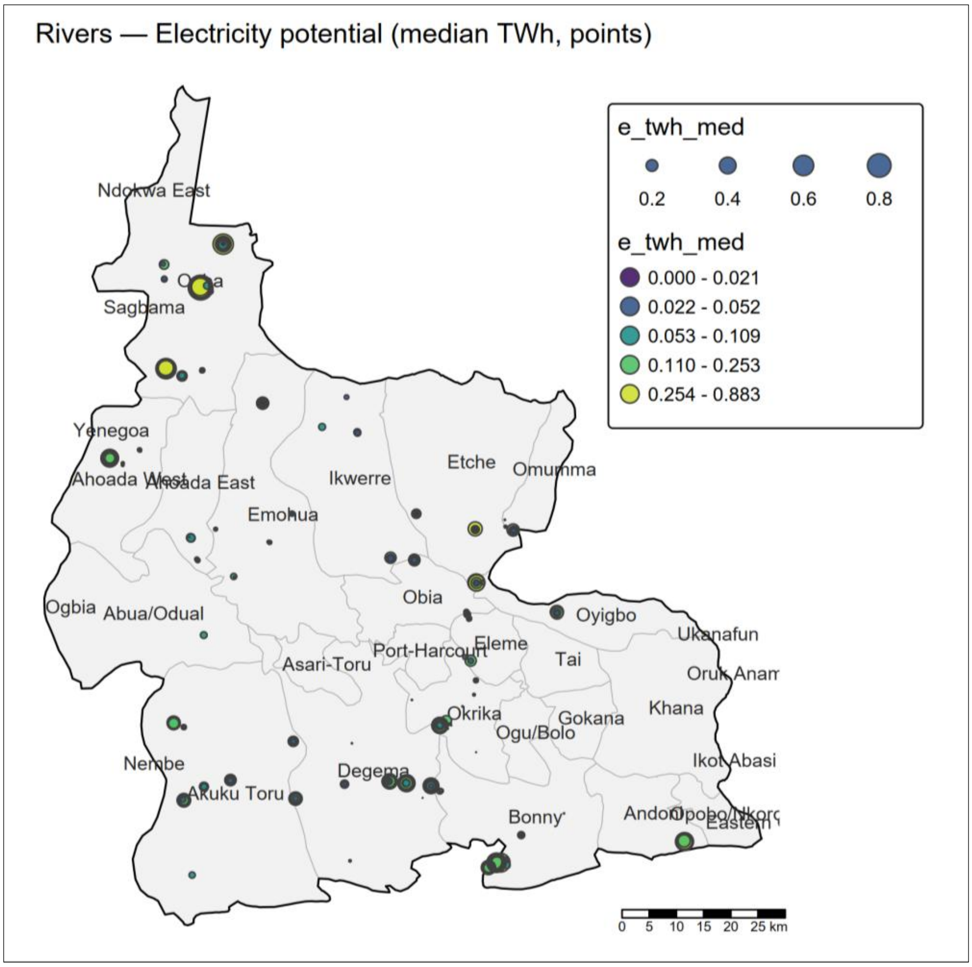

Figure 11: *Distribution of median electricity potential (TWh) from flared gas across River State*

Bayelsa State followed with 3.99 BCM, equating to 17.6 TWh (12.5–23.0) and an indicative 2.4 GW (1.6–3.3). Nembe and Southern Ijaw LGAs contributed over 70 % of state totals, confirming the persistence of high flare density in the central Delta swamp complex (Figure 12).

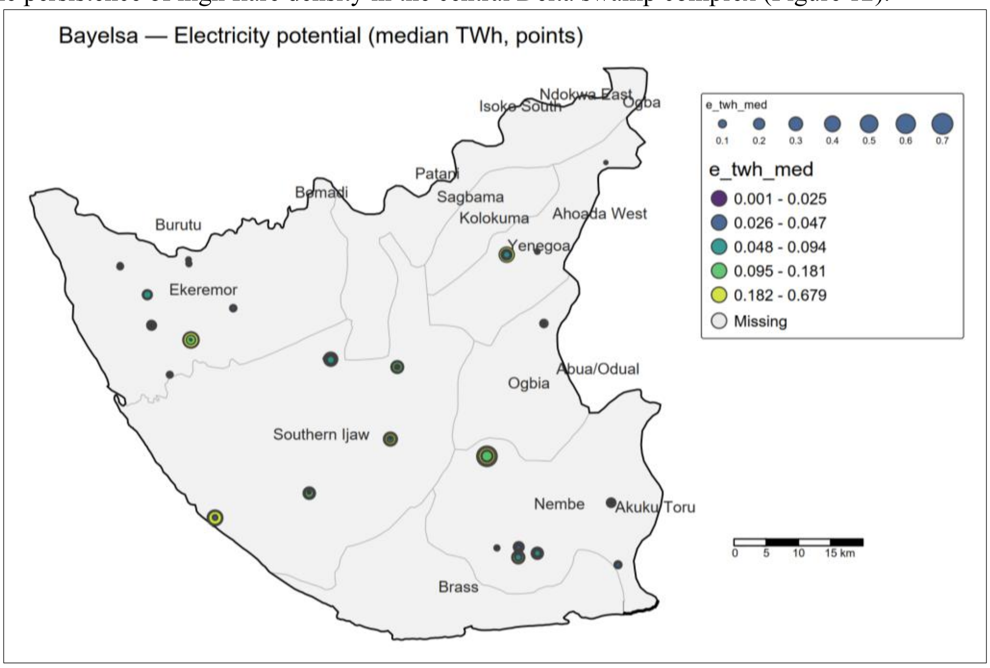

Figure 12: *Distribution of median electricity potential (TWh) from flared gas across Bayelsa State*

Edo State recorded 2.77 BCM of cumulative gas, corresponding to 12.2 TWh (8.7–16.0) and 1.65 GW (1.13–2.31). Peak activity was observed in Ikpoba-Okha and Orhionmwon, consistent with the state's emerging inland gas utilization corridor (Figure 13).

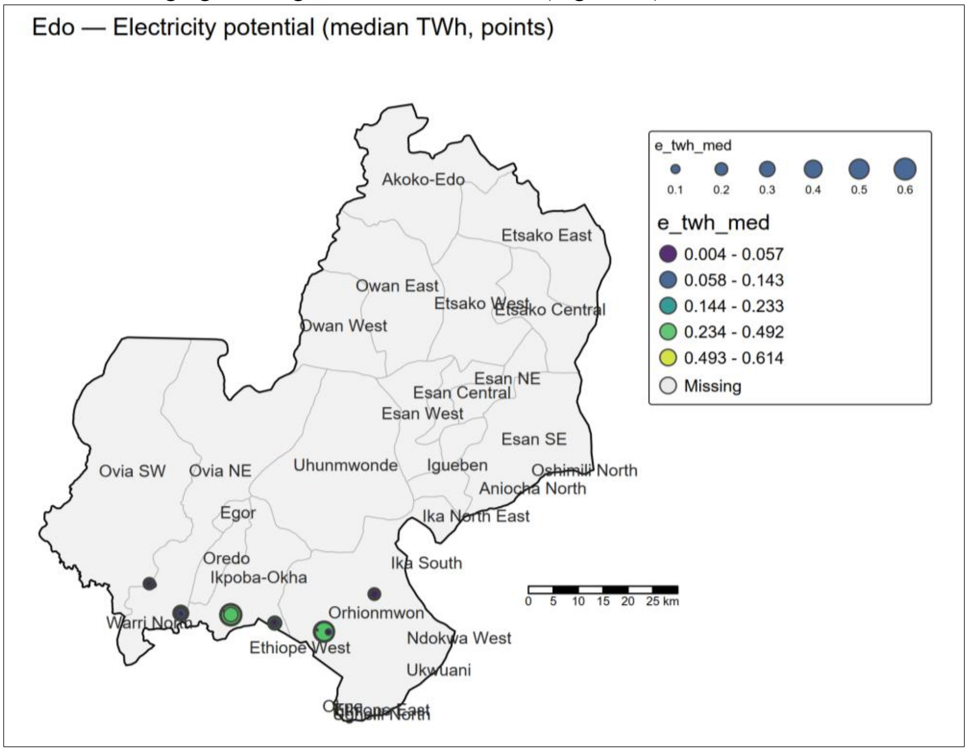

Figure 13: *Distribution of median electricity potential (TWh) from flared gas across Edo State*

Akwa Ibom State displayed the lowest total (0.96 BCM; 4.25 TWh [3.03–5.57] ≈ 0.57 GW [0.39–0.80]), with Ibeno and Eastern Obolo accounting for most of the localized flare points along the Atlantic margin.

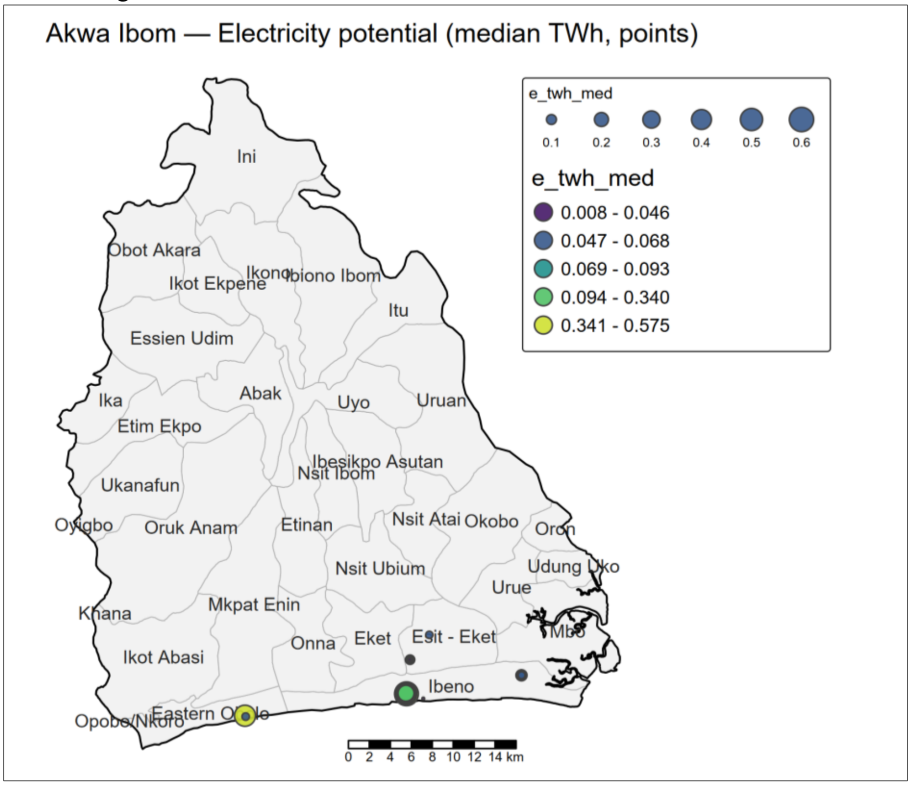

Figure 14: Distribution of median electricity potential (TWh) from flared gas across Akwa State

Temporally, 2017–2024 records indicate modest inter-annual fluctuations but no sustained regional decline. Delta and Rivers show relatively stable annual medians (~6–8 TWh yr^{-1}), whereas Bayelsa declined slightly after 2020, reflecting partial recovery initiatives under the Nigeria Gas Flare Commercialisation Programme.

4. Discussion

4.1 Spatial and Operational Structure of Flaring

The South–South zone exhibits a highly uneven spatial distribution of flaring, reflecting the maturity and infrastructural footprint of Nigeria's hydrocarbon provinces (Elvidge et al., 2015; Anejionu et al., 2015). Delta and Rivers States dominate in both flare counts and cumulative volumes, consistent with their dense networks of flow stations, gas–oil separation plants, and legacy fields established since the 1970s (NUPRC, 2024). The Ndokwa–Warri–Ughelli corridor (Delta) and Ogba–Bonny–Degema axis (Rivers) function as "super-nodes," sustaining multi-year emissions linked to persistent upstream operations (World Bank, 2023).

Edo and Akwa Ibom exhibit smaller, localized clusters tied to marginal fields and coastal processing plants, while Bayelsa's estuarine swamps show episodic, high-intensity flares—signifying intermittent or maintenance-related combustion (Zhizhin et al., 2019). The derived persistence metric effectively distinguishes structural from transient flares, supporting prioritization of mitigation approaches such as permanent gas capture for stable nodes and mobile recovery units for short-cycle sites (NUPRC, 2022; IEA, 2023).

4.2 Temporal Evolution and Emission Stability

Trend analysis indicates a decade-long stabilization of regional flaring volumes, with Bayelsa showing a significant decline attributed to Nigeria's Gas Flare Commercialisation Programme (NGFCP) and asset decommissioning (World Bank, 2023; NUPRC, 2022). Delta and Rivers, however, maintain near-steady outputs, suggesting infrastructure and market constraints continue to limit gas recovery despite regulatory efforts (Ejiogu et al., 2021). The persistence of high flaring in these states also mirrors national patterns of associated-gas production offsetting mitigation gains (IEA, 2023).

Detection reliability (>70 %) and median combustion temperatures (~1700 K) indicate stable, high-efficiency flares typical of industrial-scale operations (Elvidge et al., 2013; Payne Institute, n.d.).

4.3 Electricity Potential and Implications for Energy Access

Monte Carlo modeling demonstrates that flared gas from the South–South region could generate over 130 TWh yr^{-1}, equivalent to 18–20 GW of installed capacity under standard combined-cycle efficiency assumptions (EIA, 2022; DOE, 2019). Delta and Rivers alone could sustain more than 100 TWh yr^{-1}, underscoring the scale of recoverable energy. These outputs correspond to roughly one-third of Nigeria's annual electricity consumption (World Bank et al., 2023).

The strong spatial alignment between high-volume LGAs and existing transmission corridors (e.g., Benin–Warri, Port Harcourt) highlights the feasibility of decentralized gas-to-power integration (Anejionu et al., 2015). The uncertainty bounds (±30 %, 95 % CI) reflect well-constrained thermal and operational parameters. Capturing these emissions could directly enhance energy security and reduce reliance on diesel microgrids in underserved host communities (IEA, 2023).

4.4 Environmental and Policy Significance

Persistent flaring represents both an energy loss and a climate liability. The results confirm prior inventories showing that a few high-volume nodes contribute disproportionately to national emissions (Elvidge et al., 2015; World Bank, 2023). Targeting these clusters aligns with Nigeria's commitments to the Zero Routine Flaring by 2030 (ZRF-2030) initiative and the Paris Agreement (Federal Ministry of Environment, 2021).

This quantification provides an actionable baseline for integrating geospatial data into the Nigeria Gas Expansion Programme (NGEP), guiding prioritization of gas capture for power generation or

LNG feedstock (NUPRC, 2024). However, persistent enforcement gaps and infrastructural bottlenecks continue to hinder progress (Akinpelu et al., 2022). Improved spatial monitoring could enhance transparency, real-time verification, and policy accountability (Zhizhin et al., 2019).

4.5 Limitations and Future Research

Despite robust coverage (2017–2024), medium-resolution VIIRS data (~750 m) may miss small or transient flares, particularly under dense cloud conditions (Elvidge et al., 2013). The exclusion of deep-water offshore sites limits full basin representation but maintains methodological consistency within the terrestrial domain. The electricity potential assumes complete capture and conversion; actual yields would depend on gas quality, accessibility, and capital investment (EIA, 2022).

Future work should combine higher-resolution infrared data (e.g., Landsat-9 TIRS, MODIS MOD14A1) with economic modeling to assess investment thresholds and life-cycle emission benefits (Hyndman & Athanasopoulos, 2018; IEA, 2023). Coupling geospatial inventories with socioeconomic and sustainability indicators would further strengthen decision-making for Nigeria's energy transition.

5. Conclusions

This study demonstrates the spatial and energetic significance of gas flaring across Nigeria's South–South region. Integrating satellite-derived VIIRS Nightfire data with administrative boundaries provided a robust LGA-level inventory of flare persistence, reliability, and potential for electricity recovery. Results show that Delta and Rivers States dominate both total volume and stability of flaring, while Bayelsa, Edo, and Akwa Ibom exhibit smaller yet consistent activity.

Monte Carlo–based conversion analysis indicates that the five states collectively possess more than 130 TWh yr^{-1} of recoverable electricity—equivalent to about one-third of Nigeria's current power demand. Delta alone could generate 58 TWh yr^{-1}, followed by Rivers (43 TWh) and Bayelsa (18 TWh). These findings highlight flare-to-power utilization as a technically feasible and environmentally beneficial pathway toward achieving Zero Routine Flaring by 2030.

Targeting the most persistent LGAs for gas capture and on-grid integration would not only curb emissions but also strengthen regional energy security and equity in Nigeria's oil-producing heartland.

Supplementary Materials: Available at https://github.com/zubairgis/nigeria-hensard

Author Contributions: Conceptualization, Z.I. and Y.J.C., KU; methodology, Z.I. F.M. EIQ and U.U.E.; formal analysis, Z.I., Y.J.C., and R.K.H.; investigation, U.U.E., Y.J.D., F.M. and R.K.H.; data curation, U.U.E. EIQ and E.L.E.; writing original draft preparation, Z.I. and Y.J.C.; writing—review and editing, U.U.E., E.L.E., and R.K.H.; supervision, Z.I.; project administration, Z.I. F.M. and Y.J.C. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data presented in this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Full Meaning
BCM	Billion Cubic Metres
CF	Capacity Factor
CI	Confidence Interval
GEE	Google Earth Engine
GW	Gigawatt
LGA	Local Government Area
MW	Megawatt
NCV	Net Calorific Value
R	Statistical Computing Environment (R Project)
TWh	Terawatt-hour
VIIRS	Visible Infrared Imaging Radiometer Suite
η	Thermal-to-electric Conversion Efficiency
$p_{(MW)}$	Installed Power Capacity (in Megawatts)
$E_{(elec)}$	Electricity Generation Potential (in Terawatt-hours)

References

Akinpelu, J. A., Sanni, L. O., & Afolabi, O. (2022). Nigeria's gas flare reduction policy and its implications for sustainable energy transition. Energy Policy, 165, 112927. https://doi.org/10.1016/j.enpol.2022.112927

Anejionu, O. C. D., Blackburn, G. A., & Whyatt, J. D. (2015). Detecting gas flares and estimating flaring volumes at individual flow stations using MODIS. Remote Sensing of Environment, 158, 81–94. https://doi.org/10.1016/j.rse.2014.11.012

Department of Energy (DOE). (2019). Combined Heat and Power Technical Potential in the United States. U.S. Department of Energy. https://www.energy.gov/eere

Ejiogu, A. O., Ogbonna, A. I., & Odum, O. C. (2021). The paradox of gas flaring and energy poverty in Nigeria: Policy and infrastructural perspectives. Energy Reports, 7, 2139–2150. https://doi.org/10.1016/j.egyr.2021.04.050

Elvidge, C. D., Zhizhin, M., Baugh, K., & Hsu, F.-C. (2015). Methods for global survey of natural gas flaring from VIIRS. Energies, 8(7), 7777–7797. https://doi.org/10.3390/en8077777

Energy Information Administration (EIA). (2022). International Energy Statistics: Natural Gas and Electric Power Efficiency Factors. U.S. Department of Energy. https://www.eia.gov/international/data/world

Federal Ministry of Environment. (2021). Nigeria's Nationally Determined Contribution (NDC) Update 2021. Abuja, Nigeria.

Hyndman, R. J., & Athanasopoulos, G. (2018). Forecasting: Principles and practice (2nd ed.). OTexts. https://otexts.com/fpp2/

International Energy Agency (IEA). (2023). World Energy Outlook 2023. OECD/IEA. https://www.iea.org/reports/world-energy-outlook-2023

Morgan, M. G., & Henrion, M. (1990). Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis. Cambridge University Press.

Nigerian Upstream Petroleum Regulatory Commission (NUPRC). (2022). Nigeria Gas Flare Commercialisation Programme (NGFCP) — Programme Structure. https://ngfcp.nuprc.gov.ng/wp-content/uploads/2022/10/NGFCP-PROGRAMME-STRUCTURE.pdf

Nigerian Upstream Petroleum Regulatory Commission (NUPRC). (2022). Nigeria Gas Flare Commercialisation Programme (NGFCP): Programme Structure. https://ngfcp.nuprc.gov.ng

Nigerian Upstream Petroleum Regulatory Commission (NUPRC). (2024). 2023 NUPRC Annual Report. https://www.nuprc.gov.ng/wp-content/uploads/2024/04/UPDATED-2023-NUPRC-ANNUAL-REPORT.pdf

Nigerian Upstream Petroleum Regulatory Commission (NUPRC). (2024). 2023 NUPRC Annual Report. https://www.nuprc.gov.ng

Office of the Surveyor General of the Federation (OSGOF). (2019). Official Administrative Boundary Datasets of Nigeria (Levels 0–2). Abuja, Nigeria. https://osgof.gov.ng

Payne Institute for Public Policy. (n.d.). Global Gas Flaring Observed from Space (VIIRS Nightfire). Colorado School of Mines. https://eogdata.mines.edu/products/vnf/global_gas_flare.html

Payne Institute for Public Policy. (n.d.). Global Gas Flaring Observed from Space (VIIRS Nightfire). Colorado School of Mines. https://eogdata.mines.edu/products/vnf/global_gas_flare.html

U.S. Department of Energy (DOE). (2019). Combined Heat and Power Technical Potential in the United States. Energy Efficiency and Renewable Energy Office. https://www.energy.gov/eere

U.S. Energy Information Administration (EIA). (2022). International Energy Statistics: Natural Gas and Electric Power Efficiency Factors. https://www.eia.gov/international/data/world

World Bank, International Energy Agency (IEA), International Renewable Energy Agency (IRENA), World Health Organization (WHO), & United Nations Statistics Division (UNSD). (2023). Tracking SDG 7: The Energy Progress Report 2023. https://trackingsdg7.esmap.org/data/files/download-documents/sdg7-report2023-full_report.pdf

World Bank. (2023). 2023 Global Gas Flaring Tracker Report. World Bank Group. https://www.worldbank.org/en/topic/extractiveindustries/publication/2023-global-gas-flaring-tracker-report

tracker-report

World Bank. (2023). 2023 Global Gas Flaring Tracker Report. World Bank Group. https://www.worldbank.org/en/topic/extractiveindustries/publication/2023-global-gas-flaring-tracker-report

Zhizhin, M., Elvidge, C. D., Baugh, K., & Hsu, F.-C. (2019). Ground-truth validation of VIIRS Nightfire for gas flaring volume estimates. NOAA Earth Observation Group. https://gml.noaa.gov/publications/annual_meetings/2019/slides/6-Zhizhin.pdf