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Spatiotemporal Assessment and Plausibility Evaluation of Power-Sector Carbon Dioxide Emissions in Banten, Indonesia, 2000–2024

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Abstract: Global gridded inventories permit subnational emissions analysis, but provincial estimates can be sensitive to boundary treatment and spatial allocation. This study assessed the temporal development and physical plausibility of power-sector fossil carbon dioxide emissions in Banten Province during 2000–2024 using the Emissions Database for Global Atmospheric Research (EDGAR). Twenty-five annual NetCDF files were audited and aggregated from monthly values. Provincial totals were extracted using fractional coverage, centroid inclusion, and complete intersection, then compared with capacity-based theoretical bounds and cumulative generating capacity. The audit passed all unit and aggregation checks, with a maximum relative error of 1.66×10^{-8}. Fractional emissions increased from 6.55 Mt CO_2 in 2000 to 142.00 Mt CO_2 in 2024. In 2024, centroid and complete-intersection estimates were 22.5% and 35.8% higher, respectively, while one coastal cell contributed 96.1% of the fractional total. The fractional estimate was 1.80 times the theoretical upper bound of 78.88 Mt CO_2. Annual levels were strongly associated with cumulative capacity (Pearson $r = 0.862$; Spearman $\rho = 0.969$), but annual changes were not ($r = -0.109$). Fractional coverage is recommended as the primary extraction method, although absolute totals require cautious interpretation, explicit spatial-sensitivity reporting, and validation using complete plant-level operational data for Banten.

Keywords: EDGAR; Fossil CO_2; Power Industry; Fractional Coverage; Banten

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Introduction

Anthropogenic carbon dioxide (CO_2) emissions from fossil-fuel combustion remain a major driver of climate change. Despite accelerating renewable-energy deployment, global fossil CO_2 emissions remain high, indicating that energy-system transformation is not yet consistent with stringent mitigation pathways (Friedlingstein et al., 2025; (IPCC), 2006). The electricity sector is central to this challenge because it is both a major emissions source and a prerequisite for decarbonising transport, buildings, and industry. Reliable information on the magnitude, temporal evolution, and spatial concentration of power-sector emissions is therefore essential for identifying mitigation priorities. Indonesia is an important case because rising electricity demand has historically been accompanied by fossil-fuel generation, particularly in the interconnected Java–Bali system. If projects under construction and planned as of 2020 proceed, Southeast Asia's fossil-fuel power fleet could double long-term committed emissions and create risks of underutilised or stranded assets, particularly in Indonesia (Chen & Mauzerall, 2021).

Previous studies identified a persistent trade-off between expanding electricity supply and reducing emissions (Handayani et al., 2017) and showed that unabated coal may create long-term technological and emissions lock-in. Conversely, renewable-energy

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expansion, restrictions on new coal capacity, and earlier plant retirement could substantially alter future emissions (Ordonez et al., 2022; Reyseliani et al., 2022; Sani et al., 2021; Shah et al., 2024). However, these studies primarily examined national scenarios or interconnected electricity systems rather than observed emissions within individual provinces.

A provincial perspective is necessary because generation infrastructure and its emissions are geographically concentrated, while national totals obscure differences in provincial economic structure, energy use, and production-based carbon footprints (Rum et al., 2024). Banten Province accommodates several large coal- and gas-fired generating complexes connected to the Java–Bali system, including Suralaya, Lontar, Labuan, Banten 1, Jawa 7, and Cilegon (Ministry of Energy and Mineral Resources of the Republic of Indonesia, 2023). Its Regional Energy Plan also establishes targets for generating capacity, renewable-energy penetration, electricity consumption, and greenhouse-gas control (Government of Banten Province, 2022). Banten is therefore an appropriate case for evaluating whether a global gridded inventory provides a temporally and spatially plausible representation of provincial power-sector emissions.

The Emissions Database for Global Atmospheric Research (EDGAR) provides gridded anthropogenic CO_2 emission estimates that enable the analysis of spatial and temporal emission patterns. Its global dataset has a spatial resolution of 0.1° × 0.1° and distinguishes emissions by sector, allowing the identification of emission hotspots and the assessment of sectoral contributions to regional emission totals (Janssens-Maenhout et al., 2019; Crippa et al., 2024). EDGAR also provides monthly emission data, which can be aggregated into annual totals to examine long-term changes in emission magnitude and spatial distribution, provided that the temporal structure and units of the data are correctly accounted for (Crippa et al., 2020). These characteristics make EDGAR suitable for assessing changes in the spatial distribution and temporal trends of CO_2 emissions across Indonesian provinces during 2000–2024. However, the interpretation of provincial estimates requires appropriate spatial aggregation of grid-cell values to administrative boundaries to ensure consistency in regional comparisons.

However, provincial extraction from a global grid is not methodologically neutral. Inventory uncertainty arises from activity data, emission factors, sector classification, temporal allocation, and spatial disaggregation, while EDGAR's uncertainty assessment primarily addresses aggregated national and sectoral estimates (Crippa et al., 2021). Subnational estimates may additionally vary with grid resolution, spatial proxies, point-source information, and allocation methods (Hogue et al., 2019; Oda et al., 2018), and national agreement does not necessarily ensure local accuracy (Gurney et al., 2019). This issue is especially relevant to Banten because several major plants are coastal, where 0.1° cells may contain land and sea or intersect multiple jurisdictions. Provincial totals may therefore differ depending on whether cells are fractionally weighted, assigned by centroid, or fully included when they intersect the boundary.

Comparison with government inventories also requires harmonisation. The EDGAR data used here represent fossil CO_2 from electricity and heat production, whereas provincial inventories may cover the broader energy sector, multiple gases, and CO_2-equivalent totals. Differences in gas, sectoral, temporal, and territorial coverage can produce discrepancies without implying an error in either inventory (Banja et al., 2025). Direct numerical comparison is therefore valid only when these boundaries are equivalent.

Previous studies have separately examined Indonesian power-sector transitions and EDGAR construction and uncertainty, but few have integrated unit verification, alternative grid-extraction methods, plant-capacity information, theoretical emission bounds, and commissioning chronology in a single provincial assessment. This study addresses that gap by assessing the spatiotemporal development and physical plausibility of Banten's power-sector fossil CO_2 emissions during 2000–2024. It aims to: (1) verify EDGAR units, temporal structure, and annual aggregation; (2) construct lower, central, and upper theoretical estimates using installed capacity, capacity factors, efficiency, and fuel-specific emission factors; (3) quantify sensitivity to fractional-coverage, centroid, and complete-intersection extraction; (4) harmonise inventory boundaries before comparison with the Banten greenhouse-gas inventory; and (5) evaluate the association between EDGAR emissions and cumulative generating capacity, including changes around commissioning years. These temporal relationships are interpreted as statistical correspondence and infrastructure consistency, not causality.

Method

This Banten Province is located at the western end of Java and comprises four regencies and four cities. It is bordered by the Java Sea, Sunda Strait, Indian Ocean, Jakarta, and West Java. Its extensive coastline and concentration of fossil-fuel power plants make Banten suitable for assessing the effects of coastal grid-cell treatment on provincial EDGAR estimates. The study area and major generating facilities are shown in Figure 1. The infrastructure inventory includes Suralaya Units 1–8, Labuan Units 1–2, Lontar Units 1–4, Banten

1/Lestari Banten Energi, Jawa 7 Units 1–2, and Cilegon CCGT. Facility information was compiled from the Ministry of Energy and Mineral Resources (2023), PLN, and official operator records. These locations were used to assess the spatial and temporal consistency of EDGAR emissions with generating infrastructure, not to attribute each grid-cell value to an individual plant.

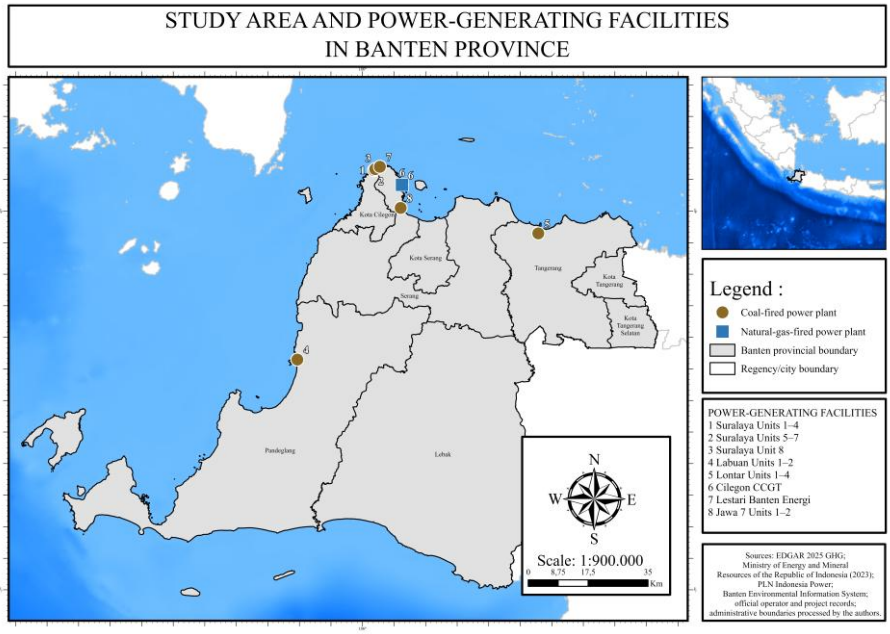


Figure 1. Study area and major fossil-fuel power-generating facilities in Banten Province.

Data

1. Monthly fossil CO_2 emissions were obtained from EDGAR_2025_GHG for the Power Industry sector (ENE/IPCC 1A1a) for 2000–2024. The 25 annual NetCDF files contain 12 monthly layers at 0.1° × 0.1° resolution, expressed in tonnes CO_2 per grid cell. Biogenic CO_2, CH_4, N_2O, and CO_2-equivalent emissions were excluded.
2. Provincial and regency/city boundaries were obtained from BIG. The Banten provincial polygon defined the extraction area, while regency/city boundaries supported map interpretation. The data were aligned in WGS 84 and projected to UTM Zone 48S for area calculations.
3. The power-plant inventory contained coordinates, fuel type, technology, capacity, and commissioning year for the facilities shown in Figure 1. The records were compiled from the Ministry of Energy and Mineral Resources, PLN, and official operator sources. The included capacity reached 9,295 MW by 2024; Jawa 9–10 were excluded because they began commercial operation in 2025.
4. Available 2023 operational data from PLN Indonesia Power included electricity generation, capacity factors, and heat rates for selected plants. These data and IPCC (2006) fuel-specific emission factors were used to construct theoretical emissions bounds rather than a complete plant-level inventory
5. Banten greenhouse-gas documents were reviewed to assess gas, sectoral, temporal, and territorial comparability. Because a separate fossil CO_2 series for IPCC category 1A1a was unavailable, broader energy-sector CO_2-equivalent totals were not used for direct numerical validation.

Table 1. Main fossil-fuel power-generating facilities included in the Banten power-plant inventory

Power plant/unit	Fuel	Technology	Capacity (MW)	Commercial operation date (COD)
Suralaya Units 1–4	Coal	Subcritical/legacy coal	1,600	1984–1989
Suralaya Units 5–7	Coal	Subcritical/legacy coal	1,800	1996–1997
Suralaya Unit 8	Coal	Subcritical coal	625	2011
Labuan Units 1–2	Coal	Coal-steam generation	600	2009–2010
Lontar Units 1–3	Coal	Coal-steam generation	945	2011–2012

Power plant/unit	Fuel	Technology	Capacity (MW)	Commercial operation date (COD)
Lontar Unit 4	Coal	Coal-steam generation	315	2023
Cilegon combined-cycle plant	Natural gas	Combined-cycle gas turbine	740	2006
Lestari Banten Energi	Coal	Coal-steam generation	670	2017
Jawa 7 Units 1–2	Coal	Ultra-supercritical coal	2,000	2019–2020
Total capacity included by 2024	–	–	**9,295**	–

Method

The NetCDF metadata were first examined to verify the variable, sector, gas, dimensions, and units. Because emissions were expressed as tonnes CO_2 per grid cell per month, no conversion based on cell area or time was required. Annual emissions for each grid cell were obtained by summing the 12 monthly values:

$$E_{i,t} = \sum_{m=1}^{12} E_{i,m,t}$$

The calculated monthly and annual totals were reconciled with the processed datasets using a relative-error tolerance of 10^{-6}. EDGAR cells intersecting Banten were converted into polygons and projected to UTM Zone 48S. Fractional coverage was used as the primary extraction method:

$$E_t^{frac} = \sum_i \omega_i \, E_{i,t}$$

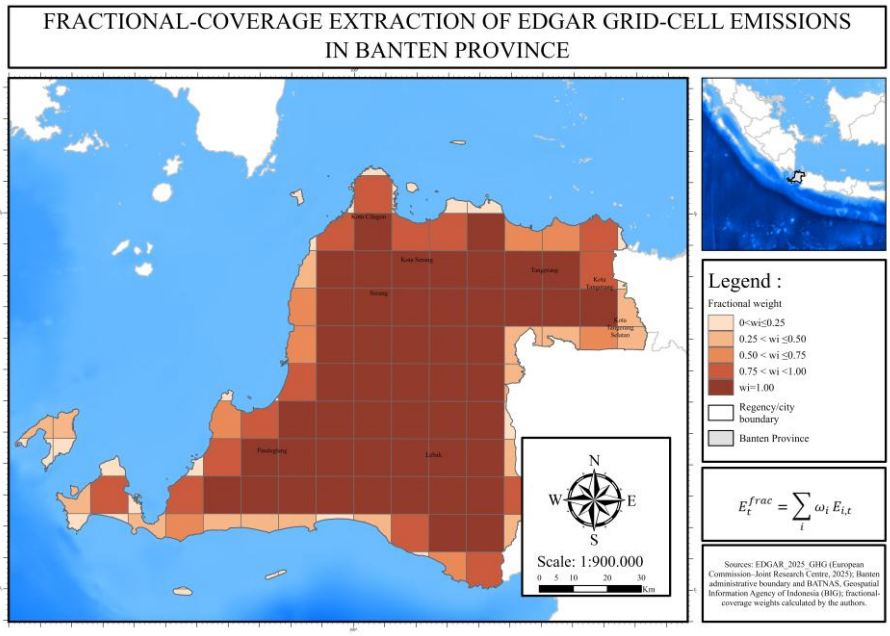
$$\omega_i = \frac{Area(A_i \cap B)}{Area(A_i)}$$

where A_i is grid cell i and B is Banten Province. Two alternative methods were applied as sensitivity tests. Centroid inclusion assigned the full emission of a cell when its centre was inside Banten, whereas complete intersection included the full value of every cell intersecting the provincial boundary:

$$E_t^{cent} = \sum_i I\,(c_i \in B) E_{i,t}$$

$$E_t^{int} = \sum_i I\,(A_i \cap B > 0) E_{i,t}$$

Differences from fractional coverage were expressed as percentages. These differences represent sensitivity to coastal boundary treatment rather than the full uncertainty of EDGAR (Hogue et al., 2019; Oda et al., 2018). The three extraction rules are illustrated in Figure 2.



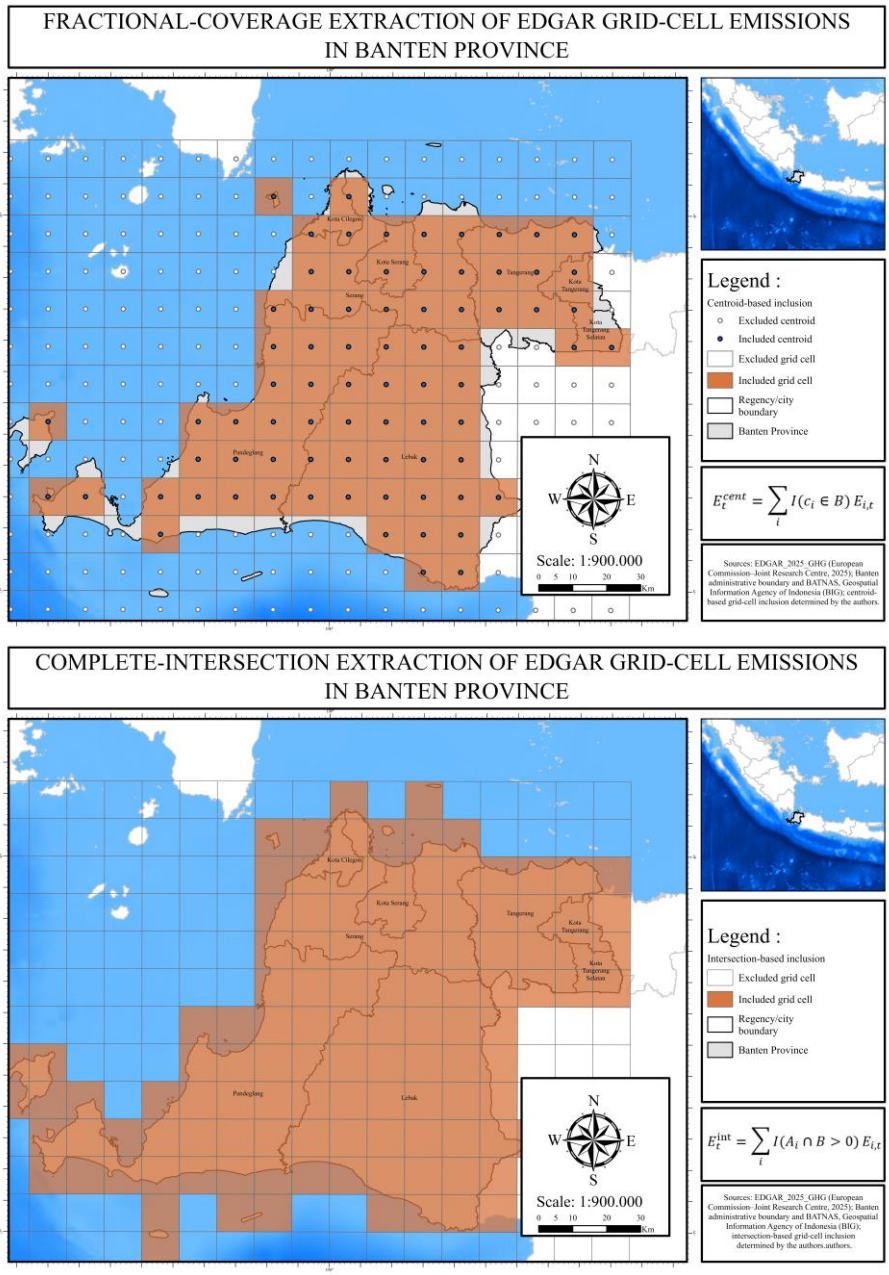


Figure 2. EDGAR grid-cell extraction methods for Banten Province: (a) fractional coverage, (b) centroid-based inclusion, and (c) complete-intersection inclusion.

The physical plausibility of EDGAR emissions was assessed using lower, central, and upper theoretical estimates:

$$E_p = C_p \times 8760 \times CF_p \times \frac{3.6}{\eta p} \times EF_p \times 10^{-9}$$

where E_p is annual emissions (Mt CO_2), C_p is installed capacity (MW), CF_p is the capacity factor, η_p is generation efficiency, and EF_p is the fuel-specific emission factor (kg CO_2 GJ^{-1}). The lower scenario combined low utilisation, high efficiency, and low emission factors, while the upper scenario applied the opposite assumptions. Coal emission factors ranged from 94.6 to 101 kg CO_2 GJ^{-1}, whereas 56.1 kg CO_2 GJ^{-1} was applied to natural gas (IPCC, 2006). Available 2023 net-generation and heat-rate data were used only as a partial operational check because they did not cover all generating facilities in Banten.

Annual cumulative capacity was calculated from plant commissioning years, with each unit included from the end of its commissioning year. Its relationship with fractional EDGAR emissions was evaluated using Pearson correlation, Spearman rank correlation, and correlations between annual changes. Three-year averages before and after major commissioning periods

were also compared. Statistical significance was evaluated at $p < 0.05$, although all relationships were interpreted as temporal correspondence rather than causality. Comparability with the Banten greenhouse-gas inventory was assessed according to gas, sector, unit, period, and territorial coverage. Because an equivalent provincial series for fossil CO_2 from IPCC category 1A1a was unavailable, broader energy-sector CO_2-equivalent totals were not used for direct numerical validation (Banja et al., 2025).

Table 2. Assumptions used to construct the theoretical CO_2-emission scenarios

Technology group	Scenario	Capacity factor	Efficiency	Emission factor (kg CO_2 GJ^{-1})
Legacy/subcritical coal and coal-steam units	Lower	0.50	0.38	94.6
Legacy/subcritical coal and coal-steam units	Central	0.70	0.33	96.1
Legacy/subcritical coal and coal-steam units	Upper	0.85	0.28	101.0
Ultra-supercritical coal units	Lower	0.50	0.45	94.6
Ultra-supercritical coal units	Central	0.70	0.43	96.1
Ultra-supercritical coal units	Upper	0.85	0.40	101.0
Combined-cycle gas turbine	Lower	0.10	0.56	56.1
Combined-cycle gas turbine	Central	0.30	0.50	56.1
Combined-cycle gas turbine	Upper	0.60	0.40	56.1

Result and Discussion

The NetCDF audit confirmed that all 25 annual files covered 2000–2024, contained 12 monthly layers, and consistently represented fossil CO_2 emissions from the Power Industry sector in tones per grid cell. Reconciliation of the monthly and annual calculations produced a maximum relative error of 1.66×10^{-8}, substantially below the adopted tolerance of 10^{-6}. The fractional-coverage estimate increased from 6.55 Mt CO_2 in 2000 to 142.00 Mt CO_2 in 2024, representing a 21.7-fold increase and a compound annual growth rate of approximately 13.7%. The increase was not uniform. Emissions rose from 67.01 Mt CO_2 in 2021 to 108.68 Mt CO_2 in 2022, equivalent to an annual increase of 62.2%, before reaching 134.86 Mt CO_2 in 2023 and 142.00 Mt CO_2 in 2024. In contrast, cumulative generating capacity remained unchanged at 8,980 MW between 2021 and 2022 and increased to 9,295 MW in 2023. The 2022 discontinuity therefore cannot be explained solely by the recorded commissioning chronology. It may reflect changes in operating intensity, underlying activity estimates, or spatial allocation, although these influences cannot be separated using the available data.

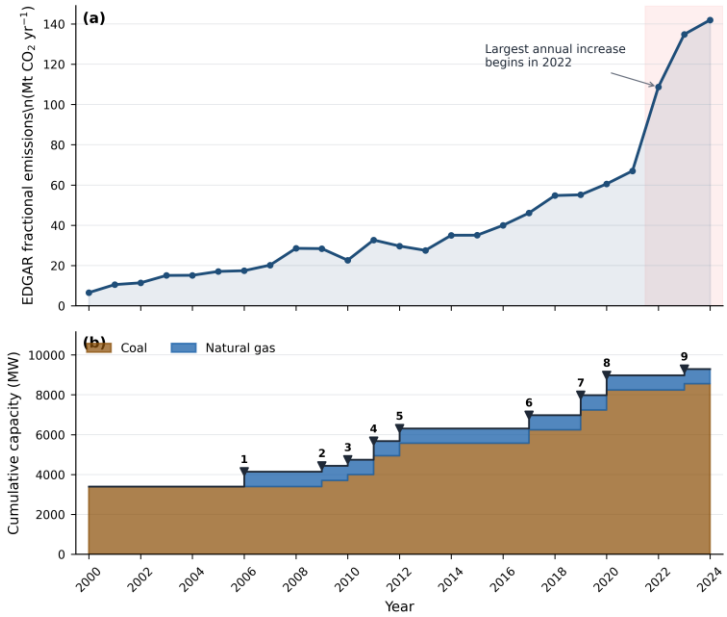


Figure 3. Annual EDGAR fractional-coverage fossil CO_2 emissions and cumulative fossil-fuel generating capacity in Banten Province during 2000–2024: (a) annual emissions and (b) cumulative coal- and natural-gas-fired capacity. Numbered markers indicate major plant-commissioning events.

The alternative extraction methods produced materially different provincial totals. In 2024, fractional coverage yielded 142.00 Mt CO_2, whereas centroid-based inclusion produced 173.96 Mt CO_2, or 22.5% more than the fractional estimate. Complete-intersection inclusion produced 192.89 Mt CO_2, representing an increase of 35.8%. The equal-area calculation differed from the original fractional calculation by only 0.0018%, indicating that the observed sensitivity was not caused by map-projection distortion. Instead, it was primarily associated with a coastal grid cell centred at 105.75° E and 6.55° S. After applying its fractional weight of 0.809, this cell contributed 136.40 Mt CO_2, equivalent to 96.1% of the provincial fractional total. Because its centroid lies inside Banten, the centroid method assigned its full value of 168.66 Mt CO_2 to the province. The provincial estimate was therefore strongly controlled by the treatment of a single coastal grid cell. This result is consistent with evidence that subnational estimates from globally downscaled inventories can be sensitive to spatial proxies and boundary-allocation methods (Hogue et al., 2016; Oda et al., 2019; Gurney et al., 2019). Fractional coverage was consequently retained as the primary method, while centroid and complete-intersection estimates were interpreted as spatial-sensitivity tests rather than equivalent estimates or a complete uncertainty interval.

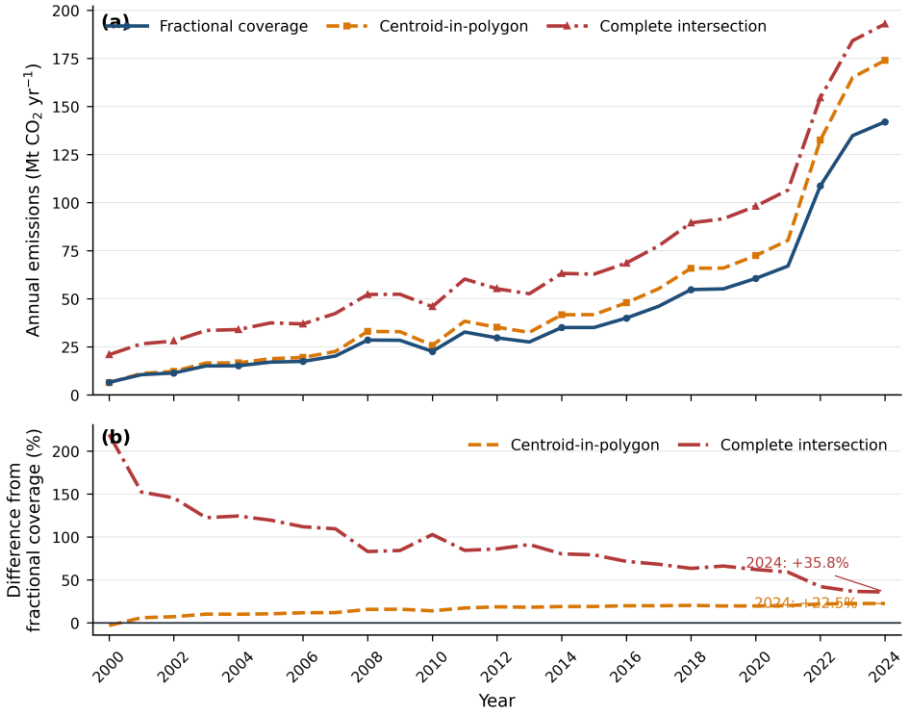


Figure 4. Sensitivity of annual EDGAR fossil CO_2 estimates to spatial-extraction method during 2000–2024: (a) annual emissions obtained using fractional coverage, centroid-based inclusion, and complete-intersection inclusion; and (b) percentage differences from the fractional-coverage estimate.

The scenario-based theoretical estimates further indicated a potential discrepancy in absolute magnitude. For the 9,295 MW of generating capacity included in 2024, the lower, central, and upper scenarios produced emissions of 32.59, 52.79, and 78.88 Mt CO_2, respectively. The fractional EDGAR estimate was therefore 4.36 times the lower estimate, 2.69 times the central estimate, and 1.80 times the upper estimate. Moreover, the weighted contribution of the dominant grid cell alone was 1.73 times the theoretical upper estimate for all inventoried facilities. The available 2023 operational data covered 6,625 MW of PLN Indonesia Power capacity and produced a derived subtotal of 37.74 Mt CO_2. The corresponding EDGAR fractional estimate was 134.86 Mt CO_2, or 3.57 times this subtotal. However, the operational dataset excluded Lestari Banten Energi and

Jawa 7 and therefore cannot be treated as a complete plant-level validation. Possible explanations include generating sources not represented in the compiled facility inventory, particularly auto producer facilities, assumptions that do not encompass actual plant performance, or spatial allocation of emissions from nearby sources into the dominant coastal cell. Accordingly, the comparison identifies a physical-plausibility concern but does not by itself demonstrate that the EDGAR estimate is erroneous.

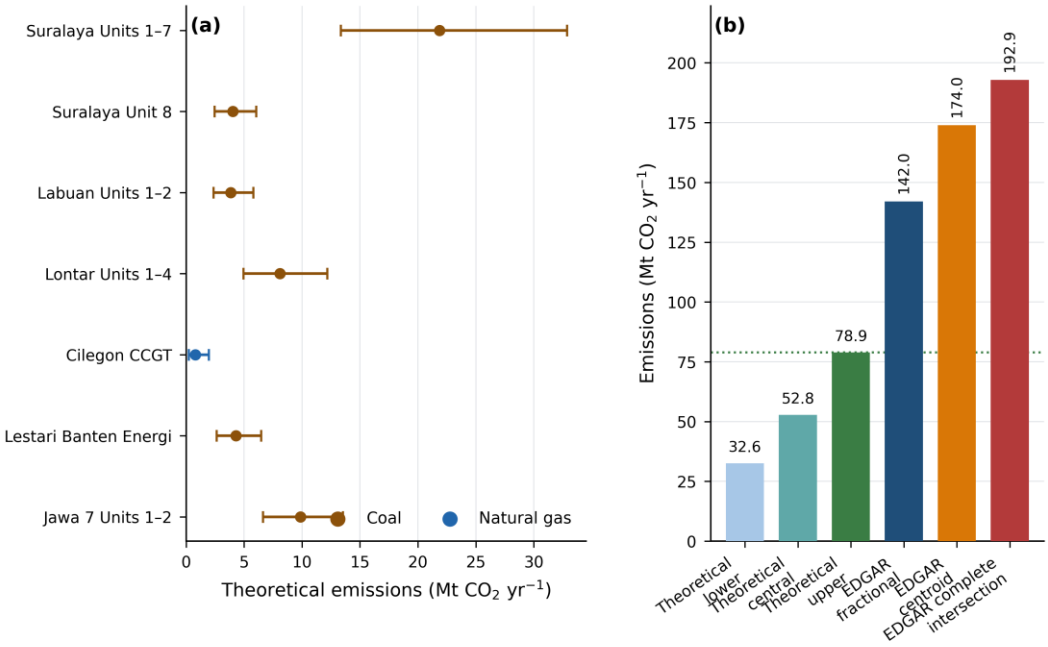


Figure 5. Comparison of theoretical and EDGAR fossil CO_2 emissions in 2024: (a) plant-level theoretical emission ranges and (b) aggregate lower, central, and upper theoretical estimates compared with EDGAR totals obtained using the three spatial-extraction methods.

Temporal analysis showed strong correspondence between the annual levels of EDGAR emissions and cumulative generating capacity. Pearson correlation produced r=0.862with p<0.001, while Spearman rank correlation produced ρ=0.969with p<0.001. The relationship remained strong before the 2022 discontinuity, with r=0.952for 2000–2021. However, the correlation between annual changes in emissions and annual capacity additions was weak and statistically insignificant (r=-0.109, p=0.612). This contrast indicates that emissions and capacity followed a similar long-term direction but that year-to-year changes in generating capacity did not explain annual emission variability. Comparisons surrounding major commissioning periods produced emission increases of 47.5% after the 2011 expansion, 54.8% after the commissioning of Lestari Banten Energi, and 99.1% around the commissioning of Jawa 7.

The comparison associated with Lontar Unit 4 produced an increase of 80.3%, but only one post-commissioning year was available. These windows overlap with other capacity additions and, in the case of Jawa 7, include the 2022 discontinuity. They should therefore be interpreted as descriptive temporal correspondence rather than causal effects.

Table 3. Correlations between EDGAR fractional-coverage fossil CO_2 emissions and cumulative fossil-fuel generating capacity in Banten Province during 2000–2024.

Statistical assessment	Period	Coefficient	p-value	n	Interpretation
Pearson correlation of annual levels	2000–2024	$r = 0.862$	2.99×10^{-8}	25	Strong long-term correspondence, but not evidence of causality
Spearman rank correlation	2000–2024	$\rho = 0.969$	2.03×10^{-15}	25	Strong monotonic correspondence
Pearson correlation of annual changes	2001–2024	$r = -0.109$	0.612	24	No significant year-to-year correspondence
Pearson correlation before the 2022 discontinuity	2000–2021	$r = 0.952$	9.00×10^{-12}	22	Strong association remained before the post-2021 increase

Direct numerical comparison with the Banten greenhouse-gas inventory was not performed because an equivalent provincial series for fossil CO_2 from IPCC category 1A1a was unavailable. The available provincial documents generally report broader energy-sector emissions or multiple greenhouse gases expressed as CO_2 equivalent. Comparing these totals directly with EDGAR Power Industry fossil CO_2 would combine different gases, sectors, units, and territorial definitions. As emphasised by Banja et al. (2025), meaningful inventory comparison requires prior alignment of these boundaries. The absence of a comparable provincial series therefore limits independent numerical validation but prevents a potentially misleading comparison with broader energy-sector totals.

Overall, the EDGAR series passed the unit, temporal-aggregation, and numerical-reconciliation checks and showed strong long-term correspondence with the expansion of generating capacity. Nevertheless, its absolute provincial magnitude was highly dependent on a single coastal grid cell and exceeded the scenario-based theoretical range. The fractional-coverage series should therefore be used as the primary provincial estimate, accompanied by explicit spatial-sensitivity results and physical-plausibility checks. The findings support interpretation of the long-term direction of Banten's power-sector emissions more strongly than precise attribution of the absolute total to individual facilities. They also demonstrate that internal consistency at the grid level does not remove the need for boundary sensitivity, infrastructure comparison, and sectoral harmonisation when EDGAR is applied at the provincial scale.

Conclusion

The EDGAR Power Industry dataset passed the metadata, temporal-aggregation, and numerical-reconciliation checks, but its provincial application revealed substantial spatial and physical-plausibility concerns. Fractional-coverage emissions increased from 6.55 Mt CO_2 in 2000 to 142.00 Mt CO_2 in 2024, with the largest annual increase occurring in 2022. Annual emission levels were strongly associated with cumulative generating capacity (Pearson $r = 0.862$; Spearman $\rho = 0.969$), whereas annual changes showed no significant correspondence ($r = -0.109$). In 2024, centroid and complete-intersection extraction produced estimates 22.5% and 35.8% above the fractional total, respectively, while one coastal grid cell accounted for 96.1% of the fractional estimate. The fractional result was also 1.80 times the theoretical upper estimate of 78.88 Mt CO_2. Fractional coverage is therefore recommended as the primary extraction method, but its absolute magnitude should be interpreted cautiously and accompanied by spatial-sensitivity and infrastructure-based plausibility checks. Further validation requires complete plant-level operational data and a harmonized provincial fossil CO_2 inventory for IPCC category 1A1a.

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