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Evaluation of Coal-Fired Power Plant Emission Reduction in Indonesia in Line with the Indonesian Government's Roadmap Towards Net Zero Emissions 2060

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Keywords	Abstract
Coal-fired power plants; Emissions trajectory; Energy transition; Indonesia; Carbon lock-in.	Indonesia aims to achieve Net Zero Emissions (NZE) by 2060, with the electricity sector as the primary contributor to emissions due to the dominance of coal-fired power plants (CFPPs). This study evaluates the emissions trajectory of Indonesian CFPPs and the alignment of their implementation with the national energy transition roadmap through 2045. The analysis was conducted using unit-level operational data from Global Energy Monitor (GEM) covering 318 CFPP units (71.63 GW) that are operational, permitted, announced, or under construction. Annual and cumulative emissions calculations were based on the technical characteristics of each unit, including capacity, commercial operation date (COD), and combustion technology. The results show that, under a baseline scenario without accelerated retirement, average annual emissions will reach 394.607 $MtCO_2$ during the period 2026–2045, with total cumulative emissions of 7.892 $GtCO_2$ by 2045. The findings also indicate a concentrated distribution of emissions, with the 20 highest-emitting units contributing 24.9% of total annual emissions, suggesting carbon lock-in in a small number of large-capacity power plants. Although the government's roadmap establishes milestones for the phase-out of CFPPs in 2031, 2037, and before 2055, it does not include quantified emission reduction targets or specify which units will be retired; therefore, consistency with the decarbonization pathway cannot yet be verified quantitatively. These findings indicate that, without explicit and measurable emissions-based interventions, the operational structure of coal-fired power plants through 2045 will not automatically align with the decarbonization trajectory toward NZE 2060.

INTRODUCTION

Indonesia's electricity sector plays a strategic role in supporting national economic growth, but it is also one of the main contributors to CO_2 emissions, primarily due to the dominance of coal use in electricity generation through CFPPs. Indonesia's electricity system remains structurally coal-dominated (Unruh, 2000), creating long-term decarbonization challenges in line with global climate stabilization objectives (Safonov et al., 2022; Weitzel & Ordonez, 2025). To date, coal remains the primary energy source in the national electricity system due to its abundant availability, relatively low production costs, and ability to provide baseload electricity supply. However, CFPPs are the largest source of carbon emissions in the electricity sector and are the focus of Indonesia's climate change mitigation strategy (International Energy Agency, 2023a).

International mitigation pathways require a rapid decline in coal-based generation (Tong et al., 2019), supported by climate science assessments emphasizing the urgency of deep emission reductions to limit global temperature rise (IPCC, 2022). As part of the global commitment to reduce greenhouse gas emissions and achieve NZE 2060, the Indonesian government, through the Ministry of Energy and Mineral Resources, has established an energy transition roadmap for the electricity sector that includes increasing the use of renewable energy, improving power system efficiency, and gradually reducing the role of CFPPs. The roadmap indicates that the energy transition will be carried out gradually through several important phases, including increasing the renewable energy mix to around 42% by 2030, increasing the dominance of renewable energy to around 57% by 2035, and reaching more than 70% by 2040 before moving toward a low-emission electricity system by 2060 (Government of Indonesia, 2021). National strategies outline transition milestones; however, they still lack clearly quantified plant-level emission reduction targets (International Energy Agency, 2022a). In addition to increasing renewable energy penetration, the government's roadmap also includes a gradual reduction in CFPP operations through a phase-down strategy, which will be implemented progressively in line with increases in renewable energy capacity and the development of supporting technologies such as power system interconnection, energy storage (battery storage), and electrification of the energy sector. This gradual approach aims to maintain the reliability of the national power system while progressively reducing carbon emissions during the energy transition period toward NZE 2060.

Based on Indonesian coal-fired power plant operational data used in this study, there are 526 coal-fired power plants with a total capacity of 127.68 GW. The total annual carbon emissions generated by all PLTU reach approximately 423.03 $MtCO_2$, indicating a significant contribution to total national emissions. In addition, an analysis of emission projections based on the operational age of the power plants shows that the total cumulative emissions of PLTU could reach 14.534 $GtCO_2$ by 2045 if all units operate according to their technical lifetimes. This value highlights the magnitude of potential carbon emissions generated by existing CFPP infrastructure and underscores the importance of evaluating the emission trajectory of the electricity sector in the context of the national energy transition. Previous studies have shown that existing fossil fuel-based power plant infrastructure has the potential to generate large amounts of carbon emissions throughout its operational life, known as the carbon lock-in effect. The existence of this infrastructure can lock in future carbon emissions and hinder the achievement of decarbonization targets if appropriate policy interventions are not implemented (Clark et al., 2016). Carbon lock-in theory explains how long-lived energy infrastructure creates structural inertia in emission trajectories (Shearer et al., 2023), a finding reinforced by committed emissions research that quantifies future emissions embedded in existing capital stock (Lorenz, 1905).

In addition, carbon emissions from CFPPs are strongly influenced by plant operational characteristics, including generation technology, thermal efficiency, and utilization rates. Power plants with lower efficiency tend to produce higher carbon emissions than plants with more efficient technologies, even if they have the same capacity (International Energy Agency, 2023a). Plant-level operational databases now enable more detailed emission tracking and verification

(Davis & Caldeira, 2010), consistent with Intergovernmental Panel on Climate Change (IPCC) inventory methodologies for sectoral accounting (Erickson et al., 2015). Differences in technical characteristics across subcritical, supercritical, and ultra-supercritical units further contribute to heterogeneity in emission intensity. Emission inequality among generating units can also be examined using Lorenz curve approaches (Pfeiffer et al., 2016) to identify disproportionately high-emitting plants within the system. The Indonesian government, through the Long-Term Strategy for Low Carbon and Climate Resilience 2050 (LTS-LCCR) document prepared by the Ministry of Environment and Forestry, emphasizes sector-based emission reduction scenarios, including the energy sector, within the framework of achieving NZE 2060 or earlier. However, the approach used in the document remains macro and systemic in nature (UNFCCC, 2021a). Similarly, the 2025–2034 Rencana Usaha Penyediaan Tenaga Listrik (RUPTL), or electricity supply business plan published by PT PLN (Persero), outlines a roadmap for developing power generation capacity and reducing the share of CFPPs in the national energy mix; however, the emissions evaluation presented is generally based on system-level projections and installed capacity rather than on analysis at the individual power plant unit level. This aggregate approach does not fully capture the emission contributions of each CFPP unit based on its operational characteristics, such as generation technology (subcritical, supercritical, ultra-supercritical), capacity factors, and operational age.

International studies show that variations in technical and operational characteristics among CFPP units can result in significant differences in emission intensity (International Energy Agency, 2022b). Coal phase-out modeling studies provide comparative evidence on the implications of alternative retirement pathways (Bertram et al., 2014), while Southeast Asian transition pathways have been extensively analyzed to assess regional decarbonization feasibility (Steckel et al., 2011). Most previous studies have also focused on energy transition analysis at the overall system level, including the International Energy Agency's assessment of decarbonization pathways for Indonesia's electricity sector in its Indonesia Energy Sector Assessment (International Energy Agency, 2022a) and Net Zero by 2050 Roadmap (International Energy Agency, 2021), which emphasize transformation of the national energy system without evaluating carbon emission trajectories based on detailed operational data from individual power generation units. Energy transition economics also highlights the risk of stranded assets arising from the premature retirement of carbon-intensive infrastructure (Jewell et al., 2019), further underscoring the importance of rigorous plant-level assessment. Policy alignment requires measurable emission reduction targets under the Paris Agreement framework (Patiño-Echeverri et al., 2020) to ensure transparency, accountability, and comparability of mitigation efforts.

The novelty of this research lies in several key aspects. First, this study develops a plant-level emission projection model for 526 CFPP units in Indonesia with a total capacity of 127.68 GW, providing the most detailed analysis of Indonesian CFPP emissions to date. Second, the research integrates actual power plant operational data (COD, capacity, technology type) with emission projections based on technical lifetime and technological characteristics, thereby providing a more detailed evaluation of the potential for carbon lock-in. Third, the study applies concentration curve analysis (CES approach) to identify emission inequality among CFPP units, revealing that a small number of units contribute disproportionately to total emissions. Fourth, the research quantitatively evaluates the alignment between Indonesia's energy transition roadmap and actual emission trajectories, identifying policy gaps where roadmap milestones lack quantified emission targets. Fifth, the study formulates mathematical expressions for policy gaps ($Gap(t) = Eproj(t) - Etarget(t)$) and rate conditions ($dEproj/dt > dEtarget/dt$) to enable more rigorous policy evaluation.

This study aims to evaluate the carbon emission reduction trajectory of all CFPPs in Indonesia based on a lifetime emission projection approach, as well as to assess its alignment with the national energy transition roadmap toward NZE 2060. Specifically, this study develops a plant-level emission projection model for 526 CFPPs with a total capacity of 127.68 GW to quantify annual and cumulative emission contributions and identify emission dynamics during the energy transition period through 2045. Unlike previous studies, which generally use an aggregate approach based on installed capacity or the national energy mix, this study integrates actual power plant operational data with emission projections based on technical lifetime and technological characteristics (subcritical, supercritical, and ultra-supercritical), thereby providing a more detailed evaluation of the potential for carbon lock-in in Indonesia's electricity sector. The novelty of this research lies in the development of a quantitative evaluation framework based on individual power plant units that directly links actual CFPP emission trajectories with the direction of government roadmap policy, thereby providing a stronger analytical basis for assessing the effectiveness of emission reduction strategies and supporting the formulation of more targeted and measurable energy transition policies aligned with national decarbonization targets toward NZE 2060.

METHOD

This study used a quantitative approach based on operational data at the power plant unit level to evaluate the carbon emission trajectory of CFPPs in Indonesia throughout their operational period. The analytical framework applies unit-based emission aggregation methods (Sovacool, 2016), integrating installed capacity, capacity factor, and emission factor modeling (Smith et al., 2019). The main data for this study was sourced from a global power plant database developed by GEM through its Global Coal Plant Tracker (GCPT) publication, which provides verified information on the status, capacity, and year of operation of CFPP units in various countries, including Indonesia (Global Energy Monitor, 2023a).

Methodologically, this study was conducted through four main stages. First, the collection, compilation, and validation of power plant unit data from official sources to ensure the consistency and reliability of the information, with reference to the GCPT dataset from GEM (February 2026 update). Second, annual emissions were calculated using an activity-based approach, which involves multiplying installed capacity, capacity factor, and fuel emission factor to obtain an estimate of annual CO_2 emissions at the unit level. This approach is in line with the emission inventory guidelines developed by the IPCC in the 2006 Guidelines for National Greenhouse Gas

Inventories (IPCC, 2006). The modeling structure is consistent with capacity and emission factor integration principles (Smith et al., 2019), ensuring methodological robustness and transparency. Third, lifetime emission projections are made by assuming a specific technical operational life and considering variations in capacity factors and the potential for early retirement. Baseline projections assume technical lifetimes of 30–40 years (Zhang et al., 2019). Sensitivity considerations reflect CCS retrofit literature (International Energy Agency, 2023b), coal retirement cost modeling (Caldecott, 2018), and the potential economic feasibility of accelerated phase-out pathways. Emission concentration metrics follow statistical inequality foundations (Rogelj et al., 2016), commonly applied in environmental economics (Xu & Ramanathan, 2015), to evaluate the distribution of emissions across units and identify high-emitting clusters. Fourth, the results of these projections were evaluated to assess their compatibility with the national energy transition roadmap towards the 2060 NZE target as stated in the national policy document published by the Ministry of Energy and Mineral Resources of the Republic of Indonesia and Indonesia's long-term commitments under the United Nations Framework Convention on Climate Change (UNFCCC, 1992). Carbon budgeting frameworks guide evaluation (Fofrich & Tong, 2021), supported by global electricity decarbonization studies (Malik et al., 2022). Transition finance risk is incorporated conceptually (Ürge-Vorsatz et al., 2015), particularly in assessing stranded asset exposure and investment alignment risks within the national electricity sector.

The main dataset for this study includes 526 CFPPs in Indonesia with a total capacity of 127.68 GW. The main sources of data include the global power plant database from GEM through the GCPT, national electricity system planning reports by PT PLN (Persero), and national energy policy documents published by the Ministry of Energy and Mineral Resources. This dataset was then verified and consolidated into a research database using excel files that included the technical and operational parameters of each CFPPs unit.

Table 1. Status of CFPPs.

No	Status	Number of Units	Total Capacity (MW)
1	Operating	287	60,705
2	Permitted	3	760
3	Announced	12	7,025
4	Construction	16	3,140
5	Cancelled	193	51,165
6	Pre-permit	7	3,180
7	Shelved	7	1,650
8	Retired	1	55
	Total	**526**	**127,680**

The data used in this study to evaluate emission trajectories is from coal-fired power plants with the following statuses: operating, permitted, announced, and under construction, with a total of 318 units and a total capacity of 71.63 GW. This is based on data available in the research database. Based on combustion technology classification, the majority of power plants use subcritical technology, with 177 units (55.6%), followed by supercritical technology with 30 units (9.4%) and ultra-supercritical technology with 11 units (3.5%). In addition, there are 100 power plants (31.5%) that do not have a specific technology classification in the dataset. In terms of capacity, subcritical power plants contribute the largest capacity at 28,675 MW (39%), while supercritical power plants contributed 14,545 MW (19.8%), followed by ultra- supercritical power plants with 10,121 MW (13.8%), and those without specific technology classifications with 20,189 MW (27.4%). This distribution shows that most coal-fired power plants in Indonesia are still dominated by conventional technology and power plants with technology classifications that have not been fully documented, which potentially have lower thermal efficiency and higher carbon emission intensity compared to more modern power plant technologies.

Table 2. CFPPs Combustion Technology.

No	Type	Efficiency	Number of Units	Total Capacity (WM)	Percentage of Units (%)	Capacity Percentage (%)
1	Subcritical	35-38	177	28,675	55.6	39
2	Supercritical	42-45%	30	12,645	9.4	19.8
3	Ultra-supercritical	45-50%	11	10,121	3.5	13.8
4	Unknown	-	100	20,189	31.5%	27.4
	Total		**318**	**71,630**	**100**	**100%**

RESULTS AND DISCUSSION

Baseline annual emissions remain near 394 $MtCO_2$ through the early 2030s (Sovacool & Griffiths, 2010), indicating a structural persistence of coal dependence under business-as-usual conditions. Without significant intervention, this plateau suggests limited short-term abatement despite incremental efficiency improvements. Cumulative emissions approach 8 $GtCO_2$ by 2045 (Heede, 2014), underscoring the long-term climate implications of delayed mitigation and the narrowing window for alignment with the temperature goals of the IPCC. Analysis shows top emitters dominate output (Tong & Davis, 2018), with a relatively small subset of power plants contributing disproportionately to total sectoral emissions. This pattern reflects ownership concentration, plant age profiles, and capacity factors that remain high in subcritical units. Similar findings appear in global coal fleet analyses (Shearer et al., 2019), including assessments aligned with the International Energy Agency net-zero pathways, which emphasize targeted early retirement of the most carbon-intensive assets. Retirement sequencing significantly alters trajectories (Rahman et al., 2021), as prioritizing high-emission and low-efficiency units can rapidly bend the emissions curve downward while minimizing system disruption.

Conversely, poorly sequenced retirements risk lock-in effects and stranded infrastructure. Economic implications include stranded capital risk (Hesterman & Popp, 2022), particularly for state-owned utilities and investors exposed to long-lived thermal assets, with potential spillovers to financial stability and public budgets. Health co-benefits of early retirement are documented

(Iyer et al., 2017), including reductions in particulate matter ($PM_{2.5}$), sulfur dioxide (SO_2), and nitrogen oxides (NO_x), which translate into lower rates of respiratory and cardiovascular disease. Renewable substitution scenarios demonstrate feasibility (Rissman et al., 2019), especially when supported by grid modernization, storage deployment, and declining levelized costs of solar and wind technologies. Empirical experience from accelerated transition frameworks under the Paris Agreement further illustrates that coordinated policy packages can maintain reliability while reducing emissions intensity. Regional cooperation mechanisms may accelerate progress (Teng et al., 2020), particularly through cross-border power trade, shared reserve margins, blended finance facilities, and technology transfer platforms. Such cooperation can reduce transition costs and address equity considerations among participating economies. Delayed action increases cumulative emissions pressure (Aklin & Urpelainen, 2013), amplifying both climate damages and the scale of future mitigation required, thereby reinforcing the urgency of near-term structural reforms in the power sector.

Baseline Emission Structure of Indonesian CFPPs

The baseline emission structure of CFPPs in Indonesia was calculated by aggregating unit-level data available in the GCPT dataset managed by GEM. This dataset records every CFPPs with a capacity of 30 MW or more, including installed capacity, operational status, and technical components of the plant such as boilers and turbines, which are released and updated twice a year (Global Energy Monitor, 2023a). In the GCPT methodology, unit-level information such as plant capacity and technical characteristics of combustion technology are used as basic parameters to estimate CO_2 emissions. Emissions calculations take into account the emission factor (amount of CO_2 per unit of fuel energy), heat rate (energy efficiency based on combustion technology), and capacity factor (ratio of actual electricity production to nominal capacity), which are combined to obtain emissions estimates for each unit (Global Energy Monitor, 2023b). All of this data is available for download on the GCPT website, which includes comprehensive metadata on each power plant, enabling structural analysis and comparison of emissions based on unit-level power plants in Indonesia (Global Energy Monitor, 2023c).

Table 3. Total cumulative CO_2 emissions (period 2026-2045)

No	Year	$MtCO_2$
1	2026	385.816
2	2027	771.633
3	2028	1,157.449
4	2029	1,541.452
5	2030	1,934.721
6	2031	2,324.989
7	2034	3,515.178
8	2035	3,913.084
9	2036	4,310.990
10	2037	4,901.286

11	2038	5,106.802
12	2039	5,504.708
13	2040	5,902.614
14	2041	6,300.520
15	2042	6,698.426
16	2043	7,096.332
17	2044	7,494.237
18	2045	7,892.143
19	2034	3,515.178
20	2035	3,913.084

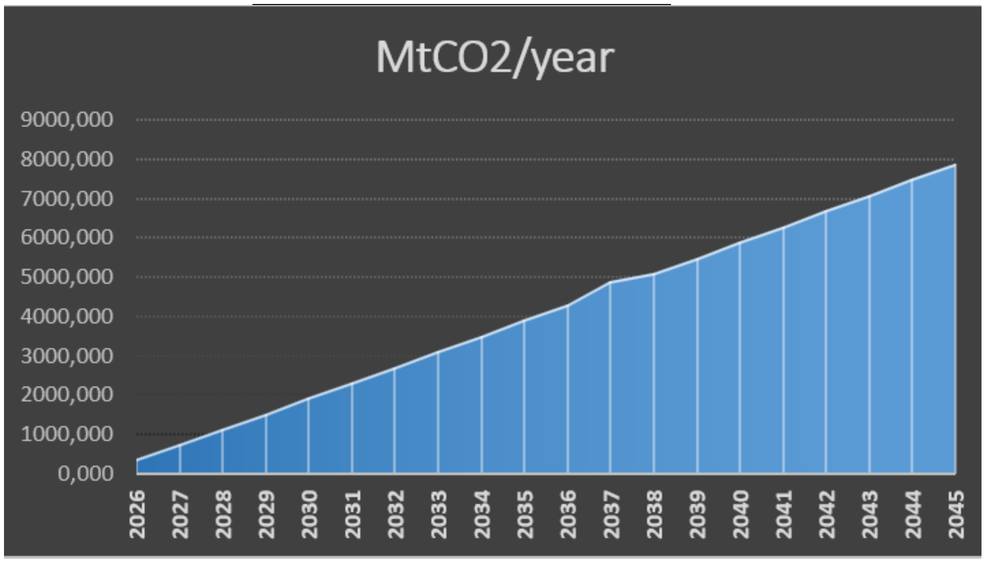

Figure. 1: Graph of Total Cumulative CO_2 Emissions (Period 2026–2045)

Table 4. List of COD for CFPPs after 2026

No	Unit Name/Capacity (MW)	COD	Owner
1	Kalselteng-3 Power Station/Unit 1/100	2029	PT Barito Pacific Tbk [100%]
2	Kalselteng-3 power station/Unit 2/100	2029	PT Barito Pacific Tbk [100%]
3	Jambi-1 power station/Unit 1/300	2030	PT PLN Indonesia Power [100%]
4	Jambi-1 power station/Unit 2/300	2030	PT PLN Indonesia Power [100%]
5	Kalselteng-4 Hybrid power station/Unit 1/100	2032	PT Barito Pacific Tbk [100%]
6	Kalselteng-4 Hybrid power station/Unit 2/100	2032	PT Barito Pacific Tbk [100%]
7	Sumatera Hybrid Power Station/Unit 1/600	2032	Independent Power Producer

			(unknown)
8	Sumatera Hybrid Power Station/Unit 2/600	2033	Independent Power Producer (unknown)
9	Parit Baru power station/Unit 1/50	2033	PT Praba Indopersada; China Gezhouba Group Co Ltd
10	Parit Baru power station/Unit 2/50	2033	PT Praba Indopersada; China Gezhouba Group Co Ltd

The figure and table above show that cumulative emissions from CFPPs in Indonesia up to 2045 will amount to 7,892.143 MtCO2 or around 7.9GtCO2 with a baseline emission in 2026 of 385.816 MtCO2 . Based on this data, the cumulative average for the 2026-2045 period is as follows

$$\boldsymbol{Emean} = \frac{\sum_{i=1}^{n} \boldsymbol{Ei}}{\boldsymbol{n}} \quad (8)$$

$$Emean = \frac{Ecum2045}{20} = 394{,}607$$

The results show that the average cumulative emissions for the period 2026-2045 are greater than the baseline in 2026. This is in line with the fact that several coal-fired power plants will only begin operating after 2026.

There are 10 new coal-fired power plants that will begin operating after 2026, two of which are the largest (Sumatera Hybrid power station). In June 2025, Indonesia released an updated electricity supply business plan (RUPTL 2025-2034). The document lists a 2 x 600 MW "hybrid" coal-fired power plant to be built by an independent power producer. The units are scheduled to start operating in 2032 and 2033. The RUPTL states that the Sumatera Hybrid power plant "can be executed as long as demand is available and in accordance with the provisions of Presidential Regulation 112/2022" [9]. The latest RUPTL 2025-2034 and national planning are still not in line with Indonesia's climate commitment to achieve NZE by 2060, as coal use is projected to continue at least until 2060. Although this has the potential to use carbon capture and storage (CCS) solutions, it could be a form of exploitation of a loophole in Presidential Regulation 112/2022, which allows new coal projects if they are deemed strategic and contribute to economic growth. Therefore, this requires serious scrutiny to determine whether these projects are truly national priorities or merely a backdoor way to build new coal- fired power plant capacity.

Emission Distribution Concentration

The results of the emission concentration distribution analysis show that the contribution of power plant emissions is not evenly distributed among units. This imbalance is in line with the characteristics of coal-fired power generation systems, where differences in installed capacity, capacity factor, thermal efficiency, operating age, and coal quality cause significant variations in emission intensity between units2). Quantitatively, this distribution imbalance can be analyzed using the CES approach. This method involves ranking power generation units based on their emissions from largest to smallest, then calculating the cumulative contribution of each unit to the system's total emissions.

This approach is conceptually similar to the principle of the Lorenz curve in distribution inequality analysis, which is widely used in economic and environmental studies to identify concentration of contributions within a population (Lorenz, 1905). In the context of the electricity sector, various studies show that a small number of power generation units often contribute a much larger proportion of emissions than other units. This phenomenon is known as the "high-emitter concentration" pattern, which indicates that priority-based mitigation policies, such as retrofitting emission control technology, improving efficiency, co-firing, or accelerating early retirement, will be more effective if focused on units with the largest cumulative contribution (IPCC, 2006). Thus, CES analysis not only describes the distribution structure of emissions between PLTU units but also provides an analytical basis for formulating more targeted and evidence-based decarbonization strategies, particularly in support of greenhouse gas emission reduction targets in the electricity sector.

Table 5 Top 20 Annual CO_2 Emissions CFPPs (2026-2045)

No	Unit Name/MW	COD	$MtCO_2$
1	Xinyi Group captive power station/2500	2026	12.229
2	Hongshi Silicon power station/2000	2026	9.783
3	Banten Suralaya power station/Unit 09/1000	2025	4.702
4	Banten Suralaya power station/Unit 10/1000	2025	4.702
5	Cilacap Sumber power station/Phase III Unit 4/1000	2019	4.702
6	Tanjung Jati B power station/Unit 5/1000	2022	4.702
7	Tanjung Jati B power station/Unit 6/1000	2022	4.702
8	Jawa-7 power station/Unit 1/991	2019	4.660
9	Jawa-7 power station/Unit 2/991	2020	4.660
10	Central Java Power Project/Unit 1/950	2022	4.467
11	Central Java Power Project/Unit 2/950	2022	4.467
12	Central Java Power Project/Unit 2/950	2023	4.345
13	Paiton-3 power station/815	2012	4.285

14	Paiton-2 power station/Unit 1/660	2000	3.918
15	Paiton-2 power station/Unit 2/660	2000	3.918
16	Paiton-1 power station/Unit 7/615	1999	3.651
17	Paiton-1 power station/Unit 8/615	1999	3.651
18	PLN Paiton Baru power station/Unit 09/660	2012	3.591
19	Banten Suralaya power station/Phase II Unit 1/660	1996	3.562
20	Banten Suralaya power station/Phase II Unit 2/600	1997	3.561

Approach is in line with the concentration curve analysis or pareto principle that the emission structure of a system is disproportionate, where a small number of entities often contribute a disproportionate share of the total overall impact of a system.

Baseline Projection Without Accelerated Retirement

In the baseline scenario without accelerated retirement, all CFPPs are assumed to operate until the end of their initial contract period without restrictions on capacity factors or additional policy interventions, so that the electricity generation structure continues to follow the applicable technical and contractual schedules; given that the technical life of CFPPs generally ranges from 30 to 40 years and many units were built in the 2010 - 2022 are still relatively young in operational terms, projections indicate that annual emissions will remain in the range of ±394,607 $MtCO_2$ per year in the early 2030s before declining significantly when these units naturally reach the end of their contracts, a pattern that reflects the effects of asset

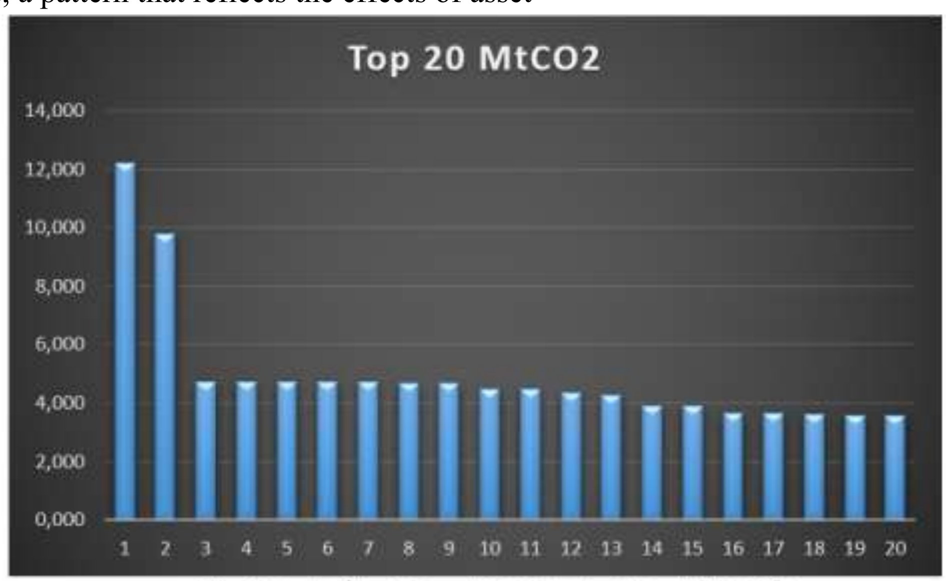

Fig. 2: Graph of Top 20 Annual CO_2 Emissions (Period 2026–2045)

From this data, it can be concluded that the distribution of CO_2 emissions from coal-fired power plants for the period 2026-2045 is uneven:

$$\boldsymbol{CES(k)} = \frac{\sum_{i=1}^{k} \boldsymbol{Ei}}{\sum_{i=1}^{n} \boldsymbol{Ei}} \qquad (9)$$

$$CES(k) = \frac{98{,}261}{394{,}607}\ x\ 100\% = 24{,}9\%$$

The results show that the 20 CFPPs with the highest CO_2 emissions out of a total of 318 units contributed 24.9% or 98,261 $MtCO_2$ of the total average emissions of 394,607 $MtCO_2$ in the period 2026–2045. This finding confirms that there is a concentration of emissions in a small number of units that contribute significantly. This aging rather than active decarbonization; these high emission levels are consistent with the carbon intensity of coal-fired power plants of around 0.8–1.0 tCO_2 per MWh as reported by the IPCC (IPCC, 2014) and in line with the findings of the International Energy Agency, which states that CFPPs without carbon capture need to be retired before 2040 to stay on track for 1.5°C (International Energy Agency, 2021). Without additional intervention, the emission trajectory risks remaining high until the final phase of the roadmap and is not in line with the objectives of the United Nations Framework Convention on Climate Change (UNFCCC, 2015). This simultaneously reinforces the phenomenon of carbon lock-in and increases the potential for cumulative emissions and stranded assets, meaning that structurally, Indonesia's coal-fired power plant system does not automatically follow an aggressive decarbonization path or, in other words, is based solely on contract age. This clearly requires active policy intervention to change the trajectory going forward.

CONCLUSION

This study finds that without accelerated retirement policies, Indonesia's CFPP fleet will generate substantial emissions—averaging 394.607 $MtCO_2$ annually between 2026 and 2045 and reaching 7.892 $GtCO_2$ cumulatively—while emissions are highly concentrated, with just 20 units contributing nearly a quarter of the total, highlighting the effectiveness of targeted mitigation. Although the national energy transition roadmap defines time-based phase-out milestones (2031, 2037, and pre-2055), it lacks quantified emission reduction targets and unit-specific retirement plans, making it time-consistent but not yet emission-consistent and creating ambiguity that risks a delayed, back-loaded transition. This is further compounded by persistent carbon lock-in from long-lived infrastructure and policy inconsistencies such as planned new coal capacity, which undermine alignment with NZE 2060 goals. Future research should focus on developing plant-level, emissions-based transition pathways that integrate explicit reduction targets, unit-specific retirement sequencing, and scenario modeling to evaluate the impact of targeted interventions and ensure a more transparent, measurable, and policy-consistent decarbonization strategy.

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