Technical Appendix

1.5°C-aligned coal power transition pathways in Indonesia: additional Strategies beyond the Comprehensive Investment and Policy Plan (CIPP)

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Emission Pathways

Business as Usual Scenario

The Business as Usual (BAU) scenario considers expected emissions from existing and future captive and on-grid power plants. For captive plants, we estimated emissions utilizing the latest data from the GCPT (2024) for operating and under-construction plants, assuming a capacity factor of 70% and plant retirement after 30 years of operation.

For on-grid plants, we estimated emissions for coal and gas-fired power plants. In the case of coal plants, the BAU scenario aligns with projected on-grid coal capacity from 2024-2030, as outlined in the CIPP report, assuming a capacity factor of 70%. After 2030, we used the data from the GCPT (2023) for operating and under-construction plants and assumed that coal plants retire after 30 years of operation, except for units that are co-firing biomass, which may have a longer operational lifetime and retire after 2040. For gas plants, we assume that emissions, which are based on the 2022 value estimated by Ember (n.a)[1], remain constant until 2050.

1.5-aligned Scenario

The 1.5-aligned scenario represents a high-ambition pathway in line with the global climate target of limiting the increase in temperature to 1.5℃. In this scenario, Indonesia aims to peak power sector emissions at 382 $MTCO_2$ by 2025 and achieve net-zero emissions by 2050. This goal encompasses emissions from both on-grid and captive power plants.

For the on-grid power system, the 1.5-aligned scenario sets a 2030 target of 230 $MTCO_2$, while the target for the captive segment in 2030 is 100 $MTCO_2$. This scenario assumes emissions will decrease linearly between 2030 to 2050, until reaching the 2050 target. For on-grid coal power plants, this scenario assumes emissions will reach zero by mid-century, while in the case of captive coal plants, emissions will decrease 76% when compared to the 2025 peak, but will not be completely eliminated, considering the challenges of decarbonizing these plants.

CIPP's Decarbonization Strategies for the On-grid Power Sector

The CIPP Business as Usual (BAU) scenario presented in the report results from estimating CO_2 emissions from existing and expected on-grid coal power plants. This estimation is based on the coal capacity provided by the CIPP report[2] (refer to Figure 1) and the capacity factor outlined in the CIPP scenario (70% in 2022)[2]. Additionally, we calculated power sector emissions using the methodology established by the Global Energy Monitor (2023)[3], using the emission parameters established for sub-bituminous coal plants, along with heat rates corresponding to the subcritical combustion technology. The CIPP report provides the basis for the CIPP target, as illustrated in Figure 2.

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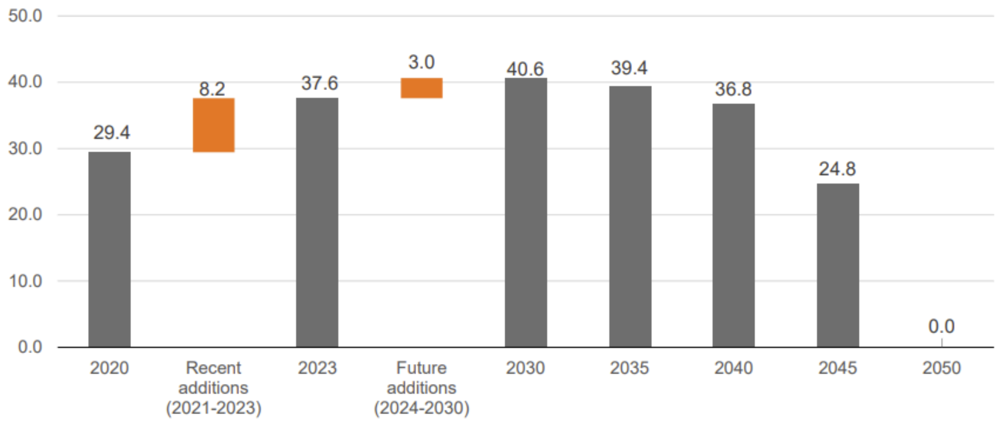
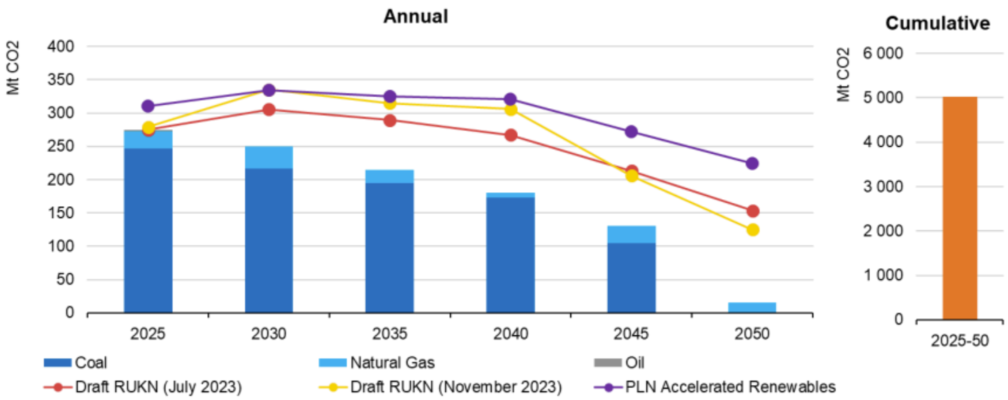
Figure 1. On-grid Coal Capacity (GW), CIPP Report



Source: CIPP (2023, p. 84)[2]

Figure 2. Power Sector Emissions Scenarios, CIPP Report



Source: CIPP (2023, p. 52)[2]

CIPP lower utilization and biomass co-firing reductions were estimated using the values and assumptions presented in the CIPP report. For the lower utilization reductions, emissions were estimated based on the coal capacity provided in the report (Figure 1), along with the capacity factors provided for the lower utilization strategy: 70% in 2022, 63% in 2030, and 50% in the early 2040s[2]. To estimate the reduction in emissions from biomass co-firing, we calculated a biomass co-firing ratio using the coal capacity presented in the report (Figure 1) and considered the expected contribution of bioenergy to the total energy mix by 2030, with 3% coming from biomass co-firing.[2]

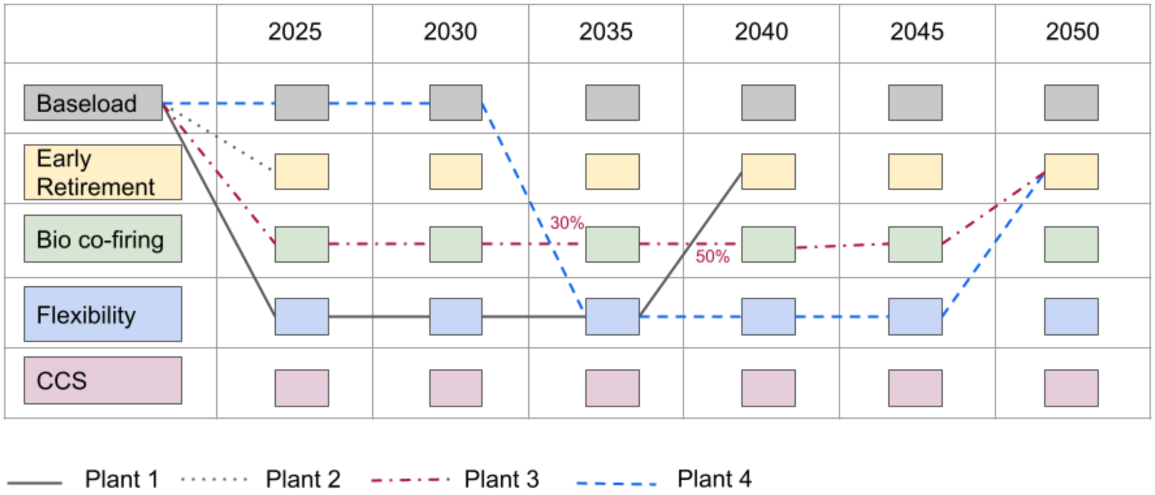
Plant-by-Plant Analysis for On-grid Plants

For the plant-by-plant analysis presented in this report, we used the Coal Global Plant Tracker (CGPT) data for Indonesia, published in January 2023.[4] We supplemented this data with updated information from PLN and other sources[5]. Overall, the on-grid dataset included information on 217 coal-fired units, detailing aspects such as installed capacity, year of operation, status, coal type, and combustion technology. This study only included plants currently operating or under construction.

Modeling methodology

The plant-by-plant analysis for on-grid coal power plants examines four strategies to reduce emissions from the power sector: i) early retirement, ii) biomass co-firing, iii) lower utilization, and iv) carbon capture and storage (CCS). We assessed each individual on-grid coal-fired power plant included in the CGPT database using different metrics and indicators to measure their suitability for each transition strategy. All strategies are mutually exclusive except early retirement. Although plants classified as low-hanging fruit for retirement are not considered for any other strategy, plants in the flexibility group, as well as biomass co-firing plants, can be early retired if necessary, to achieve the proposed emission targets.

Figure 3. Plant-by-plant Modeling Strategy



In the initial analysis period, after identifying the low-hanging fruit plants, we assessed biomass co-firing propensity. We ranked each unit, scoring them on ease of adoption of the co-firing strategy. Plants selected for this approach do not retire before 2040, and their capacity factor aligns with the trend proposed in the CIPP report (70% by 2022, 63% by 2030, and 50% from 2040 onward). We then assessed and ranked the remaining plants using flexibility criteria. Plants classified as flexible will experience lower utilization rates when emissions need to be reduced to meet the expected targets.

Lastly, we evaluated all CFPPs, excluding the low-hanging fruit units, using the CCS ranking criteria. Under the selected decision criteria for this strategy, we found only a few plants to be suited for CCS.

Decarbonization Strategies

Early Retirement Strategy

In the decarbonization analysis, we considered early retirement of CFFPs. In alignment with results found by Cui, R., et al. (2022), this report considered units identified as low-hanging fruit for early retirement.[6] The low-hanging fruit classification aggregates the scores from indicators including the technical attributes of CFPPs, their profitability, and their environmental impact. Units deemed as low-hanging fruit received scores lower than the median in each of the dimensions evaluated. The pace at which these coal units retire depends upon the emission reduction target, as well a

Table 1. Low-hanging Fruit Units

CFPP	Units	Capacity (MW)	Year	Retirement year
Asam-Asam power station	2	130	2000	2031
	2	65	2013	2031
Bangka Power Station	2	60	2014	2031
Banten Suralaya power station	1	372	1984	2031
	1	372	1985	2031
	1	372	1988	2031
	1	372	1989	2031
Bukit Asam Muara Enim power station	2	130	1987	2031
	2	130	1994	2031
Cilacap Sumber power station	2	562	2006	2031
Ombilin power station	1	91	1996	2031
	1	91	1997	2031
PLN Paiton power station	1	370	1993	2031
	1	370	1994	2031

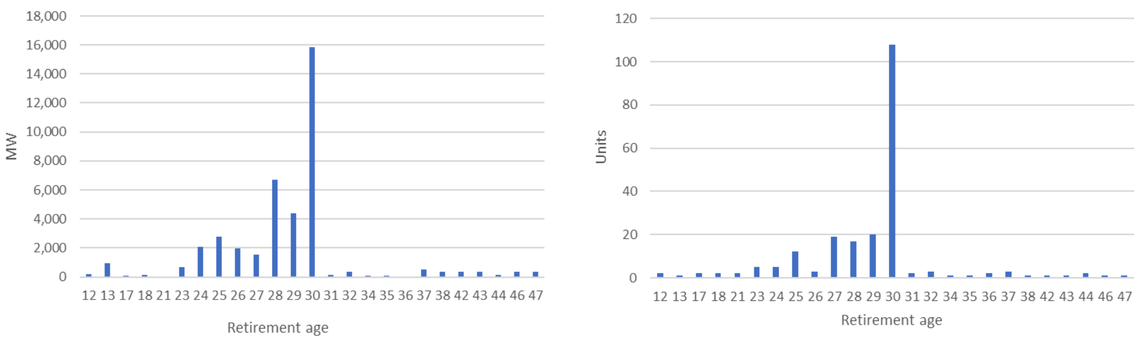
Tabalong power station	2	200	2019	2031
Tarahan power station	1	100	2007	2031
Total	23	3852		

Source: Cui, R., et al. (2022)

In addition to previously identified low-hanging fruit units, other units will face early retirement due to emission reductions required to achieve the 1.5-aligned scenario. Further early retirements will occur in later years, after retiring all low-hanging fruit units and repurposing all biomass co-firing coal plants. In this scenario, older units within the flexibility group with lower flexibility ranking scores become eligible for early retirement. Additionally, by 2050, units that are still operating and have less than 30 years of operation will be forced into early retirement.

The average age of retirement for all coal plants, including those proposed for early retirement, will be 28.9 years. Approximately 50% of units will retire at 30 years of operation, while only 3% of units will retire before reaching 20 years of operation. Regarding coal power capacity, 40% of existing and under-construction capacity will retire at 30 years of operation, with just 3% retiring before reaching 20 years.

Figure 4. Capacity and Unit Distribution by Retirement Age



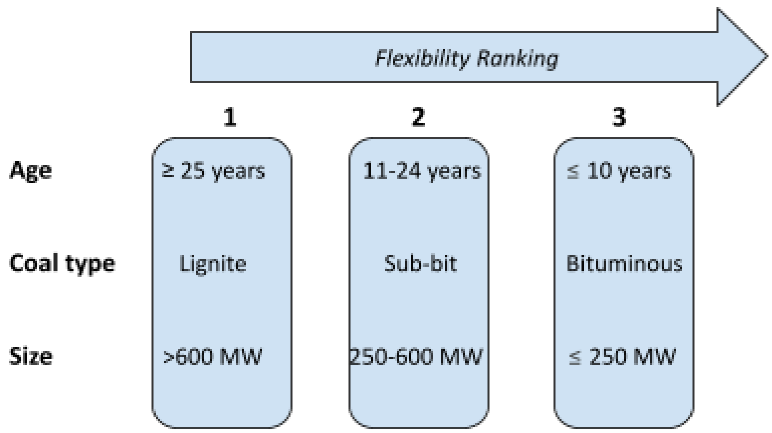
Flexibility or Lower Utilization Strategy

Coal Fired Power Plants (CFPPs) are usually designed to operate as a base load for most hours of the year.[7] However, it is possible to flexibilize their operation by enhancing their operational protocols or by retrofitting or upgrading their components and subsystems[7]. Overall, these technical transformations do not affect efficiency but can reduce plant lifetimes as a more flexible operation demands a higher use of the plant's components[7].

Flexibility solutions and costs depend on the unique characteristics and parameters of each power plant, mainly the minimum load, the start-up time, and the ramp rate[7]. However, some criteria make CFPPs more suitable for flexibility operation, such as age, coal type, and combustion technology or size. Considering this criteria, and using the data for Indonesia's coal power plants from the Global Coal Plant Tracker (GCPT, 2023), we created a flexibility ranking that shows which power plants are most able to provide flexibility services and as such can operate at a lower capacity.

The flexibility ranking considers the age of the unit and the size of the unit, as a proxy for the combustion technology (larger plants in Indonesia have ultra-supercritical and supercritical technology, while small plants have subcritical technology), and coal type. Newer plants receive higher scores, as retrofit costs are lower in these plants. In some cases, these plants reach flexible operation by adjusting their operational protocols without further investment[7]. Smaller plants in Indonesia also receive a higher score in the ranking. Although these plants have subcritical combustion technology, which is less efficient, the retrofitting costs for these plants are lower than for larger plants[7]. Finally, CFPPs that operate with anthracite and bituminous receive a larger score, as they show a greater propensity for flexibility than lignite-fired power plants, which are mainly designed for baseload operation. [7] We used data from the UNEP (2017)[8] to fill in missing coal type data, under the assumption that the coal type used in CFPPs is the same as the coal type extracted in the province where the plant is located. Although it would have been ideal to rank the power plants using more detailed operational parameters such as the ones mentioned above, this information is not public or available for power plants in Indonesia.

Figure 5. Flexibility Ranking Methodology



To calculate the final flexibility score for each coal power plant, we added each of the criteria scores together, weighting each criterion equally. We classified CFPPs with scores of 7, 8, and 9 as flexible plants, determining that they are able to operate at lower capacities than non-flexible plants. Flexible plants in emission reduction pathways will operate with capacity factors of 40%, 35%, and 30%, depending on the emission target, and the use of other strategies such as biomass co-firing and early retirement.

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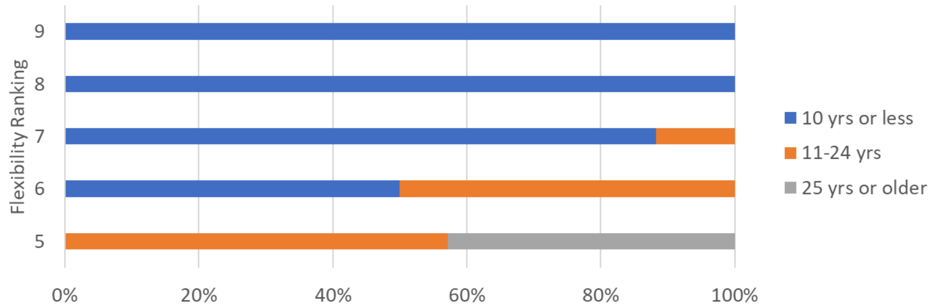
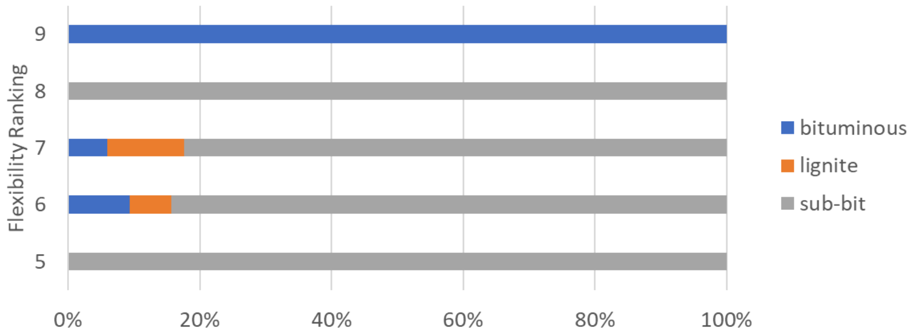
Table 2. Units and Installed Capacity by Flexibility Ranking Score

Total Score	Units	Distribution of Units	Capacity (GW)	Distribution of Capacity
5	7	8%	4.165	13%
6	32	35%	19.396	61%
7	17	18%	5.171	16%
8	34	37%	2.695	9%
9	2	2%	0.2	1%
Total	92		31.627	

We considered 92 of the 217 on-grid coal-fired power units listed in the 2023 GCPT data for the flexibility analysis. Units not considered included those already classified as biomass co-firing units or as low-hanging fruit, ready for early retirement. Of the 92 units analyzed, 61% scored 6, representing 61% of the total installed capacity within this group, while 37% scored 8, representing just 9% of installed capacity. Coal units with the highest score in the flexibility ranking represented 2% of total units and 1% of total capacity within the analysis group.

Figure 6. Distribution of Flexibility Ranking Score by age, coal type, and size





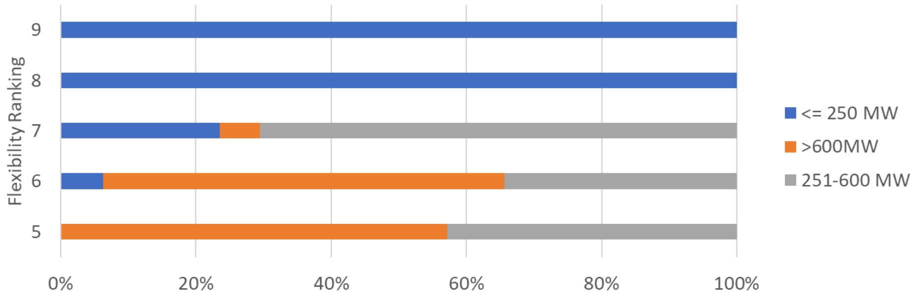


Figure 6 shows the distribution of flexibility ranking scores, considering the three criteria chosen for the analysis. As expected, newer, smaller units that operate with bituminous coal ranked higher for flexibility services, while older, larger units that operate with sub-bituminous coal scored lower in the ranking. Of the plants considered for flexibility, a large portion of plants have less than 10 years of operation (72%), around half of the plants studied have installed capacity equal to or lower to 250 MW (46%), and around 89% of the units considered in the flexibility analysis operate with sub-bituminous coal.

Biomass Co-firing

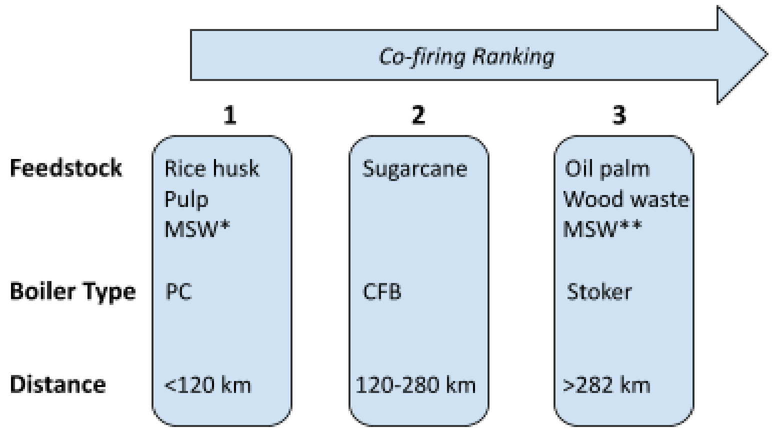
Another strategy for reducing coal plant emissions, biomass co-firing, utilizes existing coal plant infrastructure alongside adjustments in fuel input to achieve reductions. Under co-firing, plants incorporate biomass feedstocks with coal in boilers, reducing emissions approximately proportionately to the coal fraction replaced by biomass, on a thermal basis.[9] Given the risk of inducing deforestation when using biomass sourced from energy plantation forests,[10][1] we assume that existing biomass wastes (from processing facilities, agricultural fields, or the forestry industry) will supply feedstocks. Coal plants can co-fire at low biomass ratios with minimal technical retrofits, though at higher ratios, or depending on biomass type, coal boiler type, or co-firing method, investment costs may be greater.[11]

In our on-grid scenario, we implemented biomass co-firing at plants that display a propensity for this strategy. We gave each plant a score, ranging from 3-9, with 9 indicating the highest ease of implementation, and only selected plants ranked 7, 8, or 9 for co-firing. Scoring criteria include boiler type (pulverized coal (PC), circulating fluidized bed (CFB), or stoker), distance from the nearest

[1] Squire, C. Lou, J., Hilde, T. paper, forthcoming

biomass processing plant, and the type of feedstock processed at the nearest processing plant. Given relatively greater ease of co-firing within stoker plants, we ranked this boiler type highly, while we assigned PC plants, which have difficulty processing some feedstocks, the lowest score.[11] Biomass processing plants, including those for agricultural and industrial processing, produce waste by-products that can be utilized in co-firing and are already centrally gathered, unlike field-based or forestry-based residues. To represent available feedstocks we used processing plant data from OneMap.[12] Rankings for each feedstock type (rice husk, pulp, wood waste, sugarcane, municipal solid waste (MSW), and oil palm) vary based upon the calorific density of each feedstock type, which enhances ease of incorporation into coal boilers.

Figure 7. Biomass Co-firing Ranking Methodology



*MSW ranked 1 outside of Java due to complications processing feedstock.
**MSW ranked 3 within Java due to policies supporting waste-to-energy programs on the island.[5]

Table 3. On-grid Units and Capacity by Co-firing Ranking Score

Total Score	Units	Distribution of Units	Capacity (GW)	Distribution of Capacity
4	0	0%	0	0%
5	25	11%	7.6	19%
6	59	27%	13.7	34%
7	47	22%	15	37%
8	53	24%	3.9	10%
9	34	16%	0.3	1%

After ranking each plant on each of the three metrics, we summed scores per category to determine the overall score. We selected plants with scores of 7, 8, or 9 for biomass co-firing as an initial emissions reduction strategy. In addition, we included plants that have already begun testing or implementing co-firing.[13]

Biomass Co-firing Implementation

The JETP CIPP states that “bioenergy contribution to the energy mix in 2030 is 8%, with 3% coming from cofiring”, later noting that bioenergy provides 41.4 TWh of a total of 530.6 TWh of generation in 2030. Thus, under the CIPP we assume that approximately 15.9 TWh of generation comes from co-firing biomass with coal. We determined the biomass ratio to be applied at selected high-propensity coal plants by calculating the ratio needed at selected plants to reach 15.9 TWh of bioenergy generation by 2030, finding the necessary ratio to be 57.39%. The ratios selected reflect PLN co-firing goals [14] and CIPP ambition [2] (the on-grid segment co-fires at a ratio necessary to achieve the plan’s total co-firing target using a smaller fraction of the fleet). Operational plants [15] and literature [16–19] demonstrate that these ratios are technically achievable, though highly ambitious, and would require considerable investment and planning for biomass logistics..

Before 2030, we assume that plants gradually ramp up to co-fire at a rate of 57.39%. Starting at a biomass ratio of 5% in 2024, we linearly interpolate between the start year and the 2030 target.

After 2030, we enhance co-firing ratios to accelerate emissions reductions. Coal plants with CFB boilers continue co-firing at 57.39% biomass, while stoker plants ramp up their ratio to completely convert to biomass by 2035, linearly interpolating between 2030 and 2035 to reach that ratio.

Carbon Capture and Storage

In this analysis, we investigate the options for emissions reductions presented through the implementation of carbon capture and storage (CCS). We rank coal plants on the propensity for installation of CCS using factors such as capacity size, age of the plant, availability of space near the plant (measured through population density at the regency level), and distance from storage, based on previous in-country literature.[20] We find that very few plants meet the criteria for size - literature suggests that plants should have a capacity of at least 600 MW to be able to offset efficiency losses and be worth the capital cost - in particular when combined with the need for nearby storage basins. Projections indicate that much of the growth in capacity will occur within Central Sulawesi and North Maluku, which are approximately ~350-400 km from the nearest storage basins, one of which has limited capacity. We find the most ideal candidates for CCS implementation to be Adaro Aluminum Smelter Phase I power station, Bangko Tengah power station, Banjarsari power station, and Keban Agung power station, the latter three of which are all located in South Sumatra.

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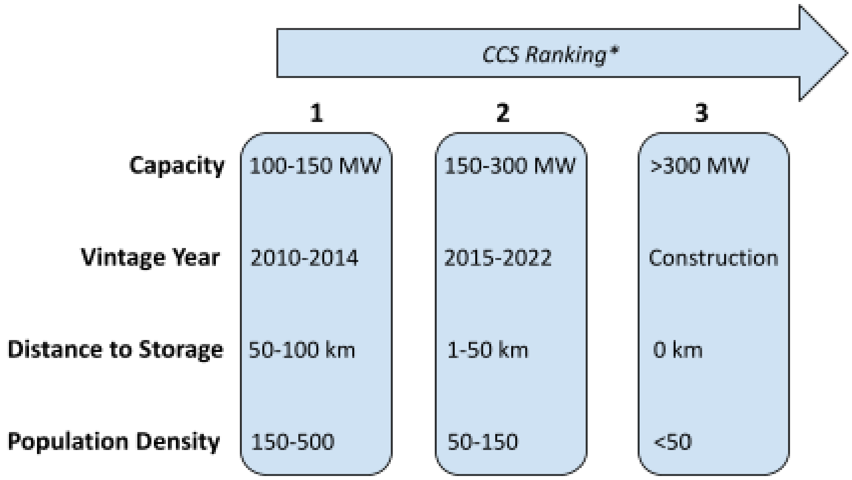
Figure 8. CCS Ranking Methodology



*Coal plants with the following characteristics are rejected outright: a capacity less than 100 MW, a vintage year from before 2010, greater than 100 km to the nearest storage, or a population density exceeding 500 people per km^2.

Table 4. High-scoring On-grid CCS Units

CFPP	Capacity by Unit (MW)	Vintage Year	Distance to Storage (km)	Population Density (per km²)	Final Score
Bangko Tengah power station Unit 1	600	Construction	0	82	11
Bangko Tengah power station Unit 2	600	Construction	0	82	11
Sumsel-1 power station Unit 1	300	Construction	0	44	11
Sumsel-1 power station Unit 2	300	Construction	0	44	11

Carbon Capture and Storage Implementation

The four selected plants begin implementing CCS in the year 2045. Based upon existing analysis of CCS in Indonesia, we assume that technology is capable of capturing 90% of the CO_2 released.[20]

Plant-by-Plant Analysis for Captive Coal Power Plants

For the plant-by-plant analysis of captive coal power plants, we used the Coal Global Plant Tracker (CGPT) data published in January 2024 for Indonesia.[21] The database includes information on 156 captive units, detailing installed capacity, year of operation, status, coal type, and combustion technology. We only included plants currently operating or under construction, assuming that plants in pre-construction phases will be canceled.

Biomass Co-firing

Among captive coal plants, we implement the same co-firing ranking system used to select on-grid plants. In addition to plants ranked 7, 8, or 9, we assume that all plants used in the pulp, paper, and textiles industries will co-fire,[422] given their ease of access to feedstocks.

Table 5. Captive Units and Capacity by Co-firing Ranking Score

Total Score	Units	Distribution of Units	Capacity (GW)	Distribution of Capacity
4	14	11%	4.5	23%
5	0	0%	0	0%
6	35	27%	1.9	10%
7	3	2%	0.2	1%
8	79	60%	13	66%
9	0	0%	0	0%

Biomass Co-firing Implementation

We assume that high-ranking plants begin co-firing in the first year of analysis, or, for those under construction, the first year of operation, co-firing at 30% among plants with CFB boilers. In 2035, we enhance co-firing ratios to 50%, except at plants supplying industries with substantial feedstock availability, such as pulp, paper, and textiles. At these plants, including nine pulp and paper units and two textiles units, we assume that full biomass conversion is undergone.

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Bioenergy with Carbon Capture and Storage

Table 6. High-scoring CCS Units

CFPP	Units	Capacity by Unit (MW)	Vintage Year	Distance to Storage (km)	Population Density (per km²)	Final Score
Adaro Phase I power station	1	1,100	Construction	0	12	12

Using the same ranking criteria utilized for on-grid plants, we scored captive plants on their ability to implement CCS. We found one suitable plant, which had already previously been selected for biomass co-firing.

Bioenergy with Carbon Capture and Storage Implementation

The selected plant begins implementing CCS in the year 2045. Given that Adaro Phase I co-fires at a ratio of 50% in that year, and under the assumption that technology is capable of capturing 90% of the CO_2 released, this plant provides negative emissions of 1.2 $MtCO_2$.

Renewable Substitution

Coal plants eligible for renewable substitution include plants installed in captive industrial parks that have publicly expressed interest in constructing renewable power plants[23]. We used announced renewable capacity to estimate coal capacity to be replaced, assuming that all renewable plants will utilize solar technology (capacity factor of 16%). We adjusted renewable capacity to ensure the replacement of entire coal units, as a lower utilization approach was not considered in this strategy.

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Table 7. Renewable Substitution Strategy

		Replaced Capacity (MW)								
		2030		2035		2040		Units retired		
	Total Capacity	Coal	Renewable	Coal	Renewable	Coal	Renewable	2030	2035	2040
PT Halmahera Persada Lygend Nickel Smelter power station	2240	60	259	570	2,463	570	2,463	2	6	6
Nanshan Industrial Park Power Station*	180	30	130	60	259	60	259	1	2	2
Weda Bay Power Station	3400	380	1,642	380	1,642	760	3,284	1	1	2
Sulawesi Labota power station	3,360	380	1,642	380	1,642	760	3,284	1	1	2
Sulawesi Mining power station	2,080	130	562	130	562	430	1,858	2	2	4
Total	11,260	980	4,235	1,520	6,568	2,580	11,148	7	12	16

Table 7 summarizes the results of this strategy. Renewable capacity in industrial parks continuously increases over time. However, even in 2040, when the strategy is at its most ambitious, only 22% of the coal capacity in these parks will be replaced by renewables. The scope of this strategy aligns with the technical attributes of renewable power plants and the electricity requirements of the industrial processes conducted in these parks. Though we selected older units for replacement, the average retirement age among plants is 13.3 years.

Grid Connection

Based on the identified investments for the transmission grid outlined in the Comprehensive Investment and Policy Plan (2023)[2], the grid connection strategy aims to reduce emissions from captive coal power plants by integrating them into the grid. The concept behind this is that by connecting these plants to the grid, the captive demand will be met with cleaner resources, and the connected coal capacity will eventually retire. In this analysis, the retirement for these plants is anticipated to occur in 2050.

The plants expected to be connected to the grid include units co-firing biomass in South, Central, and Southeast Sulawesi, providing electricity to mining activities, particularly nickel production. The selection of these plants is based on their distance to the planned grid infrastructure, according to the projects listed in the CIPP. Collectively, these plants contribute 4.8 GW (34 units) and retire at an average age of 28.8 when phased out in 2050.

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Early Retirement

Although early retirement is not a direct strategy to decarbonize captive coal power plants, as a consequence of renewable substitution and grid connection, some of these plants will face early retirement. Table 8 summarizes some of the main results. Overall, 14% of the plants eligible for retirement (20% of capacity) are still under construction; these plants retire after approximately 20 years. Operating plants facing early retirement make up the remaining 86% (80% of capacity), and retire after approximately 24.4 years of operation.

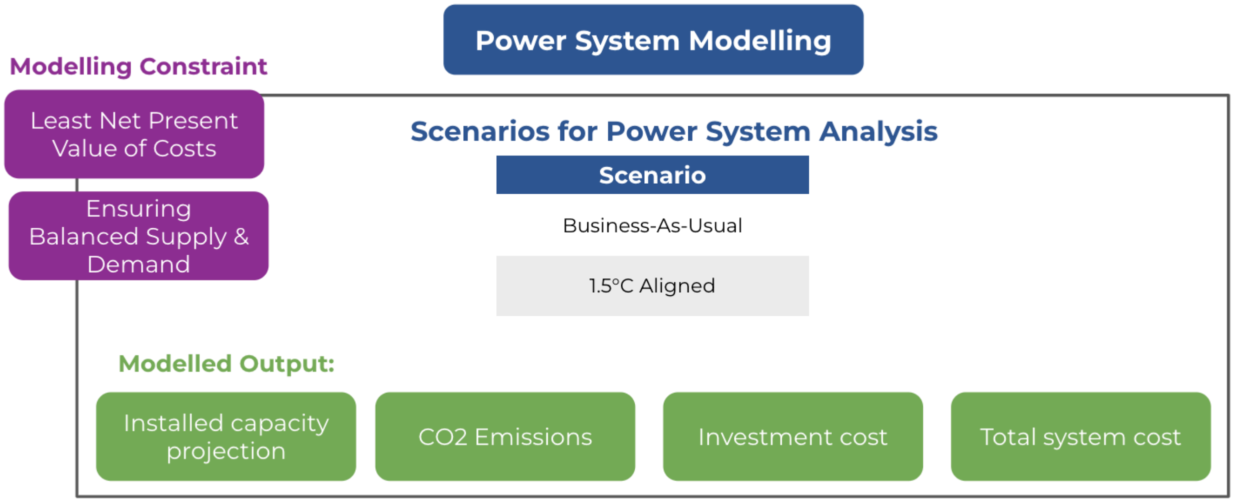
Table 8. Early Retirement of Captive Coal Plants by Region and Status

	Units	Capacity (MW)	Average Retirement Age
Construction	7	1560	20.3
Central Sulawesi	5	1350	24.2
North Maluku	2	210	10.5
Operating	43	5875	24.4
Central Sulawesi	15	2265	23.0
North Maluku	6	1120	11.7
Riau	2	60	11.5
South Sulawesi	1	30	32.0
Southeast Sulawesi	19	2400	30.5
Total	50	7435	23.8

System Operation Analysis

For the power system analysis, we used an industrial standard tool PLEXOS. Figure 9 provides an overview of the PLEXOS modeling framework used in this report. We carried out the techno-economic analysis using PLEXOS least-cost optimization to arrive at the most cost-optimal expansion pathway. The time window set for this modeling exercise is between 2022 and 2050. In addition, 2030 was selected to run the hourly dispatch calculation, i.e. Short Term (ST) mode, to evaluate the system performance, particularly its flexibility, due to some changes made in the generator's technical parameters, e.g. ramping rates, and technical minimum load. Electricity demand projection was made similar to the one used in the draft MEMR's National Electricity Planning (RUKN). Emissions were constrained in this modeling exercise following the trajectory of UMD's 1.5°C aligned pathway.

Figure 9. PLEXOS Modeling Framework



Two scenarios were carried out, namely Business-As-Usual (BAU) and 1.5°C Aligned (1.5 Aligned). Table 9 provides a more detailed description of each scenario. For certain technical parameters in both scenarios, we adopted information available in PLN's RUPTL 2021-2030.

Table 9. Scenarios Run With PLEXOS

Technical Parameters	BAU	1.5 Aligned
Electricity grid	Transmission aligned with RUPTL to 2030; interconnection between large islands starting in 2030	
Coal power additions	Committed projects in RUPTL; none thereafter	
Coal power retirement	Natural retirement	Natural retirement
		Early retirement option by cost
		Several LHF CFPP retired by 2031

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Gas power additions	Committed projects in RUPTL; still allowed to build beyond 2030	Committed projects in RUPTL; none afterwards
Dispatchable renewable power additions	Committed projects in RUPTL + additional capacity expansion from 2031	Committed projects in RUPTL + additional capacity expansion from 2025
Variable renewable power additions		
Biocofiring	None	Following UMD recommendation
CFPP flexible operation	None	Following UMD recommendation

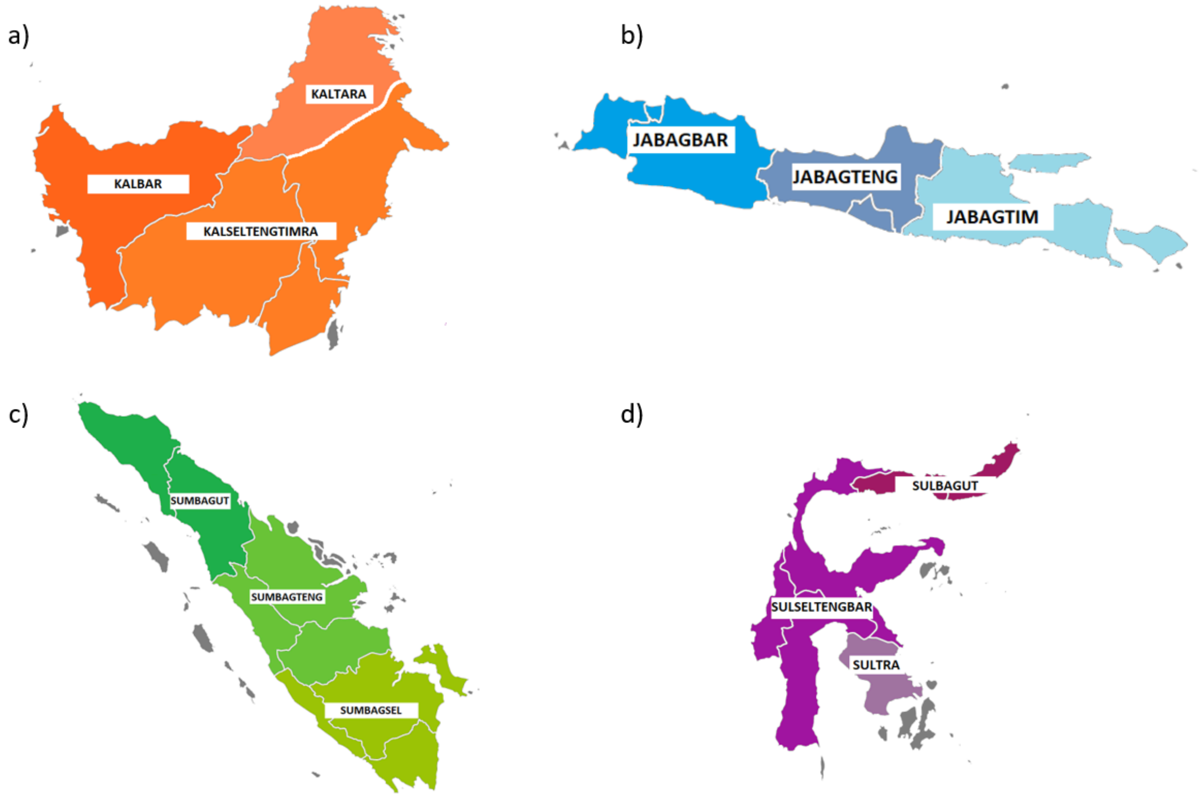
Methodology and Assumptions

On-grid Power System Topology

The Indonesian power system is modeled by decomposing it into seven regions, i.e. Java, Sumatra, Kalimantan, Sulawesi, West Nusa Tenggara, East Nusa Tenggara, Maluku, and Papua as illustrated in Figure 13. Each region consists of several nodes:

- Java-Bali system nodes: West, Central, and East (based on control regions of PLN)
- Sumatra system nodes: North, Central, and South (assumed)
- Kalimantan system nodes: North, Central-South-East, and West (assumed)
- Sulawesi system nodes: North, Central-South-West, and Southeast (assumed)
- The remaining regions, i.e. Nusa Tenggara Timur (NTT), Nusa Tenggara Barat (NTB), Maluku, and Papua, will have each node to represent each island due to the unavailability of island interconnections at the moment.

Figure 10. Power system representations: a) Java-Bali, b) Sumatra, c) Kalimantan, and d) Sulawesi



Fuel Costs

Table 10. List of Fuel Costs Assumed for the Simulation

Fuel	Price
Coal	70 USD/tonne
Gas Pipeline	6 USD/MMBTU
LNG	12 USD/MMBTU
Diesel Oil	81 USD/barrel
Biomass	70 USD/tonne

Fuel price is a key assumption in power system modeling as it determines the optimal cost between maintaining current power plants (including coal plants) against new investment in RE. The scenarios presented in the report assume prevailing regulation that favors and provides low-cost fuel to fossil fuel power plants.

The current price for domestic coal sales is based on the government's monthly reference export price for high-quality coal—the Harga Batubara Acuan (HBA), which corresponds to a calorific value of 6,322 kcal/kg (gross as received) - and is capped at USD 70/tonne.

The price of Gas is based on the Kepmen ESDM no 118.K_MG.04-MEM.M-2021, whereby the gas price at the plant gate. is limited to 6 USD/mmbtu. Biomass price follows PLN's Presidential Instruction, Perdir PLN 04/2022, which quantifies the price based on the ratio to coal calorific value.

On-grid Coal Plants' Retirement Costs

$$P = A\,\frac{(1+i)^{(N0-N1)}-1}{i(1+i)^{(N0-N1)}}$$

A = Annualize investment[2] cost PLTU

$N0$ = Natural Retirement[1]

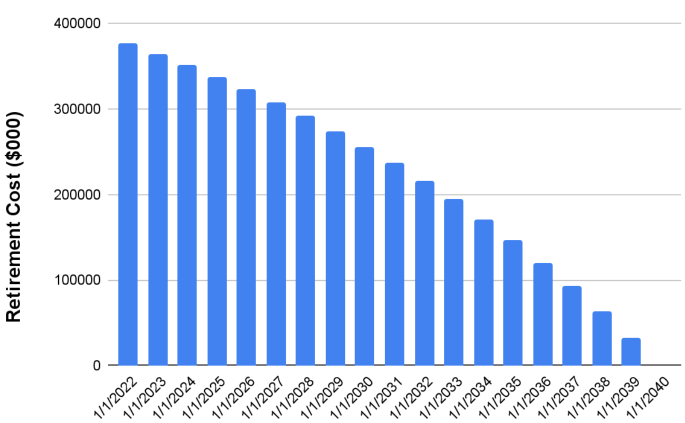
$N1$ = Accelerated time

i = Discount rate

P = Present value of additional cost for retirement

The early retirement of the coal fleet demands additional investments to compensate the unit's owner. Such cost is modeled by calculating the cost as the present value of unpaid depreciation of the total investment costs at a certain year of retirement. This cost is included in the total system cost and optimized in the modeling process.

Figure 11. Example of Estimated Coal Plant Retirement Cost



Technical Parameter per Technology

The power system modeling considered the technical parameters of the MEMR technology catalog, for different generation technologies.

Table 11. Technical Parameters from the MEMR Technology Catalog used in Plexos Modeling

Generator	Max Capacity (MW)	Min Stable Level	Efficiency	Ramping rate (%/min)	Build Cost ($/kw)	FOM Charge ($/Kw/Year)	VO&M Charge ($/MWh)	Technical Lifetime (Years)	Construction Time (Years)
CFPP	150	40%	35.00%	4	1880	51.6	1.5	30	3
OCGT	40	40%	38.00%	20	1120	26.5	3.6	25	1.5
CCGT	100	45%	57.00%	20	1090	26.8	2.6	25	2.5
Biogas	1	20%	38.00%	20	2450	110	0.13	25	1.5
Biomass	25	30%	35.00%	10	2280	54	3.4	25	2
Waste	22	20%	35.00%	10	5970	277	27.5	25	2.5
Hydro	60	0%	N/A	30	2200	43	0.74	50	4
Micro-Hydro	0.5	0%	N/A	50	2700	60.4	0.57	50	2
Geothermal	55	80%	N/A	3	4400	110	0.27	30	2
Wind Turbine	3.5	N/A	N/A	N/A	1650	40	0	27	1.5
Solar PV	50	N/A	N/A	N/A	960	7.5	0	27	0.5

1.5°C-aligned coal power transition pathways in Indonesia

Generation Projection per Region in Indonesia

The figures below present the projected generation for each region in Indonesia, segregated according to the on-grid power system topology explained above, for the 1.5°C Aligned scenario. By 2050, solar generation is expected to play a significant role in most regions, except Kalimantan, where most generation will come from hydropower. Hydropower also plays a significant role in other regions such as Sumatra and Sulawesi. In all regions, coal generation will be phased out by 2050. However, the pace of coal retirement will vary among regions, considering factors such as demand and the availability of renewable resources.

Figure 12. Java - Bali Generation Projection

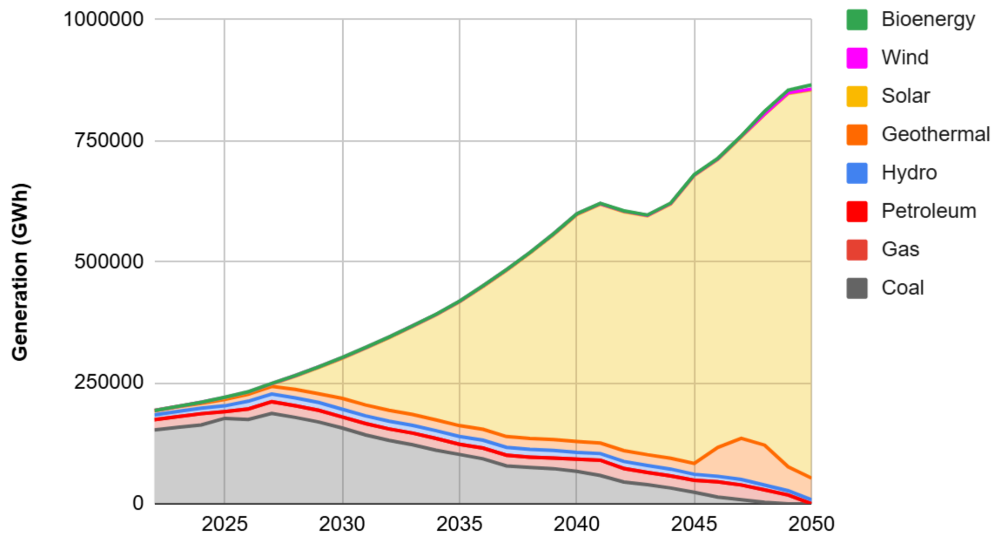


Figure 13. Sumatra Generation Projection

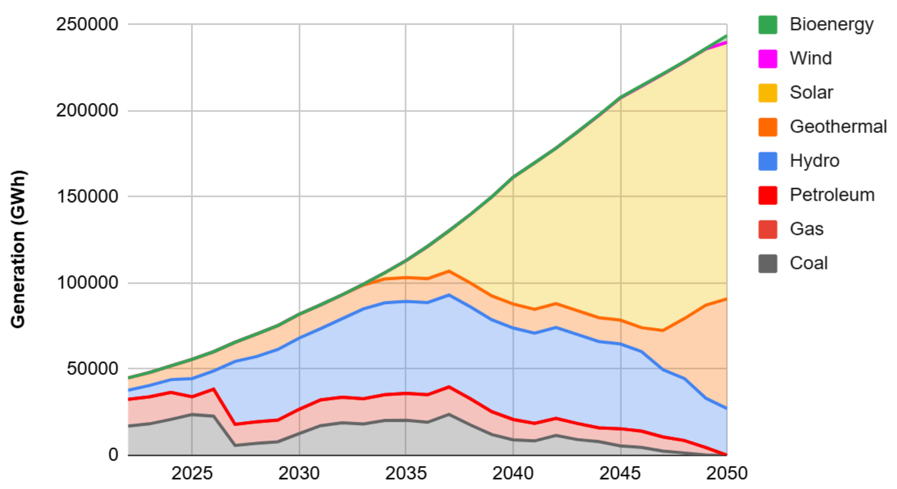


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Figure 14. Kalimantan Generation Projection

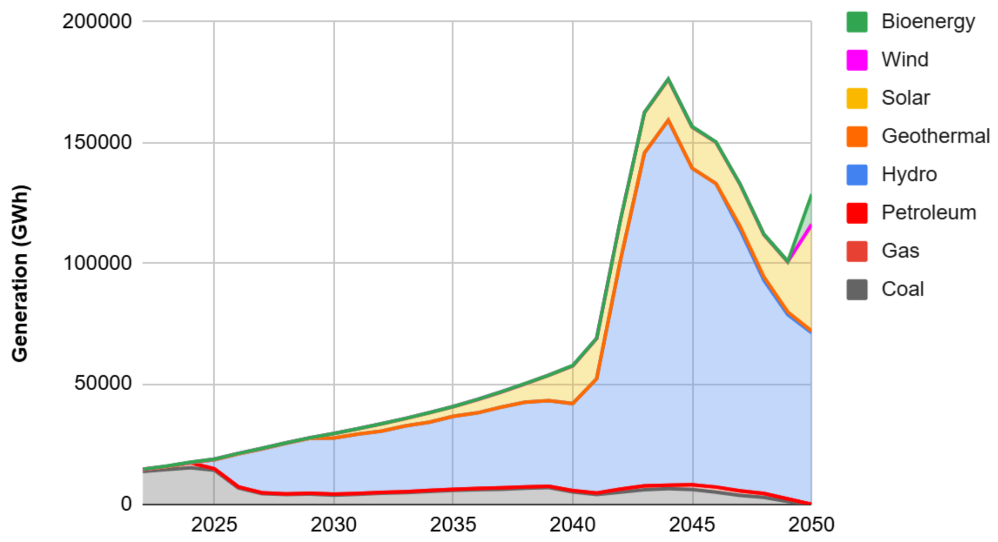

Figure 15. Sulawesi Generation Projection

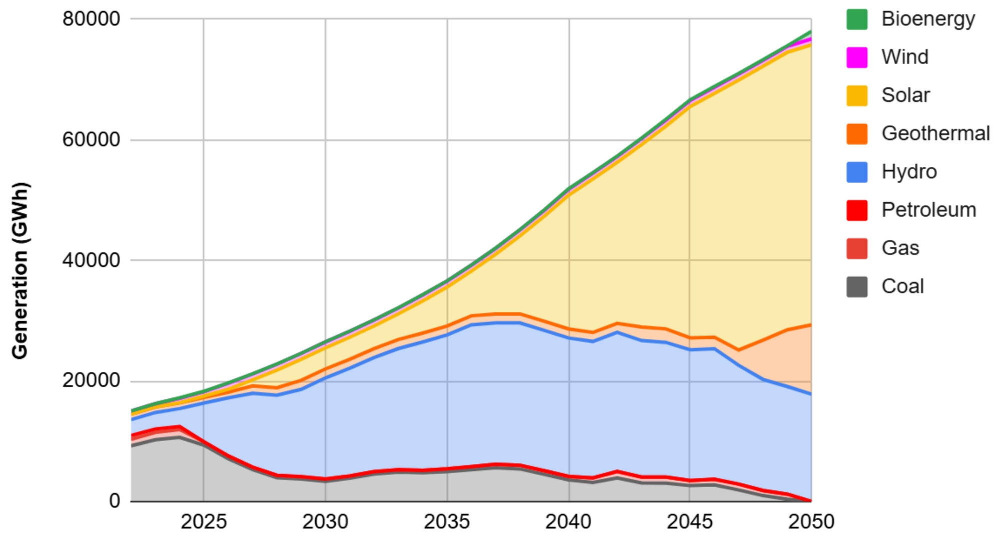

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Figure 16. NTT Generation Projection

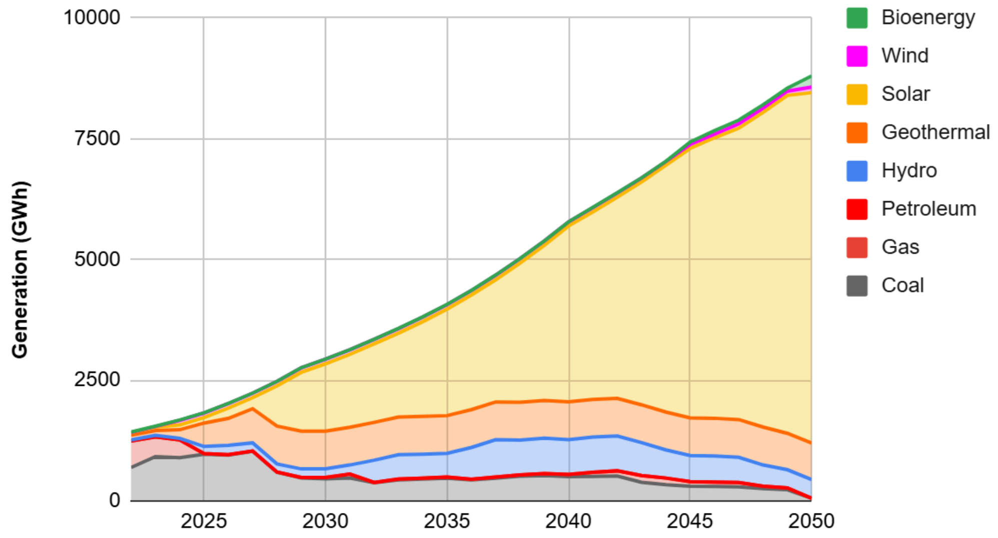
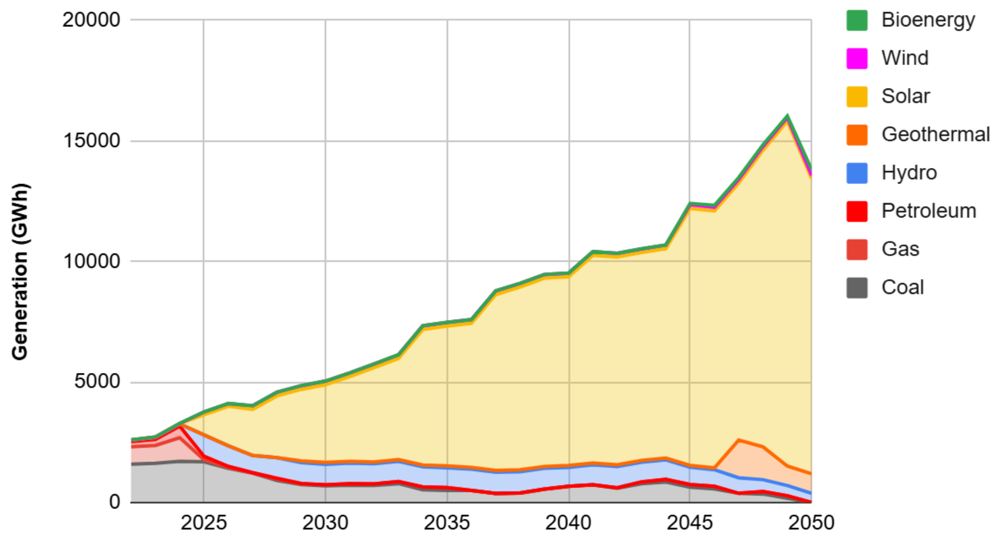


Figure 17. NTB Generation Projection



1.5°C-aligned coal power transition pathways in Indonesia

Figure 18. Maluku Generation Projection

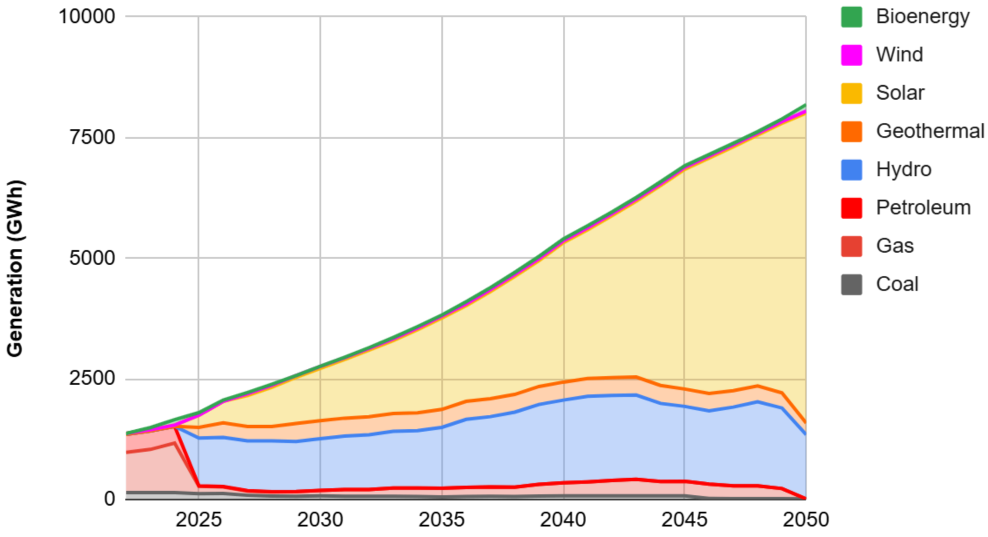
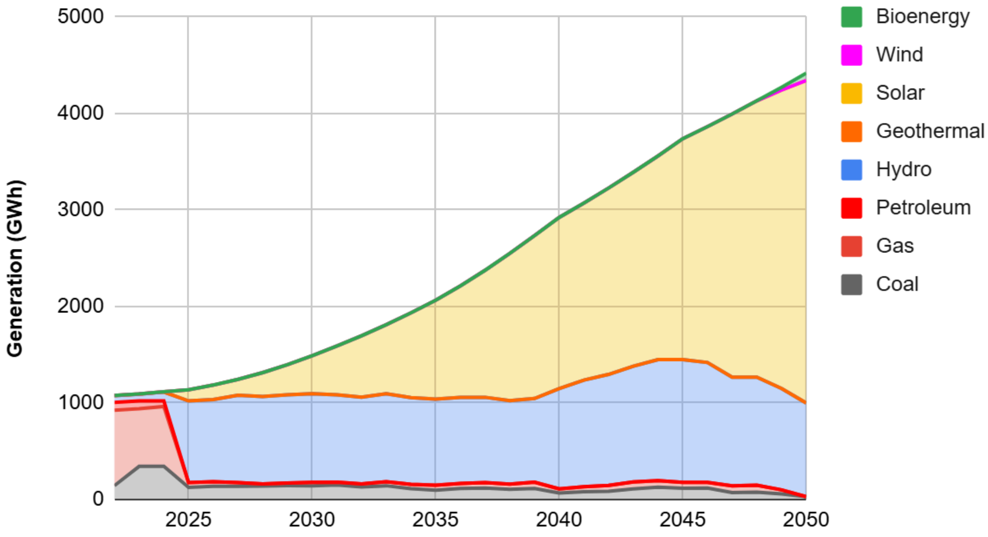


Figure 19. Papua Generation Projection



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