International Journal of Sustainable Energy Planning and Management Vol. 47 2025 43–56

International Journal of
Sustainable Energy Planning and Management

Strategies Toward Energy Transition in Indonesia: An Assessment of Multi-Regional Biomass Supply for Coal Co-Firing Power Plants

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ABSTRACT

Coal remains the dominant source of electricity generation in Indonesia, accounting for around 55% of installed capacity. As a fossil fuel, coal contributes significantly to greenhouse gas (GHG) emissions, posing a challenge to Indonesia's commitment to the Paris Agreement. Biomass co-firing in coal power plants offers a promising pathway to reduce GHG emissions. However, sustainable biomass supply is a major challenge due to Indonesia's archipelagic geography, which causes regional disparities in power capacity, fuel types, and biomass potential. This study assesses the potential of multi-regional biomass supply in relation to emission reduction targets, using secondary data for provincial biomass waste inventories was assessed. The Low Emissions Analysis Platform (LEAP) model projects coal demand from 2025 to 2045 under two scenarios: business as usual (BAU) and biomass co-firing (BCF) with biomass shares of 5%, 10%, and 15%. Findings show that municipal and industrial waste alone cannot sustain long-term co-firing at the national level. Therefore, multi-regional supply-demand analysis is essential. Provinces such as Riau, North Kalimantan, Central Kalimantan, West Kalimantan, Papua, Bangka Belitung Islands, and Jambi are identified as surplus regions. A 15% biomass co-firing scenario could reduce emissions by 108 Mt of CO_2 by 2045 and lower emission intensity nationwide.

Keywords

Biomass Supply-Demand;
Coal Co-Firing Power Plant;
Multi Regional;
Energy Transition

http://doi.org/10.54337/ijsepm.10514

1. Introduction

Indonesia's power sector plays a strategic role in supporting national economic development, industrial growth, and improving public welfare. In 2023, electricity consumption reached 288 TWh, with per capita electricity use recorded at 1,035 kWh/person [1]. This per capita consumption remains relatively low compared to other countries; for example, India reached 1,377 kWh/person, while the United States recorded 12,497 kWh/person in the same year [2]. Electricity demand is expected to continue rising in line with economic and population growth [3]. To meet this growing demand, Indonesia had a total installed power generation capacity of 91.1 GW in 2023. The greatest portion of this capacity is dominated by coal power plants, accounting for 55%, followed by natural gas (25%), renewable energy (15%), and diesel (5%) [4]. However, the continued use of coal as a fossil fuel presents a major challenge due to its significant contribution to greenhouse gas (GHG) emissions.

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Received 16.07.2025 | Accepted 12.11.2025 | Published 10.12.2025

List of Abbreviations

AR	adequacy ratio
BAU	business as usual
BCF	biomass co-firing
BPS	Statistics Indonesia
CFB	circulating fluidized bed
CO_2	carbon dioxide
DI	Special Region
DKI	Special Capital Region
EFB	empty fruit bunches
GDP	gross domestic product
GHG	greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
IPP	independent power producers
IUPTLS	entities holding business licenses for own-use electricity supply
KESDM	Ministry of Energy and Mineral Resources
LEAP	Low Emissions Analysis Platform
MF	mesocarp fibre
NDC	Nationally Determined Contribution
PC	pulverized coal
PLN	State Electriciy Company
PPU	public-private utilities
RDF	refuse-derived fuel
RUPTL	electricity supply business plan
UNFCCC	United Nations Framework Convention on Climate Change

The Government of Indonesia has committed to reducing GHG emissions under the Paris Agreement. As part of this commitment, the government is required to periodically report its GHG mitigation efforts to the UNFCCC. The most recent report was submitted in 2022 as the Enhanced Nationally Determined Contribution (Enhanced NDC). As stated in the Enhanced NDC, Indonesia aims to reduce GHG emissions by 31.89% below the business-as-usual (BAU) level by 2030 through unconditional efforts and up to 43.20% with international support [5]. Achieving these targets can be partially accomplished through the increased integration of renewable energy in electricity generation. One promising approach is the utilization of biomass for co-firing in coal power plants [3]. The use of biomass for energy transition in electricity generation has also been implemented in other countries [6].

Indonesia's biomass co-firing program was initiated in 2019 through trial projects conducted by the state electricity company, PT PLN (Persero) as part of the country's energy transition efforts [7]. Since then, the program has expanded, and by 2023, co-firing had been implemented in more than 40 coal power plant units, with biomass blending ratios ranging from 1% to 5% of total fuel input. Co-firing is part of a broader fuel-switching strategy aimed at reducing carbon emissions and supporting the achievement of the national energy mix targets. Several studies have examined various aspects of co-firing implementation. Novendianto et al. [8] highlighted technical challenges, particularly slagging and fouling caused by alkali and silica content in biomass, which can lead to deposits on boiler surfaces. Hussain et al. [9] discussed the risks of corrosion and abrasion due to volatile chlorine and alkali compounds that may damage metal surfaces in combustion systems. Environmental impacts are also a key focus, with co-firing shown to reduce GHG emissions [10] and, in some cases, decrease NO_x and SO_x emissions depending on the biomass type and combustion parameters [11].

Economically, co-firing offers fuel cost savings if local biomass is available at competitive prices, although initial investment is needed for modifications to fuel handling and combustion systems [12]. Policy support plays a critical role, with fiscal incentives, emission standards, and recognition of biomass as a renewable energy source being essential for successful implementation [7]. From a technical perspective, biomass co-firing ratios can gradually increase to 10–30% and potentially reach 100% in retrofitted power plants designed for full biomass combustion [3].

The co-firing program is not only a technical solution for reducing GHG emissions but also a critical strategy in supporting the national energy transition toward renewable energy utilization. However, the success of this program is highly dependent on the distribution and sustainable availability of biomass supply. This is particularly challenging in an archipelagic country like Indonesia, which faces significant geographical and resource disparities. Utilizing locally sourced biomass can reduce dependence on imported fossil fuels while strengthening energy security and self-sufficiency across regions. This paper introduces a novel approach by analyzing the multi-regional biomass supply potential, an aspect that has been relatively underexplored in previous studies. The novelty of this research lies in its provincial-level mapping of biomass resources to support the sustainable and more evenly distributed implementation of biomass co-firing in coal power plants throughout Indonesia.

2. Data and Methodology

This study utilizes secondary data obtained from various official sources, including Ministry of Energy and Mineral Resources (KESDM), Statistics Indonesia (BPS), and national energy policy documents containing biomass potential inventories. The available data are largely presented in detail at the provincial level. The Government of Indonesia enacted Law No. 23/2014 on Regional Governance, granting greater authority to local governments to manage their own administrative affairs. As part of the implementation of this law, regional expansion was carried out in 2022, increasing the number of provinces in Indonesia to 38 [13]. This expansion is expected to improve the quality of public services and accelerate regional development.

2.1. Biomass potential data

Biomass potential data are essential for assessing the availability and feasibility of utilizing biomass as a renewable energy source. This potential is commonly classified into three levels: theoretical, technical, and economic [14,15]. Theoretical potential refers to the maximum amount of energy available from all biomass sources, without accounting for technological or economic constraints. Technical potential narrows this estimate by considering the portion that can be practically utilized using existing technologies, factoring in energy conversion efficiency as well as limitations in collection and processing. Economic potential further refines the estimate to represent the share of technical potential that is financially viable, based on operational costs and the market value of the generated energy. All three levels of potential are critical for informing the design of sustainable and efficient energy policies.

The types of biomass considered in calculating biomass potential include agricultural residues, forestry residues, industrial waste, and municipal solid waste. By collecting data on annual volumes and geographical distribution, the multi-regional biomass supply potential can be mapped, reflecting the variability of biomass resources across different regions of Indonesia. Singangunsong et al. [16] estimated the bioenergy potential from forest harvesting residues (natural productive forests and industrial forest plantations) and wood processing residues (sawn wood, plywood, veneer, and chipwood) in Indonesia in 2013, with a total potential of approximately 132 PJ. Rhofita et al. [17] analyzed Indonesia's bioenergy potential focusing on biomass waste from the agriculture and forestry sectors, estimating a total energy potential of more than 1,261 PJ per year. The main commodities contributing the highest energy potential include rice straw, corn cobs, oil palm residues (empty fruit bunches, shells, fibres), and wood waste. Hardhi [18] assessed biomass potential for power generation, including agricultural residues (rice straw and corn cobs), oil palm plantation waste (empty fruit bunches and shells), wood waste, and organic municipal waste. Biomass potential was identified across all provinces.

The existing data and discussion remain at the level of theoretical potential, with some approaching technical potential. The biomass potential reported by KESDM [19] is more detailed at the provincial level and can be categorized as technical potential.The regional scope of discussion in this paper is defined at the provincial level. In this case, biomass waste is estimated based on data from industries that are already utilizing it, rather than from agricultural harvest yields. The overall potential is presented in Table 1 [19]. This potential represents an existing capacity of 279.62 PJ per year, which is expected to provide a sustainable biomass supply.

The largest biomass potential comes from industrial waste of the palm oil industry, with a total potential of 170.51 PJ, followed by municipal waste (93.93 PJ), industrial waste from pulp and paper (5.95 PJ), paddy (5.35 PJ), sugar (3.33 PJ), and wood (0.54 PJ). Municipal waste for this purpose is processed physically into refuse-derived fuel (RDF) [20]. This waste still faces challenges in household segregation, resulting in relatively high costs to produce RDF. Biomass waste from the palm oil industry includes shells, trunks, mesocarp fibre (MF), fronds, and empty fruit bunches (EFB) [21]. Some types of waste, such as EFB, are already traded on the international market, so not all can be allocated for co-firing purposes. The pulp and paper industry generates various forms of waste in solid, gaseous, and liquid states. Solid waste can originate from raw material handling, screening and cleaning residues, and sludge from wastewater treatment systems [22]. Paddy processing produces a significant amount of solid waste (mainly husks, rice husk ash, bran, and straw) as well as liquid waste [23]. These solid wastes can be further processed into fuel. Sugar industry waste that can be utilized as

Table 1. The biomass potential in Indonesia by region in 2023.

No.	Province	Municipal Waste (PJ/year)	Industrial Waste (PJ/year)					Total (PJ/year)
			Palm Oil	Pulp and Paper	Paddy	Sugar	Wood	
1	Aceh	0.78	5.05	-	0.36	-	-	6.19
2	North Sumatra	4.85	18.07	0.15	0.06	0.05	0.01	23.18
3	West Sumatra	2.10	3.22	-	0.04	-	-	5.36
4	Riau	3.72	49.81	3.00	0.03	-	0.00	56.56
5	Jambi	1.12	8.74	0.65	-	-	0.04	10.56
6	South Sumatra	3.51	12.97	1.57	0.05	0.15	-	18.26
7	Bengkulu	0.48	3.71	-	-	-	-	4.19
8	Lampung	1.55	2.59	-	0.06	0.82	0.00	5.03
9	Bangka Belitung Island	0.54	3.50	-	-	-	-	4.03
10	Riau Island	1.89	-	-	-	-	-	1.89
11	DKI Jakarta	4.23	-	-	-	-	-	4.23
12	West Java	13.56	0.20	0.07	1.12	0.11	-	15.07
13	Central Java	14.55	-	-	0.20	0.39	0.07	15.20
14	DI Yogyakarta	2.07	-	-	-	-	-	2.07
15	East Java	16.44	-	0.09	2.55	1.56	0.07	20.72
16	Banten	4.01	0.24	0.08	0.04	-	0.01	4.38
17	Bali	1.99	-	-	-	-	-	1.99
18	West Nusa Tenggara	0.92	-	-	0.02	0.12	-	1.05
19	East Nusa Tenggara	0.36	-	-	-	-	-	0.36
20	West Kalimantan	1.64	15.77	-	-	-	0.01	17.42
21	Central Kalimantan	2.97	18.37	-	0.02	-	0.02	21.38
22	South Kalimantan	1.72	6.13	-	-	-	0.02	7.87
23	East Kalimantan	2.07	15.12	0.34	-	-	0.16	17.69
24	North Kalimantan	0.32	1.18	-	-	-	0.01	1.50
25	North Sulawesi	1.34	-	-	-	-	-	1.34
26	Central Sulawesi	0.85	0.95	-	-	-	-	1.80
27	South Sulawesi	2.06	0.29	-	0.75	0.10	0.01	3.21
28	Southeast Sulawesi	0.75	0.43	-	-	-	-	1.18
29	Gorontalo	0.45	-	-	-	0.05	-	0.49
30	West Sulawesi	0.25	1.56	-	0.05	-	-	1.86
31	Maluku	0.29	-	-	-	-	0.01	0.30
32	North Maluku	0.15	-	-	-	-	-	0.15
33	West Papua	0.12	0.27	-	-	-	0.02	0.41
34	Southwest Papua	0.08	0.18	-	-	-	0.01	0.27
35	Papua	0.05	0.57	-	-	-	0.02	0.65
36	South Papua	0.08	0.82	-	-	-	0.03	0.92
37	Central Papua	0.04	0.42	-	-	-	0.01	0.48
38	Papua Mountains	0.03	0.35	-	-	-	0.01	0.40
Indonesia		93.93	170.51	5.95	5.35	3.33	0.54	279.62

Note:
- Calculated based on data from KESDM [18] by converting from MWe (MW electric) to PJ. Assuming the operating time of the generator is 8000 hours per year and the conversion factor is 1 GWh = 0.0036 PJ.
- The original data in 34 provinces is made into 38 provinces with the assumption of a share of the area.
- DKI: Special Capital Region, DI: Special Region

solid fuel includes bagasse and filter cake [24]. Bagasse is also widely used within the industry itself as fuel in industrial processes. The majority of wood industry waste consists of sawdust, shavings, wood pieces, and bark. This waste is commonly used as secondary raw material or, after composting, as fertilizer for soil and degraded land rehabilitation [25]. When used as fuel, the specifications need to be adjusted according to the requirements of coal power plant boilers, typically in the form of pellets or chips.

The biomass potential above does not yet account for the possible development of productive forests on critical land, which is estimated to be substantial, reaching 71,783 hectares [19]. There remain many challenges that need to be addressed when allocating critical land for productive forests. Assuming the biomass productivity from the study by Schueler et al. [26], which averages 6.6 t per hectare per year with a harvest cycle of 8 years, the productive forests on critical land are estimated to yield a total of 473,800 t of dry biomass annually. With a calorific value of 4,200 kcal/kg, the total convertible energy potential reaches 8.33 PJ. However, actual productivity may vary depending on plant species, land conditions, and management practices; thus, further studies are necessary to ensure sustainable utilization.

2.2. Coal power plant installed capacity data

The inventory of coal power plant installed capacity was conducted by referring to PLN's electricity supply business plan (RUPTL) 2021-2030 data and the 2023 annual reports from the Directorate General of Electricity. The collected data include coal power plant locations, installed capacity, capacity factors, boiler types, and operational age. This information serves as the basis for determining the technical potential for co-firing implementation in each region as well as projections of future electricity demand based on coal power plants.

The existing installed capacity data of coal power plants is presented in Table 2 [4]. In Indonesia, electricity providers are categorized into two main groups: PT PLN (Persero) and non-PLN entities. PT PLN, a state-owned enterprise, plays a central role in the generation, transmission, and distribution of electricity nationwide. The non-PLN group comprises three main types of actors: independent power producers (IPPs), public-private utilities (PPUs), and entities holding business licenses for own-use electricity supply (IUPTLS) [27]. The total installed capacity of coal power plants reaches 49,758 MW. The regions with the largest coal power generation capacities are Central Java (10,222 MW), followed by Banten (9,072 MW) and East Java (6,253 MW).

As of December 2023, the co-firing program had utilized 990.8 kt of biomass (17.4 PJ), resulting in an estimated reduction of 1.05 Mt of CO_2 emissions. Biomass accounted for an average share of 1.2% of the total energy demand for coal power plants [28]. The biomass types utilized include corn cobs, palm shells, waste pellets, sawdust, rice husks, and woodchips. The type of boiler used in co-firing technology typically depends on the existing coal combustion technology. Common boilers used in Indonesia are circulating fluidized bed (CFB), pulverized coal (PC), and stoker boilers, although other boiler types are still used in some countries [29].

2.3. Methodology for projecting biomass demand

The calculation of biomass demand for co-firing was conducted using a long-term coal demand projection approach, covering the period from the base year 2023 to 2045, which holds symbolic significance as the centennial of Indonesia's independence. Numerous projections for electricity development have been conducted for both short- and long-term horizons. PLN [30] has developed a detailed 10-year expansion plan. Fitriana et al. [31] have discussed the development of electricity to achieve net zero emissions by 2070. Meanwhile, Kuncoro et al. [32] have specifically addressed fuel demand for power plants. The latter two studies utilize the LEAP (Low Emissions Analysis Platform) model, which is widely used for long-term energy mix planning and considers various environmentally friendly energy technology options [33]. In this study, the LEAP model was selected due to it supports scenario-based analysis for energy transitions in developing countries [34]. The LEAP is widely used due to its accessibility and affordability, especially in developing countries, as it provides free or low-cost academic licenses. In LEAP, economic dispatch identifies the least-cost mix of power plants by ranking units according to short-run operating cost. Low-cost power plants supply base load, while higher-cost units operate only during peak demand. A reserve margin of 30% ensures capacity exceeds peak load, keeping backup plants available for reliability.

Electricity development planning is conducted at the national aggregate level and can be detailed by examining multi-regional data for specific types of power plants. Using the LEAP model, two scenarios were created: the business as usual (BAU) scenario and the biomass co-firing (BCF) scenario for long-term electricity

Table 2. Existing installed capacity of coal power plants in Indonesia.

No.	Province	Installed Capacity (MW)				
		PLN	Non-PLN			Total
			IPP	PPU	IUPTLS	
1	Aceh	220	460	12	0	692
2	North Sumatra	1,330	0	0	0	1,330
3	West Sumatra	424	0	0	9	433
4	Riau	234	0	0	176	410
5	Jambi	0	312	0	6	318
6	South Sumatra	260	2,027	0	6	2,293
7	Bengkulu	0	200	0	0	200
8	Lampung	400	14	0	53	467
9	Bangka Belitung Island	93	0	0	27	120
10	Riau Island	44	0	280	0	324
11	DKI Jakarta	0	0	0	0	0
12	West Java	2,040	1,666	424	55	4,185
13	Central Java	4,201	6,021	0	0	10,222
14	DI Yogyakarta	0	0	0	0	0
15	East Java	2,790	3,253	0	210	6,253
16	Banten	5,570	2,607	895	0	9,072
17	Bali	0	380	0	0	380
18	West Nusa Tenggara	207	50	0	161	418
19	East Nusa Tenggara	173	30	0	0	203
20	West Kalimantan	155	212	0	0	367
21	Central Kalimantan	120	211	51	7	389
22	South Kalimantan	260	200	60	21	541
23	East Kalimantan	239	550	66	112	967
24	North Kalimantan	7	0	8	8	23
25	North Sulawesi	110	200	0	0	310
26	Central Sulawesi	7	60	4,002	8	4,077
27	South Sulawesi	420	500	0	120	1,040
28	Southeast Sulawesi	34	14	0	60	108
29	Gorontalo	55	121	0	0	176
30	West Sulawesi	0	0	0	0	0
31	Maluku	0	0	0	0	0
32	North Maluku	14	0	3,920	0	3,934
33	West Papua	0	0	0	68	68
34	Southwest Papua	0	0	0	0	0
35	Papua	24	0	0	0	24
36	South Papua	0	0	0	0	0
37	Central Papua	0	0	219	195	414
38	Papua Mountains	0	0	0	0	0
Indonesia		19,431	19,088	9,937	1,302	49,758

development. Assumptions regarding GDP and population growth align with previous studies [31,32]. These projections consider GDP growth as a reference consistent with the Golden Indonesia Vision 2045 [35,36]. The second scenario, BCF, assumes a gradual increase in coal replacement with biomass, ranging from 5% in the short term up to 15% in the long term. Scenario BCF1 assumes a gradual increase in biomass share from 1.2% in 2024 to 5% in 2045, while BCF2 and BCF3 envision biomass shares of 10% and 15%, respectively by 2045. As the biomass share increases, coal demand decreases. The reduction in coal consumption is calculated using an exponential growth curve to achieve a gradual decline, as described in Eq. (1).

$$Growth(t) = -a \times \left(e^{-k \times (t-2023)} - 1\right) \quad (1)$$

with a = 1.2 (initial value in the year 2024), k is set to reach -5%, -10%, and -15% in 2045. The co-firing ratio is expressed as a percentage, referring to the proportion of biomass relative to coal consumption, measured in PJ.

The total coal demand (in PJ) for the electricity sector is calculated based on installed capacity (in MW), annual operating hours (8,000 hours), the thermal efficiency of the coal power plant, a capacity factor of 0.75 [37], and a conversion factor from MWh to PJ of 0.0036, as shown in Eq. (2). Subsequently, biomass demand is calculated by simulating coal substitution from the total fuel consumption. Each scenario is evaluated to assess the biomass required in each region, as well as the capacity of local supply to meet this demand.

$$Coal\ Demand = \frac{Installed\ Capacity \times Annual\ Operating\ Hours}{Thermal\ Efficiency} \times Capacity\ Factor \times Conversion\ Factor \quad (2)$$

The biomass demand for co-firing is then calculated according to the BCF scenarios of 5%, 10%, and 15% of the total coal demand. This demand is subsequently allocated to provincial regions based on the share of installed capacity of existing coal power plants. The sustainability of biomass demand and availability is analyzed using the supply-demand adequacy ratio. Biomass potential in a region (in PJ/year) represents the supply (*S*), while biomass demand in the same region (in PJ/year) represents the demand (*D*); thus, the adequacy ratio (*AR*) is defined by Eq. (3).

$$AR = S/D \quad (3)$$

Regions with a surplus are indicated by *AR* > 1, balanced regions or those with demand equal to sufficient supply have *AR* = 1, and deficit regions have *AR* < 1. The *AR* scale needs to be normalized to a 0–10 scale for easier representation. The normalization calculation is shown in Eq. (4). Thus, the interpretation of the normalized *AR*' is balanced when *AR*' = 2, surplus when *AR*' > 2, and deficit when *AR*' < 2.

$$AR' = \begin{cases} 2 \times (1 + log_{10}(AR)), AR \geq 1 \\ 2 \times (AR), AR < 1 \end{cases} \quad (4)$$

2.4. GHG emission calculation methodology

GHG emissions considered in this study are limited to carbon dioxide (CO_2) emissions. Emissions from coal power plants are calculated using a quantitative approach based on the method recommended by the Intergovernmental Panel on Climate Change (IPCC) [38], supported by local data and documents such as the National Greenhouse Gas Inventory [39]. This approach aims to provide accurate and consistent emission estimates in accordance with international standards and the national context.

The GHG emissions were calculated by multiplying coal consumption (in PJ) by the emission factor (in t of CO_2 per PJ) as shown in Eq. (5).

$$GHG\ Emission = Coal\ Consumption \times Emission\ Factor \quad (5)$$

The equation illustrates that higher coal consumption results in greater GHG emissions. Emission reductions from co-firing are calculated based on the difference between emissions in the BAU scenario (without co-firing) and emissions in the BCF scenarios with biomass substitution of 5%, 10%, and 15%. Following the IPCC approach, biomass is assumed to be carbon neutral, and thus the proportion of biomass used directly offsets GHG emissions from the total fuel consumption of coal power plants.

3. Results and Discussion

3.1. Electricity supply and demand

The largest electricity demand in Indonesia in 2023 was from the household sector, accounting for 42%, followed by the industrial sector (31%), commercial (19%), and public (8%). As a developing country, demand is still dominated by household consumption rather than productive uses. This electricity demand is supplied primarily by coal power plants, which account

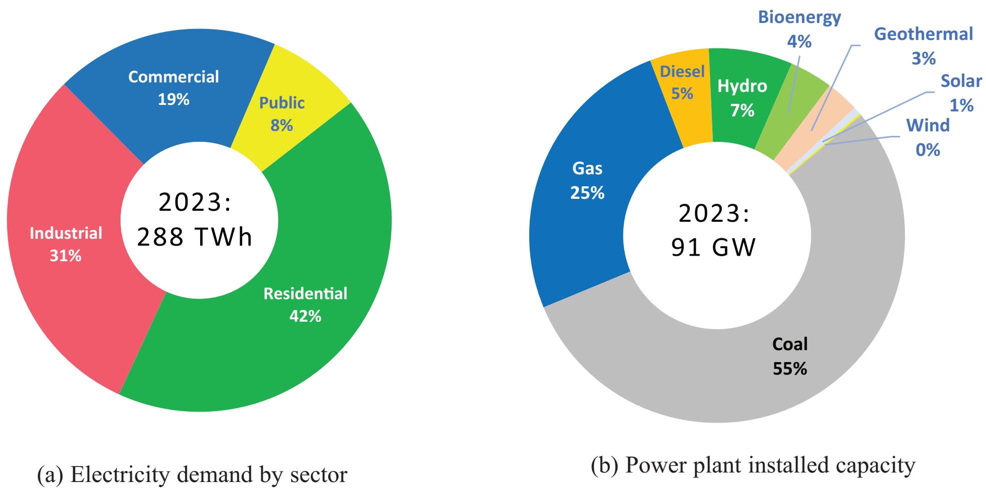


Figure 1. (a) Electricity demand per sector and (b) installed capacity per type of power plant in Indonesia (2023).

for 55%, followed by gas power plants (25%), hydro (7%), diesel (5%), bioenergy (4%), geothermal (3%), solar (1%), and the remainder from wind [4]. Electricity demand and power plant installed capacity are shown in Figure 1.

Electricity demand is expected to increase in line with GDP and population growth. According to Bappenas [35], GoI [40], and BPS [41], the projected GDP and population growth are shown in Figure 2. Indonesia has the opportunity to escape the middle-income trap and realize its vision of becoming a developed, high-income country by 2045. Economic growth is projected to average 6.1% per year, while population growth is expected to average 0.7% per year. Economic transformation is directed towards reducing dependence on the primary sector and advancing towards industrialization based on innovation, high productivity, and advanced technology.

The projected electricity demand up to 2045 based on the LEAP model is presented in Figure 3. Under the BAU scenario, coal remains the primary source of power generation in the long term. Gas power plants are expected to serve as a transitional technology to reduce coal dependence while facilitating the shift toward lower-carbon alternatives. Among renewable energy sources, hydropower and geothermal energy are identified as the most promising. Diesel power plants are primarily retained as backup generators in the event of main plant failures; however, their capacity factor is relatively low and is expected to decline further over time as they are

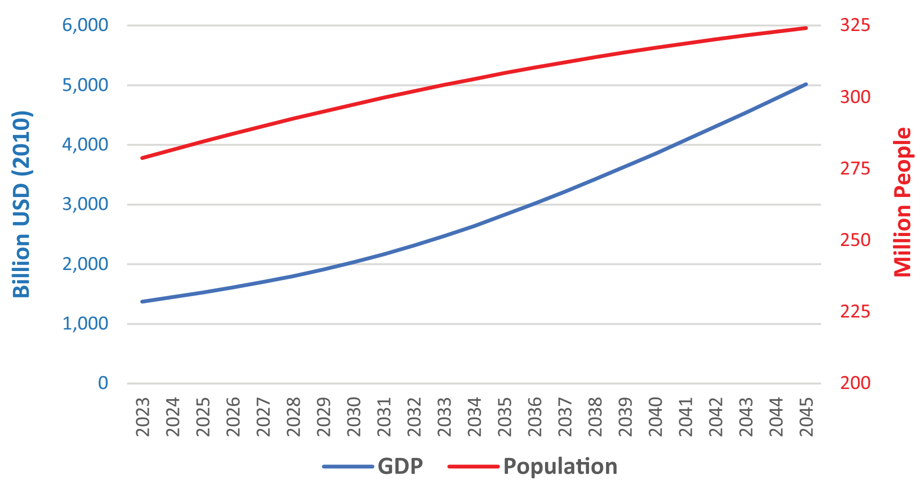


Figure 2. GDP and population growth projections.

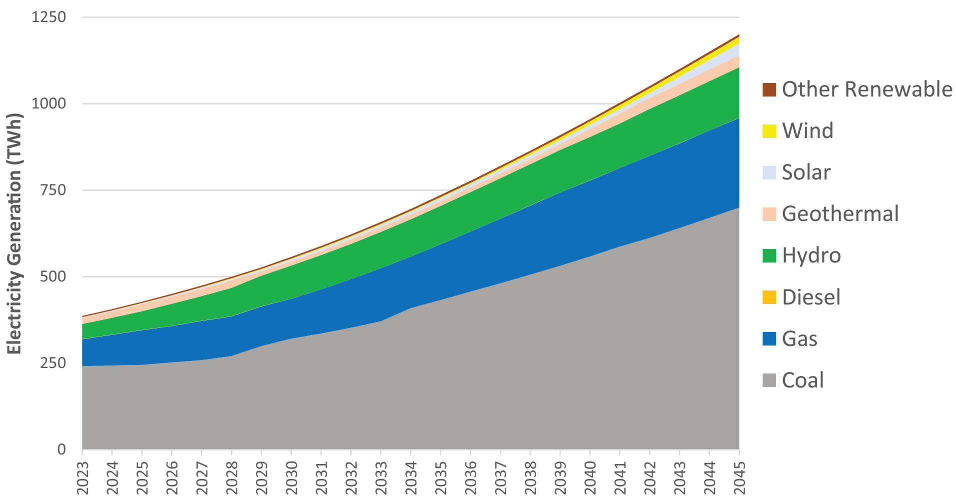


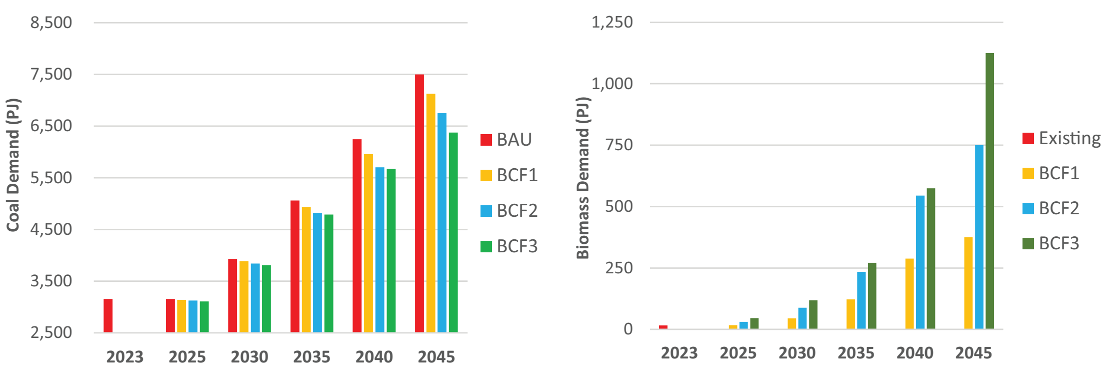
Figure 3. Electricity generation projections.

replaced by more cost-effective power generation technologies.

The development of coal power plants continues to follow existing policies, which prohibit the addition of new capacity except for projects already committed in the Electricity Supply Business Plan [30]. Looking ahead, no new coal power plants are expected to be built after 2035, as lending countries have ceased providing capital for such projects. As a consequence, the capacity factor of existing plants is projected to gradually increase in response to growing electricity demand. In this scenario, the share of renewable energy in the power generation mix is expected to increase, even in the absence of an explicit effort to phase out coal power plants.

3.2. Projected coal and biomass demand

The projected coal demand under the BAU scenario, as well as under the BCF scenarios—BCF1, BCF2, and BCF3, which assume biomass co-firing shares of 5%, 10%, and 15%, respectively—is presented in Figure 4 (a). In the base year 2023, coal demand is estimated at 3,155 PJ and is projected to increase to 7,500 PJ by 2045, corresponding to an average annual growth rate of 0.4%. Under the BCF scenarios, coal demand gradually declines, with the reduction offset by a corresponding increase in biomass demand, as shown in Figure 4 (b). In the BCF3 scenario, biomass demand rises from 17.4 PJ in 2023 to 1,125 PJ by 2045, representing an average annual growth rate of 7.1%.



(a) Coal demand

(b) Biomass demand

Figure 4. (a) Projection of coal demand and (b) biomass demand under BAU and BCF scenarios.

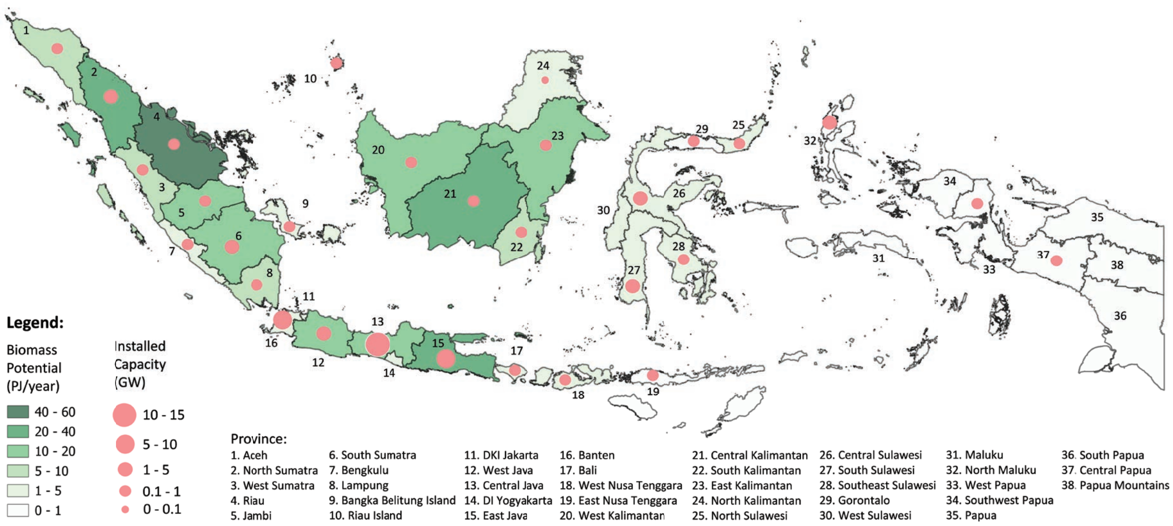


Figure 5. Mapping biomass potential and installed capacity of coal power plants (status as of 2023).

3.3. Multi-regional analysis of biomass supply and demand

A multi-regional mapping of biomass potential by provincial region and the installed capacity of coal power plants in the respective areas is illustrated in Figure 5. Four regions with biomass potential exceeding 20 PJ per year are Riau, North Sumatra, Central Kalimantan, and East Java Province. These regions also have substantial biomass demand due to their significant coal power plant capacity. However, some regions, despite having biomass potential, show no demand because there are no coal power plants in those areas. These regions include DKI Jakarta, DI Yogyakarta, West Sulawesi, Maluku, Southwest Papua, South Papua, and Papua Mountains, which have the potential to supply biomass to surrounding regions in need.

Biomass supply-demand adequacy is represented by the adequacy ratio (*AR*'), as shown in Figure 6. Nationally, until 2035, an *AR*' value greater than 2 indicates a biomass surplus condition. In 2045, under the BCF1 scenario, the *AR*' value falls below 2, indicating a national biomass supply deficit. For BCF2 and BCF3 scenarios, the national biomass supply becomes insufficient as early as 2040. These findings suggest that relying solely on biomass from municipal and industrial waste will not be sufficient in the long term. Therefore, the development of biomass from productive forests on degraded or critical lands should be considered as a complementary supply strategy. Given the significant regional variability in biomass supply and demand, national aggregates alone are inadequate for assessing long-term sustainability. Further multi-regional analysis is necessary to identify prospective areas for the sustainable implementation of the biomass co-firing program.

Regionally, seven areas exhibit a relatively high *AR*' and remain in biomass surplus for the long term even with co-firing at 15%. Ranked from highest to lowest *AR*' values, these regions are Riau, North Kalimantan, Central Kalimantan, West Kalimantan, Papua, Bangka Belitung Islands, and Jambi. Biomass availability in these areas remains abundant compared to the demand for co-firing in coal power plants, which is up to 15%. These six provinces consistently maintain surplus conditions throughout the analysis period, indicating stable supply resilience.

Regions with an *AR*' value below 2, indicating biomass supply deficits during the analysis period, include 24 provinces. North Maluku Province can only implement the co-firing program with biomass blending below 5%. Coal power plants in North Maluku have a capacity of 3,934 MW, most of which are operated by PPU. The development of co-firing programs in these areas requires serious consideration regarding long-term biomass availability. Local biomass supply is insufficient and must be supplemented by imports from outside the region, incurring additional transportation costs. Banten and Central Sulawesi Province are regions that can only implement the co-firing program with biomass blending up to 5%. In Banten, the coal power plant installed capacity reaches 9,072 MW, the majority of

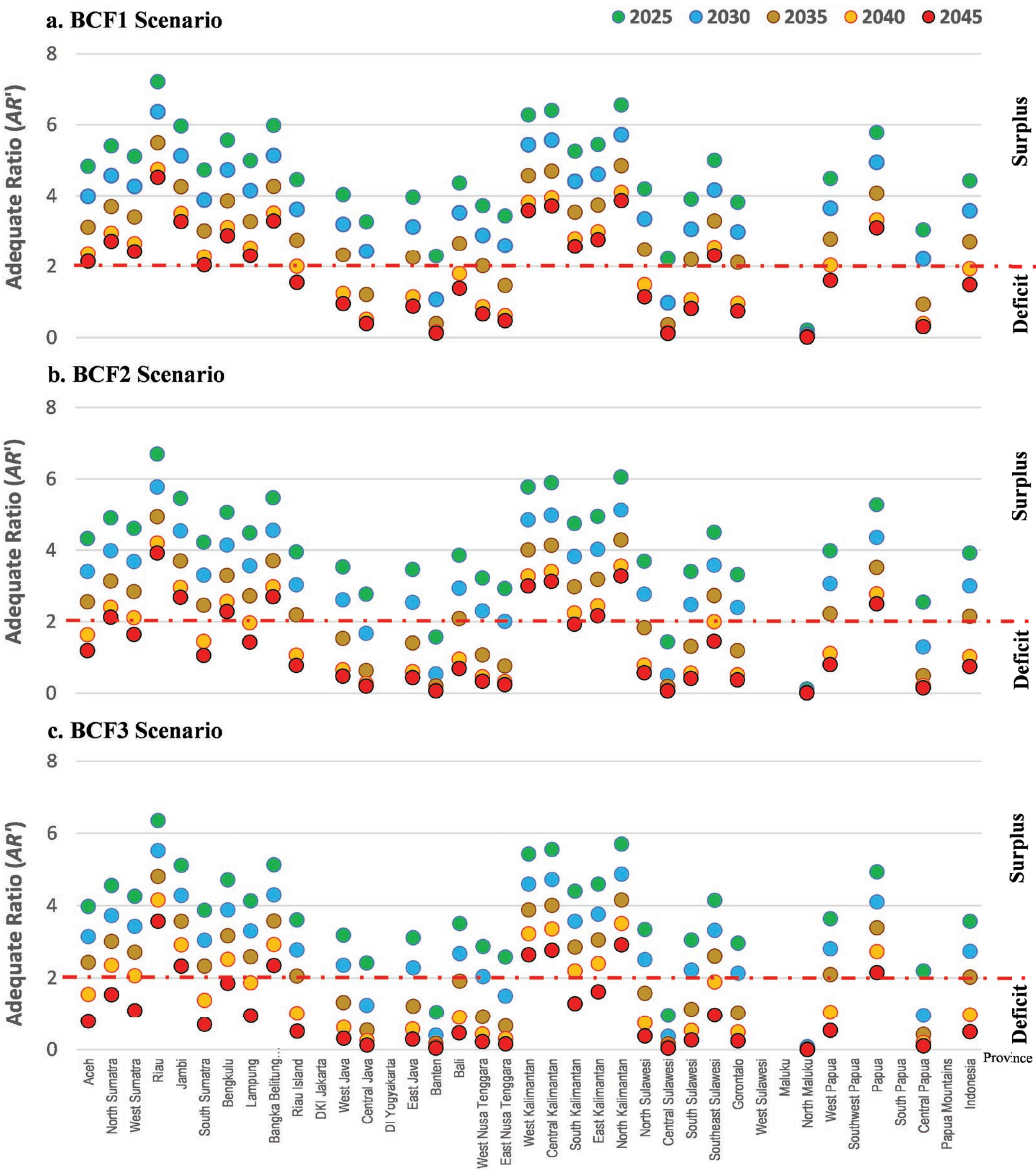


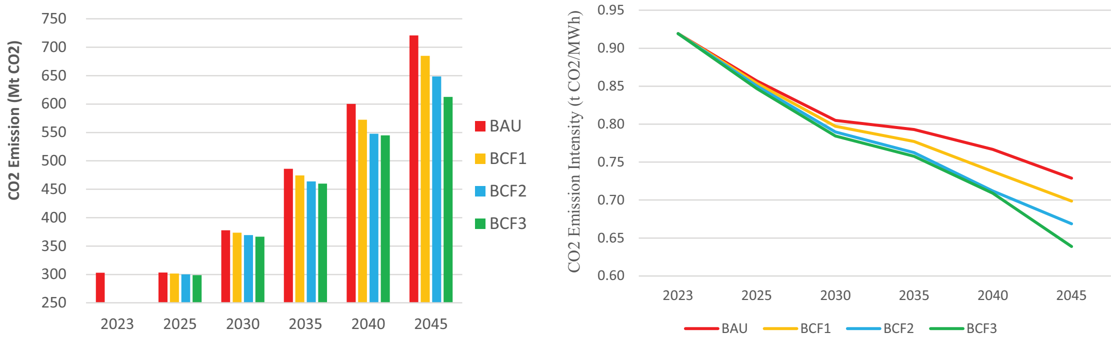
Figure 6. Biomass supply-demand adequacy ratio under BCF scenarios.

which is operated by PLN, while in Central Sulawesi, which has coal power plants with a capacity of 4,077 MW, most are operated by PPU. The biomass around this area is also likely already fully utilized.

Several regions in Sumatra and Kalimantan islands still have biomass surpluses. In contrast, other regions experience deficits when co-firing reaches 15% in the long term. Since these areas are within the same archipelago, biomass trade within the same island remains feasible with relatively low transportation costs. However, biomass deficits are expected throughout the analysis period in Java, Papua, and other islands. Meeting biomass demand in these regions will require inter-island trade or the development of biomass from critical lands, if potential exists locally. The uneven distribution of biomass across islands remains a significant challenge.

3.4. Estimated GHG emission reductions

Coal power plants emit GHG proportional to the amount of coal consumed during operation. The projected GHG emissions from coal use are shown in Figure 7 (a). The GHG emissions presented are calculated only for coal and biomass, not for all power plants modeled in LEAP. GHG emissions decrease when a portion of coal is substituted with biomass at certain shares. Under the BAU



(a) GHG emission projection

(a) GHG emission intensity projection

Figure 7. (a) GHG emission and (b) GHG emission intensity projection under BAU and BCF scenarios.

scenario, GHG emissions in 2023 amount to 303 Mt of CO_2 and are projected to increase to 721 Mt of CO_2 by 2045. In the long-term BCF scenario, emissions are estimated to decrease by up to 108 Mt of CO_2 in 2045 under the BCF3 scenario.

GHG emission intensity is calculated as the total GHG emissions divided by the total electricity production. In the base year, the emission intensity of the electricity sector in Indonesia reached 0.919 t CO_2/MWh. Considering national electricity development and energy transition policies, the emission intensity is projected to decrease to 0.729 t CO_2/MWh by 2045. The contribution of biomass co-firing to reducing GHG emission intensity is shown in Figure 7 (b). Under the BCF3 scenario, the emission intensity decreases to 0.639 t CO_2/MWh, contributing to a 12.4% reduction in emission intensity.

3.5. Multi-regional supply optimization strategy

The biomass co-firing program is expected to increase the share of renewable energy by utilizing existing coal power plants. However, its sustainability faces significant challenges from the biomass supply-demand perspective, especially if biomass is used at proportions exceeding 10%. Biomass supply potential needs to be optimized so that surplus regions can supply deficit regions through biomass trade. Regions with high biomass potential, such as Sumatra and Kalimantan Island, can prioritize the utilization of palm oil waste, while Java can utilize municipal waste in the form of RDF. Challenges arise not only from biomass supply and demand but also from the waste processing into fuel, economic feasibility, and the overall development of an optimal supply chain. Collaboration with plantation sectors and local communities can ensure sustainable biomass availability.

In line with the need to optimize existing biomass potential, biomass cultivation in critical productive forests must be initiated promptly. The development of productive forest plantations can be directed to regions with lower adequacy ratios, in order to address biomass shortfalls. Biomass potential in critical productive forests covers 71,783 hectares and can be optimized to produce biomass sustainably through integrated government policies. These policies include simplifying permits and providing fiscal incentives for industrial plantation managers and local communities through community forest schemes. This effort must also be accompanied by land rehabilitation using effective silvicultural technologies. Sustainable monitoring and funding are essential elements, facilitated through green financing schemes and international cooperation. On the other hand, downstream biomass-based industry development should be encouraged to enhance the added economic value.

4. Conclusion and Recommendation

The use of coal in power generation faces increasing challenges due to its associated GHG emissions. One promising mitigation strategy is biomass co-firing in coal power plants. Indonesia has an estimated biomass potential of 369.31 PJ derived from municipal and industrial waste, which is expected to support long-term biomass demand for co-firing through 2045, with biomass shares ranging from 5% to 15%. At the national level, biomass supply remains in surplus at a 5% co-firing rate until 2035, but a supply deficit emerges by 2045. With higher co-firing shares of 10%–15%, the deficit occurs earlier, by 2040.

Biomass supply and demand vary significantly across regions, rendering national aggregates insufficient for sustainability assessment. Provinces such as Riau, North Kalimantan, Central Kalimantan, West Kalimantan, Bangka Belitung Islands, and Jambi exhibit biomass surpluses capable of supporting co-firing shares of up to 15%. In contrast, other regions are unable to meet their biomass demand from local sources and will need to rely on interregional supply chains. In Banten and Central Sulawesi, the co-firing program can be applied with a biomass blending share limited to 5%. Despite these disparities, the co-firing program is projected to reduce GHG emissions by approximately 108 Mt of CO_2 by 2045 at a 15% biomass share, contributing to a consistent reduction in GHG emission intensity over the analysis period.

However, the sustainability of multi-regional biomass supply and demand remains a significant challenge. A region-specific assessment represents a valuable direction for future research, particularly with regard to supply chain optimization. This may include spatial modeling of biomass logistics, economic feasibility assessments, and the development of commercially viable biomass business models to support the implementation of co-firing in coal power plants.

Credit Authorship Contribution Statement

AS: Conceptualization, Methodology, Modelling, Data Analysis, Writing, Editing. AHK: Data Preparation, Review. IF: Draft Preparation, Modelling, Review, Editing. Y: Draft Preparation, Review, Editing. PTW: Data Preparation, Modelling, Editing. RR: Data Preparation, Review. A: Data Preparation, Review. EW: Data Preparation, Review. EH: Data Analysis, Review. AN: Data Analysis, Writing, Editing.

Acknowledgments

This research received funding from the Sustainable Energy Program of the National Research and Innovation Agency (BRIN) for the year 2025.

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