

# Simulation of emissions and costs of palm empty fruit bunch cofiring in coal fired power plants based on life cycle assessment and life cycle costing

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## Abstract

The utilization of biomass as an alternative fuel in coal-fired power plants (CFPPs) through cofiring schemes supports Indonesia's energy transition toward a cleaner and more sustainable electricity system. Oil palm empty fruit bunches (EFB), a major residue of palm oil processing, present substantial potential for renewable fuel applications. The environmental and economic implications of EFB pellet cofiring are examined using an integrated Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) approach. The LCA covers cultivation, processing, transport, combustion, and waste management, providing a complete view of emissions. The LCC estimates total fuel cycle costs and simulates carbon pricing scenarios relevant to national policy. Results show that 5% EFB cofiring reduces greenhouse gas emissions by 13.13% (1.46 tCO<sub>2</sub>e per ton fuel) and lowers fuel costs by 6.55% (IDR 56.47/kWh), especially when EFB follows the government's biomass benchmark price (HPT– Harga Patokan Tertinggi). Emission reduction yields a carbon value of IDR 43,695 per ton fuel, monetizable through carbon tax or trading schemes. Sensitivity analysis indicates that feasibility depends on biomass and carbon price variations. EFB cofiring thus offers a technically and economically viable solution with measurable environmental benefits, contributing to a circular, low-carbon energy system in Indonesia.

## Keywords

Cofiring, Emissions, Life cycle assessment, Life cycle costing, EFB biomass

## Introduction

Indonesia's power sector is still dominated by coal, in which coal fired power plant (CFPPs) covered around 61% of the installed capacity in 2022–2023 and renewable energy as of current contributions only reaches around 13%, less than half the targeted share for year 2025 set forth under National Energy Policy (KEN). To boost the energy transition, 69.5 GW of new capacity would be from renewable and storage, including 0.9 GW of bioenergy and 10.3 GW of storage; with only 16.6 GW fossil generating out to be added into the planned terms production plants of power [1]. Despite commitments, reliance

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on coal is the pre-dominant contributor to Greenhouse Gas (GHG) emissions which complicates Indonesia's efforts to comply with the Paris Agreement commitments and attain the updated NDC target of a 29% GHG emission reduction by 2030.

To address this situation, the government and PT PLN have adopted the biomass cofiring at existing CFPPs as part of PT PLN's "Transformation 2.0" roadmap, where up to 10% coal can be replaced [2]. However, the actual achievement is that cofiring only reached 2.83 million tons by 2024, while the national target of cofiring is assigned to be 10.2 million tons by 2025 [3]. Past research has shown that the emission reduction potential from national-scale cofiring remains relatively modest (1.5–2.4% of CFPP emissions) and more comprehensive life cycle-based analysis is necessary to correctly assess its environmental and economic efficacies [4].

More to the point, out of all available biomass sources, EFB (empty fruit bunch) from palm oil shows great potential. Indonesia which produced over 50 million tons of crude palm oil in year 2023, accounts for may scale 20–25 million ton of the EFB residues and it is partially underutilized [5]. EFB can be pelletized for cofiring, but its high moisture content and low bulk density would have to undergo pre-treatment steps of pressing, washing, drying, grinding and pelleting to meet the required specifications for fuel quality standards-implicating logistical and cost complexity thereof [6], [7]. However, the utilization of EFB also provides important environmental co-benefits by addressing waste management challenges in the palm oil industry. Large quantities of EFB generated as solid by-products of palm oil mills are often treated as waste and left to decompose or manage in low value applications, creating environmental burdens. Such unmanaged lignocellulosic residues may contribute to greenhouse gas emissions, particularly methane, from open decay processes, whereas diverting EFB toward energy recovery pathways, including solid fuel production or cofiring, can reduce waste accumulation and avoid fugitive methane emissions associated with open decomposition.

To evaluate these combined environmental and economic implications, previous research commonly applies Life Cycle Assessment (LCA) and Life Cycle Costing (LCC). LCA is widely used to quantify environmental impacts across the entire life cycle of biomass utilization systems and to identify emission hotspots beyond the combustion stage, while LCC assesses cost performance over the system lifetime. The integration of LCA and LCC has been recognized in prior studies as particularly effective for evaluating biomass cofiring systems, as it enables simultaneous assessment of emission mitigation potential and economic feasibility two key challenges in the implementation of EFB cofiring. Accordingly, the evaluation of EFB cofiring performance relies on a fully integrated cradle-to-grave LCA and LCC framework, where the LCA systematically assesses environmental impacts associated with cultivation, processing, transport, combustion, and waste management [8], comparing technology alternatives and identifying hotspots [9]. The common LCA stages consist of geographical consideration, raw material acquisition, production processes, utilization, and end-of-life stages [10].

Previous research have established the technical and economic feasibility of using EFB as cofired, with reported emission reductions up to 18.2% [11], [12], [13], [14], lower GHG and acidification impacts compared to coal [15], cost effective than most technology under reasonable economic condition [16], [17]. Nevertheless, studies integrating LCA and LCC to simultaneously evaluate environmental impacts, fuel cost performance, carbon economic value, and sensitivity to biomass and carbon price fluctuations, particularly for EFB cofiring in Indonesian coal fired power plants remain limited. Accordingly, this work aims to establish an integrated LCA–LCC simulation of a 5% EFB pellet cofiring scenario to evaluate emission reduction and fuel cost savings, as well as its carbon economic value and sensitivity to biomass and carbon price fluctuations. The results are intended to support decision-making in PT PLN and provide evidence-based insights for national energy policy makers.

## Method

This is a quantitative analysis with descriptive and exploratory components. Quantitative analysis provides measurable, analytically described results; descriptive methods describe factors and operation state of system. The exploratory part could provide an estimate whether cofiring in coal-fired power plants (CFPPs) on palm oil empty fruit bunch (EFB) would be promising in reducing greenhouse gas (GHG) emissions and fueling costs, with discussion on the policy level and future operating stages.

The study adopts a simulation-based case study design with an integrated LCA and LCC approach, drawing entirely on secondary data obtained from peer-reviewed literature, official reports, and established databases.

### *System boundary and research scope*

A cradle-to-grave system boundary is used that includes oil palm planting and fresh fruit bunch collecting oil, EFB pellet production (including the processes of drying, chipping and pelleting), transportation to CFPPs, cofiring with combustion process, as well as post-combustion and waste disposal. In the simulation a 5% cofiring application in PLN-owned CFPPs with stoker boiler technology is a conservative and widely used reference case.

### *Life Cycle Assessment (LCA)*

Life Cycle Assessment (LCA) is applied to assess environmental impacts arising from a product, process, or service over its complete life span. The LCA was carried out according to ISO 14040 standards and includes: (a) Goal and Scope Definition Assessment of EFB's use in cofiring schemes looking upon GHG emissions. The boundary of LCA included the processes, including oil palm plantation, EFB pellet production and transportation, combustion in CFPP and waste disposal (b) Life Cycle Inventory (LCI): Inventorying data to numerically characterize energy requirements, fuels consumption and emission outputs for each process stages. Sources of data are scientific

publications, PLN technical reports and other studies. Calorific value, emission factors, energy consumption and transport distance are some key parameters (c) Life Cycle Impact Assessment (LCIA): The GWP in CO<sub>2</sub>- equivalent is the chosen impact category and, on this case Global Warming Potential (GWP) has been selected (d) Interpretation: Comparative analysis between 100% coal and 5% EFB added will be considered with regard to reducing emissions.

### *Life Cycle Costing (LCC)*

Life Cycle Costing (LCC) is employed to assess the economic performance of the cofiring system, including: fuel costs (Component C) on calorific value and market prices of coal and EFB with consideration of market standards and HPT. This emphasis is reasonable as the cost of fuel also contributes to greater than 65% of electricity generated price (or Levelized Cost of Electricity- LCOE) for cofiring system, which has been shown in techno-economic and LCC studies [18], [19]. Here, not all cost components are accounted for; however, the method offers an exploratory pre-feasibility analysis appropriate for the early stages of a study. Furthermore, the value of carbon emissions is also assessed with the use of carbon pricing scenarios to determine monetizing GHG emissions for financial performance.

### *Sensitivity analysis*

Sensitivity analysis considers (i) ±20% on biomass prices to account for the market uncertainty; and (ii) carbon price scenarios up to IDR 42,000 per ton CO<sub>2</sub>e (representing maximum increase of 40%). The study determines the threshold cases at which cofiring is economically viable.

### *Data sources and output indicators*

The analysis employs secondary data from IPCC and Ecoinvent databases, PLN technical and operational reports, as well as literature on EFB pellet properties and transport distances. All estimates are performed in Microsoft Excel, and data checks are made through comparison with other sources combined with conservative estimation where necessary. Key output results are GHG emissions (kg CO<sub>2</sub>e/kWh), fuel cost (IDR/ kWh), and carbon economic value per ton of biomass used, also break-even point calculations for the price of biomass and carbon. This methodology is carried out as in the following Figure 1.

### *Data processing and calculation tools*

Microsoft Excel were utilized for all data processing, calculations, and simulations in this research. Life cycle inventory (LCI) data were organized in Excel spreadsheets to compute greenhouse gas emissions for every life cycle phase and to assess components of fuel costs within the framework of Life Cycle Costing (LCC). To calculate emissions, relevant emission factors were applied to the activity data at each processing stage, and the results were aggregated to yield cradle-to-grave emissions presented in CO<sub>2</sub>-equivalent units. Economic calculations involved processing data on fuel prices, calorific values, and electricity output to determine the fuel cost per electricity unit produced.

The carbon economic value was calculated by multiplying avoided emissions by projected carbon price scenarios. Sensitivity analyses were performed by systematically changing the biomass parameters.

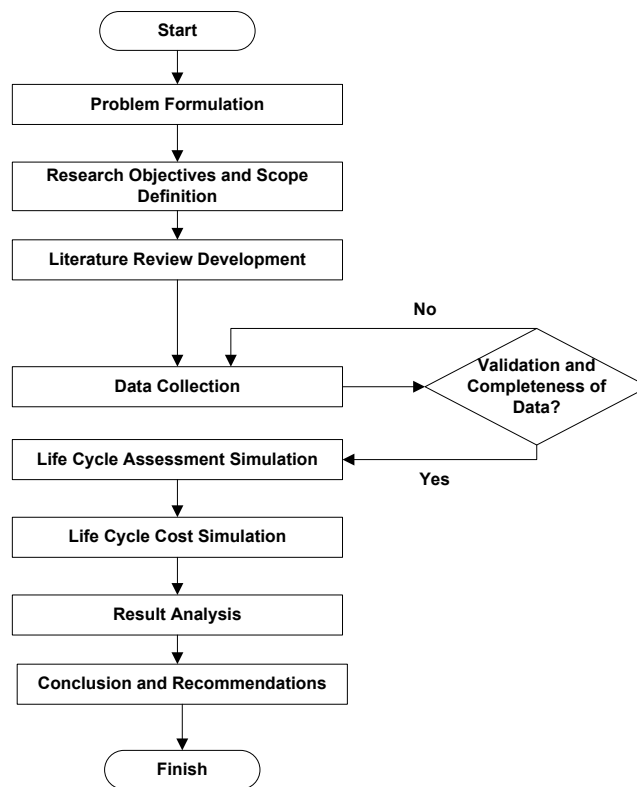


Figure 1. Methodology of research

## Results and Discussion

The section presents simulation-based results on emissions and cost performance for a 5% EFB pellet cofiring scenario in CFPPs, benchmarked against a 100% coal-fired baseline. The analysis integrates outcomes from LCA, LCC, and sensitivity analyses on fuel and carbon price parameters. These results provide a quantitative evaluation of environmental and economic impacts and serve as a basis for policy-relevant discussion within Indonesia's electricity sector.

### Data and assumptions

The analysis utilizes secondary data sourced from official reports, peer-reviewed literature, and established databases to support both LCA and LCC calculations. Key parameters include CFPP operational characteristics, fuel properties, emission factors, energy output, fuel prices, and carbon pricing assumptions. Coal prices follow prevailing market values, while EFB pellet prices refer to the Government's HPT.

The simulation assumes that a 5% cofiring ratio does not significantly affect CFPP operational efficiency, under the premise that minor technical adjustments and retrofitting have been implemented. Additional assumptions cover biomass transport distance, palletization energy consumption, and energy conversion factors, reflecting typical operating conditions of CFPPs with comparable technical specifications.

All parameters and assumptions are summarized in [Table 1](#). Data validation is conducted through cross-referencing multiple sources and applying conservative, well-justified values to ensure the robustness and representativeness of the simulation results.

**Table 1.** Data and assumptions [20][21][22][23][24][25][26]

Parameter	Value	Parameter	Value
CFSP Capacity	7 MW	GWP:	
Cofiring Fraction:		CO <sub>2</sub> to CO <sub>2</sub> e	1
Coal	95%	CH <sub>4</sub> to CO <sub>2</sub> e	25
EFB	5%	N <sub>2</sub> O to CO <sub>2</sub> e	298
Electricity Output:		CFSP Efficiency	35%
100% Coal	75.125 MWh	Carbon Tax	IDR 30,000/ton CO <sub>2</sub>
5% EFB Cofiring	63.400 MWh	Transport Distance (EFB Pellet to CFSP)	50 km
Coal Consumption:		Emission Factor:	
100% Coal	83.825 ton	- Coal Combustion	2.441 kg CO <sub>2</sub> /kg coal
Cofiring	65.000 ton	- CO <sub>2</sub>	74,100 kg/TJ
Calorific Value of Coal	13.527 MJ/kg	CH <sub>4</sub>	4.15 kg/TJ
	3,233 kCal/kg	N <sub>2</sub> O	28.6 kg/TJ
Calorific Value of EFB	18.146 MJ/kg	Grid electricity	0.85 kg CO <sub>2</sub> e/kWh
	4,337 kCal/kg	Diesel Emission Factor	2.68 kg CO <sub>2</sub> e/liter
Specific Fuel Consumption		Biomass Price (Market place)	IDR 1,747.3/kg
100% Coal	1.1158 kg/kWh	Biomass Price (HPT)	IDR 1,036.37/kg
Cofiring	1.0252 kg/kWh	Coal Price	IDR 772.56/kg

### LCA results

The LCA simulation indicates that 5% palm oil empty fruit bunch (EFB) pellet cofiring reduces greenhouse gas (GHG) emissions from 12.37 kg CO<sub>2</sub>e/kWh in the 100% coal baseline to 9.87 kg CO<sub>2</sub>e/kWh. This corresponds to a reduction of 2.49 kg CO<sub>2</sub>e/kWh, or approximately 1.46 tons CO<sub>2</sub>e per ton of fuel. The reduction is primarily driven by the biogenic carbon neutrality of EFB, in which CO<sub>2</sub> emissions from combustion are offset by carbon uptake during biomass growth [27].

Additional benefits arise from avoiding methane emissions from EFB decomposition and from lower upstream emissions in pellet processing compared with coal mining and preparation. Localized EFB supply chains also reduce transportation-related emissions relative to coal. Consequently, even at a 5% substitution level, cofiring provides measurable emission reductions supporting national decarbonization efforts. The cradle-to-grave system boundary ensures comprehensive life cycle coverage from plantation activities to combustion and ash management.

[Figure 2](#) illustrates the baseline and cofiring scenarios for CO<sub>2</sub> emissions. Contributions of fuel per ton to the emissions reductions are as follows:

1. Emissions from coal mining have decreased from 8,384.39 to 6,696.17 kg CO<sub>2</sub>e and emissions from coal processing has slightly decreased from 15.30 to 14.54 kg CO<sub>2</sub>e due to the reduced fuel consumption in proportion of the partial substitution by biomass (EFB pellets).

2. Combustion at the power plant: Emissions due to combustion were reduced from 2,441.00 to 2,348.85 kg CO<sub>2</sub>e or a reduction of 3.78%. Being EFB a carbon neutral fuel from life cycle point of view, the small reduction is due to the low cofiring percentage and use of coal in the fuel mixture remains dominant. Residual emissions are also impacted by non-CO<sub>2</sub> from biomass burning and its lower efficiency of combustion. However, the outcome suggests that a positive decarbonization trend for both fuels is apparent and there is larger mitigation potential with increasing cofiring ratio.
3. Reduced GHG emissions from waste and ash handling: down by about 3.79% (235.08 kg CO<sub>2</sub>e vs 244.35 kg CO<sub>2</sub>e) This benefit arises mainly from the reduced volume and reduced hazardousness of biomass ashes, which usually contain less Heavy Metals; but on top can be beneficially reused.

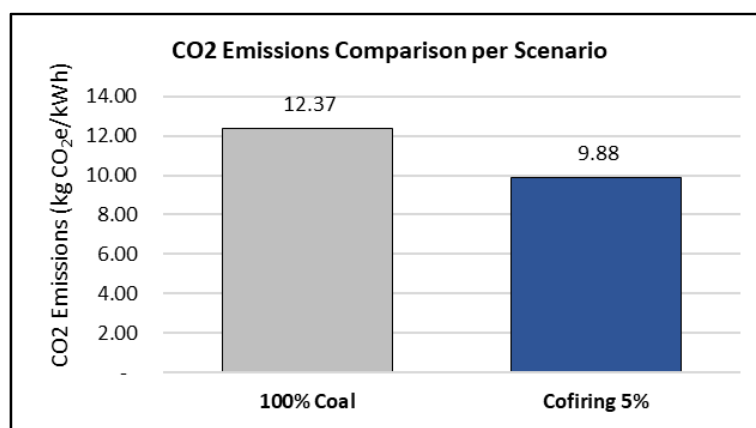


Figure 2. CO<sub>2</sub> emission comparison

### LCC results

From an economic perspective, the results of the LCC simulation indicate that the 5% EFB cofiring scenario generates fuel cost savings compared to the baseline 100% coal combustion scenario. Fuel cost comparison shown in Figure 3.

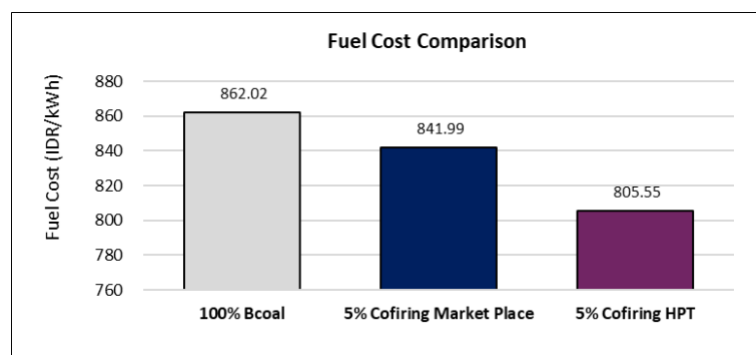


Figure 3. Fuel cost comparison

The results show that 5% EFB cofiring reduces fuel costs (Component C) relative to the 100% coal baseline, although the level of savings is highly dependent on the EFB pricing scheme. At the market price of IDR 1,747.30/kg, cost savings are modest at IDR 20.03/kWh (2.32%). In contrast, applying the Government’s Highest Benchmark Price

(HPT) of IDR 1,036.37/kg significantly increases efficiency, yielding savings of IDR 56.47/kWh, or 6.55%.

### *Carbon value potential*

In addition to environmental gains, there are further economic benefits associated with 5% EFB cofiring from carbon trading. With an assumption of the carbon price to be at IDR 30,000 per ton CO<sub>2</sub>e, the reduction of 1.46 tons CO<sub>2</sub>e by one tonne fuel can be translated into a value of around IDR 43,695. This amount can be significant when extrapolated to plant level. For instance, a CFPP with capacity of 100,000 tons EFB annually would enjoy avoided-emission benefit in the order of about IDR 4.37 billion per year, which gives strong motivation for integration with biomass.

### *Sensitivity analysis*

A sensitivity assessment is conducted to evaluate how variations in biomass and carbon prices affect the feasibility of cofiring.

1. Price sensitivity for biomass: Cofiring extensive blending level EFB prices do not surpass the Highest Benchmark Price (HPT) at Rp 1,036.37/kg, cofiring is still economically feasible. Price escalations above 20% sharply diminish the cost benefits of this feedstock, thus limited effecting of a reliable and cheap biomass supply. Policy instruments such as procurement regulation, local sourcing incentives or specific subsidies may be necessary to stay competitive compared with coal.
2. Carbon price sensitivity: The economics of cofiring are considerably improved by carbon pricing. At IDR 30,000/t CO<sub>2</sub>e a ton avoided GHG have significant economic value already; higher prices can add to that significantly. The benefit gains more than 40% when the price of carbon goes up to IDR 42,000 per ton CO<sub>2</sub>e, making the attractiveness of investment increase.

As is illustrated by [Figure 4](#), EFB prices in the ±20% range from the baseline case of IDR 1,747.30/kg have varying effects on savings in fuel costs. At the starting price, savings are IDR 20.03/kWh (2.32%) and fall steeply as prices increase but rise to IDR 37.94/kWh (4.40%) when they drop by 20%. These findings support the strong impact of biomass prices on combustion Economics.

As shown in [Figure 5](#), the monetary benefits of emission reduction are also linear with carbon price, reaching IDR 43,695 and IDR 48,065 per ton CO<sub>2</sub>e at Rp30,000 and Rp33,000 per ton CO<sub>2</sub>e respectively. The results suggest that higher carbon prices, implemented via taxation or emissions trading schemes, can strengthen the economic attractiveness of cofiring while supporting Indonesia's Net Zero Emission (NZE) 2060 goals.

Overall, the sensitivity findings indicate that EFB cofiring can provide economic and environmental benefits- from fuel cost savings to monetized green values and its future is contingent upon Biomass price stability as well as a definite carbon policy. The inclusion of environmental costs inputs in the assessment of the projects is crucial to relate cofiring strategies to national energy and decarbonization targets.

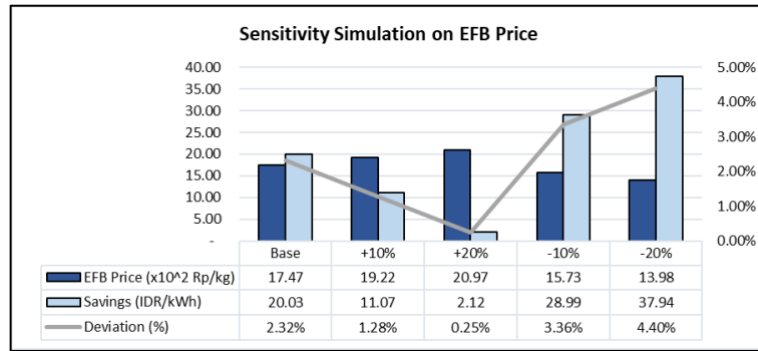


Figure 4. Sensitivity of fuel cost to biomass

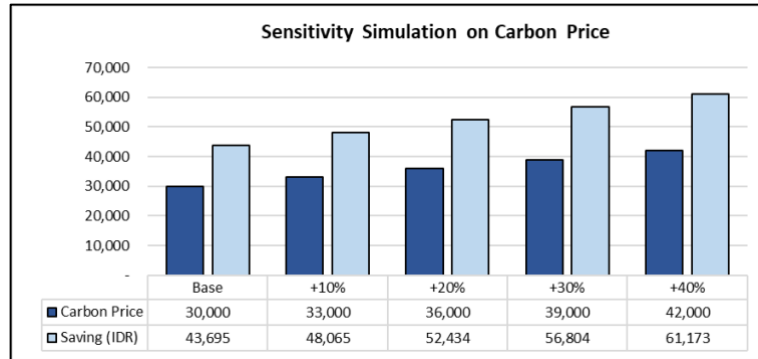


Figure 5. Sensitivity of carbon pricing

### Comparison with previous studies and implications

The results of this study are consistent with previous findings indicating that biomass cofiring in coal-fired power plants can achieve meaningful greenhouse gas emission reductions. The emission reduction obtained for the 5% EFB pellet cofiring scenario in this study falls within the range reported in earlier studies, confirming the environmental effectiveness of EFB utilization. However, most prior studies have focused on environmental or techno-economic aspects in isolation, while integrated assessments combining LCA and LCC, particularly in the Indonesian context, remain limited. By simultaneously evaluating life-cycle emissions, fuel cost savings, carbon economic value, and sensitivity to biomass and carbon price fluctuations, this study addresses an important gap in prior research. Several limitations should be acknowledged, including reliance on secondary data and simulation-based assumptions, the focus on a single cofiring ratio and boiler type, and the exclusion of capital and long-term operation and maintenance costs. Nevertheless, the findings provide important practical and policy implications, demonstrating that low level EFB cofiring can deliver measurable environmental and economic benefits without major infrastructure modifications and can support decision-making for PT PLN and national energy policy formulation.

### Conclusion

The environmental and economic sustainability of 5% palm oil EFB pellet cofiring in CFPPs is examined using an integrated LCA–LCC methodology. A cradle-to-grave system boundary is modeled, including the life-cycle transport of the fuel to its end use

destination, a full accounting of GHG emissions associated with the combustion of each biofuel (through quantification GHG emissions produced during extraction and upgradation), as well as impact on regulatory defined criteria pollutants. Summary of the major result:

1. LCA shows that 5% EFB cofiring cuts GHG emissions by 13.13% in total compared with the purely coal baseline of 100%. These savings are because of the biogenic carbon neutrality of EFB, lower upstream emissions than coal mining and processing and the reduction in avoid methane emission from decomposition of untreated EFB
2. The LCC analysis indicates that the fuel cost would decrease by 6.55% when cofiring, due mainly to the cheaper price of EFB pellet from HPT (IDR 1,036.37/kg). Avoided emissions has an added value in economic terms of around IDR 43,695 per ton EFB used with a carbon price of IDR 30,000 per ton CO<sub>2</sub>e.
3. Sensitivity analysis has shown that cofiring will still be economic if the price of EFB is maintained under or at the benchmark and there are carbon pricing mechanisms in place. This shows that, also for relatively low shares of cofiring penetration, there can be considerable environmental achievement as well as economic gains provided the market and policy conditions are right.

Overall, findings indicate that a 5% EFB cofiring ratio can result in significant emission and cost reductions without major conversion of CFPP infrastructure. This will make EFB cofiring a smooth, short- to medium-term energy transition option for the decarbonization of the current assets.

Future work may take into consideration other CFPP technologies (e.g., stoker and circulating fluidized bed boilers), cross feed capital and operation maintenance costs, and examine policy instruments like biomass feed in tariffs, long term supply contracts and linkages with national as well as international carbon credit markets.

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## Authors' Contributions and Responsibilities

Kartika Raras Hadiyati contributed to the study's conceptualization, methodology development, data curation, formal analysis, and manuscript writing and editing. Tri Wahyu Adi provided supervision, validation, and contributed to manuscript review and editing.

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