SI: Evaluating the Viability of Co-Firing Biomass Waste to Mitigate Coal Plant Emissions in Indonesia

Calculating Biomass Waste Supply

Oil Palm

We derived estimates of oil palm waste biomass from reported crude palm oil (CPO) production (BPS, 2022a), which we converted into fresh fruit bunches (FFB) produced per province using a factor of 4.16 tons of FFB per ton of CPO generated (Conrad and Prasetyaning, 2014). From there, we applied the ratios of palm kernel shell (PKS) and empty fruit bunch (EFB) produced per FFB, .215 tons of EFB per ton of FFB and .06 tons of PKS per ton of FFB (Conrad and Prasetyaning, 2014; Loh, 2017), in order to determine oil palm waste generated by province. We multiplied EFB and PKS production values by their moisture conversion factors (.35 and .85, respectively) (Loh, 2017) to determine dry weight for conversion to total energy availability (see Table S3), a value which varies based upon moisture content that we standardized as dry weight and energy availability for this study. Following conversion to dry weight, we converted all feedstocks to MJ for comparative analysis.

Wood

Wood biomass includes three categories of waste: logging residues, industrial wood waste, and pulp. We calculated each of these categories separately, then summed for the total wood biomass estimate. To calculate logging residues, we multiplied island-group level data on logs produced by type (BPS, 2022b) by wood density and residual factor, which varies based on province and species (see Table S1). Similarly, we calculated industrial wood waste by multiplying industrial wood production (veneers, sawn timber, chip and particle, and plywood) by wood density and availability factor (see Table S2).

Supplementary Table S1: Calculating Logging Residues

Logging Residue Waste Calculation		
Wood Type	**Wood density ($\frac{kg}{m^3}$)**	**Source**
Indah	611.1	(ICRAF, 2023)
Ebony	758.3	(ICRAF, 2023)
Acacia	750.76	(Amirta et al., 2016; Hidayat et al., 2021; Rhofita et al., 2022)
Meranti	686.66	(Haryanto et al., 2021; Hidayat et al., 2021; Rhofita et al., 2022)
Other	611.1	(Rhofita et al., 2022)
	Residual factor (%)	

Industrial and natural forests	.164-.312	(Simangunsong et al., 2017)

To estimate dried pulp availability, we used Badan Pusat Statistik reporting on production (BPS, 2022b), of which we estimated 68.44% to be waste product (Aryapratama and Pauliuk, 2019).

Supplementary Table S2: Calculating Industrial Wood Waste Production

Industrial Waste Calculation		
Industrial wood product	**Wood density (kg/m³)**	**Availability Factor (%)**
Chip and particle	380	0.475
Plywood	620	0.475
Veneer	440	0.475
Sawn timber	470	0.475
All values from (Rhofita et al., 2022)		

Rubber

We calculated rubber waste by multiplying the total area of rubber production (m^3) (BPS, 2022c) by .03, the fraction of plantations replanted annually (Perkebunan Nusantara, 2021; Ratnasingam et al., 2015; Smith and Wiryawan, 2021). To determine replanting quantity, we multiplied this value by the typical rubber forest density, 180 m^3 (Ratnasingam et al., 2015), and by the average dried rubber wood density of 588.45 (kg/m^3) (Lim et al., 2004; Naji et al., 2012, 2011).

Rice

Using provincial-level estimates of rice paddy production (BPS, 2023), we calculated rice husk and straw generation using ratios of 20% and 50% of paddy production, respectively (Conrad and Prasetyaning, 2014). As we measured paddy production estimates using "dry unhusked paddy", estimates of total dried husk and straw production required no further conversions.

MSW

We calculated municipal solid waste (MSW) production based upon recorded weight of waste delivered, in tons, at Final Processing Sites (TPAs) and Integrated Waste Management Sites (TPSTs) in each province (Ministry of Environment and Forestry, 2023). We omitted non-organic waste from total MSW estimates due to the health risks associated with combustion (Marganingrum et al., 2022). On average, organic matter makes up 48% of waste collected in the country (BPS, 2018). After removing non-organic MSW from the estimate, we calculated the dried value of waste, estimated to be 58% of the weight of waste as-received (Yansen, 2021).

Sugarcane Bagasse

Using provincial-level estimates of sugar production (BPS, 2022d), we calculated estimates of cane production by multiplying sugar produced (in tons) by 12.5 (Iryani et al., 2012). Bagasse makes up approximately 34.03% of each ton of sugarcane (Conrad and Prasetyaning, 2014; Daniyanto et al., 2015; Iryani et al., 2012), and after calculating total bagasse production per province, we determined the dried weight (60% of initial value) (Anwar, 2010).

Calculating Calorific Values

Coal used in Indonesia has an average calorific value of 17.44-23.865 MJ/kg, depending on type used (ESDM, 2021). To enable calculation of substitution by biomass, which has a lower calorific value than coal, we converted all residues from their production value in tons to the total energy available from a given feedstock, represented in MJ.

Supplementary Table S3: Calorific Value by Feedstock

Feedstock	Calorific Value (MJ/kg, dried) *Average of all sources*	Sources
Oil Palm PKS	18.77	(Adhiguna, 2021; Asadullah et al., 2014; Dian et al., 2021; Dirgantara et al., 2020; Idris et al., 2012; Lee et al., 2013; Loh, 2017; Pawlak-Kruczek et al., 2020; Rusdianasari et al., 2022; Uche Paul et al., 2015)
Oil Palm EFB	17.12	(Idris et al., 2012; Loh, 2017; Purwanto et al., 2010; Rusdianasari et al., 2022; Uche Paul et al., 2015)
Wood*	18.29	(Cardona et al., 2019; Efendi and Garniwa, 2022; González-García et al., 2015; Hidayat et al., 2021; Mazlan et al., 2015; Rodrigues et al., 2020; Sá et al., 2020; Willians Calonego et al., 2016)
Rubber	17.28	(Baskoro et al., 2021; Devaraja et al., 2022, 2020; Kongto et al., 2021; Purwanto et al., 2010; Tiara et al., 2018)

Rice husk	13.83	(Chen et al., 2018; McEvilly et al., 2011; Patil, 2019; Purwanto et al., 2010)
Rice straw	13.42	(Lee et al., 2013; Patil, 2019; Purwanto et al., 2010; Restrepo and Bazzo, 2016; Shafie et al., 2013)
MSW	21.79	(Gunamantha, 2016; Khuriati et al., 2017; Lokahita et al., 2019; Sukarni, 2016; Triyono et al., 2019, 2018)
Bagasse	16.94	(Brunerová et al., 2018; Patil, 2019; Purwanto et al., 2010; Valix et al., 2017)
Pulp	15.02	(Bhattacharya et al., 2005; Doddapaneni et al., 2022; Huang et al., 2017; Syamsudin and Rizaluddin, 2021; Yoh et al., 2020)

*The calorific value estimate for wood is an average of values from a range of tree species, including eucalyptus, meranti, acacia, and kaliandra.

Calculating Other Utilizations

Review of available literature revealed typical major utilizations of biomass residues. Below, we detail the percent of waste products utilized for varying purposes. National calculations of these diversions compared use with total available residue supply. At the provincial level, we determined alternate use through different methods depending on the biomass type and use. Generally, availability by province is equal to provincial supply minus the fraction used for another purpose. While trade between provinces is a possibility, provincial level estimation provides a preliminary understanding of the spatial dynamics of biomass supply and use. Availability of plant-level data enabled exact calculation of diversion of biomass by province for existing co-firing and to feed biomass power plants. For other biomass uses, we calculated provincial diversion by multiplying total biomass waste production by province by the percentage of total waste used for a given purpose. A few exceptions to this method exist, all within the wood waste sector, detailed below.

Supplementary Table S4: Biomass Use in Processing Mills

Firing Processing Mills		
Feedstock	**Amount of waste used to fire processing mills**	**Source**

PKS	50%	(Ambarita and Kawai, 2021; Paltseva et al., 2016)
Pulp and paper	76.69%	(Aryapratama and Pauliuk, 2019)
Plywood	100%	(Aryapratama and Pauliuk, 2019)
Veneer	59.81%	(Aryapratama and Pauliuk, 2019)
Sawn timber	69.36%	(Aryapratama and Pauliuk, 2019)
Other wood waste	59.81%	(Aryapratama and Pauliuk, 2019)
Sugarcane	33.33%	(Restuti and Michaelowa, 2007)

Biomass co-firing has already been implemented in a small number of coal plants in Indonesia, and we included existing initiatives when calculating available biomass supply and additional emissions reductions potential at these plants. We calculated current quantities of biomass diversion using data on plants where co-firing is currently implemented, the ratio, and the feedstock (Prasetiyo et al., 2023). For plants with an unknown co-firing ratio, we assumed thermal input of 5%. We provide detailed coal consumption calculations in the section "Calculating Biomass Demand".

$$Biomass\ used\ in\ co-firing\ (MJ/year) = coal\ cons\ (MJ) \times co-firing\ ratio \quad (1)$$

Supplementary Table S5: Biomass Use in Existing Co-firing

Biomass Utilized in Existing Co-firing			
Existing co-firing	**Capacity (MW)**	**Co-firing Ratio**	**Coal Displaced (MJ)**
PKS	287	5-25%	1,061,279,170
Wood waste	5,586	1-5%	17,597,653,414
MSW	1,776	1-5%	3,607,675,648
Rice husk	1,908	1-5%	5,770,132,905

We derived our estimate of wood waste used locally as residential firewood from two different estimates of annual household fuel use (Table S6). We determined the number of households per province that use wood for fuel by multiplying the percent of households by province that use firewood by total households per province. We then multiplied this figure by annual wood consumption per household to determine the volume of wood used as firewood by province each year.

Supplementary Table S6: Biomass Use for Firewood

Biomass Used for Firewood			
Data	**Level**	**Range**	**Source**
Households that use wood for main fuel or cooking (%)	Provincial	0-68.8%	(BPS, 2022e)
# of households, 2016	Provincial	0-12.5 million	(BPS, 2016)
Wood consumed per household	Provincial	.88 (m3/year)	(Abdullah, 2003; Siarudin et al., 2023)

Supplementary Table S7: Biomass Use in Lumber Industry

Biomass Used in Lumber Industry		
Feedstock	**Value**	**Source**
Rubber wood	27% of available wood resource	(Agustina, 2012)
Veneers	.3% of waste	(Aryapratama and Pauliuk, 2019)
Sawn timber	5% of waste	(Aryapratama and Pauliuk, 2019)
Other wood waste	.3% of waste	(Aryapratama and Pauliuk, 2019)
Pulp	14% of waste	(Aryapratama and Pauliuk, 2019)

We derived our estimate of wood waste used locally as industrial fuel for purposes including brick creation and local manufacturing from the ratio of wood waste used as household use to the ratio of waste used as industrial fuel in Ciamis Regency, West Java. We then multiplied this ratio by household use per province, which incorporated factors such as number of households that use wood as fuel and the number of households per province into wood waste demand estimates (Siarudin et al., 2023).

Supplementary Table S8: Biomass Use for Industrial Fuel

Biomass Waste Used as Industrial Fuel		
Feedstock	**Value**	**Source**
Rice husk	12.4% of husk	(Yusran et al., 2017)
EFB	16,551 GJ	(APP Sinar Mas, 2021)
Wood waste	Household use x 2.43	(Siarudin et al., 2023)

Supplementary Table S9: Biomass Use for Fertilizer

Biomass Waste Used as Fertilizer		
Feedstock	**Value**	**Source**
Rice husk	3.29% of husk	(Yusran et al., 2017)
Rice straw	72.66% of straw	(Andini et al., 2018; Dermawan et al., 2023; Widarni, 2021)
EFB	77.5% of EFB	(Faisal and Mahidin, 2013)

Supplementary Table S10: Biomass Use for Animal Feed or Other Miscellaneous

Biomass Waste Used as Animal Feed or Other		
Feedstock	**Value**	**Source**
Rice straw	25.33% of straw	(Andini et al., 2018; Dermawan et al., 2023; Widarni, 2021)
Rice husk	2.82% of husk	(Yusran et al., 2017)

Information on export of biomass waste products is only available at the national level, and as a result, we assumed that exports by province were proportional to production. Overall wood waste estimates include estimated pulp exports, due to difficulty disaggregating export data.

Supplementary Table S11: Biomass Exportation

Biomass Waste Exported		
Feedstock	**Value**	**Source**

Wood waste (incl. pulp)	1,146,804.33 tons	(FAO, 2021)
PKS	3,999,856 tons	(BPS, 2022a)

We calculated estimates of tons of bagasse, oil palm, MSW, wood, and pulp used in existing biomass power plants based upon capacity by feedstock. Since the type of oil palm feedstock (palm kernel shell, fiber, press, or empty fruit bunch) is typically non-specified in reporting, we assumed that most PLTBm use an even blend of PKS and EFB. Some specify a "blend of press cake fibre, EFB, and kernel shells", in which case we assumed an even third of each, while others stated the specific amounts "fibre (69%) and shell (31%)" fired (ESDM, 2023). Where available, we drew information on specific quantities of biomass used annually or the type of oil palm product used from reports produced by individual plants (APR, 2020; ESDM, 2023; Furqon, 2017; Kencana Agri, 2021; Musim Mas, 2018; SAI Global, 2016; Sitorus et al., 2020; Teladan Prima Agro, 2023; UNFCCC, 2013, 2010).

Supplementary Table S12: Calculating Biomass Use in PLTBm or PLTSa

Calculating Feedstock Use at Biomass Power Plants (PLTBm or PLTSa)			
Input	**Value**	**Unit**	**Source**
Capacity per feedstock	See Table S13	MW	(ESDM, 2023)
Capacity factor*	.75925	%	(BAPPENAS, 2018; Nashrulloh et al., 2020; Pulungan and Sunitiyoso, 2017; Wiloso et al., 2020)
Thermochemical efficiency	.29175	%	(Han et al., 2020; Nashrulloh et al., 2020; Rhofita et al., 2022; Wiloso et al., 2020)
Calorific value$_1$	4.1-6.1 x 10^-3	(MWh/kg)	Based on Table S3
Calorific value$_2$	See Table S3	(MJ/kg)	See Table S3

* A few capacity factors differ from this average, as precise capacity factors were used where known.

To determine biomass used annually in MJ, we converted feedstocks used from MW to MJ for each type of biomass residue:

$$Feedstock\ used\ (\frac{MJ}{year}) = (\frac{MW\ of\ PLTBm \times 8{,}760 \times capacity\ factor}{thermochemical\ efficiency \times calorific\ value_1}) \times calorific\ value_2 \quad (2)$$

Supplementary Table S13: Biomass Use in PLTBm or PLTSa

Feedstock	MW of PLTBm	Feedstock Used (MJ/year)
Palm kernel shell	162.2	13,697,573,000
Empty fruit bunches	31.51	2,299,700,874
Pulp	575.19	42,402,498,149
Wood waste	18.5	1,473,303,040
Bagasse	207.94	17,065,482,919
Municipal solid waste	16.45	1,350,039,406

Seasonality

Available data for most biomass residues, including rice, oil palm, and bagasse, provides production quantities for each month of the year, providing an indication of seasonal availability of feedstocks. For these residues, we tested inter-annual variation by comparing production over time in 2021 with past production levels in 2020 and 2019.

We estimated the timeline for rubber replanting by determining the rainy season for each province (World Bank, 2023) and splitting up replanting evenly over the three months preceding the rainy reason, as rubber replanting is most successful when conducted "during the rainy season", and as the felling of trees typically occurs three months prior to planned replanting (GPSNR, 2021). For feedstocks with a lack of data on seasonal availability throughout the year, including wood waste and MSW, we assumed that waste production is even throughout the year.

Calculating Biomass Demand

We calculated biomass demand by determining biomass required to meet the co-firing ratio under each scenario at the coal plant unit-level. We calculated coal consumption per plant (β) by determining generation and multiplying by the heat rate at each plant (Equation S3). Given that Indonesia has begun implementing co-firing at plants across the country in anticipation of meeting their 2035 goal, we calibrated coal consumption and biomass demand at these plants to reflect existing co-firing. Using data on unit-level existing co-firing (Prasetiyo et al., 2023), we calculated coal displacement from current co-firing (α) by multiplying (β) by the co-firing ratio (ϵ) used. For plants with an unknown ratio, we assumed a ratio of 5%.

$$Coal\ consumption\ per\ plant\ =\ (generation\ (KWh) \times\ heat\ rate\ (\frac{Btu}{KWh}) \times 0.001055\ (\frac{MJ}{Btu})) - \alpha \qquad (3)$$

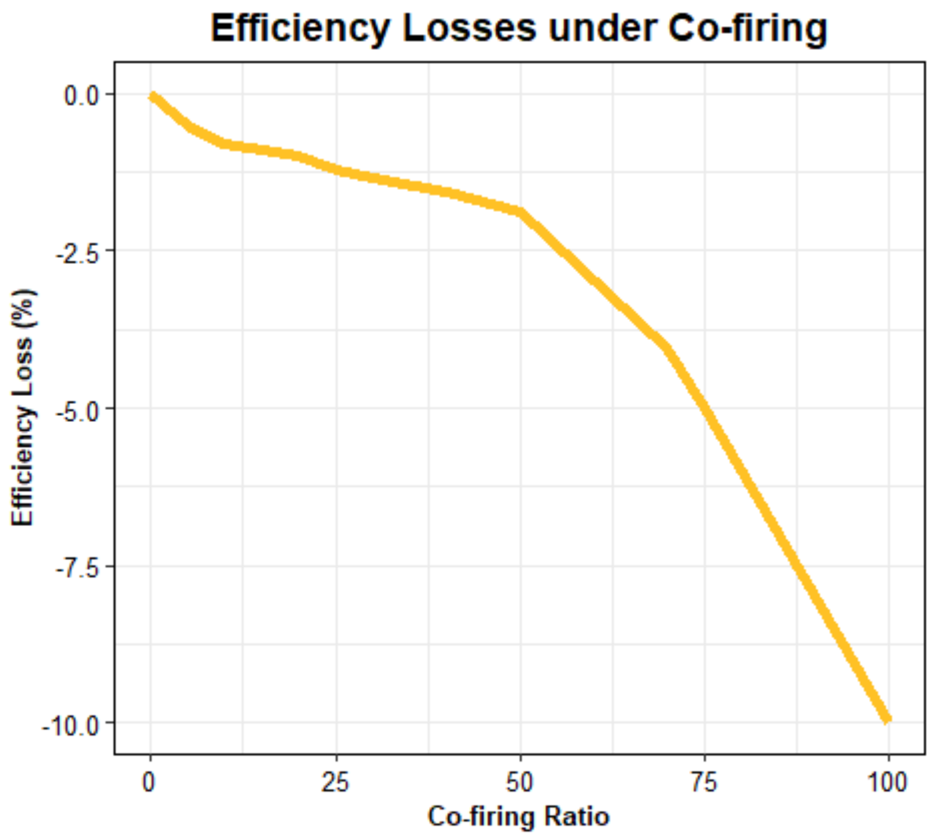
To determine biomass demanded per plant, by scenario, we multiplied total coal consumption by the co-firing ratio used at each plant (Table S14).

Supplementary Table S14: Co-firing Ratios by Scenario

Co-firing Ratios by Scenario			
Boiler Type	**Low**	**Mid**	**High**
PC	3%	10%	40%
CFB	10%	30%	50%
Stoker	20%	70%	100%

Efficiency Loss

Co-firing biomass with coal can result in efficiency losses, which, though under low ratios are sometimes considered negligible (Fernando, 2012; IEA, 2007), under high scenarios can reach 10%, assuming a full conversion from coal to biomass power plant (Cuellar and Herzog, 2015). We considered efficiency losses from co-firing at all ratios for this analysis, with low ratio losses based on (Cuellar and Herzog, 2015) and high ratio losses based on (Li et al., 2016), to determine losses at the precise ratios used in this analysis (S2).

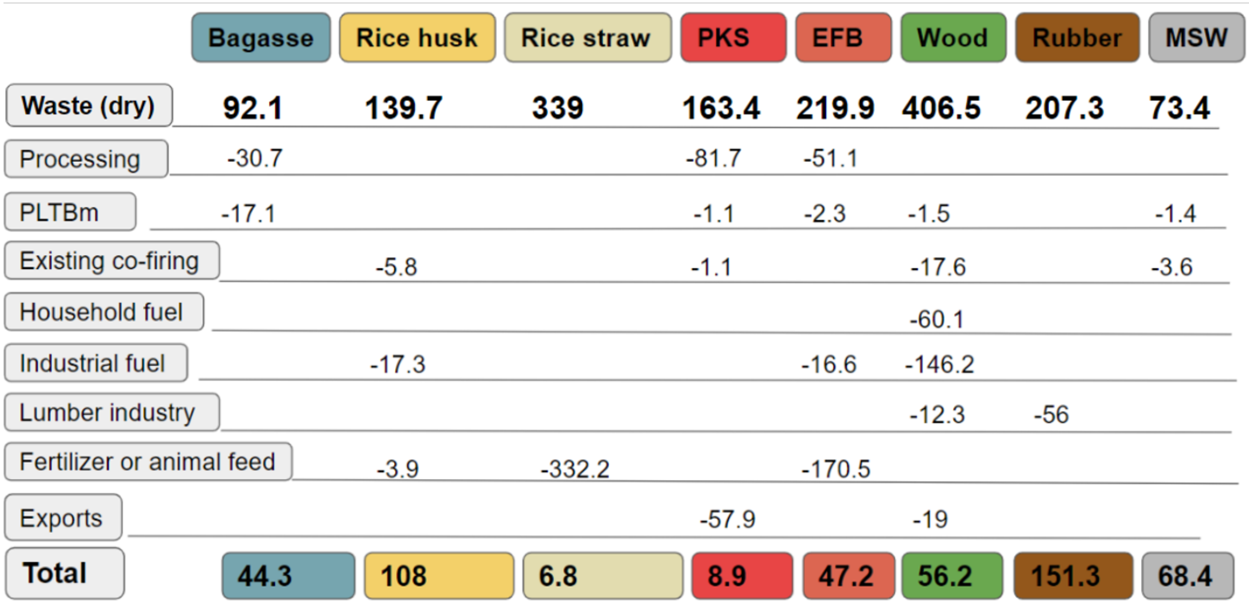


Supplementary Figure S1: Efficiency Losses from Co-firing

We then subtracted efficiency losses at each co-firing ratio from initial efficiency found at each plant (3,412/heat rate) and converted back into heat rates to determine changes due to cofiring (EIA, 2022). Assuming that coal plant operators will want to overcome generation loss from reductions in efficiency, additional coal and biomass (at a ratio consistent with the initial co-firing ratio) will be used to counteract heat loss. To calculate the additional coal consumption, biomass consumption, and emissions that result, we repeated initial calculations using updated heat rates at each coal plant.

Difference between Feedstock Supply and Demand

We first determined differences in biomass supply and demand at the national level. Given broader availability of national data on alternate uses, we utilized this level of data, or aggregated provincial figures to determine the current availability of each biomass after accounting for other uses.



Supplementary Figure S2: National Biomass Use and Remaining Supply

We determined differences between biomass supply and demand by province by aggregating previously calculated feedstocks at the provincial level and comparing those figures with the total biomass demanded by province under each co-firing scenario (Table S15).

Supplementary Table S15: Provincial Biomass Use and Remaining Supply

Difference Between Biomass Supply and Demand (million MJ)			
	Scenario		
Province	**Low**	**Mid**	**High**
Aceh	7,842	3,699	-5,181
Bali	1,716	-624	-3,044
Banten	-3,096	-51,288	-261,843
Bengkulu	5,238	2,907	497
Gorontalo	506	-1,446	-3,191
Jambi	30,599	27,405	24,091
West Java	19,950	1,116	-71,079
Central Java	30,344	-12,914	-208,850
East Java	45,017	25,260	-58,193
West Kalimantan	21,898	10,365	-1,294
South Kalimantan	12,278	6,260	-7,672
Central Kalimantan	22,217	16,619	11,779
East Kalimantan	10,459	-783	-12,356

North Kalimantan	1,757	1,048	356
Bangka Belitung Islands	2,011	1,592	1,578
Lampung	25,876	22,465	20,152
Maluku	-5,283	-17,191	-29,500
North Maluku	-24,217	-74,203	-125,721
West Nusa Tenggara	4,542	-1,259	-7,195
East Nusa Tenggara	498	-2,452	-5,230
Papua	869	-3,018	-7,017
West Papua	673	664	655
Riau	34,450	25,518	16,253
West Sulawesi	1,326	870	402
South Sulawesi	6,929	-10,105	-28,451
Central Sulawesi	-48,568	-153,554	-261,831
Southeast Sulawesi	-11,513	-37,794	-64,889
West Sumatra	11,387	6,679	-2,013
South Sumatra	46,307	26,362	-19,845
North Sumatra	22,259	7,196	-28,940
Yogyakarta	1,867	1,867	1,867
Jakarta	14,214	14,214	14,214
Riau Islands	3,143	3,143	3,143
North Sulawesi	986	986	986

Calculating Emissions

To determine the impact of co-firing on emissions targets, we calculated emissions per coal plant before and after application of co-firing, as detailed below.

Coal Emissions by Plant

To determine baseline emissions in 2023 and 2030, we calculated emissions by plant from coal use (or, in the case of a few plants, coal plus co-firing). Emissions by coal plant vary by coal type (Table S16), and for those plants with existing biomass use, we subtracted projected reductions in thermal input from the emissions baseline.

Supplementary Table S16: Coal Emissions Coefficient by Type

Emissions by Coal Type		
Coal Type	**Emissions (kgCO2/TJ)**	**Source**
Lignite	101,000	(Gomez et al., 2006)

Sub-bituminous	96,100	
Bituminous	94,600	

Emissions reductions from existing co-firing equal that plant's baseline coal emissions multiplied by its reported co-firing ratio(τ). For relevant plants, we subtract these reductions from the baseline emissions calculation, shown below (Eq. S4).

$$Emissions\ per\ plant\ = \frac{generation\ (KWh) \times heat\ rate\ (\frac{Btu}{KWh}) \times emission\ factor\ \ per\ coal\ type\ (\frac{kgCO_2}{TJ})}{947{,}817{,}077.75\ (\frac{Btu}{TJ}) * 907.2\ (\frac{kg}{ton})} - \tau \quad (4)$$

Emissions Abatement Scenarios

We calculated emissions reductions per coal plant under two scenarios: the carbon neutral biomass scenario, and the scenario in which an emissions coefficient assumes limited emissions from biomass production. Under the first scenario, we assume that emissions reductions equal the share of biomass substituted on a thermal basis. Under the second scenario, we assume that there will be emissions associated with production of biomass, so we include a biomass emissions coefficient, which estimates emissions reductions per ton of coal use abated, by coal type (Table S17).

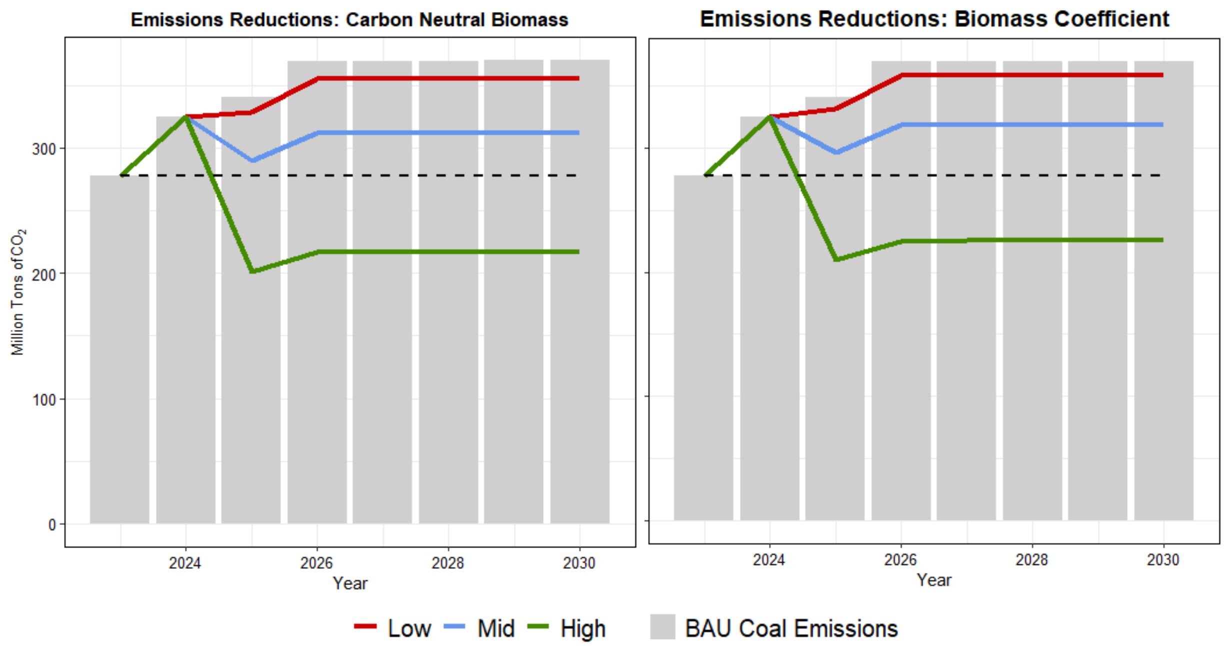
Supplementary Table S17: Biomass Emissions Coefficient by Coal Type Displaced

Emissions Abated from Biomass Substitution		
Coal Type	**Emissions (tCO2/GWh)**	**Source**
Lignite	1,129.850088	(IEA-ETSAP and IRENA, 2013)
Other Coal	1,047.178131	(IEA-ETSAP and IRENA, 2013)

In both scenarios, we incorporate the additional emissions brought about from coal and biomass burned to maintain efficiency (μ) into the final estimate (Eq. S5).

$$Emissions\ reductions\ = \frac{coal\ displacement\ (MJ) \times biomass\ emissions\ coefficient\ (\frac{tCO_2}{GWh})}{heat\ rate\ (\frac{Btu}{KWh}) \times 0.001055\ (\frac{MJ}{Btu}) \times 1{,}000{,}000} - \mu \qquad (5)$$

The results for BAU emissions over time, alongside emissions reductions by scenario, which begin in 2025 to allow time for implementation, are below. Total emissions and emissions reductions potential alike both grow as more plants become operational, particularly captive plants, in the mid-2020s.



Supplementary Figure S3: Emissions Reductions Against Baseline by Scenario

Supplementary Table S18: Emissions Reductions: Carbon Neutral Biomass Scenario

Coal Emissions and Potential Displacement from Co-firing in a Carbon Neutral Biomass Scenario (tCO2/year)				
		Emissions Reductions Scenarios		
Year	**BAU Total Emissions**	**Low**	**Mid**	**High**
2023	277,722,656			
2024	324,952,000			
2025	340,361,901	12,145,640	50,968,787	139,135,739
2026	369,236,081	14,141,117	57,797,984	152,254,716
2027	369,375,530	14,166,089	57,890,780	152,394,164
2028	369,375,530	14,166,089	57,890,780	152,394,164
2029	369,491,737	14,186,897	57,968,110	152,510,372
2030	369,491,737	14,186,897	57,968,110	152,510,372

Supplementary Table S19: Emissions Reductions: Biomass Coefficient Scenario

Coal Emissions and Potential Displacement from Co-firing IRENA Biomass Coefficients Scenario (tCO2/year)	
	Emissions Reductions Scenarios

Year	BAU Total Emissions	Low	Mid	High
2023	277,722,656			
2024	324,952,000			
2025	340,361,901	9,099,909	43,959,791	130,376,242
2026	369,236,081	11,115,838	50,850,013	143,780,696
2027	369,375,530	11,187,402	51,000,161	143,780,696
2028	369,375,530	11,187,402	51,000,161	143,780,696
2029	369,491,737	11,209,994	51,083,731	143,905,820
2030	369,491,737	11,209,994	51,083,731	143,905,820

Wood Pellet Scenario

Calculations made in the wood-pellet scenario use the methodology detailed by (Muhajir et al., 2022), which assumes that 38% of land used for wood plantations is deforested natural forest, and that acacia crops operate on a 5-year crop rotation, and can produce 18.54 tons of pellets/ hectare/year.

Supplementary Table S20: Emissions Factors and Concessions by Forest Type

Forest Type	Emission factor value (tons/hectare)	HTI concessions planted
Dry land forest (D)	375.7	10.7%
Primary mangrove ($M1$)	309.62	.2%
Primary swamp forest ($S1$)	303.53	1.8%
Secondary dryland forest ($D2$)	263.29	54.1%
Secondary swamp forest ($S2$)	249.62	32.3%
Secondary mangrove forest ($M2$)	131.59	.9%
Plantation forest (P)	100.4	-

We calculated emissions from deforestation (EDF) in Eq.S6 using information on the area deforested (Ad), derived from the land needed to produce the quantity of pellets needed to co-fire at each scenario, the percentage of concessions by type of forest deforested ($Concess\%$), emissions factor by forest type (EFj), the carbon fraction (CF), and by converting from carbon to CO2 (3.67). We determined the emissions absorbed by acacia plantations by multiplying the total area planted (Ap) by the carbon fraction and emissions factor for acacia plantations, then converting into carbon from CO2.

$$Edf = (((Ad * DConcess\% * DEFj) + (Ad * M1Concess\% * M1EFj) + \ldots)) * (CF * 3.67) - (PEFj * CF * 3.67 * Ap) \quad (6)$$

There are limitations associated with this calculation, including that it neglects to include the time needed for new acacia trees to reach maturity, and the timelines through which deforestation impacts carbon sinks. However, this is meant to be a preliminary investigation into the possible emissions ramifications of co-firing using industrial wood products.

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