Opportunities to Optimize the Palm Oil Supply Chain in Sumatra, Indonesia

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Supplementary materials

	Source of raw material (i.e.FFB) (RM)		Processing plant (P)		Intermediate products (IP)		Biomass processing technologies (Tech)		Bio-product (BP)		Demand (D)
1	Small-scale plantations	1	Palm oil mill	1	CPO	1	CPO - CPO (eff. = 1) (IP 1)	1	CPO (Tech 1)	1	Palm oil demand*
2	Large-scale plantations			2	PK	2	PK - PK (eff. = 1) (IP 2)	2	PK (Tech 2)	2	Regional power demand
				3	PKS	3	PKS - PKS (eff. = 1) (IP 3)	3	PKS (Tech 3)		
				4	PMF	4	PMF - PMF (eff. = 1) (IP 4)	4	PMF (Tech 4)		
				5	EFB	5	EFB - EFB (eff. = 1) (IP 5)	5	EFB (Tech 5)		
				6	POME	6	Composting (IP 5,6)	6	Biofertiliser (Tech 6)		
						7	Anerobic digestion, 1 MW (IP 6)	7	Power (Tech 7,8,9,10,11)		
						8	Anaerobic digestion, 2 MW (IP 6)				
						9	Low efficient CHP, 1 MW (IP 3,4)				
						10	High efficient CHP, 4 MW (IP 3,4,5)				
						11	High efficient CHP, 9 MW (IP 3,4,5)				

Figure S1. List of raw materials, intermediate products (IP), technologies (Tech), bio-products (BP) and associated demands optimized in the BeWhere model. Notes: Abbreviations: CHP (combined heat and power), CPO (crude palm oil), EFB (empty fruit bunch), FFB (fresh fruit bunch), PK (palm kernel), PKS (palm kernel shell), PMF (palm mesocarp fiber), POME (palm oil mill effluent). * For the purpose of this analysis, demand of palm oil is defined as the CPO production capacity of the palm oil mill.

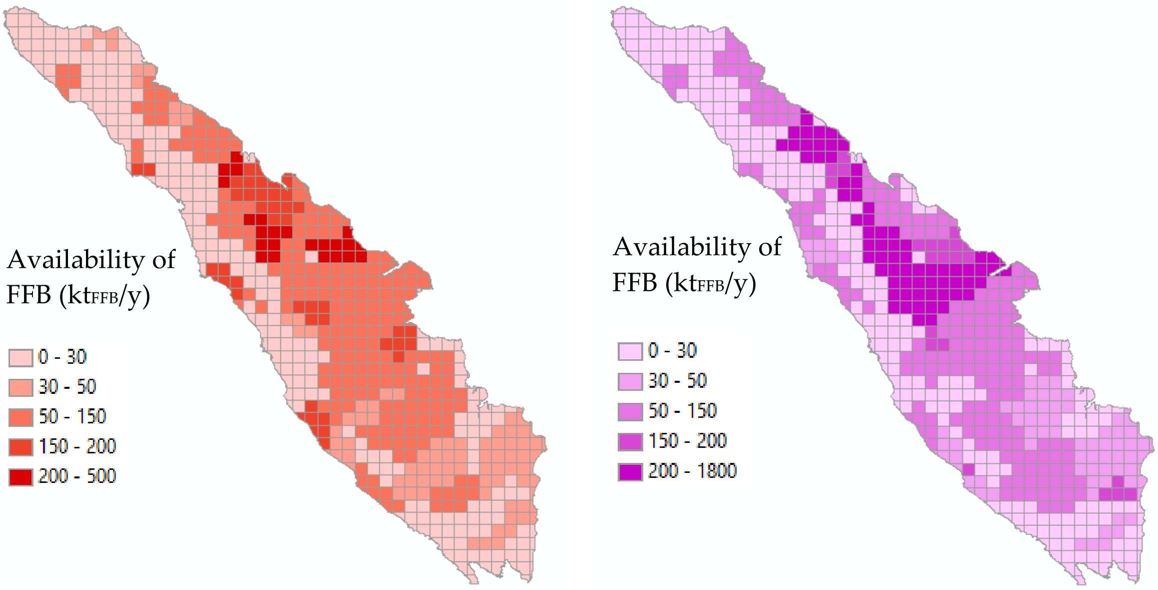

Figure S2. Representation of FFB availability in Sumatra, grid of 25 km × 25 km (left: small-scale plantations, right: large-scale plantations). Source: FFB availability in each district is quantified based on mature plantation area and average plantation yield [1].

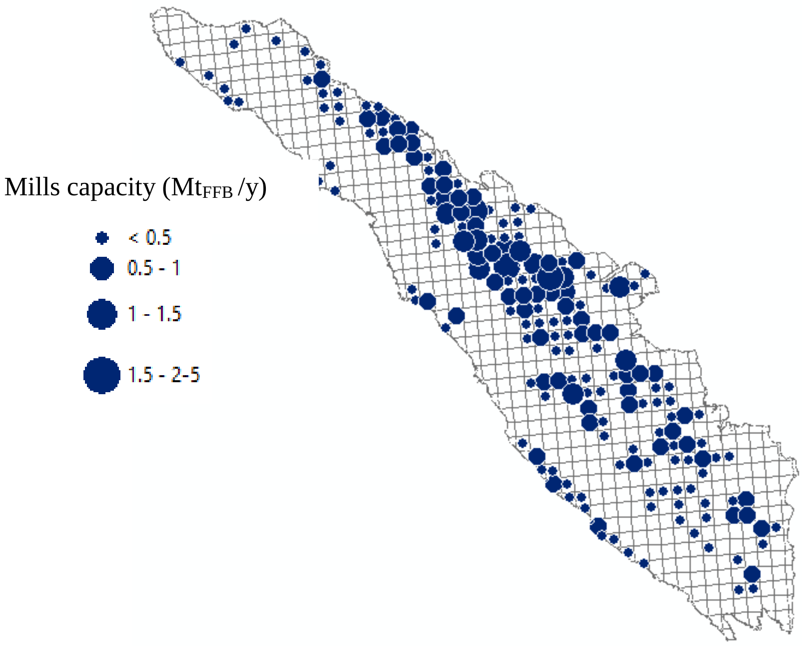

Figure S3. Mills capacity in grid of 25 km × 25 km.

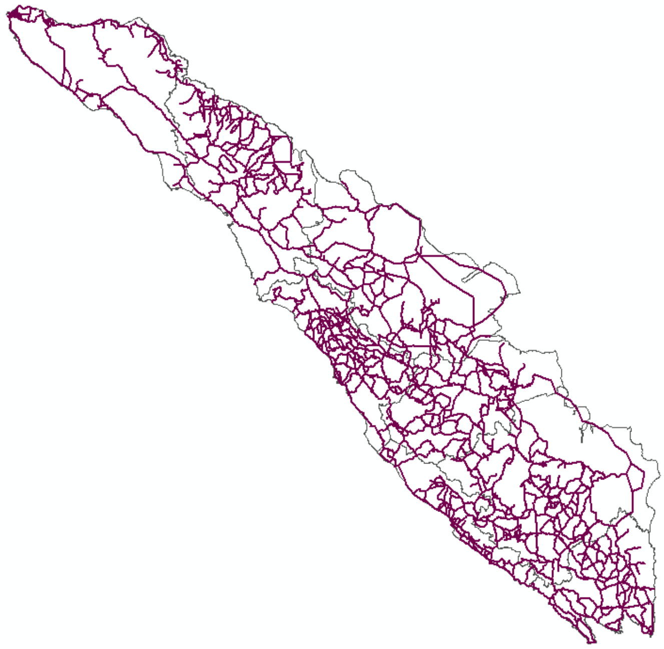

Figure S4. The road network of Sumatra. Source: Original data was obtained from Diva-GIS [2], road connection was improved by authors in ArcGis software.

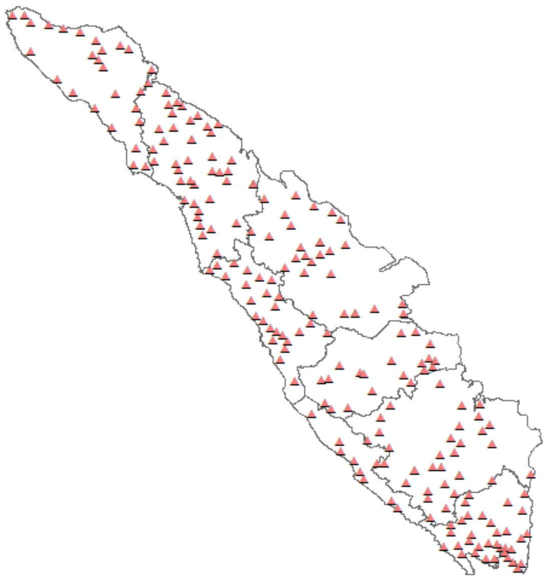

Figure S5. Geographical location of distribution transformers. Source: Original map was obtained from PLN [3] and georeferenced by authors.

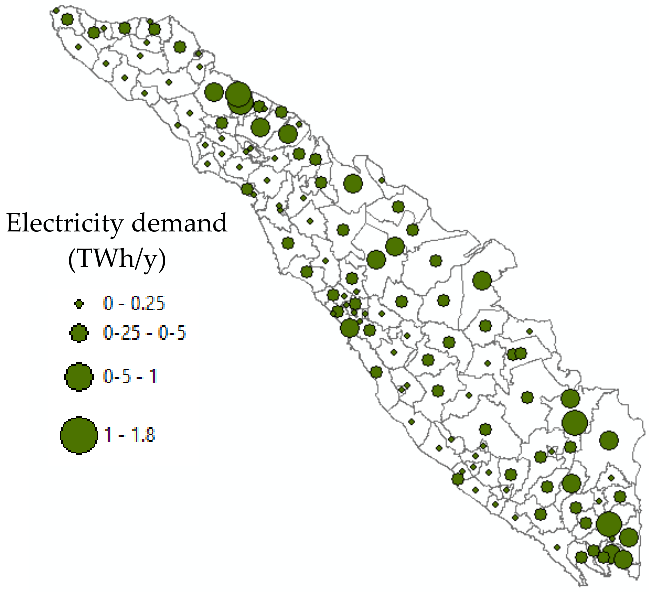

Figure S6. District's electricity demand. Source: The electricity demand per district is quantified based on population [4] and average electricity consumption per capita in Indonesia (812 kWh/y [5]). Total electricity demand in Sumatra considered in this study is 34 TWh/y.

Table S1. Conversion rate from FFB to intermediate products. (Values are expressed in $t_{product}$ per t_{FFB}).

Intermediate Product	Conversion Rate
Crude palm oil, CPO	0.2
Palm kernel, PK	0.047
Palm kernel shell, PKS	0.06
Palm mesocarp fiber, PMF	0.14
Empty fruit bunch, EFB	0.23
Palm oil mill effluent, POME	0.022

Sources: All values were obtained from field work in 2016. Dry POME considers 4% dry content of POME [6].

Table S2. Technological conversion rate for processing the biomass residue into bio-products.

Biomass Residue (Intermediate Products)	Biomass Technology	Bio-Products	Unit	Technological Conversion Rate
Empty fruit bunch, EFB	Co-composting plant	Biofertilizer	$t_{biofertilizer}/t_{FFB}$	0.32 [6]
Palm oil mill effluent, POME	Co-composting plant	Biofertilizer	$t_{biofertilizer}/t_{dry\text{-}POME}$	3.38 [6]
Palm oil mill effluent, POME	Biogas plant	Electricity	$MWh/t_{dry\text{-}POME}$	2.40 [7]
Palm kernel shell, PKS	Low efficient CHP plant	Electricity	MWh/t_{PKS}	0.57 (*)
Palm mesocarp fiber, PMF	Low efficient CHP plant	Electricity	MWh/t_{PMF}	0.58 (*)
Palm kernel shell, PKS	High efficient CHP plant	Electricity	MWh/t_{PKS}	1.37 (*)
Palm mesocarp fiber, PMF	High efficient CHP plant	Electricity	MWh/t_{PMF}	1.39 (*)
Empty fruit bunch, EFB	High efficient CHP plant	Electricity	MWh/t_{EFB}	1.19 (*)

Notes: * The technological conversion rate of the equipment producing electricity from solid biomass considers low heating values of 18.31 MJ/kg_{PKS}, 18.49 MJ/kg_{PMF}, 15.82 MJ/kg_{EFB} [8]. Low efficient CHP plant was assumed to have electrical efficiency of 11%, while the high efficient CHP plant has electrical efficiency of 30%.

Table S3. Annualized cost of biomass-based technology.

Biomass Technology	Bio-Products	Unit	Annualized Technology Cost	O&M Cost
Co-composting plant	biofertilizer	$USD/t_{biofertilizer}$	5.12 [6]	0.26
Biogas plant (anaerobic digestion), 1 MW	Electricity	USD/MWh	31.1 [9]	1.56
Biogas plant (anaerobic digestion), 2 MW	Electricity	USD/MWh	25.26 [9]	1.26
Low efficient CHP plant, 1 MW	Electricity	USD/MWh	23.65 [10]	1.18
High efficient CHP plant, 4 MW	Electricity	USD/MWh	36.12 [11]	1.81
High efficient CHP plant, 9 MW	Electricity	USD/MWh	28.32 [11]	1.42

Notes: The scaling effect of 0.7 [12] was used to adjust the costs of equipment from the reference value. Capacity factor of 80% is used to quantify the investment cost of biomass and biogas plants. O&M cost is 5% of the capital cost [13].

Table S4. Prices of bio-products used in the analysis.

Bio-Product	Unit	Market Price
Crude palm oil, CPO	USD/t_{CPO}	600 [14]
Palm kernel, PK	USD/t_{PK}	410 [15]
Palm kernel shell, PKS	USD/t_{PKS}	69 [16]
Palm mesocarp fiber, PMF	USD/t_{PMF}	7 [16]
Empty fruit bunch, EFB	USD/t_{EFB}	7 [16]
Biofertilizer	USD/$t_{Biofertilizer}$	88 (*)
Electricity from biomass source	USD/MWh	85 (Regulation 12/2017)

Note: * Calculated based on inorganic fertilizer price (NPK) [17] and considering nutrients value substitution of a tonne inorganic fertilizer equals to 7.9 dry tons of produced biofertilizer [18].

Table S5. Emissions factor applied in the model.

Item	Emission Factor
Feedstock production for small-scale plantation (a)	0.089 tCO_2eq/t_{FFB}
Feedstock production for large-scale plantation (a)	0.096 tCO_2eq/t_{FFB}
Feedstock transport (b)	90 $tCO_2eq/Mt_{FFB}/km$ [19]
Fossil diesel (c)	3.14 $kgCO_2eq/l_{diesel}$ [20]
Composting palm oil mill effluent	0.01 tCO_2eq/t_{POME} [21]
Bioelectricity production in biomass CHP plant (d)	7 $kgCO_2eq/MWh$
Bioelectricity production in biogas plant (d)	0.91 $kgCO_2eq/MWh$
Grid electricity emission factor of Sumatra	0.855 tCO_2eq/MWh [22]
Methane avoidance from POME treatment (e)	0.39 tCO_2eq/m^3_{POME}

Notes: (a) The emissions from activities required for producing FFB encompassed emissions from the use of nitrogen fertilizer in the plantation that emitted N2O. The amount of nitrogen fertilizer applied was calculated based on equation by Khasanah [23] for the relation between nitrogen fertilizer applied and the plantation yield in Indonesia: y=1.1386x2 – 28.157x + 265.36, where y is the amount of nitrogen fertilizer applied and x is plantation yield. Based on that equation the small and large-scale plantations consumed 92.94 kg/ha and 138.72 kg/ha of nitrogen fertilizer respectively, also shown in Table 1 of the main text. For the model input, the values of the fertilizer consumption were converted into 0.09 tCO2eq/tFFB for small-scale plantations and 0.1 tCO2eq/tFFB for large-scale plantations, considering conversion factors of 0.03 kgN2O/kgNfertilizer [24], conversion factor of N2O-N emissions to N2O emissions of 44/28, and GWP: 298. (b) The transportation emissions included the amount of FFB transported and the travel distance of a round trip between plantation and palm oil mill using heavy truck vehicle. (c) The emissions in palm oil mill included the use of diesel fuel for starting up daily operation (i.e., 0.768 l/tFFB [25]). (d) GHG emissions (i.e., CH4 and N2O only) for electricity generation from stationary application is 0.109 kgCH4/MWh and 0.0143 kgN2O/MWh for biomass combustion, and 0.0109 kgCH4/MWh and 0.02 kgN2O/MWh for biogas combustion [26]. CO2 emissions associated with biomass and biogas combustion were not accounted for since bioenergy is carbon-neutral along the biofuel chain. (e) The emissions factor of the methane avoidance from treating POME is calculated based on the UNFCCC methodology AMS-III.H.: Methane recovery in wastewater treatment [27]. The factors from Taylor et al. [7] are applied. Methane yield: 0.24 tCH4/tCOD, methane conversion factor: 0.8, lagoon Chemical Oxygen Demand (COD) efficiency: 0.96, POME to FFB ratio: 0.6 m3POME/tFFB, uncertainty factor: 0.9 and GWP: 25.

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