Supplemental Information

1. Detailed Explanation on the Estimation of the Availability Biomass Residues

1.1. Oil-Palm Residues

Oil palm residues consist of the following components; empty fruit bunches (generated at the palm oil mills during crude palm oil extraction), fibers and shells (generated at the palm mills), oil palm trunks (generated in the field during replanting), and pruned fronds (generated in the field during replanting). Each residue has current and potential future uses. Thus, the availability etimates were reduced to assure these uses were met (see below). Residue amounts were estimated based 2009 Peninsular Malaysia palm cultivated area of 2.5 million ha.

Private plantations use almost all EFB as a mulching agent [1]. Because 60% of oil-palm plantations are private [2], the available EFB was reduced by 60% to account for this use. Additionally, large palm-oil mills burn EFB to generate electricity (about 85 MW of capacity) for internal use [3], which is estimated to use about 5% of the total EFB. Palm-oil mills are generally accessible by road and the residues are usually piled for storage [4], thus a 100% recoverability rate was assumed. Using these data and assumption, it was estimated that between 1.2 and 1.4 million tonnes (Mt) of EFB are available for co-firing use annually.

Oil-palm fibers and shells are used in large mills to generate steam for the palm-oil extraction process. As such, the available amount was reduced 60% [2] to account for this use. A 100% recoverability rate was assumed as for the EFB [4]. Between 1.3 and 1.6 Mt of fibers, and between 0.79 and 1.1 Mt of shells were calculated to be available for co-firing use, respectively.

Trunks from oil-palm trees are available upon replanting, on average, every 25 years. However, oil-palm trunks have found a new and emerging use in the wood industry for making medium density fiber board, plywood and furniture [5]. About 40% of the trunks are used in the wood industry [6]. A 40% [6] recoverability rate was assumed on the remainder of the palm trunks for co-firing use because these residues need to be removed from the field in rural areas underserved by transportation infrastructure. This results in 1.0 and 1.8 Mt/year of palm trunks being available for co-firing use.

Fronds are left in the field to conserve the soil, act as soil conditioner and prevent erosion [7] Fifty percent of these are assumed 50% available for co-firing. Efforts are also being undertaken to utilize fronds for ruminant feed. A potential new use of fronds is related to feeding ruminants. A Malaysian study found that up to 7 kg/day of fronds can be fed to ruminants [7]. If all of the approximately 1.6 million cows are fed with a mixture of fronds in their daily diet, it would require about 4 Mt/year of fronds. Using the midpoint fronds generation rate (8.2 t/ha) and based on the country's total oil palm planted area of about 4.7 million ha in 2009, it is estimated that 11% of the total fronds could be used as an animal feed. There is no data available to estimate the collection rate of fronds, so the rubber branch recoverability rate of 50% [8] was used as a surrogate for pruned palm fronds. The recoverability rate for fronds from felled trees is assumed to be 40% as before [6]. Between 2.9 and 5.1 Mt of pruned fronds and between 0.23 and 0.23 Mt of fronds from felled trees were estimated to be available for co-firing annually.

1.2. Logging Residues

Based on Peninsular Malaysia's production data from 1998 to 2007 [9] and using the double moving average method, logs extracted in 2009 were estimated at approximately 4.4 million m^3, equivalent to 3.4 Mt (using wood density's midpoint value of 0.78 t/m^3 [10,11]). For every tonne of logs extracted, residues of between 37% [8] and 43% [12] based on the log weight are left behind in the forest. Using these estimates there an estimated 1.3 and 1.5 Mt of logging residues available. Assuming a recovery 65% [13], between 0.82 and 0.95 Mt/year of logging residues are available for co-firing.

There are 577 sawmills and 59 plywood mills operating in 2009 [9,14]. For the sawmills between 13% [12] and 33% [8] of production is residue. The estimated production of sawn timber in 2009 was about 2.2 Mt/year [9] resulting in an estimated annual residue availability of between 0.29 and 0.73 Mt. Yoshida [15] estimated that on average 25% of these residues can be collected for South-East Asian countries. Lim [8] estimated a lower recoverability rate than Yoshida at 13%. Using these recovery estimates as a lower and upper bound results in 0.04 and 0.183 Mt/year of sawmill residues available for co-firing. On average, each mill would have between 66 and 320 t/year of residues.

The estimated 2009 annual plywood production was approximately 0.35 Mt/year [16]. The residues generated were assumed between 40 and 53% [12,15] of production and the recoverability factors were assumed to be the same as for sawmills (13 to 25%) [8,15]. Thus the total recoverable residues from plywood mills were estimated at between 0.018 and 0.046 Mt/year. There are 59 plywood mills and on average, a plywood mill can supply between 305 and 790 t/year of residues for co-firing use.

1.3. Rice Residues

In 2009, there were 508,780 ha of rice-fields in Peninsular Malaysia producing 2,126,531 t of grain [17]. Rice residues consist of the rice husk and the straw. There are about between 425,000 and 447,000 t of rice husks, based on estimates that for every tonne of grain, between 0.2 and 0.21 t of husk is produced [18,19]. Rice husks are used to generate process heat for rice drying in Malaysian rice mills [19]. However, there is no data as to how extensive this is practiced. Conservatively, assuming that husks provide all of the drying energy and knowing that rice drying consumes 1,500 MJ of energy/t of rice dried [20], then approximately 230,000 t/year of rice husks are required to process 2.1 Mt of rice annually, based on rice husk's energy content of 14 MJ/kg [20]. Thus, the remaining 195,000 to 217,000 t of rice husks are available for co-firing annually. Rice mills are easily accessible having a developed transportation system and husks are usually piled [21], thus a 100% recoverability rate was assumed.

Rice straw is produced at rates between 0.5 and 1.0 t for every tonne of grain [22]. Therefore, there are about between 1.1 and 2.1 Mt of rice straw left in the field. Currently rice straw is sometimes burned but there are no official numbers. We assume with a market for the straw this practice would cease. However, rice straw is also used as ruminant feed (10%) [22]. At a 65% recoverability rate[13], rice straw, assumed baled and placed on the nearest roadside results in between 0.64 and 1.2 Mt of straw available for co-firing in this study.

1.4. Rubber Residues

Rubber residues consist of tree branches that fall naturally each year and those obtained during replanting. Trunks are used in the furniture market [8]. There are 1,021,540 ha of rubber plantations in 2009 in Peninsular Malaysia [23]. Standing biomass for a rubber tree field is between 6 and 7 t/ha [9], which 5% are naturally fallen branches, The total annual residue availability of about between 0.31 and 0.36 Mt. Lim [8] suggests that the residues are not easily collected or recovered due to labor shortages and access and estimated that only 50% of the branches can be collected economically. Thus the estimated the total recoverable biomass residues is between 0.15 and 0.18 Mt/year.

Using historical rubber cultivation area from 1975 to 2009 [16,23] and based on the economic lifespan of 30 years [24], approximately 1% of the rubber trees or about 10,200 ha are replanted annually. Using the 6 to 7 t/ha of standing biomass in rubber plantations [8], between 0.06 and 0.07 t of rubber trees are harvested annually. Felling of trees leaves residues between 30 and 54% of the original branches per tonne of rubber trees harvested. As such, between 0.02 and 0.04 Mt of branches are available annually due to replanting. At the recoverability rate of 50% [8], the amount of branches are estimated at between 0.01 and 0.02 Mt/year. Total branches (yearly operations above and replanting) is approximately 0.16 and 0.2 Mt/year

1.5. Coconut Residues

Useful coconut residues for energy production consist of the shell, husks, fronds and trunks. The coconut shells, husks and 90% of the fronds are used for domestically production of copra [8]. Based on 2006 data for Peninsular Malaysia [25], about 94,000 ha of planted coconut in Peninsular Malaysia in 2009 [17]. Between 2.3 and 3.9 t/ha of fronds are shed annually [8,26]. With 10% of the fronds available [8] and using the same accessibility rate as for rubber production (50%) [8], between 0.01 and 0.02 Mt of fronds could be used for co-firing. Trunk availability was estimated by using the total standing biomass (39 to 80 t/ha [27,28]), the annual rate at which coconut trees are replanted (1% [16,23]) and accessibility factor of 50% [8] (replanting rate and accessibility factor of rubber plantations are used as surrogates). Thus, we estimated that about 0.02, to 0.03 t of coconut trunks could be recovered for co-firing annually.

1.6. Cocoa Residues

There are only 3,662 ha of cocoa planted in Peninsular Malaysia in 2009 [29]. The cocoa tree is a small tree and obtaining branches during routine pruning is the only economic source of residues [8]. Pruned branches of cocoa trees are estimated to be between 20 and 25 t/ha [8,30]. Using rubber plantation accessibility rate at 50% as surrogate [8], about 0.04 and 0.05 Mt of cocoa branches are available for co-firing use.

1.7. Wood-Based Municipal Solid Waste (MSW)

Data from the Department of National Solid Waste Management were used to estimate the wood-based wastes in landfills in Peninsular Malaysia [31]. There are 98 landfills in operation. The total wastes disposed at landfills are 19,210 t/day or about 7.0 Mt/year [32]. Wood-based MSW in

Malaysia is 24 to 26% of the total waste and includes paper, cardboard, and yard trimmings [32,33]. The average moisture content of Malaysia's MSW is 55% [33]. Seventeen percent of the wood-based MSW is recycled or used as composting materials [32]. Also assuming a 67% recoverability rate [13], between 0.42 and 0.45 Mt/year of wood MSW is available.

2. Data for Other Input Parameters Used in the Optimization Model

Table S1. Biomass residue types and number of supply locations for each.

Residue types (*T*)	**Num. of supply locations (n_t)**
palm oil mill empty fruit bunch residues	250
palm oil mill shell residues	250
palm oil mill fiber residues	250
rice mill husk residues	230
landfill wood-based MSW residues	98
sawmill residues	577
plywood mill residues	59
oil palm plantation trunk residues	3,325
oil palm plantation frond residues	3,325
rice fields straw residues	781
logging residues	97
rubber plantation branch residues	3,879
coconut plantation trunk residues	312
coconut plantation frond residues	312
cocoa plantation branch residues	17

Table S2. Additional input data for optimization models.

Description	Unit	Distribution	Min.	Most likely	Max.	Notes
Energy content of palm EFB	GJ/t	Uniform	15.5 [34]	-	18.8 [35]	-
Energy content of palm shell	GJ/t	Uniform	20.1 [35]	-	20.7 [34]	-
Energy content of palm fiber	GJ/t	Uniform	18.5 [34]	-	19.1 [35]	-
Energy content of rice husk	GJ/t	Uniform	13.8 [36]	-	15.7 [37]	-
Energy content of paper and wood-based MSW	GJ/t	Uniform	3.4 [38]	-	6.3 [38]	-
Energy content of sawmill residues	GJ/t	Uniform	6.3 [39]	-	18.8 [40]	Used sawdust as surrogate [40].
Energy content of plywood mill residues	GJ/t	Uniform	6.3 [39]	-	18.8 [40]	Used sawdust as surrogate [40].
Energy content of palm trunk	GJ/t	-	-	17.5 [40]	-	-
Energy content of palm frond	GJ/t	Uniform	7.5 [39]	-	15.7 [3]	-
Energy content of rice straw	GJ/t	Uniform	16.8 [41]	-	17.1 [42]	-
Energy content of cocoa branches	GJ/t	Uniform	13.9 [39]	-	17.9 [43]	Rubber wood as surrogate [43].
Energy content of rubber branches	GJ/t	Uniform	13.9 [39]	-	17.9 [43]	Rubber wood as surrogate [43].
Energy content of coconut trunk	GJ/t	-	-	17.5 [40]	-	Palm trunk energy content as surrogate.
Energy content of coconut frond	GJ/t	Uniform	7.5 [38]	-	15.7 [3]	Palm frond energy content as surrogate.
Energy content of logging residues	GJ/t	Uniform	16.5 [44]	-	18.8 [44]	-
Coal energy content	GJ/t	-	-	31 (Bituminous coal) 27 (Sub-bituminous coal) [45]	-	-

Table S2. *Cont.*

Description	**Unit**	**Distribution**	**Min.**	**Most likely**	**Max.**	**Notes**
Lifecycle GHG emissions rice cultivation	t CO_2-eq/t product	Uniform	1.23 [46,47]	-	1.83 [46,47]	Blengini and Busto's [46] result showed that between 2.53 and 2.76 kg of CO_2-eq is emitted per kg rice at mill gate. But he did not give the breakdown of the unit processes. To get only up to the cultivation stage, we subtracted his values from LCA of rice milling emissions from Roy *et al.* [47].
Lifecycle GHG emissions rice milling	t CO_2-eq/t product	Triangular	0.93 [47]	1.2 [47]	1.3 [47]	-
Lifecycle GHG emissions of palm oil	t CO_2-eq/t product	Triangular	1.5 [48]	2.0 [48]	2.5 [48]	These figures do not include land use change to standardize with estimates of GHG emissions from other biomass/products.
Lifecycle GHG emissions of coconut copra	t CO_2-eq/t product	Uniform	0.38 [47]	-	0.43 [47]	-
Lifecycle GHG emissions of landfilling	t CO_2-eq/t MSW	Uniform	1.3 [49]	-	1.9 [50]	Liamsanguan *et al.* [49] did not include the methane emissions from landfilling. Cherubini *et. al.* [50] accounted for landfilling methane emissions.
Lifecycle GHG emissions of sawmill/plywood mills products	t CO_2-eq/t product	Uniform	0.34 [51,52]	-	0.52 [53]	-
Lifecycle emissions of logging	t CO_2-eq/t lumber	Uniform	0.045 [54]	-	0.21 [53]	-

Table S2. *Cont.*

Description	Unit	Distribution	Min.	Most likely	Max.	Notes
Lifecycle GHG emissions of transporting biomass	t CO_2-eq/t.km	Uniform	0.00015 [55]	-	0.00045 [55]	Campbell's *et al.* [55] estimate is for Ultra Low Sulfur Diesel in Australia. We used data from Davis [56] to calculate the energy per t.km, about 2.7 MJ/t.km. We then used NETL's [57] lifecycle GHG emissions factor of diesel fuel (90 g GHG/MJ) to calculate the emissions (about 240 g CO_2-eq /t.km). The min and max figures have taken into account 14% less energy consumption for the empty trucks return trip [58].
Lifecycle emissions of electricity in Malaysia	t CO_2-eq/MWh	Uniform	0.52 [3]	-	0.97 [3]	Using national electricity generation mix in Malaysia of 2.3% oil, 58% natural gas and 32.4% coal in 2009 [3]. This estimated range of emissions is based on an estimated CO_2–eq emission factor of 0.75–1.3, 0.52–1.2 and 0.40–0.78 kg/kWh of electricity generated from coal, oil and gas, respectively [59].
Coal transportation distance	km	-	-	4,800	-	According to a representative from the utility company, all coal is imported from three countries with 10% from South Africa and the remaining 90% from Indonesia and Australia [60]. The distance is the weighted average from these countries (South Africa ~10,500 km; Indonesia ~2,000 km; and Australia ~6,300 km).

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