WHITE PAPER

JUNE 2016

POTENTIAL FOR ADVANCED BIOFUEL PRODUCTION FROM PALM RESIDUES IN INDONESIA

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ACKNOWLEDGEMENTS

With thanks to Gary Paoli. This paper was produced with the generous support of the David and Lucile Packard Foundation.

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EXECUTIVE SUMMARY

Indonesia is the world's leading producer of palm oil, supplying almost half of the commodity globally. Its palm oil industry continues to expand rapidly, in part to meet domestic goals for increased biodiesel blending, but this expansion causes carbon losses through deforestation and peat degradation. At the same time, Indonesia has expressed a commitment to reduce its national greenhouse gas (GHG) emissions. At the moment, the link between palm oil expansion and deforestation means that there is a tension between increasing biofuel production and meeting national climate commitments. These goals could, however, be pursued synergistically through the promotion of more sustainable palm oil and biofuel production practices. One strategy to produce low-carbon renewable energy is to create advanced biofuel from unused palm residues. Biofuel made from palm fronds, trunks, or empty fruit bunches that are not needed for other purposes could deliver high GHG savings while supporting the agricultural economy and displacing oil imports. This study assesses the production and other uses of palm residues and estimates the amount that could be sustainably available for biofuel.

Palm residues are currently used primarily as a soil amendment. Palm fronds and trunks from pruning and replanting are generally left in the field, where their decomposition releases nutrients and organic carbon into the soil. Empty fruit bunches that are left over from the palm milling process are sometimes returned to the field as well. These residues also reduce erosion and help the soil retain moisture. All of these factors serve to preserve the fertility of the soil and support higher palm oil yields in subsequent years. Some level of residue retention in palm plantations is thus important for sustainable cultivation, and this practice should be continued and enhanced. However, it is not necessary to return all palm residues to the plantation. The main services provided by residues can be maintained if most of the fronds and trunks are kept in the field; a fraction of these components, as well as all processing residues produced at the mill, can be utilized for other purposes without affecting soil fertility, as long as lost nutrients are replaced with inorganic fertilizer and sustainable management practices are implemented. We estimate that on average around 32% of all palm residues can be removed without significant negative impacts on soil quality or palm yields.

Some processing residues, such as the palm kernel shells and palm press fiber, are already combusted to produce heat and electricity to power the palm oil milling process. This use of residues displaces fossil fuels and reduces greenhouse gas emissions. We estimate that around 8% of all palm residues would be used in this way if all palm oil mills in Indonesia operated on biomass heat and power. The use of biogas heat and power from anaerobic decomposition of palm oil mill effluent (POME), a milling residue, is an emerging practice, but it is not explicitly considered here. This use of POME would displace some of the solid residue biomass we assume is used to power the mills and so would not affect total net availability of residues for biofuel. While there are other occasional uses of palm residues, such as the use of felled palm trunks as a building material by local populations, it does not appear that these uses constitute a significant fraction of all palm residue production and so they are not accounted for here.

Table A summarizes our assessment of the production and other uses of palm residues in Indonesia on a per hectare basis. Around 24% of total palm residues, or 4.5 dry tonnes per hectare per year, are not needed as a soil amendment or to power the palm oil mills; this fraction can be considered sustainably available for biofuel without risking significant indirect impacts.

Table A. Annual per-hectare production, uses, and sustainable availability of oil palm residues in Indonesia

	Residue type	Production (dry t ha^{-1} yr^{-1})	Use as soil amendment (dry t ha^{-1} yr^{-1})	Use for heat and power (dry t ha^{-1} yr^{-1})	Net availability (dry t ha^{-1} yr^{-1})
Processing residues	Empty fruit bunches	1.6	0	0	1.6
	Palm kernel shells	1.1	0	0.6	0.5
	Palm press fiber	1.7	0	0.9	0.8
	Palm oil mill effluent (POME)	0.7	0	0	0.7
Field residues	Fronds	0.6 (felling) 10.4 (pruning)	11.0	0	0
	Trunks	2.8	1.9	0	0.9
	TOTAL	**18.9**	**12.9**	**1.5**	**Final residue availability: 4.5**

Of this amount of available residues, 3.8 dry t ha^{-1} yr^{-1} comprises solid biomass that could be converted to advanced biofuel, for example cellulosic ethanol or renewable diesel. This amounts to 34 million tonnes biomass per year on a national level, which could potentially displace 7.4 million tonnes of diesel and gasoline, or 15% of total road fuel consumption. Additionally, the Indonesian palm oil industry could produce 1.5 million tonnes per year of methane from POME, which could potentially displace 1.6 million tonnes of diesel or gasoline, or 3% of Indonesia's total annual diesel and gasoline demand. Biogas used in natural gas vehicles could deliver air quality benefits as this fuel burns much more cleanly than diesel. If used in Indonesia's energy and petrochemical sectors, this amount of biogas could instead displace 6% of Indonesia's current annual demand for natural gas.

In this assessment we found that a substantial fraction of Indonesia's transport fuel needs could be met with low-carbon advanced biofuel produced from sustainably harvested palm residues. Supporting advanced biofuel from wastes and residues in Indonesia could make a meaningful contribution to the country's GHG reduction targets with low risk of negative indirect impacts. At the same time, domestic biofuel production from palm residues would support the country's agricultural economy and improve its trade balance by displacing oil imports. Because advanced biofuels are often considered as high-risk ventures by investors, policy and fiscal support by the Indonesian government would be needed to encourage commercialization of this industry.

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INTRODUCTION

Indonesia is the world's leading producer of palm oil, supplying almost half of the commodity globally (FAOSTAT, 2015). In 2014, Indonesia produced 31 million tonnes of crude palm oil and exported two thirds of it, earning USD$21 billion (Indonesia-Investments, 2015). Indonesia is undergoing a long-term expansion of the palm oil industry, with plantation area growing at 10% per year (Gunarso et al., 2013). Total harvested oil palm area in Indonesia was estimated to be 8.9 million ha in 2015 (Wright and Rahmanulloh, 2015).

Palm oil production in Indonesia routinely expands onto forestland and other natural areas (Miettinen et al. 2012). Business-as-usual (BAU) oil palm expansion depletes biodiversity, destroys old growth rainforest, and causes air pollution (as land clearance is associated with fires). When land-use change emissions from palm expansion are accounted for, palm biodiesel actually increases emissions compared to fossil diesel (Malins, 2012; Page et al., 2011; Valin et al. 2015). Indonesia is one of the world's top five GHG emitters and has set a goal to reduce its emissions by 26% below BAU by 2020 (PR 61/2011). However, land-use change emissions from the palm industry threaten Indonesia's GHG reduction goals. One of Indonesia's strategies for carbon reduction is the promotion of renewable energy, with targets of 23% renewable energy in the national energy mix by 2025 (GR 79/2014), and 30% biodiesel blending in road fuel by 2025 (MEMR 12/2015). Much of the biodiesel mandate is expected to be met using palm oil. Without a new vision for biofuel production, there is great risk that this part of Indonesia's renewable energy policy will increase rather than reduce Indonesian emissions, undermining the commitment to emission reduction.

Biofuel made from residues such as palm fronds and empty fruit bunches, however, can deliver much greater greenhouse gas reductions than conventional biofuel made from corn ethanol or palm oil (Baral and Malins, 2014). Expanding use of sustainable feedstocks for biofuels can also reduce national dependence on imported fossil fuels and create agricultural jobs. But it is important to remember that the use of any feedstock for biofuel can have unintended negative consequences if that feedstock is diverted from other uses. In this study, we assess the production of the various types of palm residues in Indonesia and the quantities needed for other purposes such as fertilizer and heat and power production. We then estimate the amount of palm residues that may be considered sustainably available for biofuel production without affecting these uses.

RESIDUE PRODUCTION

Oil palms produce fresh fruit bunches (FFB) as early as 2.5 years after planting and reach peak productivity 10 years post planting. Though the natural tree lifespan is 120 years, an oil palm experiences an economic life lasting 25-30 years, after which it is felled for replanting (Wahid et al., 2005; Sridhar and AdeOluwa 2009). Some residues are produced on an annual basis, while trunks and larger amounts of fronds are generated when trees are felled. In the following sections, we describe each type of residue from the palm oil industry and provide estimates of annual production per hectare. Note that we do not include palm kernel cake, which is a by-product of extracting palm kernel oil. Palm kernel cake is nutrient rich and sold unprocessed for animal feed (Paoli at al., 2014), so we consider it a co-product and not a residue for the purposes of this report. Similarly, we do not include oily residues from palm refining, such as palm fatty acid distillates, which already have high value uses. Production of each type of residue per hectare is summarized in Table 1.

OIL PALM PROCESSING RESIDUES

These residues include: EFB, fiber, shells, and POME.

Empty fruit bunches (EFB): EFB result from the sterilization and stripping of FFB. Each FFB contains about 100 fruits that are held in place by the EFB husk. The EFB are the fibrous outer portions of the FFB once the fruits have been removed for processing by a thresher.

Palm press fiber: This is the fibrous residue obtained after crude oil is separated from the fruit by digestion and pressing. It retains large amounts of residual palm oil.

Palm kernel shells: Each fruit has a palm kernel inside it. A hard shell surrounds this kernel. Kernels are separated from their shells for the purpose of extracting crude palm kernel oil. The shells are hard, dense, and are similar in appearance to small coconut shells.

Palm oil mill effluent (POME): POME is the liquid portion of mill waste. It is the water left over from processing FFB, and it contains fruit residue, oil, and organic matter. POME comprises most of the water in FFB, as well as water added during extraction, and has an average moisture content of 94% (Table 2). Raw POME is an environmental hazard due to its high organic content, so it is kept in open ponds for a month to degrade before being released into waterways. This storage process releases methane. Of the 600 palm oil mills in Indonesia, 30 use methane capture technology on the POME that is treated in settling ponds (Paoli et al., 2014).

OIL PALM FIELD RESIDUES

These residues include trunks from felling, and fronds from felling and pruning.

Oil palm trunk: This residue is produced when palms are felled in order to replant the plantation with younger, more productive trees. Felling only occurs once every 25 years, but plantations vary in age and any particular plantation generally has trees that were planted in different years. Felling generates around 75 dry tonnes trunks ha^{-1}; annualized, this amounts to 2.8 dry tonnes trunks ha^{-1} yr^{-1} (Table 1).

Oil palm fronds: These are the leaves of the palm tree. They consist of the leaflet portion and a long petiole that attaches the frond to the trunk of the tree. Palm trees do not have branches. Fresh fruit bunches form at the base of the fronds where the fronds are attached to the trunk. In order to harvest the FFB, the fronds must be removed. Fronds are pruned periodically and are also generated during tree felling. About 15 dry tonnes frond biomass is generated during felling; annualized, this equates to 0.6 dry tonnes fronds ha^{-1} yr^{-1}, while the annual production of fronds from pruning is 10.4 dry tonnes ha^{-1} yr^{-1} (Table 1).

Table 1. Annual production of palm residues (dry tonnes ha^{-1} yr^{-1}).

	Residue type	Production (dry t ha^{-1} yr^{-1})	References
Processing residues	**Empty fruit bunches**	1.6	Sulaiman and Abdullah, 2011; Yusoff, 2006; Lim, 1986 (as cited in Lim, 1998)
	Palm kernel shells	1.1	Sulaiman and Abdullah, 2011; Yusoff, 2006; Lim, 1986 (as cited in Lim, 1998)
	Palm press fiber	1.7	Lim, 1986 (as cited in Lim, 1998); Sulaiman and Abdullah, 2011; Yusoff, 2006
	POME	0.7	Yusoff, 2006
Field residues	**Fronds**	0.6 (felling) 10.4 (pruning)	Lim, 1986 (as cited in Lim, 1998); Chan et al., 1980 (as cited in Yusoff, 2006); UNEP, 2012
	Trunks	2.8	Chan et al., 1980 (as cited in Yusoff, 2006); Lim, 1986 (as cited in Lim, 1998)

RESIDUE RETENTION FOR SOIL QUALITY

Palm field residues (trunks and fronds) are typically left on the soil of the plantation, and empty fruit bunches are often returned to the soil as well. Residues left on the field improve soil quality by acting as fertilizer, increasing the water retention capacity of the soil, reducing erosion, and increasing soil carbon.

Current practice

In Indonesia, field residues are typically not removed from the field. Fronds are trimmed and either left in plantations as mulch, heaped between planting rows (Teh, 2016), or sometimes burned, even though this practice is prohibited in Indonesia (Paoli et al., 2014). At present, there is no means to collect fronds on a large scale. Collection is theoretically possible, but challenging due to the bulky nature of this residue. Felled trunks are typically chopped into smaller pieces and left on the ground to decompose, which can take up to three years (Teh, 2016).

Empty fruit bunches are the only type of processing residue typically returned to the field. A study of palm oil mills in Aceh, Indonesia found that 75-80% of EFB are returned to the plantations, and the remainder is incinerated at the mill for disposal (Faisal and Mahidin, 2013). This material is heaped between palms or around the base of palm trunks. Where EFB is applied, it is usually done at a higher rate per unit area than it is generated (40-60 t $ha^{-1}yr^{-1}$ compared to 4.4 t ha^{-1} yr^{-1} that is produced, in fresh weight)[1] (Teh, 2016). Thus, even if all EFB were returned to the plantations, this material could only cover a small fraction of the total plantation area under current practices. It is possible that one factor preventing a more even distribution of EFB is the cost of transporting this bulky material throughout the plantations. One way to reduce the bulkiness of EFB is to compress them into a carpet-like material, known as EFB-mat or “Ecomat,” that is easier to transport and apply to plantations. However, the high heat and pressure used to process this material significantly reduces its nutrient content (Moraidi et al., 2012; 2014). Another way to reduce the bulk of EFB is to compost it together with POME. Composting also reduces the nutrient content of the material, but to a lesser extent than producing Ecomat (Abner & Foster, 2006). Composting may also reduce the value of the material in preventing erosion and soil carbon loss.

Environmental benefits of residue retention

Residues release nutrients upon decomposition, acting as fertilizer. Applying palm biomass to the plantation soil can reduce the amount of inorganic fertilizer necessary to produce high palm oil yields in subsequent years, although typically some amount of fertilizer must still be applied in order to avoid nutrient depletion of the soil. Fronds and EFB have the greatest fertilizer value per tonne, followed by POME, while trunks carry a low concentration of nutrients. Retaining fronds and trunks on the plantation soil effectively returns all of the nutrients contained in this biomass, except what is lost through runoff, leaching, and erosion. A large fraction of nutrients are stored in FFB (20-45%), and FFB removal represents a substantial nutrient loss for the plantation. EFB can be returned to the plantation, but this residue only contains 27% of the major nutrients (nitrogen, potassium, phosphorous, and magnesium) in FFB, and so only mitigates the nutrient removal from palm fruit harvest to a small degree. Palm oil

1 Assuming a moisture content of 66% for EFB (Teh, 2016).

and other processing residues that are typically not returned to the field contain the remaining nutrients (Teh, 2016).

Application of most types of palm residues has been found to significantly improve the soil carbon content in plantations, because the carbon in the decomposing biomass is added to the soil (reviewed in Teh, 2016). One study determined that of all residues, EFB is most effective in contributing to soil carbon formation on a per-tonne basis, followed by fronds and trunks (Moraidi et al., 2013). Another study found that the soil carbon benefit leveled off beyond a certain application rate of EFB, suggesting that in terms of soil carbon, the current typical application rate of 40 t ha^{-1} EFB may be unnecessary (Abu Bakar et al., 2011). Residue application also limits soil carbon and nutrient loss by reducing erosion (Maena et al., 1979, as cited in Teh, 2016), and can reduce evaporative losses of soil moisture (Teh, 2016). Overall, residue retention in palm plantations has been associated with higher oil palm yields (reviewed in Teh, 2016).

Some level of residue removal may actually provide environmental benefits by reducing pest and disease pressure on oil palms. Felled trunks can host the *Oryctes rhinoceros* beetle and the *Ganoderma* fungal disease, which can cause FFB yield losses (Teh, 2016; UNEP, 2012; Liau and Ahmad, 1991). Palm biomass left in the fields can also host rats.

Sustainable removal of palm residues

Some amount of palm biomass can be removed from palm plantations without adverse environmental impacts as long as sustainable management practices are implemented. Based on a review of nutrient inputs from residue decomposition compared with nutrient demand from oil palms, Teh (2016) estimated that 3-5 t ha^{-1} yr^{-1} of field residues (fresh weight) could be removed from plantations, in addition to FFB removal, without leading to soil degradation. According to this assessment, there are viable alternative management practices to returning EFB to the field. The additional nutrient loss in 3-5 t ha^{-1} yr^{-1} of field residues is roughly equivalent to the nutrient loss that typically occurs through runoff, leaching and erosion, and this biomass should only be removed if its harvest is offset by introducing sustainable management practices. For example, planting cover crops can reduce erosion and soil water evaporative losses, and in particular leguminous cover crops such as *Mucuna bracteata* or *Pueraria phaseoloides* can return nitrogen to the soil. Cover crops require regular weeding to ensure they do not climb up and envelop the oil palm trees (Teh, 2016).

It should be understood that the level of sustainable residue removal identified here represents a broad generalization across all Indonesian palm plantations. The risk of erosion, nutrient depletion, and soil water deficit vary greatly on a local scale, depending on soil type, slope, management practices, and other factors. A site-level assessment should be performed to determine the sustainable residue removal rate for any particular palm plantation.

OTHER USES OF RESIDUES

This assessment does not consider residues to be sustainably available if they would be diverted from existing uses. The main use of palm process residues is combustion to produce heat and power to run palm oil mills, mostly using fiber and shells. EFB is not typically combusted due to its high moisture content (Yusoff, 2006). The amount of processing residues produced at palm oil mills may be more than sufficient for the energy needs of those mills (Yusoff, 2006). Palm oil mills could potentially be independent power producers that export power to the grid. This could be particularly attractive to small mills that don't operate their own plantations and only process FFB (Husain et al., 2003). Due to the monopoly held by PLN (PT Perusahaan Listrik Negara, the Indonesian state-owned electricity company), it is unlikely that any mills currently sell power generated by biomass boilers to the grid, but this arrangement could potentially occur in areas where power shortages are a problem and mills are near the grid (G. Paoli, personal communication, June 28, 2015).

Palm kernel shells are also sometimes used as a material for road surfacing on plantation and mill estates (Yusoff, 2006). Palm trunks are occasionally employed by local communities for temporary structural use, such as in the construction of small bridges or road maintenance around villages and plantations (UNEP, 2012). However, in Indonesia for the most part fronds and trunks are left in the plantations to decompose.

Palm residues have several potential uses in other industries. Trunks could potentially be used for plywood production, and fronds could be used for the production of animal pellets (UNEP, 2012). Fronds, trunks, and fiber could also be used to produce pulp for papermaking (Wanrosli et al., 2007; UNEP, 2012; Prasertsan and Prasertsan, 1996). Shells could be processed into activated charcoal to treat POME (Paoli et al., 2014). EFB could be used as a substrate for mushroom cultivation or to manufacture medium density fiberboard (Prasertsan and Prasertsan, 1996). According to available information, none of these practices are typical or widespread in Indonesia at present.

POME is typically treated as wastewater in large, open-air settling ponds before release into waterways. Release of untreated POME is hazardous due to its high organic matter and nutrient content. POME decomposition results in a high emission rate of methane, a potent climate forcer. An increasing number of palm oil mills are installing methane capture technology; this practice has the dual benefit of preventing methane release into the atmosphere, and of producing a fuel that can be combusted for energy (Paoli et al., 2014). POME is sometimes used as a water and nutrient source for oil palm trees (Prasertsan and Prasertsan, 1996).

ESTIMATING THE SUSTAINABLE AVAILABILITY OF PALM RESIDUES FOR BIOFUEL

In this section we estimate the amount of palm residues that could be sustainably available for biofuel without negative impacts on soil quality or existing uses.

As discussed above, residue retention in the field is important for returning nutrients and carbon to the soil and reducing erosion and evaporative water loss. We follow the conclusions in Teh (2016) to estimate the amount of palm biomass that can sustainably be removed from plantations without significant environmental impacts. In the present study, we assume that a portion of felled trunks, as well as all processing residues, can be sustainably harvested from palm plantations as long as sustainable management practices are implemented. Removing palm trunks would be ecologically preferable compared to removing fronds because, as discussed above, the trunks contain lower nutrient concentrations and carry higher disease and pest risks. Trunks are also less bulky and costly to transport. We assume that 3 t ha^{-1} yr^{-1} of felled trunks (fresh weight), the lower end of the range given in Teh (2016), can be sustainably removed; this corresponds to 0.9 t ha^{-1} yr^{-1} biomass in dry weight, assuming an average trunk moisture content of 71% (Teh, 2016). The remainder of felled trunks would remain in the field. Following Teh (2016), we assume that all processing residues are available for biofuel and other uses.

The only existing use of processing residues that we consider here is heat and power. Although our literature review above indicates that palm trunks and palm kernel shells occasionally have other uses, the quantity of residues used for these purposes is not quantifiable and likely negligible at the national scale. We treat POME separately below.

ESTIMATING RESIDUE USE FOR HEAT AND POWER

Some palm oil mills currently combust processing residues to produce heat and power to run the mills. This practice reduces the carbon intensity of the palm oil production process compared to using fossil fuels. In this analysis, we assume that all Indonesian palm oil mills shift to biomass heat and power in order to provide a conservative estimate of what would be available for biofuel production.

We estimate feedstock needs to power palm oil mills on a per-tonne FFB basis. Husain et al. (2003) reviewed the energy needs of seven palm oil mills in Malaysia that used palm residues for electricity and process heat. Most of the energy used in the palm milling process is process heat. This study found that, on average, 10.5% of the FFB biomass on a wet basis is used for energy. The mills in this study use shells and fiber for energy; EFB is not a preferred combustion fuel due to its high moisture content. Approximately 20% of an FFB on a wet basis consists of shells and fiber (Table 2). Thus, about half (53%) of the shell and fiber fractions would be needed for energy production if all palm oil mills used biomass.

Table 2. Moisture content and composition of a fresh fruit bunch.

Residue type	Percentage of FFB (wet basis)	Moisture content	Percentage of FFB (dry basis)	Dry residue (kg) per tonne wet FFB	REFERENCES
Palm oil	22%	0%	42%	220	Sulaiman & Abdullah, 2011
Palm kernel	6%	0%	11%	60	Sulaiman & Abdullah, 2011
Empty fruit bunches (EFB)	22%	65%	14%	77	Chua, 1992; Chuah et al., 2006; Yusoff, 2006; Husain et al., 2003; Paoli et al., 2014; Sulaiman & Abdullah, 2011
Palm kernel shells	6%	10%	10%	54	Chua, 1992; Husain et al., 2003; Chuah et al., 2006; Husain et al., 2003; Paoli et al., 2014; Yusoff, 2006; Sulaiman & Abdullah, 2011
Palm press fiber	14%	40%	15%	84	Chua, 1992; Husain et al., 2003; Chuah et al., 2006; Prasertsan and Prasertsan, 1996; Husain et al., 2003; Paoli et al., 2014; Yusoff, 2006; Sulaiman & Abdullah, 2011
Palm oil mill effluent (POME)	67%*	94%	8%	40	Chua, 1992; Chuah et al., 2006; Paoli et al., 2014; Sulaiman and Abdullah, 2011

** POME weight includes added water for FFB processing; total is 136% of original FFB fresh weight.*

We then subtract 53% of each of palm kernel shells and fiber from the total sustainably available biomass (Table 3). Since EFB are not used for energy, this entire fraction can be considered sustainably available.

We can now estimate the total amount of palm residues (excluding POME) that are sustainably available. We calculate availability as:

Availability = production—soil amendment—heat and power use

The net availability of solid palm residues is 3.8 t ha^{-1} yr^{-1}, which is about 20% of total solid residue production (Table 3).

Table 3. Annual production and use of oil palm residues, including the calculated availability of residues for use as biofuels. Note this table excludes POME availability.

	Residue type	Production (dry t ha^{-1} yr^{-1})	Retained as soil amendment (dry t ha^{-1} yr^{-1})	Use for heat and power (t ha^{-1} yr^{-1})	Net availability (t ha^{-1} yr^{-1})
Processing residues	**Empty fruit bunches**	1.6	0	0	1.6
	Palm kernel shells	1.1	0	0.6	0.5
	Palm press fiber	1.7	0	0.9	0.8
Field residues	**Fronds**	0.6 (felling) 10.4 (pruning)	11.0	0	0
	Trunks	2.8	1.9	0	0.9
	TOTAL	**18.2**	**12.9**	**1.5**	**Final residue availability: 3.8**

Planted and harvested oil palm area in Indonesia was estimated to be approximately 10.8 and 8.9 million ha respectively in 2015 (Wright and Rahmanulloh, 2015; Ulum and Hariyanto, 2013). The harvested area, multiplied by final residue availability of 3.8 dry tonnes ha^{-1} yr^{-1}, results in 34 million dry tonnes of total residues available per year.

CONVERSION TO BIOFUEL

Here, we estimate the potential volume of biofuel that could be produced from the residues that are sustainably available. Because conversion of palm residues to biofuel has not been as thoroughly studied as some other feedstocks, we estimate conversion rates based on rates for other types of lignocellulosic material. The average heat content of available palm residues (weighted by availability and using the middle of the range in heat content when given) is 18.1 MJ kg^{-1} (Table 4). This heat content is approximately that of sawdust (~18 MJ kg^{-1}),[2] so we assume the same renewable diesel yield for palm residues as for sawdust: 0.22 tonnes diesel[3] per tonne feedstock using the Fischer Tropsch process (GREET, 2014).

Table 4. Heat content of oil palm biomass wastes, shown as the Higher Heating Value (HHV).

Residue category	Residue type	Heat content (MJ kg^{-1}, dry basis)	REFERENCES
Process residues	**Empty fruit bunches (EFB)**	15.5—18.8	Chua, 1992; Minowa et al., 1998; Chuah et al., 2006
	Palm kernel shells	20.1—21.4	Chua, 1992; Husain et al., 2003; Yusoff, 2006; Minowa et al., 1998; Chuah et al., 2006
	Palm press fiber	18.5—19.2	Chua, 1992; Husain et al., 2003; Yusoff, 2006; Chuah et al., 2006
	Palm oil mill effluent (POME)	17.0	Chuah et al., 2006
Field residues	**Oil palm fronds**	17.3—18.7	Trangkaprasith and Chavalparit, 2011; Lim, 1986
	Oil palm trunks	17.5	Chuah et al. 2006

The total of 34 million tonnes available residues per year could then be converted into approximately 7.4 million tonnes renewable diesel per year.[4] National diesel and gasoline demand in Indonesia is in the ballpark of 50 million tonnes per year in total.[5] Drop-in biofuel made from sustainably available residues could thus displace approximately 15% of that annual demand.

2 Phyllis2 database for biomass and waste: https://www.ecn.nl/phyllis2/

3 In reality, synthetic fuel production processes are likely to deliver a mix of hydrocarbons, including some renewable gasoline, in addition to renewable diesel, but the overall yield should be comparable.

4 A similar conversion factor is given for biomass to renewable gasoline.

5 Based on the following data sources for Indonesian fuel consumption: 2015 projections of gasoline consumption of 31 billion litres/yr *(26,601,686 tonnes/yr)* and diesel consumption of 28.13 billion litres/yr *(24,138,885 tonnes/yr)* from USDA (2014), citing the Center for Energy and Mineral Resources Data and Information. These projections roughly agree with those reported by *The Jakarta Post* (April 2015) based on data from Pertamina: 2015 projection of gasoline demand of 39 billion litres/yr *(33,466,637 tonnes/yr)* and diesel demand of 34 billion litres/yr *(29,176,043 tonnes/yr)* (Cahyafitri, 2015).

BIOGAS POTENTIAL FROM POME

POME is a processing waste that accumulates in mills during palm oil extraction. It must be treated in holding ponds before being released into waterways. This treatment involves anaerobic decomposition of POME, which releases methane, a potent greenhouse gas but also a potentially valuable energy source. The released methane could be captured, purified, and utilized for energy.

Biogas production from POME is an emerging industry in Indonesia. PT Asian Agri operates 5 biogas plants near palm oil mills in Sumatra, and it plans to build 20 more. Overall, the company expects to produce 2 MW of electricity and plans to use 30% of this to support operations at the palm oil mills, selling the rest to the public (Gunawan, 2015). According to the IPOB (2012), many mills are planning to implement methane capture, and the IPOB expects that 60% of palm oil mills will "have methane capture facilities in the near future", with 100% of mills using methane capture by 2022.

Here, we estimate the amount of biogas that could be produced from POME in Indonesia. Although there is some usage of POME biogas for electricity to power mills in Indonesia, this practice appears to be less common than combustion of other processing residues. Because our solid residue availability calculation above reserved enough processing residues to power all palm oil mills, we do not assume POME biogas is used for this purpose here. Indonesia produces 0.67 t ha^{-1} yr^{-1} POME on a dry basis (13.45 t ha^{-1} yr^{-1} on a wet basis) (Yusoff, 2006). Every wet tonne of treated POME generates 28 m^3, equivalent to 0.02 tonnes, of biogas (Chuah et al., 2006; Yacob et al., 2006). The biogas produced during POME decomposition is 60-70% methane and 30-40% carbon dioxide (Ma et al., 1999; Quah and Gillies, 1981). Multiplying 13.45 t ha^{-1} yr^{-1} wet POME by the total harvested area of palm oil in Indonesia (8.9 million hectares, discussed above) and the methane yield of POME results in approximately 1.5 million tonnes methane production per year.

Indonesia's natural gas consumption in the transportation sector is very low, at less than 0.01% of all transportation fuel consumption (calculated from Anindhita & Adiarso, 2014). Natural gas burns much more cleanly than road diesel and gasoline in Indonesia, and the country could shift toward CNG vehicles as an air pollution mitigation strategy, for instance for urban heavy duty vehicles such as buses. POME biogas could potentially displace 1.6 million tonnes of diesel or gasoline,[6] or 3% of Indonesia's total annual diesel and gasoline demand. If used in Indonesia's energy and petrochemical sectors, this amount of biogas could instead displace 6% of Indonesia's current annual demand for 26 million tonnes of natural gas (IEA, 2014; BP, 2015).

POLICY OPTIONS TO SUPPORT ADVANCED BIOFUEL

Here, we have identified a substantial biomass resource in Indonesia that could be used to fuel the growth of a domestic advanced biofuel industry, but support from the Indonesian government is needed to realize this potential. Because biofuel production from cellulosic biomass such as palm residues is capital intensive and is still seen as a high-risk technology, investors have been reluctant to support these projects (Miller et al., 2013; Peters et al., 2016). A suite of incentives would be most effective in drawing

6 Assuming the following heating values: 45.1 MJ kg^{-1} for natural gas; 43.1 MJ kg^{-1} for diesel; and 43.2 MJ kg^{-1} for gasoline.

investment to an emerging cellulosic industry, including both (a) policy support, such as an advanced biofuel volume blending mandate, or a carbon savings target for the transport sector with a specific subtarget for advanced biofuels, and (b) fiscal or investment support for advanced biofuel projects (Peters et al., 2016).

CONCLUSIONS

This assessment shows that a significant fraction of Indonesia's transport fuel demand could be met by sustainably produced advanced biofuel from palm residues. Indonesia's growing palm oil industry generates hundreds of millions of tonnes of biomass per year, a vast resource that is not entirely utilized. Most palm residues should be left in the field to return nutrients and organic carbon to the soil, protecting soil fertility and supporting high palm oil yields in future years. Some residues are used to produce electricity and process heat to power palm oil mills. These uses of palm residues make palm oil production more efficient, reduce greenhouse gas (GHG) emissions, and should be continued and expanded to support a more sustainable palm oil industry.

Our analysis shows that if all palm oil mills in Indonesia shift to using biomass power and sustainable palm management practices are implemented, around 20% of the country's solid palm residues could be made available for advanced biofuel production. This level of biofuel production would displace approximately 15% of Indonesia's gasoline and diesel consumption. If biogas produced from palm oil mill effluent (POME) is used in natural gas vehicles, the country could displace another 3% of its transport fuel demand while also reducing air pollution by burning a cleaner fuel. The mobilization of these resources could support the development of a domestic advanced biofuel industry that would significantly reduce the Indonesia's GHG emissions, while supporting the agricultural economy and reducing its dependence on oil imports. Because advanced biofuels are often considered as high-risk ventures by investors, policy and fiscal support by the Indonesian government would be needed to encourage commercialization of this industry.

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