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Abstract

Malaysia's transportation sector accounts for 48% of the country's total energy use. The country is expected to become a net oil importer by the year 2011. To encourage renewable energy development and relieve the country's emerging oil dependence, in 2006 the government mandated blending 5% palm-oil biodiesel in petroleum diesel. Malaysia produced 16 million tonnes of palm oil in 2007, mainly for food use. This study addresses maximizing bioenergy use from oil-palm to support Malaysia's energy initiative while minimizing greenhouse gas emissions from land use change. When converting primary and secondary forests to oil-palm plantations between 270 - 530 g and 120 -190 g CO_2 equivalent (CO_2-eq) per MJ of biodiesel produced, respectively, is released. However, converting degraded lands results in the capture of between 23 to 85 g CO_2-eq per MJ of biodiesel produced. Using various combinations of land types, Malaysia could meet the 5% biodiesel target with a net GHG savings of about 1.03 million tonnes (4.9% of the transportation sector's diesel emissions) when accounting for the emissions savings from the diesel fuel displaced.

Fossil fuels contributed about 93% to Malaysia's electricity generation mix and emit about 65 million tonnes (Mt) or 36% of the country's 2010 Greenhouse Gas (GHG) emissions. The government has set a target to install 330 MW biomass electricity by 2015, which is hoped to avoid 1.3 Mt of GHG emissions annually. The availability of seven types of biomass residues in Peninsular Malaysia is estimated based on residues-to-product ratio, recoverability and accessibility factor and other competing uses. It was found that there are approximately 12.2 Mt/yr of residues. Oil-palm residues contribute

about 77% to the total availability with rice and forestry residues at 17%. Electricity from biomass can be produced via direct combustion in dedicated power plants or co-fired with coal. The co-firing of the residues at four existing coal plants in Peninsular Malaysia was modeled to minimize cost or GHG emissions. It is found that Malaysia can meet the 330 MW biomass electricity target via co-firing with a cost reduction of about $24 million compared to 100% coal. Optimal GHG reduction for co-firing was found to be 17 Mt lower than 100% coal at a cost of carbon mitigation (COM) of about $22.50/t CO_2-eq mitigated. This COM is lower than an implied COM under the newly introduced levy on heavy electricity users in Malaysia.

Gasoline consumed roughly 370 PJ of energy in Malaysia's transportation sector in 2009. Ethanol can be blended with gasoline up to 10% by volume in most vehicles. Peninsular Malaysia's 12.2 Mt/yr of agro-forestry residues can be used for potentially producing 3.8 billion liters ethanol annually. Using a large scale mixed-integer linear optimization, it is found that if Malaysia introduces a 10% ethanol-gasoline blend (E10), approximately 2.9 Mt (24%) of the residues would be used at $5.4 million more cost compared to 100% gasoline (reference case) estimated at $5.2 billion/yr. In the E10 scenario, all cities receive 10% ethanol altogether producing 900 million liters of ethanol. The GHG emissions for 100% gasoline is estimated at 26.4 Mt/yr. The minimum GHG emissions if E10 is implemented in Peninsular Malaysia was found to be 24.5 Mt, 2.0 Mt lower than 100% gasoline, which implies a $4.70/t CO_2-eq cost of carbon mitigation (COM). Since only 24% of the available residues are used to produce the E10, the possibility of producing the E10 and electricity via co-firing with coal simultaneously was investigated. This is done by combining the fuel (gasoline/E10)

model with the electricity (coal-only/co-firing) model. The costs of the reference case combined scenario (100% gasoline and 100% coal) is estimated at $6.3 billion/yr and emits 63 Mt/yr of GHG emissions. The minimum cost for producing the E10 and co-firing is found to be $30 million lower than the combined reference case. This is achieved by using 5.9 Mt of residues. The minimum GHG emissions level obtained is 17 Mt lower implying a COM of $19.00/t CO_2-eq mitigated.

The findings in this research are used to recommend policies for mitigating GHG emissions impacts from the growth of palm oil use in the transportation sector. Policy recommendations are also discussed to ensure a successful implementation of co-firing of biomass and the production of E10 by ensuring a guaranteed supply of residues and financing the high capital cost of the renewable energy program.

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Abbreviations

CDF	Cumulative distribution function
CO_2-eq	Carbon dioxide equivalent
CoFR	Co-firing rate
CPKO	Crude Palm Kernel Oil
CPO	Crude Palm Oil
EFB	Empty fruit bunch
FFB	Fresh fruit bunch
g	gram
GDP	Gross domestic product
GHG	Greenhouse Gas
GJ	Gigajoule
ha	Hectare
HN	Here-and-now
kg	kilogram
km	kilometer
KVDT	Klang Valley Distribution Center
L	liter
LUC	Land use change
m^3	Cubic meter
MJ	Mega joule
MPOB	Malaysian Palm Oil Board
MSW	Municipal solid waste
Mt	Million tonne
Mtoe	Million tonne of oil equivalent
MW	Megawatt
MW_b	Megawatt biomass
MWh	Megawatt-hour
NETL	US National Energy Technology Laboratory
PDF	Probability density function

PJ	Petajoule
PME	Palm methyl ester
POME	Palm oil mill effluent
t	tonne
TWh	Terawatt-hour
WS	Wait-and-see

1 Introduction

1.1 Overview of Malaysia's Transportation and Electricity Sector

The transportation and electricity sectors were the two biggest final energy users in Malaysia in 2009, consuming approximately 820 PJ (48%) and 350 PJ (21%), respectively, from a total of about 1,700 PJ [1]. In comparison, the world's energy consumption during this same period was 500,000 PJ with transportation at about 200,000 PJ (40%) and electricity generation at approximately 72,000 PJ (15%) [2, 3]. Thus, Malaysia's share of the world's energy consumption in the two sectors was only 0.63%.

Malaysia's ground transportation consumes about 89% of the energy used in the transportation sector, while aviation consumes 12% and water only 1%. The transportation sector utilizes 99% fossil fuels, in particular gasoline (370 PJ), diesel (360 PJ) and aviation fuel (88 PJ) [4]. Using GHG emissions factors from the US National Energy Technology Laboratory (NETL) for the combustion of gasoline, diesel and aviation fuel [5], it is estimated that GHG emissions from Malaysia's transportation sector is roughly 52 million tonnes (Mt) per year. This is approximately 29% of the country's GHG emissions in 2010 [6]. Although there are very few technological options in Malaysia to reduce GHG emissions in the transportation sector, the use of biodiesel could potentially reduce GHG emission while at the same time ensuring a sufficient energy supply. In Malaysia, biodiesel is produced using palm-oil. The 5% palm biodiesel mandate [7] in the land transportation sector could reduce GHG emissions by 1.03 million tonnes a year based on 2010 diesel consumption in Malaysia [8].

Malaysia's electricity sector depends on approximately 93% fossil fuels, mainly natural gas at 57 million MWh (58%) and coal at 37 million MWh (32%) [9]. Coal's share has been increasing since 1990, when it was only about 12%. The use of coal is expected to increase from

37 million MWh (32%) in 2008 to 155 million MWh (49%) by the year 2030, while natural gas is projected to decrease to 44% [10]. Using the midpoint lifecycle GHG emissions factor for coal and natural gas [11], it is estimated that Malaysia's electricity sector's GHG emissions accounted for about 65 Mt (36%) out of the 180 Mt of the country's total GHG emissions in 2008 [2]. The increasing consumption of coal in the electricity sector is the main contributor to the increase of GHG emissions from the electricity sector from 20 Mt in 1990 to an estimated 65 Mt in 2008 [12]. In response, Malaysia has targeted a reduction of 3.2 Mt of GHG emissions in the electricity sector by 2015 with an increased use of renewable fuel. This target is to be achieved through the Tenth Malaysia Plan policy decision to install 330 MW of electricity from biomass out of the 975 MW planned capacity by 2015. The remainder of the renewable electricity would include mini-hydro (220 MW), solid waste (200 MW) and biogas (100 MW) [13]. In comparison, the world's biomass electricity generation is estimated on the order of 50,000 MW [14]. Achieving this goal would put Malaysia's biomass electricity share in the world at roughly 0.66%.

1.2 Motivation

Renewable energy resources are abundant in Malaysia and include biomass and solar energy. Malaysia's main biomass resources come from its agro-forestry sector: In Peninsular Malaysia, forest covers approximately 45% (5.8 million ha) of the land, while another 35% (4.5 million ha) is agricultural land. Out of the 4.5 million ha of agricultural land, oil palm (62%) and rubber plantations (29%) cover the largest area. This agro-forestry sector generates biomass residues from its activities, which can be used as a source of energy. However, how much and whether residue generated from Malaysia's agricultural and forestry activities can be collected

economically and sustainably is unknown. Without this knowledge, it is difficult to say that it is more economical to transport the residues for energy production at power plants or bio-refineries without resulting in net GHG emissions.

Malaysia's renewable energy policy for the transportation and electricity sectors are motivated by the goal to reduce the country's reliance on fossil fuels imports, an important measure of energy security [7]. However, these policies have failed to meet the mandated targets for many reasons. Salient among these are insufficient regulatory frameworks (e.g. no requirement for a mandatory grid interconnection on the part of renewable energy operators) and the lack of institutional measures to facilitate the flow of information (e.g. the availability of renewable energy resources and prospects) to industry players [15]. Nevertheless, the Government is increasing renewable energy with the overall energy mix and is updating the policies (e.g. the 975 MW renewable electricity by 2015 and enforcing 5% PME blend in the central region of Peninsular Malaysia in June 2011), which shows the Government is seriously considering GHG emissions reduction as another important metric other than energy security in its renewable energy policies.

Malaysia’s GHG emissions were estimated at 6.7 tonnes per capita and 1.3 tonnes per $1,000 gross domestic product (GDP) for the year 2008, while the world’s averages were 4.4 tonnes and 0.73 tonnes, respectively [2]. Malaysia has committed to voluntarily reducing its emissions by up to 40 percent in terms of emissions intensity of GDP by the year 2020 compared to 2005, levels that would bring it closer to the world average [6, 16]. To help meet this commitment, a mandated 5% biodiesel blend with petroleum diesel has been targeted, among other approaches; new lands may need to be opened in order to meet the target. However, it is

uncertain whether there would be enough land and what types of land can be used to meet the demand without resulting in higher GHG emissions than the displaced diesel fuel.

There are several options to convert biomass into energy that includes biofuel. Since Malaysia is a country that has 80% of its land area covered in biomass, it seems logical to encourage as many economic sectors as possible to use bioenergy. Until now, for the land transportation sector, the government has only considered utilizing a so-called conventional technology, namely the transesterification of vegetable oil into biodiesel, in its renewable policy. Fifty-one percent of Malaysia's land transportation sector energy use is gasoline. The most promising technology for using renewable fuels in the land transportation sector is the second-generation biofuel, cellulosic ethanol. Ethanol can be blended with gasoline up to 10% in a standard vehicle [17]. However, there is not enough detailed knowledge on the availability of these biomass resources in Malaysia after taking into account other competing uses. Having this information is imperative to enable the government to set an optimal energy strategy/policy that includes cellulosic ethanol. If a policy on bioethanol in the land transportation sector is introduced, Malaysia could save up to 3.4 Mt of GHG emissions annually. This is based on the assumption that 10% of gasoline energy is displaced by cellulosic ethanol and uses the lifecycle GHG emissions of gasoline [5].

1.3 Literature Review

1.3.1 Biomass as energy source

Biomass contains three main chemical building blocks/polymers that influence the suitability of biomass as feedstock for different products and uses. These polymers are cellulose

(40 - 50% by weight), hemicellulose (20 – 40%) and lignin, which together forming a complex structure better known as lignocellulose [18, 19]. The energy content of biomass ranges from 18 – 22 MJ/kg (dry basis) [20]. Biomass can be converted into three main categories of useful products, namely transport fuels (biofuels), electricity/heat generation, and chemical feedstock [19]. The choice of biomass for energy production depends on the quantity and availability of the supply of biomass resources such as: crop residues, forest residues and landfills, and their locations and the conversion technology chosen. If the target is to reduce GHG emissions, the net result could be affected by the types of biomass used (solid/liquid) and how they are being cultivated.

In Peninsular Malaysia, forest covers approximately 45% of the land, while agricultural land covers another 35% that could contribute significantly to the biomass energy supply from the residues generated by the agro-forestry activities. These residues could be categorized into two types: field residues and process-based residues. Field residues are those that come from the plantations such as from the annual pruning of fronds, branches and trunks from felled trees; process-based residues are derived from the mills. Currently there are 100,000 ha of logging area and approximately 650 sawmills and plywood mills in Peninsular Malaysia [21, 22]. Residues from the forestry sector comprised of leftovers from logging (branches) as well as residues generated at the mills (sawdust, slabs, trimmings and edgings) are estimated to be around 9.8 million m^3 (7.4 Mt) [23]. Agricultural residues in Malaysia are mainly comprised of residues generated by the oil-palm industry (empty fruit bunches, fronds, fibers, shells and trunks) and rubber plantations (branches and trunks), with rice (husks and straw), cocoa branches and coconut (fronds and trunks) to a lesser extent. There are currently about 250 palm oil mills and

230 rice mills in Peninsular Malaysia [24, 25]. The gross availability of residues from the agricultural sector was estimated to be about 23 million m^3 (17 Mt) [23].

Even though biomass energy is assumed by most to produce net-zero GHG emissions [26], positive emissions could still come from the harvesting activities, including land use change and delivering biomass to facilities. The expansion of oil-palm plantations in Malaysia has led to an increase in GHG emissions from the agricultural sector [27]. Based on data collected between 1980 to 2005, Henson et al. [28] concluded that oil-palm cultivation and palm-oil production involved a net emission of CO_2-eq. According to Henson, in 2005, oil-palm cultivation (planting and harvesting) and palm-oil production in Malaysia emitted about 13 Mt a year of GHG, a 29% increase from the year 2000 [27]. The main sources of GHG emissions were land conversion (60%), methane emissions from palm oil mill effluent (POME) treatment via anaerobic digestion (13%), fossil-fuel combustion (13%) and fertilizer use (4%). The process of collecting, transporting and pre-treating biomass residues for direct combustion into electricity or co-firing with other fossil fuels could result in a significant amount of fossil fuel usage and eventually significant GHG emissions. In Malaysia, rubber estates, oil-palm plantations, rice fields, logging areas and landfills and mills are generally located far from existing coal and natural gas power plants. As a result, transporting residues long distances from these plantations and mills may make biomass energy use appear less attractive in terms of minimizing total cost and maximizing GHG reduction.

1.3.2 Biomass energy for electricity generation

One way of generating electricity from biomass is via direct combustion in dedicated biomass power plants [19, 29]. However, biomass can also be co-fired with other fossil power

plants. Co-firing of biomass, in particular with coal, has lower operating cost ($0.05 vs. $0.13/kWh), potentially making it a better technological choice in the effort to increase the biomass share in the global electricity sector [14]. Small facilities cannot take advantage of economies of scale. Coal power plants generally are larger than dedicated biomass fired plants by a factor of ten [14]. Because of this reason and among others, such as the plant capacity factor, conventional coal plants' generation costs in the US are projected to be between $86 and $110/MWh by 2016, while biomass dedicated power plants would be between $99 and $130/MWh [30]. Biomass properties also result in inherent inefficiency. For example, a typical direct combustion steam cycle has a wide range of efficiency as low as 22% for MSW to only around 34% for a drier and bulkier biomass. In contrast, the co-firing of biomass with coal could take advantage of the large capacity of coal power plants to utilize more biomass; thus, biomass capacity could be two times higher as compared to dedicated biomass combustion (10 – 50 MW vs. 5 – 25 MW), while also obtaining a higher efficiency with a smaller range (35 – 40%) [14]. As such, the co-firing of biomass could provide a platform for the evolution of a large scale biomass global electricity system in the future [29].

Electricity from biomass in Malaysia comes from oil palm and rice residues (170 MW or 75%), wood chips and sawdust (24%), and municipal solid wastes (MSW) (1%) [9]. In 2009, there were about 1.5 million MWh of electricity generated from these stand-alone biomass power plants. In comparison, Lim et al. [31] estimated that the annual potential energy from biomass in Malaysia suitable for electricity generation *via* a combustion technology is around 900 million GJ (250 million MWh). This was approximately twice the electricity generated in Malaysia in 2009 [9]. Two potential sources of biomass for electricity generation are logging residues and oil palm residues, estimated to be between 530 and 670 million GJ (150 - 190 million MWh). The

remaining 60 million MWh could come from residues from the rubber industry, cocoa, coconut, sugar cane plantations, as well as rice production (husks and straws) [31, 32]. Lim's et al. study estimated the total energy potential of biomass; however, to understand the real potential of biomass and its important environmental effects, important factors first need to be determined, including the recoverability rate, competing uses, and accessibility such as road infrastructure and operational limitations. Perlack et al. [33] showed that when these factors were considered, only 12% of the 8.4 billion (short) tons of biomass resources available in the US were suitable for energy use.

For Malaysia, there are no detailed studies that have determined whether it is beneficial to harness the various types of biomass for electricity generation in Malaysia on a large scale. A recent study by Muis et al. [34] has estimated that biomass-based electricity could replace up to 9% of the total electricity generation in Malaysia with a savings of up to 29 Mt (50%) of CO_2-eq annually. However, the authors did not include detailed locations of biomass resources in relation to the existing power plants and optimal facility locations; in addition, only oil palm residues, rice residues, MSW and landfill gas were considered. In comparison, Morrow et al. [35] who conducted a detailed transportation-problem study, showed that in the US the co-firing of 190 million (short) tons of switchgrass with coal at the national level could mitigate 260 million (short) tons of CO_2-eq annually, which is about a 9% reduction of the US electricity emissions in 2005.

In 1979, the Fuel Diversification Policy in Malaysia's electricity sector was introduced in response to the declining supply of domestic petroleum reserves [36]. As a result, the use of oil dropped to less than 1% at present from 50% in 1990 [12]. However, the use of coal rose from 12% in 1990 to about 32% at present. Coal is given preference, amongst others, because of its

higher energy return per dollar spent compared to oil and natural gas. The international market price of coal between 2005 – 2009 has always been in the range of $20 - $50/tonne or less than $2/MJ [37]. However, this lower cost per energy advantage comes at the expense of higher GHG emissions per unit of energy produced. For every MWh of electricity produced from coal, between 0.75 and 1.3 tonnes of lifecycle CO_2-eq are emitted compared to 0.52 – 1.2 and 0.4 – 0.78 for oil and natural gas, respectively [11, 38].

1.3.3 Biomass energy as transport fuels

Bioethanol and biodiesel are the two main types of bio-energies that are commercially produced all over the world. Ethanol is produced via a fermentation process of sugars [18] while biodiesel comes mainly from the transesterification of bio-oil [39]. Unlike in the US, where the nation has a target of producing about 57 billion liters of domestic bioethanol from corn sugars by 2022, it is unlikely that Malaysia will have enough domestic feedstock to produce the first generation bioethanol on a commercial scale. This is because Malaysia is not known for corn or sugarcane production. However, there could be significant amount of biomass residue produced to generate second-generation cellulosic ethanol [40]. Perhaps more importantly, Malaysia has great potential to become one of the world's largest producers of biodiesel [41].

1.3.3.1 Biodiesel

Johnston and Holloway [42] estimated that the global biodiesel volume potential could reach 51 billion liters annually, which could be produced in 119 countries using soybean oil (28%), palm oil (22%), animal fats (20%), and other feedstock (coconut, rapeseed, sunflower and

olive oils). Biodiesel has several potential environmental benefits, notably reduced tailpipe hydrocarbons, SO_2, NO_x and particulate matter emissions compared to petroleum diesel [43-45]. In Southeast Asia, biodiesel also has a social cost advantage over its counterpart, petroleum diesel. A vehicle that operates on a 10% blend of palm biodiesel with petroleum diesel is estimated to have a lower societal cost (-$700 per vehicle per year) than using petroleum diesel alone ($2,500 per vehicle per year) [46]. Some biofuels could also support agricultural economies and increase rural income through increased employment while helping to reduce petroleum dependence from foreign imports [47].

Biofuels also have a better net energy ratio (NER) compared to fossil fuels [48]. Net energy ratio is defined as the energy contained in the biofuels divided by the total energy used in producing the biofuels [49]. For example, palm biodiesel has a NER of between 6 and 8 compared to petroleum diesel's net energy ratio of 0.84 [50]. The ratio could be higher if the fuel is produced together with surplus electricity taken as credits [51]. Lower values have also been reported, such as 2.4 (without co-product allocation) [52] and 3.5 (with co-product allocation) [52, 53]. Non-food feedstock crop such as jatropha could also replace the current generation biodiesel feedstock (palm oil, soybean oil etc.). However, this option is not expected to be viable on a large scale until beyond 2020 [47]. As such, the current-generation feedstock will still be the choice for biodiesel expansion over the next decade. Nevertheless, jatropha could potentially supply a huge amount of feedstock for biofuel production in countries with large land areas, such as China and India, although commercial success has yet to be seen [54]. For now, the biomass feedstock used for the production of biodiesel in Malaysia solely comes from palm oil. Palm-oil production in Malaysia began in the 1930s [55]. In 2011, the industry harvested approximately 5.0 million ha of oil-palm, yielding an average of 3.8 tonnes of palm-oil per hectare after

processing [56]. In 2009, 99% of palm oil was used for food and one percent for fuel production [24]. The industry has more than doubled since 1990 and grew 38% from 2000 to 2009 [24, 57]. About 1.1 million ha (55%) of the expansion came at the expense of other tree crops such as: cocoa, coconut and rubber. It is estimated that the remaining area (740,000 ha) came from clearing a combination of primary and secondary forests [58] as well as reusing abandoned/idled agricultural land [59].

Oil palm produces two types of oil, crude palm oil (CPO) and crude palm kernel oil (CPKO). The latter constitutes 10% of the total palm oil produced. Accounting for the two types of palm oil, average yield is about 4.5 t/ha, which is the highest yield among the major edible oils (see Figure 1-1) [60]. In 2009, Malaysia exported approximately 220,000 tonnes of palm biodiesel valued at about $180 million [61]. This is approximately 1.4% of the country's total palm-oil production. It is estimated that Malaysia could potentially produce 17 billion liters or 19 Mt of biodiesel [56] if all of the palm-oil produced is used to make biodiesel.

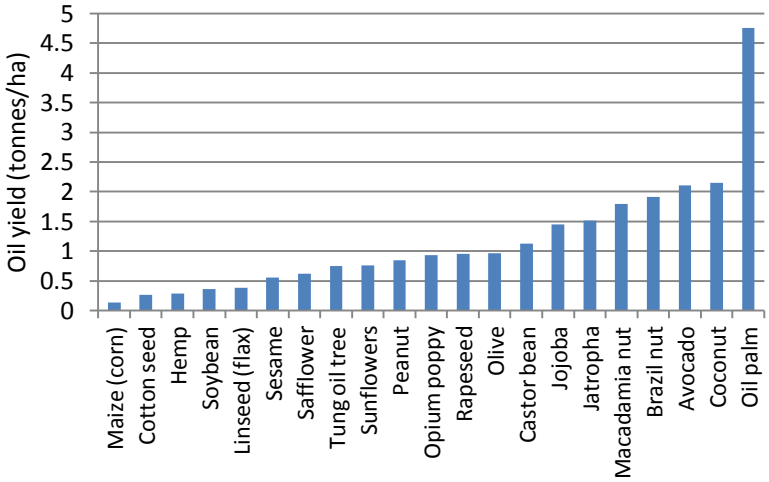


Figure 1-1: Oil yield of the world's major crops

Source: [60]

Biodiesel from palm-oil or palm methyl ester (PME) is made from crude palm oil (CPO). Generally, biodiesel is produced via a chemical process that involves the transesterification of triacylglycerol lipids from any vegetable oil by alcohols to alkyl esters, with or without the use of a catalyst for the purpose of lowering the viscosity of the oil [62-67]. Alkaline based catalytic conversion is preferred over the acids because of the shorter reaction time with high yields of methyl esters, using either metal alkoxides and hydroxides as well as carbonates [64].

1.3.3.2 Cellulosic ethanol

Bioethanol is a product of the conversion of simple sugars via a traditionally widely used fermentation method. However, using biomass residues that contain approximately 30% lignin and hemicelluloses by weight requires additional pre-treatments before the 5-carbon sugars (xylose and arabinose) and 6-carbon sugars (galactose and mannose) are suitable to be used by the microbes in the fermentation process. The pre-treatment of lignin and hemicelluloses is also required to permit access to the cellulose polymer (a 6-carbon sugar known as hexose), which forms 50% of the residues by weight. An 85% conversion efficiency of the 5-carbon sugars into ethanol is currently a respectable figure compared to 95% for the 6-carbon sugars [68]. Biomass residues can also undergo a thermochemical conversion to produce ethanol, albeit at a lower ethanol yield. In the thermochemical process, a mixture of syngas (mainly carbon monoxide and hydrogen) is produced and further converted to produce ethanol and other liquid fuels.

Cellulosic ethanol is envisioned to be the most viable alternative to replace non-renewable fuel and decrease GHG emissions in the land transportation sector, especially in the near/mid-term future [69]. Cellulosic ethanol can be produced from either a dedicated energy crop, which would spark the food and fuel debate in a small country like Malaysia where land is

scarce, or by using biomass residues, which is a better option if the objective is to minimize GHG emissions. It was estimated that cellulosic ethanol's lifecycle GHG emissions is about 26 g/MJ, or approximately 75% lower than that of gasoline (92 g CO_2-eg/MJ). However, if the land use change effect is included, the GHG emissions could be 50% higher than gasoline [70], though with improved feedstock yield it could still be between 27% to 37% lower than gasoline [71]. Another advantage of cellulosic ethanol exists in terms of its positive net energy ratio where it was shown that the figure is around 10 compared to 2 – 3 for sugar-based (corn) ethanol [72], and around 0.81 for gasoline [50].

Kocoloski et al. [73] showed that building ethanol refineries closer to the biomass resources is preferred compared to placing them near demand areas simply because the amount of biomass transported to each refinery is higher than the amount of ethanol transported from the refinery to the users. This is because about 4 tonnes of biomass is required to produce 1 tonne of ethanol (~ 340 L). Refineries should also be built in a size that is most economical to operate. The minimum economical capacity is said to be around 250 million L/yr [68]. However, there are refineries that operate below that capacity. For example, in the US, the average corn ethanol plant capacity in 2011 was about 260 million L/yr ranging from as small as 20 million to 400 million L/yr [74]. Ethanol may be blended with gasoline in most modern gasoline engine vehicles by up to 10% ethanol [17]; assuming a displacement of 10% by volume of gasoline use in Malaysia's land transportation sector in 2008, producing 1.1 billion L of ethanol requires approximately 3.4 Mt of biomass.

1.3.4 GHG emissions and land use change

The choice of land brought into production for producing bioenergy could be a major factor in the net result of GHG emissions [75]. Land use change (LUC) may result in higher emissions compared to just accounting for agricultural practices such as the use of machineries, fertilizers, etc. [70]. Efforts to increase biomass based energy would result into a debate between energy and food supplies competing for finite land resources [76]. It has been suggested that biomass resources for energy generation should have a high yield and utilize surplus land so as not to compete with food production [77]. Indeed, biodiesel and bioethanol production were found to be less advantageous in terms of energy sustainability if land was dedicated to producing fuel instead of using residues and by-products as feedstock [78]. Dedicated energy plantations are also not sustainable because surplus land (e.g., ex-mining and idled lands) is scarce [79].

Converting virgin lands, such as primary forest and grassland, into crop plantations may have also contributed to the increase in GHG emissions. It has been suggested that biofuels could have higher GHG emissions than fossil fuels if the bioenergy production involved conversion of forest and grassland into the crop used as feedstock [70]. This is because conversion of the original land could emit about 25% of soil carbon over time and all standing biomass carbon, at once [70]. An effective system would be to use carbon-poor lands that will not trigger large emissions from land use change. For example, grassland and degraded land have much lower above- and below-ground carbon stock compared to primary tropical forests. Converting woody perennial and other crops are the other options but depending on the types of tree crops, the loss of carbon stock from these types of lands could be as high as half of what is in the tropical primary forests [80].

Another potentially large source of GHG emissions in the agricultural sector is from the application of fertilizers. In the oil-palm industry, for example, three types of fertilizers are being used in a large quantities, namely nitrate, phosphate and potash; boron and magnesium are also used, albeit at much lower amounts. It was estimated that more than 85% of the GHG emissions in the oil-palm plantation phase, for example, was attributed to the use of fertilizers (mainly nitrate) due to the large amount of energy used in the process of producing the fertilizers [81].

1.3.5 Optimizing for the best use of biomass energy

The decision of the best technology to adopt in exploiting biomass energy that will return the lowest cost could be solved using linear optimization. However, when there are uncertainties in the model's input parameters, decision makers are faced with the problem of not being able to determine a single optimal solution and be content with it. In most cases, when uncertainties are present, decisions must be made before the values of the uncertain parameters are known. Uncertainty in a model can take two forms: (i) estimation errors for parameters of unknown value of constants, and (ii) stochasticity of random variables [82]. In solving this type of problem (under uncertainty), literature has often divided optimization under uncertainty into two different approaches, either (i) "wait-and-see" (WS), or (ii) "here-and-now" (WN) [83]. The first approach (which is the focus of this study) will provide a set of optimal solutions assuming that the unknown parameters have been resolved prior to making the decision. The range of optimal solutions found under WS will allow the decision maker to estimate the probability of how much a total cost or profit would be below or above a certain value. As for the HN, the decision maker will have to decide on some probabilistic measure of the objective (e.g. mean of profit / costs) where the decision must be made as though the uncertainties have yet to be resolved. With

regards to policy decisions on a biomass energy project, assessing the potential of biomass energy requires decision makers to consider the uncertainties inherent in the various input parameters such as the annual supply of the different types of biomass, their energy content, costs associated with various activities, etc.

1.4 Scope and importance of the research

This study determines the implications of using biomass resources in Malaysia to reduce GHG emissions when producing biodiesel from palm oil, biomass combustion via coal co-firing and/or cellulosic ethanol. The government has not formally considered the adoption of more advanced technologies that could assist in the efforts to reduce GHG emissions such as carbon capture and sequestration and nuclear power generation. There is also no indication as to whether the government is encouraging other biomass to liquid conversion technologies. Consequently, investigating the implications of adopting these technologies, although they could have great potential in the future, is not considered in this research.

This study provides a clearer picture of the potential of biomass energy in Malaysia in terms of the best fit policy options with regard to its usage as an energy source for two different sectors: transportation, and electricity that enhances the country's energy security. A life-cycle analysis on GHG emissions of the bioenergy production helps in determining the environmental sustainability of fuel. The results provide some important foundations for reference and guidance to the government in formulating its science and technology policy, particularly the policy initiatives to promote an environmentally friendly energy sector.

1.5 Outline of Dissertation

This dissertation first discusses the implications of producing palm biodiesel on GHG emissions in relation to meeting the government's 5% blend mandate, including the assumption of land expansion (Chapter 2). The availability of biomass considering the types, locations, and competing uses are then discussed in Chapter 3 together with an analysis of potentially using the biomass for coal co-firing. The fourth chapter discusses the cellulosic ethanol's possible use in Malaysia and also examines scenarios where the residues are used for two competing energy sectors: electricity and transportation energy. A summary of the findings of the three chapters is discussed in the final chapter of the dissertation. Overall, this study answers three main questions with regard to the use of biomass energy resources in Malaysia in the electricity and transportation sectors, as described in the following sub-sections.

1.5.1 Biodiesel in the land transportation sector

As mentioned above, the government of Malaysia has put in place a policy and an Act of Parliament to blend 5% palm-biodiesel with petroleum diesel in the land transportation sector by 2010. Increasing palm-oil production would require the expansion of oil-palm plantations into new lands, where using certain types of land may result in higher GHG emissions to produce the biodiesel than to produce petroleum diesel. Thus, the research questions are:

(i) What is the lifecycle GHG emission of producing palm biodiesel in Malaysia? Data from Malaysia's oil palm industry are used to estimate the well-to-wheel GHG emissions of palm biodiesel and compare the result with petroleum diesel.

(ii) What is Malaysia's GHG impact of meeting the 5% palm biodiesel mandate? Meeting the mandate will require the expansion of the oil palm plantation area into new lands. I determined the GHG emissions factor (g CO_2-eq/MJ) of palm biodiesel produced on different types of land that are currently being used to plant oil palms in Malaysia.

(iii) What is the minimum GHG emission needed to meet the 5% mandate? Minimum amounts of GHG emissions may be achieved through a combination of suitable lands to plant oil palms. A simple linear optimization model was used with the objective of minimizing GHG emissions where the constraints are the amount of land by different types that still meet the target PME production.

(iv) What is the maximum amount of biodiesel that can be produced with breakeven GHG emissions? The linear optimization model is modified with the objective of maximizing biodiesel production where the constraints are the amount of land available and ensuring the total GHG emissions from the displaced petroleum diesel is not exceeded.

1.5.2 Electricity generation from biomass residues

The Malaysian government revised its Renewable Fuel Portfolio for the electricity sector to use 330 MW of electricity generated from biomass by 2015. In terms of the supply of biomass resources, residues from the agro-forestry sector are the most promising compared with other sources, such as biogas and landfill gas. It is therefore crucial to determine the availability and locations of the biomass residues. In terms of generating electricity in the shortest time and least

expensive manner possible, the co-firing of biomass with coal could be undertaken almost immediately. If co-firing is encouraged, the biomass residues will then need to be brought to the coal plants. There are three research questions that follow:

i) How much biomass residue is there in Peninsular Malaysia and where is it located? Estimates of biomass potential for energy use have previously been reported in several studies without considering their competing uses and accessibility factor. In addition, estimates in these studies were done in terms of overall potential. This study differs by estimating the availability of biomass residues and taking into account the competing uses and accessibility factors (road infrastructure), and determining their specific spatial locations. This data is useful and critical for further analysis regarding the detailed implications of costs and GHG emissions in utilizing the biomass residues.

ii) How much biomass residue can be co-fired with coal with a minimal cost compared to using only coal? Detailed information on the uncertainty in supply, price, and GHG emissions of the biomass residues and coal will be needed to generate the distributions of the total costs of co-firing biomass with coal, a WS approach.

iii) How would the total costs of biomass-coal co-firing change if the objective is to minimize GHG emissions instead of total costs? Answering the first question is a pre-requisite. Co-firing may no longer be an advantage in terms of total cost compared to coal-only generation.

1.5.3 Second-generation bioethanol

Producing cellulosic bioethanol from biomass residue could present another opportunity for Malaysia to reduce its GHG emissions while strengthening energy security in the land transportation sector. However, there is no policy or plan to produce bioethanol to be blended with gasoline in Malaysia. If such a policy exists, it is not known whether producing bioethanol from biomass residue is better than other options to utilize renewable energy that has a lower cost, such as biomass coal co-firing. If cost and GHG emissions are the main factors to decide between the two competing users (i.e. bioethanol and co-firing), it is critical to analyze the tradeoff between GHG emissions and total costs associated with delivering the residues to coal plants and bioethanol refineries. There are two questions in this research, as follows:

(i) What is the optimal use of biomass residue in Malaysia in terms of cost minimization and GHG emissions for cellulosic ethanol production? The answer can be used to recommend a new policy or mandate blending bioethanol with gasoline in the ground transportation sector.

(ii) What would be the optimal total cost and GHG emissions of using the biomass residue if the production of cellulosic ethanol competes with co-firing with coal for electricity generation? The answer might be different from the first research question and can have different results for different objectives between minimizing for total costs of (a) cellulosic ethanol, (b) co-firing, and (c) bioethanol and co-firing combined. The answer can provide options for the decision makers if there are different priorities between cost or GHG emissions savings from the electricity and transportation sectors.

2 Life Cycle GHG Emissions from Malaysian Oil Palm Bioenergy Development: The Impact on Transportation Sector's Energy Security

2.1 Introduction

Malaysia's oil and other energy imports are projected to increase from the current 15 million tonnes of oil equivalent (Mtoe) to 45 Mtoe in 2030 [84]. Transportation is the second largest energy user in Malaysia and consumes approximately 820 PJ/year or 48% of total energy consumption. This is expected to increase to about 1,100 PJ in 2015 extrapolating the historical average annual growth rate of 6% between 2000 – 2010 [85]. In 2008, approximately 33% of the vehicle fuel use was diesel [4]. Based on the latest available data, in 2004 the transportation sector contributed an estimated 41 million tonnes (Mt) of GHG or 24% of Malaysia's total inventory [86]. Energy efficiency technologies, conservation practices, and renewable energy development are being encouraged to reduce import needs [87], improve security of supply, and reduce Malaysia's greenhouse-gas (GHG) emissions associated with fossil fuel combustion [43, 88]. To that end, in 2006 the government mandated that the transportation and industrial sectors replace 5% (by volume) of petroleum diesel use with palm oil biodiesel [7].

Malaysian palm-oil production began in the 1930s [55]. In 2011, the industry harvested approximately 5.0 million ha of oil palm yielding, after processing, an average 3.8 tonnes of palm oil per hectare [56]. In 2009, 99% of palm oil was used for food and one percent for fuel production [24]. The industry has more than doubled since 1990 and grew 38% from 2000 to 2009 [24, 57]. About 1.1 million ha (55%) of the expansion came at the expense of other tree crops such as cocoa, coconut and rubber. It is estimated that the remaining area (740,000 ha) came from clearing a combination of primary and secondary forests [58] as well as reusing abandoned/idled agricultural land [59].

Oil palm produces two types of oil, crude palm oil (CPO) and crude palm kernel oil (CPKO). The latter constitutes 10% of the total palm oil produced. Accounting for the two types of palm oil, average yield is about 4 t/ha, which is the highest yield among the major edible oils [60]. Palm methyl ester (PME) biodiesel is made from crude palm oil (CPO). The fuel has several potential environmental benefits, notably reduced hydrocarbons, SO_2, NO_x and particulate matters emissions from the tailpipe when compared to petroleum diesel [43-45].

The overall process for PME production is shown in Figure 2-1. Six-month-old trees are transferred from the nursery to oil-palm plantations where the trees are ready for palm-oil harvest after 24 months. Harvesting of the fresh fruit bunches (FFBs) is done manually. The FFBs are transported in small trailers to mills where the CPO is extracted. Crude palm oil is then transported to a biodiesel plant where it undergoes transesterification to produce PME.

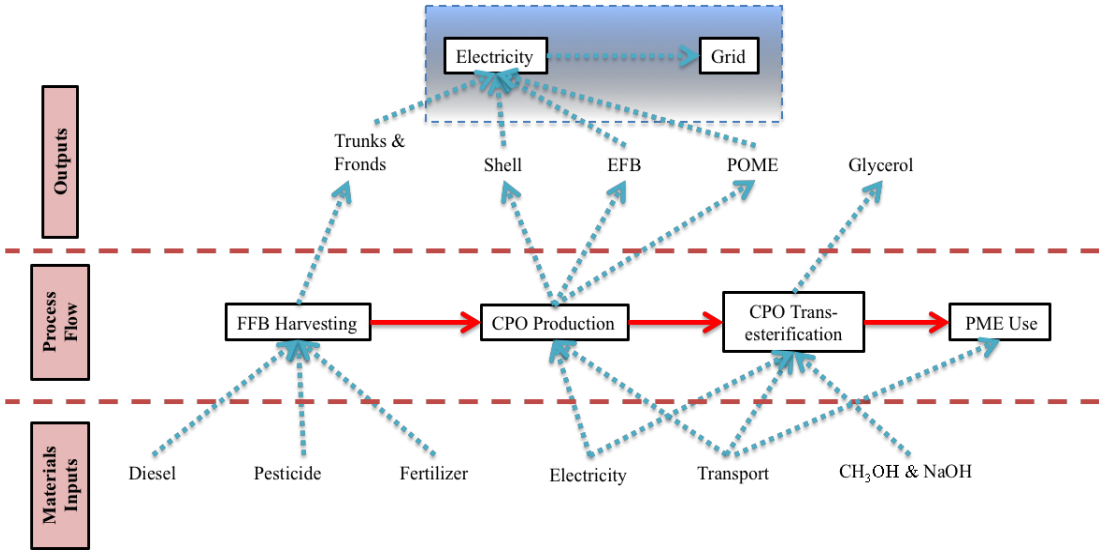


Figure 2-1: Overall PME production

Note: producing grid electricity is a potential practice.

The expansion of oil-palm plantations has led to an increase in GHG emissions from the agricultural sector [27]. According to Henson, in 2005, oil-palm cultivation (planting and harvesting) and palm-oil production in Malaysia emitted about 13 Mt a year of GHG, a 29% increase from the year 2000 [27]. The main sources of GHG emissions were from land conversion (60%), methane emissions from palm oil mill effluent treatment via anaerobic digestion (13%), fossil-fuel combustion (13%) and fertilizer use (4%).

This work estimates the future GHG emissions associated with palm-oil to PME for the Malaysian transport sector. Appropriate policy decisions that address the impacts of a developing palm-oil industry related to land use are discussed. This study does not address other important metrics such as wastewater release, eco-toxicity, human health and biodiversity or the implications of other costs and benefits.

2.2 Methods and Data Sources

2.2.1 Life-cycle analysis

This study uses a life-cycle assessment (LCA) approach [89] to determine the GHG emissions of producing PME in Malaysia. All GHG emissions are expressed on a CO_2-equivalent (CO_2-eq) basis using 100-year global warming potential from the IPCC Fourth Assessment Report [90]. Data for all input materials used in each unit process were gathered from the literature or from public data on Malaysia's oil palm industry.

2.2.2 System boundary and functional unit

The system boundary includes all major inputs and outputs for oil-palm cultivation to produce FFB (FFB Harvesting), FFB milling to produce CPO (CPO production), conversion of CPO to PME (PME Production), and the use of PME (PME Use) (Figure 2-1). The impact of land use change (LUC) is investigated for various types of available land (primary and secondary forests, peat forests, grassland and degraded land). In this study, the use of lands currently used for other tree crops (or economic crops) cultivation was excluded, since using this land would result in GHG emissions associated with indirect land use change (iLUC) [75]. Indirect land use change related emissions have been found to be significant in other studies [70, 75] and the focus of this paper is to identify land use that could be used to meet Malaysia's biodiesel target and reduce GHG emissions.

This study accounts for GHG emissions associated with the production and use of 1 MJ of land-to-wheel PME in domestic consumption, the functional unit selected for this study. Potential co-products, such as palm kernel expeller used as animal feed, CPKO used as surfactant in the oleo-chemical industry, and glycerol used for animal feed and in other food and chemical industries, were not considered due to limited and inconsistent data. If GHG emissions were allocated to the co-products the impact would be small whether based on economic value [91] or mass [92]. Since there is no allocation of emissions to co-products, estimates can be considered a slight overestimate of impacts.

2.2.3 Oil-palm cultivation

Oil-palm trees have a 25 year life span, the average efficient productive years [32]. This period is used for modeling the GHG emissions where total emissions are distributed over 25 years. In Malaysia, oil-palm trees are planted at a density of 136 – 160 trees per ha [93]. In this study, an average density of 148 trees per ha is assumed [57]. The average Malaysian FFB yield is 19 t/ha [32, 53, 94]. The average yield was used for palm oil produced on peat forest, primary forest and secondary forest [95] but was reduced by 10% and 20% for grassland and degraded land, respectively [96-99]. There is no published report on yield of FFB on grassland and degraded land. However, crop yields have been shown to be between 20% and 50% lower on these land types [99]. Hamdan et al. [96] showed that there is no significant drop of FFB (less than 5%) for trees planted on bris or sandy soil. Thus using the 20% less yield from the average for degraded land seemed a reasonable first approximation.

2.2.4 FFB milling

The conventional milling process produces one tonne of CPO from 5.2 tonnes of FFB [100]. The FFBs are heated in a large pressure vessel and then FFB fruitlets are pressed to extract the oil and the oil clarified to produce CPO. Data used for the input materials for one tonne of CPO production are presented in Table 2-1 and presented in detail in Appendix A. Almost all oil-palm mills generate the required steam input using biomass, and therefore it is considered as a net-zero emission energy input [32].

The extraction of CPO generates palm-oil mill effluent (POME) that needs to be treated. Biogas is released from the POME treatment and contains 65% methane and 30% CO_2 by

volume. The amount of methane produced from POME was estimated by Shirai et al. [101]. In this study, it is assumed that 85% of the biogas is released to the atmosphere while the remaining 15% is captured and flared as it is the common practice in the industry [102].

Processing FFB to CPO requires heat and electricity. Heat is generated on site using the oil-palm wastes and as such it has net zero GHG emissions. About 17 kWh of electricity is required to process one tonne FFB [103]. Based on the approved installed capacity of about 170 MW from Malaysia's Small Renewable Energy Program that uses oil-palm biomass [76], a 70% operating capacity would generate about one million MWh. To achieve that, it is estimated that approximately 10% of the EFB, or 1% of the total waste biomass from the palm-oil industry, is collected for conversion into electricity. This is based on 28% conversion efficiency of a direct-fired biomass power plant [104] using oil-palm biomass wastes with the availability and energy content of oil-palm biomass as shown in Table 2-1. Approximately13 kWh/tonne FFB processed are thus generated. Therefore, about 4 kWh is purchased from the grid per tonne of FFB. This study assumes the transportation of the oil-palm biomass to generate electricity requires an average distance of 11 km from the plantation to the mill [105] (see Appendix A).

Table 2-1: Availability of dry matter biomass wastes from oil palm tree

Types of dry matter	**Quantity (t/ha/yr)** [106]	**Calorific value – dry matter (MJ/kg)** [107]
Empty Fruit Bunch	1.6	18.8
Fiber	1.6	19.1
Shell	1.1	20.1
Fronds (annual pruned and old trees distributed over 25 years)	11.0	15.7
Trunks (old trees distributed over 25 years)	3.0	17.5

2.2.5 Palm methyl ester (PME) production

Unrefined CPO is trucked from the mills to the PME production plant; a 200 km round trip is assumed [108] (refer to Appendix A for the data and assumptions). The CPO is then refined to produce Refined, Bleached and Deodorized (RBD) oil. The materials input and energy use in this process is shown in Table 2-2 and in Appendix A. The RBD is then used in the transesterification process to produce biodiesel [64, 67]. Short-chain alcohols (methanol or ethanol) are used to form alkyl esters with the triacylglycerol lipids and glycerol as a reaction byproduct. Three primary inputs are needed for the transesterification reaction: 150 kg of methanol, 8 kg of sodium hydroxide, and 1.1 tonne of CPO. Approximately 32 kWh of electricity is used to run the equipment and produce 200 kg of required steam. Currently 19 of the 20 established biodiesel plants in Malaysia use a continuous, conventional methanol transesterification and sodium hydroxide as the catalyst [92]. All electricity supply for making biodiesel at the biodiesel plant comes from the grid (see Table 2-2).

2.2.6 PME use

The major feedstock used for PME production is biomass, so that the GHG released from the combustion of the oil that originates from the fruits is considered net-zero [76]. However, PME also contains fossil carbon from methanol used during the transesterification process. Based on palm biodiesel's average carbon content of 76% [109], every tonne of PME combusted releases 760 kg of CO_2-eq (combination of both biomass and fossil carbon). However, since Malaysia's PME average fossil carbon content is only 5.9% of the total emissions [110], approximately 45 kg of CO_2/tonne PME is released at this stage. Also accounted for in this stage is the transport of the blended petroleum and biodiesel from a blending facility assumed to be

located on average 100 km from a refueling station [92] (refer to Appendix A for data and assumptions).

2.2.7 **Land use change (LUC)**

Five different land types were modeled in this study including: peat forest, primary forest, secondary forest, grassland and degraded land (refer to Appendix B for a brief description of each of the land type). These land types were chosen based on current land use by Malaysian oil-palm plantations [27]. The impact of GHG emissions from LUC is quantified on a per hectare basis from estimates of the total standing biomass of the original forest and soil carbon change. The total standing biomass for the five land types are summarized in Appendix C. Once cleared, all standing biomass carbon is released to the atmosphere from the burning activity as well as natural decay of plant materials. However, the trees can be used to make furniture, building materials, etc. and carbon is temporarily sequestered (possibly for more than 50 years). Henson [27] has estimated that about 100,000 tonnes of carbon per year of the cleared forest trees was sequestered as products between 1981 - 2005. In that period the oil-palm area grew by 2.3 million ha. As such, it was estimated that about 0.04 tonne of carbon per ha per year is sequestered in products and credited against GHG emissions from the land clearing. A carbon credit is also taken for permanent ground-cover biomass under the oil palm trees at 0.08 t/ha/yr [27].

Malaysian law requires forests that are converted to economic activities be replaced with reforested areas of approximately the same size [111]. For this practice, the impact of directly converting primary and secondary forests to palm-oil production and replacing them with reforested areas was modeled. The reforested areas are assumed to be undisturbed indefinitely.

The biomass (standing and below ground) of these new forests is taken as credits from the LUC of the original primary and secondary forests.

Carbon is released over time from the soil when land is cleared for oil-palm plantation. The soil carbon content per ha of land for various forests types is given in the Appendix D. This study assumes some soil carbon is released from the soil when converted to palm-oil production but distributed over the 25-year modeling period. Oil-palm plantations have about 55% to 65% of the soil carbon content of primary forest soil [112] or between 66 to 78 t/ha. Using the midpoint, 72 t/ha of soil carbon, converting primary forest would release 48 t C/ha while converting degraded lands would capture 71 t C/ha in the soil (see Appendix E).

When modeling future oil-palm expansion scenarios, including LUC, future improvements in the PME production chain were added to capture developing trends in the environmental management of the palm-oil industry. The improvements included: (i) increasing production of electricity from the waste biomass using about 2% of the total waste biomass collected vs. the current 1% and (ii) capturing and flaring 50% of the biogas instead of 15%. System expansion by offsetting the average grid emissions was used to obtain emissions credits from excess biomass electricity not used in PME production. The availability of these residues and their calorific values are described in Table 2-1.

2.2.8 Sensitivity and uncertainty analysis

There are 57 or 58 variables, depending on the land type, that affect the final output. Sensitivity analysis was conducted for all five different land types and the two forest replacements (see Appendix F). Variables, except FFB yield, that were found to have the largest

influence on the results were then assigned triangular distributions. The FFB yield was assigned a Weibull distribution, based on the yield data from 1987-2007. Data for the lower and upper limit were taken from literature as in Table 2-2 and in Appendix A while the parameters that have relatively small impacts, i.e. less than 1% change from the median values, were frozen during the Monte Carlo (MC) simulation. Results of 10,000 runs of the MC simulation were reported on a 90% credible interval where the 5th and the 95th percentile values are used as the lower and upper bound of GHG emitted for each land type.

2.2.9 Important inputs and assumptions for the model

The important inputs, values, assumptions, and data sources for the making of 1 MJ of PME in the model are shown in Table 2-2.

Table 2-2: Materials input per MJ of PME

Amount	Unit	Sources	Notes
		Oil Palm Cultivation Phase	
a) Nitrogen based fertilizer			GHG emissions associated with the production of the fertilizers, herbicides and pesticides are from Simapro [113]. In addition to the carbon emissions associated with N fertilizer production, the use phase results in N_2O which has a GWP of 298 is also emitted when nitrogen based fertilizers is used. The emission of N_2O is calculated using the method from US EPA AP 42 [114]. Data and assumptions for other input materials are presented in the Appendix A.
1.3*	g	[100]	
Range: 0.3 - 2.3	g	[115], [116]	
		FFB Milling Phase	
a) FFB yield			5.2 tonnes of FFB is required to produce 1 tonne of CPO.
0.14*	kg	[100]	
Range: 0.13 – 0.17	kg	[103], [117]	
b) Electricity			The emission factor of 660 g/kWh from the average national electricity generation mix is used for electricity. This is based on an estimated CO_2 emission factor of 1.18, 0.85 and 0.53 kg/kWh of electricity generated from coal, oil and gas respectively [118]. Data and assumptions for other input materials are presented in the Appendix A.
2.4*	Wh	[103]	
Range: 0.008 – 4.4	Wh	[100], [119]	
		PME Production Phase	
a) CPO			1.06 tonne of CPO is required to produce one tonne of PME. The amount is normalized based on the PME's Lower Heating Value of 38,900 MJ/tonne [67]. Data and assumptions for other input materials are presented in the Appendix A.
0.027*	kg	[120]	
Range: 0.025 – 0.029	kg	[53], [117]	

Note: * - indicate the input used in the calculations. The range values are used as the lower and upper limit for the distributions.

2.3 Results and Discussion

2.3.1 GHG emissions from the PME production

For every MJ of PME produced, the median value from the MC simulations of the GHG emissions is about 56 g of CO_2-eq (Table 2-3). This is in contrast to the results found by Chen [100] and Lam et al. [121] where they estimated net capture of about 18 g and 180 g of CO_2-eq per MJ of PME produced, respectively. The difference in study results relates to a GHG credit from the growth of the oil palm tree. Oil palm trees have a 25 year time horizon during which they are considered commercially productive [32]. Many authors claim a credit for this standing biomass [100, 115, 121, 122]. However, here the credit is ignored since at the end of the 25-year life span the trees are cleared, resulting in a net zero carbon sequestration. If the credit were taken here, 44 g of CO_2-eq per MJ PME produced would be captured.

The production of FFB results in 24 g CO_2-equivalent emissions per MJ biodiesel produced (Table 2-3). Fertilizer use accounts for about 20 g of the emissions and, specifically, ¾ of the emissions comes from nitrogen fertilizer production and use. Crude palm-oil production (FFB milling) releases about 21 g of GHG emitted per MJ PME produced (Table 2-3). Our results indicate that 34% of emissions of the overall production emissions are from POME treatment, where biodegradation of the high organic load results in the production of approximately 8.7 m^3 of CH_4 per tonne of FFB treated or about 19 g CO_2-eq/MJ of PME (Table 2-3). By comparison, Chen [100] estimated the FFB milling emissions between 14 and 27 g/MJ PME, while Reijnders and Huijbregts [122] found approximately 7 to 54 g/MJ PME. These values are comparable to Chavalparit et al. [116], where the authors found that palm-oil production in Thailand emitted about 9 m^3 of CH_4 per tonne of FFB from the anaerobic treatment

of POME. Another 2.2 g of GHG comes from the use of diesel (for transport and mill operation) and grid electricity (4 kWh) at the mill.

Palm methyl ester production results in the production of 6.7 g of GHG per MJ PME (Table 2-3). Refining CPO into RBD for use in the transesterification process emitted approximately 3.0 g GHG/MJ PME that comes from electricity (0.6 g of GHG/MJ PME) and diesel (2.4 g GHG/MJ PME). The transesterification process results in the emission of approximately 3.7 g of GHG per MJ of PME (Table 2-3). About 80% of the transesterification process GHG emissions come from the production of methanol used in the process (3 g/MJ PME). However, since the efficiency of the transesterification is already about 94%, there is little opportunity to reduce emissions at this phase. A 100% efficient conversion would only result in 0.4% reduction of GHG emissions per MJ PME.

The use phase of PME releases a total of 5 g CO_2-eq per MJ of PME. The fossil carbon in the PME contributes approximately 4.2 g while the process of transporting the biodiesel to a refueling station emits 0.8 g (Table 2-3).

Table 2-3: GHG emissions per MJ PME from the PME production.

Items	GHG (g/MJ)
Oil Palm Cultivation	
Biomass credit from ground cover in oil palm plantation	-2.2
Materials input	26.0
• *Diesel*	*1.0*
• *Seed & nursery*	*0.1*
• *Nitrogen fertilizer*	*15.0*
• *Other fertilizers (P, K, Mg, B)*	*4.6*
• *Pesticides & herbicides*	*4.6*
Sub-Total Oil Palm Cultivation	***24.0***
FFB Milling	
Palm Oil Mill Effluent (POME)	19.0
Materials input	1.7
• *Diesel for transport*	*0.8*
• *Diesel at mill*	*0.2*
• *Electricity*	*0.7*
Sub-Total FFB Milling	***21.0***
PME Production	
Materials input	
• *Methanol*	*3.0*
• *Sodium hydroxide*	*0.2*
• *Calcium bentonite*	*0.1*
• *Phosphoric acid*	*0.02*
• *Electricity (refinery and transesterification process)*	*1.1*
• *Diesel (transport from refinery to biodiesel plant)*	*2.4*
Sub-Total PME Production	***6.7***
PME Use	
• *Diesel (transport)*	*0.8*
• *Combustion*	*4.2*
Sub-Total PME Use	***5.0***
Grand Total per MJ PME	**56.0**

2.3.2 PME production improvements

Overall, PME production results in two major sources of GHG emissions, those from the use of fertilizers (20 g/MJ PME) and methane released during decomposition of the POME (19 g/MJ PME). Inorganic fertilizer, including nitrogen fertilizer, reduction is being encouraged by

the government [123, 124]. With increased use of organic fertilizers, especially using the wastes that come from the oil-palm plantations such as the EFB and palm kernel expeller, the emissions trend is improving. The industry is also moving towards reducing the release of methane to the atmosphere from POME decomposition. Methane in the biogas can be used to generate electricity, process heat or if nothing else, simply flared (the latter is modeled in this study) to release only CO_2 and water, reducing the GHG emissions impact. Shirai et al. [101] estimated a mill in Serting Hilir, Negeri Sembilan, that produces 65,000 tonnes of CPO annually could generate about 8.2 GWh of electricity every year if all the biogas is captured and converted into electricity. Assuming all the 19 million tonnes of CPO produced annually is processed in mills that are equipped with biogas to electricity facilities, approximately 2.4 TWh of electricity could be generated which is equivalent to about 1.8% of Malaysia's 2010 projected electricity generation [125]. Thus, utilizing the gas could be a significant source of renewable energy.

In the future it might be possible to collect enough waste biomass to generate excess electricity at the mills to obtain emission credits from the grid. For example, an increase from 10% of EFB collected to generate electricity, modeled here, to 21% to generate 2.1 million MWh/yr [125] would result in 9 kWh per tonne FFB of surplus electricity. Assuming the surplus electricity is sold to the grid, additional emission credits of approximately 0.8 g/MJ PME is obtained. A higher collection rate would result in a higher emission credit from grid electricity per MJ PME produced. If 100% of the oil-palm waste biomass were to be collected, the potential electricity generation is about 100 TWh/yr, approximately 75% of Malaysia's total projected electricity generation in 2010 [125].

2.3.3 GHG emissions from land-use change

Incorporating LUC effects in the life cycle model (the five land types and two forest replacements) results either in net GHG emissions or net capture depending on the land type brought into production (Figure 2-2). Planting oil palm trees on peat forest land results in GHG emissions of between 225 to 3,300 g CO_2-eq /MJ PME (not shown in Figure 2-2 for scaling purposes). Planting on primary and secondary forests, as well as grasslands release between 270 to 530 g CO_2-eq/MJ, 120 to 190 g CO_2-eq /MJ and 26 to 77 g CO_2-eq/MJ PME, respectively. These results are consistent with Reijnders and Huijbregts [122] estimate between 70 to 450 g CO_2-eq /MJ of net emissions when converting primary forests to oil-palm plantations and 40 to 180 g CO_2-eq /MJ while planting on secondary forests. However, planting on secondary forests with replacement of the forest results in a range of emissions from 60 g CO_2-eq/MJ to the capture of 46 g CO_2-eq/MJ PME. Planting on degraded land results in capture of between 23 to 85 g CO_2-eq/MJ PME. These results show that producing PME on specific lands could result in lower life cycle GHG emissions compared with diesel fuel if the land use is restricted to certain types of land.

The main contributor to emissions from LUC is the carbon loss during land clearing. In the case of secondary forest, about 130 g CO_2-eq is released from forest standing biomass per MJ of PME. Degraded land loses only 53 g CO_2-eq/MJ of PME from standing biomass. Depending on the original land type, soil carbon content may increase. For instance, if secondary forests are replaced by oil palm, the soil carbon content increases from 67 t/ha to 72 t/ha [112]. When converting secondary forests, secondary forests with replacement and degraded land into oil palm trees, the loss of standing biomass is offset by the increase in soil carbon content.

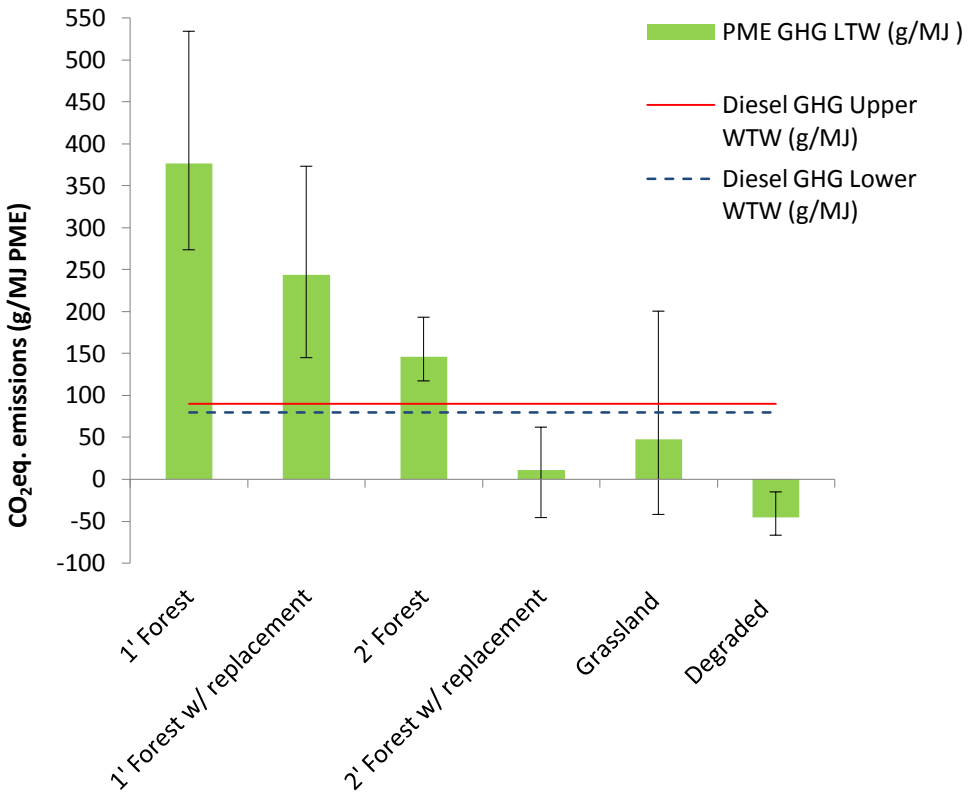


Figure 2-2: Lifecycle GHG emissions for land-to-wheel (LTW) PME production by type of LUC.

The error bars in Figure 2-2 represent the 90% credible intervals from the MC simulations. Between 7 and 30, depending on the land use type, of the highly sensitive parameters were assigned the appropriate probability distributions in the MC simulations for each of the different land types.

2.3.4 Land use and GHG emissions in meeting the biodiesel target in the transportation sector

Future expansion of the palm-oil industry is required to meet the 5% biodiesel target for transportation while preserving the supply of palm-oil used as food. The main motivations for this decision is to decrease dependence on petroleum (energy security), strengthen the price of CPO, and improve environmental performance [126]. In 2008 transportation consumed about 5.7 billion liters of petroleum diesel, 33% of the energy used for transportation [4]. Using the double moving average regression method to estimate diesel use through 2010 based on past trends [4], the consumption of diesel would reach 6 billion liters by that year. The year 2010 is used as the modeling year knowing that the current mandate has not been achieved to illustrate how the industry could achieve production levels envisioned in the policy. About 340 million liters of PME would be needed to achieve the 5% target. Depending on the land type, it is estimated that every hectare of land could produce between 110,000 and 130,000 MJ of PME, thus requiring between 87,000 ha and 110,000 ha of land directly used to plant the oil-palm trees to meet the 5% biodiesel target. This is about 2% to 2.6% of the current total oil-palm plantation area in Malaysia. Table 2-4 shows the land requirements for each planting case as well as total and feasible areas available for each land type. Feasible lands were identified as land located close to existing oil-palm plantations in order to effectively share infrastructure [27].

Table 2-4: Land requirements and available land to meet the 5% biodiesel share in the fossil diesel transportation sector

Planting on a single land type	Land Area ('000 ha)		
	Required	**Available [1]**	**Feasible [2] ('000 ha)**
Peat forest	87	1,500	8
Primary forest	87	18,000	180
Primary forest with replacement[3]	Primary Forest: 87 Land for Reforestation[4]: 87	Primary Forest: 18,000 Grassland: 330 Degraded land: 41	Primary Forest: 180 Grassland: 50 Degraded land: 28
Secondary forest	87	4,400	220
Secondary forest with replacement[3]	Secondary Forest: 87 Land for Reforestation[4]: 87	Secondary Forest: 4,400 Grassland: 330 Degraded land: 41	Secondary Forest: 220 Grassland: 50 Degraded land: 28
Grassland	96	330	50
Degraded Land	110	41	28

1- [127-129]
2- [27]
3- Replacement is defined as replanting/reforestation with an equivalent size of land at other locations as provided for under Section 11 of the National Forestry Act of Malaysia [111]. Only grassland and degraded lands are available for reforestation.
4- Only grassland and degraded land are used to be re-forested in this study.

As can be seen in Table 2-4, there is not enough land classified as feasible to reforest the 87,000 hectares of forest converted to oil-palm plantations. Similarly there are not enough feasible grasslands or degraded lands that could be used to meet the 5% biodiesel target. However, the available land area for each land type shows that there could be enough land if more feasible land were identified. Table 2-5 shows the GHG emissions associated with meeting the 5% biodiesel target for each planting case if there were enough feasible land for each case.

Table 2-5: GHG emissions for each land types converted to oil-palm plantations in meeting the 5% biodiesel share in the fossil diesel transportation sector

Planting on a single land type	GHG Emission (t/ha)	Total CO_2 emitted to meet 5% biodiesel (million tonnes)	
		Without credit	Including credit for displacement
Peat forest	280	22	21
Primary forest	51	3.9	2.8
Primary forest with replacement	33	2.5	1.5
Secondary forest	20	1.5	0.45
Secondary forest with replacement	1.5	0.11	-0.93
Grassland	5.7	0.49	-0.56
Degraded Land	-4.9	-0.47	-1.5

The level of emissions expected in obtaining the 5% biodiesel target is dependent on the choice of land brought into production. Expanding into peat, primary and secondary forests and grasslands results in net emissions of GHG (Table 2-5). Options exist, however, for obtaining lower overall emissions, including the use of primary and secondary forests (primary forests or peat forests that have been previously logged) accompanied by re-forestation on alternative lands. Also, degraded lands can store carbon due to soil carbon increases. The use of degraded land could result in the net capture of about 45 g CO_2-eq/MJ of PME produced, a total of about 470,000 tonnes of carbon captured. Using degraded lands to produce the 5% PME could reduce the country's transportation sector's GHG emission by 2.2%. The policy to use or rehabilitate degraded lands such as ex-mining lands has already been introduced by the Government of Malaysia [130]. The policy provides incentives to rehabilitate the lands such as facilitating and expediting approval for physical development and transfer of titles.

As previously discussed, land classified as feasible is insufficient to obtain the minimum possible GHG emissions in meeting the 5% PME mandate. Thus planting of oil-palm trees on a combination of various land types would be required (unless more feasible land is identified). This could be achieved by converting 54,000 ha of secondary forest and 28,000 ha of degraded lands. Out of the 54,000 ha of the secondary forest, 50,000 ha must be reforested using grasslands. This would result in the conversion of approximately 82,000 ha (including the 50,000 ha of grasslands that are used to plant new forests) and result in a reduction of 1.03 million tonnes of GHG emissions, including one million tonnes of emissions offsets from displacing 5% of petroleum diesel use. Since one can capture CO_2 while meeting the 5% goal, a number of land combinations exists that can achieve net zero emissions along with an increase biodiesel production above the current target.

Alternatively, Malaysia could decide that the goal is to keep GHG emissions in its transportation sector at current levels. This could be accomplished by using all degraded lands (28,000 ha) and about 160,000 ha of secondary forests. Again, approximately 50,000 ha of grasslands will also need to be reforested. There exist a number of combinations of land types that can achieve similar results. Under these constraints Malaysia could produce 25 PJ of PME, approximately 700 million liters, which is about 12% of the country's projected fossil diesel consumption by vehicles in 2010.

Changing land-use patterns brings about a number of important social and environmental changes not investigated here. Costs are also not evaluated and some of these scenarios are highly dependent on the replacement of forests, which can be costly and may never provide the biodiversity or ecosystem services of native forests. This analysis is meant as a "what is

possible" study. Additional analysis will be required to determine what is feasible and cost-effective.

One important factor that can bring different implications on cost-effectiveness of the PME blend mandate, which is not considered, is the effect of price volatility of palm-oil. The palm-oil price have been rising steadily for the past five years [131], which follows similar pattern with crude oil. Having only a 5% mandate, PME cannot compete with petroleum diesel in supplying transportation fuel in Malaysia. Substituting a low portion of the petroleum diesel will have little effect on dampening the price volatility of transportation fuel in the country.

2.3.5 Policy implications

Malaysia can meet its target to blend 5% of palm oil biodiesel to reduce diesel consumption in the transportation sector and lower GHG emissions from its transportation fuel use. This can be achieved with careful expansion of the oil-palm industry using suitable land types, i.e. those with low GHG emission factors or with the potential to provide a net-capture of GHGs. To this end, there are three policy issues that could aid in attaining such a goal.

The first is the mitigation of GHG emissions while producing the 5% biodiesel. The government should mandate the requirement to reduce GHG emissions from the use of palm-biodiesel by adding a provision in the Biofuel Industry Act, Malaysia 2007 (Act 666) that spells out the requirement that "the lifecycle GHG emissions from producing the biodiesel and displacing the petroleum diesel is less than the lifecycle GHG emissions of the petroleum diesel being displaced." It is shown here that Malaysia could increase the biodiesel share up to 12% with constant GHG emissions in its transport fuel. Considering the uncertainty in LCA results, at

least 9% blend of biodiesel in the petroleum diesel transportation sector is likely achievable under these constraints. This is based on the upper value of the GHG emissions for each land type included in this study.

The second policy issue is to assure the mitigation of the impacts of oil-palm expansion. It was shown that planting oil-palm trees on peat, primary and secondary forests results in higher GHG emissions compared with diesel use. Forest replacement mitigates these impacts to some extent but is more applicable for secondary forests because it could result in a lower GHG emissions compared with diesel fuel (Figure 2-2) and thus should be encouraged. The government should prohibit the expansion of oil palm plantations into peat and primary forests as well as displacing other economic crops which cause market mediated indirect land use change and severely impacts the overall greenhouse gas emissions associated with oil-palm production [132]. This strategy can be accomplished by amending the Malaysian Palm Oil Board Act, (1998) giving the Malaysian Palm Oil Board (MPOB), a statutory body, the task to regulate the industry and by strict enforcement of Section 11 of the National Forestry Act, Malaysia (1984) making it mandatory for oil-palm plantation companies to replace the forest with other appropriate land. Section 11 of the Act should also be amended to include secondary forest as a type of forest that needs to be replaced by an approximately equal area of land if it is converted to other economic activities.

The third policy is reducing GHG emissions in the PME production process. Particular attention should be given to PME feedstock production where the largest emissions result from inorganic fertilizer use and methane production from POME treatment. Regulations under the MPOB Act could be modified to require oil palm plantations to increase organic fertilizer use and reduce methane emissions by requiring new and current POME-treatment facilities to use a

closed digester tank. At a minimum, the capture gas should be flared but preferably be used to generate process heat or electricity.

3 Availability of Biomass Residues for Co-firing in Malaysia: Implications for Cost and GHG Emissions in the Electricity Sector

3.1 Introduction

Malaysia's electricity sector was the second largest final energy user in 2009, representing approximately 350 PJ, 21% of Malaysia's total consumption [1]. Malaysia's electricity sector depends on roughly 93% fossil fuels, producing 57 million MWh of electricity from natural gas and 37 million MWh from coal [9]. The coal share increased from 12% in 1990 to 32% in 2008. Coal use is expected to increase four-fold to 155 million MWh by the year 2030 while natural gas share is projected to decrease by almost half [10]. This is because Malaysia wants to decrease its high dependence on natural gas.

GHG emissions from Malaysia's electricity sector are estimated at 65 million tonnes (Mt) comprising 36% of the country's total GHG emissions in 2010 [2, 133], using average world direct GHG emissions factors for coal and natural gas [11]. The increasing consumption of coal is the main contributor to the increase in electricity sector GHG emissions [12]. To curb this increase, Malaysia has set a reduction target of 3.2 Mt of GHG emissions by 2015. This target is to be achieved by installing 975 MW of renewable electricity including 330 MW biomass, increasing the use of renewable fuel in the electricity sector to 1.8% [13]. However, the technology for generating the biomass electricity is not specified.

Currently, electricity from biomass in Malaysia is generated from oil-palm and rice residues (170 MW or 75%) wood chips and sawdust (24%), and municipal solid waste (MSW) at 1% [9]. In 2009, about 1.5 million MWh of electricity was generated from these stand-alone biomass power plants. Lim et al. [31] estimated the total annual potential energy from biomass in

Malaysia that could be used for electricity generation to be around 250 million MWh, double the amount of electricity generated in 2008 [9]. He estimated that electricity generation could come mainly from logging and oil-palm residues of between 530 and 670 million GJ (150 and 190 million MWh), with residues from rubber, cocoa and coconut plantations as well as rice (husks and straws) making up the rest [31, 32]. A more recent study by Muis et al. [34] has estimated that biomass electricity could replace up to 9% of the total electricity in Malaysia with savings of up to 29 Mt of CO_2-eq annually. However, neither study accounted for factors such as recovery rates, competing uses, and recoverability/accessibility factors such as road infrastructure and detailed locations of biomass resources in relation to the existing power plants.

Renewable energy resources are abundant in Malaysia and include biomass and solar. Malaysia's biomass resources mainly come from the agro-forestry sector. In Peninsular/West Malaysia, forest covers approximately 5.8 million ha, while 4.5 million ha is agricultural land. The agricultural land includes mainly oil-palm (62%) and rubber plantations (29%). The other 9% includes rice fields (7%) and other cash crops (coconut, cocoa, sugar cane and orchids) [134]. This agro-forestry sector generates residues from its activities, which can be combusted to generate electricity [135]. Having more than 80% of its land area covered with biomass, Malaysia could put more emphasis on increasing the use of bioenergy by utilizing residues from the agro-forestry sector. However, there are several factors that affect the availability of these residues, such as accessibility and recoverability factors as well as competing uses.

Even though biomass energy is assumed by most to have net-zero GHG emissions from the biogenic carbon [26], positive emissions could still come from the harvesting activity and delivering of the biomass to the processing facilities. For example, the expansion of oil-palm plantations in Malaysia has led to an increase in GHG emissions from the agricultural sector

[27]. According to Henson, in 2005 oil-palm cultivation (planting and harvesting) and palm-oil production in Malaysia emitted about 13 Mt GHG annually, a 29% increase from the year 2000 [27]. The main sources of GHG emissions were from land conversion (60%), methane emissions from palm oil mill effluent treatment via anaerobic digestion (13%), fossil-fuel combustion (13%) and fertilizer use (4%). In addition, rubber estates, oil-palm plantations, rice fields, logging areas, landfills and mills are generally located far from existing power plants. Therefore, delivering residues from these plantations / logging areas and mills long distances may make the use of biomass energy less attractive in terms of minimizing total costs and GHG emissions.

To our knowledge, there are no studies assessing the usability of biomass residues for electricity generation and evaluating the benefits of utilizing the various types of biomass residues at a large scale for electricity generation in Malaysia. As mentioned above, all of Malaysia's current biomass electricity is generated from direct combustion power plants. However, the additional 330 MW targeted by 2015 did not specify the type of technology that will be used. Biomass co-firing with coal could be a good alternative that will not require additional investments for grid connection and can obtain the various benefits of co-firing. In this Chapter I determine: (i) the amounts of biomass residues in Peninsular Malaysia that can be used for electricity generation and the locations of the residues; (ii) the amount of biomass residues that can be co-fired with coal that minimize cost compared to only using coal; and (iii) the minimum GHG emissions that can be achieved via biomass coal co-firing.

3.2 Data and Methods

3.2.1 Data sources

Data were obtained from the literature and government reports and statistics. Data from the literature were used primarily for estimating residues-to-product ratio (RPR), energy content, emissions factors, price, cost, efficiency, accessibility/recoverability factor, competing uses, and energy requirement. Malaysia is divided into two regions: Peninsular/West and East Malaysia. Peninsular Malaysia is used for this study to represent the country's energy sector because it is the more developed region. For example, 91% of the country's electricity is generated in Peninsular Malaysia. Malaysia's coal-fired power plant locations and capacities and biomass energy targets were obtained from government agency reports, e.g., from the Ministry of Energy, Water and Green Technology [1, 15], Energy Commission [9] and Tenaga Nasional Berhad (government owned utility company) [136]. Data on area of biomass, such as logging areas and plantations, were obtained from Ministry of Agriculture and Agro-based Industry [134, 137] and Ministry of Natural Resources and Environment [22]. Data with regard to the downstream processing industry was obtained from regulatory agencies, such as the Malaysian Palm Oil Board [138] and the Department of National Solid Waste Management [139]. Figure 3-1 shows the general process flow starting from data gathering, processing, modeling, outputs and analyzing the results, each described in the following sub-sections.

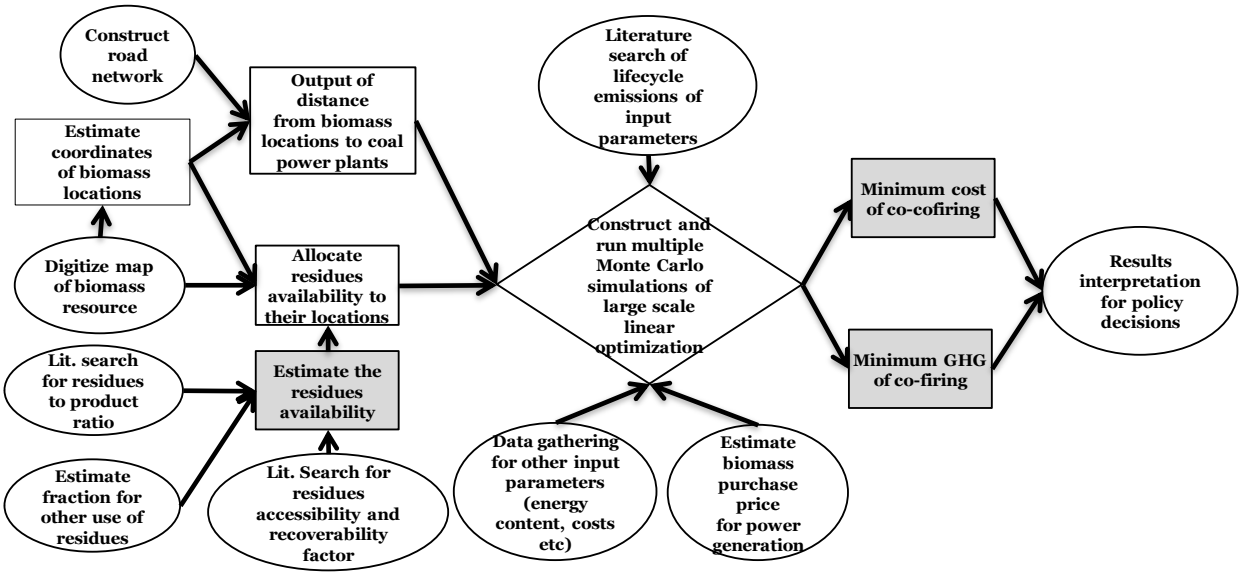


Figure 3-1: Process flow chart of the study
Note: Shaded boxes represent main outputs.

3.2.2 Biomass sources and amounts

Residues from the forestry sector comprise of leftovers from logging areas (branches) as well as residues generated at mills (sawdust, slabs, trimmings and edgings), estimated to be around 9.8 million m^3 (7.4 Mt) annually [23]. Currently there are about 100,000 ha of logging area and approximately 650 sawmills and plywood mills in Peninsular Malaysia [21, 22]. Agricultural residues in Malaysia are mainly comprised of residues generated by the oil-palm industry (empty fruit bunches (EFB), fronds, fibers, shells and trunks) and rubber plantations (branches and trunks). Rice residues (husks and straw), cocoa branches and coconut (fronds and trunks) are generated at a lesser extent. There are currently about 250 palm oil mills and 230 rice mills in Peninsular Malaysia [24, 25]. The amount of residues from the agricultural sector is estimated to be about 23 million m^3 (17 Mt) [23]. However, these estimates did not include other factors such as accessibility, recoverability and other competing uses.

The following biomass residues are considered for electricity generation in Malaysia: logging, oil palm, rubber, cocoa, coconut, rice and wood-based MSW. The first four resources are chosen because they are important agro-forestry commodities that generate export income to the country [140]. Rice is widely harvested in the region, occupying approximately 7% of the total agricultural area of Peninsular Malaysia [137]. Wood-based MSW was modeled because it is available throughout the region with 98 landfill sites in Peninsular Malaysia [141]. These seven resources cover approximately 10.3 million ha (79%) of Peninsular Malaysia's land area (Table 3-1). I have excluded other resources not widely harvested in Peninsular Malaysia or not a significant commodity [137].

Table 3-1: Land coverage of the sources of residues studied

Biomass Type	Area ('000 ha)	Percentage (%)
Forest	5,800	56
Oil Palm	2,800	27
Rubber	1,280	13
Rice	330	3.2
Coconut	104	1.01
Cocoa	13	0.13
MSW	2	0.02
Total	**10,300**	**100**

To estimate the amounts of residues available to be used, the residue to product ratio (RPR) of crops/products, the accessibility and recoverability factor and the estimated percentage of residues being used in other sectors/products are used (see Table 3-2), which were obtained from the literature. The estimated total amount of residues available for each type of biomass were then distributed (by weight) to the specific mills (for process-based residues) and

fields/plantations (for field-based residues) according to mill capacity and area, respectively. As an example, the 120,000 tonnes of total rice husks available were assigned to the 230 rice mills according to their processing capacities. Rice mills were found to have capacity between 2 and 1,900 t/yr with an average of about 520 t/yr. See Appendix A for a detailed explanation on the estimation of the residues amounts.

Table 3-2: Residues to product ratio (RPR), accessibility and recoverability factor and fraction used for other purposes of the different biomass types used in this study

Residue type	RPR	Accessibility and recoverability factor	Fraction used for other purposes
Palm Empty Fruit Bunch (EFB)	1.6 t/ha [107]	1.0 [93]	0.65 [9] [57] [142]
Palm shell	1.0 t/ha [138]	1.0 [93]	0.6 [9] [57]
Palm fiber	1.6 t/ha [107]	1.0 [93]	0.6 [9] [57]
Rice husk	0.78 t/ha [137]	1.0 [25, 143]	0.55 [144] [137]
Wood and paper-based MSW	0.22 t/t MSW [139]	0.67 [33]	0.17 [145]
Sawmills	0.25 t/t of input logs [21, 23]	1.0 [22]	0.81 [31, 146]
Plywood mills	0.47 t/t of input logs	1.0 [22]	0.81 [31, 146]
Palm trunks	3.0 t/ha [107]	0.9 [93]	0.9 [147]
Palm fronds	7.75 t/ha [138]	0.1 [93]	0.4 [55] [148]
Rice straw	2.6 t/ha [137]	0.65 [33]	0.1 [149]
Cocoa branches	23 t/ha [31, 150]	0.5 [31]	0
Rubber branches	0.47 t/t branches [31, 146] 146]	0.5 [31]	0

Coconut trunks	0.19 t/ha [80, 151]	0.5 [31]	0
Coconut fronds	0.17 t/ha [31, 152]	0.5 [31]	0.9 [31]
Logging residues	0.39 t/t log produced [23] [31]	0.65 [33]	0

3.2.3 Biomass locations and distance to coal plants

Each location was allocated the amount of available residues using the method described in sub-section 3.2.2 above. The locations of the biomass residues were estimated using three approaches, namely (i) using exact addresses (for rice mills, sawmills and plywood mills) or coordinates (for landfills), (ii) assumed locations in the center of administrative districts (for palm-oil mills), and (iii) centers of areas represented by polygons (for rice straws, cocoa and rubber branches, oil-palm and coconut fronds and trunks, and logging areas). Using an online locater [153], geographic coordinates were assigned for residues with exact addresses, residues assumed to be located in the center of administrative districts and residues located in the center of polygons. For field-based residues that are assumed to be located in the center of polygons, locations were determined by digitizing the image (jpeg format) of a land-use map of Peninsular Malaysia for the year 2006 obtained from the Department of Agriculture, Malaysia [134] using a Geographic Information System (ArcGIS) [154]. Altogether 8,372 polygons (for plantations and logging areas) and 1,214 coordinates (for mills and landfills) were projected onto Peninsular Malaysia's map. The locations of the four coal-fired power plants were also projected on the map using their coordinates.

Distance from biomass residues to the four coal power plants is estimated using the network analysis tool in the ArcGIS software. The tool generates a matrix of distances using existing road network data obtained from the Malaysian Center for Geospatial Data Information. The values in the matrix represent the shortest road distance between the biomass locations and the coal pants via major toll highways, interstate federal roads, major state roads and trunk roads. The range of distance was found to be between less than 1 km and about 700 km.

3.2.4 Electricity generation

Approximately 37 million MWh (32%) of electricity was produced from coal in Malaysia in 2008 [9], which is the latest data available. However, the publication did not give the breakdown for each coal plant's electricity generation, four in Peninsular Malaysia and three in East Malaysia. Malaysia's coal plants have an average efficiency of about 37% [9]. To estimate the electricity generation for each coal plant in Peninsular Malaysia I used the installed capacity of each coal plant. Since about 94% (by capacity) of the coal plants are located in Peninsular Malaysia [9], about 35 million MWh are assumed to be generated by the four coal plants in this region. As such, each coal plant is assumed to have generated between 6.9 and 10.3 million MWh.

3.2.5 Optimization model

A large scale linear optimization model is constructed to estimate the total cost and GHG emissions associated with biomass coal co-firing in Peninsular Malaysia. Co-firing of biomass with coal is assumed to displace the electricity generated only by coal while maintaining the

current amount of electricity generation by each coal plant. Minimization of total costs and GHG emissions were evaluated in separate models. The Analytica Optimizer version 4.4.2.2 from Lumina Decision Systems that incorporates Frontline's large scale linear solver engine version 11 [155] is used. The mathematical formulation is as follows:

Minimize cost:

$$C = \sum_{t\in T}\sum_{i\in N_t}\sum_{j\in J} c_t x_{i,j}^t + \sum_{t\in T}\sum_{i\in N_t}\sum_{j\in J} d_{i,j}^t c_{i,j}^t x_{i,j}^t + \sum_{j\in J} c_j^{\mathrm{COAL}} x_j^{\mathrm{COAL}} + \sum_{j\in J}\sum_{l\in L} W_j c_l^{\mathrm{RET}} x_{j,l}^{\mathrm{RET}}$$

(from biomass purchase + biomass transport + coal purchase and transport + plant retrofit)

or

Minimize GHGs:

$$G = \sum_{t\in T}\sum_{i\in N_t}\sum_{j\in J} g_t x_{i,j}^t + \sum_{t\in T}\sum_{i\in N_t}\sum_{j\in J} d_{i,j}^t g_{i,j}^t x_{i,j}^t + \sum_{j\in J} g_j^{\mathrm{COAL}} x_j^{\mathrm{COAL}}$$

(from biomass pre-treatment + biomass transport + coal transport, pre-treatment and combustion)

With respect to:

$x_{i,j}^t \in \mathbb{R} \quad \forall i \in N_t, j \in J, t \in T$	Quantity of each residue type *t* shipped from each supply location *i* to each plant *j* (tonnes)
$x_j^{\mathrm{COAL}} \in \mathbb{R} \quad \forall j \in J$	Quantity of coal shipped to each plant *j* (tonnes)
$x_{j,l}^{\mathrm{RET}} \in \mathbb{R} \quad \forall j \in J, l \in L$	Variables defining the portion of plant *j*'s capacity that is retrofitted to co-fire biomass, where *l* indexes distinct levels of retrofit for modeling a piecewise linear (convex hull of five points) cost curve (%)

Subject to:

$\sum_{j\in J} x_{i,j}^t \leq s_i^t$ $\forall t \in T, i \in N_t$	At each supply location the use of biomass resources must not exceed its supply limit (tonnes).

$\sum_{t\in T}\sum_{i\in N_t}\eta_t x_{i,j}^t + \eta_C x_j^{\mathrm{COAL}} = E_j$ $\forall\, j = J$	The sum of electricity generated from biomass and coal at each plant must be equal to the total required (amount generated in the year 2008).
$\sum_{t\in T}\sum_{i\in N_t}\eta_t x_{i,j}^t = E_B$	The total energy generated from biomass should be E_B = 2 mil. MWh in one scenario. This constrained is omitted for the Optimal Residue Use scenario.
$\sum_{t\in T}\sum_{i\in N_t}\eta_t x_{i,j}^t \leq E_j \sum_{l\in L} x_{j,l}^{\mathrm{RET}} r_l$ $\forall\, j = J$	The total biomass generation at each plant must be within the co-firing capacity of that plant
$x_{i,j}^t, x_j^{\mathrm{COAL}} \geq 0$ $0 \leq x_{j,l}^{\mathrm{RET}} \leq 1$ $\sum_{l\in L} x_{j,l}^{\mathrm{RET}} \leq 1$ $\forall\, j = J, l \in L, t \in T$	Quantities must be nonnegative, and the retrofit variables are bound between zero and one with sum not greater than one to formulate the piecewise linear cost curve in the objective (convex hull of points {(0%, \$0/kW), (2%, \$100/kW), (10%, \$200/kW), (20%, \$300/kW), (100%, \$2000kW)}) [156, 157]. The retrofit capital cost is annualized over a 40 year assumed remaining life span of coal plants using a 4% discount rate [158-160].

where N_t = {1,2,...,n_t} is the set of supply locations for biomass residue type *t*; *T* and n_t, defined in Table 3-3, are the set of biomass residue types and the number of locations for each type, respectively; *J* = {1,2,3,4} is the set of coal plants; *L* = {1,2,3,4} is the set of co-firing retrofit levels in the piecewise linear retrofit cost curve; c_t is the purchase cost (\$/t) of biomass type *t*; $d_{i,j}^t$ is the distance (km) from biomass *t* location *i* to plant *j*; $c_{i,j}^t$ is the cost (\$/t) for shipping biomass type *t* from location *i* to plant *j*; c_j^{COAL} is the cost (\$/t) for purchase, transport, and pre-treatment of coal for plant *j*. Other coal plant operation and maintenance costs (labor, environmental controls, etc.) are assumed constant with respect to co-firing rate and are thus not

included in the cost estimation for the purpose of comparing the cost of co-firing vs. coal-only electricity generation; W_j is the capacity of plant j (MW); c_l^{RET} = \${100, 200, 300, 2000}/kW for l = {1,2,3,4}, respectively, is the cost per unit capacity of retrofitting plant j at breakpoint level l of the piecewise linear cost curve; g_t is the emissions intensity (tCO_2eq/t) from pre-treatment of biomass type t; $g_{i,j}^t$ is the emissions intensity ($tCO_2eq/t \cdot km$) of shipping from biomass type t location i to plant j; g_j^{COAL} is the emissions intensity (tCO_2eq/t) of pre-treating, transporting and combusting coal; s_i^t is the maximum supply of biomass type t at location i (t); η_t is the efficiency of converting biomass type t into electricity (MWh/t); η_{C} is the efficiency of converting coal into electricity (MWh/t); E_j is the annual electricity generation of plant j (MWh); E_{B} is the biomass co-firing capacity target; and r_l = {2%, 10%, 20%, 100%} for l = {1,2,3,4}, respectively, is the retrofit portion at each level l (breakpoint) of the piecewise linear cost curve.

Table 3-3: 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	3325
oil palm plantation frond residues	3325
rice fields straw residues	781
logging residues	97
rubber plantation branch residues	3879
coconut plantation trunk residues	312
coconut plantation frond residues	312
cocoa plantation branch residues	17

The total cost and emissions for coal-only electricity generation is also minimized $\left(x_{i,j}^{t} = x_{j,l}^{\mathrm{RET}} = 0 \quad \forall i \in N_t, j \in J, t \in T, l \in T\right)$ as a reference case, to compare its total cost with total cost of co-firing.

3.2.6 Uncertainty in input parameters

Several of the parameters in this formulation are uncertain or may vary with time. I follow the "wait-and-see" (WS) approach, taking 1000 Monte Carlo draws from the parameter distributions and identifying the optimal solution for each. This represents the case where purchasing and shipping decisions can be made after the uncertain parameters (e.g.: biomass prices, etc.) have been realized (i.e.: after they are known with certainty). This stands in contrast to the "here-and-now" approach, where decisions must be made before uncertain parameters are resolved [82, 83]. The values of the key input cost parameters and their assumed distributions are listed in Table 3-4. The set of optimal solutions are used to construct a probability distribution of total cost (given the optimal solution for each outcome). Data and assumptions for other input parameters are presented in Appendix I.

Table 3-4: Important cost parameters and ranges used in the model

Notation	Parameters	Unit	Distribution	Min	Most likely	Max	Note
c_t	Price of palm EFB	$/t	Triangular	$1.80 [105]	$5 [105]	$6.70 [105]	
c_t	Price of palm shell	$/t	-	-	$16.70 [105]	-	
c_t	Price of palm fiber	$/t	Triangular	$2.30 [105]	$5.50 [105]	$7.20 [105]	The price of EFB was used as surrogate and adjusted the value based on the energy content.
c_t	Price of rice husk	$/t	Uniform	$4.70 [161]	-	$11.80 [161]	This is a case study in the Philippines, a developing country similar to Malaysia.
c_t	Price of paper-based MSW	$/t	-	-	$1.90 [162]	-	The tipping fee for 1 t of solid MSW in Malaysia in 1994 was $1.20/t. A GDP deflator [163] was used to get the fee in 2010 ($1.70/t). A 10% premium [164] is added to get $1.90/t.
c_t	Price of sawmills residues	$/t	-	-	$7.40 [135]	-	Junginger‘s et al. [135] Eucalyptus wood waste in Thailand was used as surrogate.
c_t	Price of plywood mills residues	$/t	-	-	$7.40 [135]	-	Junginger‘s et al. [135] Eucalyptus wood waste in Thailand was used as surrogate.
c_t	Price of palm trunks	$/t	Triangular	$1.90 [105]	$5.10 [105]	$6.80 [105]	I used the price of EFB as surrogate and adjusted the value based on the energy

							content.
c_t	Price of palm fronds	$/t	Triangular	$1.40 [105]	$4.60 [105]	$6.30 [105]	The price of EFB is used as surrogate and adjusted the value based on the energy content.
c_t	Price of rice straw	$/t	-	-	$14.90 [135]	-	The cost of collecting and baling of rice straw is about $13.50 in Thailand as surrogate [135]. A premium of 10% [164] is assumed to estimate the selling price of $14.90/t.
c_t	Price of cocoa branches	$/t	Uniform	$13.50 [135]	-	$16.20 [135]	I used logging residues price as surrogate.
c_t	Price of rubber branches	$/t	Uniform	$13.50 [135]	-	$16.20 [135]	I used logging residues price as surrogate.
c_t	Price of coconut trunks	$/t	Triangular	$1.90 [105]	$5.10 [105]	$6.80 [105]	I used palm trunk's price as surrogate.
c_t	Price of coconut fronds	$/t	Triangular	$1.40 [105]	$4.60 [105]	$6.30 [105]	I used palm frond's price as surrogate.
c_t	Price of logging residues	$/t	Uniform	$13.50 [135]	-	$16.20 [135]	
c_t	Biomass drying cost	$/t	-	-	$2.50 [165]	-	Sokhansanj et al. [165] also listed the operation and maintenance cost (including producing hot air) usage at $7.80/t. However, it is assumed that excess hot air from the coal plant is used to dry the biomass and as such, only other pre-processing costs of $2.50/t is adopted [165].

c_t	Biomass pulverizing cost (for coal plant use only)	$/t	-	-	$8.50 [166, 167]	-	Pulverizing/grinding involves a two- stage process: (i) hog pulverizer to reduce the size down to 2.5 cm consuming 44 kWh/tonne, and (ii) fine pulverizer to further reduce the size down to 0.3 cm that consumes 125 kWh/tonne. The cost estimation is based on $0.05 / kWh average industrial electricity rate in Malaysia [167].
c_t	Biomass storage cost	$/t	Uniform	$5.25 [168]	-	$10.30 [168]	LaTourrette et al. [168] assumed the use of corn and switchgrass residues, which is used as surrogate for the storage cost of residues in Malaysia.
c^t	Biomass variable transportation cost – high bulk density	$/t.km	Uniform	$0.1114 [169]	-	$0.23 [105]	Palm EFB is used as surrogate for high bulk density residues. The transport cost is $0.23/t.km from a ground study by EcoIdeal Consulting [105].
c^t	Biomass variable transportation cost – low bulk density	$/t.km	Uniform	$0.1309 [169]	-	$0.58 [105]	It is assumed only rice residues (straw and husk) have low bulk density. Since EFB bulk density is about 2.5 times higher than rice straw [170], it is assumed that rice straw costs 2.5 times more than palm EFB as a conservative estimate.

c_t	Biomass fixed transportation cost	$ / t	Uniform	$3.60 [171]	-	$5.00 [169]	
c^{coal}	Coal price	$/t	Triangular	$25 [37]	$60 [37]	$127 [37]	
c^{coal}	Coal pulverizing cost	$/t	Uniform	$0.60 [167, 172]	-	$1.10 [167, 172]	Subbarao [172] suggested between 12 kWh/t and 22 kWh/t to grind coal. The cost estimation is based on $0.05/kWh average industrial electricity rate in Malaysia.
c^{coal}	Coal storage cost	$/t	-	-	$6.30 [163, 173]	-	Gaehr [173] estimated the cost of storing coal at the power plants to be about $0.37/t. The GDP deflator method [163] was used to estimate the 2010 value, which is about $6.30/t.
c^{coal}	Coal shipping cost	$/t.km	-	-	$0.002 [174]	-	
c^{RET}	Coal plant retrofit at 2% co-firing rate	$/kW$_b$	Triangular	$50 [156, 157]	$100 [156, 157]	$150 [156, 157]	
c^{RET}	Coal plant retrofit at 10% co-firing rate	$/kW$_b$	Triangular	$150 [156, 157]	$200 [156, 157]	$250 [156, 157]	
c^{RET}	Coal plant retrofit at 20% co-firing rate	$/kW$_b$	Triangular	$250 [156, 157]	$300 [156, 157]	$350 [156, 157]	
c^{RET}	Coal plant retrofit cost at 100% co-firing rate	$/kW$_b$	-	-	$2,000 [157]	-	

3.3 RESULTS AND DISCUSSIONS

3.3.1 Total amount of residues

The residues were divided into two broad categories, field-based and process-based. Fifty-five percent of the residues are field-based: those whose supply chain is directly from the "field" to the power plant. The remaining residues (45%) are process-based, originating at mills (Figure 3-2). This is an important distinction. Generally, Peninsular Malaysia has a developed transportation system that supports a mill activity whereas agricultural areas may have only limited transportation access (see Figure 1-2 and Figure 1-3). Nevertheless, the accessibility factor of field-based residues using the existing roads have already taken into account. A robust transportation system is required to permit efficient supply of residues for co-firing. However, the costs of constructing such an infrastructure in order to enhance accessibility to field-based residues are not modeled nor are the multifaceted benefits and improved infrastructure to the rural communities which would result from such development. Nonetheless, road damages may be worsened due to the increased traffic [175] as a result of transporting the residues. The cost implications of the increased road maintenance is discussed in the policy implications sub-section.

The total amount of biomass residues available for co-firing is estimated at about 12 Mt/yr (Figure 3-2). Oil palm biomass is the largest source of residues available (77% of the total), followed by rice (9.1%) and forestry residues (8.2%). The remaining residues (5.7% of the total) are available in relatively small amounts, and in decreasing order of availability include wood-based MSW, rubber, cocoa, and coconut residues. The latter two sources are negligible. The results on the amount of residues available show that field-based residues, which originate in the fields/forest/plantations, dominate their process-based counterparts.

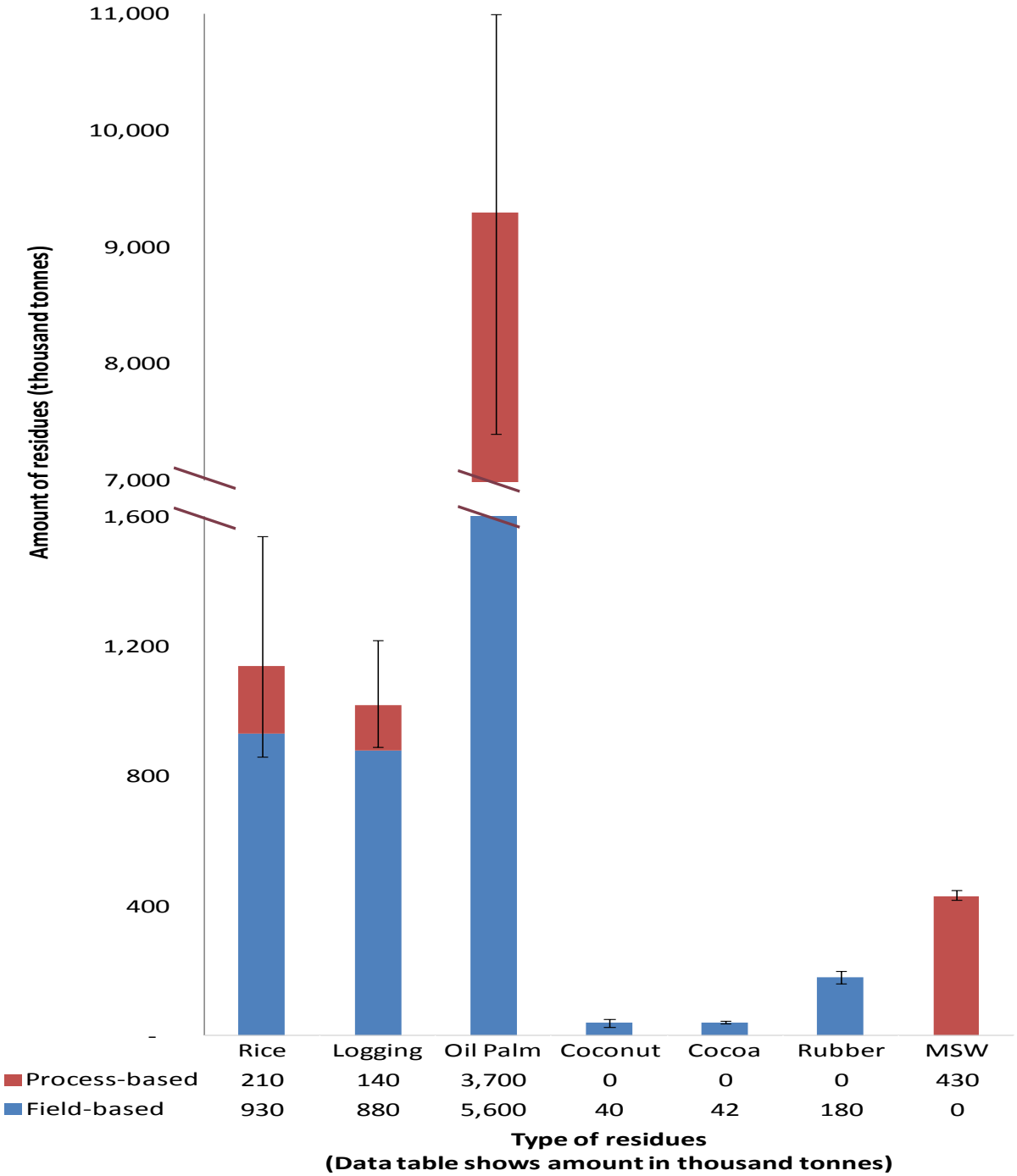
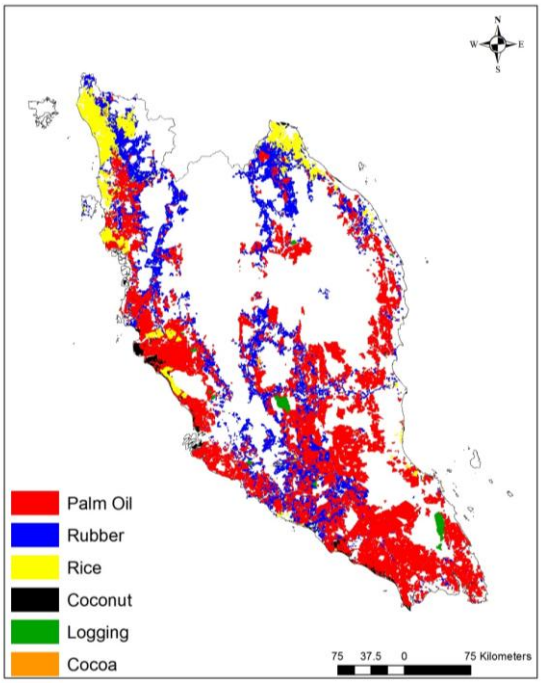


Figure 3-2: **Amount of residues (Mt) by type available for co-firing in Peninsular Malaysia. The error bars for the total residues represent 90th percentile confidence intervals over 10,000 Monte Carlo simulations. The y-axis is broken to accommodate for the total amount of oil-palm residues, which are one order of magnitude higher than the other residues.**

3.3.2 Distribution and locations of biomass residues

Figure 3-3 shows the locations of the residue resources available in Malaysia. The map of field-based residues (Figure 3-3a) shows that most residues are located in the coastal areas, particularly on the west coast. There is some concentration of residues in the southern part of the peninsula where 53% of the country's palm-oil is grown [138]. Forest covers 54% of Peninsular Malaysia but logging areas, shown here, are located in several small areas. Generally, mills are co-located near their feedstock source (e.g., palm-oil mills are located in area where palm is grown). Sawmills and plywood mills are an exception, where they are located throughout the region and associated with their end market, towns and cities.



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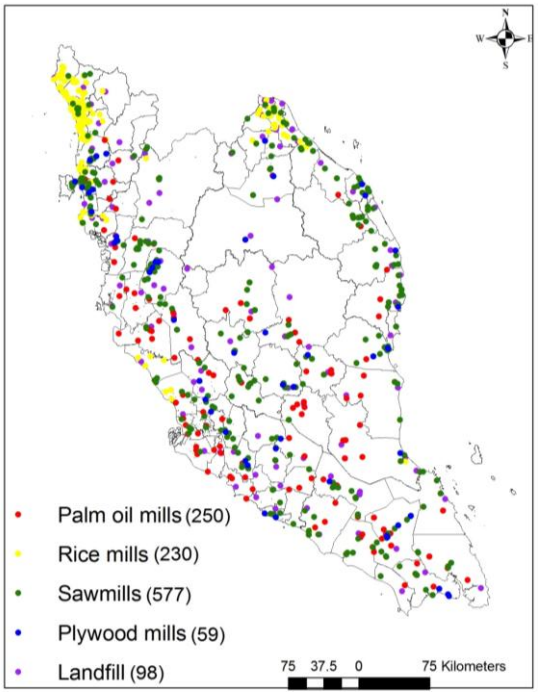
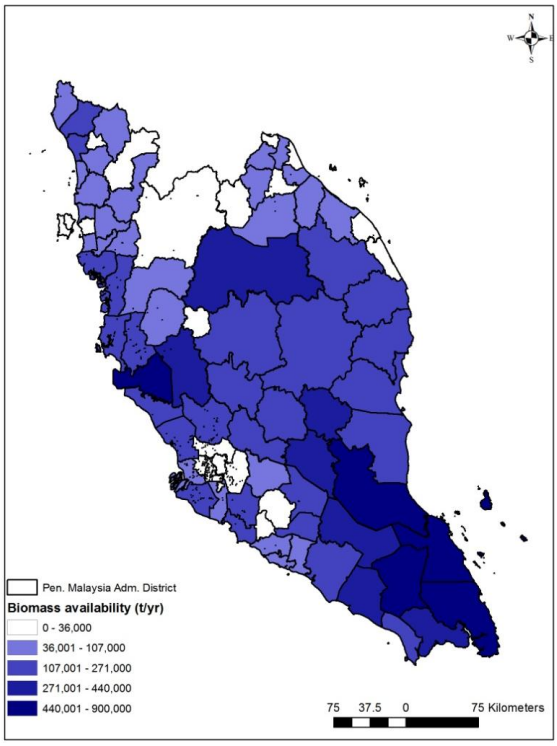


(b)

Figure 3-3: Locations of residues in Peninsular Malaysia: (a) field-based residues; and (b) process-based residues. Values in parenthesis in (b) represent the number of mills/landfill.

Figure 3-4a shows the distribution of available residues by quantity based on the 82 administrative districts in Peninsular Malaysia. Residues are concentrated in the southeast of the region as well as in one area of the west coast. Nevertheless, the locations of coal power plants are all in the west coast of Peninsular Malaysia. Visual observation of the map in Figure 3-4b also shows that the road network concentrates in the coastal areas mostly in the west coast. This shows that where the residues are most dense are where the road network is the least extensive as evident by the road density, i.e., ratio of road length over the total area (km/km^2). For example, from Figure 3-4a, administrative districts with dark colors (high concentration of residues) on the southeast area have a road density of between 0.1 and 0.2 km/km^2 whereas those with lighter colors (low concentration of residues) in the west coast have road density of between 0.45 and 0.69 km/km^2.



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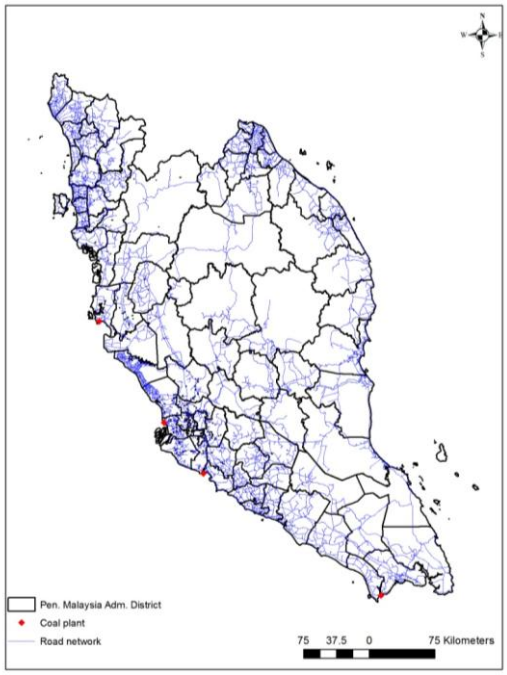

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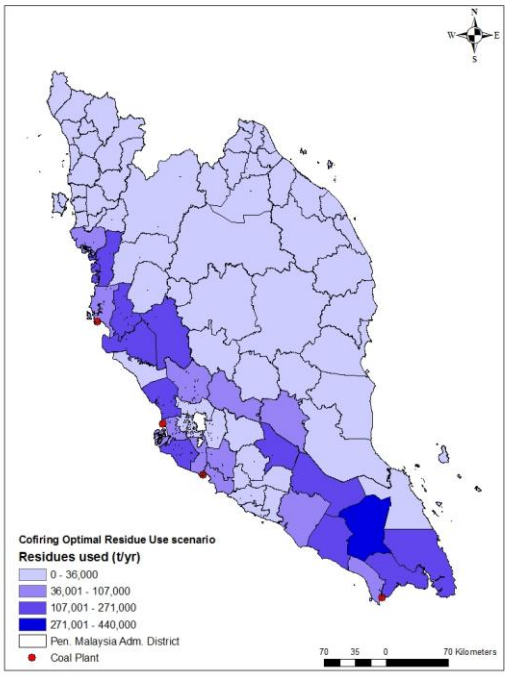


(c)

Figure 3-4: (a) Distribution of residues availability by weight; (b) the road network and locations of coal power plants in Peninsular Malaysia; and (c) amount of residues used at each coal plant (values in parenthesis in tonnes) and distribution of residues used for the Optimal Residues Use scenario.

3.3.3 Costs of co-firing

To understand the overall potential of biomass co-firing, I first investigated the current renewable energy policy target of producing 2.0 million MWh of electricity (equivalent to 330 MW capacity with a 70% capacity factor). The policy is ambiguous as to the method for using biomass i.e., developing and expanding biomass electricity generation, technology to be used (direct combustion/co-firing/gasification), use of certain types of residues for on-site electricity production facilities and/or selling excess electricity, etc. Biomass co-firing has a number of advantages over other approaches. First, co-firing can be adopted with minimal capital investment depending on level of co-firing and achieve higher combustion efficiencies than dedicated biomass power plants [14]. Also, the residues are currently produced, requiring only the development of a collection system [29]. This system can be developed incrementally and evaluated for efficacy periodically. If so desired, the program can be modified or even stopped with minimal risks in comparison to a stand-alone biomass fired electricity plant.

Currently, Malaysia imports coal from Australia, Indonesia and South Africa. To meet the current 35 million MWh of electricity of coal-only generation (referred to as reference case), the cost is approximately $1.16 billion annually. Here, about 11.4 Mt of fuel used is coal (see Table 3-5). The majority of the total cost of coal-only generation comes from purchasing of coal ($970 million/yr), which is based on a coal price of $85/tonne. Alternatively, co-firing that generates 2.0 million MWh or equivalent to 330 MW biomass capacity (on 70% capacity factor) results in the minimum total cost of $24 million less than using coal-only (i.e. $1.14 billion), of which $43 million is biomass related costs (purchase, transport, and electricity plant associated costs) and the remainder from 10.8 Mt of coal used. Only 1.1 Mt of the total 12.2 Mt of biomass available was consumed. The savings results from lower costs of biomass on an energy basis

compared to coal ($20/MWh vs. $32/MWh). In comparison, if all the 2.0 million MWh is generated using dedicated power plants, additional capital cost (land, buildings, equipment etc.) is estimated to be between $495 million and $990 million [14] compared to only $43 million for costs associated with biomass in this 330 MW_b co-firing scenario. The reason why only 1.1 Mt of residues were used is because the optimization model has a constraint on the amount of energy to be produced using biomass (i.e. at 2 million MWh).

Malaysia has an abundance of residues. To understand the full potential of biomass co-firing the amount of biomass that can provide the greatest savings from reducing coal costs (use) is determined, i.e., minimizing the total costs of co-firing (Optimal Residue Use scenario, see Table 3-5). Here, 29% of the 12.2 Mt of available residues was used. The amount of residues received by each coal plant and their distribution for the Optimal Residue Use scenario is presented in Figure 3-3c. The total cost of producing 35 million MWh was $1.12 billion, $44 million less than using coal alone. Increasing residue use beyond this point increases costs. As such, Malaysia can target higher than 330 MW biomass electricity via co-firing and still achieve total cost lower than coal-only generation.

In this study, I compared the total cost of co-firing vs. coal-only using existing coal plants. The total cost for co-firing mainly comes from the production cost, i.e. ranging from 95% (Optimal Residue Use) to 99% (Residues Producing 2.0 million MWh scenario). The components of capital cost for co-firing come from retrofitting of coal plants and storage for residues. Nevertheless, if we were to compare the cost of co-firing with new coal plants, co-firing would still result in cost savings. Coal plant construction cost is estimated at between $1,500 and 3,500/kW [176, 177], while retrofitting coal plants for co-firing only requires between $50 and $2,000/kW biomass [156, 157].

Table 3-5: Deterministic results for costs and amount of residues used that minimized total cost under 100% coal (reference case) and different co-firing scenarios

Model output	Scenario		
	100% Coal (Reference case)	Residues producing 2.0 mil. MWh	Optimal Residues Use
Costs ($millions)			
Total	1,160	1,140	1,120
Biomass	0	40	150
Coal	1,160	1,094	950
Retrofit	0	2.98	15
Difference: scenario vs. 100% coal			
($millions)	0	-24	-44
(%)	0	-2.04	-3.8
Fuel use (million tonnes)			
Biomass	0	1.1	3.6
Coal	11.4	10.8	9.4
% of total residues available consumed	0	9.0	29
Co-firing capacity (MW)	0	330	1,040

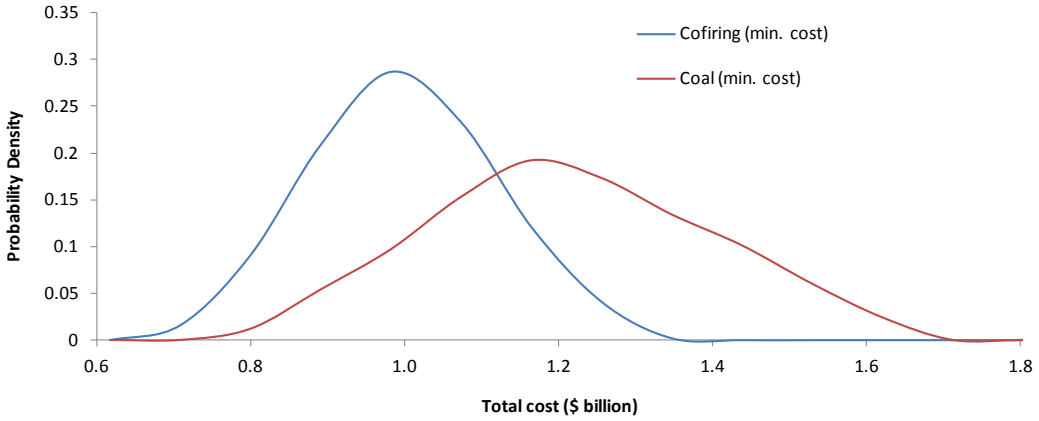
Note: Values may not add up due to rounding.

3.3.3.1 Distribution of total cost

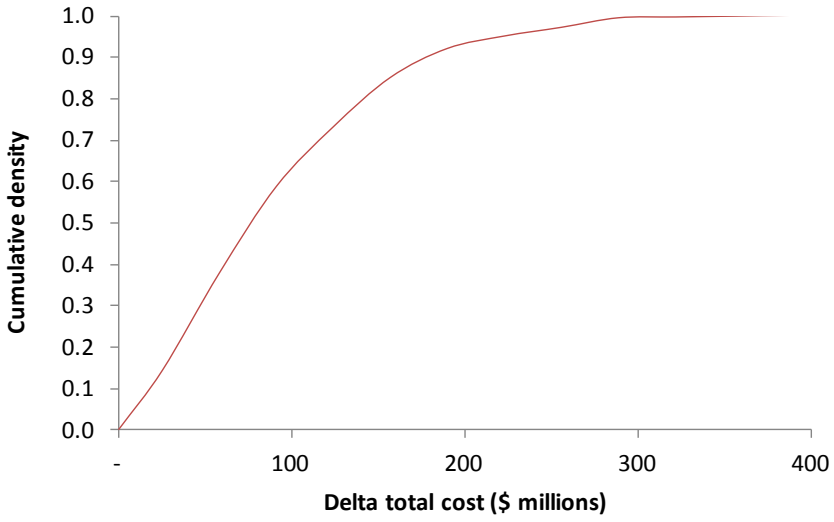
The optimal cost solutions above (Table 3-5) were calculated based upon the most-likely or median values of the probability distributions assigned to the input parameters (see Table 3-4 and Appendix I). To look at the stochastic effect on the total cost, multiple optimizations of

separate samples (MOSS) of 1,000 separate Monte Carlo simulations were ran to construct the distribution of total cost. I ran the MOSS for Optimal Residue Use scenario and 100% coal scenario to compare the cost distribution between co-firing and coal-only. The Optimal Residue Use scenario is chosen instead of the 330 MW scenario because it has the highest cost savings in a deterministic run (see Table 3-5). The probability distribution function (PDF) in Figure 1-4a shows that co-firing has a narrower variance of total cost compared to 100% coal. The total cost for co-firing ranges from $0.756 billion - $1.45 billion and the mean is about $1.08 billion. In comparison, the total cost for 100% coal is wider, ranging from $0.764 billion - $1.61 billion with a mean of $1.16 billion. The wider range of cost for 100% coal is attributed to the wide range of coal price ($49/t to $130/t) assumed in this study (see Table 3-4). Perhaps, coal price can only be heading in one direction i.e. higher in the future. On the other hand, the narrower range of residue prices ($1.90/t - $16.20/t) has influenced the smaller variance in total cost for the co-firing scenario. Since co-firing resulted in a narrower range of total cost compared to coal-only, the decision to implement co-firing should be supported because it reduces the uncertainty range of the cost of generating electricity. Also, the total cost of co-firing is almost all the time less expensive than 100% coal as exhibited by the distribution of the difference in total cost (Figure 3-5b) between the 100% coal and co-firing scenarios. The total cost of coal-only scenario can be as high as $300 million more expensive than co-firing. Therefore, the lower variance and the lower total cost of co-firing prove that co-firing is the better option than 100% coal in terms of cost minimization. Other studies have shown similar results. For example, co-firing 1.4% of gross electrical generation in Spain (4.6 TWh) could achieve up to 50% reduction in costs [178].

Simulation under MOSS gives a set of optimal solutions assuming that the unknown parameters have been resolved prior to finding optimal solution and, therefore, is considered an optimistic approach [83]. In some cases, an optimal solution has to be found before the uncertainties are resolved. The optimal solution by optimizing for a particular probabilistic measure (e.g., mean cost) under this case is considered a pessimistic solution. In cost-minimization, the true total cost will most likely lie between the two estimates (i.e., optimistic and pessimistic). We can then bound the optimized solution using the mean of the optimistic solution (as lower bound) and the pessimistic one (as upper bound). The range of the mean total cost under the pessimistic solution is found to be $17 million more expensive than the mean for the optimistic solution. Thus, regardless of whether the uncertainty has been resolved or not before finding the optimal solution, the range of the mean total cost of co-firing is still lower than 100% coal.



(a)



(b)

Figure 3-5: (a) The probability distribution function (PDF) of total cost of co-firing (Optimal Residue Use scenario) and 100% coal at four coal plants in Peninsular Malaysia; and (b) CDF of delta of total cost between 100% coal and co-firing (Optimal Residue Use).

3.3.4 GHG emissions of co-firing

The current policy to install 330 MW biomass electricity capacity also targets 1.3 Mt of GHG emissions reduction by 2015 [15]. The result of the 330 MW co-firing scenario reduces about 1.9 Mt of GHG emissions compared to 100% coal (Table 3-6). Thus, our estimate of the GHG emissions is 0.6 Mt lower than the Government's policy target. Our lower emissions is due to the use of a coal electricity generation lifecycle GHG emissions factor of 1.0 CO_2-eq/MWh [11], whereas the government's policy uses the average Malaysia's electricity emissions factor of 0.63 t CO_2-eq/MWh [15]. Because we displace coal electricity, it is more appropriate to also displace coal electricity's GHG emissions instead of the country's average electricity GHG emissions factor.

Biomass replacing coal results in CO_2 emissions reduction. Biomass combustion releases recent biogenic carbon, which is considered a net-zero carbon emission. However, the life cycle emissions of biomass also include emissions from transportation to the generation facilities. To capture this dynamic an unconstrained biomass scenario (the model could use all biomass available) is also modeled that sought to minimize GHG emissions (Optimal GHG scenario, see Table 3-6). The scenario resulted in 17 Mt of CO_2 reductions compared to the use of 100% coal. This is because the process of collecting, transporting and pre-treating of all the residues for co-firing (12.2 Mt) has lower GHG emissions than the displaced coal. Although the residues used were 0.8 Mt more than coal used in a 100% coal scenario (11.4 Mt), the net-zero residue emissions and low emissions from transportation of the residues (short distances) offset the high GHG emissions from coal combustion and high transportation emissions from coal transportation because coal is shipped from far away exporting countries. Use of residues reduces Malaysia's total GHG 2010 emission between 1.1% and 9.4% (Table 3-6).

In LCA studies, biomass residues are considered as having no emissions associated with their production [179]. Also, LCA traditionally allocates production emissions to multiple products (defined as those having a market and price). Thus, a residue that is sold as a fuel becomes a product. To bound this analysis to see if there was a significant impact on residue co-firing without the necessity of conducting a detailed LCA, I simply allocated 100% of the associated production emissions to the residue (for instance, emissions associated with rice production were all allocated to the rice husk and straw). Adding these emissions reduced the emission savings from 48% (Optimal GHG) to 27%. Even with the inclusion of these upstream emissions the emissions reduction remains robust and 96% of all biomass residues are consumed. The unused residues were wood and paper-based MSW that have higher GHG emissions per unit

energy than coal (0.33 t CO_2-eq/GJ vs. 0.29 t CO_2-eq/GJ). The emissions arise from the collection and transportation activities as well as methane emission from landfills [179].

Table 3-6: Deterministic results for GHG emissions, amount of residues used that minimized GHG and cost of carbon mitigation under different co-firing scenarios

Model output	Scenario			
	100% Coal (Reference case)	**Residues Producing 2.0 mil. MWh**	**Optimal GHG Emissions**	**Optimal GHG incl. upstream emissions***
Scenario GHG emissions (million tonnes)				
Total	36.2	34.3	19	26.5
Biomass	0	0.15	2.1	9.5
Coal	36.2	34.1	16.8	17
Difference between scenario and reference				
(tonne)	0	-1.9	-17	-9.7
%	0	-5.3	-48	-27
Fuel use (million tonnes)				
Biomass	0	1.0	12.2	11.7
Coal	11.4	10.8	5.3	5.4
% of total residues available consumed	0	8.4	100	96
Cost of carbon mitigation ($/t CO_2-eq)	0	-2.40	22.50	38.70
Co-firing capacity (MW)	0	330	3,090	3,050

** - This scenario represents the upper bound of upstream GHG emissions from co-firing.*

3.3.4.1 Cost of carbon mitigation

One of the benefits or penalties with efforts to reduce GHG emissions can be measured using the cost of carbon mitigation (COM). In the 330 MW scenario, the reduction of 1.9 Mt/yr of GHG emissions is obtained at a lower cost compared to the reference case, thus implying a zero cost of COM (Table 3-6). For the other two scenarios (Optimal GHG with and without upstream emissions), the COM are $39 ($370 million cost increase) and $23/t CO_2 mitigated ($390 million cost increase), respectively. In comparison, Morrow [35] found that co-firing of switchgrass with coal in the US has a marginal cost ranging from $20 to $86/t CO_2 mitigated. This is because switchgrass in the US has a higher price than the price of residues used in our study ($6 - $50/tonne vs. 1.90 - $16/tonne). Morrow [35] showed that a $10/t increase in switchgrass price would result in an increase of the COM by $7.25/t CO_2 mitigated. In our case, a $10/t increase in prices to all residues would increase the COM by $6.20/t CO_2 mitigated.

The government has imposed a levy on heavy electricity users (>350 kWh/month). The levy will collect about $100 million/year and will be used to subsidize the installation of 975 MW of renewable electricity by 2015 [180].The government estimates that the 975 MW renewable electricity will avoid 3,707,825 tonnes of CO_2-eq/year[15], which implies a COM of about $27/t CO_2-eq mitigated. In this study, the maximum GHG reduction is 17 Mt with the maximum COM for the Optimal GHG Emissions scenario (with upstream emissions) of $39/t CO_2-eq mitigated. This COM is higher than the levy's implied COM but without the upstream emissions, our COM is lower by $5/t CO_2-eq (see Table 3-6). This means that co-firing in Malaysia can still be a more cost effective measure to reduce GHG emissions than imposing an indirect carbon tax (levy).

3.3.4.2 Carbon price to reduce emissions

Because reducing GHG emissions beyond the minimum cost solution will increase cost, it is less likely that coal plant industry players will adopt additional co-firing. One way to compel the industry to adopt co-firing is to impose a carbon tax. The results presented in Table 3-5 and Table 3-6 were based on zero carbon prices. To estimate the relative effects of carbon price on the trade-offs between emissions and total cost, we simply assigned several carbon prices on co-firing cost-minimization objective (i.e.: we use the objective $C + p_{CO2}G$, where p_{CO2} is the carbon price (\$/tCO_2eq). By doing this we are penalizing the coal plants in proportion to their emissions by paying carbon tax to the government. Figure 3-6 shows a Pareto curve summarizing the effect of different carbon prices on GHG emissions and direct cost (excluding carbon taxes) of the resulting cost-minimum solution. Based on this quick analysis, at a carbon price of \$20/tonne, the direct cost to the industry increases by about \$38 million and emits about 5.5 Mt less GHG than when there is no carbon price. In addition, the government would collect about \$440 million/year in the form of taxes that could be used to fund other measures to reduce GHG emissions, such as rebates to users of energy efficient equipment/appliances.

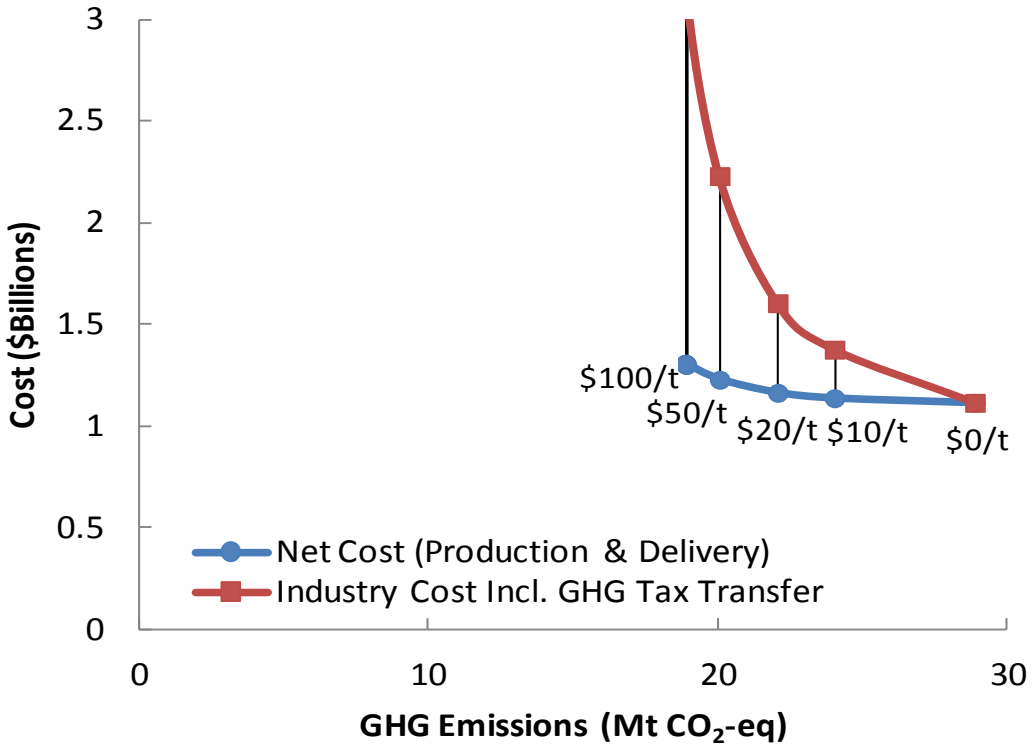
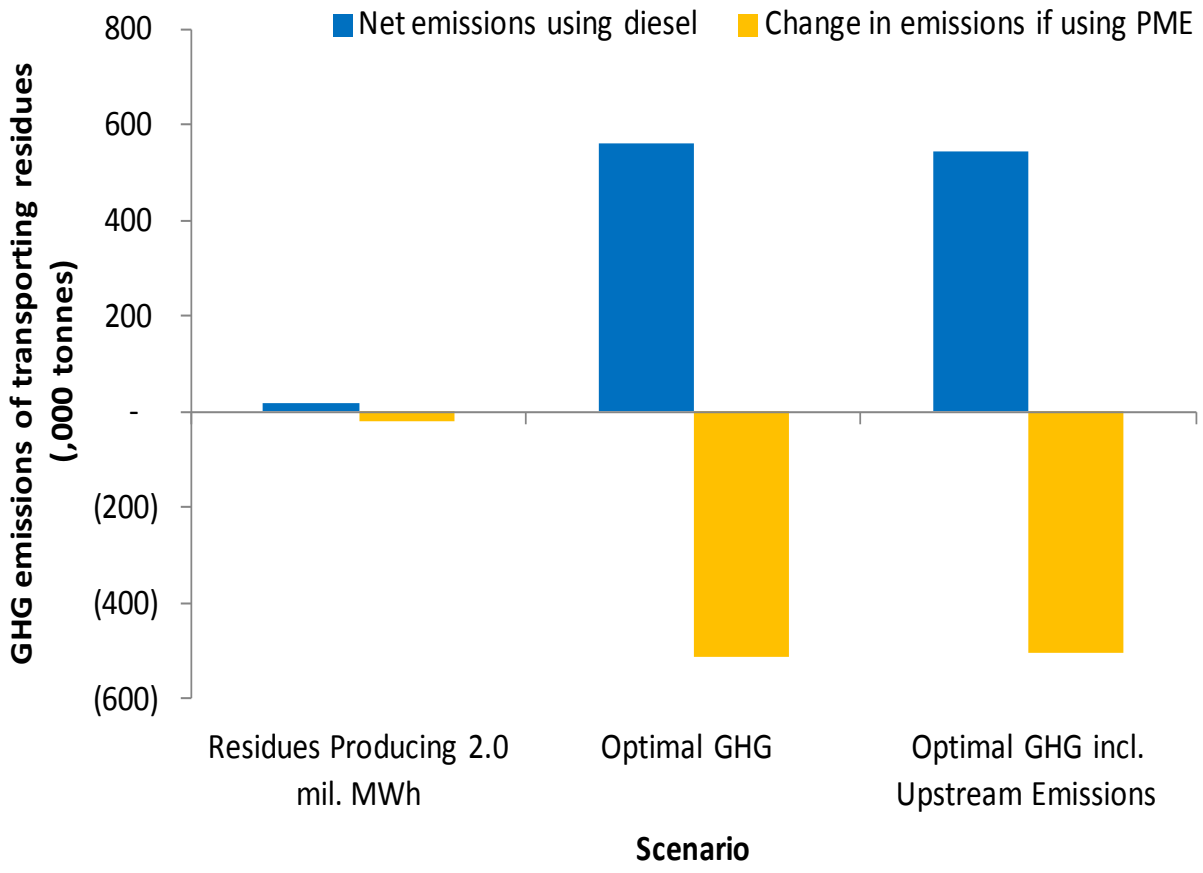


Figure 3-6: Pareto curve of different carbon price effect on GHG emissions and direct cost (excluding carbon tax) (blue curve). The graph of GHG emissions vs. total cost (red curve) is presented to show the amount of transfers to the government in the form of carbon tax represented by the height of the vertical lines between the two curves at different carbon prices.

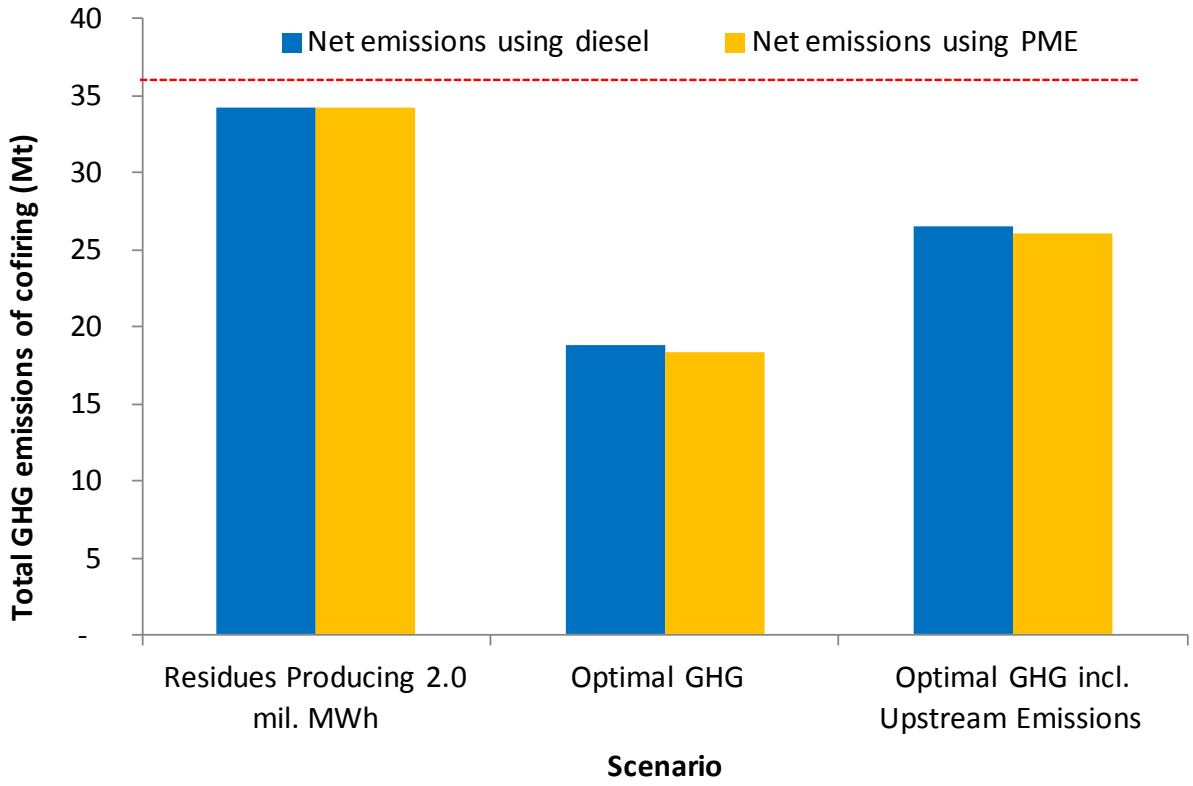
3.3.4.3 Emissions from biomass transportation

Emissions from the transportation of residues were found to be relatively small compared to the total emissions (see Figure 3-7a). However, further emissions reduction could be obtained by using palm biodiesel (PME) as a fuel to displace petroleum diesel in the transport of residues. Using the simple linear optimization PME production model developed by Hassan et al. that minimized GHG emissions [8], it was found that that the use of PME that displaces the same amount of energy in petroleum diesel has managed to reduce emissions in the transport of residues by between 37,000 tonnes (Residues Producing 2.0 mil. MWh scenario) and 1.0 Mt

(Optimal GHG scenario) (see Figure 3-7a). This is because the use of PME that is produced on lands with low GHG emissions factor gave between 19,000 (Residues Producing 2.0 mil. MWh scenario) and 500,000 tonnes (Optimal GHG scenario) of GHG emissions savings. Emission savings in the Optimal GHG solution including Upstream Emission scenario is lower than without the upstream emission because less biomass residue is used (see Table 3-6). However, emissions from other sources (coal combustion and residues pre-treatment) overwhelmed the small savings in the transport of residues (as a result of using PME), as shown by the small difference in total GHG emissions of co-firing between the use of petroleum diesel and PME (Figure 3-7b).



(a)



(b)

Figure 3-7: (a) Greenhouse gas (GHG) emissions comparisons from transportation of residues when using diesel (net emissions) and if palm biodiesel (PME) is used (change in emissions) in co-firing scenarios; and (b) Total net GHG emissions associated with using biomass residues when using diesel and if PME is used for transporting residues in co-firing scenarios. Horizontal dashed line represents total GHG emissions on 100% coal (reference case).

3.3.5 Policy Implications

Malaysia can meet its 330 MW biomass electricity capacity (or 2.0 million MWh of generation per year) by means of co-firing residues with coal at costs lower than coal-alone while reducing GHG emissions. If desired, co-firing can also be executed at a higher rate (up to 1,000 MW capacity) and still attain costs and GHG emissions advantages. This can be achieved by requiring the coal plant operators to retrofit the existing facilities to use the domestic agro-

forestry residues. To achieve this, there are two policy implications that need to be addressed to facilitate the objectives in the long run.

Firstly, Malaysia needs to ensure a stable and effective supply of residues. It was shown that there is sufficient supply of available residues (12 Mt, accounting for other uses as well as accessibility and recoverability factors). Oil-palm residues contribute about 77% to these available residues, which means that (i) Malaysia can focus on oil-palm rather than other biomass residues, which would reduce expenses related to this activity; and (ii) Malaysia will have to depend on oil palm residues to produce renewable electricity. This suggests that if the government's objective is to minimize GHGs at minimum cost, then Malaysia should, as much as possible, limit the use of oil-palm residues in other sectors. This is because compared to other uses, such as for pulp and paper making, composting of EFBs, and producing furniture from palm trunks, it was shown here that co-firing of oil-palm residues with coal can reduce GHG emissions at virtually no net cost. However, limiting the use of oil-palm residues in other sectors could be detrimental to industries that rely on the oil-palm residues. In the past, several renewable energy projects were unsuccessful because of a difficulty to secure a long term supply of residues [15]. To help ensure the supply of residues is sustainable in the long run, regulations under the respective acts such as the Environmental Quality Act, Malaysia (1974) and the National Forestry Act, Malaysia (1984) would have to be amended if the government wants to increase the effectiveness of the collection of residues. The amendments will have to require operators/licensees to collect, sort and gather the residues for easy removal from mills/fields and prohibit unsustainable disposal of residues, such as open burning and dumping into landfills.

Since this study focuses on private cost, the external cost of using the existing roads to deliver residues to the coal plants was not quantified. However, increased weight and usage on

existing roads will require increased road maintenance, presently borne by the government. Forkenbrock et al. [175] suggested that for every tonne.km increase of freight transported by truck, an additional $0.24 is required to maintain the roads that include resurfacing of the damaged sections. Therefore, this external cost can be as high as $110 million/yr if all residues are used for co-firing (Optimal GHG scenario). However, in the same scenario, about 6.2 Mt of coal is saved. At a price of $85/tonne of coal, this in a monetary savings from coal import of about $530 million/yr compared to the $390 million cost increase for co-firing. The government can use this saving to compensate for the road damage external cost. Nevertheless, if we considered the road damage cost as a private cost to be borne by the utility, the minimum cost under the Optimal Residue Use scenario would still be lower (by $11 million) compared to coal-only electricity, although only 9% of residues is used, producing roughly 2.0 million MWh from biomass.

Secondly, the government should introduce a policy to encourage co-firing residues with coal in existing and future coal plants in Malaysia. In order to do this, the Feed-in-Tariff (FiT) in Schedule for Section 2 of the newly introduced Renewable Energy Act, Malaysia (2011), should be revised. The FiT subsidizes the purchase of electricity generated using renewable fuels at a higher price compared to conventional fuels. Presently, the FiT has a limit (30MW) on the amount of biomass electricity that qualifies for the higher price. This limit could be increased to at least 110 MW (based on the 330 MW cost minimization scenario), or preferably a higher limit. Under this scenario the highest portion of electricity generated from biomass at a particular coal plant is about 680,000 MWh. This amount of electricity is equivalent to 110 MW (using 0.7 capacity factor) and is made possible because co-firing of residues took advantage of the coal plant's 37% efficiency. The Schedule could also be amended to explicitly include the use of the

co-firing technology that can receive this special tariff. Presently, only gasification and steam-based technology are listed.

This analysis has been a scoping study on co-firing in Malaysia's context. There are limitations with implications not considered here. They are: (i) All existing biomass used in direct combustion plants is considered fixed. It is possible that there exists a better solution where some of the existing biomass might be rerouted for co-firing and some of the new biomass might be taken to nearby direct combustion plants. However, these considerations are not expected to change the results substantially because the current dedicated biomass power plants generate a small amount of energy (1.5 mil. MWh); (ii) Other uses of residues are considered fixed / exogenous. If co-firing affects prices, this could affect the portion of residues sold for these other uses. Residue price increases might make co-firing less attractive. However, the price of coal, as a globally traded commodity, is also likely to increase in the future; and (iii) Timing is ignored. It is assumed that if a sufficient amount of biomass is shipped for the year then it can deliver the annual electricity required. Biomass supply varies seasonally, and the potential for storage is limited, so co-firing availability could vary throughout the year, and co-firing could make the electricity sector more susceptible to droughts.

3.4 Conclusions

This research has given a clearer picture on the availability of biomass energy in Malaysia. There are about 12 Mt/yr of residues available to be used for energy production including for co-firing in Peninsular Malaysia. It was also shown that co-firing can achieve cost reduction of up to $44 million annually compared to using 100% coal (ignoring road infrastructure costs). At least 1.9 Mt of GHG emissions can be reduced from co-firing that can be

obtained without any cost of carbon mitigation (COM). If need be, GHG emissions reduction can be as high as 17 Mt at a COM as low as \$23/t CO_2-eq mitigated. The results provide some important foundations for reference to the government in formulating its renewable electricity policy. Malaysian policies that encourage or mandate collection of biomass residues for co-firing can have substantial cost and emissions benefits.

4 Cost and GHG Emissions of Cellulosic Ethanol from Biomass Residues in Malaysia: Implications on Energy Security in the Transportation Sector

4.1 Introduction

In 2009, the transportation sector was the biggest energy user of petroleum products in Malaysia, consuming approximately 720 PJ from a total of about 1,000 PJ [1]. The remaining users of petroleum products were in the electricity (fuel-oil), residential (liquefied natural gas) and non-energy (chemical feedstock) sectors. The transportation sector consumed 99% fossil fuels as gasoline (370 PJ), diesel (260 PJ) and aviation fuel (88 PJ) [1]. Malaysia's ground transportation sector consumes about 89% of the energy used in the transportation sector, aviation 12% and water 1%.

In order to reduce the reliance on fossil fuels in the transportation sector, Malaysia introduced a renewable energy policy of blending 5% palm-biodiesel (by volume) with petroleum diesel by 2010 [7]. One of the motivations for this policy is to reduce the country's dependence on petroleum import, an important factor of energy security. Among the environmental benefits of introducing this policy is the reduction of Greenhouse gas (GHG) emissions. Using the lifecycle GHG emissions factors from US National Energy Technology Laboratory (NETL) for gasoline, diesel and aviation fuel [5], Malaysia's transportation sector emits approximately 76 million tonnes (Mt) of GHG per year, approximately 42% of the country's overall GHG emissions of 180 million tonnes [2]. If Malaysia can achieve the palm biodiesel blend target, the country could save 1.03 Mt of GHG emissions annually [8].

Renewable energy resources are abundant in Malaysia and include biomass and solar. Malaysia's biomass resources mainly come from the agro-forestry sector. In Peninsular/West Malaysia, forest covers approximately 5.8 million ha, while 4.5 million ha is agricultural land.

Agricultural land includes mainly oil-palm (62%) and rubber plantations (29%). The remaining 9% includes rice fields (7%) and other cash crops (coconut, cocoa, sugar cane and orchids) [134]. It is estimated that there are about 12.2 Mt of agro-forestry residues available for energy production in Peninsular Malaysia (see Chapter 3). Contrary to other studies [23, 31], the amounts of available residues have taken into account for other usages and the accessibility/recoverability factor of the residues.

Even though using biomass for energy generation is considered to have net-zero GHG combustion emissions [26], additional emissions arise from activities such as the harvesting and transporting of biomass. For instance, Henson [27] found that in 2005, oil-palm cultivation (planting and harvesting) and palm-oil production emitted about 13 Mt a year of GHGs. The main sources of GHG emissions were from land conversion (60%), methane emissions from palm-oil mill effluent treatment via anaerobic digestion (13%), fossil-fuel combustion (13%) and fertilizer use (4%).

Biomass can be used to produce cellulosic ethanol. Ethanol can be blended with gasoline in most vehicles up to 10% (by volume) without any modification but vehicles manufactured after 2001 can take up to 15% [17]. In comparison to many developed countries and several Southeast Asian countries, Malaysia does not have an ethanol production target [181]. Goh et al. [182] attempted to quantify the maximum amount of cellulosic ethanol that can be produced in Malaysia. They found that Malaysia could produce 12 billion L/yr, potentially replacing all the gasoline in Malaysia. However, they did not assess the cost implication of this program.

The life cycle GHG emissions of cellulosic ethanol have been shown to be 27 to 65% less [71, 183, 184] than gasoline. Thus, simple substitution can reduce the overall GHG emissions from transportation. Cellulosic ethanol is thought to be a viable alternative to gasoline, especially

in the near to mid-term [69]. Cellulosic ethanol can be produced from either a dedicated energy crop or using biomass residues. Residues are favored since their use avoids the potential land use change that might result from using dedicated energy crops, which can have life cycle GHG emissions higher than gasoline [70].

Previous studies have shown that costs and emissions from the transportation activity of making and delivering ethanol can influence the total cost and emissions [73, 185-187]. Wakeley et al. [186] found that ethanol transported long distances loses its economic and environmental benefit (GHG emissions reduction) and thus suggested that the use of ethanol blend should be regionally concentrated. Morrow et al. [187] created an optimization model for transport of ethanol and found shipping cost to be between $0.01 and $0.02/L of ethanol in the US. Although this transportation cost is a small fraction from the total cost of producing ethanol, it is higher than gasoline's transport cost. As such, Morrow et al. [187] suggested that pipelines be developed to make the overall cost of shipping ethanol more competitive with gasoline.

Most studies on optimizing cellulosic ethanol's economic and environmental performance were done using one or a few types of biomass [68, 73, 186-188]. Suh et al. used only corn stover [189], Kocoloski et al. used switchgrass [73] and forest thinnings [188] while Wakeley et al. and Morrow et al. worked on corn and switchgrass [186, 187]. There are very few studies that utilized multiple residues to optimize ethanol production and transportation cost. Huang et al. [185] used four different biomass species to assess the effect on production cost. They concluded that the most abundant residue (corn stover) was the cheapest compared to the others (hybrid poplar, aspen wood and switchgrass). Goh et al. [182] used multiple biomass residues (agro-forestry and solid waste) in the case of Malaysia but they did not perform cost or GHG emissions optimization to produce ethanol.

This study deals with the future use of biomass residues to produce bioethanol via fermentation in Malaysia utilizing seven different types of residues. A mixed integer linear optimization model was used to determine and optimize the total cost and GHG emissions associated with the collection, transportation, conversion and use of the biomass/ethanol. I evaluate the differences in (i) total production and shipping cost and (ii) GHG emissions of instituting the 10% bioethanol blend and (iii) compare the results to the alternative use of residue as a feedstock for co-firing with coal to generate electricity.

4.2 Data

4.2.1 Residues availability and locating biorefineries

The availability of residues used in this study is based on the previous work on co-firing (see Chapter 3). The location of the various types of residues is reproduced in Figure 4-1a and b. The majority of the residues are contributed by oil-palm residues at about 79% from the overall residues availability. Oil-palm plantations are ubiquitous throughout the region and hence their mills are also omnipresent. Rubber plantations follow the same pattern of oil-palm plantations. However, the other types of residues are more concentrated in certain parts of the region, such as rice fields and coconut plantations, while others are more sparsely distributed, such as cocoa plantations and landfills. The total residues availability is about 12 Mt per year.

Figure 4-1c shows that most biomass residues are concentrated in the southeastern part of the region followed by the center region. There are also a few places in the northwest region where biomass residues are high in quantity although they are not close to each other. To locate a refinery, the biomass density around the location is ensured to be at least 500 t/km^2 and a

maximum radius of 40 km [190]. The refinery will only operate at a minimum capacity of about 250 million L/yr or receiving 730,000 t/yr of residues. Capital cost is almost flat beyond this capacity [68, 185]. Based on the biomass density map (Figure 4-1d), and to take advantage of economies of scale [68], it is assumed that potential refineries that are located in the same cluster as a single biorefinery. This means that it is also assumed that the each potential location of biorefinery can have more than one similar sized refineries (730,000 tonnes/year) at the same location. Thus, there are five potential locations of biorefinery in this study (see Figure 4-1d).

Figure 4-1: Distribution and concentration of biomass residues in Peninsular Malaysia. (a) locations of field-based residues; (b) locations of processed-based residues (values in parenthesis are the number of mills/sites); (c) distribution of biomass availability by administrative districts; and (d) densities of biomass residues and location of potential biorefineries.

4.2.2 Gasoline energy demand and supply

Malaysia's energy data used for this study is for the year 2009, which is the latest available [1]. Malaysia consumed about 370 million GJ of gasoline energy, which is about 36% of the energy amongst petroleum products [4]. The breakdown of the locations of vehicles that use gasoline in the country could not be obtained. As such, I used population as the surrogate for estimating the total energy use in Peninsular Malaysia, which was about 23 million or 80% of the country's total population. Therefore, it is assumed that Peninsular Malaysia consumed about 300 million GJ of gasoline energy. Figure 4-1c also shows the locations of 143 cities that were used to represent the locations of population centers in Peninsular Malaysia [191]. The population in 2010 in these cities were about 14 million, which is approximately 61% of the total population of Peninsular Malaysia [192]. The population of each city is given a weighted value by dividing its population from the total population. The weighted value is then multiplied with the assumed total gasoline energy consumption in Peninsular Malaysia (300 million GJ), which gives the amount of gasoline energy demand in the cities. There are six oil refineries/distribution centers that supply gasoline to all the cities. Table 4-1 lists the refineries and the supply limit used in this study.

Table 4-1: Oil refineries and supply of gasoline in Peninsular Malaysia

Refinery	Gasoline production (billion L/yr) [193]	Assumed gasoline delivered via pipeline (billion L/yr) [193]	Balance of gasoline at refinery (billion L/yr)	Final supply of gasoline (L/yr)
Melaka Refinery PSR-1	2.1	1.3	0.75	0.75
Melaka Refinery PSR-2	3.5	2.3	1.3	1.3
Port Dickson (Shell)	3.2	2.1	1.2	1.2
Port Dickson (Esso)	1.8	1.2	0.66	0.66
Kertih refinery	0.83	-	-	0.83
KVDT Putrajaya	-	-	-	6.9
Total	**11.0**	**6.9**	**3.9**	**11.0**

4.2.3 Ethanol yield

The ethanol yield for 15 types of biomass residues used in this study was estimated based on their ratios of cellulose and hemicellulose content (by weight) obtained from literature (see Table 4-2), the efficiencies of conversion and recovery of sugars, and the fermentation efficiency. The efficiency of conversion and recovery of glucose (a 6-carbon sugar) from cellulose is between 0.76 and 0.9 [68, 194], while that of xylose (a 5-carbon sugar) from hemicelluloses is 0.91 [195]. One molar of glucose ($C_6H_{12}O_6$) can produce two molars of ethanol (CH_3CH_2OH) and using this stoichiometric balance, the stoichiometric yield of ethanol from glucose is 0.511. Three molars of xylose ($C_5H_{10}O_5$) are needed to balance a stoichiometric equation to produce five molars of ethanol i.e. a stoichiometric yield of 0.5175. Glucose's fermentation efficiency is between 0.75 and 0.85, while xylose's fermentation efficiency is between 0.5 and 0.85 [68, 196]. Ethanol's density assumed in this study is 0.00081 t/L [197]. An

example calculation (Equation 4-1) using midpoint values of the residues content and conversion/efficiency factors for rice straw is as follows:

$$Ethanol\ yield\ \left({}^{L}/_{t\ rice\ straw}\right) = \{(Cellulose\ content \times Glucose\ conversion\ \&\ recovery\ efficiency \times\ Stoichiometric\ ethanol\ yield\ from\ glucose \times fermentation\ efficiency) + (Hemicellulose\ content \times Xylose\ conversion\ \&\ recovery\ efficiency \times\ Stoichiometric\ ethanol\ yield\ from\ xylose \times fermentation\ efficiency)\} \div ethanol\ density$$

Equation 4-1

$$E.g., Rice\ straw\ ethanol\ yield = \{(0.34 \times 0.83\ \times 0.511 \times 0.8) +\ (0.4\ \times 0.91\ \times\ 0.518 \times 0.68)\} \div 0.00081 = 300\ {}^{L\ ethanol}/_{t\ rice\ straw}$$

Table 4-2: Cellulose and hemicellulose range of fractions (by weight) for various types of residues used in this study

Residues type	Cellulose fraction		Hemicellulose fraction	
	Low	**High**	**Low**	**High**
MSW (paper and wood-based)	0.15 [198]	0.6 [198]	0.2 [198]	0.85 [198]
Rice husks	0.36 [199]		0.12 [199]	
Sawmills (using wood as surrogate)	0.4 [200]	0.55 [198]	0.13 [200]	0.4 [198]
Plywood mills (using wood as surrogate)	0.4 [200]	0.55 [198]	0.13 [200]	0.4 [198]
Oil-Palm EFB	0.46 [201]	0.5 [202]	0.22 [202]	0.3 [201]
Oil-Palm Shell	0.27 [201]		0.27 [201]	
Oil-Palm Fiber	0.34 [201]		0.24 [201]	
Rice straw (using wheat straw as surrogate)	0.3 [198]	0.38 [203]	0.29 [203]	0.5 [198]
Cocoa branches (using rubber wood as surrogate)	0.44 [204]		0.33 [204]	
Rubber branches	0.44 [204]		0.33 [204]	
Oil-Palm trunk	0.41 [205]		0.34 [205]	
Oil-Palm fronds	0.31 [201]	0.62 [182]	0.23 [182]	0.28 [201]
Coconut trunk (using oil-palm trunk as surrogate)	0.41 [205]		0.34 [205]	
Coconut fronds (using oil-palm fronds as surrogate)	0.31 [201]	0.62 [182]	0.23 [182]	0.28 [201]
Logging residues (using wood as surrogate)	0.4 [200]	0.55 [198]	0.13 [200]	0.4 [198]

Uniform distribution is assigned to parameters that have ranges: (i) cellulose and hemicellulose content for residues (Table 4-2); (ii) the pre-treatment conversion/recovery factor i.e. cellulose to glucose (0.76 - 0.9) [68, 194] and hemicellulose to xylose (0.906) [194]; and (iii)

the fermentation efficiencies i.e. glucose (0.75 - 0.95) and xylose (0.5 - 0.85) [68, 196]. Using Equation 4-1 and the assumed distributions, I ran Monte Carlo simulations on the ethanol yield (L/t) on all types of residues. Figure 4-2 shows the range of results of ethanol yield for the different type of residues, which were then used as input parameters for the optimization model.

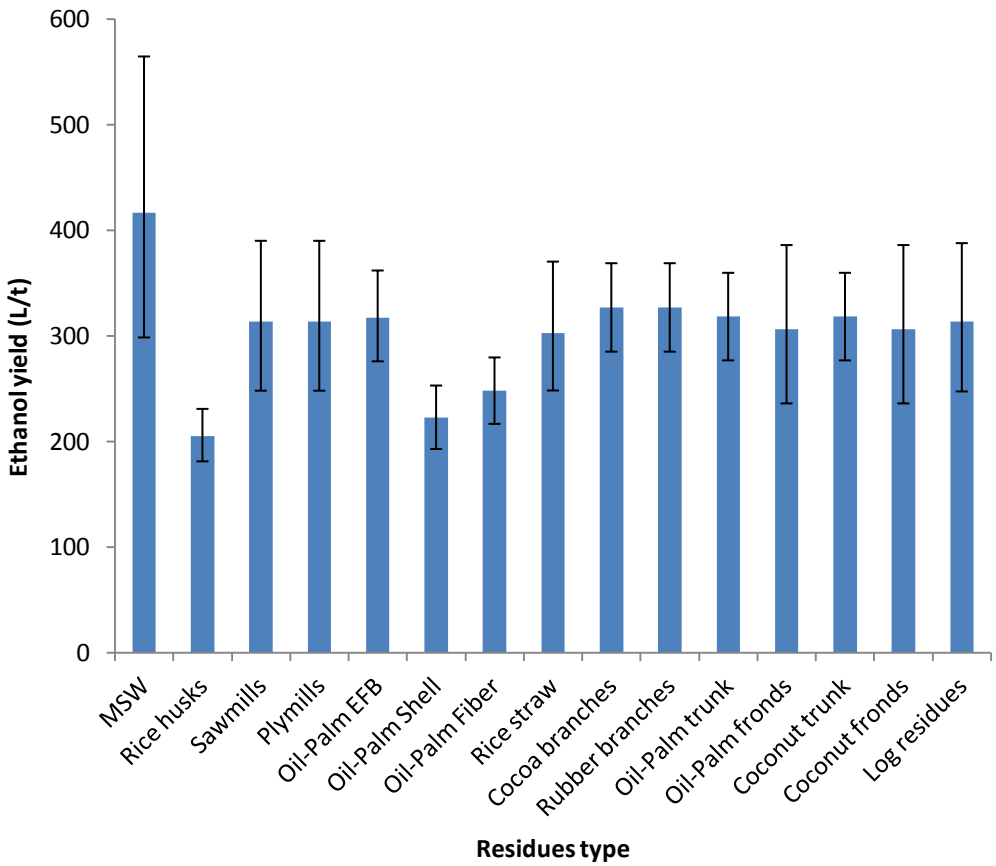


Figure 4-2: Range of ethanol yields for the various types of residues used in this study.
Note: The peaks of the solid bars represent median values and the error bars represent 90th percentile credible intervals from 10,000 Monte Carlo simulations.

4.2.4 Costs estimation

Data on the cost of refining gasoline specific to Malaysia could not be obtained. The US data was used as surrogate since its trend of gasoline demand (from the total petroleum products)

is close to Malaysia's, i.e. 43% (US) vs. 36% (Malaysia) [206]. This could be a slight overestimation of the true cost because Malaysia's labor cost is lower than the US [207]. To estimate the gasoline refining cost, the historical data of gasoline component costs was used, which was obtained from the US Energy Information Administration (EIA) [208]. This refining cost was then subtracted from historical refining margins for the US Gulf Coast refineries [209] to get the net refining cost. This is done because the US EIA data also includes refining margins. A distribution fitting on the net historical refining cost data was performed, which is then assigned a lognormal distribution ($\mu = 0.08$; $\sigma = 0.04$) and used as an input parameter for the optimization model. For gasoline feedstock cost, crude oil price is used as surrogate [210] ($/bbl) (1 bbl ~ 159 L). As with estimating gasoline refining cost ($/L), a distribution fitting on the crude oil historical price was performed to assign a lognormal distribution ($\mu = 0.29$; $\sigma = 0.13$), which is also used as an input parameter in the optimization model. The range of cost for ethanol refining is assigned a uniform distribution ($0.15 - $0.49/L) [68, 185, 189, 200, 211, 212], which includes capital cost for a refinery processing. Cost estimates of biomass residues and other important cost parameters and their ranges are presented in Table 4-3 (see also Appendix I for other input parameters).

Table 4-3: Important cost parameters and ranges used in the ethanol optimization model

Parameters	Unit	Distribution	Min	Most likely	Max	Note
Price of palm EFB	$/t	Triangular	$1.80 [105]	$5 [105]	$6.70 [105]	
Price of palm shell	$/t	-	-	$16.70 [105]	-	
Price of palm fiber	$/t	Triangular	$2.30 [105]	$5.50 [105]	$7.20 [105]	The price of EFB is used as surrogate and adjusted the value based on the energy content.
Price of rice husk	$/t	Uniform	$4.70 [161]	-	$11.80 [161]	This is a case study in the Philippines, a developing country similar to Malaysia.
Price of paper-based MSW	$/t	-	-	$1.90 [162]	-	The tipping fee for 1 t of solid MSW in Malaysia in 1994 was $1.20/t. A GDP deflator [163] is used to get the fee in 2010 ($1.70/t). A 10% premium [164] is added to get $1.90/t.
Price of sawmills residues	$/t	-	-	$7.40 [135]	-	Junginger‘s *et al.* [135] Eucalyptus wood waste in Thailand is used as surrogate.
Price of plywood mills residues	$/t	-	-	$7.40 [135]	-	Junginger‘s *et al.* [135] Eucalyptus wood waste in Thailand is used as surrogate.
Price of palm trunks	$/t	Triangular	$1.90 [105]	$5.10 [105]	$6.80 [105]	The price of EFB is used as surrogate and adjusted the value based on the energy content.
Price of palm fronds	$/t	Triangular	$1.40 [105]	$4.60 [105]	$6.30 [105]	The price of EFB is used as surrogate and adjusted the value

Parameters	Unit	Distribution	Min	Most likely	Max	Note
						based on the energy content.
Price of rice straw	$/t	-	-	$14.90 [135]	-	The cost of collecting and baling of rice straw is about $13.50 in Thailand as surrogate [135]. I used a premium of 10% [164] to estimate the selling price of $14.90/t.
Price of cocoa branches	$/t	Uniform	$13.50 [135]	-	$16.20 [135]	Logging residues price is used as surrogate.
Price of rubber branches	$/t	Uniform	$13.50 [135]	-	$16.20 [135]	Logging residues price is used as surrogate.
Price of coconut trunks	$/t	Triangular	$1.90 [105]	$5.10 [105]	$6.80 [105]	Palm trunk's price is used as surrogate.
Price of coconut fronds	$/t	Triangular	$1.40 [105]	$4.60 [105]	$6.30 [105]	Palm frond's price is used as surrogate.
Price of logging residues	$/t	Uniform	$13.50 [135]	-	$16.20 [135]	
Biomass variable transportation cost – high bulk density	$/t.km	Uniform	$0.1114 [169]	-	$0.23 [105]	Palm EFB is used as surrogate for high bulk density residues. The transport cost is $0.23/t.km from a ground study by EcoIdeal Consulting [105].
Biomass variable transportation cost – low bulk density	$/t.km	Uniform	$0.1309 [169]	-	$0.58 [105]	It is assumed only rice residues (straw and husk) have low bulk density. Since EFB bulk density is about 2.5 times higher than rice straw [170], I assumed that rice straw costs 2.5 times more than

Parameters	Unit	Distribution	Min	Most likely	Max	Note
						palm EFB as a conservative estimate.
Biomass fixed transportation cost	$ / t	Uniform	$3.60 [171]	-	$5.00 [169]	
Gasoline/ethanol truck transportation cost	$ / t.km	-	-	0.05 [213]	-	
Gasoline pipeline transportation cost	$ / L	-	-	0.0066 [214]	-	

4.2.5 GHG emissions

Since agro-forestry residues are used as the feedstock, which are considered wastes, the residues themselves do not have upstream emissions [215]. A distribution fitting was performed on the simulation data of lifecycle GHG emissions of gasoline (t CO_2-eq/GJ) obtained from Venkatesh et al. [216]. The data was assigned a shifted-LogNormal distribution ($\mu = 0.099$; $\sigma = 0.0036$; $\delta = 0.079$). For ethanol, only the production emission (refinery) simulation data from Mullins et al. [71], (t CO_2-eq/GJ) was used, which was assigned a beta distribution ($\alpha = -0.06$; $\beta = 0.028$) as an input parameter in the optimization model. Other GHG emissions used are for truck transportation (t CO_2-eq/t.km) of biomass residues, ethanol and gasoline (uniform distribution: min=0.00015; max=0.00045) [5, 108, 217, 218] and pipeline transportation emission for gasoline (0.000034 t CO_2-eq/t-km) [118, 219].

4.3 Method

4.3.1 Optimization model

A family of large scale mixed-integer linear optimization models is constructed to estimate the total cost and GHG emissions associated with producing cellulosic ethanol in Peninsular Malaysia. The combined model for optimal use of biomass residues both to produce cellulosic ethanol and for co-firing with coal to produce electricity is first presented. The co-firing portion of this model is based on Chapter 3, and all co-firing variables are fixed to zero and ignore power generation costs when examining ethanol-only cases. The Analytica Optimizer version 4.4.2.2 from Lumina

Decision Systems that incorporates Frontline's large scale linear solver engine version 11 [155] is used. Minimization of costs and GHG emissions were evaluated in separate models. Cellulosic ethanol is assumed to be blended with gasoline while maintaining the current amount of energy consumed by gasoline-only. The supply of biomass residues comes from the fields/plantations (12,046 points of origin) and mills (1,714 points of origin). These residues are delivered to five potential bioethanol refineries and four coal plants. The five biorefineries and six oil refineries supply ethanol/ gasoline to 143 cities in Peninsular Malaysia. Biorefineries can be constructed in the model only if they received at least 730,000 tonnes/yr of residues. Therefore, there are 70,378 decision variables in the cellulosic ethanol portion of the model. The mathematical formulation for the optimization model is as follows:

Minimize cost:

$$C = \left(\sum_{t \in T} \sum_{i \in N_t} \sum_{k \in K} \left(c_t x_{i,k}^t + d_{i,k}^t c_{i,k}^t x_{i,k}^t \right) + \sum_{k \in K} \sum_{v \in V} \left(c_k^{\mathrm{ETOH}} x_{k,v}^{\mathrm{ETOH}} + d_{k,v}^{\mathrm{ETOH}} c_{k,v}^{\mathrm{ETOH}} x_{k,v}^{\mathrm{ETOH}} \right) \right.$$
$$\left. + \sum_{m \in M} \sum_{v \in V} \left(c_m^{\mathrm{GAS}} x_{m,v}^{\mathrm{GAS}} + d_{m,v}^{\mathrm{GAS}} c_{m,v}^{\mathrm{GAS}} x_{m,v}^{\mathrm{GAS}} \right) \right)$$
$$+ \left(\sum_{t \in T} \sum_{i \in N_t} \sum_{j \in J} \left(c_t x_{i,j}^t + d_{i,j}^t c_{i,j}^t x_{i,j}^t \right) + \sum_{j \in J} c_j^{\mathrm{COAL}} x_j^{\mathrm{COAL}} \right.$$
$$\left. + \sum_{j \in J} \sum_{l \in L} W_j c_l^{\mathrm{RET}} x_{j,l}^{\mathrm{RET}} \right)$$

from liquid fuel production (biomass purchase and transport + ethanol refining and transport + gasoline purchase, refining and transport) and electricity production (biomass purchase and transport + coal purchase and transport + plant retrofit)

or

Minimize GHGs:

$$G = \left(\sum_{t \in T} \sum_{i \in N_t} \sum_{k \in K} \left(g_t x_{i,k}^t + d_{i,k}^t g_{i,k}^t x_{i,k}^t \right) + \sum_{k \in K} \sum_{v \in V} \left(g_k^{\mathrm{ETOH}} x_{k,v}^{\mathrm{ETOH}} + d_{k,v}^{\mathrm{ETOH}} g_{k,v}^{\mathrm{ETOH}} x_{k,v}^{\mathrm{ETOH}} \right) \right.$$
$$\left. + \sum_{m \in M} \sum_{v \in V} \left(g_m^{\mathrm{GAS}} x_{m,v}^{\mathrm{GAS}} + d_{k,v}^{\mathrm{GAS}} g_{k,v}^{\mathrm{GAS}} x_{k,v}^{\mathrm{GAS}} \right) \right)$$
$$+ \left(\sum_{t \in T} \sum_{i \in N_t} \sum_{j \in J} \left(g_t x_{i,j}^t + d_{i,j}^t g_{i,j}^t x_{i,j}^t \right) + \sum_{j \in J} g_j^{\mathrm{COAL}} x_j^{\mathrm{COAL}} \right)$$

from liquid fuel production (biomass pre-treatment and transport + ethanol refining and transport + gasoline refining, combustion and transport) and electricity production (biomass pre-treatment and transport + coal transport, pre-treatment and combustion)

With respect to:

Ethanol production variables:

$x_{i,k}^t \in \mathbb{R} \quad \forall\, i \in N_t, k \in K, t \in T$	Quantity of each residue type *t* shipped from each supply location *i* to each biorefinery *k* (tonnes)
$x_{k,v}^{\mathrm{ETOH}} \in \mathbb{R} \quad \forall\, k \in K, v \in V$	Quantity of ethanol shipped from biorefinery *k* to city *v* (liters)
$x_{m,v}^{\mathrm{GAS}} \in \mathbb{R} \quad \forall\, m \in M, v \in V$	Quantity of gasoline shipped from refinery *m* to city *v* (liters)
$y_k \in \{0,1\} \quad \forall\, k \in K$	Decision whether to build (1) or not build (0) biorefinery *k*

Electricity production variables:

$x_{i,j}^t \in \mathbb{R} \quad \forall i \in N_t, j \in J, t \in T$	Quantity of each residue type *t* shipped from each supply location *i* to each power plant *j* (tonnes) (set to zero for ethanol-only cases)
$x_j^{\mathrm{COAL}} \in \mathbb{R} \quad \forall j \in J$	Quantity of coal shipped to each power plant *j* (tonnes)
$x_{j,l}^{\mathrm{RET}} \in \mathbb{R} \quad \forall j \in J, l \in L$	Variables defining the portion of plant *j*'s capacity that is retrofitted to co-fire biomass, where *l* indexes distinct levels of retrofit for modeling a piecewise linear (convex hull of five points) cost curve (%) (set to zero for ethanol-only cases)

Subject to:

$$\sum_{j \in J} x_{i,j}^{t} + \sum_{k \in K} x_{i,k}^{t} \leq s_i^t \quad \forall t \in T, i \in N_t$$

The biomass shipped from each supply location to coal plants and refineries must not exceed its supply limit (tonnes).

Ethanol production constraints:

$$\sum_{k \in K} q_{\text{ETOH}} x_{k,v}^{\text{ETOH}} + \sum_{m \in M} q_{\text{GAS}} x_{m,v}^{\text{GAS}} = E_v \quad \forall\, v \in V$$

The sum of biomass and gasoline delivered to each city must meet its energy demand (in the year 2009).

$$\sum_{k \in K} x_{k,v}^{\text{ETOH}} = 0.1\, Q_v \quad \forall\, v \in V$$

Liquid fuel is 10% ethanol and 90% gasoline (by volume) in each city for the 10% Ethanol Blend scenario (E10). The constraint's RHS is changed to $\leq Q_v$ for the No Blend Wall scenario.

$$\sum_{t \in T} \sum_{i \in N_t} q_t x_{i,k}^{t} = \sum_{v \in V} q_{\text{ETOH}} x_{k,v}^{\text{ETOH}} \quad \forall\, k \in K$$

Energy contained in the biomass residues shipped to bio-refineries must be equal to the energy contained in the ethanol leaving the bio-refineries at each biorefinery.

$$\sum_{t \in T} \sum_{i \in N_t} x_{i,k}^{t} \geq y_k b_{\text{MIN}} \quad \forall\, k \in K$$

Minimum biorefinery capacity constraint, ensuring that a plant cannot be built unless it produces at least b_{MIN} = 730,000 t/yr.

$$\sum_{t \in T} \sum_{i \in N_t} x_{i,k}^{t} \leq y_k b_{\text{MAX}} \quad \forall\, k \in K$$

Maximum biorefinery capacity constraint (b_{MAX} = 12,000,000 t/yr), which also ensures that a plant must be built before it can produce ethanol.

$$x_{i,k}^{t}, x_{k,v}^{\text{ETOH}},\ x_{m,v}^{\text{GAS}} \geq 0 \quad \forall t \in T, i \in N_t, k \in K, m \in M, v \in V$$

Quantities must be nonnegative.

Electricity production constraints:

$$\sum_{t \in T} \sum_{i \in N_t} \eta_t x_{i,j}^{t} + \eta_{\text{C}} x_j^{\text{COAL}} = E_j \quad \forall\, j = J$$

The sum of electricity generated from biomass and coal at each plant must be equal to the total required (amount generated in the year 2008).

$$\sum_{t\in T}\sum_{i\in N_t}\eta_t x_{i,j}^t \leq E_j \sum_{l\in L} x_{j,l}^{\mathrm{RET}} r_l \quad \forall\, j = J$$

The total biomass generation at each plant must be within the co-firing capacity of that plant

$$x_{i,j}^t, x_j^{\mathrm{COAL}} \geq 0$$

$$0 \leq x_{j,l}^{\mathrm{RET}} \leq 1$$

$$\sum_{l\in L} x_{j,l}^{\mathrm{RET}} \leq 1 \quad \forall\, j = J, l \in L, t \in T$$

Quantities must be nonnegative, and the retrofit variables are bound between zero and one with sum not greater than one to formulate the piecewise linear cost curve in the objective (convex hull of points {(0%, \$0/kW), (2%, \$100/kW), (10%, \$200/kW), (20%, \$300/kW), (100%, \$2000kW)}).

where J = {1,2,3,4} is the set of power plants; K = {1,2,3,4,5} is the set of potential biorefinery sites; L = {1,2,3,4} is the set of power plant co-firing retrofit levels in the piecewise linear retrofit cost curve; M = {1,2,3,4,5,6} is the set of oil refineries; N_t is the set of supply locations for biomass residue type t and T is the set of biomass residue types (shown in Table 3-3); V = {1,2,…,143} is the set of cities where liquid fuel is consumed; c_t is the purchase cost (\$/t) of biomass type t; $d_{i,k}^t$ is the distance (km) from biomass t location i to bio-refinery k; $c_{i,k}^t$ is the cost (\$/tkm) for shipping biomass type t from location i to bio-refinery k; c_k^{ETOH} is the cost (\$/L) for refining ethanol at bio-refinery k; $d_{k,v}^{\mathrm{ETOH}}$ is the distance (km) from bio-refinery k to city v; $c_{k,v}^{\mathrm{ETOH}}$ is the cost (\$/tkm) for shipping ethanol from bio-refinery k to city v; c_m^{GAS} is the cost (\$/L) of purchase and refining of gasoline at oil-refinery m; $d_{m,v}^{\mathrm{GAS}}$ is the distance (km) from oil-refinery m to city v; $d_{i,j}^t$ is the distance (km) from biomass t location i to plant j; $c_{i,j}^t$ is the cost (\$/t) for shipping biomass type t from location i to plant j; c_j^{COAL} is the cost (\$/t) for purchase, transport, and pre-treatment of coal for plant j; W_j is the capacity of plant j (MW); c_l^{RET} = \${100, 200, 300, 2000}/kW for l = {1,2,3,4}, respectively, is the cost per

unit capacity of retrofitting plant j at breakpoint level l of the piecewise linear cost curve; g_t is the emissions intensity (tCO_2eq/t) from pre-treatment of biomass type t; $g_{i,k}^t$ is the emissions intensity (tCO_2eq/tkm) of shipping from biomass type t location i to biorefinery k; g_k^{ETOH} is the emissions intensity (tCO_2eq/L) of refining ethanol at bio-refinery k; $g_{k,v}^{\mathrm{ETOH}}$ is the emissions intensity (tCO_2eq/Lkm) of ethanol transport from bio-refinery k to city v; g_m^{GAS} is the emissions intensity (tCO_2eq/L) of refining and combustion of gasoline at oil-refinery m; $g_{m,v}^{\mathrm{GAS}}$ is the emissions intensity (tCO_2eq/Lkm) of gasoline transport from oil-refinery m to city v; $g_{i,j}^t$ is the emissions intensity (tCO_2eq/tkm) of shipping from biomass type t location i to plant j; g_j^{COAL} is the emissions intensity (tCO_2eq/t) of coal transport, pre-treatment and combustion; s_i^t is the maximum supply of biomass type t at location i (tonne); q_{ETOH} is the energy content (GJ/L) of ethanol; q_{GAS} is the energy content (GJ/L) of gasoline; E_v is the annual vehicle fuel energy requirements of city v (GJ); Q_v is the annual vehicle volume requirements of city v (L); q_t is the energy content (GJ/t) of biomass type t; b_{MIN} is the minimum input (t/yr) of each biorefinery that is built; b_{MAX} is the maximum input (t/yr) of each biorefinery; η_t is the efficiency of converting biomass type t into electricity (kWh/t); η_{C} is the efficiency of converting coal into electricity (kWh/t); E_j is the annual electricity output required of plant j; and r_l is the retrofit level associated vertex l of the piecewise linear cost curve.

4.3.2 Scenarios

There are three fuel blend scenarios evaluated to estimate the cost and GHG emissions, namely: (i) 100% gasoline (as the reference case); (ii) E10, which is a 10% ethanol blend with gasoline where all cities receive 10% ethanol and 90% gasoline; and (iii) No Blend Wall, which relaxed the blend limit with gasoline. For 100% gasoline and No Blend Wall scenarios, the bioethanol energy demand constraint in the E10 mathematical formulation above (section 4.3.1) is modified to 0% ethanol and 0 - 100% ethanol, respectively. The E10 scenario is a situation where gasoline vehicles manufactured before 2001 can take up to 10% ethanol blend without the need for any modification. This was modeled because about 50% of passenger vehicles in Malaysia were manufactured before 2001 [220]. The No Blend Wall scenario is a situation where if flex-fuel vehicles (FFV) are available, the cities' energy demand would be met up to 100% ethanol.

Additionally, I modeled competing use of residues for fuel and electricity (coal/coal co-firing) simultaneously, in combined scenarios. These were done by combining the optimization formulation in this Chapter with the formulation used in the previous co-firing work (see Chapter 3), which has, depending on the combined scenario, up to 125,418 decision variables. There are five combined scenarios, namely: (a) 100% gasoline and 100% coal (as the combined scenario reference case); (b) E10 and 330 MW biomass co-firing; (c) E10 and Optimal Residue Use of co-firing; (d) No Blend Wall and 330 MW biomass co-firing; and (e) No Blend Wall and Optimal Residue Use of co-firing. Depending on the scenario, each deterministic cost minimization model run takes between 30 seconds (100% gasoline scenario) to 5

minutes (combined scenario of E10 and Optimal Residue Use co-firing) to complete while GHG minimization can take up to 20 minutes. The scenarios are summarized in Table 4-4.

Table 4-4: Summary of modeling scenarios

Scenario	Liquid Fuel			Electricity		
	100% gasoline	10% Ethanol Blend (E10)	No Blend Wall	100% coal	Residues producing 2.0 mil. MWh	Optimal Residue Use
Fuel-i	X					
Fuel-ii		X				
Fuel-iii			X			
Combined-a	X			X		
Combined-b		X			X	
Combined-c		X				X
Combined-d			X		X	
Combined-e			X			X

4.4 Results and Discussions

4.4.1 Fuel blend

4.4.1.1 Cost of fuel blend

As mentioned in the introduction, Malaysia does not have a policy to blend ethanol with gasoline. However, there is a potential to produce ethanol using the abundant availability of biomass residues. It was estimated that the amount of available residues is roughly 12 Mt/yr (see Chapter 3). The analysis begins with estimating the minimum cost of producing and shipping 100% gasoline (as the reference case/Fuel-i scenario) in Peninsular Malaysia in 2009, which is $5.182 billion/yr (Table 4-5). The 2009 gasoline level of consumption uses 9.0 billion L of all petroleum-based gasoline. The minimum cost for the E10 scenario (Fuel-ii) was found to be $5.187 billion, $5.4 million more expensive compared to the reference case (see E10 scenario in Table 4-5).

This higher cost is, however, only 1.0% higher than the cost of producing and shipping 100% gasoline. The higher cost for E10 is attributed to the more expensive crude oil ($0.49/L) that offsets the lower feedstock cost ($0.043/L) for producing the E10. The E10 scenario requires the production of roughly 930 million L of ethanol where about 2.9 Mt of residues or 24% from the total available residues are used (Table 4-5). In this E10 scenario, all 143 cities receive the 10% ethanol.

Since producing the E10 used 24% of the available residues resulting in a higher cost compared to 100% gasoline, the amount of ethanol that can be produced to provide cost savings from reducing 100% gasoline costs was further determined. The No Blend Wall (Fuel-iii) scenario allows for optimal use of residues that results in a minimum cost to produce ethanol. Compared to the E10 scenario where gasoline was forced to be blended with 10% ethanol, there is no blend constraint in the No Blend Wall scenario. It was found that the No Blend Wall scenario results in a cost $2.8 million less than 100% gasoline where 870,000 tonnes of residues are used (Table 4-5). The resulting lower cost compared to 100% gasoline is because of the lower production and shipping costs for the amount of ethanol produced compared to the displaced gasoline. In this scenario, only seven cities receive ethanol between 73% and 74% displacement of gasoline. The rest of the cities do not receive any ethanol. Altogether, about 280 million L of ethanol is blended with 9.0 billion L of gasoline, thus represents an overall blend of only 3.2%.

Table 4-5: Deterministic results for costs and amount of residues used that minimized cost under 100% gasoline (reference case) and different ethanol blend scenarios

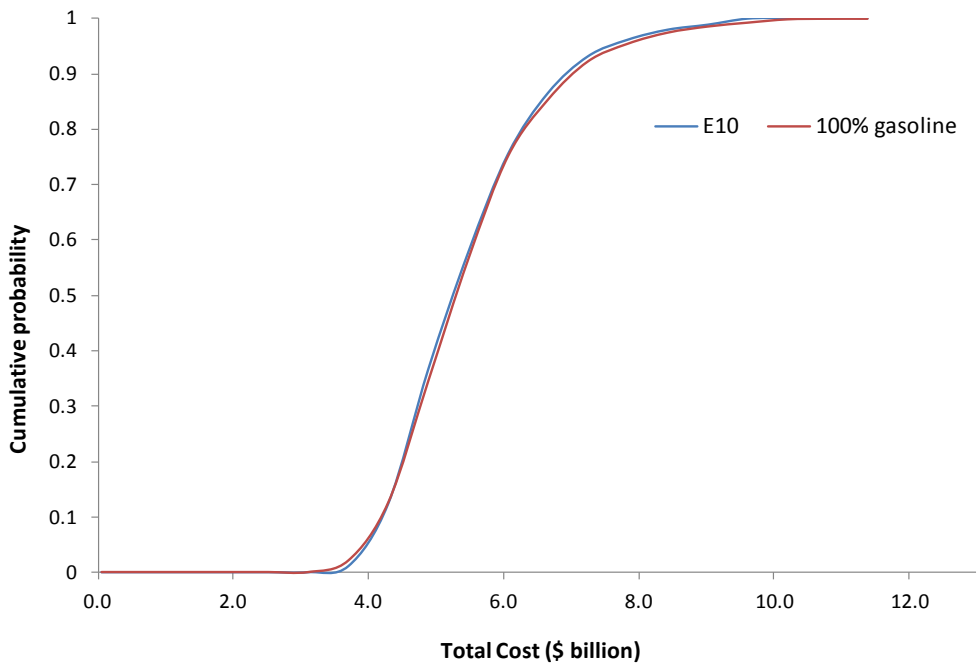
Model output	Scenario		
	100% gasoline (Reference Case)	**E10**	**No Blend Wall**
Costs ($millions)			
Total	5,182	5,187	5,179
Biomass	0	48	11
Ethanol	0	300	91
Gasoline	5,182	4,840	5,076
Cost difference: scenario vs. 100% gasoline			
($millions)	0	5.4	-2.8
(%)	0	1.0	-0.05
Residues used (million tonnes)	0	2.9	0.87
% of total residues available consumed	0	24	7.2

Note: Values may not add up due to rounding.

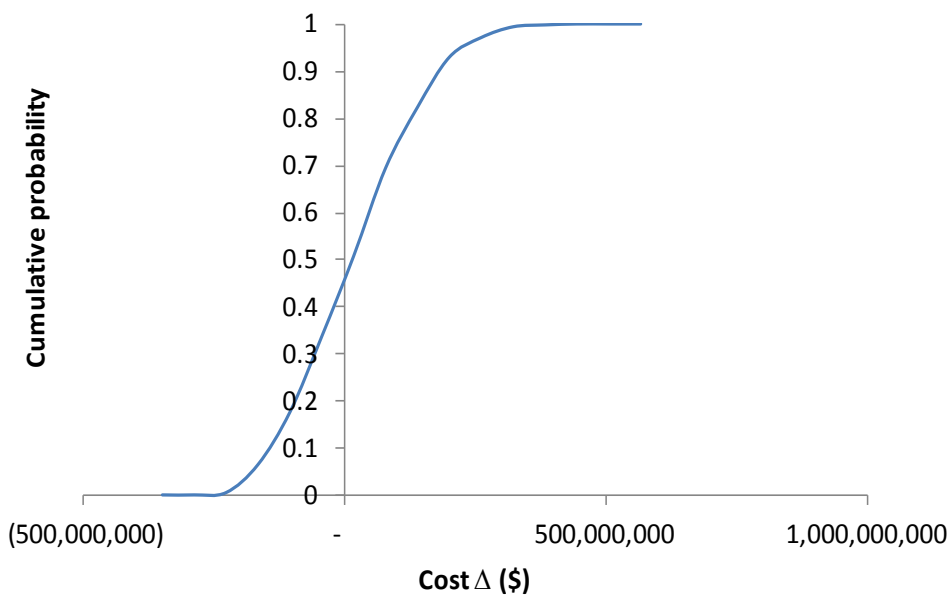
Under the E10 scenario, standard gasoline vehicles that are manufactured before 2001 can be operated without any engine modification. Although the No Blend Wall scenario results in a costs that is $8.2 million lower than the E10 scenario, the saving is offset by the need to replace approximately 8.0 million passenger vehicles [220] on Malaysian roads with flex-fuel vehicles (FFV) to be able to operate on 100% ethanol. Each FFV will have to cost $1 to take advantage of the cost saving. Instead, instituting an E10 policy is more feasible because there is no additional cost required to enable vehicles to operate on this ethanol blend.

4.4.1.2 Distribution of total cost for ethanol blend

The optimal cost solutions above (Table 4-5) were calculated based upon the median values of the probability distributions assigned to the input parameters (see Table 4-3 and Appendix I). To look at the stochastic effect on the total cost, multiple optimizations of separate samples (MOSS) of 1,000 separate Monte Carlo simulations were conducted to construct the distribution of total cost. I chose to compare the MOSS of the E10 scenario with 100% gasoline (the reference case). The E10 scenario (Fuel-ii) is chosen because it is more feasible in terms of costs implication compared to the No Blend Wall (Fuel-iii) scenario. For the E10 scenario, the 1,000 simulations MOSS results in a range of total cost between $3.3 billion and $9.6 billion, whereas the 100% gasoline scenario has a range of between $3.3 billion and $10.3 billion (Figure 4-3a). The relatively wide range of costs is driven by the wide uncertainty in the crude oil price assumed in this study ($37 - $150/bbl). The cost of crude oil contributes about 85% to the total cost of the E10. However, the cumulative distribution function curves of the two scenarios do not exhibit any stochastic dominance over the other (see Figure 4-3a). This is an important finding because if the government is comfortable using gasoline to fuel the transportation sector under huge uncertainty in costs, then the government should be indifferent to blend gasoline with 10% ethanol because the uncertainty is not going to be affected.



(a)



(b)

Figure 4-3: (a) Cumulative distribution functions (CDF) of total cost for E10 and 100% gasoline scenarios; and (b) the CDF of the delta of total cost between 100% gasoline and E10.

Figure 4-3b shows the result of MOSS for the cost of 100% gasoline scenario subtracted by the cost of E10 scenario. It is found that the cost of 100% gasoline or E10

has almost an equal chance of being more expensive or cheaper than the other. Any probability that the cost of the E10 scenario being higher than 100% gasoline scenario is due to the sampling of ethanol refinery cost at a higher value than crude oil price from the probability distribution of the input parameters in a particular simulation, and vice versa. Note that the ethanol refinery cost ranges from $0.15 - $0.49/L, while the crude oil price ranges from $0.23 - $0.92/L . The breakeven price of crude oil i.e. the price where the total cost of E10 scenario is equal to 100% gasoline scenario is about $80/barrel ($0.50/L). As long as the crude oil price is more than $80/barrel, the use of the E10 will result in cost savings.

4.4.2 GHG emissions of ethanol blend

In 2009 the gasoline consumption in Peninsular Malaysia was estimated at 9.0 billion liters. Using the US lifecycle GHG emissions of gasoline as surrogate [5], an estimated 33 Mt of GHGs are emitted annually. Cellulosic ethanol produced from biomass residues replacing gasoline results in GHG emissions reduction. Biomass combustion releases recent biogenic carbon, which is considered a net-zero carbon emission. However, the life cycle emissions of biomass energy also include emissions from transportation to the generation facilities. To investigate this interaction, I also modeled the minimum GHG emissions of producing and shipping the E10 as well as the No Blend Wall scenarios and compare them with 100% gasoline (as the reference case). The No Blend Wall allows for the use of all biomass available that sought to minimize GHG emissions. Table 4-6 shows the results of GHG emissions difference for producing and shipping ethanol blends with gasoline. The minimum GHG emissions of

the E10 and No Blend Wall scenarios were found to be 2.0 Mt and 7.8 Mt lower than 100% gasoline's GHG emissions, respectively. In comparison, Goh et al. [182] suggested that 34 Mt of GHG emissions could be avoided if Malaysia replaces all of its gasoline with ethanol. The difference in the results between their finding and this study is due to the different assumptions about gasoline's displacement. Goh et al. assumed a 100% displacement of gasoline with ethanol with the idea that there are enough residues to meet the ethanol production. In this study, even if all of the available residues are used (No Blend Wall scenario), only 3.8 billion L of ethanol can be blended with gasoline, which translates to an overall 58% ethanol blend. There are 65 cities that receive 74% ethanol and five cities receive between 24% and 52% ethanol blend. Although GHG emissions for the No Blend Wall scenario is much lower (by 5.8 Mt/yr) than the E10 scenario, the advantage is outweighed by the needs to replace all the vehicles in Peninsular Malaysia with a flex-fuel technology.

4.4.2.1 Cost of carbon mitigation of ethanol blend

Efforts to reduce GHG emissions come at a cost. In this study, the penalty of achieving lower GHG emissions is measured by the carbon cost of mitigation (COM), i.e. the increase in cost divided over the amount of GHG emissions reduced when ethanol blend is assumed as compared to 100% gasoline. Although the No Blend Wall scenario yields a larger reduction in GHG emissions compared to the E10 scenario (7.8 Mt/yr vs. 2.0 Mt/yr), it also increases the cost by about $200 million compared to 100% gasoline scenario. On the other hand, the E10 scenario increases the cost by only $9.2 million. The costs increase imply a COM of about $4.70/t CO_2-eq mitigated (for the E10

scenario) and \$25/t CO_2-eq mitigated (for the No Blend Wall scenario). Since the E10 has a relatively low COM, it should not be of a concern to the government to institute such a policy because the only existing implied GHG emissions reduction target in the transportation sector is 1.1 Mt/yr [7]. As a comparison, the COM for producing cellulosic ethanol in the US was estimated at \$80/t CO_2-eq mitigated [221], which is much higher than this estimate for Malaysia. This study's low COM is attributed to the lower price of residues assumed than in the US (\$1.90 - \$16.20/tonne vs. \$25 - \$50/tonne). Also, the COM of the E10 scenario is only 17% of the implied COM suggested under the Renewable Energy Act, Malaysia (2011) estimated at \$27/t CO_2-eq mitigated [15, 180].

Table 4-6: Deterministic results for Greenhouse gas (GHG) emissions, amount of residues used that minimized GHG and cost of carbon mitigation under 100% gasoline scenario (reference case) and different ethanol blend scenarios

Model output	Scenario		
	100% Gasoline (Reference case)	E10	No Blend Wall
Scenario GHG emissions (million tonnes)			
Total	26.4	24.5	18.6
Biomass/Ethanol	0	-0.2	-0.62
Gasoline	26.4	24.7	19.2
GHG emissions difference between scenario and reference			
(tonne)	0	-2.0	-7.8
%	0	-0.07	-30
Amount of residues used (million tonnes)	0	2.9	12.2
% of total residues available consumed	0	24	100
Cost of carbon mitigation (\$/t CO_2)	0	4.70	25.00

4.4.3 Producing ethanol and co-firing simultaneously

4.4.3.1 Cost of producing ethanol blend and co-firing simultaneously

Biomass residues can be used as a source of energy for different services, such as for making biofuels and electricity. In my previous work (see Chapter 3), it was showed that co-firing of 330 MW_b resulted in total cost of $24 million less than 100% coal (see Table 3-4). A minimum cost of $44 million less than 100% coal can also be achieved by optimizing for residue use (i.e. the co-firing Optimal Residue Use scenario. See Table 3-4). In the 330 MW_b scenario, 1.1 Mt of residues were used while the co-firing Optimal Residue Use scenario resulted in 3.6 Mt of residues used out of the 12 Mt available (see Table 3-4). In this Chapter, it was shown that (i) producing E10 resulted in a cost that is $5.4 million more expensive than 100% gasoline; and (ii) the No Blend Wall scenario resulted in a minimum cost that is $2.8 million cheaper than 100% gasoline (see Table 4-5). The E10 scenario utilized 2.9 Mt while the No Blend Wall scenario used 870,000 tonnes of residues. Since there are cost-savings and unused residues in the fuel-only and electricity-only scenarios, I further investigate the impact on minimum cost when co-firing and ethanol blend compete for the residues, and whether there is enough residue to produce ethanol and co-firing simultaneously.

Figure 4-4 shows that the lowest cost savings for producing ethanol and co-firing simultaneously is $46 million lower than the combined reference case i.e. 100% gasoline and 100% coal. This occurs when the No Blend Wall scenario is combined with the co-firing of Optimal Residue Use scenario. This lowest cost is a reduction of about 0.7% from the total cost of the combined reference case estimated at $6.3 billion. However, producing E10 and Optimal Residue Use for co-firing also results in costs

reduction. Here, the cost is $30 million lower compared to the combined scenario's reference case (Figure 4-4). Previously in section 4.4.1.1, it was estimated that the E10-only (Fuel-ii) scenario resulted in a cost that is $5.4 million more expensive than 100% gasoline, while in the co-firing work (see section 3.3.3), the Optimal Residue Use for co-firing-only scenario resulted in a cost saving of $44 million compared to 100% coal. In the combined scenario, the result of the E10 and Optimal Residue Use of co-firing (Combined-c) scenario suggests that the cost associated with E10 is $7.8 million more expensive than 100% gasoline, while the costs associated with co-firing is $38 million less than 100% coal. The increase in cost (by $2.4 million) associated with E10 in the combined (Combined-c) scenario compared to its fuel-only (Fuel-ii) scenario is due to the increased use of residues that are sourced further at one of the refineries (i.e. EtOH3 in Figure 4-5). The lower cost savings (by $6 million) associated with co-firing in the combined scenario compared to its co-firing-only scenario is because there is now a lower amount of residues used for co-firing, and thus only displacing smaller amount of coal at the coal plants (18% for co-firing-only scenario vs. 16% for co-firing in the combined scenario on an energy basis).

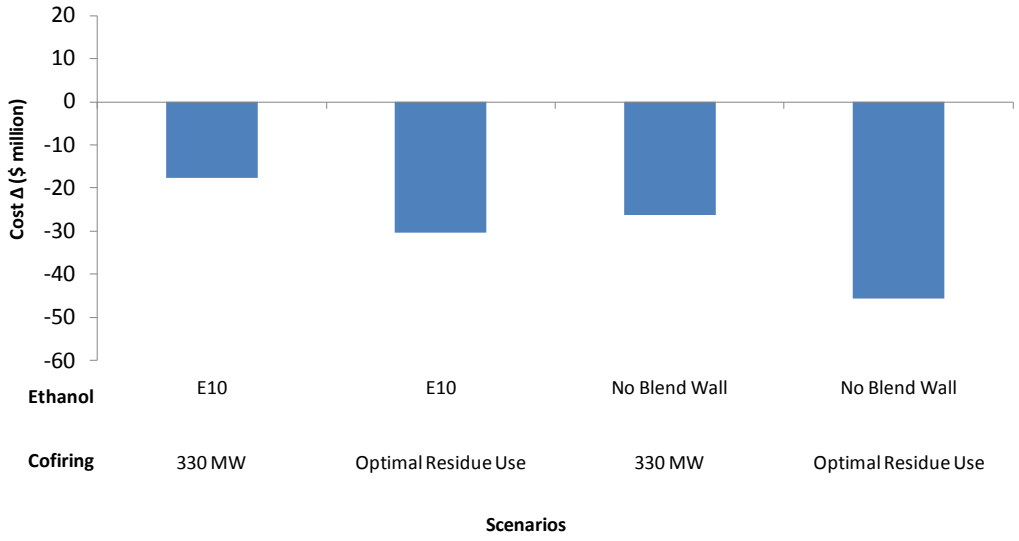


Figure 4-4: Cost difference of combined ethanol and co-firing scenarios compared to the combined total cost of 100% gasoline and 100% coal.

To determine whether there is competition for residues, the residues used for the E10 and co-firing Optimal Residue Use (Combined-c) scenario were compared. This combined scenario is chosen because it represents the optimum residue use for co-firing and the feasible policy option for ethanol blend that minimizes costs. It is found that there is a sufficient supply of residues to produce both the E10 and co-firing with coal simultaneously (Figure 4-5). Combined E10 and co-firing scenario results in the use of 2.8 Mt of residues for producing ethanol and 3.1 Mt for co-firing compared to 2.9 Mt and 3.6 Mt when E10 and co-firing scenarios were modeled separately, respectively. Although the use of residues for producing ethanol are about 100,000 tonnes less in the combined scenario compared to its fuel-only scenario, a supply of 10% ethanol blend to all cities is still able to be achieved. On the contrary, the residues used for co-firing in the combined scenario has been reduced to 3.1 Mt compared to 3.6 Mt in the co-firing-only scenario. Two coal plants receive residues at a significantly reduced amount in the

combined scenario (by 380,000 tonnes) compared to when co-firing is under the stand-alone scenario (Figure 4-5). This is because it is more expensive to transport the residues to the two coal plants compared to the EtOH4's ethanol refinery, which is also located in the same area/region (see Figure 4-5). Nevertheless, the lower amount of residues for co-firing under the combined scenario still results in an overall 16% co-firing rate, down just 2% compared to co-firing-only scenario. Therefore, it is conclude that there are enough residues to supply renewable energy sources to produce E10 and co-firing simultaneously.

The maps in Figure 4-5a-d also show the five potential locations of biorefineries. Each refinery is assigned a symbol, e.g., EtOH1 is ethanol refinery at location 1. In the E10 stand-alone scenario (Figure 4-5a) four refineries are selected by the model (EtOH1, 2, 3 and 4) to supply ethanol to the cities. These refineries are located in areas where biomass is more dense (see Figure 4-1c and d) and are close to population centers/cities that have high energy demand, which minimizes shipping costs. For example, EtOH3 supplies ethanol to the population centers in the central-west of the peninsula instead to smaller cities in the northeast because the cities in the central west have higher ethanol demand, thus minimizes shipping cost. Each refinery receives 730,000 t/yr, which is the minimum capacity assumed in the model. This constraint is a limitation of the model (assuming a-priori that plants will operate at a particular economy of scale). The results suggest that it may be more cost- effective to build fewer plants and run them at higher unit cost, but the model does not allow it.

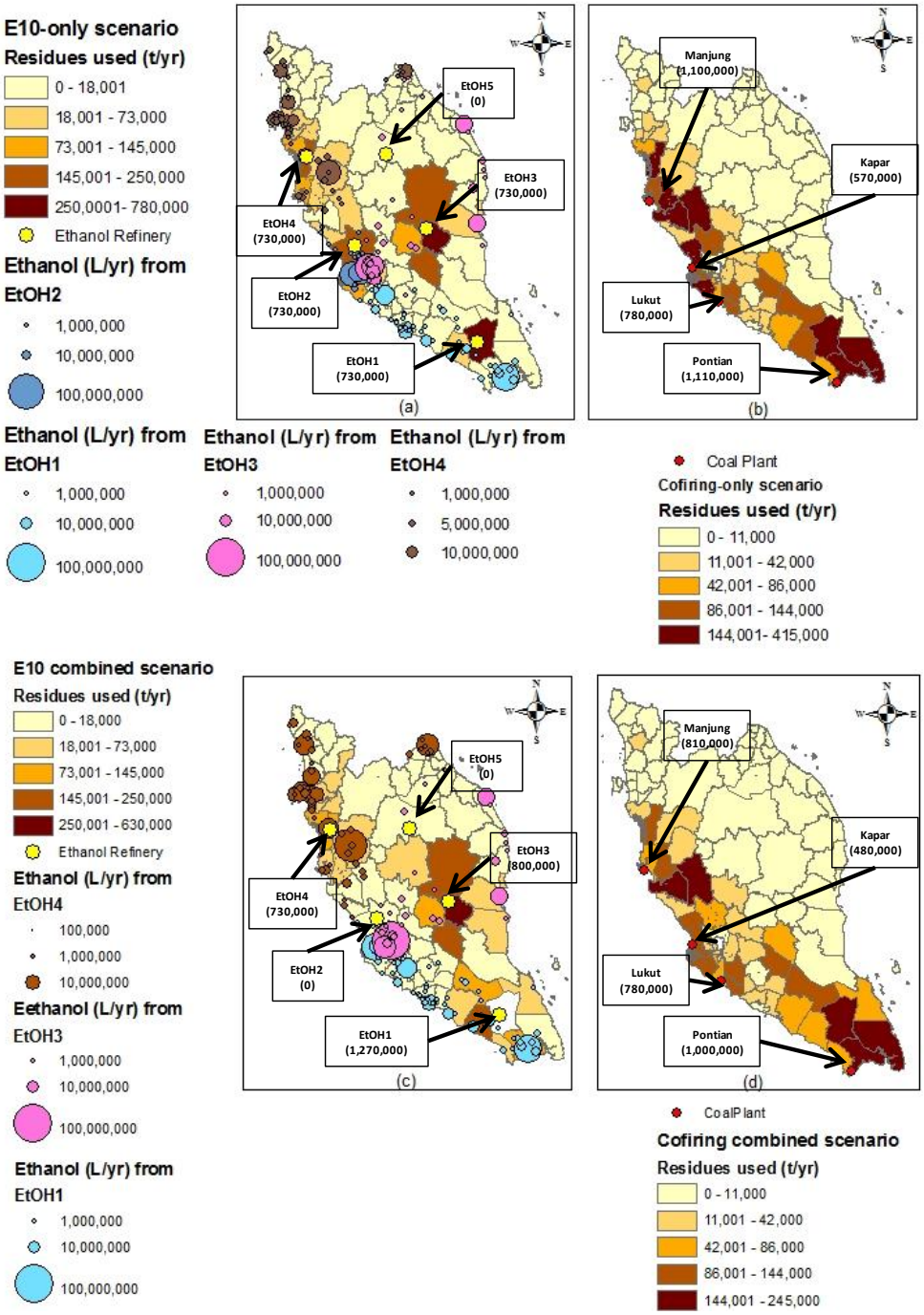


Figure 4-5: Maps of residues used at minimum cost for (a) E10-only scenario; (b) Co-firing-only (Optimal Residue Use) scenario; (c) E10 combined scenario with co-firing; and (d) co-firing combined scenario with E10.

Note: Values in parenthesis at each refinery represent the amount of residues delivered to the refineries (in tonnes) and values next to each coal plant represent amount of residues delivered to each coal plant (in tonnes). Also shown are the amount of ethanol delivered (L/yr) to each city and the origin of the ethanol from the refineries.

4.4.3.2 GHG emissions of producing ethanol and co-firing simultaneously

The minimum GHG emissions for the combined E10 and co-firing (Optimal Residue Use) is about 17 Mt lower than the GHG emissions of the combined reference case (Figure 4-6). In this scenario all 12.2 Mt of residue is used at $320 million (5%) increase in cost compared to the combined total cost for the combined reference case ($6.3 billion). This increase in cost is mainly attributed to the increase in co-firing cost ($240 million). The increase in cost by $320 million that reduces 17 Mt of GHG emissions for the E10 and co-firing combined scenario (Combined-c) implies a relatively low COM of about $19/t CO_2-eq mitigated. As a comparison, the COM for (i) co-firing of switchgrass and coal in the US was estimated at $20 - $86/ t CO_2-eq mitigated [35]; and (ii) producing ethanol in the US was $80/ t CO_2-eq mitigated [221].

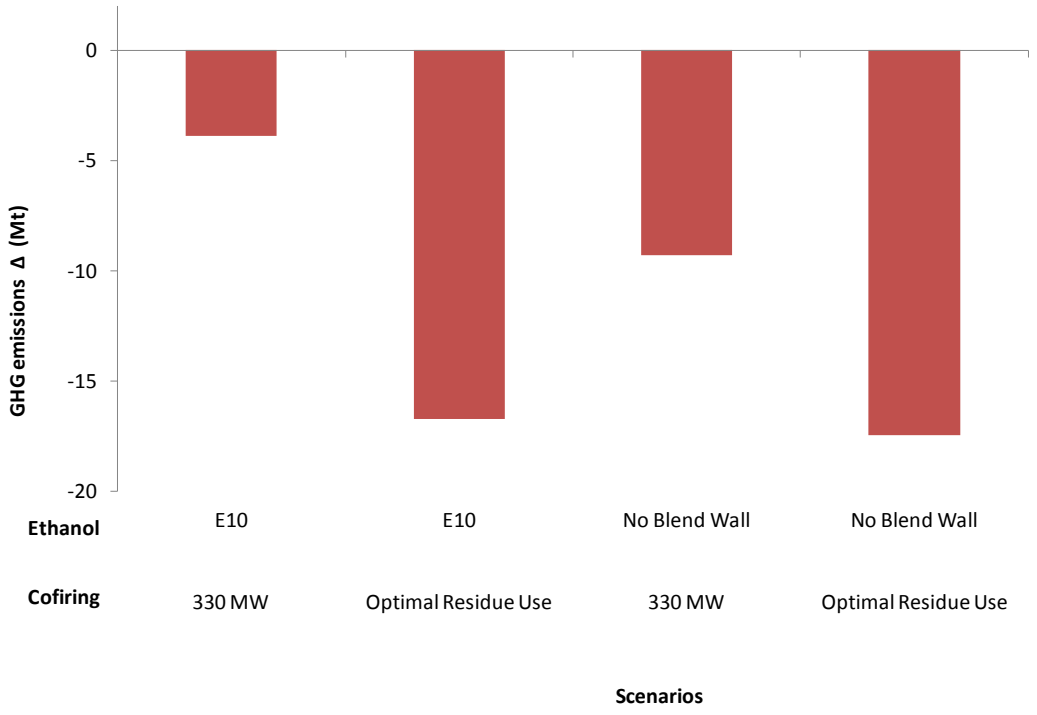


Figure 4-6: Greenhouse gas (GHG) emissions difference of combined ethanol blend and co-firing scenarios compared to the combined GHG emissions of 100% gasoline and 100% coal (combined reference case).

4.4.4 Policy implications

Incorporating renewable energy use with gasoline in Malaysia's ground transportation sector can be cost effectively implemented by blending 10% ethanol with gasoline in Peninsular Malaysia. However, in order to implement this option, a new policy mandate will have to be instituted. It is recommended that two approaches be undertaken that can ensure a successful implementation of this new policy mandate. First is the need to ensure a stable and guaranteed supply of residues, and the second is the need to finance and offset the high capital requirement for the program.

Altogether about 2.9 Mt of residues is needed to produce the 10% ethanol blend. However, suppliers (e.g., palm-oil mills, rice mills and plantations) will need to be incentivized to sell their residues to ethanol refineries. In the past, several renewable energy projects in Malaysia were unsuccessful because operators failed to secure a long term supply of feedstock from mills [15]. Offering to purchase the residue at higher prices can increase the probability of a guaranteed supply of residues to the biorefineries. This can be achieved by means of a price subsidy. For example, it was estimated that the direct cost savings of the E10 and co-firing combined is about $30 million. Using oil-palm residues as an example, about 5.4 Mt is used, which means that the government/utility could purchase the residues up to $5.60/t of residues higher than the initial purchase price. Under this scenario, even if all the direct cost savings is spent towards subsidizing the purchase price of residues, the country can still benefit from the reduction in GHG emissions (7.8 Mt/yr).

It was also shown that there is sufficient supply of residues to meet the renewable energy demand in both the transportation and electricity sectors. However, to enhance the effectiveness of the collection of residues, regulations under the respective acts such as the Environmental Quality Act, Malaysia (1974) and the National Forestry Act, Malaysia (1984) should be amended to include the provision to compel the operators/licensees to collect, sort and gather the residues for easy removal from mills/fields as well as prohibiting unsustainable disposing of residues e.g., open burning and dumping in landfills.

The second policy implication is the need to subsidize and offset the high capital investment for the ethanol program. The start-up cost to produce cellulosic ethanol (equipment, buildings, land etc.) can be as high as $300 million for a 730,000 t/yr residues input biorefinery capacity [200]. The government can attract investors either by offering tax deduction incentives such as a pioneer status (between 70% and 100% income tax relief for five years) or an investment tax allowance (up to five years from the date of equipment purchase) or both by including investors in this program into the promoted program areas status, under the Industrial Co-ordination Act, Malaysia (1975). The loss of income from tax credits can be offset by the indirect cost savings in crude oil imports and internalize the savings into the transportation sector. For example, the 10% ethanol blend can save 600 million L/yr of gasoline. At $80/barrel ($0.50/L) crude oil, this is an import saving of $300 million. Petroleum companies can contribute a certain percentage of the saving to the newly established Renewable Energy Fund under the Renewable Energy Act, Malaysia (2011). To enable this, Section 19 of the Act should

be amended to require oil companies to contribute an appropriate amount of monies to the Fund.

The country could also benefit from spin-off economic activities that can also offset the tax credit. The spin-off effects from the ethanol program could create about 8,300 new employment opportunities. These new jobs are estimated based on the import savings of $300 million/yr and using the average income of executives in the Malaysian manufacturing sector of about $3,000/month [167]. Apart from the job creation, other positive spin-off economic effects could also be generated in the form of new businesses, constructions and other small industries in the new and expanding townships particularly in areas near the biorefineries.

4.5 Conclusions

It was shown that Malaysia can cost-effectively reduce GHG emissions by blending 10% ethanol with gasoline in the ground transportation sector. A new policy mandate will have to be introduced. The COM of having this mandate is between $5.70 and $19.00/t CO_2-eq mitigated. It was also found that there is sufficient residues that can be used to produce the 10% ethanol blend and co-firing simultaneously at a minimum cost of $30 million compared to 100% gasoline and 100% coal. In this scenario, 48% of the 12 Mt of available residues are used. A guaranteed supply of residues could be met by subsidizing the purchase of residues using the $30 million direct cost savings, and also by strengthening the relevant acts to require a compulsory collection of residues. Apart from increasing the country's energy security through the reduction in imports of fossil fuels, the crude oil import saving of up to $300 million/yr can offset the income

and investment tax credits given to biorefineries. The tax credits can help attract new investments into the capital intensive ethanol program.

5 Conclusions and Future Work

As a developing country, Malaysia needs to support its economic activities with a reliable supply of energy. The two biggest energy users are the transportation and electricity sectors, consuming 48% and 21%, respectively, of Malaysia's total energy use of about 1,700 PJ [1]. The transportation and electricity sectors are also significant contributors to Malaysia's GDP at about $10 billion and $5.6 billion, respectively [222, 223]. Thus, it is important to ensure the security of supply of primary energy to both sectors. To assure that supply, it was demonstrated that Malaysia can generate a significant amount of cost competitive renewable energy for the transportation and electricity sectors. This bodes well for the country's economic development because new renewable energy industries have the potential to reduce Malaysia's imports of fossil fuels and bring spin-off economic activities.

In this chapter, the three main research questions that addressed three separate energy solutions are revisited. A summary and ramifications of the policy needs to assure renewable energy production based on the research findings is discussed. This chapter ends with recommendations for future work.

5.1 Research questions revisited

5.1.1 Producing 5% palm-biodiesel blend

In Chapter 2, four research questions were addressed that stemmed from a government policy target to blend 5% of palm biodiesel (PME) with petroleum diesel (B5) for the ground transportation sector. Although this policy was introduced in 2006,

its success has been limited. As of July 2011, the roll out of the B5 fuel is only in force in the central region of Peninsular Malaysia. Nevertheless, the mandate marked the first policy initiative of a renewable energy target in the transportation sector. Attaining the 5% PME mandate nationally will displace about 340 million L of petroleum diesel, and avoid approximately 1.1 million tonne (Mt) of GHG emissions annually.

a) What is the lifecycle GHG emission of producing palm biodiesel in Malaysia?

Palm-oil is the feedstock for making PME. In Malaysia, oil-palm trees are grown on either peat-land, primary forest, secondary forest, grassland, degraded land or converted lands that had produced other tree crops. Greenhouse gas emissions can arise indirectly from land-use-change as well as directly from processing activities. It was found that PME produced from trees grown on peat land and primary forest have the highest GHG emission factor. Although peat land's lowest emissions factor is smaller than primary forest (225 – 3,300 g CO_2-eq/MJ vs. 270 – 530 g CO_2-eq/MJ), its highest emissions factor is six times higher than primary forest. Other lands yielded less GHG emissions and PME produced from trees planted on degraded land had a negative GHG emission factor of -23 to -85 g CO_2-eq /MJ, indicating sequestered carbon. The results showed the importance of land-use-change in the overall GHG emissions of palm biodiesel production. The land choice can result in having a better or worse emissions profile than petroleum diesel.

b) What is Malaysia's GHG impact of meeting the 5% palm biodiesel mandate?

Biodiesel can be produced from oil sourced from a dedicated energy crop or an edible oil. Since palm-oil is mainly used for food, it was assumed that the food demand would be met and the PME mandate would require additional land. To answer the second research question, the GHG emissions from PME production using palm-oil was modeled grown on different types of land. Malaysia requires 340 million L of PME, equivalent to 11.7 PJ of energy to meet the 5% mandate. Producing the required amount of PME using peat-land results in about 21 Mt of GHG emissions and should be avoided. Primary forest (2.8 Mt) and secondary forest (1.5 Mt) also results in net emissions. Three types of land resulted in negative emissions when producing the mandated PME: (i) secondary forest with replacement (-930,000 tonnes), (ii) grassland (-560,000 tonnes), and (iii) degraded land (-1.5 Mt).

c) What is the minimum GHG emission needed to meet the 5% mandate?

Although these land types can save GHG emissions, their availability is limited. Using a simple linear optimization model, GHG emissions were minimized while constraining the available land by type and palm oil yield. The results indicated that Malaysia can save approximately 1.03 Mt of GHG emissions while meeting the mandate using a combination of land types: secondary forest, 47%, grassland, 28%, and degraded land, 25%, of the total 114,000 ha of land used.

d) Want is the maximum amount of biodiesel that can be produced with breakeven GHG emissions?

One of the motivations to produce PME is to strengthen Malaysia's energy security by reducing the imports of petroleum in the ground transportation sector. Energy security can be enhanced if Malaysia can produce as much PME as possible. However, Malaysia must make sure that increasing the production of PME does not result in additional GHG emissions. Again using a combination of different land types, up to 12% PME blend can be produced at 2010 diesel consumption level without increasing GHG emissions related to the transportation sector. Thus, Malaysia can take advantage of its renewable energy source to enhance the country's energy security while maintaining the current emissions levels.

5.1.2 Co-firing of biomass with coal

a) How much biomass residue is there in Peninsular Malaysia and where is it located?

Malaysia has an abundant of biomass resources, coming mainly from the agro-forestry sector. Several studies estimated that Malaysia can generate electricity equivalent to twice current generation using biomass. However, these estimates did not consider limitations such as the recoverability / accessibility and competing uses. Seven types of biomass residues were evaluated in this work because they were either important commodities/crops (large volumes available) or are widely distributed throughout the region. Using only the residues-to-product ratios, available residues were

estimated at about 49 Mt/yr for Peninsular Malaysia. The amounts of available residues are reduced to about 12.2 Mt/yr when taking into account accessibility and recoverability factors as well as other competing uses. Residues that originate from processing mills are generally located close to population centers, which permits easy access compared to residues in the fields/plantations. Residues from the mills constitute 37% of the 12.2 Mt. Oil-palm residues are the majority of these residues at 79%, rice and forestry residues at 17% and the remaining residues (cocoa, coconut, rubber and wood-based MSW) at 6%. Based on this information, Peninsular Malaysia has a significant amount of residues that can be used for energy production.

b) How much biomass residue can be co-fired with coal with a minimal cost compared to using only coal?

Malaysia introduced a renewable fuel policy in the electricity sector in 2000. The policy targeted a 5% share of electricity from renewable resources by 2005. This policy was revised in 2010 to simply require the installation of 975 MW of renewable generation capacity by 2015. This increases the share of renewable fuels from less than 0.5% at present to about 1.8% but is much less than the original target of 5%. Biomass will supply 330 MW of the renewable electricity target. However, the policy does not explicitly specify the methods for delivering the energy such as using biomass dedicated power plants or co-firing with fossil fuels. Using a large scale linear optimization model that minimizes costs of producing electricity via co-firing of residues with coal, it was found that if Malaysia incorporated 330 MW biomass electricity into its production mix by co-firing with coal electricity, cost could be reduced by $24 million per year from a

baseline cost of $1.16 billion using only coal. The 330 MW_b of biomass electricity requires approximately 1.1 Mt of residues (9%) out of the 12 Mt available. A higher biomass co-firing rate is achieved (1,040 MW_b or 18%) with optimal biomass use (3.9 Mt) resulting in $44 million lower costs than current coal. Thus, co-firing is cheaper than coal at a higher co-firing rate and result in a maximum cost savings.

c) How would the costs of biomass-coal co-firing change if the objective is to minimize GHG emissions instead of total costs?

The government assumes that installing the 330 MW of biomass electricity will result in 1.3 Mt of GHG emissions reduction. However, the impact of upstream life cycle emissions is not considered in the government's estimate. When included, it was found that co-firing 330 MW biomass with coal results in 1.9 Mt of GHG emissions reduction compared to coal use. The co-firing cost is lower compared to the coal-only generation ($1.156 billion vs. $1.161 billion). So there is no cost increase, which implies a zero cost of carbon mitigation (COM). A much higher emissions reduction (17 Mt) was obtained by optimizing for GHG emissions i.e. without a constraint on the co-firing rate. In this scenario, all of the 12.2 Mt of available residues was used. Nevertheless, it resulted in a $390 million increase in costs compared to coal use alone. This translates to a COM of $23/t CO_2-eq. Based on this relatively low COM, it is concluded that co-firing is a cost effective measure to reduce GHG emissions compared to the Government's newly introduced levy on heavy electricity users (> 4,200 kWh/yr), which has an implied COM of about $27.00/t CO_2-eq mitigated [15].

5.1.3 Cellulosic ethanol potential

At 370 PJ annually, gasoline is the number one fuel used in Malaysia's ground transportation sector. Gasoline consumption has increased by 200% since 1990 [224]. At current consumption, gasoline contributes about 33 Mt of GHG emissions yearly, approximately 19% of the country's 2010 total GHG emissions. The increasing dependence on gasoline and the significant GHG emissions associated with its use motivates the research to find an alternative fuel to displace gasoline use described in Chapter 4. Cellulosic ethanol can be produced from biomass residues and since Malaysia has an abundant availability of residues, a renewable energy mandate to displace gasoline could be a cost competitive option to reduce GHG emissions.

a) What is the optimal use of biomass residue in Malaysia in terms of cost minimization and GHG emissions for cellulosic ethanol production?

A large scale, mixed-integer linear optimization model was constructed that included the residue collection and transportation, ethanol production, and ethanol and gasoline shipping in Peninsular Malaysia. When minimizing the costs and using a 10% cellulosic ethanol blend (E10) overall system costs increases by $5.4 million compared to gasoline-only use at $5.2 billion annually. This is a rather insignificant increase in the cost of transportation energy being only 0.1% of the current gasoline's cost and still attained GHG emissions reduction (by 1.96 Mt) compared to gasoline-only use at 26 Mt annually. This implies a COM of $2.80/t CO_2-eq mitigated. When minimizing GHG emissions, a 10% ethanol blend reduced emissions by 1.97 Mt, which implies a COM of $4.70/t CO_2-eq mitigated. Therefore, with a low COM regardless of minimizing cost or

GHG emissions, the 10% ethanol blend is a cost effective option for reducing GHG emissions in the transportation sector.

It is possible to achieve higher GHG emissions reduction when the ethanol blend wall is unconstrained. In this case 7.8 Mt of GHG emissions are removed from the transportation system. However, the resulting cost increased by $196 million compared to gasoline-only use, implying a COM of $25/t CO_2-eq mitigated. Un-constraining the blend wall requires roughly 8.0 million vehicles to be replaced by flex-fuel technology (FFV), which adds additional costs compared to a 10% ethanol blend wall. Since the 10% ethanol blend has a lower COM and does not require additional cost to modify/replace vehicles compared to the No Blend Wall limit option, instituting a policy to blend 10% ethanol with gasoline in Malaysia can result in a cost effective measure to reduce GHG emissions.

b) What would be the optimal cost and GHG emissions of using the biomass residue if the production of cellulosic ethanol competes with co-firing with coal for electricity generation?

In Chapter 3, the implications on cost and GHG emissions of biomass co-firing with coal in Peninsular Malaysia were determined. Similarly in Chapter 4, the cost and GHG implications of using cellulosic ethanol were estimated. The modeling work assumed that the two sectors used residues independently. In the real world, limited resources have multiple users and this creates competition. In Chapter 4, a model was developed to ascertain whether co-firing and cellulosic ethanol production can coexist. It was found that the supply of residues is sufficient to both produce 920 MW_b co-firing

and use a 10% ethanol blend throughout peninsular Malaysia. The cost for having both co-firing and 10% ethanol was $30 million less than the current combined coal and gasoline only costs of $6.3 billion. Overall a 16% co-firing rate was achieved, 2% lower than the stand-alone co-firing result. The combined scenario resulted in a reduction of 17 Mt of GHG emissions compared to the current coal and gasoline, which is the same as the maximum GHG emissions reduction achieved under the co-firing-only scenario. The total residue use was 5.9 Mt (48% of total available) with 3.1 Mt going to co-firing and 2.8 Mt to making bioethanol. There appears to be some level of competition for residues between co-firing and 10% ethanol blend because residues use for co-firing in the combined scenario is roughly 500,000 tonnes less than its stand-alone scenario.

5.2 Policy recommendation in the transportation and electricity sector

There are two major policy recommendations in the electricity and transportation sectors evaluated in this research. The first policy recommendation is to assure that Malaysia can enhance its energy security, and the second is to ensure that Malaysia can reduce GHG emissions in the two sectors.

Enhanced energy security can be achieved by reducing Malaysia's reliance on imported fossil fuels i.e. coal and crude oil. To that end modeling conducted here shown that there is sufficient feedstock to produce PME and cellulosic ethanol that can be blended with petroleum diesel and gasoline, respectively. Displacing 5% diesel and 10% gasoline can save the country approximately $150 million/yr and $300 million/yr, respectively from imports of crude oil.

In the electricity sector, optimizing the use of biomass residues via co-firing with the current coal can save 1.8 Mt of coal equivalent to about $150 million/yr of coal imports. In order to implement the 10% ethanol blend and co-firing, the relevant Acts should be amended rather than enacting a new law. This is because, it is quicker and easier to include an additional provision into a current statute compared to enacting a whole new bill at the Parliament. In the case of ethanol blend, the Biofuel Industry Act, Malaysia (2007) can be amended to mandate the production of cellulosic ethanol from residues while for co-firing, the Schedule of Section 2 in the Renewable Energy Act, Malaysia (2011) can be amended to increase the installed capacity of biomass energy production facilities. The current maximum of 30 MW is too low to take advantage of all potential cost saving. At least 110 MW should be mandated.

Co-firing and cellulosic ethanol can be produced in Malaysia at a cost that is competitive with coal and gasoline, respectively. However, the same cannot be said for producing PME. Although the cost of producing PME was not estimated in this work, others have shown that biodiesel production cost is as high as 2.8 times the cost of producing petroleum diesel [225, 226]. The palm-oil price have risen almost 1.5-fold ($800 to $1,100/tonne) from 2006 to 2011 [131]. Therefore, it is highly likely that the Government will have to subsidize the production cost because of the high price of palm-oil. Nevertheless, the country will reduce currency outflow from savings of fossil fuels imports via the co-firing and cellulosic ethanol programs. The government can then use the savings (directly or indirectly) to incentives players in both sides of the energy sectors (electricity and transport fuel) by means of tax credits, reimbursement from a special fund, etc. In terms of fiscal policies, the government should extend the

existing financial incentives to co-firing and cellulosic ethanol projects. This could include extending the maximum income tax exemptions and investment tax allowances under the Industrial Co-ordination Act, Malaysia (1975) to include cellulosic ethanol and co-firing projects under its promoted areas. Suppliers should be given incentives to supply residues for co-firing and for making bioethanol. The government can require the industry players (coal utility and oil companies) to contribute a percentage of this revenues to the Renewable Energy Fund, which can fund co-firing and cellulosic ethanol projects. To do this, Section 19 of the Renewable Energy Act, Malaysia (2011) on the utilization of the Renewable Energy Fund should be modified to include disbursements from the Fund to subsidize the purchase of the residues at a higher price, inducing participation in the biomass supply chain. The Fund could also be used to invest in technological innovations such as finding new ways to produce ethanol more efficiently (e.g. domestic research and development of enzymes). Generally, import savings can also be internalized by investing in new infrastructures in particular in rural areas (roads, new townships, schools etc.), which can enhance local economies from spin-off economic effects (e.g. farmers spending additional income from selling of residues in their area). In the past, several renewable energy projects in Malaysia were unsuccessful because operators failed to secure a long term supply of feedstock from mills [15]. A guaranteed supply of feedstock can be aided by streamlining relevant Acts to enhanced residues collection. For instance, a guaranteed consistent supply of residues could be ensured by reconciling Regulations under the Environmental Quality Act, Malaysia (1974) and the National Forestry Act, Malaysia (1984) to compel mills, plantations and logging concessionaires to collect and gather the residues as well as

prohibiting unsustainable disposing of residues e.g., open burning and dumping in landfills. Another option to help build a sustainable supply of residues is to allow individual residues suppliers to plan their participation in a managed market of residues. There are trade-offs between the command/control approach (regulations) and a managed market. Regulations could speed up implementation of renewable energy programs at the initial stage but may negatively affect other industries that are also using the same input materials. Sustainable market could be better in the long run (many participants) but may increase the price of residue as a traded commodity.

The second policy recommendation is concerned with ensuring the success of reducing GHG emissions in Malaysia's electricity and transportation sectors. Malaysia has committed to a voluntary reduction of GHG emissions of up to 40% in terms of emissions intensity of GDP by the year 2020 compared to 2005 level [133]. This means reducing 26 Mt of GHG emissions from the energy sector compared to the sector's business-as-usual scenario in 2020 [133]. Utilizing renewable energy by means of producing PME, cellulosic ethanol and co-firing result in GHG emissions reduction that can help Malaysia achieve this target. Producing 5% PME was found to reduce 1.0 Mt of GHG emissions annually. Meeting the 330 MW biomass electricity target via co-firing with coal can reduce up to 1.9 Mt/yr of GHG emissions while introducing a 10% ethanol blend policy target can also save 2.0 Mt of emissions annually. Greenhouse gas emissions reduction by instituting the 10% ethanol blend and co-firing can be achieved in a cost effective manner. Reducing 1.9 Mt of GHG emissions can be achieved at no cost if 330 MW biomass is co-fired with coal, while reducing 2.0 Mt of GHG emissions in the 10% ethanol blend implies a COM of only \$4.70/t CO_2-eq mitigated. To ensure

that Malaysia can successfully meet the GHG emissions reduction target by 2020, the government should strengthen the legal framework that governs the industries' activities. The legislation that regulates the activities of producing PME, in particular the use of inorganic fertilizer, palm-oil mill effluent (POME) treatment and the expansion of oil-palm plantations into certain types of land that emits a lot of GHGs, needs to be reinforced. The Biodiesel Industry Act, Malaysia (2007) should explicitly prohibit the use of peat land and primary forest for PME production and to insert a provision that assures that the lifecycle GHG emissions of PME is lower than those of the displaced petroleum diesel. The Renewable Energy Act, Malaysia (2011) should include a provision to explicitly approve the co-firing technology as a means to reduce GHG emissions in the electricity sector. Currently, only combustion and gasification technology are supported.

5.3 Future work

The feedstock for producing palm biodiesel is palm-oil, and currently palm-oil is mainly used for food. As an internationally traded commodity, the palm-oil price has risen steadily over the past five years due to increasing food use demand. Meeting the 5% PME mandate would be financially challenging if the government must continue subsidizing the price of PME to keep it low. The feasibility of using other feedstock, such as non-food crops, waste oil etc., to produce biodiesel and the implications on GHG emissions and cost should be conducted. This study will help answer questions on the cost effectiveness and the extent of GHG emissions reduction possible.

Although East Malaysia has a slightly larger land area than Peninsular/West Malaysia, only Peninsular/West Malaysia was model here simply because more than 80% of the energy demand comes from this region and richer sources of data were available. East Malaysia most certainly has an abundant biomass resource from the agro-forestry sector because the oil-palm industry occupies an area in East Malaysia as large as in Peninsular Malaysia. However, East Malaysia's land use data is still being developed and reliably estimating the availability of residues was not possible. More efforts should be made to complete the land use data acquisition to complete the potential renewable energy picture for all of Malaysia. For instance, a very interesting series of question might be: Does East Malaysia have significant biomass resources to generate electricity and produce cellulosic ethanol? Is it possible that cellulosic ethanol to be transported from East Malaysia to Peninsular Malaysia (via tankers)? Is it possible to develop a robust biomass energy to supply East Malaysia's needs and shipped to Peninsular Malaysia to benefit the country?

Cost and GHG emissions data used in this research specific to Malaysia's oil industry (refining and pipeline transportation) was not available. Instead, the US data was used as surrogate. In addition, biomass cost estimates were based on literature and government reports. More accurate cost and emissions data might be obtainable from the industry players through questionnaires. In this dissertation, for example, the range of the total operating cost of a 10% ethanol blend is between $3.3 billion and $9.6 billion annually. With more accurate data, uncertainties in the cost estimates can be reduced. It would likely not change the conclusions here but the incremental improvement can improve policy implementation in Malaysia. One way to approach this

work is to prioritize the parameters that are going to be surveyed. For example, an uncertainty importance analysis that was performed for the jointly co-firing and E10 ethanol blend scenario shows that the top five most influential input parameters on the total costs are biomass storage cost, palm trunk price, palm EFB price, biomass variable transportation cost and palm fiber price. These input parameters should be given more priority for doing the survey.

A new research work on advanced fuel pathways using biomass as the feedstock should be investigated that can offer additional renewable energy alternatives to Malaysia's transportation sector. For example, biomass residues can be used to produce diesel-blend stock via Fischer-Tropsch (FT) processes. Since FT diesel-derived fuel has similar chemical and physical characteristics with petroleum diesel, it can be blended with petroleum diesel at any blend rate without the need to modify vehicles' engine or fueling infrastructure. The cost and GHG emissions of producing this fuel can be compared with PME in meeting the country's energy security and emissions goals. Also, it could be more cost-effective to use residues for producing the FT fuel compared to cellulosic ethanol.

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Appendix A. Other materials input in making 1 MJ PME

Amount	Unit	Sources	Notes
		Oil Palm Cultivation Phase	
b) Diesel			Diesel fuel is mainly used for transporting materials from outside as well as within the plantation. The lifecycle well-to-wheel CO_2 emission factor for fossil diesel is taken as 0.74 kg per kg produced based on 18.4 kg/MMBtu from NETL [5].
0.0003*	L	[100]	
Range: 0.00003 - 0.0005	L	[53], [103]	
c) Seeds			
1.4*	g	[52]	
d) Phosphate based fertilizer			
0.8*	g	[100]	
Range: 0.2 – 0.8	g	[103], [100]	
e) Potassium based fertilizer			
1.2*	g	[103]	
Range: 0.1 – 2.3	g	[100], [52]	
f) Magnesium based fertilizer			There were no data for CO_2 emissions from the production of magnesium and boron-based fertilizers. I used emissions data for the production of phosphate and potash, respectively, as a surrogate.
0.3*	g	[103]	
0.3 – 1.9	g	[116], [100]	
g) Boron based fertilizer			
0.1*	g	[100]	
Range: 0.07 - 0.15	g	[116]	
h) Herbicide glyphosate			Paraquat and glyphosate were the only herbicides and pesticides collected for this study because they are the two major chemicals used in the oil palm industry. Data for other weed, insect and fungus control such as
0.01*	g	[227]	
0.01 - 0.04	g	[227], [52]	

Amount	Unit	Sources	Notes
			2,4-D amine, carbofuran and benymyl were not collected because they are used in a very small amount [227].
i) Pesticide paraquat			
0.3*	g	[227]	
0.007 – 0.3	g	[52], [227]	
j) Nursery			Mutert [228] estimated about 35 ha of land is required for a nursery that could support 5000 ha of oil palm plantation. Using the materials input for the production of 1 tonne of FFB as the surrogate inputs for the nursery, gives a scaling factor of 0.7%. This gives about 1 kg of CO_2-eq is emitted from the nursery for every tonne of FFB produced.
		FFB Milling Phase	
a) FFB			
0.14*	kg	[100]	
Range: 0.13 – 0.17	kg	[103], [117]	
b) Diesel for transport from field to mill			
0.0002*	L	[100]	
Range: 0.00008 – 0.0008	L	[117], [103]	
c) Diesel at mill			
0.00005*	L	[53]	
Range: 0.00002 – 0.0002	L	[116], [100]	
d) Steam			Steam is assumed to have been generated from oil palm biomass renewable sources. As such, it is a net-zero emission. However, the transport of the oil-palm waste emits GHG assuming an average 22* km round trip from the plantation to the mill consuming 1.8 MJ/t.km [108].
96*	g	[103]	
Range: 96 – 200	g	[103], [116]	

Amount	Unit	Sources	Notes
			The return trip is estimated to consume 14%* less energy [229].
		PME Production Phase	
a) Methanol			Life-cycle GHG emission for methanol is taken from several reported results in Simapro [113]. The average value obtained from the data i.e. 0.77 kg GHG per kg of methanol produced was used in this study.
0.004*	kg	[117]	
Range: 0.002 - 0.004	kg	[230], [117]	
b) Electricity for refining CPO into RBD			As in the case of FFB milling, CO_2 emission factor of 660 g/kWh was used.
0.79	Wh	[231]	
c) Electricity for transesterification reaction			As in the case of FFB milling, CO_2 emission factor of 660 g/kWh was used.
0.82*	Wh	[53]	
Range: 0.76 – 0..82	Wh	[230], [53]	
d) Steam			Steam is generated using electricity purchased from the grid.
5.1*	g	[117]	
Range: 5.1 - 20	g	[117], [230]	
e) Sodium hydroxide			The life-cycle GHG emission from the production of sodium hydroxide (NaOH) is 0.79 kg per kg NaOH produced [232].
0.15*	g	[117]	
Range: 0.15 – 0.2			
f) Diesel for transport from mills to biodiesel plant			Based on an average distance of 100* km one way is assumed consuming 1.8 MJ/t.km [108]. The return trip is estimated to consume 14%* less energy [229].
0.0002	L		
g) Diesel for refining CPO into RBD			
0.0005	L	[231]	
h) Calcium bentonite			Calcium bentonite is the main chemical in bleaching earth used in the process of refining CPO into RBD.
0.2*	g	[233]	
Range: 0.1 – 0.3	G		
i) Phosphoric acid			Phosphoric acid is used in the process of refining CPO into RBD.

Amount	Unit	Sources	Notes
0.01*	g	[233]	
Range: 0.009 – 0.01	g		
		PME Use Phase	
a) Diesel for transport from blending facility to refueling station			Based on an average distance of 100* km one way is assumed consuming 1.8 MJ/t.km [108]. The return trip is estimated to consume 14%* less energy [229]. The biodiesel plant are assumed to be located close to a blending facility which is normally at a petroleum refinery.
0.0002	L		

Note: * - indicate the input used in the calculations. The range values are used as the lower and upper limit for the distributions.

Appendix B. A brief description of the land types modeled

i) Primary Forest

Malaysia's forest coverage is estimated to be about 19 million ha or 58% of its land area [127]. This was a reduction of about 11% from 1990. Malaysia's tropical primary forest is characterized by mature trees exceeding the height of 5 meters with a coverage area of more than 0.5 ha. The standing biomass value used in this study is 235 t/ha and is released upon clearing. This would mean that over the 25 years modeling period, about 9.4 t/ha/yr of carbon is released to the atmosphere. As a comparison, Danielsen et al. [234] estimated that about 163 t/ha of stored carbon is emitted to the atmosphere upon conversion of rainforest to oil palm plantation attributed to the difference in their aboveground carbon stock. Nevertheless, planting of oil-palm could have potentially reduced 9% of carbon emissions which would otherwise emitted if other annual cash crops such as rice, pineapple, etc. are planted [151]. The value of soil carbon content used in this study is 120 t/ha. Assuming 25% loss over the 25 year modeling period, 1.2 t C/ha/yr is lost. However, since soil carbon in oil-palm plantation is only 72 t/ha the actual loss of soil carbon for this study is estimated at 1.9 t C/ha/yr.

ii) Secondary Forest

Malaysia's secondary forest in 2000 is estimated to be about 26% of the total forest area, an increase from 21% in 1992 but still within the average percentage in Asia of 28% [127, 235, 236]. Secondary forest is basically referred

to as "*Forests regenerating largely through natural processes after significant human disturbance of the original forest vegetation …"* [236]. Using figures for the standing biomass of secondary forest of 116 t/ha and the same approach for estimating carbon loss from the conversion of primary forest into oil palm plantation, this model gives a much lower estimate of total carbon loss of only about 4.6 t/ha/yr from secondary forest compared to primary forest while the soil carbon loss (67 t/ha) is lower than the oil palm plantation. This translates to a gain in soil carbon content of about 0.9 t/ha/yr.

iii) Peat Forest

In 2005, only about 6.1% of oil palm plantations are on peat land, an increase of 1.8% in 1990 [27]. Malaysia has approximately 2.3 million ha of peat land of which 34% is used for agriculture [237]. Peat land is said to have a lower yield of FFB per ha and as such is less preferred for oil palm planters due to a higher start cost such as for dewatering and irrigation as well as maintenance such as a much higher fertilizers requirement [27]. However, this study assumes similar yield with primary forest soils i.e. minerals soil. Using similar approach previously, the loss of carbon from the standing biomass is 7 t/ha/yr while the loss of soil carbon, a 90% rate after 25 years, is estimated about 68 t/ha/yr.

iv) Grassland

There are approximately 330,000 hectares of grassland in Malaysia [127] of which only around 50,000 [238] would be suitable for oil-palm plantation in

terms of its close proximity to the existing plantation estates, logistics as well as soil suitability. This type of land, characterized by trees that are less than 2 meters in height, has a lower standing biomass of about 10 t/ha [27]. Murdiyarso in Danielsen et al. [234] estimated that this type of vegetation has a relatively high amount of soil carbon content of about 80 t/ha due to its close resemblance to a tropical forest soil [47]. This resulted into a net emission from land use change into oil palm plantation of about 1.3 t/ha/yr.

v) Degraded Land

The Food and Agriculture Organization refers to degraded land as a land that exhibits a temporary or permanent reduction in the productive capacity of land as a result of human action [239]. Their classification is based on land that is degraded due to deforestation and agricultural activities. Degraded land has little standing biomass and soil carbon content is estimated to be about 1 t/ha, respectively [96]. Because of that, planting a much better plant in terms of increasing the degraded land's soil carbon content such as oil-palm could capture more carbon on this type of land. It is still possible to obtain a respectable FFB yield on degraded land such as an ex-mining land. For example, a combination of EFB, acting as a mulching agent as well as organic fertilizers, with inorganic fertilizers together with proper management shows that planting of oil palm on bris/sandy soil (90% sand) could yield up to 23 t/ha of FFB in the first six years of harvesting [96]. However, this study assumes a 20% reduction in the FFB yield.

In Malaysia, it was estimated that there were about 10.3 million ha of degraded lands that includes poorly stock logged over forest, shifting, degraded secondary forests cultivated areas, ex-mining land and abandoned agricultural land [235]. However, in this study, the first two categories are already categorized as secondary forests. Due to unavailability of a more recent data and uncertainty of estimates of abandoned agricultural land that may have been rehabilitated, ex-mining land (more than 95% are ex-tin mine) was used to represent degraded land in this study. Currently there are approximately 130,000 ha of ex-mining land of which 85,000 ha have been rehabilitated [128]. However, in order to represent a more feasible area that could be cultivated for oil-palm (based on logistics), from the balance of about 41,000 ha of the degraded land that can be used, it is estimated that only 70% or about 28,000 ha are used for oil palm expansion in this model.

vi) Replacement of forests

A 1993 amendment to Section 12 of the National Forestry Act 1984 of Malaysia provides the requirement for a permanent forest that are converted to other economic activity such as for timber production, mining, quarrying and agricultural crops to be replaced by an approximately equal area of land as the permanent reserved forest [111]. However, the decision to declare Malaysia's forest as a permanent forest reserve is up to the respective State Governments. As of end 2006, 14.3 million ha (74%) of the total forest coverage are permanent forest reserve [240]. In order to achieve sustainable PME production, the model

developed for this study assumes an extension of the Act's provision to make it mandatory for oil-palm planters who convert forests, either primary or secondary, to replace them by replanting forest trees at another suitable location with an equivalent size.

Appendix C. Standing biomass content of different vegetation / forest types

Types of forest / vegetation	Biomass / total carbon content (t/ha)	Source
Tropical peat forest (closed undisturbed)	176*	[241]
Tropical peat forest (open broadleaf)	61	[241]
Tropical primary forest	235*	[151]
	171.5	[115]
	188	[28]
	250	[242]
	254	[243]
	229	[47]
Tropical secondary forest	116*	[47]
	88	[115]
	97	[244]
Rubber tree (used as surrogate data for other three crops where they are replanted after 25-30 years, thus a net zero accumulation of standing biomass)	0*	[245]
Grassland	10*	[28]
	39	[243]
	2	[115]
	8	[47]
Degraded land	1*	[47]

Note: * - indicate the input used in the calculations. The lowest and the highest values were used inputs for assigning distribution values for the Monte Carlo simulation. Data with single value was varied +/- 50% to obtain the low and high value.

Appendix D. Soil carbon content of different forest/tree types

Types of forest / tree	Soil carbon content (t/ha)	Source
Tropical peat forest	1,600*	[246]
	3,770	[247]
Tropical primary forest	120*	[27]
	60	[115]
Tropical secondary forest	67*	[248]
	62	[249]
Grassland	80*	[249]
	40	[80]
Degraded land	1*	[96]
Oil palm plantation	72*	[112]
	(66 – 78)	

Note: * - indicate the input used in the calculations. The lowest and the highest values were used inputs for assigning distribution values for the Monte Carlo simulation. Data with single value was varied +/- 50% to obtain the low and high value.

Appendix E. Calculations for total carbon loss from one hectare of six types of land converted into oil-palm plantation over 25 year modeling period

Items	Types of Forest / Land					
	Peat Forest	**Primary forest**	**Secondary forest**	**Other tree crops**	**Grass land**	**Degraded land**
Total forest/tree biomass (t/ha)	176	235	116	67	10	1
Total loss of carbon from forest/tree standing biomass (t/ha/yr) (A)	**7.0**	**9.4**	**4.6**	**2.7**	**0.4**	**0.04**
Soil carbon in forest/tree land (t/ha) **(B)**	1600	120	67	54	80	1
Soil carbon after clearing of forest/tree (t/ha) **(C)**	160	90	50	41	60	0.75
Soil carbon in oil palm (t/ha) **(D)**	72	72	72	72	72	72
Soil carbon gain / loss (t/ha/yr) * **(F) = If(C>D), Use ((B-D)/25), Otherwise (((C-D)/25).**	61	1.9	-0.87	-1.3	-0.48	-2.9
Total carbon loss / gain from soil and	68	11	3.7	1.4	-0.08	-2.9

standing biomass of original land type (t/ha/yr) * **(G) = A + F**						
Ground cover oil palm biomass (t/ha/yr) **(H)**	0.08	0.08	0.08	0.08	0.08	0.08
Carbon sequestered in tree / crops products (t/ha/yr) **(I)**	0.04	0.04	0.04	0.04	0	0
Carbon credits from planting of oil palm tree (t/ha/yr) **(J) = H + I**	0.12	0.12	0.12	0.12	0.08	0.08
Net loss / gain of carbon from LUC (t/ha/yr) **(K) = G - J**	68	11	3.6	1.3	-0.16	-3.0
Net loss / gain of CO_2 from LUC (t/ha/yr) **(L) = K x 44 ÷ 12**	250	40	13	4.8	-0.59	-11

Note: * A loss (release) of carbon is denoted as a positive number while a gain (capture) is denoted as a negative number.

Appendix F. Top 10 most sensitive (of 57 or 58) variables for different LUC scenarios

Variables	Ranking of Variables in the Sensitivity Analysis by Different Land Types / Land Treatment							
	Forest	Peat	Secondary Forest	Primary Forest Replacement	Secondary Forest Replacement	Other Tree Crops	Grass land	Degraded Land
FFB yield	1	3	1	4	8	2	12	1
Soil C in forest/land	2	2	12	1	10	1	2	27
Modeling period	3	4	2	2	2	3	17	2
FFB input	4	5	3	6	19	11	8	3
Total biomass of converted forest or land	5	7	4	5	3	44	1	24
CPO	6	6	6	7	14	38	9	7
Nitrogen fertilizer used	7	8	8	8	5	5	5	5
Soil C of oil-palm	8	11	7	9	6	6	4	4
% biogas released	9	24	9	10	7	7	6	6
% of methane in biogas	10	23	10	11	9	8	7	8

Appendix G. Detail description on the estimation of the availability of biomass residues

i) Oil-palm residues

Oil-palm was grown on about 2.5 million ha in 2009 in Peninsular Malaysia. Empty fruit bunches are generated at rates between 1.33 [250] and 1.55 [32, 106] t/ha. Private plantations use almost all EFB as a mulching agent [142]. Since 60% of oil-palm plantations are private [57], the available EFB was reduced by 60% to account for this use. Additionally, large palm-oil mills burn EFB to generate electricity for internal use. There are about 85 MW of capacity [9], 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 [93], thus, a 100% recoverability rate was assumed. Therefore, the availability of EFB for co-firing use is between 1.2 and 1.4 Mt/yr.

Oil-palm fibers and shells are generated at rates between 1.32 [250] and 1.63 [32, 106] t/ha, and 0.79 [250] and 1.1 [32, 106] t/ha, respectively. Oil-palm fibers and shells are used in large mills to generate steam for palm-oil extraction process. As such, 60% of the total fibers and shells was discounted from co-firing use [57]. A 100% recoverability rate for fibers and shells [93] was assumed. Therefore, there are about between 1.3 and 1.6 Mt of fibers, and between 790,000 tonnes and 1.1 Mt of shells available for co-firing use, respectively.

Oil-palm trunks are generated at rates between 1.6 [250] and 3.0 [32, 106] t/ha. 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 [147]. About 40% of the trunks are used in the wood industry [251]. A similar 40% [251] recoverability rate was assumed on the remainder of the palm trunks for co-firing use. That leaves a total of between 960,000 tonnes and 1.8 Mt/yr of palm trunks for co-firing use.

Pruned fronds are generated at rates between 6.0 [250] to 10.4 [32, 106] t/ha, while fronds from felled trees are generated at rates between 0.58 [32, 106] to 0.6 [250] t/ha/yr. Since most fronds are left in the field to conserve the soil, act as soil conditioner and prevent erosion [148], it is assumed that 50% is not available for co-firing. Efforts are also being undertaken to utilize fronds for ruminant feed. A study conducted in Malaysia showed that up to 7 kg/day of fronds can be fed to ruminants [148]. If all of the approximately 1.6 million cows in Malaysia are fed with a mixture of fronds in their daily diet, it would require about 4 Mt/yr 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 are used as animal feed. Since there is no data available to estimate the collection rate of fronds, the rubber branches recoverability rate of 50% [31] is used for pruned palm fronds. The recoverability rate for fronds from felled trees is assumed to be 40% [251]. Thus, between 2.9 and 5.1 Mt of pruned fronds and between 226,000 and 234,000 tonnes of fronds from felled trees are available for co-firing annually.

ii) Logging residues

Based on Peninsular Malaysia's production data from 1998- 2007 [21] and using the double moving average method, it is estimated that there were approximately 4.4

million m^3 or equivalent to 3.4 Mt (using an average wood density of 0.78 t/m^3 [252, 253]) of logs extracted in 2009. For every tonne of log extracted, between 37% [31] and 43% [23] of residues are left behind in the forest. Using these estimates there were approximately between 1.3 and 1.5 Mt of logging residues available. Assuming a recovery fraction of 0.65 [33], between 0.82 and 0.95 Mt/yr of logging residues is used for co-firing in this study.

A model of 577 sawmills and 59 plywood mills [22] is constructed using an estimated production data for 2009 [21]. For the saw mills, it is assumed that a residue production rate is between 13% [23] and 33% [31]. The estimated production of sawn timber in 2009 was about 2.2 Mt/yr [21] resulting in an estimated annual residue availability of between 290,000 and 730,000 tonnes. Yoshida [146] estimated that on average 25% of these residues can be collected for South-East Asian countries. Lim estimated a lower recoverability rate than Yoshida at 13% [31]. Using these recovery estimates as a lower and upper bound results in 38,000 and 183,000 t/yr of sawmill residues available for co-firing. On average, each mill would have between 66 and 320 t/yr of residues.

The estimated 2009 annual plywood production was approximately 350,000 t/yr [21]. The residues generated were assumed at between 40 and 53% [23, 146] of production and the recoverability factors were assumed to be the same as for sawmills (13 to 25%) [31, 146]. Thus the total recoverable residues from plywood mills were estimated at between 18,000 and 46,000 t/yr. There are 59 plywood mills and on average, a plywood mill can supply between 305 and 790 t/yr of residues for co-firing use.

iii) Rice residues

In 2009, there were 508,780 ha of rice-fields in Peninsular Malaysia producing 2,126,531 tonnes of grain [137]. Rice residues consist of the rice husk and the straw. There are about between 425,000 and 447,000 tonnes of rice husks, based on estimates that for every tonne of grain, between 0.2 and 0.21 tonne of husk is produced [254, 255]. Rice husks are used to generate process heat for rice drying in Malaysian rice mills [255]. 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 [144], then approximately 230,000 t/yr of rice husks are required to process 2.1 Mt of rice annually, based on rice husk's energy content of 14 MJ/kg [144]. Thus, the remaining 195,000 to 217,000 tonnes of rice husks are available for co-firing annually. Rice mills are easily accessible having a developed transportation system and husks are usually piled [25], thus a 100% recoverability rate was assumed.

Rice straw is produced at rates between 0.5 and 1.0 tonne for every tonne of grain [149]. 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. It is assumed that with a market for the straw this practice would cease. However, rice straw is also used as ruminant feed (10%) [149]. At a 65% recoverability rate, rice straw, assumed baled and placed on the nearest roadside [33] results in between 0.64 and 1.2 Mt of straw available for co-firing in this study.

iv) Rubber residues

Rubber residues consist of tree branches that fell off naturally each year and those obtained from trees removal for replanting. Trunks of removed rubber trees are used in the furniture market [31]. There are 1,021,540 ha of rubber plantation area in 2009 in Peninsular Malaysia [256]. With an estimated standing biomass of between 6 and 7 t/ha [31], of which 5% are naturally fallen branches, results in a total annual residue availability of about between 310,000 and 360,000 tonnes. Lim [31] 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. This results in the total recoverable natural fallen branch residues between 150,000 and 180,000 t/yr.

Using historical rubber plantation area from 1975 to 2009 [256, 257] and based on the economic lifespan of 30 years [258], approximately 1% of the rubber plantation or about 10,200 ha are replanted annually. Therefore, using the 6 to 7 t/ha of standing biomass in rubber plantations [31], between 61,000 and 71,000 tonnes 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 18,000 and 38,000 branches are available from felled rubber trees. At the recoverability rate of 50% [31], the amount of branches from felled rubber trees are between 9,000 and 19,000 t/yr. Altogether, the recoverable amount of rubber branches used in this study is between 160,000 and 200,000 t/yr.

v) 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 [31]. Based on 2006 data for Peninsular Malaysia [134], it is estimated that there are about 94,000 ha of planted coconut in Peninsular Malaysia in 2009 [137]. Between 2.3 and 3.9 t/ha of fronds are shed annually [31, 152]. With only about 10% of the fronds available [31] and using the same accessibility rate as for rubber (0.5) [31], between 11,000 and 18,000 tonnes of fronds could be used for co-firing. Trunk availability was estimated by using the total standing biomass (39 to 80 t/ha [80, 151]), the annual rate at which coconut trees are replanted (1% [256, 257]) and accessibility factor of 0.5 [31] (replanting rate and accessibility factor of rubber plantations are used as surrogates). Thus, it is estimated that about 17,000 to 34,000 tonnes of coconut trunks is recovered for co-firing purpose annually.

vi) Cocoa residues

There are only 3,662 ha of cocoa planted in Peninsular Malaysia in 2009 [259]. The cocoa tree is a small tree and obtaining branches during routine pruning is the only economic source of residues [31]. Pruned branches of cocoa trees are estimated to be between 20 and 25 t/ha [31, 150]. Using rubber plantation accessibility rate at 0.5 as surrogate [31], it is estimated that about 37,000 and 46,000 tonnes of cocoa branches are available for co-firing use.

vii) Wood-based Municipal Solid Waste (MSW)

Data from the Department of National Solid Waste Management (DNSWM) was used to estimate the amount of wood-based wastes in landfills in Peninsular Malaysia [141]. There are 98 landfills in operation. The total wastes disposed at landfills are 19,210 t/day or about 7.0 Mt/yr [141]. Wood-based MSW in Malaysia is 23.7 to 25.8% of the total waste and includes paper, cardboard, and yard trimmings [145, 260]. The average moisture content of Malaysia's MSW is 55% [260]. Seventeen percent of the wood-based MSW is recycled or used as composting materials [145]. Also assuming a 0.67 recoverability rate [33], between 420,000 and 450,000 t/year of wood MSW is used in this study.

Appendix H. Obtaining and processing Peninsular Malaysia's land use data

i) Data Source

Peninsular Malaysia's land use map for six out of seven biomass resource used in this study (forest, oil palm, rubber, cocoa, coconut and rice) was obtained for the year 2006 [134], which is the latest year available. A shapefile format of the land use map has a size of about 900 MB, and would cost about $30,000 to purchase. Instead, an image file (.jpeg) was purchased for $100 from the Department of Agriculture, Malaysia, which was supplied separately with attributes for the different types of biomass. The image file was digitized using ESRI's software, ArcGIS ver. 9.3.1 [154]. The map also contains the total land size for each biomass type by States in Peninsular Malaysia. However, the land use data supplied was generalized such that it was not possible to determine whether the biomass are secondary forests, young oil-palm plantations, old rubber estates, etc.

ii) Digitizing Process

The land use map was broken down by 11 different States in Peninsular Malaysia. The image file of each State (.jpeg) was first assigned a Geographic Coordinate System's (GCS) coordinates at least at three end-points using known coordinates as a reference [261]. The process was done in the ArcGIS environment. A histogram that assigns two unique values ("1" for black (foreground); and "2" for white (background)) for the image document was then created to enable a faster display of the image for the next step in the process. The image was then added to a blank shapefile (.shp) to enable it to be converted into a vector format (i.e. a raster to vector

conversion). Under the editing mode of the ArcScan tool, polyline features were created from the raster. The new polyline shapefile was then cleaned-up to remove dangles, extended lines, boxes, titles etc. The polyline feature was then converted into polygon features using ArcGIS Arc Toolbox (Data Management tool). The newly created polygon shapefile now has attribute tables with automatic identification number for each polygon. The State of Perlis (the smallest State) has about 500 polygons while the State of Pahang (the largest State) has about 20,000 polygons. Attribute table of the types of biomass is then populated. It is done by overlaying the polygon shapefile onto its original polyline shapefile, which had attributes for each biomass type from the original image file. Using the polyline shapefile as a guide, every single polygon for a particular biomass type is selected (using the ArcMap selected feature tool), thereafter the codes are then populated in the attribute table. The Peninsular Malaysia's land use map was then constructed by combining the new digitized shapefile of the 11 States.

Appendix I. Other input parameter values, ranges and assumptions used in the co-firing and ethanol optimization model

The types of distribution for the input parameters/variables and their references are described in the following table. The multiple optimizations of separate samples (MOSS) with Monte Carlo simulation used the distribution assumed in the table to sample a value of each variable to evaluate the optimization objective. The results of 1,000 runs of the MOSS (cost minimization) were used to plot a cumulative distribution function (CDF) and a probability density function (PDF).

Description	Unit	Distribution	Min.	Mode	Max.	Notes
Supply of Palm Empty Fruit Bunch (EFB)	t/ha	Triangular	1.3 [138]	1.6 [107]	1.7 [138]	Based on Fresh Fruit Bunch (FFB) average yield of 19 t/ha [53]. Chow's et al. [107] estimate of 1.6 t/ha EFB to calculate the residue-to-product radio (RPR). Mills capacity data is used to distribute the availability to each mill [262] in the unit of tonnage. The lowest and highest historical yield of FFB from 1990 – 2009 [138] were used to estimate the lowest and highest availability of residue.
Supply of Palm Shell	t/ha	Uniform	0.9 [138]	-	1.1 [138]	Same as EFB above.
Supply of Palm Fiber	t/ha	Triangular	1.3 [138]	1.6 [107]	1.7 [138]	Same as EFB above.
Supply of	t/ha	Triangular	0.65 [137]	0.78	0.84 [137]	The lowest, average (3.9 t/ha) and highest grain yields from 2004-2009 [137] and RPR of 0.2 and

Description	Unit	Distribution	Min.	Mode	Max.	Notes
Rice husk				[137]		0.21 [254, 255] to get the availability. Capacity data for 230 rice mills [25] is used to generate the tonnage supply at each rice mills.
Supply of wood and paper-based MSW	t/t MSW	Triangular	0.11 [263]	0.22 [139]	0.40 MSW [263]	Data for handling capacity of 98 landfills [141] is used to generate availability at each location in tonnage.
Supply of Sawmills residues	t/t of input logs	Uniform	0.13 [23]	-	0.37 [21]	Total sawn timber production is used to distribute the supply to 577 mills [22] where the residues is estimated in tonnage at each mill.
Supply of Plywood Mills residues	t/t of input logs	Uniform	0.4 [146]	-	0.53 [21]	Total plywood production is used to distribute the supply to 59 mills [22] where the residues is estimated in tonnage at each mill.
Supply of Palm Trunks	t/ha	Triangular	2.8 [138]	3.0 [107]	3.2 [138]	Based on Fresh Fruit Bunch (FFB) average yield of 19 t/ha [53]. Chow's et al. [107] estimate of 3 t/ha EFB is used as the residue-to-product radio (RPR). Polygon area is used to convert the availability into tonnage in each polygon. The lowest and highest historical yield of FFB from 1990 – 2009 [138] were used to estimate the lowest and highest availability of residue.
Supply of Palm Fronds	t/ha	Uniform	10.98 [32, 106]	-	21 [250]	
Supply of Rice straw	t/ha	Triangular	2.4 [137]	2.6 [137]	2.7 [137]	Average grain yield of 3.5 t/ha from 2004-2009 [137] and RPR of between 0.5 and 1.0 [149, 254] to

Description	Unit	Distribution	Min.	Mode	Max.	Notes
						get the availability in t/ha. Polygon area from ArcGIS [134] is used to generate the tonnage availability in each polygon.
Supply of cocoa branches	t/ha	Uniform	20 [150]	-	25 [31]	These are branches that fall naturally/pruned. Polygon area from ArcGIS [134] is used to generate the tonnage availability in each polygon.
Supply of rubber branches	t/t branches after felling	Uniform	0.35 [31, 146]	-	0.59 [31, 264]	This is a combination of branches recoverable annually and after felling of trees every 25 years [31]. The range is heavily (90%) influenced by branches available after felling.
Supply of Coconut Trunks	t/ha	Uniform	0.13 [80, 151]	-	0.24 [80, 151]	This is based on standing biomass of coconut plantation between 39 – 80 t/ha [80, 151]. Assuming 1% is replanted yearly using rubber plantation (used as surrogate) trend, which is used to estimate the tonnage availability at source.
Supply of Coconut Fronds	t/ha	Uniform	0.13 [31, 152]	-	0.20 [31, 152]	A combination of shed fronds and fronds available after felling.
Supply of logging residues	t/t log produced	-	0.35 [31]	-	0.43 [23]	Total log production from Forestry Department of Peninsular Malaysia [21] is used to allocate availability of residues in polygon areas of logging, which is derived using ArcGIS from National Forestry Inventory 3 [265].
Lifecycle GHG emissions	t CO_2-eq / t product	Uniform	1.2 [266]	-	1.9 [266]	Blengini and Busto's [266] result showed that between 2.53 and 2.76 kg of CO_2-eq are emitted per kg rice. But he did not give the breakdown of the

Description	Unit	Distribution	Min.	Mode	Max.	Notes
rice cultivation						unit processes. To get these figures, I subtracted these figures from rice milling emissions LCA conducted by Roy [267].
Lifecycle GHG emissions rice milling	t CO_2-eq / t product	Triangular	0.93 [267]	1.2 [267]	1.3 [267]	
Lifecycle GHG emissions of palm oil	t CO_2-eq / t product	Triangular	1.5 [8]	2.0 [8]	2.5 [8]	These figures do not include LUC so as to standardize it with GHG emissions from other biomass types.
Lifecycle GHG emissions of coconut copra	t CO_2-eq / t product	Uniform	0.38 [268]	-	0.43 [268]	Tan's et al. [268] results: 1 kg coconut biodiesel (CME) is produced per 1.667 kg copra. This process emits between 16.3 and 18.2 g CO_2-eq /MJ CME. The figures for the GHG emissions per tonne copra are estimated using the average 39 MJ/kg energy content of biodiesel. The emissions value from coconut for rubber and cocoa as surrogate were used.
Lifecycle GHG emissions of landfilling	t CO_2-eq / t MSW	Uniform	1.3 [269]	-	1.9 [179, 270]	There is about 25% paper and wood based items in MSW. But Liamsanguan and Gheewala [269] did not count the emissions from landfilling. Cherubini et al. [179], accounted for landfilling methane emissions. DiStefano [85] did for US that includes all anaerobic digestion.

Description	Unit	Distribution	Min.	Mode	Max.	Notes
Lifecycle GHG emissions of sawmill / plywood mills products	t CO_2-eq / t product	Uniform	0.34 [271, 272]	-	0.52 [273]	This is a combination of harvesting operations (cradle to mill gate) and mill operations (mill gate to mill gate).
Lifecycle emissions of logging	t CO_2-eq / t lumber	Uniform	0.045 [274]	-	0.21 [273]	McCallum [274] estimated wood product density of 800 kg/m^3. As such, 27 kg CO_2 emitted per m^3 is converted to per tonne by using this density value to get 45 kg CO_2-eq /t lumber. Puettman et al. [273] estimated between 81kg CO_2-eq /t lumber (SE USA softwood lumber) to kg 212 CO_2-eq /t lumber of (NE USA hardwood flooring product).
Lifecycle GHG emissions of transporting the biomass	t CO_2-eq / t.km	Uniform	0.00015 [275]	-	0.00045 [217]	Campbell's et al. [275] estimates is for Ultra Low Sulfur Diesel in Australia. For Davis's et al. [217], I have used their data to calculate the energy per t.km, i.e. truck's energy consumption divided by t.km goods shipped to get about 2.7 MJ/t.km and then used NETL's [5] WTW GHG emissions factor of diesel fuel (90 g GHG/MJ) to calculate the emissions (about 240 g CO_2-eq /t.km). The figures used (150 and 450 g) have taken into account 14% less energy consumption for the empty trucks return trip [229].
Lifecycle emissions of electricity in	tonne CO_2-eq /	Uniform	0.52 [9]	-	0.97 [9]	Based on national electricity generation mix in Malaysia of 2.3% oil, 58% natural gas and 32.4% coal in 2009 [9]. This estimated range of emissions

Description	Unit	Distribution	Min.	Mode	Max.	Notes
Malaysia	MWh					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 [11].
Energy content of Palm EFB	GJ / t	Uniform	15.5 [32]	-	18.8 [107]	
Energy content of Palm Shell	GJ / t	Uniform	20.1 [107]	-	20.7 [32]	
Energy content of Palm Fiber	GJ / t	Uniform	18.5 [32]	-	19.1 [107]	
Energy content of Rice husk	GJ / t	Uniform	13.8 [276]	-	15.7 [277]	
Energy content of paper and wood-based MSW	GJ / t	Uniform	3.4 [263]	-	6.3 [263]	
Energy content of sawmills residues	GJ / t	Uniform	6.3 [278]	-	18.8 [279]	Using sawdust as surrogate.

Description	Unit	Distribution	Min.	Mode	Max.	Notes
Energy content of plywood mills residues	GJ / t	Uniform	6.3 [278]	-	18.8 [279]	Using sawdust energy content as surrogate.
Energy content of palm trunks	GJ / t	-	-	17.5 [107]	-	
Energy content of palm fronds	GJ / tonne	Uniform	7.5 [278]	-	15.7 [2]	
Energy content of rice straw	GJ / t	Uniform	16.8 [280]	-	17.1 [281]	
Energy content of cocoa branches	GJ / t	Uniform	13.9 [278]	-	17.9 [264]	Using rubber wood as surrogate.
Energy content of rubber branches	GJ / t	Uniform	13.9 [278]	-	17.9 [264]	Using rubber wood as surrogate.
Energy content of coconut trunks	GJ / t	-	-	17.5 [107]	-	Using palm trunk energy content as surrogate.

Description	Unit	Distribution	Min.	Mode	Max.	Notes
Energy content of coconut fronds	GJ / t	Uniform	7.5 [278]	-	15.7 [2]	Using palm frond energy content as surrogate.
Energy content of logging residues	GJ / t	Uniform	16.5 [282]	-	18.8 [282]	
Coal energy content	GJ/t	-	-	31 (Bituminous coal) 27 (Sub-bituminous coal) [283]	-	All four coal plants use pulverize coal (PC) [34] with one plant on 100% bituminous and the other three, on average 70% bituminous and 30% sub-bituminous [136]. The energy content used in this model is a weighted average to each coal plant. A fixed energy content is adopted in order to set a fixed energy generation target from existing coal plants.
Lifecycle emissions of coal for electricity generation	tonne CO_2-eq / MWh	Uniform	0.75 [11]	-	1.3 [11]	
Coal transportation distance	km	-	-	4,800	-	According to a representative from the utility company (Tenaga Nasional Berhad), all coal is imported from three countries with 10% from South Africa and the remaining 90% from Indonesia and Australia [136]. The distance is the weighted average from these countries (South Africa ~

Description	Unit	Distribution	Min.	Mode	Max.	Notes
						10,500 km; Indonesia ~ 2,000 km; and Australia ~ 6,300 km).
Coal plant efficiency	%	-	-	0.37 [284]	-	All four coal power plants are sub-critical category. A single value is adopted to have a fixed target of energy generation.