Bioelectricity in Malaysia: Economic Feasibility, Environmental and Deforestation implications

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The Australian Journal of Agricultural and Resource Economics

DOI:
https://doi.org/10.1111/1467-8489.12345

Published: 08/04/2020

Peer reviewed version

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Abstract

We investigate the economic feasibility of bioelectricity production from biomass in Malaysia, and its impact on greenhouse gas (GHG) emissions and storage, agricultural prices, agricultural employment, and deforestation. For this purpose, we develop a partial equilibrium (PE) model that projects agricultural prices, production, imports, exports, domestic consumption, and land use in five-year increments between 2015 and 2065. Our results show that by 2030 biomass-generated electricity can supply 36.5% of the electricity generated in Malaysia, 16 times more than the 2016 electricity supply from biomass. Increased bioelectricity production from biomass will significantly reduce GHG emissions and will help Malaysia meet its commitment in the Paris Agreement to mitigate GHG emission by 45% before 2030. Our modelling shows that biomass-generated electricity creates a derived demand for waste biomass that expands the area of oil palm plantations. The expansion lowers agricultural prices, boosts agricultural employment and leads to some deforestation as landowners clear rainforest to plant oil palm trees. Nonetheless, the deforestation does not increase GHG emissions since GHG gains from bioelectricity significantly exceed GHG losses from deforestation.

Keywords: bioelectricity; waste biomass; partial equilibrium model; cost competitiveness

JEL: C61, O13, Q42

1. Introduction

The Paris Agreement on climate change was adopted in December 2015 with 197 countries signing it as of January 2019. The primary goal of the Paris Agreement is to ensure the global average temperature does not exceed 2 °C above pre-industrial levels (United Nations Framework Convention on Climate Change 2015). The goal represents the degree of climate change that maintains the climate system while minimizing the negative impacts on food production and economic development (Randalls 2010). To achieve this goal, the world must significantly reduce greenhouse gases (GHG) such as carbon dioxide (CO2) that are emitted in the atmosphere (Stocker 2014). Fossil fuel production and use is the major contributor of GHG emissions. Low-carbon energy sources such as biomass, biofuels, hydro, solar, wind, tidal, and nuclear power must replace fossil fuels to help countries meet their GHG targets (van Vuuren *et al.* 2018). However, low-carbon energy sources could raise agricultural prices and spur deforestation as the agricultural sector expands to supply both food and bioenergy (e.g. Searchinger *et al.* 2008; Timilsina *et al.* 2012).

In this paper, we investigate the economic feasibility of bioelectricity production (primarily from waste biomass) in Malaysia and also examine its impact on GHG emissions, agricultural prices, employment, and deforestation. We focus on Malaysia for three reasons. First, the Malaysian government signed the Paris Agreement and pledged to cut GHG by 45% by 2030 relative to its 2005 levels (Begum 2017). The energy sector emits most of GHG emissions (66%) in Malaysia, which includes electric power generation (Sharif 2012). Therefore, Malaysia provides an opportunity to examine whether replacing fossil fuels with biomass for electric power generation in Malaysia could help to meet its GHG targets as promised in the Paris Agreement.

Second, Malaysia is the world’s second-largest producer and exporter of palm oil after Indonesia (Sulaiman *et al.* 2011).[1] By 2016, oil palm plantations grew to 5.74 million hectares (Economics & Industry Development Division 2017), which significantly exceeds the area of land used by Malaysia’s second largest crop, rubber plantations with about a million hectares (Department of Statistics 2016). Consequently, the oil palm sector creates about 90% of the total biomass from wastes in Malaysia (Loh 2017) and the palm oil sector waste biomass can be used to generate bioelectricity.

Third, some researchers suggest that bioelectricity generated from waste biomass may not be competitive. For example, McCarl *et al.* (2000) and Maung and McCarl (2013) argue that using biomass to generate electricity cannot compete with coal and natural gas in the United States. However, they assume producers haul the waste biomass to co-fire with coal at electric power plants, which raises costs. In contrast, Malaysian palm oil mills source most of their biomass onsite, the mills avoid additional biomass hauling costs and generate electricity onsite which they deliver to the national gird.

We develop a partial equilibrium model of the Malaysian agricultural sector that projects in five-year increments between 2015 and 2065, agricultural prices, production, imports, exports, domestic consumption, and land use. Our model allows for technical and economic analysis of bioelectricity production from waste biomass using different technologies that industry currently uses on a small scale. The model includes the dominant agricultural commodities of Malaysia including nine crops (banana, durian, kenaf, mango, papaya, pepper, pineapple, rambutan, and rice) and five plantation species (cocoa, coconut, forest, oil palm, and rubber).

[1] https://www.indexmundi.com/agriculture/?commodity=palm-oil

Our results support bioelectricity generation from waste biomass in Malaysia. For instance, we find that with minor government subsidy, biomass-generated electricity can supply up to 36.5% of the electricity generation of Malaysia by 2030, which is 16 times higher than the supply from biomass in 2016. This large-scale bioelectricity generation will reduce Malaysia's use of fossil fuels. Furthermore, our results show three additional benefits of bioelectricity production from waste biomass. First, bioelectricity production could mitigate a considerable amount of GHG emissions and help Malaysia to meet its commitments in the Paris Agreement. Second, biomass generated electricity would reduce agricultural prices as the agricultural sector expands to supply additional biomass. Third, the expansion of agriculture would boost agricultural employment.

We make three contributions to research literature. Our paper is the first to construct a comprehensive partial equilibrium model of the Malaysian agricultural sector that allows palm oil mills to utilize a variety of feedstocks and technologies to generate bioelectricity. The model gives insights into the economic feasibility of bioelectricity, GHG emissions, impacts on agricultural prices and employment, and deforestation. Second, our findings suggest that increased bioelectricity generation will lead to increased deforestation and lower agricultural prices because it creates a derived demand for waste biomass. Consequently, our results challenge the prevailing view that bioelectricity generation has a negligible impact on deforestation and agricultural prices since bioelectricity generation uses leftover wastes from processing. Thus, we suggest policymakers should take into consideration the secondary effects of increased bioelectricity generation such as deforestation when considering the use of biomass to generate bioelectricity or biofuel. Third, our findings on the economic feasibility of bioelectricity production in Malaysia suggest that results from other countries such as the United States cannot be generalized to the rest of the world.

The paper has four substantive sections. Section 2 reviews relevant literature. Section 3 describes the research methodology and the partial equilibrium model. This section also shows the production coefficients and cost of bioelectricity generation. Section 4 presents the simulation results while the last Section concludes the study.

2. Literature Review

Biomass, mainly agricultural waste such as wood, is the oldest form of energy used by humans and via direct combustion is still widely used worldwide. As well, biomass is also used to produce bioenergy i.e., bioelectricity, biogas and biofuels (Larson and Kartha 2000; Khatiwada *et al.* 2016). Nonetheless, the use of biomass to produce bioenergy can impart secondary effects on the economy, environment and society.

Farmers and landowners may clear pristine forests, convert them to cropland to supply bioenergy to an economy (Searchinger, Heimlich et al. 2008; Timilsina, Beghin et al. 2012; Elbehri *et al.* 2013). Calvin *et al.* (2016) use a computable general equilibrium model (CGE) called Global Change Assessment Model (GCAM) to explore the interaction of fossil fuel use, bioenergy, agriculture, carbon emissions, and land use changes. They find limited petroleum resources leads to greater production of bioenergy crops, greater rates of deforestation, and higher carbon dioxide emissions from land use changes.

Increased reliance on bioenergy may lead to higher food prices if biofuel production diverts land and commodities away from agriculture and food production and into biofuel production. Wise *et al.* (2014) using the GCAM find increased biofuel production increases corn and sugar producer prices by 7% and 12% compared to the base year as producers divert land away from crops and dedicate it to growing energy crops such as switchgrass, miscanthus, willow, eucalyptus, and jatropha. They also find carbon dioxide emissions from land use changes exceed the emissions that biofuels offset.

Research literature, accordingly, has moved towards the utilization of waste biomass as potential feedstocks for bioenergy because use of waste biomass overcomes the problems of land use changes and higher food prices. For example, Suttles *et al.* (2014) find the United States can reduce its carbon dioxide emissions by 11% by utilizing forest biomass. However, their results include the impact of the Renewable Fuel Standards, a U.S. Law that mandates minimum biofuel usage in the U.S. transportation sector. Other studies confirm that waste biomass for electricity production mitigates more GHG emissions than does biomass for liquid fuel production (Campbell *et al.* 2009; Farine *et al.* 2012). In addition, a thriving bioelectricity industry may increase employment opportunities in rural areas as the industry creates a derived demand for waste biomass that expands the agricultural sector (Thornley *et al.* 2008; Elbehri, Segerstedt et al. 2013).

Waste biomass has two potential problems. First, bioelectricity may only offset a small portion of electricity consumption. Ignaciuk and Dellink (2006) using a CGE model find waste biomass can only offset 2 – 3% of Poland’s electricity consumption. Second, bioelectricity generated from waste biomass may not be competitive. For example, McCarl, Adams et al. (2000) and Maung and McCarl (2013) using a PE model, called the Forest and Agricultural Sector Model with Greenhouse Gases (FASOMGHG) find biomass cannot compete with coal and natural gas to generate bioelectricity in the United States. However, they assume producers haul the waste biomass to co-fire with coal at electric power plants, which raises production cost.

Research literature also utilizes two pricing mechanisms for bioelectricity generation: A minimum renewable energy mandate, or carbon dioxide emission permits. For example, many studies impose the U.S. Renewable Fuel Standard whereby the U.S. government mandates transportation fuels must comprise a minimum percentage of biofuel. The quantity mandate forces producers to supply bioenergy even at an economic loss (Suttles, Tyner et al. 2014). Another assumption imposed on some models is the country has a tradable carbon dioxide emissions permit market McCarl and Schneider (2000) and (Maung and McCarl 2013). Electric companies can either buy permits to emit carbon dioxide or implement carbon savings by implementing new technology such as co-firing biomass with coal. On the other hand, a government or regulatory agency sets the retail price of electricity for the consumers via the feed-in tariff where small electricity producers can sell electricity to the national grid for a fixed price. The feed-in tariff allows a small producer to generate bioelectricity on site near the sources of waste biomass and deliver the electricity via power lines to the national grid.

Research literature uses both CGE and PE models to study the relationships between bioelectricity, GHG emissions, food prices, land use, agricultural employment, and deforestation. CGE models represent a whole economy while PE models examines a network of closely related markets. CGE models have emerged as a standard technique to appraise many policies (Wing 2009). Nevertheless, CGE carries three drawbacks. For example, scholars have widely criticized CGE for poor performance and possessing weak econometric and empirical foundations in behavioral relationships (McKitrick 1998; Bewley 2009). Second, information gaps and data quality problems make developing CGE models difficult (Feng and Babcock 2010). As well, CGE models tends to overestimate the influence of biofuels on agricultural markets (Thaeripour and Tyner 2007).

PE models can simulate detailed production chains, need little data to be able to represent as-yet nonexistent markets, allow exploration of new latent technologies, and permits comprehensive GHG accounting (Latta *et al.* 2013). Furthermore, they excel at integrating engineering, geography, and economics to predict bioenergy usage and capture regional economic and environmental effects (Kretschmer and Peterson 2010; Okoro *et al.* 2018). PE models come with two drawbacks. PE models exclude linkages to markets not represented in the model (Kretschmer and Peterson 2010), and lack of competition for land (Kretschmer and Peterson 2010). In sum, we judge a PE approach is more suitable for this research than a CGE model because CGE models exhibit lower price swings and greater supply responses than PE models (Kretschmer and Peterson 2010). We also overcome one of the limitations of PE models by incorporating competing land uses between rainforests and oil palm plantations.

3. Methodology

Methodology comprises three sections: the first provides an overview of the PE model, the second covers bioelectricity generation and costs in detail, and the third describes data sources.

3.1. Model Description

We develop a PE model called the Malaysian Agriculture and Plantation Greenhouse Gas Model (MAPGEM). Details of the model are explained so that researchers can adapt it for use in other countries. We assume Malaysia represents a large country that influences market prices for key items. As Figure 1 shows, domestic consumption and exports drive demands in the model for commodities that agricultural producers supply via detailed production chains. Consequently, consumer demand for commodities leads to derived demand for resources such as land, labor and fertilizer as producers manufacture commodities.

MAPGEM is coded in the General Algebraic Modeling System (GAMS) and comprises of 29 blocks of equations. The inverse Marshallian demand and supply functions are constant elasticity. The demands originate from domestic consumption and exports while the supply comes from imports and resource supply markets. We assume Malaysia trades with the rest of the world as one homogenous block. Equation (1) shows the export inverse demand function, where the export price (P^E) of commodity i at time t depends on exports (E) and population. A growing world population forecast (POP) from the Department of Economic and Social Affairs (2015) raises both the demand and price over time. Thus, the model predicts market prices and quantities between 2020 and 2065 in five-year increments. The parameters, b and c, are derived from elasticities with parameter a calibrated for the base year, 2015. The export demand includes a duty and a sales and services tax (SST). The inverse demand functions for domestic consumption shares a similar construction. The commodities include banana, banana residue, cocoa bean, coconut, coconut husk, durian, empty fruit bunches (EFB), kenaf, latex, mango, methane, palm biodiesel, palm fiber, palm frond, palm kernel cake, palm kernel oil, palm oil, palm shell, papaya, pepper, palm fatty acid distillates (PFAD), pineapple, pineapple waste, palm oil mill effluents (POME), rambutan, rice, rice husk, rice straw, and yellow grease.

$$P_{i,t}^{E}\left(E_{i,t}\right) = a_i E_{i,t}^{b_i} POP_t^{c_i}(1 + duty)(1 + SST) \tag{1}$$

Equation (2) illustrates the import (I) inverse supply function. Parameter b is derived from the import supply elasticity while parameter a is calibrated for the base year 2015.

$$P_{i,t}^{I}\left(I_{i,t}\right) = a_i I_{i,t}^{b_i}(1 + duty)(1 + GST) \tag{2}$$

Equation (3) shows the objective function (OF), whereas the MINOS solver in GAMS finds the market quantities and prices that maximize the discounted consumers' plus producers' surpluses. Even though the integral is easy to solve, the integral allows the equation to be written succinctly. The asterisks, *, indicates the optimal values to maximize the objective function given domestic consumption (C), exports (E), imports (I), and resources used (RU). Figure 1 shows the domestic consumption, exports, and imports on the right side and supply of resources on the left. Other terms include growing and harvesting costs, processing costs from the three Leontief production functions, transportation costs, subsidy revenue, bioelectricity revenue, and carbon taxes. Revenues, of course, are positive while costs are negative. Terminal conditions (TC) place a value on newly planted oil palms, yielding zero fresh fruit bunches (FFB), in the last time period, denoted by T. Finally, δ is the discount.

$$OF = \left(1+\frac{\delta}{100}\right)^{-5t-5} \sum_t \left[\sum_i \left[\int_0^{C*} P_{i,t}^C(C_{i,t}) dC_{i,t} + \int_0^{E*} P_{i,t}^E(E_{i,t}) dE_{i,t} - \int_0^{I*} P_{i,t}^I(I_{i,t}) dI_{i,t} \right] \right.$$
$$\left. - \sum_s \sum_r \int_0^{RU*} P_{r,s,t}^{RU}(RU_{r,s,t}) dRU_{r,s,t} + other\ terms \right] + \left(1+\frac{\delta}{100}\right)^{-5T-5} TC \quad (3)$$

Equation (4) ensures the domestic consumption (C) and exports (E) cannot exceed total imports (I) and domestic production (DP). The literature does not provide enough details to allow each Malaysian state to have its own domestic consumption, export, and import functions. However, the literature provides enough detail to allow each state to differ in growing costs, resource usage, crop yields, and land use. Notably, Malaysia has thirteen states: Johor, Kedah, Kelantan, Melaka, Negeri Sembilan, Pahang, Penang, Perak, Perlis, Selangor, and Terengganu on the peninsula and Sabah and Sarawak located on Borneo.

$$C_{i,t} + E_{i,t} \leq I_{i,t} + \textstyle\sum_s DP_{i,s,t} \quad (4)$$

Farmers and landowners harvest the crops and plantations and haul them to the processing mills. The processing mills are Leontief multi-input and multi-output production functions. Figure 1 shows the plantations and crops have their own production functions. Equation (5) shows the input, while (6) shows the output for plantations. The manufacturing input (MI) and manufacturing output (MO) are the ratios of input and output for one process while processing input (PI) shows the tonnes of harvest input allocated for each process. Plantation products have six processes, such as processing fresh fruit bunches (FFB) from oil palms, manufacturing of palm biodiesel, yellow grease collection, rubber processing, cocoa processing, and coconut processing. The variable hectares (H) holds the land for the plantation trees, plantation yield (PY) indicates the harvest from one hectare of land, while the matrix (COM) combines the FFB from five-year-old and 10-year-old oil palm trees. The output becomes available to domestic consumption and exports via domestic production (DP) or transferred (T) to the Leontief production functions for bioelectricity. The subscripts P, P1, and PP stand for plantation type, an alias of plantation type, and plantation products. The crops have an identical Leontief production function with nine processes.

$$\sum_{process} MI_{process,p} \cdot PI_{process,s,t} \leq \sum_{p1} COM_{p,p1} \cdot PY_{p1,s} \cdot H_{p1,s,t} \ \forall\, process, s, t \qquad (5)$$

$$\sum_{process} MO_{process,p} \cdot PI_{process,s,t} = DP_{pp,s,t} + T_{pp,s,t} \ \forall\, pp, s, t \qquad (6)$$

We assume plantation landowners maximize profits and have perfect foresight for future prices and costs. In the model, we split agriculture into two because plantation owners have converted land from cocoa, coconut, rainforest, and rubber crops to oil palms (Kamalrudin and Abdullah 2014). Once they plant oil palms, the land remains dedicated to oil palms for the life of the model. We find no evidence that landowners convert land from oil palms to other agricultural uses as oil palms are profitable. Oil palms yield the highest quantity of edible oil per hectare compared to soybean and rapeseed, and also yield palm kernel oil, palm kernel meal, and PFAD as additional commodities. The remaining agriculture land is used to grow crops including banana, durian, kenaf, mango, papaya, pepper, pineapple, rambutan, and rice.

Equations (7) – (9) represent three growing phases of the oil palm in hectares (H) and reflect fresh fruit bunch (FFB) yield. Equation (7) takes the land away from cocoa, coconut, rainforest, and rubber and plants oil palms via the land conversion variable (CN). Newly planted oil palms yield zero FFB. Equation (8) represents five-year-old palms and yield 53.85% of FFB compared to mature oil palms (Michael 2012). Finally, (9) reflects ten-year-old and older oil palm trees as FFB yield holds steady for 25 years. Then FFB begins declining. We assume the oil palm trees are uniformly distributed in age, and landowners replant 1/30 of their mature oil palms to maintain high FFB yields, and (10) shows the replanting. The oil palm trunks become available as waste biomass. Finally, the $\phi()$ is an indicator function that loads the tree inventory (TI) in 2015 (t = 1) and then the equations become dynamic for 2020 and later (t > 1).

$$H_{oil\ palm\ 0y,s,t} = \sum_p CN_{p,s,t} + RT_{s,t}\ \forall\ s,t \tag{7}$$

$$H_{oil\ palm\ 5y,s,t} = TI_{oil\ palm\ 5y,s} \cdot \emptyset(t=1) + H_{oil\ palm\ 0y,s,t-1} \cdot \emptyset(t>1)\ \forall\ s,t \tag{8}$$

$$H_{oil\ palm\ 10y,s,t} = TI_{s,oil\ palm\ 10y,s} \cdot \emptyset(t=1) + H_{oil\ palm\ 10y,s,t-1} \cdot \emptyset(t>1) + H_{oil\ palm\ 5y,s,t-1} \cdot \emptyset(t>1) - RT_{s,t}\ \forall\ s,t \tag{9}$$

$$RT_{s,t} = \frac{1}{30} H_{oil\ palm\ 10y,s,t}\ \forall\ s,t \tag{10}$$

Equations (11) – (14) represent cocoa, coconut, forest, and rubber trees. The equations are dynamic for 2020 and later (T > 1) and load the tree inventory (TI) in 2015 (t = 1). The plantations can lose land via the land conversion (CN).

$$H_{cocoa,s,t} = TI_{cocoa,s} \cdot \emptyset(t=1) + H_{cocoa,s,t-1} \cdot \emptyset(t>1) - CN_{cocoa,s,t-1} \cdot \emptyset(t>1)\ \forall\ s,t \tag{11}$$

$$H_{coconut,s,t} = TI_{coconut,s} \cdot \emptyset(t=1) + H_{coconut,s,t-1} \cdot \emptyset(t>1) - CN_{coconut,s,t-1} \cdot \emptyset(t>1)\ \forall\ s,t \tag{12}$$

$$H_{forest,s,t} = TI_{forest,s} \cdot \emptyset(t=1) + H_{forest,s,t-1} \cdot \emptyset(t>1) - CN_{forest,s,t-1} \cdot \emptyset(t>1)\ \forall\ s,t \tag{13}$$

$$H_{rubber,s,t} = TI_{rubber,s} \cdot \emptyset(t=1) + H_{rubber,s,t-1} \cdot \emptyset(t>1) - CN_{rubber,s,t-1} \cdot \emptyset(t>1)\ \forall\ s,t \tag{14}$$

Farmers grow crops to maximize their profits. They plant crops in any combination until they have utilized all the available land in each state. Cropland remains the same area at 446,929 hectares because Malaysian agriculture has experienced no expansion in land use except the oil palms (Economic Planning Unit 2001). In addition, MAPGEM imposes land constraints on crops in 2015 that broadens the restrictions over time, so the crop statistics match the national crop statistics from the Ministry of Agriculture and Agro-Based Industry (2015). Farmers can grow any combination of crops on cropland (CL), as shown in Equation (15) until they have used up all available land (AL) in each state (s).

$$\sum_c CL_{t,s,c} \leq AL_s \; \forall \; s, t \tag{15}$$

The growing, cultivating, and harvesting of the crops and plantations require resources (r) such as labor, nitrogen, phosphorus, and potash. The model does not restrict the use of resources per se, but a higher derived demand for a particular resource in a state induces a greater quantity supplied and thus raises the resource price. Equation (16) imposes the supply of resources used (RU) must equal or exceed the resources used to cultivate plantation (p) trees in hectares (H) and crops (c) in cropland (CL). The matrices, plantation resources (PR) and crop resource (CR), hold the coefficients for per hectare resource usage. Subscript s denotes the state.

$$\sum_p H_{p,s,t} \cdot PR_{p,s,r} + \sum_c CL_{c,s,t} \cdot CR_{c,s,r} \leq RU_{r,s,t} \; \forall \; r, s, t \tag{16}$$

Equation (16) is the inverse supply of resources used (RU) and is incorporated into the objective function in (3). The resource price (P) of labor starts at RM20,809.36 per year for one worker in 2015 (Prices Income and Expenditure Statistics Division 2014) while one tonne of fertilizer (containing nitrogen, phosphorus, and potash) begins at RM1,178.85 (Sabri 2009). Higher demand for resources in a particular state can raise resource prices. The parameter e is calculated for the base year 2015 while parameter d is derived from price elasticities of supply.

$$P_{r,s,t}(RU_{r,s,t}) = e_{r,s} RU_{r,s,t}^{d_{r,s}} \tag{17}$$

This paper only illustrates a handful of equations because of the size of the model. Supplemental equations impose production capacities, allow the analysis of government policies, track GHG emissions, and impose quantity constraints.

3.2. Bioelectricity Production Coefficients and Costs

Palm oil mills can annex the capital needed to generate bioelectricity using four technologies. Table 1 provides the bioelectricity production coefficients and costs for the technologies. For the first technology, the mill employs direct combustion to burn the waste. Direct combustion is the standard technology where biomass is burned to generate heat that converts water into steam. Then the steam turns a turbine-generator. For example, one tonne of oil palm fiber with 37.09% moisture content generates 923.23 kWh of power. We assume the mills use the residual heat to remove the moisture from the biomass and incurs cost of RM0.3080 per kWh, as shown in Table 1.

For the second technology, the mills use IGCC, a latent technology. The biomass is heated and releases a hydrocarbon gas. Once the gas is combusted, the heat and pressure directly turn a turbine-generator. Meanwhile, the residue heat converts water to steam that turns a second turbine-generator. The IGCC has greater energy conversion efficiency but entails greater operating and capital costs. The mills incur cost of RM0.5097 per kWh. We find no studies that implement integrated gasification combined cycle (IGCC) in the economic literature. Consequently, MAPGEM has 10 biomass feedstocks with two technologies that yield 20 processes for the bioelectricity Leontief production function.

The last two technologies deal with methane emitted from palm oil mill effluents (POME), wastewater from FFB processing. Microorganisms in the ponds consume the organic waste and emit methane, a hydrocarbon gas. Since methane is a potent GHG, the mills can improve their GHG efficiency by collecting, storing, and utilizing the methane to generate bioelectricity. Nevertheless, gas collection and storage increase the capital and operating costs. Direct combustion of one tonne of methane generates 4,279.45 kWh and costs RM0.3944 per kWh while the natural gas combined cycle (NGCC) generates 5,716.24 kWh per tonne of methane and costs

RM0.6626 per kWh. Methane is included by adding two additional processes to the bioelectricity Leontief production function. Table 1 shows the RM and USD equivalent costs.

3.3. Data Sources

MAPGEM contains a large number of demand and supply elasticities, production coefficients, prices, costs, and GHG coefficients from a range of sources. Those sources include:

- The price elasticity of demand, exports, imports, and population are derived from the research literature for Malaysia such as Jafari *et al.* (2017), Kochaphum *et al.* (2015), Sheng *et al.* (2008), and Talib and Darawi (2002).
- The inverse demand and supply functions are calculated for prices and quantities from the Food and Agriculture Organization of the United Nations (2013), Department of Statistics (2016), Department of Statistics (2016), Statistics Unit (2011; Statistics Unit 2012; Statistics Unit 2013; Statistics Unit 2014; Statistics Unit 2015), and Wahab (2016).
- Land use for crops and plantations originate from Economics & Industry Development Division (2015), Ghani (2016), Ministry of Agriculture and Agro-Based Industry (2015), Ministry of Plantation Industries and Commodities (2015), Ministry of Plantation Industries and Commodities (2015), Ministry of Plantation Industries and Commodities (2015), the Statistics Unit (2015).
- Growing costs and labor intensity come from Abdelrhman *et al.* (2016), Azhar and Lee (2004), Department of Agriculture (2015), George *et al.* (2005), Malaysian Rubber Board (2009), and Wah (1998).
- Food and Agriculture Organization (2004) supplies fertilizer applications at the state level.

- GHG emission data are from Henson (2009), Ginoga *et al.* (2005), Maggiotto *et al.* (2014), Pehnelt and Vietze (2013), Selvaraj *et al.* (2016), and Turner and Gillbanks (2003).
- The production coefficients for bioelectricity are derived from energy balance equations.

The numerous sources prevent the entire listing of all model references in this paper. The authors, upon request, can provide an e-book that explains the detailed construction and source code of MAPGEM.

4. Results and Discussion

In this section, we present results for the economic feasibility of electricity generated from biomass and include the most relevant, insightful variables such as GHG savings, agricultural prices, agricultural employment, and deforestation.

4.1. The Economic Feasibility of Bioelectricity

The results of MAPGEM suggest Malaysian agriculture generates substantial levels of waste biomass. The palm oil mills process 965,660,000 tonnes of FFB in 2015 and extracted 18,821,960 tonnes of palm oil from the fibers that surround the palm kernel. Then the mills crush the kernels to extract 2,433,470 tonnes of palm kernel oil, which created 3,360,500 tonnes of palm kernel cake. The mills sell the palm kernel cake to the animal feed industry because it contains a high level of protein. Moreover, the mills produced 463,370 tonnes of palm biodiesel which supplied the national biodiesel mandate and exported the surplus. Finally, the mills created 965,660 tonnes of palm fatty acid distillates (PFAD), a chemical byproduct of palm oil refining that the mills sell to the oleochemical industry.

As Table 2 shows, Malaysia's agriculture produced 38,839 million tonnes of dry waste biomass with the oil palm sector producing the bulk. The processing of FFB leaves behind 21,244,600 tonnes of EFB, 13,036,400 tonnes of palm fiber, and 5,311,100 tonnes of palm shells. By using waste biomass to generate bioelectricity on site, mills can avoid high hauling costs of the bulky biomass to power plants for co-firing with coal and natural gas (Evans *et al.* 2010). Furthermore, landowners are always weeding and maintaining the oil palms, so the cost would be minimal to collect the 55,235,900 tonnes of palm fronds in 2015. The plantations cut down and replace mature oil palm trees and create 1,411,800 tonnes of oil palm trunks. The mills pay RM100 per tonne (or USD25.61) to haul the leftover oil palm trunks to the mills. Mills can also utilize banana wastes, coconut husks, pineapple wastes, rice husks, and rice straw to generate electricity and pay the farmers RM264.26 per tonne (67.69 USD) to collect and haul the biomass (Maung and McCarl 2013).

Every electrical generation system is organized whereby electric companies use long-term generation facilities to satisfy the base demand. Then electric companies quickly start up (shut down) generating facilities to meet peak demand. Bioelectricity mills generate electricity and deliver the power via power lines connected to the national grid. We estimate, on average, the mills are located 23.035 km from the national grid (Umar *et al.* 2013) for all the states and pay RM 0.000040525 per kWh-km for operating and capital costs for the power lines (Kumar *et al.* 2003). We assume every kilowatt-hour the mill supplies to the national grid is offset by electricity companies reducing their power generation. Consequently, the mills receive revenue via the feed-in tariffs set by the Malaysian government.

Table 3 reports the quantity of bioelectricity the palm oil industry can supply for electricity tariffs of RM0.20, RM0.40, RM0.60, and RM0.80 per kWh or in USD, \$0.051, \$0.102, \$0.154, and \$0.205 per kWh. We choose the range of RM0.20-0.80 because the commercial electricity price was RM0.38 per kWh in 2017 (Tenaga Nasional Berhad 2017).

The first row of Table 3 shows that palm oil mills are unable to generate/produce bioelectricity at RM0.20 since the operating and capital costs are RM0.3101 per kWh. If the government sets the tariff to RM0.40 per kWh, the palm oil mills use direct combustion to generate 55.262 billion kWh in 2020 which increases to 63.671 billion kWh in 2065. Thus, waste biomass can supply a significant portion of Malaysia's electricity production since Malaysia consumed about 154.3 billion kWh in 2015 (Suruhanjaya Tenaga 2016). Consequently, bioelectricity can displace electricity generated from coal and natural gas and would extend Malaysia's natural gas and coal reserves because Malaysia has approximately 52 years of natural gas reserves and 64 years of coal reserves remaining (Muda and Pin 2012).

The palm oil mills utilize only the biomass created onsite as they avoid paying for hauling costs to bring additional biomass from outside the mills. Prior research has found biomass-generated electricity cannot compete with its fossil fuel counterparts (see Evans, Strezov et al. (2010), Maung and McCarl (2013), and McCarl, Adams et al. (2000)). Malaysia as the second largest palm oil producer, has vast reserves of waste biomass that the palm oil mills can use without incurring additional haulage costs to generate cost-competitive bioelectricity, which is not the case in other countries, e.g., the United States.

Economic theory suggests that if government sets a higher electricity tariff mills would boost bioelectricity generation by accessing new sources of biomass or implementation of more efficient generation technologies, or both. At RM0.60 per kWh, the palm oil mills increase bioelectricity production to 61.570 billion kWh in 2020 that grows to 82.503 billion kWh in 2065. The mills pay the hauling cost for rice straw and rice husk and implement technology to collect and burn the methane from POME. Accordingly, the government could set the tariff to RM0.60 per kWh to encourage the palm oil mills to improve their GHG efficiency. For example, the mills collect 841.94 tonnes of methane in 2030. If released, the methane would contribute 21.0 million tonnes of carbon dioxide equivalent emissions but, when combusted, the CO2-eq. emissions drop to 1.90 million tonnes. Finally, if the government sets tariffs to RM0.80 per kWh, the palm oil mills upgrade to the IGCC technology for waste biomass that further boosts bioelectricity generation. The mills never utilize the INCC because of the high operating and capital costs.

For reader's convenience, we present the results of Table 3 graphically in Figure 2. The graph shows that bioelectricity production increases over time as the oil palm plantations expand. In sum, our results indicate the government should set the electricity tariff to RM0.40 to encourage the palm oil mills to generate bioelectricity. The government would need to ensure the feed-in tariff would not cause hardship for the electric power companies since the companies pay the tariffs. The government could set the tariff higher to improve the GHG efficiency of the palm oil industry but higher tariffs could impose economic hardship on the electric power companies.

4.2. Greenhouse Gas Savings

The Malaysian government signed the Paris Agreement on 5 October 2016 and pledged to cut greenhouse gas emissions (GHG) by 45% by 2030 relative to its 2005 levels (Begum 2017). The Malaysian government needs to identify cost effective strategies to meet its obligation, and bioelectricity generation can help. Table 4 shows the savings in carbon dioxide equivalent (CO_2-eq) emissions that bioelectricity can recycle while Figure 3 plots the results for the reader's convenience. The second row of Table 4 shows that the production of bioelectricity at a price of RM0.40 per kWh can offset 47.2 million tonnes of CO_2-eq emissions in 2030. Furthermore, the Malaysian energy sector emitted 218.914 million tonnes of CO2-eq in 2011 (Ministry of Natural

Resources And Environment Malaysia 2015). Although we would expect the emission of the energy sector to keep rising, bioelectricity provides a large offset.

If the government sets the feed-in tariff to a higher price such as RM0.60 or RM0.80, the palm oil mills produce more bioelectricity and, thus, raise the GHG offset. However, the high tariffs may impose hardship on the electric power industry. The government should maintain a tariff close to the commercial price of electricity in Malaysia. Consequently, bioelectricity production can help the nation to mitigate a considerable amount of GHG emissions that will enable Malaysia to meet its commitment in the Paris Agreement to reduce its carbon footprint.

4.3. Impact on Agricultural Prices

Economic theory suggests that the palm oil mills would create a derived demand for waste biomass as the mills supply electricity to the national grid. Table 5 shows the Fisher domestic price index for the agricultural sector based on the electricity prices of RM0.20, RM0.40, RM0.60, and RM0.80. The Year 2015 serves as the base year and sets the Fisher domestic index price to 100. All prices and costs are deflated to 2015, so any change in price originates from changing demand and supply functions. For the price of RM0.20, the first row in Table 5 shows the decline in agricultural prices as Malaysia produces zero bioelectricity from the biomass. The model predicts falling prices as the agricultural supply of commodities is increasing relatively faster than rising demands from a growing population. We plot the Fisher Index in Figure 4 for the reader's convenience. The figure indicates that the Fisher domestic price index decreases to 94.1 in 2065 at the price of RM0.40 per kWh as mills generate bioelectricity.

The mills have an economic incentive to expand oil palm plantations in order to increase the derived demand for biomass and, hence, generate more electricity to supply to the national grid. The expansion of the oil palms leads to decreasing prices for palm oil products as palm oil mills supply more palm oil, palm kernel oil, palm kernel cake, and PFAD commodities. Although the Malaysian government may not set electricity tariffs to RM0.60 and RM0.80, the oil palm plantations expand and produce more commodities that reduce the price index further. In sum, a thriving bioelectricity industry from biomass may expand the agricultural sector to generate more waste biomass to generate additional bioelectricity.

4.4. Impact on Agricultural Employment

A thriving bioelectricity industry leads to a derived demand for both waste biomass and resources such as agricultural employment. Table 6 shows the total number of workers employed in the agriculture and plantation sectors. The first row shows that agriculture industry employs 1.035 million workers in 2020. The number of workers holds steady from 2020 to 2065, which excludes the economic impact of biomass-generated electricity. However, the aggregate number of workers increases with bioelectricity production from biomass since the palm oil mills expand the oil palm plantations as increased bioelectricity generation leads to greater derived demand for both biomass and resources. For example, the total number of workers employed in agriculture industry rises to 1.052 million in 2020 at the electricity price of RM0.40 per kWh with further increases for RM0.60 and RM0.80 prices. For the reader's convenience, we present the results of Table 6 graphically in Figure 5. The level of agricultural employment becomes flat after 2030 because the contraction of rice farming nullifies the gain in employment in other agricultural sectors. The contraction of the rice industry flows from higher growing costs since the expansion of the oil palms increases labor wages and fertilizer prices from the greater derived demand. Our results agree with Thornley, Rogers et al. (2008) and Elbehri, Segerstedt et al. (2013) that biomass can boost agricultural employment in rural areas.

4.5. Deforestation

The spillover effects of expanding oil palm plantations leads to deforestation and the amount of carbon the trees can sequester falls because the palm oil mills require an increasing source of waste biomass to generate bioelectricity. Table 7 shows the loss of rainforests as landowners convert forests into oil palm plantations. The first row of Table 7 indicates that the oil palm plantations increase by 807.40 thousand hectares between 2015 and 2065 as the palm oil industry expands to satisfy rising demand, even without considering the use of palm oil for electricity. In contrast, the oil palm plantations expand about 1.00, 1.50, and 2.00 million hectares, when biomass from palm oil is used to generate electricity at prices of RM0.40, 0.60, and 0.80, respectively. For the reader's convenience, we present the results of Table 7 graphically in Figure 6 which shows most of the land transfers occur within 20 years, i.e., from 2020 to 2040 and begins slowing after that. Consequently, if government set the electricity tariff to RM0.40 per kWh that could increase deforestation by an additional 231.7 thousand hectare.

The deforestation impacts the carbon credit that the Malaysian government can claim. For example, the nation claimed a carbon credit of 262.946 million tonnes of CO_2-eq from forests in 2005 (Ministry of Natural Resources And Environment Malaysia 2015). As landowners clear rainforests to plant oil palm trees, they will reduce the aggregate forest carbon credit. For instance, one hectare of rainforest stores about 9.33610 tonnes of carbon dioxide per year (Food and Agriculture Organization of the United Nations 2015) while oil palm trees remove 4.00 tonnes per hectare per year (Henson 2009). Table 7, Panel B shows the carbon storage potential of the plantation trees. For a bioelectricity price of RM0.20, the model estimates the plantation trees store 225.65 million tonnes of CO_2-eq. in 2030 compared to 224.59 million tonnes of CO2-eq. for RM0.40. The Malaysian government would need to determine the economic value of the loss of

1.06 million tonnes of carbon storage of the forests for bioelectricity generation. Nevertheless, the results show the GHG gains from bioelectricity significantly exceed the loss of GHG credit resulting from deforestation.

5. Conclusion and Policy Implications

In this paper, we have developed MAPGEM to investigate the economic feasibility of bioelectricity production from waste biomass in Malaysia and also examine potential impacts on GHG savings, agricultural prices and employment, and deforestation. Our results show the strong potential for Malaysia to produce a significant amount of bioelectricity from biomass if the Malaysian government sets the electricity tariff to RM0.40 per kWh. Thus, using biomass to produce bioelectricity on a large scale will not only extend the life of fossil fuels in Malaysia but will also reduce a considerable amount of GHG emissions that aids the government to meet its commitment in the Paris Agreement to reduce GHG emissions. Our results also show that the use of biomass to generate electricity leads to lower agricultural prices as the bioelectricity industry expands the agricultural sector and helps Malaysia to reduce rural unemployment. However, our results show that biomass-generated electricity leads to some deforestation and a slight loss of carbon storage from altering the forest cover. Nonetheless, our results show that the deforestation does not increase aggregate GHG emissions since GHG gains from bioelectricity significantly exceed GHG losses from deforestation.

Our results and modeling have significant implications for policymakers, business, and researchers. The policymakers of not only Malaysia, but also other countries with vast reserves of biomass, can implement policies to encourage the use of waste biomass to generate bioelectricity that will not only help to reduce GHG emissions but will also extend the life of fossil fuel reserves of those countries. Businesses can consider making investments to generate bioelectricity from biomass since our results show that the cost of generating and supplying bioelectricity from biomass is at par with electricity that is produced from fossil fuels in Malaysia. Our results provide an exciting research avenue for researchers since previous studies have restricted technologies to generate bioelectricity while our research incorporates several technologies to determine which technology mix provides the best prospects for biomass utilization. Our model provides an excellent opportunity for researchers to analyze other forms of renewable energy such as biodiesel, bioethanol, and biobutanol, or study the economic impact of carbon taxes and biosecurity issues.

Acknowledgement

The construction of MAPGEM was supported by the Ministry of Higher Education (MOHE) Malaysia [grants FRGS/1/2016/SS08/CURTIN/02/1 and FRGS/1/2017/SS08/CURTIN/02/1].

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Figure 1. MAPGEM Overview

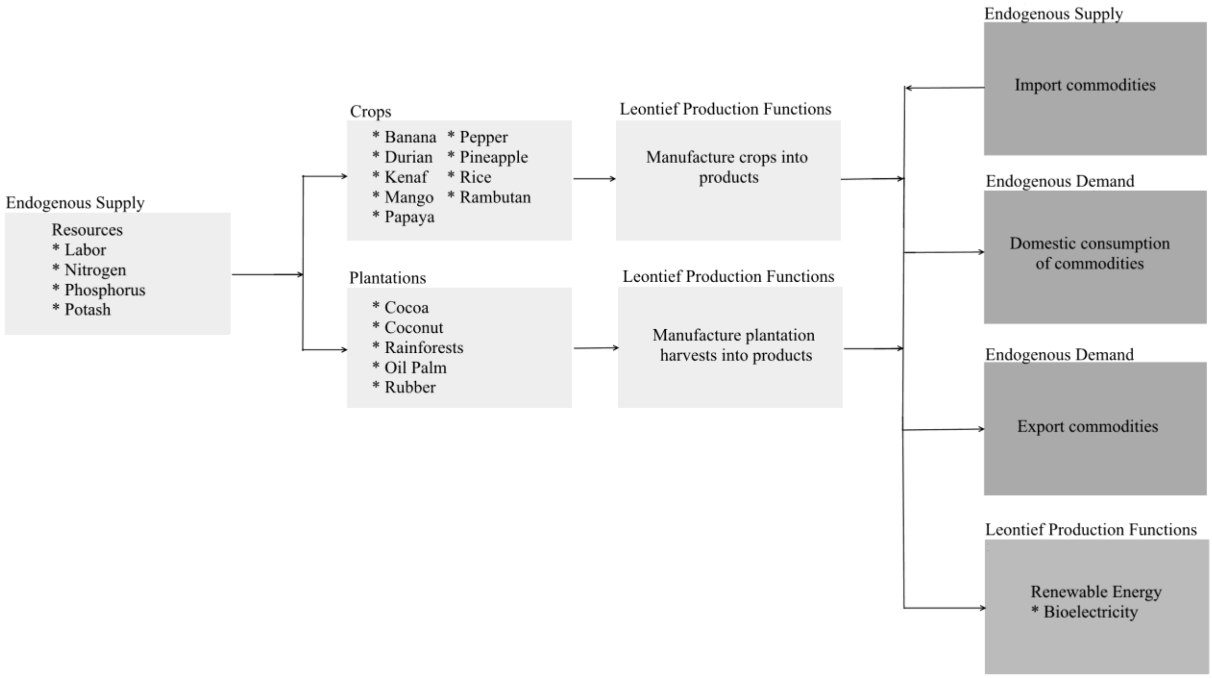
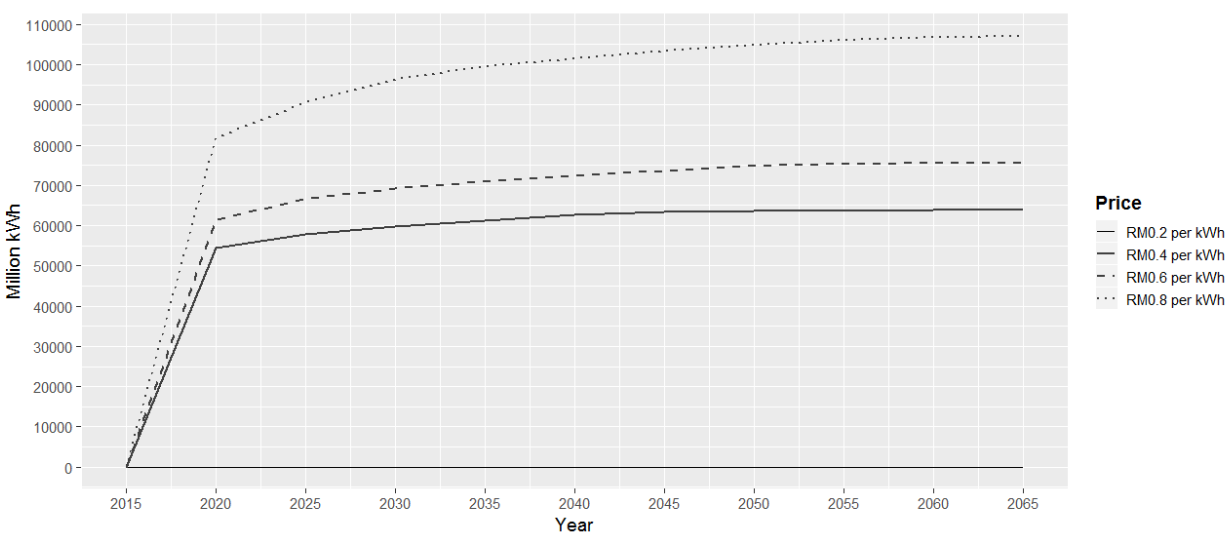
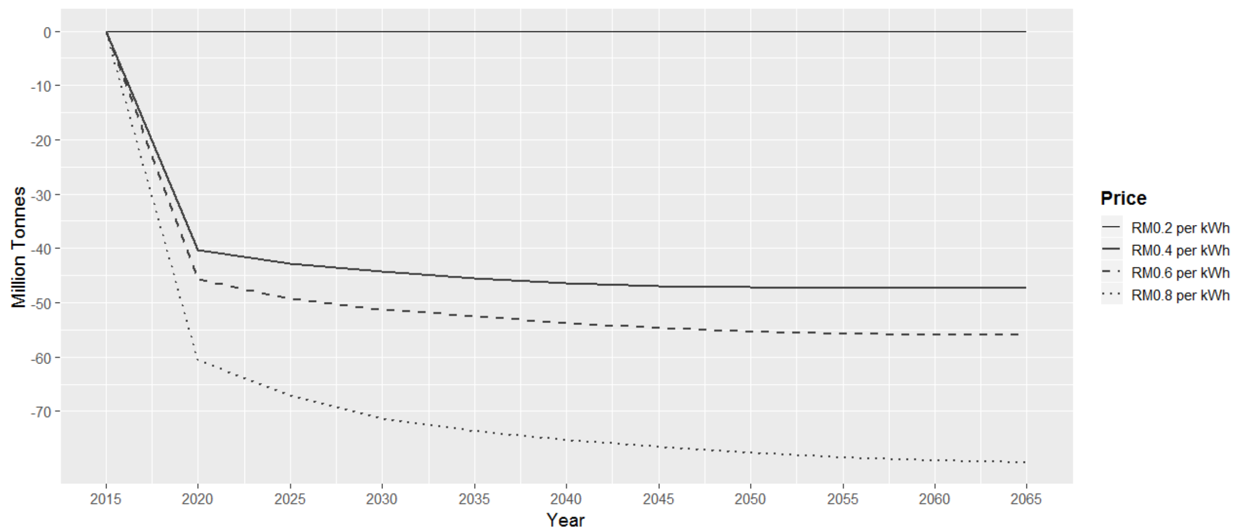


Figure 2. Aggregate Bioelectricity Production (million kWh)



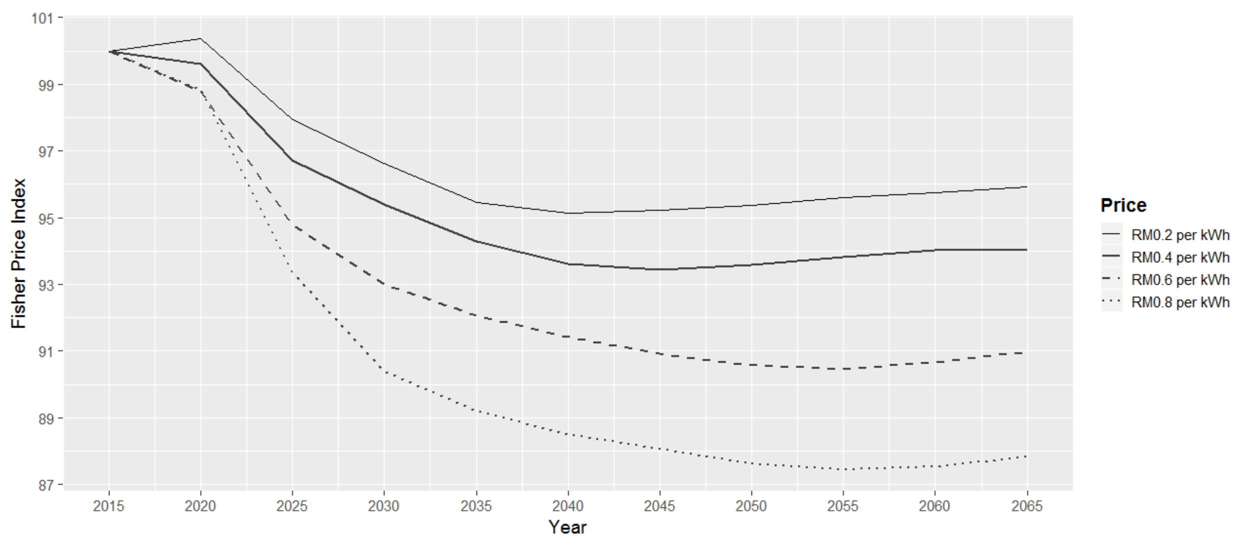
See Table 3 for details.

Figure 3. Carbon Dioxide Equivalent Emissions from Bioelectricity (million tonnes)



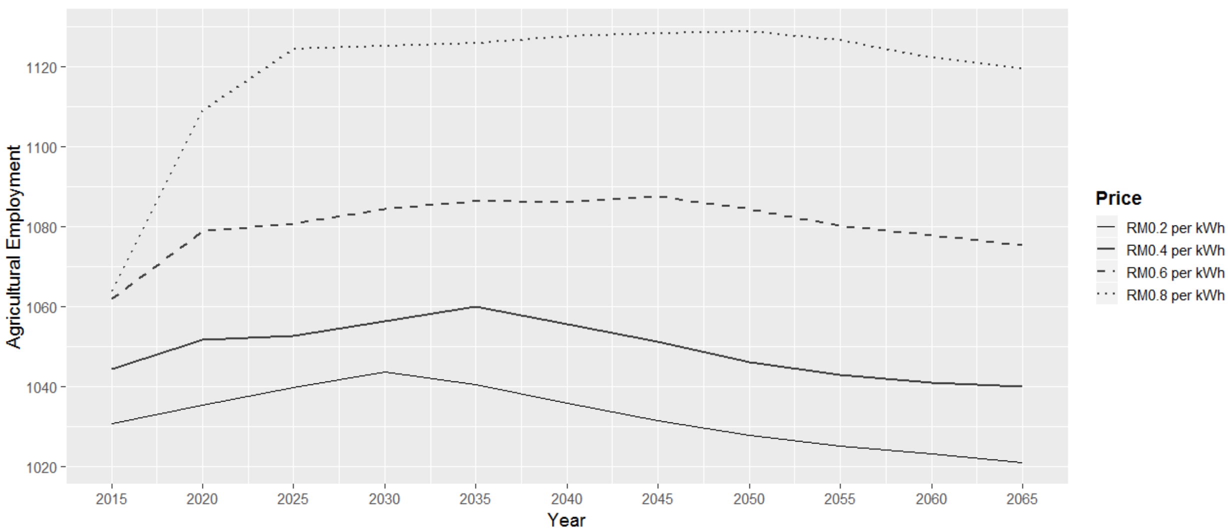
See Table 4 for details.

Figure 4. Fisher Domestic Price Index



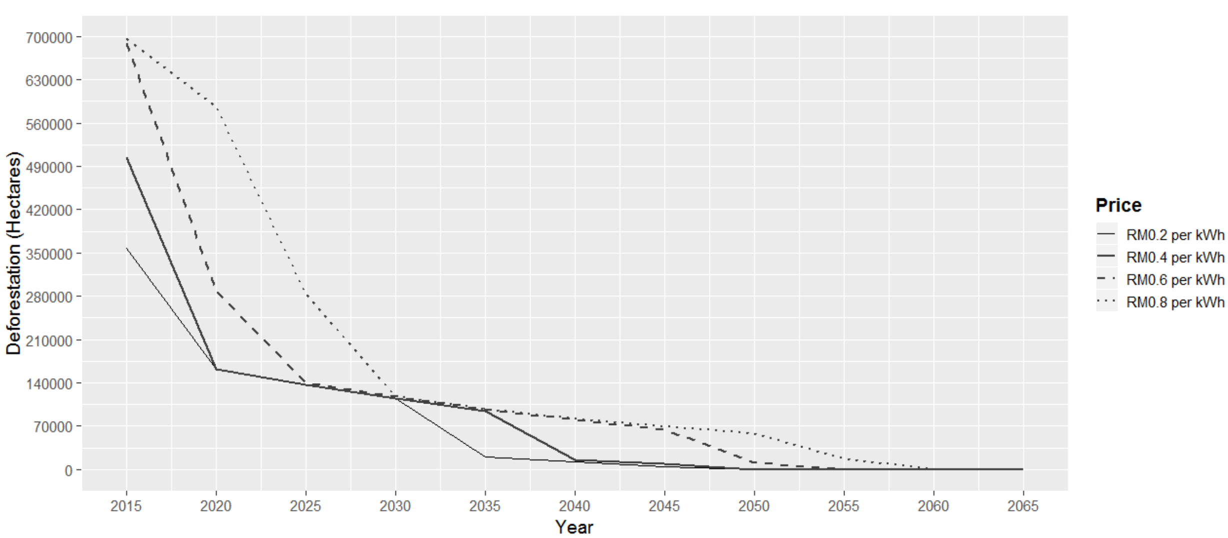
See Table 5 for details.

Figure 5. Labor Employed in Agriculture (workers)



See Table 6 for details.

Figure 6. Aggregate Deforestation (hectares)



See Table 7 for details.

Table 1. Bioelectricity Production Coefficients and Costs

Biomass	Feedstock Source	Moisture Content %	Biomass Direct Fired kWh / tonne	Biomass Direct Fired kWh / tonne	IGCC kWh / tonne	INCCn kWh / tonne
Banana residues	Banana	10.70	1,259.13	-	1,571.68	-
Coconut husk	Coconut	11.50	1,247.85	-	1,557.60	-
EFB	FFB	67.00	479.72	-	640.78	-
Methane	POME	~	-	4,279.45	-	5,716.24
Oil palm fibers	FFB	37.09	923.23	-	1,233.20	-
Oil palm fronds	FFB	70.60	355.85	-	475.32	-
Oil palm shells	FFB	12.00	1,361.23	-	1,818.24	-
Oil palm trunk	Replant	75.60	328.21		438.40	
Pineapple waste	Pineapple	61.20	547.08	-	682.88	-
Rice husk	Paddy	9.00	1,283.10	-	1,601.60	-
Rice straw	Paddy	11.00	1,254.90	-	1,566.40	-
Costs						
RM per kWh			0.3080	0.3944	0.5097	0.6626
USD per kWh			0.0789	0.1010	0.1306	0.1697

Sources: The moisture content and electricity production coefficients are derived from Loh (2017). Ma *et al.* (1994) cites Chua (1993), Maung and McCarl (2013), National Renewable Energy Laboratory (2005), and Soom *et al.* (2006). We derive operating and capital costs from Kumar, Cameron et al. (2003), Kumar *et al.* (2010), Delivand *et al.* (2011), International Renewable Energy Agency (2012),. Upadhyay *et al.* (2012), and Yagi and Nakata (2011).

Table 2. Aggregate Waste Biomass Production (1,000 tonnes)

Waste Biomass	MC	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065
POME		47,584.0	52,105.6	54,845.2	56,606.7	58,105.5	58,946.1	59,291.4	59,502.0	59,577.0	59,597.9	59,610.6
Methane		623.8	683.1	719.0	742.1	761.8	772.8	777.3	780.1	781.0	781.3	781.5
Banana residue	10.7	642.4	645.6	650.1	656.1	663.7	673.0	695.3	729.7	757.7	772.1	787.6
Coconut husk	11.5	195.1	184.5	175.7	168.3	162.0	157.1	152.9	149.4	146.9	144.9	143.3
EFB	67.0	21,244.6	23,263.3	24,486.4	25,272.9	25,942.1	26,317.4	26,471.5	26,565.5	26,599.0	26,608.4	26,614.0
Palm fiber	37.1	13,036.4	14,275.2	15,025.8	15,508.4	15,919.0	16,149.3	16,243.9	16,301.6	16,322.1	16,327.9	16,331.3
Palm frond	70.6	55,235.9	60,484.6	63,664.7	65,709.6	67,449.4	68,425.1	68,826.0	69,070.4	69,157.5	69,181.8	69,196.4
Palm shell	12.0	5,311.1	5,815.8	6,121.6	6,318.2	6,485.5	6,579.3	6,617.9	6,641.4	6,649.8	6,652.1	6,653.5
Palm trunk	75.6	1,411.8	1,546.0	1,627.2	1,679.5	1,724.0	1,748.9	1,759.2	1,765.4	1,767.6	1,768.3	1,768.6
Pineapple waste	61.2	197.6	213.5	225.1	239.7	251.6	263.9	278.2	296.1	315.6	331.6	347.7
Rice husk	9.0	611.7	629.3	635.5	642.9	654.1	661.3	669.8	677.9	687.1	699.4	712.1
Rice straw	11.0	1,112.2	1,144.1	1,155.4	1,169.0	1,189.3	1,202.4	1,217.8	1,232.6	1,249.3	1,271.6	1,294.7
Total (dry mass)		38,839.13	42,348.48	44,464.66	45,838.12	47,021.02	47,692.11	47,999.95	48,216.47	48,327.51	48,391.85	48,452.29

Source: MAPGEM provides the biomass estimates for a bioelectricity price of RM0.20 per kWh because the mills do not utilize biomass at this price. The total dried biomass aggregates all biomass except POME and methane and removes the moisture content (MC).

Table 3. Aggregate Bioelectricity Production (million kWh)

Bioelectricity price	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065
RM0.20 / kWh	0	0	0	0	0	0	0	0	0	0	0
RM0.40 / kWh	0	54,441	57,898	59,780	61,325	62,613	63,330	63,620	63,753	63,777	63,790
RM0.60 / kWh	0	61,569	66,535	69,112	70,923	72,456	73,693	74,682	75,280	75,483	75,579
RM0.80 / kWh	0	81,876	90,485	96,330	99,441	101,533	103,298	104,798	106,035	106,824	107,136

Source: MAPGEM computes the equilibrium market prices and quantities for the four bioelectricity prices in the table. Bioelectricity is aggregated over all states.

Table 4. Carbon Dioxide Equivalent Emissions (million tonnes)

Bioelectricity price	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065
RM0.20 / kWh	0	0	0	0	0	0	0	0	0	0	0
RM0.40 / kWh	0	-40.3	-42.9	-44.3	-45.4	-46.4	-46.9	-47.1	-47.2	-47.3	-47.3
RM0.60 / kWh	0	-45.6	-49.3	-51.2	-52.6	-53.7	-54.6	-55.3	-55.8	-55.9	-56.0
RM0.80 / kWh	0	-60.7	-67.1	-71.4	-73.7	-75.2	-76.5	-77.7	-78.6	-79.2	-79.4

Source: MAPGEM is solved for the four bioelectricity prices in the table. Methane and nitrous oxide are converted to their CO2-eq. using the 100-year global warming potential (GWP). For example, methane has a GWP of 25 while nitrous oxide with 298 (Intergovernmental Panel on Climate Change 2007). Consequently, one tonne of nitrous oxide absorbs the same thermal energy as 298 tonnes of carbon dioxide. All GHG is summed over all gases and states.

Table 5. Fisher Domestic Price Index

Bioelectricity price	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065
RM0.20 / kWh	100.0	100.4	98.0	96.6	95.5	95.1	95.2	95.4	95.6	95.8	95.9
RM0.40 / kWh	100.0	99.6	96.7	95.4	94.3	93.6	93.4	93.6	93.8	94.0	94.1
RM0.60 / kWh	100.0	98.8	94.8	93.0	92.1	91.4	90.9	90.6	90.5	90.7	91.0
RM0.80 / kWh	100.0	98.8	93.4	90.4	89.2	88.5	88.1	87.6	87.5	87.5	87.8

Source: MAPGEM solves for the equilibrium prices and quantities for the four bioelectricity prices in the table. The Fisher price index equals the geometric average of the Laspeyres and Paasche price indices with 2015 as the base year. The agricultural wastes do not contribute to the price index since they have zero prices.

Table 6. Labor Employed in Agriculture (thousand workers)

Bioelectricity price	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065
RM0.20 / kWh	1,031	1,035	1,040	1,044	1,040	1,036	1,031	1,028	1,025	1,023	1,021
RM0.40 / kWh	1,044	1,052	1,053	1,056	1,060	1,055	1,051	1,046	1,043	1,041	1,040
RM0.60 / kWh	1,062	1,079	1,081	1,084	1,086	1,086	1,087	1,084	1,080	1,078	1,075
RM0.80 / kWh	1,064	1,109	1,124	1,125	1,126	1,128	1,128	1,129	1,127	1,122	1,120

Source: MAPGEM is solved for the four bioelectricity prices in the table. The workers are aggregated over all crops, plantations, and states.

Table 7. Panel A. Aggregate Deforestation (hectares)

Bioelectricity price	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065
RM0.20 / kWh	356,901	162,722	136,833	115,062	19,953	11,927	4,015	0	0	0	0
RM0.40 / kWh	504,493	162,722	136,833	115,062	94,752	16,105	8,825	285	0	0	0
RM0.60 / kWh	688,178	287,827	139,335	117,166	97,992	80,711	64,491	10,459	0	0	0
RM0.80 / kWh	697,266	586,329	284,168	117,166	97,992	82,198	69,120	58,123	16,972	0	0

Table 7. Panel B. Plantation CO2-eq Emissions (million tonnes)

Bioelectricity price	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065
RM0.20 / kWh	-230.87	-228.09	-226.76	-225.65	-224.72	-224.35	-224.08	-223.97	-223.95	-223.95	-223.95
RM0.40 / kWh	-230.87	-227.30	-225.69	-224.59	-223.66	-222.89	-222.58	-222.36	-222.34	-222.34	-222.33
RM0.60 / kWh	-230.87	-226.29	-223.96	-222.61	-221.49	-220.55	-219.90	-219.37	-219.16	-219.14	-219.14
RM0.80 / kWh	-230.87	-226.13	-222.12	-219.94	-218.78	-217.82	-217.02	-216.35	-215.88	-215.66	-215.66

Source: MAPGEM computes the equilibrium prices and quantities for the bioelectricity prices in the table. Deforestation are summed over all states, crops, and plantations. Rainforests include forest plantations, inland forests, mangroves, and peat swamps. The plantation CO2-eq emissions are aggregated over plantation trees using the 100-year global warming potential to convert methane and nitrous oxide into their carbon equivalents.