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Review

Solid Fuel from Oil Palm Biomass Residues and Municipal Solid Waste by Hydrothermal Treatment for Electrical Power Generation in Malaysia: A Review

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Abstract: Malaysia generated 156,665 gigawatt-hours (GWh) of electricity in 2016 of which the biggest share of 48.4% was sourced from coal and coke. Malaysia coal consumption was met by 90.5% of imported coal due to high demand from the power sector. Malaysia also has a vast biomass resource that is currently under-utilised for electricity generation. This paper reviews the potential of oil palm residues and municipal solid waste (MSW) for alternative coal replacement employing hydrothermal treatment (HTT). In 2017, about 51.19 million tonnes (Mt) of oil palm waste was available with 888.33 peta-joule (PJ) energy potential to generate 88.03 terawatt-hours (TWh) electricity from oil palm fronds (OPF) and oil palm trunks (OPT), empty fruit bunch (EFB), mesocarp fibre (MF), palm kernel shell (PKS) and palm oil mill effluent (POME). Meanwhile, the MSW energy potential and electricity generation potential was estimated at 86.50 PJ/year and 8.57 TWh/year, respectively. HTT with washing co-treatment eliminates the use of drying for converting range of biomass and MSW into clean solid fuel known as hydrochar. The hydrochar increased in caloric value with lower moisture, Potassium (K) and Chlorine (Cl) contents. These value-added fuels can be used as coal alternative and reduce dependency on imported coal for energy security in Malaysia.

Keywords: solid fuel; energy potential; oil palm residues; municipal solid waste; hydrothermal treatment; renewable energy

1. Introduction

Malaysia is located in the South East Asia region with a total area of 330,345 km^2. The country is separated by the South China Sea into western coast Peninsular Malaysia which made of 11 states and 2 federal territories with area of 131,990 km^2 and the eastern coast of Sarawak and Sabah with an area of 124,451 km^2 and 73,904 km^2, respectively. Out of 32.02 million population in 2017, 79% of them were located in Peninsular Malaysia followed by 12% and 9% in Sabah and Sarawak, respectively. The country has an equatorial climate and is extremely hot and humid almost all year round [1,2]. Malaysia is categorized as a middle-income country with the primary energy supply dependent on fossil fuels. Production of electricity in Peninsular Malaysia, Sarawak and Sabah are monopolized by three (3) largest states-owned utility companies namely Tenaga Nasional Berhad (TNB), Sarawak Energy Berhad (SEB) and Sabah Electricity Sdn. Berhad (SESB) respectively besides independent power producers (IPPs). Peninsular Malaysia shares electricity interconnection systems with Thailand and Singapore and gas pipe link with Thailand, Singapore and Indonesia [3].

The total primary energy supply increased 3.6% to 93,395 ktoe in 2016. The supply from natural gas decreased to 40.7% from 43.6% while the shares from crude oil and petroleum products increased slightly from 32.3% in 2015 to 33.5% in 2016. The share of coal and coke registered a growth at 20.2% compared to 19.3% in 2015 due to strong demand from the power sector for imported coal and coke. The share of hydro and renewables has also increased from 4.7% to 5.6% in 2016 [1]. The installed capacity of power plants in 2016 was 8.5% increased from 30,439 megawatt (MW) in 2015 to 33,023 MW in 2016. The installed capacity from natural gas was the highest at 42.6% (14,074.5 MW) followed by coal at 28.9% (9546 MW) and hydro at 8.6% (6128.1 MW). The share from diesel or Medium Fuel Oil (MFO) was at 6.3% (2090.3 MW), biomass was 2.2% (742.4 MW), solar at 0.9% (289.6 MW), others at 0.4% (117.3 MW) and biogas at 0.1% (34.6 MW) [1].

Gross electricity generation and consumption is estimated at 156,665 GWh and 144,024 GWh, respectively. The total energy input to power stations for electricity generation increased 6.7% in 2016 at 35,348 kilo ton of oil equivalent (ktoe) as compared to 33,134 ktoe in 2015. Coal and coke remained as the main energy source for electricity generation with a share of 48.4% (17,101 ktoe), followed by natural gas at 37.5% (13,260 ktoe), hydropower at 12.7% (4499 ktoe), diesel and fuel oil at 0.9% (320 ktoe) and renewables at 0.5% (168 ktoe). For the electricity generation mix in 2016, the share of coal and coke constituted 46.0%, followed by natural gas at 39.7%, hydropower at 13.3%, oil at 0.7% and the remaining 0.4% by renewables [1]. Coal dominates the electricity generation mix in Peninsular Malaysia, while for Sabah and Sarawak the biggest share come from natural gas and hydroelectric consecutively. It is estimated the electricity demand increasing more rapidly than overall energy use at 4% per year average to reach 400 TWh until 2040.

Malaysia coal reserves and production in 2016 was 1938.37 Mt and 2.414 million metric tonnes consecutively where most of the coal mining activities located in Sarawak, Sabah and Selangor. From 18,886 ktoe of coal consumption in 2016, 90.5% (17,101 ktoe) used in power stations and 9.5% (1785 ktoe) for industry. In 2016, Malaysia coal consumption was met by 90.5% (17,186 ktoe) of imported coal. This number increased by 8.1% (15,895 ktoe) in 2015 was due to high demand from the power sector. Approximately 60% of the coal was imported from Indonesia and 40% from Australia, Russia and South Africa [4–6].

The generated electricity from coal was 41% (60,128.83 GWh) of the total electricity generation in 2015. The average conventional coal power plant thermal efficiency in 2015 was 33.93%. The coal consumption and CO_2 emissions can be reduced with the installation of high-efficiency low-emission (HELE) coal technologies such as supercritical (SC), ultra-supercritical (USC) and advanced ultra-supercritical (A-USC) that utilize a low volume of coal to produce the same amount of energy and reduce carbon dioxide (CO_2) emissions. As part of the eleventh Malaysia plan for energy security, the government issued new tenders in stages to replace 7,626 MW generation capacity of the first generation of IPPs that will retire in phases by end of 2020 [7]. The Malaysian government target for to ensure security of supply, efficient utilisation and environmental preservation for the electricity subsector under the Eleventh Malaysia Plan as summarised in Table 1.

Currently, the average base electricity tariff is RM 0.3853 per kWh and dependent on the price of natural gas and imported coal. The natural gas sources are supplied by locally-produced company, Petroliam National Berhad (Petronas) and also from imported gas. Meanwhile TNB Fuel Services Sdn Bhd (TNBF), a wholly owned subsidiary of TNB, is responsible for procuring the steam coal or thermal coal used to generate electricity in coal power plant to the IPPs in Malaysia that have entered a power purchase agreement (PPA) with TNB. By utilising the imported coal, the cheaper electricity tariff can be achieved from RM 0.24 to 0.25 per kWh in comparison with utilisation of natural gas from RM 0.34 to 0.38 per kWh [8]. Notwithstanding this, the new government's efforts are focused on energy security to meet the country's rising electricity demand through utilisation of renewable sources and to a reduce the reliance on imported coal. Fuel switching from natural gas to coal has gained attention in the power sector in Peninsular Malaysia to overcome power shortages caused by the decline in natural gas supply. Considering coal abundant reserves globally and competitive prices, coal will remain as main energy demand despite the concern on CO_2 emission and air pollution.

Table 1. Eleventh Malaysia Plan (2016–2020) target for electricity [9].

Item	Target
Fuel diversity index, the Hirchmann–Herfindahl Index (HHI)	Achieve below 0.5
Installed Capacity and Reserve Margin for:	
Peninsular Malaysia Sabah Sarawak RE capacity in Peninsular Malaysia and Sabah Increase generation capacity in Peninsular Malaysia	24,943 MW with reserve margin of 20% 1782 MW with reserve margin of 34% 5103 MW with reserve margin of 19% 2080 MW or 7.8% of total installed capacity 7626 MW from new generation capacity & 2253 MW by extending retiring units
System Average Interruption Duration Index (SAIDI) for generation, transmission and distribution	
Peninsular Malaysia Sabah Sarawak	50 min/customer/year 100 min/customer/year 157 min/customer/year
Strengthen Sabah electricity grid for reliability	Transmission and distribution networks reinforcement
Subsidy rationalisation for electricity tariff	Tariff review to achieve market price
Initial milestones for nuclear power development	Establishment of an atomic energy regulatory commission Atomic Energy Regulatory Bill passed by Parliament Public engagement for acceptance of nuclear power plant development
Augmenting rural electrification	Achieve 99% national coverage
A high-level focal point in the Government for decision making on energy policy	Instituted before 2020
Increasing share of renewables in energy mix	Exploring new RE sources Enhancing capacity of RE personnel Implementing net energy metering
A comprehensive communications plan on issues related to tariff increase as well as construction of coal and nuclear power plants	Initiated by 2017

Approximately, 24 million metric tonnes of coal are burnt annually in the Malaysian coal-fired IPPs which the figure is expected to rise to 40 million metric tonnes in year 2020. As the government will gradually phase out subsidies for natural gas due to a decline in production, the gas price will eventually increase. It is estimated that coal will supersede natural gas and represent almost 60% of the energy mix with about 85 GW increase of installed power plant capacity in 2040 from 30.4 GW in 2015 [10].

This paper aims to provide a comprehensive review focusing on the availability and energy potential from oil palm residues and MSW for renewable energy (RE) mix in Malaysia. The existing management practices and salient issues in the oil palm industry and MSW management will address the potential of HTT from oil palm waste and MSW as value added fuel for a clean coal alternative.

2. Renewable Energy (RE)

Notwithstanding, Malaysia is blessed with indigenous renewable resources such as solar, biomass, mini hydro, wind, ocean, geothermal and wind energy. Malaysia has submitted Intended Nationally Determined Contributions (INDC) to tackle climate change under the Paris Agreement following the 21st Conference of the Parties (COP) to the United Nations Framework Convention (UNFCCC) to reduce greenhouse gas (GHGs) emissions namely CO_2, methane (CH_4) and nitrous oxide (N_2O). Hence, investment of renewable energy (RE) projects provides energy security to the country and simultaneously eradicates 40% of CO_2 by 2020 relative to the emission intensity in 2005 level. Thus, the government is committed towards diversify its RE deployment by maintaining the Hirschman index (HHI) of less than 0.5 by gradually reducing fossil fuel dependence due to unstable price and alleviate occasional electricity interruptions [6]. However, based on the current scenario there are challenges to reduce the CO_2 emission with the increment in growth of coal-fired generation in Malaysia scenario as a result of the increasing price of natural gas in the electricity sector.

Malaysia has faced challenges in sustaining fossil fuels production from natural gas and coal in electricity generation. Therefore, the government introduced various financial incentives such as feed-in tariffs, tax incentives for green project in terms of investment tax allowances and income tax exemption and policies to promote the use of renewables such as the Five-Fuel Policy in 2001, National Green Technology Policy in 2009, National Renewable Energy Policies and the Action Plan (NREPAP) in 2010 as a mechanism to attract investors in the RE sector. The Five-Fuel diversification policy aims to utilise RE from four renewable sources: biomass and MSW, biogas inclusive of landfill and sewage, solar photovoltaic (PV) and mini-hydro as additional sources of fuel for electricity generation besides the conventional sources of oil, gas, hydro and coal.

Malaysia has a target to install RE capacity of 2080 MW, 11% of RE mix and 42.2 Mt cumulative CO_2 avoidance in 2020. By 2030, the renewable capacity target is expected to reach 4000 MW, 17% of RE mix and 145.1 Mt cumulative CO_2 avoidance excluding the large scale hydroelectric [10]. The Malaysia National Biomass target is to achieve 800 MW (38%) and 54 MW (17%) installed capacity from biomass and MSW by 2020, respectively (Figure 1). By 2030, the biomass installed capacity is expected to increased 67.5% with 1340 MW installed capacity [11].

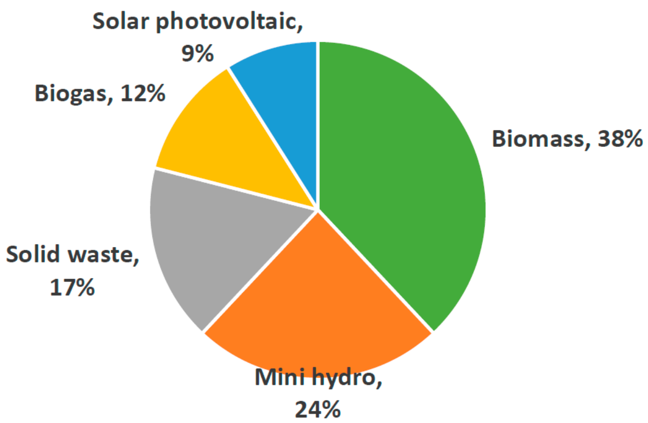

Figure 1. 2080 MW renewable energy (RE) installed capacity target by 2020 [12].

The Sustainable Energy Development Authority (SEDA) of Malaysia was established under the Sustainable Energy Development Authority Act 2011 (Act 726) for implementation of feed in tariff (FiT) mechanisms. The FiT was gazetted on 2011 under the Renewable Energy Act 2011 (Act 725) for the Distribution Licensees to buy electricity from RE resources by signing the RE Power Purchasing Agreement (REPPA) between RE producers or known as Feed-in Approval Holders (FiAHs) and distribution licensees for a specific duration and at a fixed premium price from RE fund which was established under Act 725 [13].

The FiT will be financed from the consumers electricity bill under the RE fund from NREPAP. Initially, the collection was 1% from the total electricity tariff invoices issued by the Distribution Licensees without involvement of Sabah. Since 2014, The FiT has increased to 1.6% with addition of Sabah. This is a polluter's pay concept, applicable to only domestic consumers who consume more than 300 kWh per months to the RE fund. However, the commercial and industrial consumers will be charge 1.6% even though the usage below 300kWh. The government target to collect 2% FiT for the RE Fund under NREPAP [13–15].

As of 2016, the PV FiT had reached maturity stage which resulted to installation of Large-Scale Solar (LSS) and Net Energy Metering (NEM) as compared to biomass, biogas and small hydro installations. After 5 years of the FiT system, the RE capacity installed successfully reached 500 MW. In comparison, the Small Renewable Energy Program (SREP) to introduce RE as the fifth fuel under the 8th Malaysian Plan (2001-2009) took 9 years to add 53 MW of RE to the power grid [13]. In 2014, 243.4 MW (out of 415.5 MW) of RE installed capacity was connected to the grid. This is due to challenges in securing adequate feedstock for the long-term supply for biomass, difficulties in securing financing for RE technologies and lack of experts in the technology project developers, financial personnel and service providers [9]. The RE policy deployment and development in Malaysia is summarized in Figure 2.

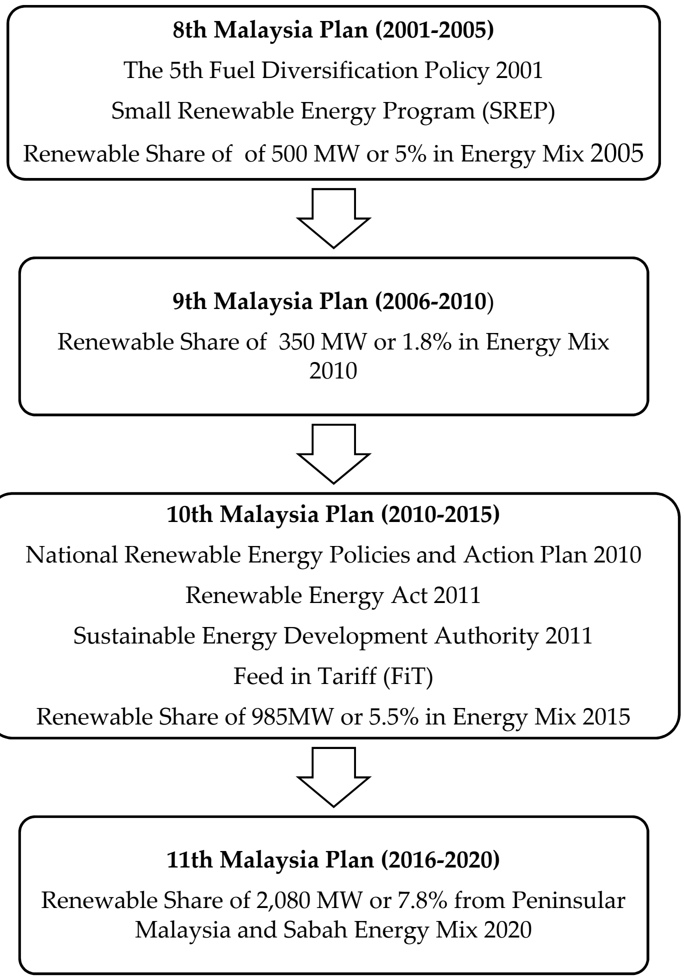

Figure 2. RE policy development in Malaysia, modified from [16].

As shown in Table 2, the digressions rate will not affect for RE technologies within the effective period under REPPA and will apply after the maturity of the technology. The average base electricity tariff by sector is capped at RM 0.3853 per kWh as the government had agreed to subsidise RM929.4 million or RM1.8 cent/kWh for first half of 2018 [17]. The FiT mechanism allows electricity to be produced from indigenous RE resources to be sold to power utilities at a fixed premium price for a specific duration with a maximum capacity of 30 MW for all renewable resources.

Table 2. Feed in tariff (FiT) for biomass and municipal solid waste (MSW) with effective period 16 years from the commencement date.

Capacity of RE installation Installed	FiT Rate (RM per kWh)	Fit Rate (USD per kWh)	Digressions Rate Effective 1st Jan 2014 [18]
Installed capacity up to and including 10 MW	0.3085	0.079	0%
Installed capacity above 10 MW, and up to and including 20 MW	0.2886	0.074	0%
Installed capacity above 20 MW, and up to and including 30 MW	0.2687	0.069	0%
Additional for use of gasification technology	+0.0199	+0.005	0%
Additional for use of steam-based electricity generating systems with overall efficiency of above 20%	+0.0100	+0.003	0%
Additional for use of locally manufactured or assembled boiler or gasifier	+0.0500	+0.013	0%
Additional use of MSW as fuel source	+0.0982	+0.025	0%

Developing biogas facility at palm oil mills is the fifth Entry Point Projects (EPPs) out nine EPPs under the Economic Transformation Programme's (ETP) for the oil, gas and energy sector. Since 2014, the government mandated new palm oil mills as well as palm oil mills that are expanding their capacity to install methane avoidance facilities to reduce greenhouse gas emissions from POME. This project focuses on limiting the GHGs, connection to the grid, supplying electricity to rural area, flaring and internal usage. The application depends on location of mills and vicinity to grid or commercial and residential area [19].

The first commercial bio-compressed natural gas (BioCNG) plant to produce CH_4 in Sungai Tengi, Selangor, was commissioned in 2015 in collaboration between Malaysia Palm Oil Board (MPOB), Felda Palm Industries Sdn Bhd and Sime Darby Offshore Engineering Sdn Bhd. In 2016, 92 biogas plants had been built, 9 under various stages of construction and another 145 under various stages of planning. This rapid growth of national biogas development is the result of the politically driven NKEA of fifth EPPs, the Renewable Energy Act (2011), increase in biomass FiT, tax incentives under the Promotion of Investment Act 1986, and the Green Technology Financing Scheme (GTFS) [20].

A biomass stored solar energy source that can be converted into useful RE for electricity, heat and transportation fuels. Thermal treatment of biomass as solid fuel has been traditionally used for cooking and heating in the form of fuelwood, dried dung, wood chips, straw, saw dust, logging residues, and briquettes. In addition, thermal treatment of biomass will have a significant impact for coal replacement in the electricity sector. It has great potential for energy security, environmentally and improved social living by creation of job. The main advantage of biomass as compared to coal is the availability for carbon sequester where the CO_2 produce from combustion to generate power can be reused for photosynthesis. Moreover, it will significantly reduce air pollution from sulphur oxide (SO_X) and nitrogen oxide (NO_X) released from combustion with coal.

However, there is challenge in feedstock availability and pre-treatment for large scale power generation as the treatment cost would result in high feedstock cost than coal. In comparison with biomass, fossil fuels require thousands or millions of years for reproduction whilst biomass is renewable and available annually. The annual yield of biomass depends on the location, weather and climate condition, crops management, fertilisation and type of soil. The agricultural residues have gained attraction for biomass feedstock due to low cost by-products make a good economic value for solid fuel production. However, the thermochemical conversion for agriculture residues is more challenging than wood as the ash content in wood is usually less than many agricultural residues.

3. Oil Palm Residue

The RE Policy and Action Plan sets a target of 2080 MW and 4000 MW of installed RE capacity for 2020 and 2030 respectively which focus on biomass (including MSW), biogas (from landfill and agriculture residues, small hydro and PV. The main agricultural commodities grown in Malaysia are oil palm, rubber, rice, cocoa and coconut. In Peninsular Malaysia, agriculture residue has been estimated at 17 Mt which 77% of the total residues are from oil palm, 9.1% rice residues, 8.2% forestry residues and 5.7% other residues like rubber, cocoa and coconut [21]. About 75% of the oil palm waste is made up of OPF and OPT which are readily available in the plantation sites, while EFB, MF, PKS and POME that account for the remaining 25% which are usually available at the mill sites during palm oil extraction from the fresh fruit bunch. The general oil palm yield for commodity trading includes crude palm oil (CPO), crude palm kernel oil (CPKO) and palm kernel cake (PKC).

3.1. Properties of Oil Palm Solid Residues

The OPT are obtained during the replanting to replace the old oil palm trees and OPF are available throughout the year when the palms are pruned during the harvesting of the fresh fruit bunches. EFB is the woody fibrous residue that remains after the fruits are removed from the bunch and the oil is extracted in the palm oil mill. MF is the fibrous material in the press cake where it is passed through a screen to remove the fibre. The PKS are separated from the kernel and serve as fuel for internal use in the palm oil mill boilers. Smaller mills might dry and sell the unprocessed nuts to other companies who process them into palm kernel oil [22].

The main constituents of the oil palm residues are cellulose, hemicellulose and lignin. The remaining contents are ash and extractives such as resins, fats, tanning agents, starch, sugar, proteins, and minerals. This high cellulose and hemicellulose content can be converted into simple sugars and processed into biofuels or biochemicals. From Table 3, PKS is seen to have highest lignin content which has proven to be the most preferred fuel for thermal combustion.

Table 3. Chemical composition (dry basis) of oil palm solid residues from mills [23].

Type of Biomass	Chemical Components (% Dry wt.)				
	Cellulose	**Hemi-Cellulose**	**Lignin**	**Extractives**	**Ash**
Empty fruit bunches	38.3	35.3	22.1	2.7	1.6
Mesocarp fibre	33.9	26.1	27.7	6.9	3.5
Palm kernel shell	20.8	22.7	50.7	4.8	1.0
Oil palm frond	30.4	40.4	21.7	1.7	5.8
Oil palm trunk	34.5	31.8	25.7	3.7	4.3

The lowest moisture content of oil palm residues is PKS at 12% followed by MF, EFB, OPF and OPT at 37%, 67%, 70% and 76%, respectively (Table 4). For thermochemical process efficiency, it is significant to have the lowest possible moisture content of biomass since high moisture content of biomass will incurred in drying cost. The fuel composition is important with respect to calorific value or heat released during combustion. The calorific value of oil palm residues varies between 18 to 21 MJ/kg on a dry basis. Due to the properties of PKS and MF with high calorific value and low moisture content, it is widely used as fuel without pre-treatment in the boilers to generate electricity in the oil palm mills. The calorific value of mill residues such as PKS, MF and EFB are higher than plantation residues like OPF and OPT. The calorific value of mill waste is comparable to low rank coal due to presence of hexane-extractable content which is unique to oil-derived biomass residues [24]. High-quality coals, such as anthracites and bituminous coals, can be expected to have calorific values in the range from 25 to 33 MJ/kg whereas low-quality coals, such as lignite, and peat-based fuels have calorific values of below 20 MJ/kg.

Table 4. High heating value and proximate analysis of oil palm biomass residues in comparison with coal (mass fraction in % dry basis except for moisture content) [24].

Sample	Gross Calorific Value (MJ kg^{-1})	Moisture Content (wt.%)	Ash Content (wt.%)	Volatile Matter Content (wt.%)
Empty fruit bunch	18.88	67.00	4.60	87.04
Mesocarp fibre	19.06	37.09	6.10	84.91
Palm kernel shell	20.09	12.00	3.00	83.45
Oil palm fronds	15.72	70.60	3.37	85.10
Oil palm trunks	17.47	75.60	3.35	86.70
Bituminous Coal	28.3	11.00	8.7	46
Lignite Coal	2.8	39.00	10.7	29

Generally, it can be seen that OPF has the highest nitrogen (N) content which probably explains why most of palm plantation mulched the OPF to improve soil fertility. The PKS has the highest carbon content followed by OPT. With regard to chemical properties of biomass fuel, it generally has low sulphur, low fixed carbon, and low fuel bound to N, but more oxygen than coal (Table 5).

Table 5. Ultimate analysis of oil palm biomass residues in comparison with coal [24].

Sample	Nitrogen (wt.%)	Carbon (wt.%)	Hydrogen (wt.%)	Oxygen (wt.%)	Sulphur (wt.%)
Empty fruit bunch	0.249	48.715	7.858	48.179	ND
Mesocarp fibre	0.391	46.396	9.283	50.212	ND
Palm kernel shell	0.043	57.909	12.600	49.994	ND
Oil palm fronds	12.402	48.431	10.476	46.75	ND
Oil palm trunks	0.169	51.408	11.816	51.16	ND
Bituminous Coal	1.4	73.1	5.5	~10	2.4
Lignite Coal	1.6	56.4	4.2	26.0	0.4

In addition, the presence of alkali and alkaline earth metal content of oil palm biomass such as sodium (Na), magnesium (Mg), calcium (Ca) and potassium (K) is very important in thermochemical combustion as it may react with silica (Si) causing operational problems in the boiler with slagging in the grates and fouling of the tubes [24]. Sulphur (S), Cl, and alkali metals vaporize during combustion and deposit in a molten form, particularly as alkali chloride, resulting in severe corrosion and machinery failure. Cl is a major factor in ash formation where it facilitates the transport of alkali from the fuel to surfaces, where the alkali often forms sulphate [25]. In addition, based on the alkali index, only PKS complies the guideline for bioenergy application limit of below 0.34 mol GJ^{-1} whilst the EFB has the highest alkali index correspond to high K with potential of slagging during combustion. Therefore, it is important to reduce these elements by leaching or washing with water to avoid fouling or slagging during combustion [24]. The effect of biomass physical and chemical properties as fuel for combustion is summarized in Table 6.

Technical challenges of biomass are low bulk, energy density and calorific value which requires upgrading and densification that make the feedstock costly. Moreover, biomass is more susceptible to moisture or hydrophilic that cause problem for fuel storage and handling. Most power station operators were concerned about logistics and boiler issues such as fouling and corrosion of heat exchanger surfaces, slagging, ash deposition, SOx and NOx emissions [26,27]. Therefore, there is a need for biomass pre-treatment to improve chemical and physical properties by increasing the energy content, grind ability and hydrophobicity.

Table 6. Physical and chemical characteristics of solid biomass fuels and their effects [28].

Characteristics	Effects
Physical Properties	
Moisture content	Storage durability and dry-matter losses, NCV, self-ignition, plant design
Net Calorific Value (NCV), Gross Calorific Value (GCV)	Fuel utilization, plant design
Volatiles	Thermal decomposition behaviour
Ash content	Dust emissions, ash manipulation, ash utilization/disposal, combustion technology
Ash-melting behaviour	Operational safety, combustion technology, process control system, hard deposit formation
Fungi	Health risks
Bulk density	Fuel logistics (storage, transport, handling)
Particle density	Thermal conductance, thermal decomposition
Physical dimension, form, size distribution	Hoisting and conveying, combustion technology, bridging, operational safety, drying, dust formation
Fine parts (wood pressings)	Storage volume, transport losses, dust formation
Abrasion resistance (wood pressings)	Quality changes, segregation, fine parts
Chemical Properties	
Elements:	
· Carbon, C	GCV
· Hydrogen, H	GCV, NCV
· Oxygen, O	GCV
· Chlorine, Cl	HCl, PCDD/PCDF Emissions, corrosions, lowering ash-melting temperature
· Nitrogen, N	NO_x, N_2O emissions
· Sulphur, S	SOx emissions, corrosion
· Fluorine, F	HF emissions, corrosion
· Potassium, K	Corrosion (heat exchangers, superheaters), lowering ash-melting temperature, aerosol formation, ash utilization (plant nutrient)
· Sodium, Na	Corrosion (heat exchangers, superheaters), lowering ash-melting temperature, aerosol formation
· Magnesium, Mg	Increase of ash-melting temperature, ash utilization (plant nutrient)
· Calcium, Ca	Increase of ash-melting temperature, ash utilization (plant nutrient)
· Phosphorus, P	Ash utilization (plant nutrient)
· Heavy metals	Emissions, ash utilization, aerosol formation

3.2. Availability and Energy Potential from Oil Palm Residues

From MPOB statistics in 2017 (Table 7), the total oil palm planted area reached 5.81 million hectares (ha), an increase of 1.3% as against 5.74 million ha in the previous year. The total oil palm planted area in Peninsular Malaysia in 2017 was 2.70 million ha (46.6% of the total) followed by Sarawak with 1.56 million ha (26.8% of the total) and Sabah with 1.55 million ha (26.6% of the total).

Table 7. Total oil palm planted area by location in Malaysia from 2014 to 2017 [29].

Year	2014		2015		2016		2017	
Location	Sabah and Sarawak	Peninsular Malaysia	Sabah and Sarawak	Peninsular Malaysia	Sabah and Sarawak	Peninsular Malaysia	Sabah and Sarawak	Peninsular Malaysia
Planted Area (ha)	2,774,901	2,617,334	2,983,582	2,659,361	3,058,483	2,679,502	3,102,732	2,708,413
Total	5,392,235		5,642,943		5,737,985		5,811,145	

As shown in Figure 3, from 5.81 million ha of oil palm plantations, 61% belongs to private estates, 17% from independent smallholders and the remaining belongs to state schemes or government agencies, the Federal Land Development Authority (FELDA), Federal Land Consolidation and Rehabilitation Authority (FELCRA) and Rubber Industry Smallholders Development Authority (RISDA). With the increasing trend of oil palm planted area since 2010, it is estimated the oil palm biomass will generate approximately 85 to 110 million dry tonnes of solid biomass by 2020. Besides, there is also target to reduce 12% of methane emission by installing 410 MW biogas capture facilities by 2030 in the oil palm mills and subsequently gain profit from selling power to the national grid [30].

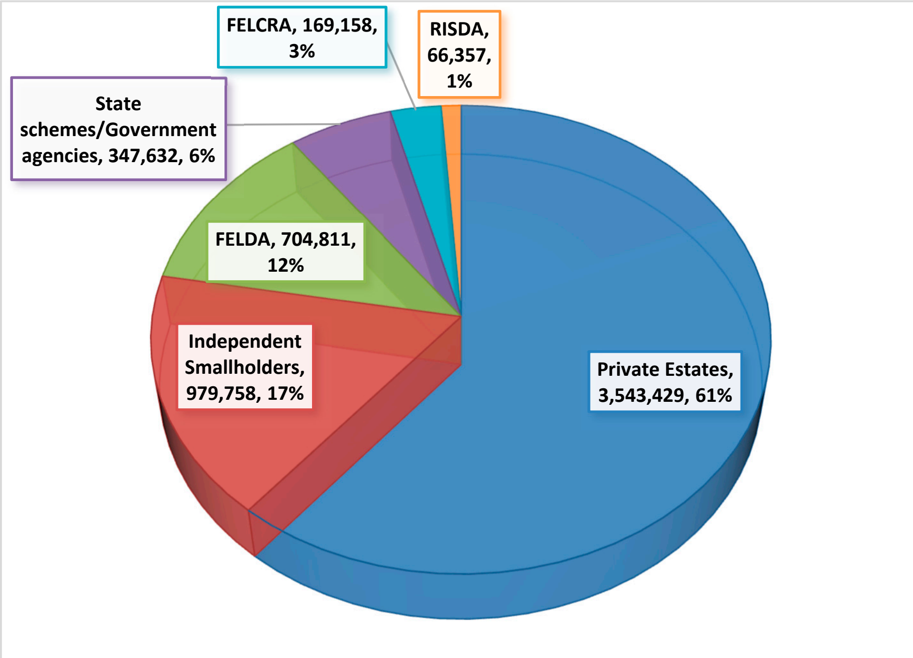

Figure 3. Breakdown of oil palm planted area by category [31].

As of 2017, there were a total of 454 operating mills in Malaysia with the capacity to process 112,187,800 tonnes of fresh fruit bunches per year. In addition, 244 mills were located in Peninsular Malaysia, 130 mills were in Sabah and 80 mills were in Sarawak [29]. The oil palm mills ownership is categorised into private mills which receive fresh fruit bunch from other private palm oil plantation and plantation-based mills that possess their own plantations.

The OPF are available throughout the year as they are regularly cut due to ripe fruit bunches during the harvesting; meanwhile, the OPT are generated during replanting in the plantation every 25 to 30 years due to decease fruit and oil yields. The shredded OPF are sometimes used for ruminant feed while 40% of OPT are sold to the wood industry for making medium density fibre board, plywood and furniture [21]. The remaining OPF are decomposed for soil fertilization and erosion control. The OPT are also used for furniture industry in manufacturing plywood, medium density fibreboard (MDF) and bioethanol production [32].

Meanwhile, around 98% and 62% of MF and PKS, respectively are used as fuel for the boilers in mills to generate electricity for palm oil extraction with the balance sold to open market [23]. However, based on observation, these palm oil mills faced the problem of supplying the electricity due to insufficient feedstock supply as fuel from the MF and PKS. In addition, they are also processed to be sold as pellets and briquettes. Besides, the MF is also used to produce plastic pellets which can also be used as a filler for fibre-reinforced thermoplastic [32].

Based on a previous study by [33], most of the private palm oil mills owner returned back the EFB with some cost paid for the transportation to the plantation for mulching and replenishing the soil due to high K and ability to conserve water due to limited space for disposal in the mills. However, this practice results in an odour problem at the plantation. As EFB contain around 67% moisture, it requires high intensity of drying to use as fuel in the boilers. Furthermore, the high alkali content of EFB such as K and Na play an important role for organic fertilizers or bioethanol production but not suitable for combustion as it will cause slagging and fouling in the boiler that resulted in plant shutdown and economic losses.

In Sabah, the biomass plant utilises surplus EFB for grid-connected such as Kina Biopower Sdn. Bhd. and Seguntor Bioenergy Sdn. Bhd. Alternatively, there are various applications and value-added products from EFB like the pulp and paper industry, cushion and rubberized mattress, briquette and pellets as fuel [23]. Moreover, there was also a joint project between the Malaysian and Japanese governments in 2014 to produce alternative fuel to coal from EFB and tyre waste used in the cement plant [34].

The availability and energy potential of oil palm biomass residues along its supply chain are calculated from the fresh fruit bunch processed in palm oil mills and the standard biomass to Fresh Fruit Bunch (FFB) extraction as in Tables 8 and 9.

Table 8. Fresh Fruit Bunch (FFB) yield and processed by mills in Malaysia from 2014 to 2017 [29].

Year	2014	2015	2016	2017
FFB Yield (Tonnes/hectare)	18.63	18.48	15.91	17.89
FFB Processed by Mill (Tonnes)	95,380,438	97,566,393	85,836,769	101,022,441

Table 9. Oil palm biomass availability based on standard biomass to FFB extraction rate [24].

Type of Oil Palm Biomass	Availability
Empty fruit bunches (EFB)	EFB (wet basis) = 22% of FFB EFB (dry weight) = 35% of EFB (wet basis)
Palm Kernel shell (PKS)	PKS (wet basis) = 5.5% of FFB PKS (dry weight) = 85% of PS (wet basis)
Mesocarp fibres (MF)	MF (wet basis) = 13.5% of FFB MF (dry weight) = 60% of MF (wet basis)
Palm oil mill effluent (POME)	POME (wet basis) = 67% of FFB or 0.65 m^3 t^{-1} FFB
Oil palm trunks (OPT)	OPT (replanting, dry weight) = 74.48 t ha^{-1}, an average of 142 OPT is available from a ha of oil palm, and only 50% can be removed from the plantation.
Oil palm fronds (OPF)	OPF (pruned, dry weight) = 10.40 t ha^{-1}, 75% of oil palm trees aged 7 years are due for pruning, and only 50% can be removed from the plantation. OPF (replanting, dry weight) = 14.47 t ha^{-1}, and only 50% can be removed from the plantation.

The FFB processed by mills was 101.02 Mt with 5,811,145 ha planted area in 2017. The oil palm replanted area was estimated at 100,550.31 ha [29]. From this data, the total availability of oil palm solid residue generated along its supply chain on a dry weight basis from pruning, milling and replanting activities was calculated. The pruned OPF was estimated 22.66 Mt, 7.78 Mt of EFB, 8.18 Mt of MF, 4.72 Mt of PKS and 3.38 Mt POME. The estimated dry weight of OPF and OPT from replanting was 0.73 Mt and 3.74 Mt, respectively. The total dry oil palm residues available for replanting, pruning and milling activities in 2017 was estimated 51.19 Mt out of 101.02 Mt of FFB processed.

As summarised in Table 10, the energy potential of each biomass type has been estimated from the calorific value and availability. The electricity generation potential from the oil palm biomass residues obtained is calculated based on the energy potential value for each biomass type, assuming that the average thermal efficiency of conventional coal-firing power plants in 2017 was 35.67% [4].

Table 10. Availability, energy and electricity generation potential of oil palm residues in Malaysia in 2017.

Biomass Type	OPF	EFB	PKS	MF	POME	OPT	Total
Availability (Mt)	23.39	7.78	4.72	8.18	3.38	3.74	51.19
Gross calorific value (MJ kg^{-1}) [24]	15.72	18.88	20.09	19.06	16.99	17.47	-
Energy Potential (PJ)	367.71	146.86	94.88	155.96	57.50	65.42	888.33
Electricity Generation (TWh)	36.44	14.55	9.40	15.45	5.70	6.48	88.03
Power Plant Size (MW)	5060.67	5666.35	3660.79	6017.46	2218.54	2524.12	12,225.80

1 MJ = 1/3600 MW h.

Overall, the potential RE from solid fuel of OPF was the highest among all biomass types, with 367.71 PJ, followed by MF, EFB, PKS, OPT and POME showed the least energy potential, with 57.50 PJ due to liquid in nature. The total electricity generation potential of all residues was 88.03 TWh with 12,226 MW electricity generation installed capacity. The installed capacity of POME for solid fuel was 2218.54 MW, whilst installed capacity for biogas or methane energy exceeded the national target of 410 MW biogas by 2030 at 511.82 MW (Table 11).

Table 11. Biogas potential from POME in 2017 (Modified from [24]).

Material	Production Rate	Quantity
FFB Processed (tonnes)		101,022,441
POME Availability (million m^3)	67% to FFB	67.69
Biogas (million m^3)	28 m^3 per m^3 of POME	1895.18
Total heat value (million MJ)	1895.18 million $m^3 \times 20$ MJ m^3	37,903.62
Total heat value (million MWh)		10.53
Power Output (MWh)	35.65% of heat value	3.69
Power plant size (MW)	Plant operates 300 days a year = 7200 h	511.82

Calorific value = 20 MJ m^3 at STP, 1 MJ = 1/3600 MW h.

In summary, the oil palm solid waste has significant potential for the biomass energy target as compared to biogas with electricity installed capacity of 12,226 MW which surpassed the nation biomass target to reach 800 MW and 1340 MW by 2020 and 2030, respectively.

3.3. Salient Issues Faced by Oil Palm Biomass Developers

Developing a biogas facility at palm oil mills is one of EPPs identified under Malaysia NKEA for palm oil. Since 2014, the government has mandated new palm oil mills as well as palm oil mills that are expanding their capacity to install methane avoidance facilities in a bid to move to reduce greenhouse gas emissions. This project focus to limit the GHGs emissions from POME, connection to the grid, supplying electricity to rural areas, flaring and internal usage. The application depends on the location of mills and proximity to the grid or commercial and residential areas [19].

In a study by [35], the three (3) main barriers identified for developing biomass energy in Malaysia are security of supply, unattractive electricity tariffs and high capital expenditure. Malaysia's oil palm plantations are largely based on private estate, independent smallholder, state schemes or government agencies, FELDA, FELCRA and RISDA. The long-term supply is the main factor for the biomass energy producer as they depend on third parties which has resulted in fluctuation of fuel price and competing demand. Unlike the plantation owner who has control on the feedstock supply, the high risk for a biomass market player especially the non-estate small producers which have to depend and invest on the third party to generate electricity from biomass make it unattractive for business. Conversely, 68% of the respondents from the plantation owner who have full access to their feedstocks preferred to sell their feedstocks at an attractive buying price on the open market instead of utilising their waste for RE generation. The large oil palm companies play significant role in controlling the oil palm market as the common practice for the mill operators to return the waste generated to the plantation for various purposes such as mulching instead of electricity generation.

Furthermore, it is found that 77% of palm oil mills in Malaysia are using combustion or combined heat and power (CHP) systems or a combination of both, while only 5% of plants are fitted with a gasification for self-consumption power generation [36]. Some of the palm oil mills faced a problem in terms of frequent power supply interruption due to insufficient feedstock of fuel from MF and PKS and inefficiency of old and conventional boilers in the palm oil mills that have been in operation more than 10 years. Most of these mills owner found that replacement to high pressure boiler for grid connecting requires high investment cost and insignificant as the current capacity is capable to supply the palm mills daily operations [35]. In addition, palm mills located in remote areas are reluctant to replace their current inefficient boiler for connection to the grid to due to the distance of the mills from the grid lines which can be quite far for RE business. However, the scenario will be different if the infrastructure cost such as the transmission line is borne by the government [36]. Instead of supplying the surplus electricity to the grid, palm oil mills in remote area should have the option to supply to the rural communities nearby with comparable tariffs charged especially in Sabah and Sarawak by turning the plants into small-scale IPPs [37].

Notwithstanding this, over-reliance on the use of MF and PKS for boiler feedstock is due to lack of development of biomass conversion technology in Malaysia. Diversification of fuels is a sensible solution to avoid overreliance on the existing boiler fuels such as utilisation of other residues like EFB, OPF, OPT and POME. Therefore, pre-treatment technology that is able to process these residues into fuel is crucial. Moreover, a smart-partnership collaboration of technology provider with government is significant to use the technology at economies of scale.

Economic viability and feasibility study are required to identify a suitable location and to ensure sufficient supply of fuels, avoiding high transportation cost as well as determining a reasonable size or capacity for the plant. The upfront costs which correspond to a high payback period of pre-treatment technology can be compensated by better operability of the fuel in handling, storage, transportation and operability of the boiler and combustion process.

4. Solid Waste Management

Solid waste management falls under the purview of both the federal and state government. Malaysia is made of 13 states and 3 federal territories. In 2017, only 8 states and federal territories, including Kuala Lumpur, Putrajaya, Melaka, Perlis, Negeri Sembilan, Pahang, Kedah and Johor have adopted the Solid Waste and Public Cleansing Management Act 2007 (Act 672), where the National Solid Waste Management Department (NSWMD) under Ministry of Housing and Local Government has national oversight on MSW management while the remaining under the purview of state government authorities. In order to facilitate handling of MSW through an integrated management system, the collection of MSW was privatized, and concessions were given to handle the waste collection in three different regions; southern, northern and eastern.

The NSWMD assisted by the Solid Waste Management and Public Cleansing Corporation (SWCorp) develops solid waste and public cleansing policies and strategies, action plans, and formulates the necessary legislative measures to support management at the Federal level. The Act 672 was enacted as a measure to standardise the level of Solid Waste Management and Public Cleansing across all local authorities in order to create an economically and environmentally sound solid waste management industry.

Solid wastes are generally categorized into five groups, namely MSW, industrial wastes, hazardous wastes, agricultural wastes and e-wastes. The MSW is the main source of waste that contributes to the large amount generated compared to the other types of waste. For that reason, MSW does not qualify as biomass as it has a mix of discarded organic and non-organic materials or trash including plastic, glass and metals. Scheduled and hazardous wastes, generated from industrial activities requires proper handling, treatment and disposal are regulated under the Environmental Quality Act 1974

(Act 127) and the Environmental Quality (Scheduled Waste) Regulations 2005 under the purview of Ministry of Energy, Science, Technology, Environment and Climate Change.

4.1. Municipal Solid Waste (MSW) Composition and Characterisation

Landfilling remains the most common MSW disposal method in Malaysia with 150 landfills in 2017 which comprised 18 sanitary landfills and 132 non sanitary landfills [38]. Malaysia aimed to divert 40% of the waste from the landfilling. In 2020, the government target to achieve 22% recycling rate and 1 waste to energy (WtE) thermal plant and by year 2030, a 28% recycling rate with 3 WtE thermal plants [7].

The MSW composition differs from one location to another as it depends on seasons, geographical region and socio-economic. In a study conducted by [39], the MSW studied in Malaysia is divided into household waste, industrial, commercial and institutional (ICI) waste. Approximately 45% of Malaysian household waste was food waste and 46% of ICI waste was from plastic and paper (Figure 4).

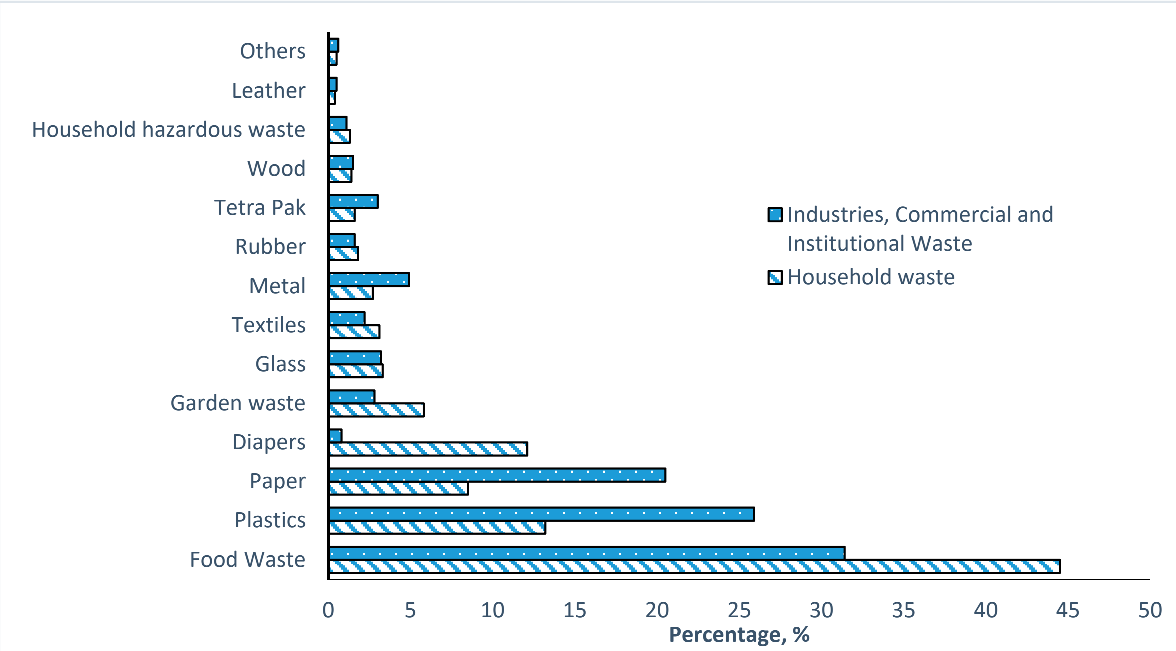

Figure 4. Average Malaysian household and industrial, commercial and institutional (ICI) waste composition [39].

The large organic waste disposed to landfills caused large volume of methane gas 21 to 25 times the global warming potential (GWP) from anaerobic condition. Malaysia produced 23% of methane from the total GHGs emission where 90.9%, 8.6% and 1% was generated from landfills, POME and bio effluent [7]. The MSW proximate and ultimate analysis together with average heavy metals are tabulated in Tables 12–14.

4.2. Availability and Energy Potential from MSW

With a population of 32,022,600 in 2017, the daily MSW generation in Malaysia is estimated at 37,466 tonnes per day or 13.68 Mt per year at a 1.17 kg average rate per capita per day of waste generated from household, commercial, industrial and institution [39]. The average Malaysian MSW calorific value was determined at 5060 kcal/kg [39]. The MSW availability and energy potential from 2014 to 2017 are tabulated in Table 15. The reported average thermal efficiency of coal power stations as a measure of potential power generation were then used to determine thermal power potential of MSW for that particular year [4]. Considering that the average thermal efficiency of coal-fired power stations in Peninsular Malaysia is 35.67%, 8.57 TWh energy is generated with installed capacity 1190.42 MW from MSW.

Table 12. Calorific value, bulk density and proximate analysis of MSW [39].

	Higher Heating Value, HHVdry, kJ/kg (kcal/kg)	Lower Heating Value, LHVwet, kJ/kg (Kcal/kg)	Average Bulk Density (kg/m^3)	Moisture Content (wt. %)	Ash Content (wt.%)	Volatile Matter Content (wt.%)	Fixed Carbon Content (wt.%)
Household Waste	21,185 (5060)	6325 (1511)	202.54	59.45	8.65	20.79	11.10
ICI Waste	20,765 (4960)	7727 (1846)	134.38	51.75	8.40	26.57	13.28

Table 13. Ultimate analysis of MSW [39].

	Nitrogen	Carbon	Hydrogen	Oxygen	Sulphur	Organic Chlorine	Ash content	Total Chlorine
	(wt.%)	(wt.%)	(wt.%)	(wt.%)	(wt.%)	(wt.%)	(wt.%)	(wt.%)
Household Waste	1.05	17.36	5.89	5.89	3.35	0.04	6.96	-
ICI Waste	1.37	24.11	5.00	9.09	0.08	0.07	8.36	0.17

Table 14. Average heavy metals of MSW (wet basis, %) [39].

Part per Million (ppm)	Household Waste	ICI Waste
Mercury	0.092	0.127
Vanadium	3.59	1.371
Chromium	46.58	21.94
Manganese	21.97	7.71
Iron	318.27	163.17
Cobalt	0.53	0.51
Copper	5.92	4.59
Zinc	19.35	10.06
Arsenic	0.66	0.50
Silver	0.66	0.31
Cadmium	2.38	0.64
Lead	1.98	1.59
Aluminium	148.23	118.27
Magnesium	88.30	31.22
Nickel	1.94	2.29

Note: Non-combustible fraction of the waste removed before analysing the sample.

Table 15. Availability, energy and electrical potential value of solid MSW from 2014 to 2017.

	2014	2015	2016	2017
Population	30,708,500	31,186,100	31,633,500	32,022,600
Average rate per capita per day (kg/cap/day)	1.17	1.17	1.17	1.17
MSW Generated per day (tonnes)	35,929	36,488	37,011	37,466
Estimated Annual MSW Generated (tonnes/year)	13,114,065	13,318,024	13,509,086	13,675,251
Average Net Calorific Value of Mixed MSW (MJ/tonnes) [39]	6.325	6.325	6.325	6.325
Energy Potential (PJ/year)	82.95	84.24	85.44	86.50
Power output (TWh/year)	8.36	8.34	8.60	8.57
Power Plant Size (MW)	1161.73	1158.67	1193.75	1190.42

1 MJ = 1/3600 MWh, Plant operates 300 day/year = 7200 h/ year.

In comparison, methane emission energy potential from waste disposal sites is determined by referring to the method proposed by the Intergovernmental Panel on Climate Change (IPCC) [40].

$$Q = (MSW_T \times MSW_F \times MCF \times DOC \times DOC_F \times F \times 16/12 - R)(1 - OX) \quad (1)$$

where,

- Q = Total methane emissions (Gg/year);
- MSW_T = Total solid waste generated (Gg/year);
- MSW_F = Fraction of solid waste disposed to landfill = 0.8 (80% of the total MSW generated in Malaysia is sent to the landfill);
- MCF = Methane correction factor (fraction) = 0.6 (for uncategorised SWDS);
- DOC = Degradable organic carbon (fraction) = 0.14;
- DOC_F = Dissimilated organic fraction (i.e., fraction converted to LFG) = 0.77;
- F = Fraction of CH4 in landfill gas = 0.55;
- R = Recovered CH4 (Gg/year) = 0;
- 16/12 = Molecular weight ratio of methane and carbon;
- OX = Oxidation factor (fraction) = 0.

By applying the above equation, the total methane emission and energy potential is calculated and summarized in Table 16. Methane is the main source of energy obtained from the combustion of biomass residues. Processing of MSW will produce landfill gases (LFG) which account for 55% of methane with a density of 0.667 kg/m^3 at 30 °C and LFG calorific value of 17 MJ/m^3 [41]. Hence, in 2017, 778 $\times$ 10^6 m^3 of methane with a calorific value of 13.23 $\times$ 10^9 MJ is obtained and this is equivalent to an electricity generation of about 1.31 TWh per year. In conclusion, it is estimated that 8.57 TWh energy is generated per year from solid MSW while only 1.31 TWh equivalent energy from methane gas.

Table 16. Availability and energy potential resulting from emission of methane from 2014 to 2017.

	2014	2015	2016	2017
Population	30,708,500	31,186,100	31,633,500	32,022,600
Average rate per capita per day (kg/cap/day)	1.17	1.17	1.17	1.17
MSW Generated per day (kg)	35,928,945	36,487,737	37,011,195	37,466,442
Estimated Annual MSW Generated (tonnes/year)	13,114,064.93	13,318,024.01	13,509,086.18	13,675,251.33
Total Methane Emissions (tonnes/year)	497,621.05	505,360.40	512,610.37	518,915.60
Volume of Methane (m^3)	746,058,545	757,661,767	768,531,285	777,984,413
Calorific Value (MJ)	12,682,995,265	12,880,250,039	13,065,031,845	13,225,735,021
Power Output (TWh)	1.28	1.28	1.31	1.31
Power Plant Size (MW)	177.63	177.17	182.53	182.02

1 MJ = 1/3600 MWh, Plant operates 300 day/year = 7200 h/year.

4.3. Current Problems on Waste to Energy from MSW

Landfilling is the preferred practice of MSW disposal in Malaysia due to cheaper cost while incineration is commonly used for scheduled and clinical waste treatment. Incineration without energy recovery for MSW treatment on a small capacity has been used in the Cameron Highland (40 tonnes/day), Pangkor (20 tonnes/day), Langkawi (100 tonnes/day), Tioman (15 tonnes/day) and Labuan (50 tonnes/day) [42]. However, some of the incinerators have been discontinued as the high moisture content leads to extensive drying and high cost of operation. In Malaysia, the average moisture content ranges from 52% to 60% as a result of Malaysia having a hot and humid climate. Another problem was due to poor skilled personnel in maintaining the incinerators. The use of incinerator for treatment of high moisture content MSW will result in low plant efficiency, as high energy and combustion temperature are required for the combustion of wet MSW. Generally, the process efficiency of conventional incineration is 25 to 30%.

In Malaysia, energy recovery initiatives are focused on incineration for production of refuse-derived fuel (RDF) technologies and MSW landfill gas capture. Currently, an integrated solid waste facility at Ladang Tanah Merah, Negeri Sembilan, with a capacity 600 tonnes per day of WtE is in operation. The other WtE proposed to be built in Taman Beringin, Kuala Lumpur (1000 tonnes/day) and Sungai Udang, Melaka [7]. The first WtE plant in Semenyih in 2009 was only able to operate partially due to high moisture content of waste, public concerns on dioxin and furan emission and other technical flaws [43]. The opposition of incineration has been based on both technical and socio-economics arguments such as the Not in My Back Yard (NIMBY) syndrome and public concerns on flue gas emission such as particulate matter or dust, SO_x, NO_x, heavy metals, dioxins and furans that may affect health and the environment.

The main advantage of solid waste incineration is the ability to reduce the volume of waste and at the same time retrieve the energy in terms of electricity or heat. Scarcity of land often creates conflict in land used for waste treatment and disposal facilities. However, incinerators still require landfill to manage their discharged ash and treatment of wastewater. There are negative perceptions and fear of the ultrafine particles generated particularly PM_{10} and $PM_{2.5}$ associated with lungs and respiratory problems. Therefore, the particulate must be removed by installation of gas cleaning equipment. Incineration is expected to comply with very stringent emission standards as compared to other combustion devices. In Malaysia, the Department of Environment (DOE) is responsible for monitoring the dioxin/furan emission limit of 0.1 ng-TEQ/Nm^3 listed under the Environmental Quality (Dioxin and Furan) Regulations 2004 [44].

One barrier for national solid waste management is due to the local authority not fully subscribing to the Solid Waste and Public Cleansing Management Act 2007 (Act 672) making it difficult to secure the wastes for power generation [18]. Moreover, the WtE technology cost is still high, and this impacts the proposed tipping fees. As a consequence, low tipping fees will limit the attractiveness of the sector to new investment and technology exploration in Malaysia [45]. In 2012, SEDA introduced FiT for WtE, although the FiT rate should only be considered as an additional income apart from waste treatment not to solve health, social and environmental issue. Government support on waste volume guarantees, an increase in tipping fee and a high electricity tariff can help in the economic viability of WtE technology [7]. The Government should take a good policy measure to increase the price of landfilling like the Sweden government policy to introduce the landfill tax.

In summary, thermochemical conversion of biomass residues and waste for solid fuel production as alternative energy source to coal will solve the problem on limited availability of biomass as feedstock to power plant for large-scale electricity generation and consequently can solve the nation's solid waste management issues.

5. Hydrothermal Treatment Studies of Oil Palm Solid Wastes and MSW

There are few pre-treatment techniques that have been developed based on biomass characteristics with aim to enhance the properties of feedstock for solid fuel and to make the storage, transportation, handling and more efficient and cost effective. However, most of the thermal pre-treatment studies focused on the development of bio-ethanol, biofuel and biochemicals from oil palm residues especially from EFB. Generally, the thermal pre-treatment for solid fuel includes torrefaction, pyrolysis and HTT. Based on availability of oil palm wastes in Malaysia, OPF was the highest at 45.7% from 51.19 Mt of residues in 2017 followed by MF, EFB, PKS and OPT at 16%, 15.2% 9.2%, 7.3% and 6.6%, consecutively. The studies on solid fuel production from oil palm residues and MSW is not attractive due to limitation of technology to process the residues into clean fuel.

The differences in characteristics of coal and biomass make it challenging for solid fuel production for co-firing with coal. There are some problems associated with the use of agricultural residues and MSW for cofiring with coal such as high moisture content, presence of alkali and alkaline in nature in the ash like K, Na and Cl which may aggravate slagging and fouling in the boiler. Volatile matter content of biomass is higher than in coal resulting in earlier combustion for biomass than for coal. Therefore, pre-treatment of biomass prior to co-firing with coal is significant to avoid fouling and slagging.

Torrefaction is a thermo-chemical process conducted in the absence of oxygen, at temperatures from 250 to 300 °C, typically for 60 min residence time, during which biomass partially decomposes giving off volatiles and remaining solid known as torrefied char. Torrefaction of agro-residues appears to be more complicated than wood due to the challenging physical and chemical characteristics. The bulk and energy density of palletised torrefied wood is 25% and 30% more than wood pellets respectively where it can facilitate transportation and storage. The process improves the grindability and hydrophobicity with relation to coal co-firing [46]. The most important technical challenges in the development of torrefaction processes relate to achieving constant and well-controlled product quality, scaling up the process and product densification. Moreover, the torrefied wood pellets can generate larger amounts of explosive fine dust than wood dust. Torrefaction technologies have relatively limited feedstock flexibility as it only applies for feedstock materials with less than 15% moisture content and smaller particles size. Typically, lignocellulosic biomass with high moisture content needs to be dry before entering the torrefaction reactor [47].

Pyrolysis or carbonisation is a thermal decomposition process of biomass in the absence of oxygen to produce combustible gas, biochar and bio oil. Slow pyrolysis at temperatures around 300 to 500 °C and a lower heating rate (0.1–0.8 °C/s) with longer residence time produces mostly biochar, gas and bio oil. The yield of biochar decreases with the increase in temperature. Meanwhile fast pyrolysis at a temperature of 450–550 °C at a very high heating rate (10–1000 °C/s) for a very short residence time is an option to obtain approximately 70% bio oil, 15% bio char and 15% gas. The yield efficiency of the pyrolysis process depends on the feedstock, process configuration, and conditions [46,48].

HTT involved treatment of biomass or waste using hot compressed water or subcritical water temperature from 150 °C to 220 °C, at a pressure from 2 mega-pascal (MPa) to 2.5 MPa. The product is subsequently dried by ambient air or by air blowing as shown in Figure 5. The process is also called hydrothermal carbonisation, wet torrefaction and hot compressed water treatment. It is an artificial coalification process which converts raw biomass or waste into three products namely gases, aqueous chemicals, and hydrochar. Dehydration, decarboxylation, aromatization, hydrolysis and condensation polymerization reactions take place during the HTT process. The significant advantage of HTT compared to torrefaction, pyrolysis and incineration is the process eliminates the needs for drying which essential for solid fuel production from wet biomass or waste in Malaysia. The high moisture content in many cases of biomass is unfavourable as it has to be below 20% for combustion where active drying should be applied before conversion into pellets or useful energy. Intensive drying process will result in decreased combustion efficiency and net calorific value and increased overall cost involve including transportation.

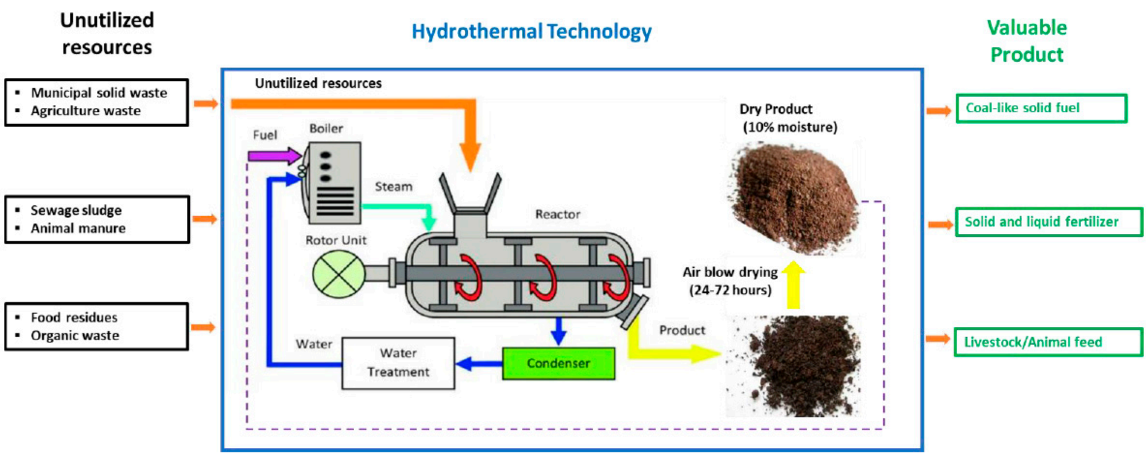

Figure 5. Hydrothermal treatment process [49].

The potential on the use of HTT for treatment with a broader range of lignocellulosic biomass and waste feedstock to produce hydrochar has been proven in the laboratory and commercial scale. In the lab scale study, HTT of EFB was conducted at temperature of 180 °C, 200 °C and 220 °C for 30 min. Subsequent washed treatment was done for 15 min at 60 °C to further remove the alkali metal such K and Na [50]. In another study, HTT at 200 °C with 5 min holding time was capable of removing up to 90% of Ca, S, P, Mg, and K from corn stover, mischantus, switch grass and rice hull biomass [51]. This finding is consistent with another study conducted at 180 °C of EFB with washing co-treatment where 92% of K is removed. The treatment also lowered the ash and Cl content to 0.9% and 0.19%, consecutively. Moreover, the calorific value of EFB was improved after combination of HTT with washing from 16.69 MJ/kg to 18.49 MJ/kg as compared with the raw feedstock [52].

In addition, a commercial scale study of HTT of EFB was performed using saturated steam at temperatures between 150 °C and 180 °C and 2 MPa pressure with 30 minutes' holding time. Subsequently, the slurry product is washed at room temperature using centrifugal machine for 30 min and naturally dried. The result shows that the calorific value of EFB increased from 18 MJ/kg to 23.3 MJ/kg which similar to low-grade Indonesian coal and Cl content reduced from 0.35% to 0.22%. Furthermore, the carbon and fixed carbon content increased, and oxygen and volatile matter decreased as compared to raw EFB. The hydrochar also offered low ash and sulphur content in comparison to Indonesian coal. Moreover, it was also found that the grindability of hydrochar was significantly better than the raw EFB which improved the fuel properties [50]. The development of HTT that enables utilization multi range of biomass to produce high quality pellet will significantly increase performance of Malaysian biomass pellet industry as commercialising second generation biofuel is stipulated in NKEA of oil palm industry under seventh EPPs of oil palm NKEA of the ETP of the oil, gas and energy sector in Malaysia.

Currently, the EFB and OPF are mulched and left on the plantation where they function as soil improver and fertiliser that result in odour problem. The ability for nutrient recovery (N, P and K) of macronutrients into the liquid phase during HTT has potential for fertilizer application [53]. The waste water produced from HTT of the agriculture residues can be used as substitution for mulching. Another study of HTT of rice straw found that the process water content solubilised N, P and K similar to that of the micronutrients compound in liquid fertilizer [54]. Developing a high value of ole-derivatives and bio-based chemicals is stipulated under the sixth EPPs of oil palm NKEA of the ETP.

Notwithstanding this, it is found that HTT with water washing co-treatment of MSW at 200 °C and 2 MPa was able to remove up to 96% of inorganic Cl [55]. In comparison with RDF, the significant reduction of Cl content is important for MSW treatment which is known to promote clogging, corrosion and dioxin in combustion. Moreover, the average HHV value of hydrochar from MSW was recorded at 20 MJ/kg and the highest value was 24 MJ/kg which was almost equal to low grade sub-bituminous coal [56]. The HTT can be used to convert mixed MSW into uniform powder samples with low moisture content, regular shapes and high bulk density [57]. A commercial HTT plant at Tangerang, Indonesia with capacity of 50 tonnes/day to process mixed MSW at 220 °C and 2.5 MPa with 30 min holding time was able to reach heating value of 17.9 MJ/kg of naturally dried hydrochar with no bad smell. It was claimed that the plant utilises 10% to 15% of the hydrochar as fuel to run the boiler with capacity 2 tonnes/hour and the rest are sold as alternative to coal. The HTT requires no special gas treatment as the analysis confirmed according to environmental standards. However, the waste water discharge must be treated before discharge to the wetland [58]. Therefore, HTT is more environmentally than conventional incineration technologies.

HTT technology has been proven to treat the high in moisture content feedstock such as empty fruit bunch and MSW into hydrochar with a great reduction of K and Cl. The natural dried hydrochar can be use directly use in the boiler as fuel or can be sell to oil palm mill, coal and cement plant. It can be further process into value added product such as pellet or activated carbon and the liquid by product from the EFB can be utilized as a fertiliser. Besides, the surplus power generated from the oil palm mills or MSW treatment plant can be sold to the national grid to take advantage of the Feed-in-Tariff from biomass and MSW in Malaysia. HTT is a promising pre-treatment of biomass and waste to produce uniform solid fuels with low fouling index, alkali index, and chlorine content and increase calorific value equal to low grade sub-bituminous coal. This is one of most effective means to reduce CO_2 emission associated with coal-firing.

6. Conclusions and Recommendations

In conclusion, the estimated electricity generation potential for solid fuel from oil palm solid residues and MSW in 2017 was 12,226 MW and 1190.42 MW, respectively. This shows that the energy potential from biomass and MSW alone shows remarkable potential to achieve the RE Policy and Action Plan target of 2080 MW and 4000 MW of installed RE capacity in 2020 and 2030, respectively. Notably this value is the theoretical limit and it is impractical to utilize all of the available residues for conversion into solid fuel, even if only 5% of all of these wastes captured would give a value of 670.82 MW, 84% out of the 800 MW national biomass target capacity, by 2020. The findings indicate that OPF has the highest availability and energy potential to serve as promising source of solid fuel for Malaysia. Both oil palm biomass residue and MSW possess huge potential in the Malaysian biomass RE mix for long-term fuel sustainability of feedstock supply. Hydrochar opens possibilities for coal replacement in coal power plants and a variety of value-added extras such as fertilizer and activated carbon. This technology will benefit the policy makers, managers and bioenergy business sector in Malaysia.

Techno economic assessment should be done to compare with the cost for installation of existing WtE technology such as incineration and anaerobic digesters in palm oil mills. Installation of HTT or other similar technology should be included in the FiT and the policy should be revised as the current policy has favoured gasification technology. For rapid technological change without a high investment cost, the installation of HTT facilities at the palm oil mills or within the biomass supply chain should be considered. Government can play an important role by designing a suitable business partnership model. On the other hand, development of new sanitary landfills, upgrading non-sanitary landfills and safe closure of non-sanitary landfills in the long term should be assessed with HTT technology for its economic and environmental viability. Due to fact that HTT technology demands a huge financial investment, technology transfer in terms of local expertise in designing the reactor and boiler, and personnel skilled for operation and maintenance, is an ideal way to reduce dependency on foreign technology.

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