Original Research

Life Cycle Assessment of Waste-to-Energy: Energy Recovery from Wood Waste in Malaysia

Joo Ee Choong[1], Chiu Chuen Onn[1]*, Sumiani Yusoff[2], Nuruol Syuhadaa Mohd[1]

[1]Civil Engineering Department, Faculty of Engineering, University of Malaya,
Kuala Lumpur, Malaysia
[2]Institute of Ocean and Earth Science, Institute of Graduate Studies,
University Malaya, 50603 Kuala Lumpur, Malaysia

Abstract

This paper presents life cycle assessment for a biomass-fired power plant that utilizes recycled wood waste as fuel. Life cycle analysis of the wood WtE plant was done using SimaPro software using an Ecoinvent 3.4 database and ReCiPe Midpoint impact assessment method. The main concern was given to climate change factor through the evaluation of GHG emissions of the wood WtE plant. The results showed that 31.9 g CO_2 eq of GHG emissions are emitted for every kWh of electricity generated by the wood WtE plant. The emissions value was 96.1% lower than the electricity generated by the national grid, which is 820 g CO_2 eq of GHG emissions. In conclusion, WtE emerged as a sustainable approach in disposing of solid waste while reducing GHG emissions and increasing the share of renewable energy in energy mix simultaneously. A scenario was created to show the relationship between the percentage of carbon emissions reduction that is in line with Malaysia's commitment to reduce GHG emissions by up to 45% by 2030, hence making the utilization of biomass and solid waste a reliable source of renewable energy as targeted by SEDA Malaysia.

Keywords: waste-to-energy; solid waste; life cycle assessment; biomass fired power plant; greenhouse gases

Introduction

Solid waste management is one of the most serious and controversial issues encountered by the local and regional authorities of Malaysia. Solid waste generation for the whole of Malaysia is about 33,000 tonnes per day in 2012 and 38,200 tonnes per day in 2016 [1]. Other than waste generation by household, waste generation by industrial, commercial and institution (ICI) also encompasses municipal waste, but construction and demolition waste, as well as industrial scrap, are excluded [2]. ICI waste includes food wastes, packaging, housekeeping wastes, paper, cardboard, plastics, wood, glass and metals. The generation of solid waste in

Malaysia is estimated to reach 45,900 tonnes per day in 2020, whereas 16.76 million tonnes of waste is expected to be generated annually by 2020 [1]. Solid waste management will be a tough challenge since Malaysia depends solely on landfilling for waste disposal. Direct disposal of 91.3% of total solid waste generated in 2012 has resulted in more than 10 million tonnes of solid waste being disposed of in landfills [1]. In 2016, 82.5% of total solid waste generated, which is approximately 13 million tonnes of solid waste, is being disposed of in 161 landfills across Malaysia, with 17.5% being recycled [1]. Undeniably, landfill is always the best disposal method, especially in developing countries, due to its economically simple management. Although landfilling offers an economical waste disposal method, tremendous increases in solid waste disposal will accelerate environmental degradation through air and water pollution if not properly managed.

Out of the total 33,000 tonnes of solid waste generated per day as reported in 2012, ICI waste generation is about 11,500 tonnes while the average ICI per capita waste generation is 0.41 kg/capita/day. Generally, industrial waste in Malaysia mainly consists of plastic, paper, food waste and wood, which is accumulated for 39.1%, 35.1%, 5.8% and 4.5% respectively [2]. Energy content of ICI waste is generally high except for food waste, which has high moisture content. Plastic, rubber, leather, cardboard and wood wastes have lower calorific value (LCV) more than 14 MJ/kg. The average calorific value for wood waste is between 16.488 MJ/kg (lower heating value, wet basis) and 20.092 MJ/kg (higher heating value, dry basis) [2]. A better option should be available to dispose of these wastes instead of landfilling.

Waste-to-energy (WtE) has emerged as one of the solutions for solid waste management in Malaysia. Waste-to-Energy includes gasification, incineration and pyrolysis processes that thermally treat solid waste and directly recover energy in the form of electricity and/or heat. Also, WtE involves bio-chemical processes such as landfill gas recovery and anaerobic digestion that converts chemical energy in solid waste to yield products of high energy value, for example methane [3]. WtE systems fit well within the concept of 'zero waste,' along with the recycling and reuse of the MSW as WtE can provide additional economic benefits in recovering up to 90% of ferrous materials from both waste-stream inflow and bottom-ash outflow [4]. Studies suggest that waste incineration power generation is a better option than landfill gas utilization from the perspective of GHG emission reduction, while some studies have suggested that the environmental impact of MSW management can be reduced by WtE [5]. WtE has the potential to solve the problems of waste management, energy demand and greenhouse emissions simultaneously [6]. WtE is a good option for waste management as it is effective in reducing the weight and volume of waste, thus saving land space for landfilling. WtE is able to convert the waste into heat and electrical energy. Since Malaysia's climate is hot and humid throughout the year, the heat energy can be supplied to industries instead of residential heating for households. Generated electricity can be fed into the national grid and act as a source of renewable energy (RE) to curb the increasing demand for electricity generation, since electricity consumption in Malaysia has risen extensively over the past few decades along with the growth of Malaysia's population and gross domestic product (GDP). Annual electricity generation of Malaysia in 2015 is 144,565 GWh, which has increased 0.513% from 143,827 GWh of the previous year [7]. Although both conventional and renewable sources of energy contribute to power generation in Malaysia, only a very small portion of electricity that is less than 1% is generated by renewable sources such as biomass, solar and biogas. Fossil fuels such as coal, crude oil and natural gas are the most reliable source of energy supply globally, which accumulate for 84% of global electricity production, while 88.4% of Malaysia's electricity output is generated from burning fossil fuel resources [7, 8]. Electricity generated from the combustion of fossil fuels has created various environmental issues where the primary concerns will be emissions of carbon dioxide and climate change issues. Therefore, renewable energy sources have gained more attention in the last two decades [9]. In order to promote the use of renewable energy in Malaysia, a feed-in tariff (FiT) system has been established with the enforcement of the Renewable Energy Act 2011. Under this FiT system, the Sustainable Energy Development Authority (SEDA) of Malaysia has targeted increasing renewable energy capacity up to 4,000 MW by 2030, during which 1,340 MW of RE capacity is expected to be generated from biomass while 360 MW will come from solid waste [10]. Malaysia has great biomass and wood waste resources available for immediate exploitation [11]. There are more biomass resources to be exploited in all regions of Malaysia – especially in rural areas.

Life-cycle thinking (LCT) has been introduced as a guiding principle of resource management where the strategic goal of moving toward more sustainable patterns of consumption and production has been set with a view to decoupling resource use and waste generation [12]. Tools and methods are used in quantifying and comparing the environmental impacts of providing products and services to society for sustainable development. Life cycle assessment (LCA) is a useful tool that considers the entire life cycle of a specified product from cradle to grave. It is guided by ISO 14040 (2006). LCA is a well-established research method allowing for the identification of environmental threat and evaluation of the amount of used raw materials and produced energy, as well as the amount of impurities, discharged waste and their environmental impact. LCA helps identify potential threats and establish new ways of improving environmental quality

standards [13]. Thus, LCA is able to help the decision makers in selecting suitable strategies and comparing the energetic and environmental performances of different WtE options. Life cycle assessment is one of the most effective methods allowing for evaluation and comparison of the environmental impact of energy production of different power plants [13, 14].

This study aimed to use the life cycle assessment method to study the potential of implementing WtE technology in Malaysia. This study considers a biomass-fired power plant with a capacity of 7 MW in Selangor, Malaysia. The WtE plant uses wood waste as fuel for electricity generation. Life cycle assessment methodology is used to evaluate the environmental impacts associated with the wood WtE plant. The environmental impacts generated by WtE are used to make a comparison with the national grid to determine the potential of WtE technology implementation in Malaysia.

Material and Methods

Life Cycle Assessment

Life cycle assessment (LCA) is a useful tool for determining the environmental impacts of products,

services or processes, considering their entire life cycle from cradle to grave. LCA is chosen as the methodology to carry out this study to evaluate environmental impacts of wood waste to energy plant in generating electricity.

Goal and Scope Definition

The goal of this study is to identify the potential of WtE technology as an alternative of landfilling in a developing country. The focus is on the case of Malaysia, a developing country that depends solely on landfilling in solid waste management. The objectives of the study are to develop an LCA model for wood waste-to-energy plant and to evaluate the environmental impacts of wood waste-to-energy plant in generating electricity. The results will then be compared to the current national grid in generating 1 kWh of electricity from the perspective of environmental impacts.

Data Sources

The obtained data was from a 7 MW biomass-fired power plant owned by a paper mill at Rasa, Selangor, Malaysia. This plant was the only WtE plant that utilized wood from ICI waste as fuel that enrolled in a feed-in tariff (FiT) mechanism introduced by the Malaysian government under biomass-solid waste category as
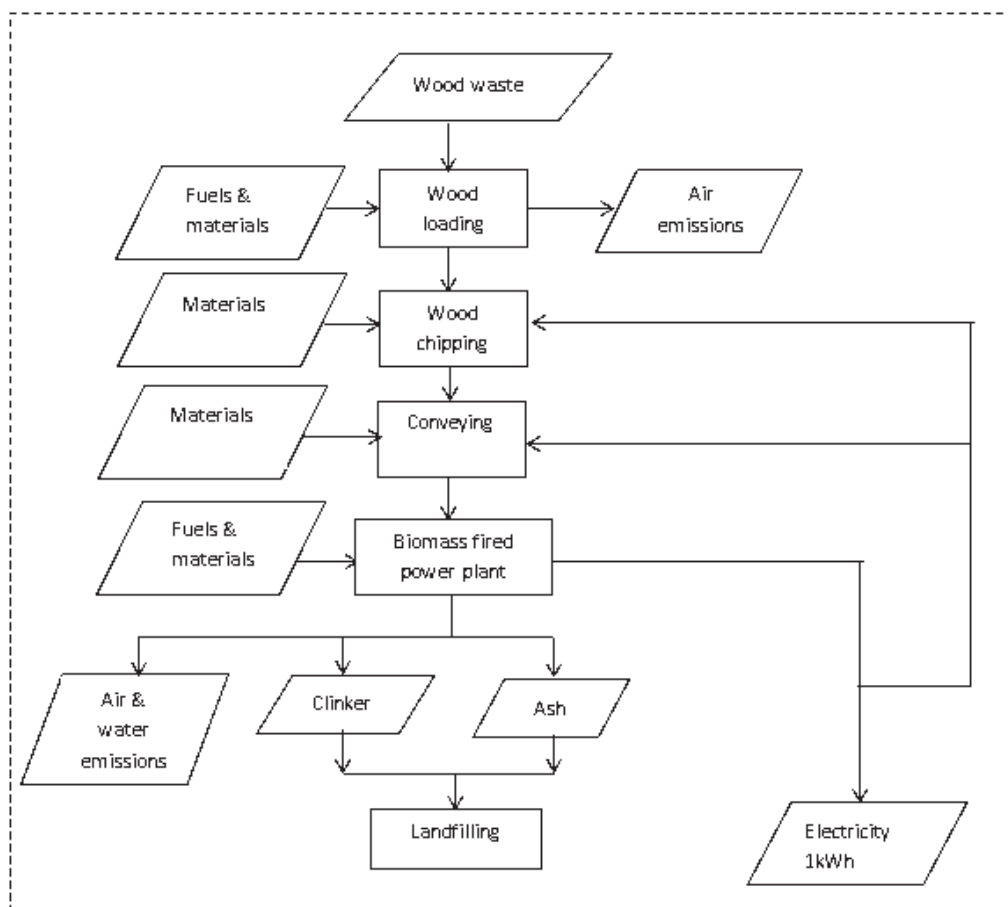

Fig. 1. The system boundary for the LCA study.

Table 1. Inventories for generation of 1 kWh electricity fed into national grid by wood WtE plant.

	Input	Unit	Amount	Output	Unit	Amount
	Input from technosphere: materials/fuels			Emissions to air		
Wood loading within facility	Diesel {GLO}| market group for	APOS, U	kg	0.0020176	Carbon monoxide, fossil	kg	6.1498E-06
	Shed {GLO}| market for	APOS, U	m²	8.536E-07	Carbon dioxide, fossil	kg	0.003201
	Tractor, 4-wheel, agricultural {GLO}| market for	APOS, U	kg	1.1407E-04	Dinitrogen monoxide	kg	1.23578E-07
				Methane, fossil	kg	1.3289E-07
				Nitrogen oxides	kg	4.6754E-05
				NMVOC, non-methane volatile organic compounds, unspecified origin	kg	3.0846E-06
				PAH, polycyclic aromatic hydrocarbons	kg	3.395E-09
				Particulates, < 2.5 um	kg	4.365E-06
				Sulfur dioxide	kg	1.0379E-06
Wood chipping	Input from technosphere: materials/fuels					
	Chipper, stationary, electric {GLO}| market for	APOS, U	kg	1.04372E-07			
	Lubricating oil {GLO}| market for	APOS, U	kg	3.96924E-06			
	Steel, low-alloyed, hot rolled {GLO}| market for	APOS, U	kg	7.9152E-06			
Conveying	Input from technosphere: materials/fuels					
	Conveyor belt {RER}| production	APOS, U	m	3.145E-09			
	Conveyor belt {RoW}| production	APOS, U	m	6.368E-09			
	Lubricating oil {GLO}| market for	APOS, U	kg	9.925E-14			
Biomass fired power plant	Input from technosphere: materials/fuels			Emissions to air		
	Waste wood, post-consumer {GLO}| waste wood, post-consumer, Recycled Content cut-off	Cut-off, U	kg	1.94	Benzene	kg	3.345E-05
	Ammonia, liquid {RoW}| market for	APOS, U	kg	2.999E-07	Cadmium	kg	2.5605E-08
	Chlorine, gaseous {RoW}| market for	APOS, U	kg	2.89E-05	Carbon dioxide, biogenic	kg	3.529
	Dust collector, electrostatic precipitator, for industrial use {GLO}| market for	APOS, U	p	1.90959E-08	Carbon monoxide, biogenic	kg	0.007336
	Lubricating oil {GLO}| market for	APOS, U	kg	0.00012	Dinitrogen monoxide	kg	8.418E-05
	Furnace, wood chips, with silo, 5000kW {GLO}| market for	APOS, U	p	1.90959E-08	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	p	1.137E-12
	Heat and power co-generation unit, organic Rankine cycle, 1000kW electrical {GLO}| market for	APOS, U	p	1.90959E-08	Lead	p	9.181E-07
	Sodium chloride, powder {GLO}| market for	APOS, U	kg	2.89E-05	Methane, biogenic	kg	5.5132E-05
	Water, decarbonised, at user {GLO}| market for	APOS, U	kg	0.069286	Nitrogen oxides	kg	0.005513

NMVOC, non-methane volatile organic compounds, unspecified origin	kg		$1.285E^{-04}$
Particulates, < 2.5 um	kg		$9.181E^{-04}$
Water/m^3	m^3		0.0021298
Zinc	kg		$1.1E^{-05}$
Outputs to technosphere: waste treatment			
Waste mineral oil {RoW}| market for waste mineral oil	APOS, U	kg		0.00012
Wastewater, average {RoW}| market for wastewater, average	APOS, U	m^3		$6.9286E^{-05}$
Inert waste, for final disposal {RoW}| market for inert waste, for final disposal	APOS, U	kg		0.194
Biomass fired power plant			

of December 2017. The data enquiries were made through a site visit from March 2017 to November 2017. There were interview sessions with the plant engineer and operator to get the actual data of the operating plant. However, some data was unobtainable due to industrial confidentiality. Hence, secondary data of case studies from the Ecoinvent database (version 3.4) were used as part of the inventories for this LCA study.

System Boundary

The boundaries of the wood waste-to-energy system incorporated the incoming of wood waste until its final discharge, including the production of steam and electricity. Only inputs and outputs relative to the operation were included. Construction and maintenance of the plant were neglected. The system boundary for this LCA study was shown in the schematic diagram in Fig. 1.

Functional Unit

The functional unit reflects the function of the investigated product. In this case study, waste wood acts as a kind of biofuel to supply heat and electrical energy. The focus is given to the potential of electricity generated by the wood WtE plant. Thus, the chosen functional unit for this LCA study is 1 kWh of electricity generated by the wood WtE plant.

Limitation and Assumption

For this LCA model, transportation will only involve the transfer and loading of wood waste during the operation. Transport distance and route during the collection of the wood waste and final disposal of clinker to landfill are neglected. No additional fuel is added for the combustion of wood waste in boiler as the plant is operating continuously since the first ignition. The wood waste consists of all kind of wooden furniture from households, plus branches, stumps, timbers, whole trees from street or park maintenance, wood pallets, wood chips and sawdust. The wood waste that was being fed into the boiler has a moisture content of less than 25%.

Life Cycle Impact Assessment Methodology

SimaPro software (version 8.5) was chosen to perform the LCA of wood WtE plant due to its reputation as an accredited LCA tool that was widely used globally. The software comes with an updated Ecoinvent database (version 3.4) libraries as well as various impact assessment methods.

Life cycle impact assessment (LCIA) methodology is the method used to determine the potential impacts of the selected attributes. Different methodologies used different approaches, but all will ultimately give

the potential impacts associated to the study. Multiple impact assessment methods can be distinguished by midpoint and endpoint, referring to different stages in the cause-effect chain when calculating the result of LCA.

Among available LCIA methods, a selection had been made where ReCiPe Midpoint (H) was chosen to determine the potential impacts of the wood WtE plant. The ReCiPe method converted the long list of LCI results into a limited number of indicator scores that represent relative severity on environmental impact categories. The environmental impacts are quantified based on 18 impact subcategories. Levels of indicator for this method cover three cultural perspectives:

i) Individualist (I), based on short-term interest and effective for optimism future technology development to avoid arising problems.

ii) Hierarchist (H), considered the medium time frame, is the most common policy principles, also acts as the default model.

iii) Egalitarian (E), considered the longest time-frame, is a long-term based precautionary principle thinking; among all, Hierarchist (H) was selected as the main goal of this study to evaluate the potential of implementing WtE technology in Malaysia, so that policy-makers may consider this choice in planning an integrated solid waste management system.

Results and Discussion

Inventory Analysis

Environmental performance of each life cycle process was evaluated by identifying inputs and outputs for every process. The inventory data was collected, calculated and then related to the functional unit for calculating the energy and material flows linked to each life cycle process and passed the system boundary. The WtE selected for this study was a biomass cogeneration power plant with a capacity of 7 MW, which utilizes recycled wood waste as fuel for generating electricity and heat. The process started after the collected wood waste reached the site until the final disposal of the ash and clinker remained from being generated during the combustion of the wood waste.

Inventory Selection

The inventory selection was made based on the LCI database that exactly or partially matched the data collected at the studied WtE plant. Missing data would be extracted from literature and case studies done by other LCA practitioners, which was available in the database. Table 1 showed the inventories for generating 1 kWh electricity fed into the national grid by the wood WtE plant.

Results that referred to the environmental impacts will be calculated with reference of the functional unit, which was 1 kWh of output electricity generated by the wood WtE with ReCiPe Midpoint (H) V1.13 / World Recipe H method.

LCA of Wood WtE Plant

For impacts to human health, generating 1 kWh electricity by wood WtE plant contributed 31.9 g CO_2 eq to climate change, $1.65E^{-06}$ g CFC-11 eq in term of ozone depletion, $3.55E^{-04}$ g NMVOC of photochemical oxidant formation, 0.219 g PM_{10} eq of particulate matter formation, 3.13 Bq U235 eq of ionizing radiation and 21.7 g 1,4-DB eq of human toxicity. For impacts to the ecosystem, generating 1 kWh from wood WtE plant caused 2.15 g SO_2 eq impacts to terrestrial acidification, 0.0978 g P eq impacts to freshwater eutrophication, 0.0605 g N eq impacts to marine eutrophication, 6.06 g 1,4-DB eq impacts to terrestrial eco-toxicity, $-8.61E^{-03}$ g 1,4-DB eq of impacts to freshwater eco-toxicity, 0.591 g 1,4-DB eq of impacts to marine eco-toxicity, $3.98E^{-05}$ m^2a of impacts to agricultural land, $7.4E^{-05}$ m^2a of impacts to urban land and $3.12E^{-04}$ m^2 of impacts to natural land transformation. For impacts to resource availability, generating 1 kWh from wood WtE plant caused fossil depletion, metal depletion and water depletion of $2.2E^{-05}$ kg oil eq, 0.00021 kg Fe eq and 0.00311 m^3 respectively.

LCA of Wood WtE Plant vs. National Grid for Every kWh of Electricity Generation

The environmental impact of each kWh of electricity generated by the wood WtE plant will be compared to the environmental impacts of every kWh generated from the national grid based on a previous study by Onn, C.C., et al. 2017 [15]. A total contribution of 31.9 g CO_2 eq GHG emissions (96.1% lower) was generated by the wood WtE plant, whereas 820 g CO_2 eq was emitted by the national grid for every kWh of electricity generated. The wood WtE plant would produce more impacts to human health than the current national grid for every kWh of electricity generation in term of ozone depletion (33.82%) and ionizing radiation (29.01%). However, the wood WtE plant generated slightly lower impacts in term of human toxicity (13.2%), photochemical oxidant formation (99.99%) and particulate matter formation (89.05%) than the current national grid in generating 1 kWh of electricity.

Generating 1 kWh electricity from both wood WtE plant and the national grid resulted in low impacts to the ecosystem. The current national grid had zero impact on agricultural land occupation, urban land occupation and natural land transformation. The wood WtE plant would produce impacts of $3.98E^{-05}$ m^2a, $7.4E^{-05}$ m^2a and $3.12E^{-04}$ m^2 respectively in term of agricultural land occupation, urban land occupation and natural land transformation impacts. Impacts to terrestrial acidification (46.25%), marine eutrophication

Table 2. Impact assessment of wood WtE plant vs current national grid in generating 1 kWh electricity.

SimaPro 8.5.0.0			
Project	Wood WtE		
Calculation	Impact assessment		
Results	Analyse		
Product	Generation of 1kWh electricity by wood WtE		
Method	ReCiPe Midpoint (H) V1.13 / World Recipe H		
Indicator	Characterisation		
Skip categories	Never		
Exclude infrastructure processes	No		
Exclude long-term emissions	No		
Sorted on item	Impact category		
Sort order	Ascending		
Impact category	Unit	Wood WtE	National Grid
Climate change	kg $CO_{2\ eq}$	0.0319	0.820
Ozone depletion	kg CFC-11 eq	$1.65E^{-09}$	$4.739E^{-11}$
Ionizing radiation	kBq U235 eq	0.00313	0.0001043
Photochemical oxidant formation	kg NMVOC	$3.55E^{-07}$	0.003
Particulate matter formation	kg PM_{10} eq	0.000219	0.002
Human toxicity	kg 1,4-DB eq	0.0217	0.025
Terrestrial ecotoxicity	kg 1,4-DB eq	0.00606	$1.262E^{-05}$
Terrestrial acidification	kg SO_2 eq	0.00215	0.004
Agricultural land occupation	m²a	$3.98E^{-05}$	0.000
Urban land occupation	m²a	$7.4E^{-05}$	0.000
Natural land transformation	m²	0.000312	0.000
Marine ecotoxicity	kg 1,4-DB eq	0.000591	0.0001968
Marine eutrophication	kg N eq	$6.05E^{-05}$	0.00011
Freshwater eutrophication	kg P eq	$9.78E^{-05}$	$5.385E^{-07}$
Freshwater ecotoxicity	kg 1,4-DB eq	$-8.61E^{-06}$	$7.657E^{-06}$
Fossil depletion	kg oil eq	$2.2E^{-05}$	9.569
Metal depletion	kg Fe eq	0.00021	0.225
Water depletion	m³	0.00311	0.014

(45%) and freshwater eco-toxicity (212.45%) generated by wood WtE plant were lower than the national grid, whereas impacts to terrestrial eco-toxicity (47919%), marine eco-toxicity (200.3%) and freshwater eutrophication (18061.56%) generated by wood WtE plant were higher than the national grid.

Generating 1 kWh from wood WtE plant created lesser impacts to resource availability than the national cycle, which produced a huge impact on fossil depletion, which was 9.569 kg oil eq (100%) higher compared to wood WtE plant with only 2.2E⁻⁰⁵ kg oil eq due to electricity generation in Malaysia being dominated by fossil fuels such as natural gas, coal and oil. Generating 1 kWh electricity by national grid contributed 99.91% higher in term of metal depletion and 77.79% higher to water depletion than wood WtE plant.

Potential of WtE as Renewable Energy

The government of Malaysia has been promoting renewable energy (RE) resources such as biogas, biomass, hydro and solar since the 8th Malaysia Plan (2001-2005). RE was added to the national

Table 3. Malaysia's cumulative total RE target.

Year	Targeted cumulative total RE (MW)						Annual RE generation (GWh)	RE mix (%)
	Biogas	Biomass	Biomass (solid waste)	Small hydro	Solar PV	Total		
2017	155	500	280	400	105	1440	5385	5
2020	240	800	360	490	190	2080	11246	9
2030	410	1340	390	490	1370	4000	17232	12

electricity mix due to the rise of climate change as a global issue. Table 3 stated the outcome and target of cumulative total RE in National Renewable Energy Policy 2010.

Since Malaysia has pledged to cut the country's carbon emissions intensity based on the GDP by up to 45% by 2030 relative to 2005 value, where 35% on an unconditional basis with a further 10% condition upon climate finance, technology transfer and capacity building during the 21st United Nations Framework Convention on Climate Change (UNFCCC), massive transformation should be taken to develop the national grid toward greener sources [15, 16].

Malaysia's government aimed to increase the share of RE progressively in the national electricity mix for reducing carbon emissions as the highest carbon emissions were contributed to by the energy sector. However, the targeted cumulative total RE was not achieved due to output intermittency, location and system constraints, as well as technology development in Malaysia. Recently, the total cumulative total RE was far from the target and only achieved about 35% of the targeted cumulative total RE. Based on the target set by the Minister of Energy, Green Technology and Water, cumulative total RE should achieve 1440 MW, where 10.76% of RE was contributed by biogas, 34.72% by biomass, 19.44% by solid waste, 27,78% by small hydro and 7.3% by solar PV. Until 2017 there was only 514.44 MW of cumulative total RE. The largest share was contributed to by solar PV, which was 66.8% of the cumulative total RE. 15.7% was from biomass while 10.2% of current RE was from biogas. 5.9% of RE was from mini hydro. There was only 1.4% of cumulative total RE contributed by solid waste, which utilized waste wood for electricity generation.

31.9 g CO_2 eq of GHG emissions are emitted for every kWh of electricity generated by the wood WtE plant. Based on work done by the Intergovernmental Panel on Climate Change in 2014, carbon dioxide equivalent (CO_2 eq) findings on biogenic CO_2 emissions and albedo effect of biomass power plant is 27 g CO_2 eq/kWh [17]. This value does not consider the emissions of infrastructure and supply chains, while a biomass power plant emitted 10-101 g CO_2 eq GHG emissions for every kWh of electricity generation as reported by the World Nuclear Association [18]. The life cycle greenhouse gas emissions for biomass electricity generator are varied from 14 to 35 g CO_2 eq/kWh as reported by Sovacool (2008) [19]. The percentage of carbon emissions from WtE is 96.1% lower than the carbon emission generated from the electricity generation mix of the current national grid as more than 90% of the electricity generation mix in Malaysia is composed of fossil fuels. As reported by the Malaysia Energy Commission, electricity mix Malaysia is dominant by 41% of coal and 46.3% of natural gas. Hydropower contributed 10.7% to the generation mix at the end of 2015 [7]. Coal power plants emitted an average of 820 g CO_2 eq while gas power plants emitted 490g CO_2 eq of GHG emissions for 1 kWh electricity generation [8]. The value for emissions of GHG is much lower in wood WtE due to biogenic CO_2 emissions considered in this case study. Biogenic and fossil CO_2 emissions are not equated in this case as combustion of wood waste does not increase the amount of carbon in the global carbon cycle. WtE could be the potential source for RE generation as it produced as low as 31.9 g CO_2 eq GHG emissions for every kWh of electricity generation. Malaysia aimed to achieve 9% of RE in the generation mix by 2020 and 12% by 2030. If Malaysia succeeds in achieving the target set by the Sustainable Energy Development Authority by introducing WtE as a potential RE source from biomass, there will be an avoidance of 928,000 tonnes CO_2 eq of GHG emissions annually beginning in 2020, and in 2030 there will be an avoidance of 1,384,000 tonnes

Table 4. The potential of CO2 avoidance as RE target is achieved.

Year	WtE generation (GWh)	GHG emissions with current electricity mix (tonnes of CO_2 eq)	GHG emissions with WtE (tonnes of CO_2 eq)	GHG emissions avoidance with targeted RE capacity and WtE as potential source (tonnes of CO_2 eq)
2020	1160	951200	23200	928000
2030	1730	1418600	34600	1384000

CO_2 eq of GHG emissions annually. These will ultimately help Malaysia cut the country's carbon emissions intensity as the highest carbon emissions were contributed by the energy sector in Malaysia.

Conclusions

Although WtE technologies are effective in solid waste management and electricity generation, the installation of a WtE plant in Malaysia, a developing country, is still limited. In order to study the potential of implementing WtE technology in Malaysia, LCA methodology was applied to assess a WtE plant which, was the only one currently involved in the FiT mechanism introduced by government under biomass-solid waste category from environmental perspective.

The biomass-fired power plant that utilized wood waste as fuel produced only 31.9 g CO_2 eq in generating 1 kWh of electricity. Its GHG emissions was much lower than the national electivity grid, which was dominated by a fossil fuel-fired power plant. However, the biomass-fired power plant would produce more impacts on the environment than the national grid for every kWh of electricity generation in term of ozone depletion, ionizing radiation, terrestrial eco-toxicity, agricultural land occupation, urban land occupation, natural land transformation, marine ecotoxicity and freshwater eutrophication.

The government of Malaysia had been promoting the use of RE where biomass and solid waste were included in generation of RE. The government aimed to achieve 1440 MW of cumulative total RE by 2017, where 34.72% was contributed by biomass and 19.44% by solid waste, but there was only 514.44 MW of cumulative total RE achieved in 2017. There was only 1.4% of cumulative total RE contributed by solid waste, which utilized waste wood for electricity generation and 15.7% from biomass. If Malaysia succeeded in achieving the RE target set by the Sustainable Energy Development Authority, there could be an avoidance of 928,000 tonnes CO_2 eq of GHG emissions annually after 2020 and 1,384,000 tonnes CO_2 eq of GHG emissions annually after 2030. The implementation of WtE technologies could be seen as a potential drive to reduce greenhouse gas emissions and act a source of RE toward green growth and sustainable development of Malaysia.

Acknowledgements

Conflict of Interest

The authors declare no conflict of interest.

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