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Energy and emissions benefits of renewable energy derived from municipal solid waste: Analysis of a low carbon scenario in Malaysia

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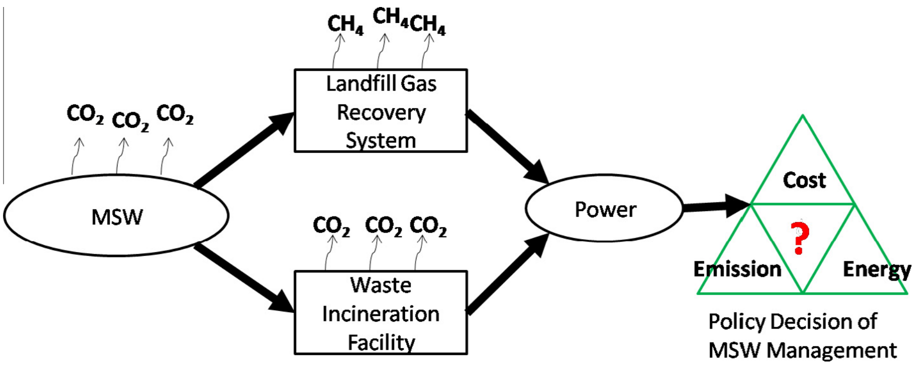
HIGHLIGHTS

- Feasibility study on the energy and GHG emission reduction for WtE strategies for municipal solid waste (MSW) in Malaysia.
- Greenhouse gases (GHG) emissions from WtE strategies analysed using IPCC guideline.
- Scenario analysis by comparison of different WtE strategies.
- Impact of moisture content of MSW towards energy potential and GHG emission reduction.

GRAPHICAL ABSTRACT



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ABSTRACT

Ineffective waste management that involves dumping of waste in landfills may degrade valuable land resources and emit methane gas (CH_4), a more potent greenhouse gas than carbon dioxide (CO_2). The incineration of waste also emits polluted chemicals such as dioxin and particle. Therefore, from a solid waste management perspective, both landfilling and incineration practices pose challenges to the development of a green and sustainable future. Waste-to-energy (WtE) has become a promising strategy catering to these issues because the utilisation of waste reduces the amount of landfilled waste (overcoming land resource issues) while increasing renewable energy production. The goal of this paper is to evaluate the energy and carbon reduction potential in Malaysia for various WtE strategies for municipal solid waste (MSW). The material properties of the MSW, its energy conversion potential and subsequent greenhouse gases (GHG) emissions are analysed based on the chemical compositions and biogenic carbon fractions of the waste. The GHG emission reduction potential is also calculated by considering fossil fuel displacement and CH_4 avoidance from landfilling. In this paper, five different scenarios are analysed with results indicating a integration of landfill gas (LFG) recovery systems and waste incinerator as the major and minor WtE strategies shows the highest economical benefit with optimal GHG mitigation and energy potential. Sensitivity analysis on the effect of moisture content of MSW towards energy potential and GHG emissions are performed. These evaluations of WtE strategies provides valuable insights for policy decision in MSW management practices with cost effective, energy benefit, environmental protection.

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1. Introduction

Rapid generation of solid waste resulting from economic development and population growth had become one of the most significant environmental issues of our time. It requires an appropriate management of municipal solid waste (MSW) which involves control of the atmospheric emissions and aqueous effluents coming from landfills, waste collection, transportation, and processing of waste. MSW can be processed in one of three ways: thermal treatment, biological treatment, or landfilling [1]. Thermal MSW treatment reduces the volume of waste through heat energy and produces biofuels (i.e., syngas, char, or bio-oil). The typical thermal treatment of waste involves combustion (incineration), gasification, and pyrolysis. Biochemical treatment on the other hand, is an environmentally friendly method of waste disposal which is based on enzymatic decomposition of organic matter by microbial action to produce methane (CH_4) or alcohol. Waste residues obtained through both thermal conversion and biological conversion is then landfilled. These waste treatment approaches and their products are illustrated in Fig. 1.

Waste-to-energy (WtE) is recognised as a promising alternative to overcome waste generation problem and a potential renewable energy (RE) source. Energy can be recovered from biodegradable and non-biodegradable matter through thermal and biochemical conversions [2]. The most two common practice for WtE method is waste incineration and landfill gas (LFG) recovery system. Waste incineration is suitable for waste which is non-biodegradable matter with low moisture content. It solves the degradation of valuable land resources for landfill and avoids generation of methane gas (CH_4) from landfill. Some large-scale WtE has been implemented in developed countries such as Japan, Germany, Sweden, The Netherlands, Denmark, and the United Kingdom. However, WtE is still under development in Malaysia [3]. Only one incineration plant is currently in operation, with an energy recovery system that can produce 1 MW of electricity from 100 t/d of MSW, in Langkawi, Malaysia [4]. The other four Malaysian incineration plants, located at Pangkor Island (20 t/d), Tioman Island (15 t/d), Cameron Highland (40 t/d) and Semenyih (100 t/d), have been discontinued due to the high operation costs arising from high moisture content of waste [5]. Challenges remain for the other existing incinerators, where many units require improvements before they can be incorporated into an energy recovery system, nevertheless, because the high moisture content of waste (52.65–66.2%) [6], it leads to high operational and fuel costs.

Due to high price of incineration technologies, the generation of LFG from landfill site has gained increasing attention. LFG recovery system is well suited to a high percentage of biodegradable matter with high moisture content. It helps in mitigation of GHG emissions from waste by converting CH_4 to carbon dioxide (CO_2). This option has therefore been considered as an important and crucial factor to successful waste management. Most of the landfills in Malaysia involve small-scale operations in controlled or uncontrolled open dumps with minimal or non-existent environmental control [7]. In 2007, there were approximately 291 waste disposal landfill sites in Malaysia, but only 3% were sanitary landfills [8]. The number of landfills in Malaysia encourages the implementation of LFG recovery at landfill sites because it would reduce environmental problems such as GHG emissions and river pollution arising from discharged leachate [8]. The utilisation of LFG as a RE could reduce CH_4 emissions from the landfill sites. Statistically, 47% of the total CH_4 emissions in Malaysia are generated from landfills [9], and there are currently four LFG recovery plants in Malaysia, located at Bukit Tagar (Kuala Lumpur), Taman Beringin (Kuala Lumpur), Seelong (Johor) and Kampung Kelichap (Johor). The first grid-connected RE facility in Malaysia was commissioned at the Air Hitam Sanitary Landfill in 2004, with a capacity for processing 7 Mt of MSW and the ability to generate up to 2 MW of power. However, this facility's operations were halted in 2007 due to technical problems [4].

Feasibility analyses of WtE in Malaysia have been explored by local researchers over the past decade. Johari et al. (2012) have conducted a study of the economic and environmental benefits of LFG, using the Intergovernmental Panel on Climate Change (IPCC) methodology to estimate the CH_4 generated by the disposal landfill. They have concluded that approximately 310,220 t CH_4/y could be generated from MSW in Malaysia, and approximately 1.9 billion kW h of electricity could be generated from these sources [8]. Another similar study by Noor et al. (2013) has estimated the projection of CH_4 emissions from 2015 to 2020 using IPCC methodology, also proving that LFG could be a promising energy source that would fulfil approximately 1.5% of Malaysia's energy requirement [10]. Moreover, Kalantarifard and Goh (2011) have presented a real case study of the feasibility of landfill gas use at the Tanjung Langsat landfill in Johor Bahru, Malaysia. Their

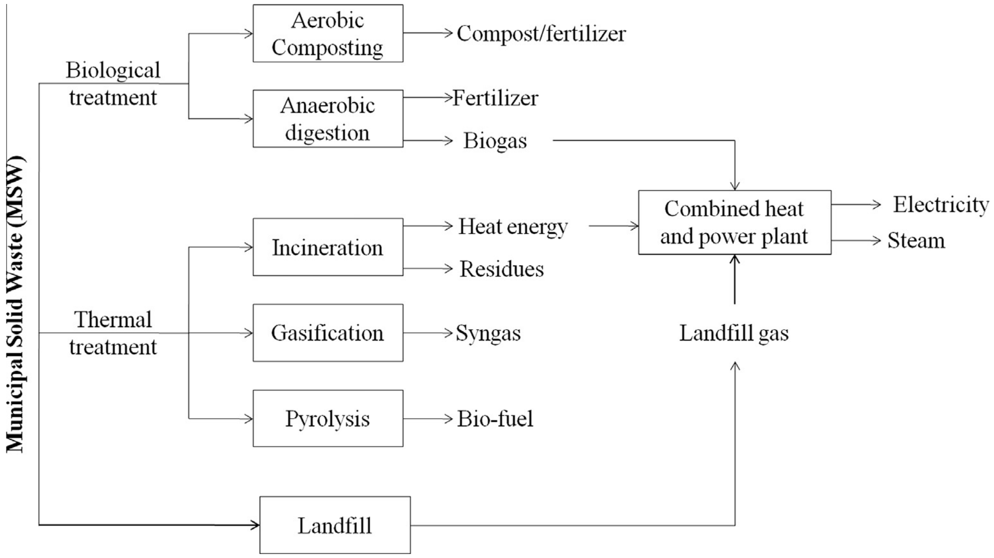

Fig. 1. Alternative waste treatment technologies and their products.

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study has focused on the physical and chemical characteristics of MSW and their effect on energy conversion at the Tanjung Langsat landfill. The heating value has been determined and compared using mathematical models and based on proximate analysis results, and the study has found that the MSW at the selected landfill in Malaysia has a high heating value (approximately 23,000 kJ/kg) [11]. Another study by Johari et al. (2012) has analysed the effect of moisture content in waste on thermal conversion by simulating the heat content of MSW using mathematical equations and comparing it with actual lab-scale results. A generalisation technique has been used to estimate the chemical and physical properties of simulated MSW and successfully overcome the heterogeneous complexity of actual MSW [12].

While most studies have focused on RE production from LFG, there is still a need for a comprehensive study on the feasibility of WtE strategies for MSW in Malaysia in terms of energy conversion and carbon reduction. Therefore, the goal of this paper is to assess the potential of WtE for RE production and carbon reduction in Malaysia. Two WtE technologies, waste incineration and landfill gas recovery, are selected in this study because as they are the most preferable WtE techniques in existence today. An overview of a current waste management scenario in Malaysia is presented in Section 2 as a case study. The proposed methodology with which this study is conducted is then described in Section 3, and the results are reported and discussed in Section 4, along with a sensitivity analysis.

2. A waste management scenario in Malaysia

Malaysia's Solid Waste and Public Cleansing Management Act of 2007 define MSW as controlled solid wastes that include commercial, household, institutional and public solid wastes (Act 672). Malaysia's MSW generation in Malaysia has recently approached a critical limit, especially in terms of composition and amount. Among the key factors contributing to the increase in MSW generation are population growth, rapid urbanisation, economic growth and a multicultural society that celebrates various festivals [1]. The amount of solid waste generated increased by 28% over a 10-year period, from 5.6 Mt in 1997 to 7.65 Mt in 2007 [10], and it is predicted to further increase by 30% in 2020 and 39% in 2030 compared to the baseline year of 2007 [9]. Table 1 shows the recorded and projected population and waste generation in Malaysia between the years 2000 and 2030. MSW composition is dominated by organic waste (food waste), which accounts for approximately 41.1% of the total, followed by plastics (22.2%), paper (20.9%), textile (7.7%), glass (3.6%), wood and garden waste (2.2%) and metal (2.0%) [14]. MSW in Malaysia is characterised by its high moisture content, attributable to a tropical climate with heavy rainfall, and a lack of segregation at its source.

Table 2 shows the current practices and technologies relevant to MSW management in Malaysia and future targets for 2020. Current waste management in Malaysia is very much dependent on landfilling as only 5.5% of its MSW is recycled and 1.0% is composted, while the remaining 93.5% is disposed at landfilling sites [13]. Over dependency on landfilling has caused many environmental issues and alerted the government to gradually diminish open landfill sites and replace them with sanitary and inert landfill sites. The government also interested to engage incineration technologies to process up to approximately 17% of total generated MSW, while simultaneously emphasising on 3R (reduce, reuse and recycle) practices, notably recycling, beyond 2020 [14].

Table 1
MSW generation in Malaysia (2000–2030) [10].

Year	Population (M)	Quantity (Mt)
1997	21.13	5.60
1998	21.67	6.00
1999	22.22	6.11
2000	23.51	6.37
2002	24.60	6.61
2006	26.90	7.34
2010	28.60	8.19
2020[a]	32.40	9.82
2030[a]	36.09	13.38

[a] Forecasted value.

Table 2
Current practices and future targets for MSW management in Malaysia [14].

Treatment technology	Percentage of waste disposed (%)	
	2006	2020 Target
Recycling	5.5	22.0
Composting	1.0	8.0
Incineration	–	16.8
Inert landfilling	3.2	9.1
Sanitary landfilling	30.9	44.1
Open landfilling	59.4	–
Total	100	100

3. Methodology

A research framework explaining the study approach is illustrated in Fig. 2. First, data such as population, MSW generation, composition, waste element, moisture content and other chemical and physical properties of the MSW in Malaysia are collected and reported in Section 2. An energy conversion model through Eqs. (3) and (4) is used to calculate the energy potential from incineration (Section 3.2) and LFG recovery system (Section 3.3), subject to the lower heating value (LHV) of the waste and its CH_4 emissions. The results of the energy conversion model are then applied to a net carbon emission model through Eqs. (5) and (6) to calculate the potential for carbon emission avoidance resulting from the displacement of fossil fuels (Sections 3.4 and 3.5). The potential electricity generation from energy generation model, the carbon

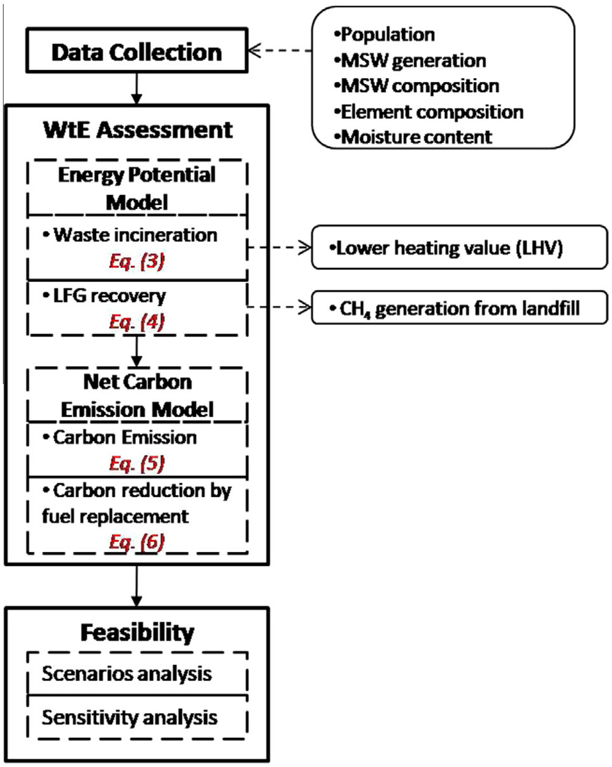

Fig. 2. Research framework for the WtE strategy proposed in this study.

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emission from net carbon emission model will be used as indicator for the WTE feasibility analysis under five different scenarios. The carbon credits and associated costs of WTE will also be analysed. A sensitivity analysis to evaluate the effects of waste moisture content fluctuation on the overall energy potential and GHG emissions for the selected case will also be presented.

3.1. Physical and chemical characteristic of MSW

Information on physical and chemical characteristics of MSW is important in evaluating alternative processes and recovery options. The physical characteristics of MSW include waste composition fraction, moisture content, and dry weight fraction. The chemical properties consist of molecular composition in terms of C_{org} (organic carbon), C_{iorg} (inorganic carbon), H (hydrogen), O (oxygen), N (nitrogen), S (sulphur) and ash. Table 3 presents the properties of MSW in Malaysia. The physical properties, including waste fraction and moisture content, have been obtained from a survey conducted by [13]. The dry weight composition of the waste is essential to determining the actual chemical properties of MSW and can be expressed by Eq. (1).

$$\text{Dry weight fraction}(\%) = \text{Wet weight fraction}(\%) \times (100 - \text{Moisture content}(\%)) \quad (1)$$

The major molecular composition of the waste is determined through ultimate analysis [15], which uses the dry weight fraction of MSW, as presented in Table 3.

3.2. Lower heating value of waste incineration

Direct waste incineration is the primary approach to waste treatment technology that converts waste to electricity, which allows for a huge volume reduction in MSW. The waste feedstock consists of the organic matter combusted in a furnace or boiler under high temperature conditions with excess oxygen. Waste material is converted into incinerator bottom ash, flue gases, particulates and heat. The heat is then converted using the Rankine cycle in a steam turbine to generate electricity [16]. The general chemical reaction of waste combustion under ideal conditions can be represented by Eq. (2).

$$\text{Organic matter} + \text{Excess air} = N_2 + CO_2 + H_2O + O_2 + \text{Ash} + \text{Heat} \quad (2)$$

The energy content of the organic components in MSW can be determined using a full-scale boiler as a calorimeter, by a laboratory scale bomb calorimeter, or through calculation using a mathematical equation correlating the waste element and energy content [16]. The energy content of MSW is expressed by its LHV or typically named the calorific value. In this study, the approximate LHV of MSW is predicted using the mathematical correlation of the modified Dulong's equation, as shown in Eq. (3). The moisture content of the MSW is one of the key variables in determining the LHV because it influences the dry basis value of the MSW components, as shown in Eq. (3).

$$\begin{aligned}\text{Energy content(LHV)} = {} & [7831X_{C_{org}} + 35932\left(X_{H_2} - \frac{X_{O_2}}{18}\right) \\ & + 2212X_S - 354X_{C_{iorg}} + 1187X_{O_2} \\ & + 578X_{N_2}] \times (100 - \text{MC}) \end{aligned} \quad (3)$$

where energy content is in the unit of kcal/kg. X represents the weight fraction (in wet basis) of organic carbon, inorganic carbon, hydrogen, oxygen, nitrogen and sulphur in the MSW (denoted as C_{org}, C_{iorg}, H_2, O_2, N_2, and S), as presented in Table 3. The moisture content is denoted as MC.

3.3. Landfill methane generation

The potential energy recovered from a landfill is calculated based on the CH_4 produced by the anaerobic decomposition of various organic wastes, such as food, paper, wood, and yard waste. The amount of CH_4 generated from a landfill is obtained through a simplified method created by the IPCC Guidelines [17] and given by Eq (4):

$$CH_4\text{emission from landfill} = \sum_j \text{MSW} \times \text{WF}_j \times \text{MCF} \times \text{DOC}_j \times \text{DOCF} \times \text{F} \times \text{Y} \quad (4)$$

where MSW = total waste generation (t); WF_j = waste fraction for MSW_j disposed to landfills; and Y = a conversion factor for converting C to $CH_{4,}$ which is 16/12. The following are several coefficients involved in the IPCC model.

- Methane correction factor (MCF): The MCF is a coefficient for different types of landfill practices. According to IPCC guideline, the MCF is set to 0.4 for unmanaged and shallow landfills and at 1.0 for properly managed sanitary landfills. In the case of Malaysia, the MCF is set to 0.4 for the years 1997 to 2012, assuming the worst landfill conditions. The MCF is then set to 1.0 for the years 2013 to 2025 by assuming good landfill conditions, with the LFG in line with the government's plans for waste management.
- Degradable organic carbon (DOC_j): The DOC is the organic carbon accessible for biochemical decomposition and is represented by C_{org} in Table 3.
- Dissimilatable degradable organic carbon under anaerobic conditions (DOCF): The DOCF is the proportion of DOC that dissimilates under anaerobic conditions, which occurs because the DOC process does not occur completely over a long period. A default value of 0.77 is set for the DOC_F.

Table 3
Properties of MSW in Malaysia.

	Food	Yard	Paper	Plastic	Glass	Metal	Textile	Total/average
Physical properties [13]								
Wet weight fraction (%)	41.06	2.45	20.93	22.23	3.63	1.96	7.74	100.00
Moisture content (%)	37.23	0.885	14.65	0.680	0	0	0.085	53.53
Dry weight fraction (%)	25.77	2.43	17.86	22.08	3.63	1.96	7.73	46.47
Chemical properties – ultimate analysis (Wet basis) [16]								
C_{org} (%)	48.00	47.8	43.50	0	0	0	55.00	27.76
C_{iorg} (%)	0	0	0	60.00	0.50	4.50	0	9.29
H (%)	6.40	6.00	6.00	22.80	0.10	0.60	6.60	6.93
O (%)	37.60	38.00	44.00	7.20	0.40	4.30	31.20	23.24
N (%)	0.40	0.30	0.20	0.10	0.00	0	0.10	0.16
S (%)	2.60	3.40	0.30	0.00	0.10	0	90.50	13.86
Ash (%)	5.00	4.50	6.00	10.0	98.90	0.46	2.50	18.19

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- Fraction of methane in LFG (F): The fraction of methane production from LFG is set as 0.55 for Malaysia [10].

A calculation example for the CH_4 emission in Malaysia for landfilled food waste (WF = 0.25) at year 2010 (MSW at 2010 = 8.19) is shown as follow based on Eq. (4):

$$\begin{aligned} CH_4 \text{ emission} &= (8.19)(0.25) \times (0.4) \times (0.48) \times (0.77) \times (0.55) \\ &\quad \times \left(\frac{16}{12}\right) \\ &= 0.222 \end{aligned}$$

3.4. Combustion and GHG emissions

Waste combustion converts chemical energy into the thermal energy of combustion gas at high temperatures of 800 °C and above. The combustion of waste is a carbon emission process where the WtE obtained from MSW offsets the use of fossil fuels while avoiding the release of CH_4 at landfill sites. However, such combustion is also a carbon credit-claimable process in which the combustion of MSW converts fossil carbon in the fuel into CO_2 and biogenic carbon. Apart from CO_2, the combustion process also releases insignificant amounts of N_2O and CH_4 [18]. Therefore, the direct emission of GHG from WtE is the sum of the anthropogenic CO_2 emissions converted into an equivalent amount of CO_2 in Eq. (5).

$$CO_2 \text{ emissions from waste combustion} = \sum_j (WF_j C_{iorg_j} \times OF_j) \times Z \qquad (5)$$

where the CO_2 emissions are in t CO_2/t MSW; WF_j = waste fraction for component j in terms of dry mass; C_{iorgj} = fraction of anthropogenic carbon in terms of dry mass of component j, as given in Table 3; OF_j = oxidation factor, where the default value is 1 for MSW; Z = conversion factor for converting from C to CO_2, which is 44/12 here; and j = component of Malaysian MSW incinerated.

A simple calculation example for the CO_2 emission in Malaysia for combusted plastic waste (WF = 0.25) at year 2010 (C_{iorgj} = 0.6, [16]) is showed:

$$\begin{aligned} CO_2 \text{ emissions from plastic waste} &= 0.25 \times 0.6 \times 1 \times \left(\frac{44}{12}\right) \\ &= 0.55 \end{aligned}$$

3.5. GHG emissions reduction by fossil fuel displacement

The utilisation of MSW through waste incineration or the conversion of LFG to energy in the form of heat or electricity displaces the consumption of fossil fuel, and hence decreases CO_2 emissions. The avoidance of CO_2 through fossil fuel displacement can be calculated using Eq. (6), which considers coal as the basis for calculation. All of the electricity generated using MSW is assumed to replace electricity generated from coal.

$$CO_2 \text{ avoidance by fossil fuel replacement} = \text{Elec} \times EF_{elec} \qquad (6)$$

where Elec = total electricity generation through WtE technology (kW h/t MSW) and EF_{elec} = carbon avoided factor for every unit of power generation. In this study, EF_{elec} is adapted from [19] and measures 0.000619 t CO_2/kW h.

4. Results and discussion

The energy potential and GHG emission form WtE strategy will be presented. First, the basic of calculation for WtE analysis will be presented, followed by the WtE assessment performed in Malaysia (Section 4.2) from the perspectives of potential electricity generation, carbon credits and associated costs. The potential for GHG emissions reduction under five different scenarios is presented in Section 4.3. Finally, sensitivity analysis is performed to evaluate the effects of waste moisture content fluctuation on overall energy potential and GHG emissions for selected case.

4.1. Basis for WtE analysis

The basis of calculation for the WtE analysis is obtained using the model discussed in Section 3 is presented in Table 4.

The average calorific value of Malaysian MSW for incineration is calculated using Eq. (3), which is 1799.98 kcal/kg, equivalent to 7.53 MJ/kg of MSW. Assuming that the electricity and heat recovery efficiency for an incineration plant is 80% and the heating rate of the incineration process is 15.65 GJ/MW h, a total of 0.481 MW h electricity can be generated per t of MSW. Based on Eq. (5), it is predicted that the CO_2 emissions of the incinerated MSW in Malaysia will be 0.49 t CO_2/t MSW.

Through Eq. (4), the CH_4 emissions of landfills in Malaysia are calculated as 0.053 t CH_4/t MSW, equivalent to 1.11 t CO_{2eq}/t MSW. Approximately 55% of this CH_4 is generated from the total LFG, with a density of 0.667 kg/m^3 at 30 °C, and LHV of 17 MJ/m^3. The potential energy conversion from the CH_4 generated from landfills is 0.374 MW h/t MSW.

Table 4
Calculation basis for WtE analysis.

Parameter	Value
Incineration	
Calorific value of MSW (MJ/kg)	7.53
Heat recovery efficiency (%)	80
Heat rate (GJ/MW h)	15.65
Energy recovered from waste incineration (MWH/t MSW)	0.481
CO_2 emissions from incineration (tCO_2/t MSW)	0.49
Operating hours	24
Landfill	
CH_4 emissions (tCH_4/t MSW)	0.053
CO_2 emissions factor ($tCO_{2\ eq}$/t MSW)	1.11
CH_4 generation from LFG (%)	55
LHV of LFG (MJ/m^3)	17
Energy recovered from landfill (MW h/t MSW)	0.374
General	
Factor for CO_2 avoidance by fossil fuel replacement (t CO_2/kW h)	0.000619
Electricity sale price (RM/kW h)	0.39

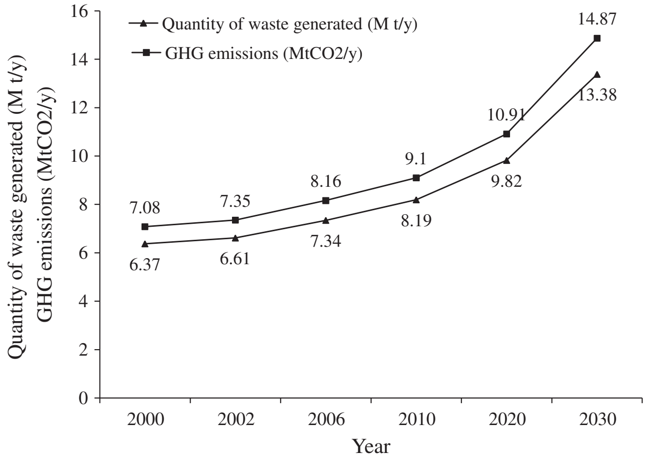

Fig. 3. WtE assessments in GHG emission for Malaysia from year 2000 to year 2030.

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4.2. WtE assessment for Malaysia from 2000 to 2030

The results of the WtE analysis performed for the Malaysian case study from year 2000 to 2030 using the model discussed in Section 3 are presented in Figs. 3–5.

Fig. 3 presented the WtE assessments in GHG emission for Malaysia from year 2000 to year 2030. As the waste generation increase from 6.37 Mt to 13.38 Mt from year 2000 to 2030, the GHG emission from untreated MSW increase gradually from 7.08 Mt CO_2 to 14.87 Mt CO_2. As calculated through Eq. (4), the waste generates 4.987 t CO_2/t MSW, and produces a total of 9.10 Mt CO_2 in 2010, 10.91 Mt CO_2 in 2020 and 14.87 Mt CO_2 in 2030. The increase generation rate of MSW lead to the direct increment of GHG emission.

Fig. 4 presents the energy potential from WtE strategy for a 30 year period. The energy of MSW can be recovered through landfill LFG recovery or incineration. As shown in Fig. 4, the electricity generation from landfilled MSW and incinerated MSW is estimated to be increased from year 2000 to 2030, due to increasing of waste resources. Comparing waste incineration and LFG recovery, incineration has a higher electricity generation, as the combustion of MSW generated higher energy as presented in Table 4 in Section 4.1.

The economical analysis for electricity sales, carbon credits, and the cost of both WtE strategies are shown in Fig. 5. Higher electricity production from incineration increases the profits as result of higher sales of for electricity and claiming of carbon credits due to larger avoidance of CO_2. Approximately USD2511.11M and USD61.30M of revenue can be generated from the sales of electricity and claiming of carbon credits resulting from incineration, respectively, while the corresponding profits for LFG recovery are only USD588.82M and USD47.68M. However, incineration requires higher capital and operating costs than LFG recovery system, as shown in Fig. 5.

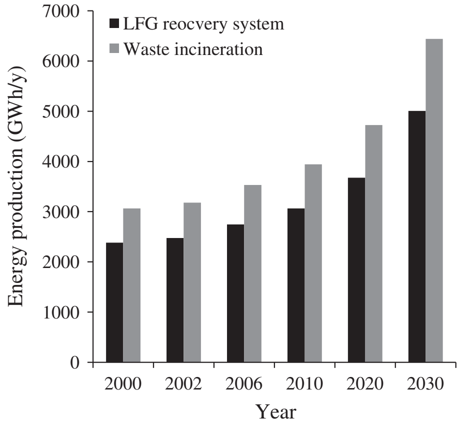

Fig. 4. WtE assessments in energy potential for Malaysia from year 2000 to year 2030.

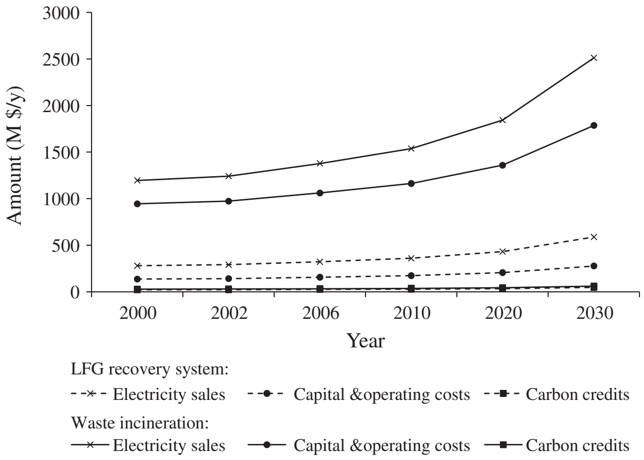

Fig. 5. Cost analysis for LFG recovery system and waste incineration in Malaysia from year 2000 to year 2030.

Table 5
WtE scenarios.

Scenario	Description
Scenario 1	Business as Usual (BaU), with no WtE implementation
Scenario 2 (LFG recovery only)	WtE through LFG recovery only for electricity generation
Scenario 3 (LFG/ incineration)	Integration of WtE (landfill and incineration) strategy, where waste utilisation rate is 64% in LFG recovery system and 36% in incineration
Scenario 4 (Incineration/ LFG)	Integration of WtE (landfill and incineration) strategy, where waste utilisation rate is 64% in incineration and 36% in LFG recovery system
Scenario 5 (Incineration only)	WtE through MSW incineration only for electricity generation

4.3. Scenario analysis by comparison of different WtE strategies

Besides investigating the WtE potential and its economical value in Malaysia, five scenarios with different WtE strategies are presented in a summary table as shown in Table 5 to evaluate the impacts of MSW utilisation options in terms of their energy conversion and GHG emissions. Scenario 1 represents the Business as Usual (BaU) case of current waste management practise in Malaysia, which is landfill or dumpsite without energy recovery. Scenario 2, 3, 4, and 5 serves as the counter measure (CM) scenarios, to represent the policy framework for the waste management in Malaysia until 2030. Scenario 2 proposed the utilisation of WtE through LFG recovery system only, while Scenario 3 introduced only waste incineration as the only WtE strategy. Scenarios 4 and 5 presented an integration of LFG recovery system and waste incineration for WtE strategy in Malaysia, with different domain of WtE

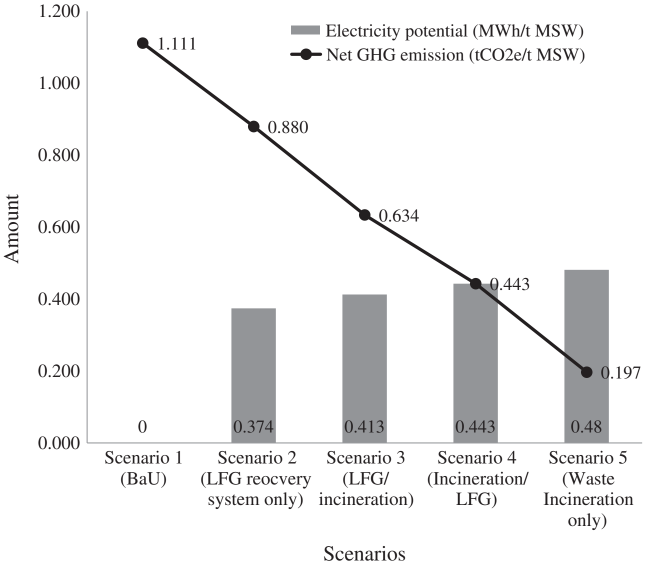

Fig. 6. Comparison of energy recovery potential and GHG emissions for different WtE scenarios in Malaysia.

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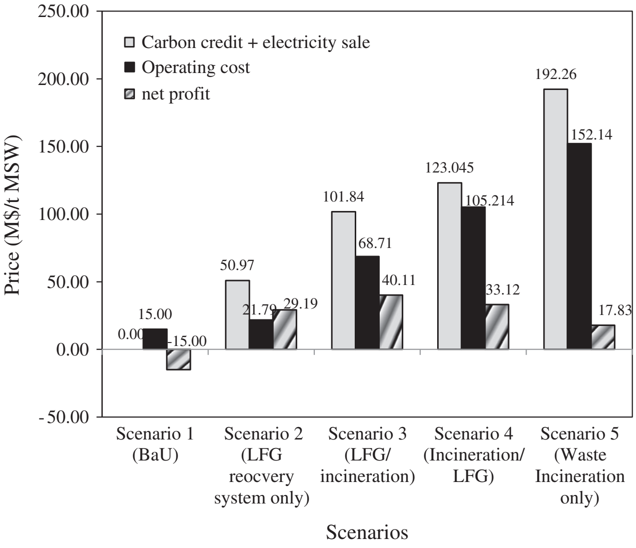
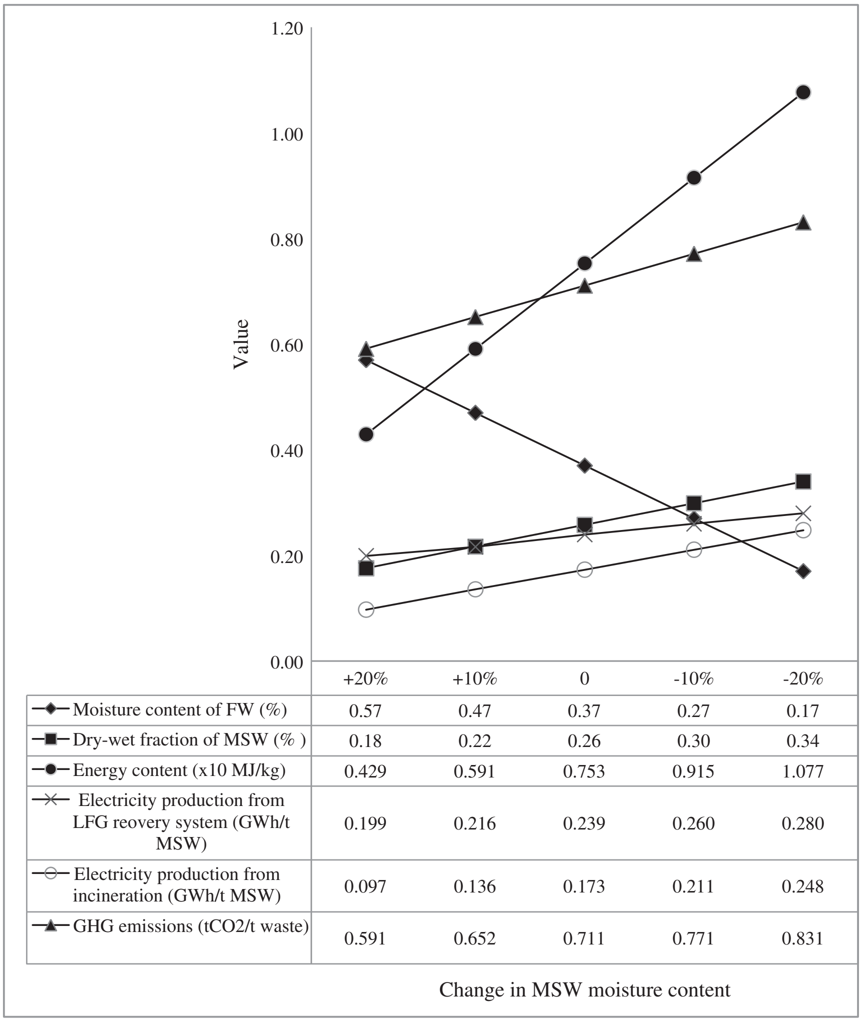


Fig. 7. Cost analysis for different WtE scenarios in Malaysia.

approach, based on a study by Tan et al. (2012) that considers 64% LFG and 36% incineration and vice versa [20].

The scenarios analysis in energy recovery potential and GHG emissions for different WtE strategy in Malaysia is presented in Fig. 6. The net GHG emission for all scenarios range from 1.111 to 0.197 t CO_2/t MSW. As expected, the worst scenario is BaU scenario with the highest net GHG emission compare to CM scenarios. Therefore, policy makers are advised to consider others alternative for MSW management in Malaysia for environment protection and economical benefit. Hence, four CM scenarios with WtE strategies are promoted in this study. Given the same composition of MSW, the results reflect that net GHG emissions from LFG recovery system are noticeably higher than waste incineration. In opposite, waste incineration has higher energy potential. Scenario 2 with LFG recovery system as the only WtE strategy, generating 0.374 MW h/t MSW of electricity and generated approximately 0.880 t CO_2/t MSW of net GHG emissions. Integration of LFG recovery system and incineration with the ratio of 64% and 36% in Scenario 3, results a total of 0.413 MW h/t MSW of electricity production and a moderate rate of net carbon emission (0.634 t CO_2/t MSW). On the other hand, better performance is noticed in Scenario 4 compared to Scenario 3, where waste incineration as the major strategy in the integration of WtE (64% waste incineration and 36% LFG recovery system). The best scenario in term of GHG emissions and energy potential fall on Scenario 5 with the implementation of waste incineration as the only WtE strategy, achieves the lowest net carbon emissions (0.197 t CO_2/t MSW) and the highest production of energy (0.48 MW h/t MSW) compare to the LFG recovery system.

Nevertheless, interesting phenomena is observed for the cost analysis of different WtE scenarios as shown in Fig. 7. A negative



	+20%	+10%	0	-10%	-20%
◆ Moisture content of FW (%)	0.57	0.47	0.37	0.27	0.17
■ Dry-wet fraction of MSW (%)	0.18	0.22	0.26	0.30	0.34
● Energy content (x10 MJ/kg)	0.429	0.591	0.753	0.915	1.077
× Electricity production from LFG reovery system (GWh/t MSW)	0.199	0.216	0.239	0.260	0.280
○ Electricity production from incineration (GWh/t MSW)	0.097	0.136	0.173	0.211	0.248
▲ GHG emissions (tCO2/t waste)	0.591	0.652	0.711	0.771	0.831

Fig. 8. Sensitivity analysis of various MSW moisture contents of WtE performance.

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net profit is expected for BaU Scenario, as the conventional landfilling did not implemented any effort to recover energy or treat the waste to produce by-product Scenario 5 provided the best energy potential and GHG emission reduction, however, the implementation of waste incineration required the highest cost with the lowest positive net profit of USD17.83 M/t MSW. The most profitable case is presented under Scenario 3 where both LFG (64%) and incineration (34%) technology is integrated, achieve a total net profit of USD 40.1 M/t MSW. Scenario 3 can be considered as the optimal scenario, with acceptable performance of energy potential and GHG emission and the best economical beneficial result. Through the comparison of different WtE scenarios in term of energy potential, GHG emission and economical potential, we noticed that the higher performance WtE strategies come with higher prices. Therefore, policy makers are suggested to evaluate the ultimate goal of management on productivity, profitability or environmental protection, before consideration of any WtE strategies.

4.4. Sensitivity analysis on the effects of moisture content on energy potential and GHG emissions

Given the complexity of the system studied and some uncertainty about primary data collection, sensitivity analysis presented in this section provide a better understanding of the relationship between waste disposal facility and the variations degree for key parameter might alter final WtE strategy. Moisture content of MSW is identified as the key parameter; therefore, sensitivity analysis is performed to evaluate the effects of moisture content fluctuation in MSW to the overall energy potential and GHG emissions performance. Scenario 3 which integrated 64% of LFG recovery system and 36% of waste incineration facility considered as optimal scenario, is selected to be tested in the sensitivity analysis. The moisture content of MSW is adjusted within the range of ±0–20%.

The results of the sensitivity analysis performed on the moisture content of MSW are presented in Fig. 8. The results show that the moisture content of MSW has a great influence on the overall GHG emission and energy generation. With $a \pm 20\%$ fluctuation in moisture content leading to $a \pm 43.9\%$ change in GHG emissions and $a \pm 16.7\%$ change in overall energy performance. As the moisture content of MSW changes from its original value of 0.37 (37%) by ±20%, the total dry–wet fraction of the MSW, its energy content, the electricity generated from WtE technology, and GHG emissions changed oppositely with the increase/decrease of moisture content. This analysis verifies the importance of pre-treatment of MSW such as pre-sorting and pre-heating of MSW to reduce the moisture content and hence increase its energy potential and reduce GHG emissions.

5. Conclusion

Malaysia's increasing demand for energy and abundance of MSW have necessitated the need for a national WtE strategy. In this study, the selection of a WtE technology through calculations based on waste characteristics and waste generation rates has demonstrated the potential of WtE to mitigate greenhouse gas emissions in an economically feasible manner. A detailed WtE analysis of both LFG and incineration in terms of potential electricity production, GHG emissions, economic benefits been simulated based on the presented energy conversion model and net carbon emission model. This study has also evaluated five scenarios for WtE in Malaysia considering LFG recovery system and incineration technologies. Scenario 3 which comprises of LFG recovery system and waste incineration provides the highest net profit with better energy potential net GHG emissions reduction. Pre-treatment of MSW is essential to boost energy recovery and GHG emission reduction through WtE strategies.

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