Energy Conversion and Management 102 (2015) 111–120

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Energy, economic and environmental (3E) analysis of waste-to-energy (WTE) strategies for municipal solid waste (MSW) management in Malaysia ☆

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ARTICLE INFO

Article history:
Available online 26 March 2015

Keywords:
Anaerobic digestion (AD)
Gasification
Incineration
Landfill gas recovery system (LFGRS)
Municipal solid waste (MSW)
Waste-to-energy (WTE)

ABSTRACT

The utilisation of municipal solid waste (MSW) for energy production has been implemented globally for many decades. Malaysia, however, is still highly dependent on landfills for MSW management. Because of the concern for greenhouse gases (GHG) emission and the scarcity of land, Malaysia has an urgent need for a better waste management strategy. This study aims to evaluate the energy, economic and environmental (3E) impact of waste-to-energy (WTE) for municipal solid waste management. An existing landfill in Malaysia is selected as the case study for consideration to adopt the advanced WTE technologies including the landfill gas recovery system (LFGRS), incineration, anaerobic digestion (AD), and gasification. The study presented an interactive comparison of different WTE scenarios and followed by further discussion on waste incineration and AD as the two potential WTE options in Malaysia. The 3E assessment reveals incineration as the superior technology choice when the production of electricity and heat were considered; however, AD is found to be more favourable under the consideration of electricity production only.

1. Introduction

Municipal solid waste (MSW), commonly known as refuse or rubbish, is discarded from residential, commercial, and institutional areas [13]. As the global population increases dramatically, and with changing consumption patterns, economic development, rapid urbanisation and industrialisation, MSW is being generated at a rate that outstrips the ability of the natural environment to assimilate it and municipal authorities to manage it. The situation is more severe in developing countries such as Malaysia. The rapid growth of the economy and population have caused MSW to proliferate by 28% in a period of a decade, from 5.6 Mt in 1997 to 7.65 Mt in 2007 [26], and it is predicted to further increase by 30% in 2020 and 39% in 2030 compared to the baseline year of 2007 [21]. Despite the government's efforts, waste management remains one of the critical environment issues in Malaysia. MSW in Malaysia is typically disposed of in a bin or container within the house premises and collected by regional private concessionaires. The waste is first sent to transfer stations for compaction, with a minimum of sorting, before being sent to the waste disposal sites [36]. Approximately 93.5% of MSW in Malaysia is in landfills or open dumpsites without gas recovery, meanwhile only 5.5% of MSW is recycled and 1.0% is composted [1]. Landfill is the cheapest technique to handle the waste in large quantities. On the other hand, there is public opposition and a shortage of available land for disposal purposes. The over dependency on landfilling and inappropriate waste disposal has been continuously pressing the environmental, health and safety issues for the citizens. It is also amplifying the share of total global anthropogenic greenhouse gas (GHG) emission, which is caused by the production of methane gas (CH_4) through the anaerobic decomposition of solid waste in landfills. GHG emission in the waste sector increased 54% from 1990 to 2008. Meanwhile, comparing the sub-sectors within the waste sector, the main release of GHG comes from waste landfill sites, which contributed up to 90% of the total emission from the waste sector in Malaysia [21].

The government of Malaysia is seeking practical solutions to improve the current waste management situation, including the

☆ This article is based on a four-page proceedings paper in Energy Procedia Volume 61 (2015). It has been substantially modified and extended, and has been subject to the normal peer review and revision process of the journal.

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http://dx.doi.org/10.1016/j.enconman.2015.02.010
0196-8904/

sanitation and closure of illegal landfills, upgrading landfills with CH_4 recovery, waste incineration with energy recovery, composting of organic waste, and recycling and waste minimisation. Amongst the proposals, Waste-to-Energy (WTE) stood out as a promising alternative to overcoming the waste generation problem and a potential renewable energy (RE) source for Malaysia [37]. WTE encompasses thermal and biological conversion technologies that unlock the usable energy stored in solid waste [17]. The utilisation of MSW as a RE source could overcome waste disposal issues, generate power for fossil fuel displacement and mitigate GHG emissions from waste treatment by converting CH_4 to carbon dioxide (CO_2). Currently, more than 800 thermal WTE plants are operated in nearly 40 countries globally; they treat approximately 11% of MSW generated worldwide and produces up to about a total of 429 TW h of power [30]. Some large-scale alternatives for WTE have been implemented in developed countries, such as Japan, Germany, Sweden, the Netherlands, Denmark, and the United Kingdom. For example, over 80% of the MSW in Japan is incinerated; Japan also has the largest number of incineration plants in the world (1900 waste incineration plants) and 10% are equipped with power generation facilities [38]. In Germany, only 1% of waste was landfilled and the WTE share is approximately 35% of the waste treatment, which is higher than the Europe Union (EU)'s WTE ratio (~24%) [11]. Sweden is another successful example of WTE in the EU, where nearly 50% of waste is incinerated with energy recovery [35]. In addition, Sweden also utilised the biogas from landfills for district heating, vehicle fuel, and power plants [7].

WTE has been practiced in Malaysia in recent decades and is implemented for biomass from agricultural waste and forestry residues (i.e., palm oil biomass, paddy straw and logging residues) [23]. WTE from MSW is still underutilised in Malaysia. Feasibility analyses of WTE from MSW in Malaysia have been conducted by local researchers over the past decade. For example, Kalantarifard and Goh (2011), Johari et al. [18], and Noor et al. [26] studied the potential of landfill gas in Malaysia for economic and environmental benefits. Those models forecasted the production of landfill gas from the existing landfill and calculated the energy production for economic analysis, nevertheless, they have not considered the investment of energy production in terms of capital and operation costs. In another feasibility study of MSW for WTE, Ng et al. [25] concluded that MSW utilisation is not economically profitable due to the high cost of technologies for incineration, gasification and pyrolysis. Ng's model did not address the environmental potential for WTE. On the other hand, Tan et al. [37] concluded that WTE for MSW could be profitable and could contribute to reducing GHG emission, however pre-treatment of MSW is crucial for better economic benefits of WTE. Nevertheless, Tan's research had a narrow scope by only considering two WTE technologies – landfill recovery and incineration.

Despite the previous work, none of the studies addresses the impact of WTE from MSW from the perspective of holistic sustainability, which includes energy, economics and environmental (3E); the current study aims to fill this gap.

2. Research objective, framework and methodology

This study aims to evaluate the 3E impact change from the baseline study in Malaysia represented by existing landfills that would result from the implementation of advanced WTE technologies, including landfill gas recovery system (LFGRS), incineration, anaerobic digestion (AD), and gasification. The four waste treatment alternatives are selected because they are considered by the Malaysia Government to be the best available technologies for WTE. In this study, the energy potential of MSW is in the form of electricity and heat. The economic assessment considers both the cost (capital cost, operation cost, and transportation cost), and profit (selling of energy, carbon credit through carbon avoidance, and additional profit from selling the by-products). Meanwhile, the environmental assessment includes the GHG emission during the energy conversion process, the transportation of MSW to the waste treatment plant, and carbon avoidance by fossil fuel replacement to renewable energy. Hence, the framework of this study, namely the 3E assessment of the four WTE technologies considered for Malaysia, is presented in Fig. 1.

A case study of Taman Beringin landfill in Malaysia was conducted with the proposed 3E framework. The work is novel as it is pioneer 3E assessment work framework for Malaysia case study. Another novelty lies in the discussion where the study comprehensively discusses the trade-off between waste incineration and anaerobic digestion for MSWM. Even though the case study is specific on Malaysia case, the novelty and discussion in the paper could be a good review for others case study worldwide.

A comprehensive review on each of the WTE technologies is performed in Section 3 to compare their advantages and disadvantages. The 3E parameters in this study are described in Section 4, followed by the information of the case study in Section 5. The results are reported and discussed in Section 4 with a comparison of 3E assessment for different WTE scenarios in Malaysia and a detailed analysis on the feasibility of both incineration and AD.

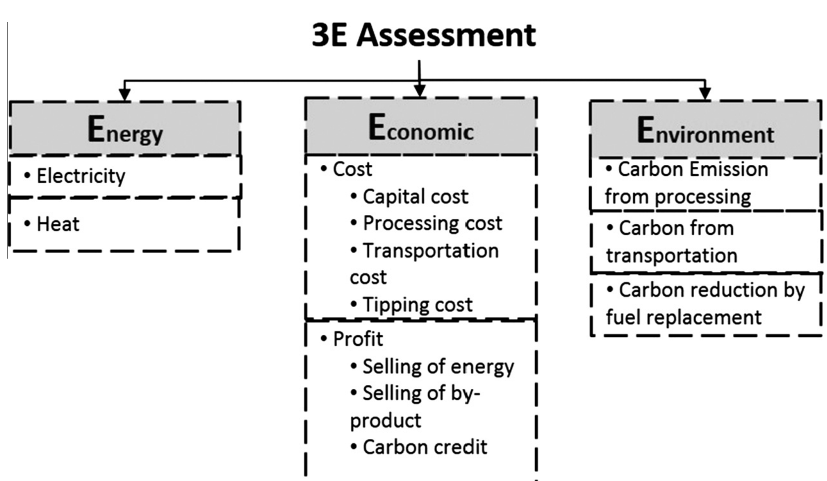

Fig. 1. 3E assessment framework for WTE technologies.

3. Review on WTE technologies

WTE refers to the recovery of the energy from waste materials into useable heat, electricity, or fuel. In the hierarchy of solid waste management, as shown in Fig. 2, WTE is ranked before the final disposal, indicating the limitations of this option in terms of economic and environmental benefits [12]. Waste minimisation, reuse, and recycling ranked in the top three of the hierarchy, however they require the behaviour of people and society to change, which creates uncertainty. In addition, the generation of waste is inevitable; the remaining waste after waste minimisation, waste reuse and recycling should be treated to reduce the negative impacts to the environment. WTE is recognised as a promising alternative for waste management to overcome the waste generation problem and as a potential renewable energy (RE) source.

WTE approaches can be categorised into three types, as shown in Fig. 3: thermal treatment, biological treatment and landfill [37]. Options for thermal treatment of WTE to produce electricity and heat included waste incineration and gasification. Biological treatment of WTE included anaerobic digestion with the production of biogas. Landfill with CH_4 gas recovery can also generate electricity and heat through turbines.

In this study, LFGRS, waste incineration, AD and gasification are selected because the maturity of the technologies has reached the implementation and commercialisation stage. A short review of each WTE technology will be presented in Sections 3.1–3.4 along with a comparison of their advantages and disadvantages in term of economic and environmental impact.

3.1. Landfill gas recovery system (LFGRS)

As the majority of global garbage ends up in a landfill site, the generation of CH_4 from landfill sites has gained increasing attention. Landfilling can be considered as a WTE technology when the generated CH_4 (commonly known as biogas) is captured and utilised for energy generation. LFGRS is well-suited to a high percentage of biodegradable matter with high moisture content. Average gas recovery rates range from 120 to 150 m^3/t of dry MSW, equivalent to a heating value of 2500 MJ/t [40]. It helps in the mitigation of GHG emissions from waste by converting CH_4

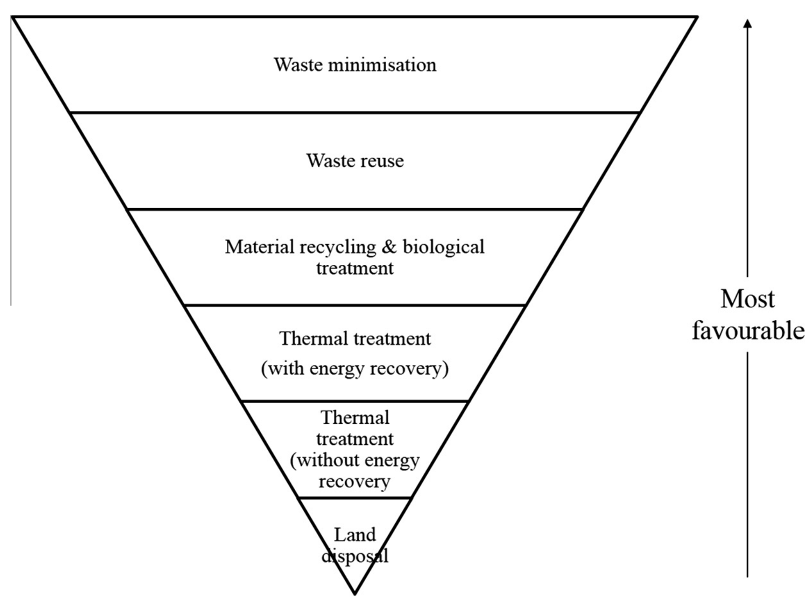

Fig. 2. Hierarchy of solid waste management [12].

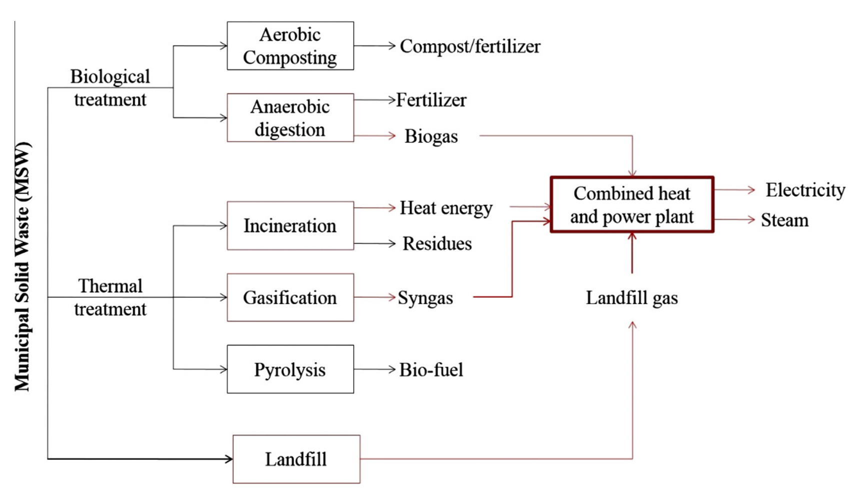

Fig. 3. Alternative waste treatment technologies and their products[37].

to CO_2. This option has therefore been considered as an important and crucial factor to successful waste management. The majority of Malaysian waste ends up in landfills, however only 3% of the landfills in Malaysia are sanitary landfills with leachate treatment. Out of the 3%, only 1% sanitary landfill is equipped with CH_4 recovery for electricity production. One of the reasons that LFGRS is not commissioned on a large scale in Malaysia is because MSW with a high percentage of undegradable material (e.g. metal, plastic, glass) decreases the potential energy production to the least feasible in term of economics.

3.2. Waste incineration

Waste incineration is the primary approach of waste treatment technology that converts biomass to electricity. The waste feedstock commonly involves the organic matter of waste to be reacted with excess oxygen in a combustion process in a furnace or boiler under high pressure. The end product derived from the combustion of waste is hot combusted gas – composed primarily of nitrogen (N_2), CO_2, waster (H_2O, flue gas), oxygen (O_2) and non-combustible residues [39]. Hot flue gases are then produced and will enter the heat exchanger as a hot stream to generate steam from water. Electricity is generated through the Rankine cycle in the steam turbine. The single steam cycle normally only produces electricity, while the cogeneration of steam and electricity requires an extracting steam cycle. Nevertheless, the biomass requires prior preparation and processing, such as pre-drying to remove the high moisture content of the waste before it enters the combustion chamber to be combusted with air. The process normally requires temperatures between 850 and 1100 °C. Currently, only one incineration plant is in operation in Malaysia, which can produce 1 MW of electricity from 100 t/d of MSW [44].

3.3. Gasification

Gasification is the conversion of solid waste to fuel (syngas) through gas-forming reactions. It is also recognised as “indirect combustion” with partial oxidation of the waste in the presence of an oxidant amount lower than that required for stoichiometric combustion [3]. The minimum operating temperature for gasification is 1100 °C. The products of the process are ash, carbon, hydrogen, nitrogen, sulphur, CH_4 and oxygen – the specific products depend on the type of raw materials used. Gasification of solid materials is an old technology that has been applied for many years. However, it has only recently been applied in waste management [39]. During the gasification process, the waste is combusted with a controlled amount of oxygen to supply a sufficient amount of heat for the predominantly syngas reaction, in the operating temperature range of 780 °C to 1650 °C. The syngas is sent to the power generation plant to produce energy, such as steam and electricity. The solid by-products of the gasification reaction are known as char and consist mainly of carbon and ash. The by-products are then gasified in the second gasification process using steam and oxygen. The second gasification process also provides the required heat energy for the earlier processes. Usually, biomass gasification requires only a single pass due to its high reactivity. Therefore, the common practice is to dispose of the residues in a landfill.

3.4. Anaerobic digestion

Anaerobic digestion is a natural biodegradable process of organic compounds by microorganisms in the absence of air. This is a complex process that requires specific environmental conditions and different bacterial populations to decompose the organic waste to the end product, a valuable high energy mixture of gases (mainly CH_4 and CO_2) named biogas [20]. The process of anaerobic digestion consists of four main biological and chemical stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis [9]. In the first step, hydrolysis, the complex chain of organic compounds is broken down into basic structural molecules, such as fatty acids, monosaccharides, amino acids, and related compounds. The process is followed by acidogenesis, where further breakdown of the remaining components by acidogenic (fermentative) bacteria takes place. At this stage, gases such as CO_2, CH_4, and NH_3 are produced. The third stage of anaerobic digestion is acetogenesis, during which simple molecules created through the acidogenesis phase are further digested by acetogens to produce largely acetic acid, as well as carbon dioxide and hydrogen. The last stage of anaerobic digestion is methanogenesis during which the methanogens bacteria convert the intermediate products into CO_2, CH_4, and water.

4. 3E parameters of the study

4.1. Energy assessment

Waste can be converted into energy in term of heat and electricity. In this study, the energy production is through the recovery of biogas gas from landfill or anaerobic digestion or combustion from incineration and gasification. The data for the energy assessment are obtained from previous study of WTE in Malaysia [37] and literature reviews [41,42].

4.2. Economical assessment

The costs considered in this work were obtained through a national review and were adjusted to the Malaysian context. The main source of information about the costs of investment, including the capital cost, the processing costs, and the transportation cost for WTE projects in Malaysia were obtained from Tolis et al. [41] and Tsilemou and Panagiotakopoulos [42]. The pre-treatment cost is not considered in this study as the pre-treatment processes do not included in the study boundary. In addition, the cost of investment does not apply to the existing landfill, which serves as the base case of the study, however a tipping fee is considered. The tipping fee is the waste collection fee for sending the waste to the landfill. Meanwhile, revenue is realised from the production of multiple products including electricity, heat, and fertiliser, as well as the carbon credit. The carbon credit represents the tradable profit obtained from the quantifiable reductions in GHG emissions.

4.3. Environmental assessment

In the environmental assessment, the carbon emissions from both the transportation and the processing of WTE through different approaches are considered. The utilisation of RE from waste displaces the consumption of fossil fuel, thus the carbon avoidance from it is also accounted for in this study. The data were obtained from a previous study of a Malaysian WTE scenarios [37].

5. Case study –Taman Beringin landfill, Malaysia

Taman Beringin landfill is located in Jinjang Utara, 10 km North West of Kuala Lumpur city centre, Malaysia, as shown in Fig. 4. This site has been used by Kuala Lumpur City Hall for disposal of domestic and commercial waste collected in the city. With an area of 16 h, the landfill had served the city since 1991 and closed in 2005 [31]. The landfill currently serves as a waste transfer station to transfer the 2500 t/d of MSW to another sanitary landfill located in the northern part of Selangor state, 60 km from Kuala Lumpur. The second landfill, however, has not been commissioned with

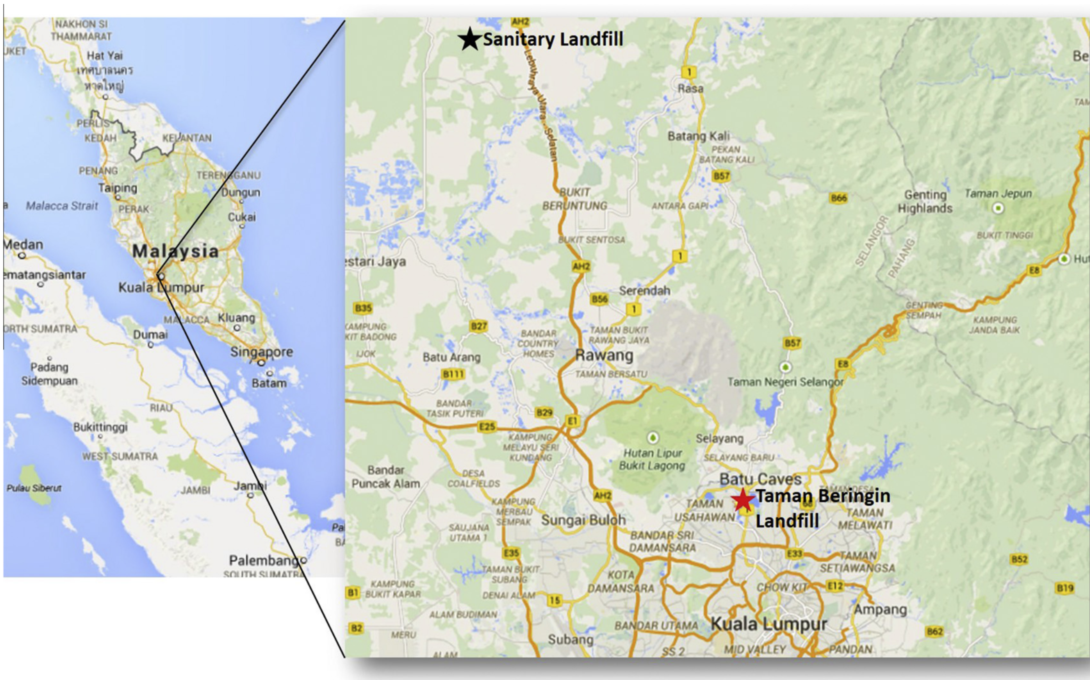

Fig. 4. Location of Taman Beringin landfill.

energy recovery. Currently, the Malaysian government is considering further upgrades to the waste management system with WTE technologies, including LFGRS, waste incineration, AD, or gasification to mitigate the global warming potential while gaining profit from selling the by-products (electricity, heat, and fertiliser). In this study, the existing sanitary landfill is planned to be upgraded with a CH_4 recovery system, known as LFGRS, while the other WTE approaches, such as an incineration plant, a gasification plant, and an AD plant are proposed to be built closer to the waste transfer station (Taman Beringin landfill). The comparative study of the existing baseline and the new proposed WTE scenarios is illustrated in Fig. 5.

Table 1 explains the 8 scenarios in this study. The first scenario is the baseline of the study area where the MSW from Taman Beringin will be landfilled in the new sanitary landfill without any landfill gas recovery for the production of energy. The future WTE scenarios are categorised into two types: isolated WTE system or integrated WTE system. In the isolated WTE system only one type of WTE technology is proposed to be implemented for the case study area: 2500 t/d of MSW generated in the study area will be treated via LFGRS, incineration, AD, or gasification, which are represented by scenarios A, B, C, and D, respectively. The integrated WTE approach recommends three WTE utilisations in order to reduce the waste burden to the landfill. For the integrated WTE

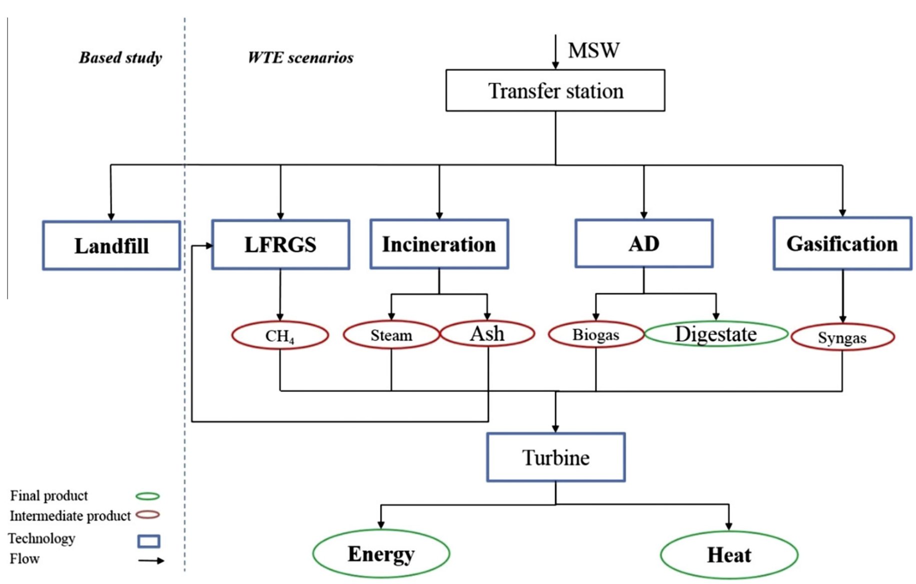

Fig. 5. Base study and new proposed waste management strategies involving WTE scenarios for Taman Beringin landfill.

Table 1
Detail description of each scenario for new waste management strategies in Taman Beringin landfill.

WTE system	Scenario	Technologies	Description (amount)
	Base	Landfill	Sanitary landfill (2500 t/d)
Isolated	A	LFGRS	Sanitary landfill with energy recovery for electricity and heat (2500 t/d)
	B	Incineration	Waste incineration to produce electricity and heat (2500 t/d)
	C	AD	AD to produce biogas for electricity and heat (2500 t/d). The digestate by-product of AD will be sold as fertiliser
	D	Gasification	Waste gasification to produce electricity (2500 t/d)
Integrated	E	LFGRS + Incineration	LFGRS (1500 t/d) with incineration (1000 t/d) to produce electricity and heat; 10% of the waste converted to ash in incineration will be sent to LFGRS
	F	LFGRS + AD	LFGRS (1500 t/d) with AD (1000 t/d) to produce biogas for electricity and heat. The digestate by-product of AD will be sold as fertiliser
	G	LFGRS + Gasification	LFGRS (1500 t/d) with gasification (1000 t/d) to produce electricity

approach, LFGRS is combined with three different WTE treatments, i.e. incineration, AD and gasification under the scenarios of E, F and G respectively. For each scenario, 1500 t/d of MSW will be sent to the LFGRS, together with the processing output ash from the incineration, while approximately 1000 t/d of MSW will undergo the respective WTE approach, according the policy plan [34], as shown in Table 1. The parameters for both the economic and environmental assessment for this study are presented in Table 2.

6. Results and discussions

6.1. Technologies selection for 3E comparative assessment

This study focuses on 3E assessment of various technologies considered for managing MSW in a case study for Malaysia. The baseline of this study considered the landfilling of waste without any generation of energy products, which results in a negative cost impact of 222,000 USD/d due to the costs of transportation, tipping fee, operation & maintenance, and emitted 3117 tCO_2/d. With the implementation of WTE, more profitable and environmentally beneficial scenarios can be observed. Based on the seven scenarios considered as WTE strategies, from the perspective of energy generation (electricity and heat), incineration technology provides the most attractive option. Incineration (scenario B) is able to produce up to a total of 1200 MW h/d of electricity and 3575 GJ/d of heat. This is followed by AD (scenario C), gasification (scenario D), and LFGRS (scenario A). As for economic factors, gasification may not be attractive due to its high capacity and operational cost (250,400 USD/d); in terms of decreasing cost, gasification is followed by incinerator, LFGRS, and lastly, AD. However, due to the high energy generation potential, the net profit (assuming all energy is sold) from each technology is different. In terms of profit, the incinerator could generate the most income with a net profit of 563083.40 USD/d, followed by AD, gasification, and LFGRS. Nevertheless, from the environmental point of view, gasification technology has the highest potential for carbon mitigation – it is able to achieve up to 3207.50 tCO_2/d of carbon reduction –

Table 2
Parameters for the various technologies considered for solid waste management in Taman Beringin landfill.

Parameter	Technologies				
	Landfill	LFGRS	Incineration	AD	Gasification
[a]Case study information					
Waste feed to primary option (t/d)	2500	2500	2500	2500	2500
Waste feed to secondary option (t/d)		1500	1000	1000	1000
Average distance from transfer station to hub (km)	60	60	5	5	5
Tipping fee/waste collection fee (USD/t)	60				
Truck capacity (t/truck)	50				
[b]MSW conversion factor					
Electricity production ([a]MWh/ t MSW; [b]MWh/m^3)		0.0021	0.48	0.0021	0.4
Heat production ([a]MWh/ t MSW; [b]MWh/m3)		0.0025	1.43	0.0025	
Biogas production (m^3/t MSW)		47.7		203.6	
Ash production from incineration (t/t MSW)			0.1		
Digestate production from AD (t/t MSW)				0.3	
[c]Costs					
Capacity cost (USD/t waste)		0.78	2.18	1.08	3.2
Processing cost (USD/t)	18	24.02	67	35.45	96.06
Transportation cost (USD/t-km)	9				
[d]Product price					
Carbon Credit (USD/t CO_2)	15.38				
Electricity (USD/MWh)	380				
District Heating (USD/MWh)	50				
Fertiliser (USD/t)	100				
Emission factor					
[e]CO_2 emission from transportation (tCO_2/km)			0.114		
[b,d]CO_2 emission from processing (tCO_2/t MSW)	1.11	0.35	0.28	0.253	0.2
[d]Carbon avoidance (tCO_2/kWh)	0.000619				

[a] From the study
[b] Tan et al. [37]
[c] Tolis et al. [41] and Tsilemou and Panagiotakopoulos. [42]
[d] Tan et al. [36]
[e] EPA [43]

Table 3
Results for each scenario.

Result	Scenarios							
	Baseline	A	B	C	D	E	F	G
Production								
Biogas (m^3)		131175.00		500000.00		76320.00	276320.00	76320.00
Electricity (MWh/d)		275.47	1200.00	1050.00	1000.00	640.27	580.27	560.27
Heat (MWh/d)		524.70	3575.00	2000.00		1735.28	1105.28	305.28
Digestate (t/d)				750.00			300.00	0.00
Costing								
Capital cost (USD/d)		2145.00	5450.00	2700.00	8000.00	3428.00	2328.00	4448.00
Processing cost (USD/d)	45000.00	66055.00	137500.00	88625.00	240150.00	93432.00	73882.00	134492.00
Tipping cost (USD/d)	150000.00							
Transportation cost (USD/d)	27000.00	27000.00	4950.00	2250.00	2250.00	18720.00	17100.00	17100.00
Total costs (USD/d)	222000.00	95200.00	147900.00	93575.00	250400.00	115580.00	93310.00	156040.00
Profit (USD/d)								
Electricity		104677.65	456000.00	399000.00	380000.00	243303.36	220503.36	212903.36
Heat		30432.60	207350.00	116000.00	0.00	100646.24	64106.24	17706.24
Fertiliser				75000.00			9000.00	
Carbon credit		30498.76	47633.40	47769.51	49331.35	37574.08	38166.83	38791.56
Total profit		165609.01	710983.40	637769.51	429331.35	381523.68	331776.43	269401.16
Net profit	−222000.00	70409.01	563083.40	544194.51	178931.35	265943.68	238466.43	113361.16
Emission (t CO_2/d)								
Processing emission	2775.00	962.50	700.00	632.50	500.00	840.00	778.00	725.00
Transportation emission	342.00	342.00	62.70	28.50	28.50	230.28	216.60	216.60
Total emission	3117.00	1304.50	762.70	661.00	528.50	1070.28	994.60	941.60
Carbon avoidance by fuel displacement		170.51	742.80	649.95	619.00	396.33	359.19	346.81
Net carbon emission	3117.00	−1983.01	−3097.10	−3105.95	−3207.50	−2443.05	−2481.59	−2522.21

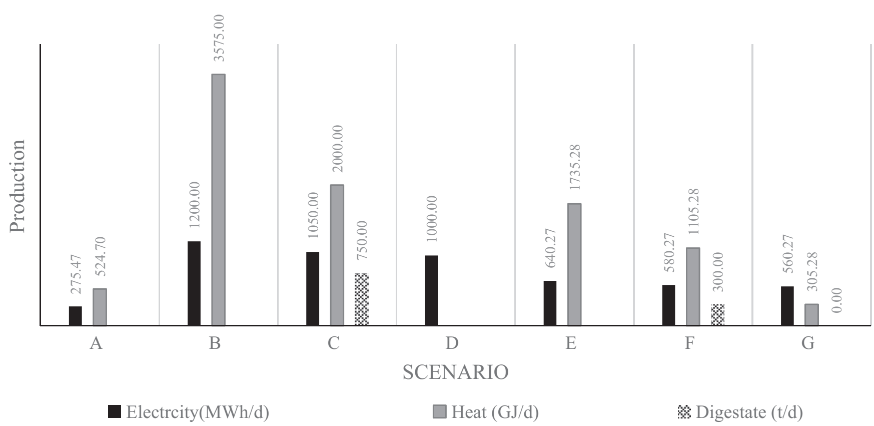

Fig. 6. Potential production from different scenarios of waste management in Taman Beringin landfill.

followed by AD, incinerator and lastly LFGRS. A detailed representation of the results is shown in Table 3, Fig. 6 (energy potential), Fig. 7 (economic potential), and Fig. 8 (environmental benefits).

The comparative 3E assessment for different WTE technologies shows that gasification technology is not an attractive option for the case study in Malaysia. Gasification technology generates less significant carbon reduction, differing by only 100 tCO_2/d compared to incinerator and AD technology; in terms of profit, gasification generates less than half of the profit generated through an incinerator and AD. The trade-off between carbon emission and profit for gasification technology is not justifiable.

The potential of LFGRS is not in the same league as the other 3 options. However, LFGRS technology is important as an intermediate option to solve the current issue of energy scarcity, waste management, and global warming. Landfill sites are currently in operation in Malaysia and cannot be eliminated in a short period of time. Even with the advancement of the other WTE technologies, the total replacement of waste management from landfill to other WTE technologies is impossible over a short period of time due to the high capital cost needed for the initial investment. By considering these factors and not wasting energy resources from the landfill, LFGRS should come as a transition state from landfilling practice to other waste treatment options. The evaluation of an integrated system, which possibly represents the intermediate phase of waste management, is described under scenarios E (LFRGS and incineration), F (LFGRS and AD), and G (LFGRS and gasification). The corresponding details of the energy, economic, and environment evaluations are shown in Table 3.

On the other hand, for incinerator and AD technologies, both technologies have almost similar potential. However, in all cases, the incinerator proves to be a better option than AD, especially in terms of heat generation. Solely based on these comparisons, the incinerator is recommended for implementation, however, it is also important to consider other external factors that may affect the suitability and viability to implement these technologies. Several other crucial factors that should be studied include, requirement of pre-treatment, waste characteristic, waste availability, marketability, and pollution (other than CO_2). Hence, further elaboration on the potential implementation of incineration and AD in Malaysia is presented hereafter.

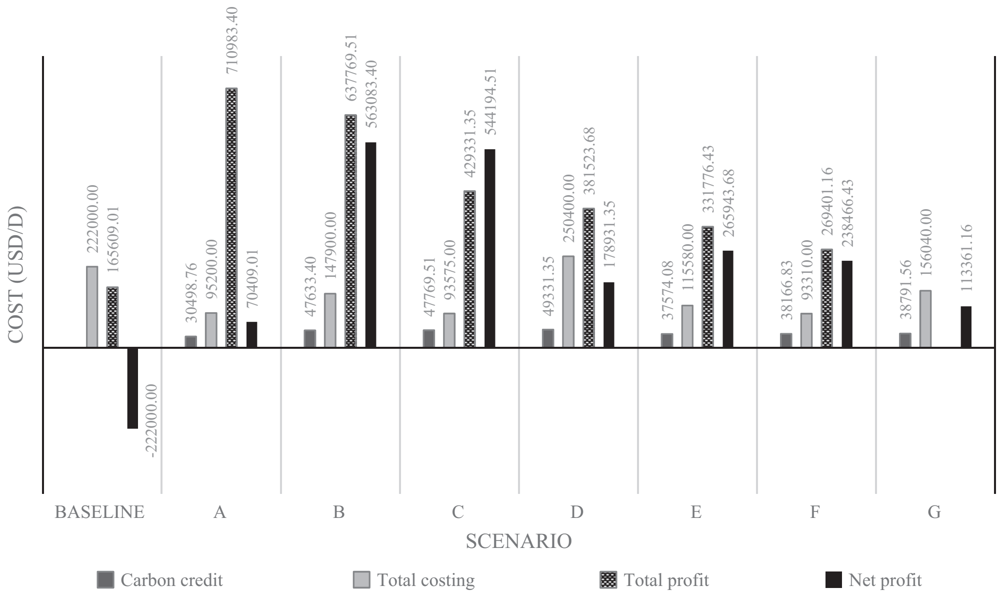

Fig. 7. Economic potential analysis for different scenarios in Taman Beringin landfill.

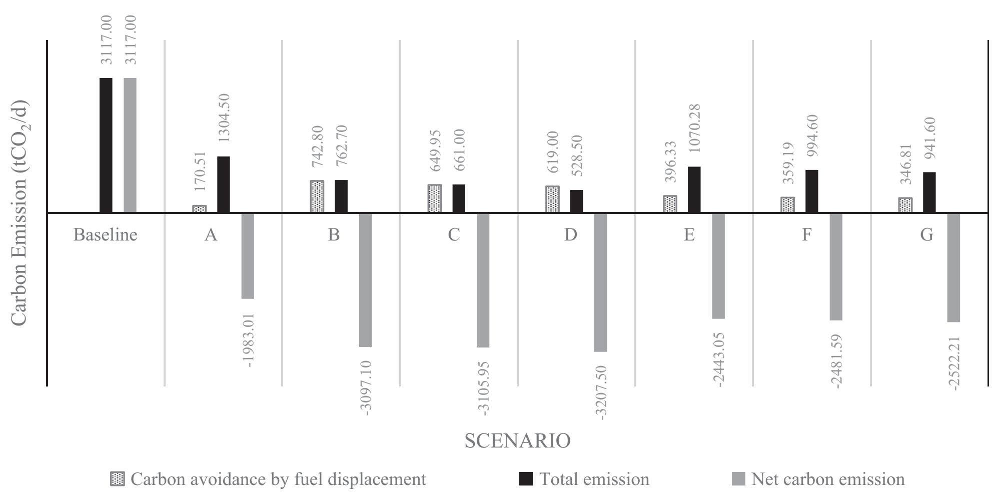

Fig. 8. Environmental potential analysis for different scenarios in Taman Beringin landfill.

6.2. Incinerator vs. AD

6.2.1. Waste characteristic

Waste characteristics are crucial to the operation of WTE technologies. Waste characteristics discussed in this context include waste composition and humidity. In Malaysia, due to the tropical climate, the waste often has a high moisture content (52.65–66.2%) [2]. The moisture content of waste greatly affects incinerator operation because the moisture will lower the calorific value of the waste. However, in the case of AD, water is generally added to the digestion process, thus, the amount of moisture in the waste will not be a problem in an AD system. Bouallagui et al. [6] reported that the highest methane production rates occur at 60–80% of humidity of input waste. On the other hand, increase of waste moisture will decrease the calorific value of waste, resulting reduction of energy production [28,37]. The correlation of moisture to waste calorific value is shown in Fig. 9.

In another context, the waste composition also plays an important role if an incinerator or AD is to be selected. An incinerator could treat a larger variety of waste, to a large extent these wastes

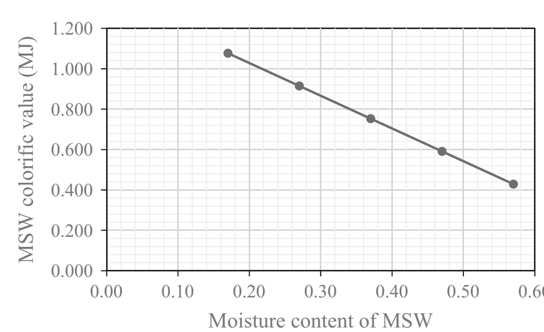

Fig. 9. Correlation of moisture content and calorific value for MSW in Malaysia [37].

do not need to be segregated in order to be treated. AD on the other hand, could only digest organic waste, which does not solve the issue of other waste treatment and requires organic waste to be segregated from the waste mix before it can be used in the process. Even in the case of organic wastes, different organic wastes might

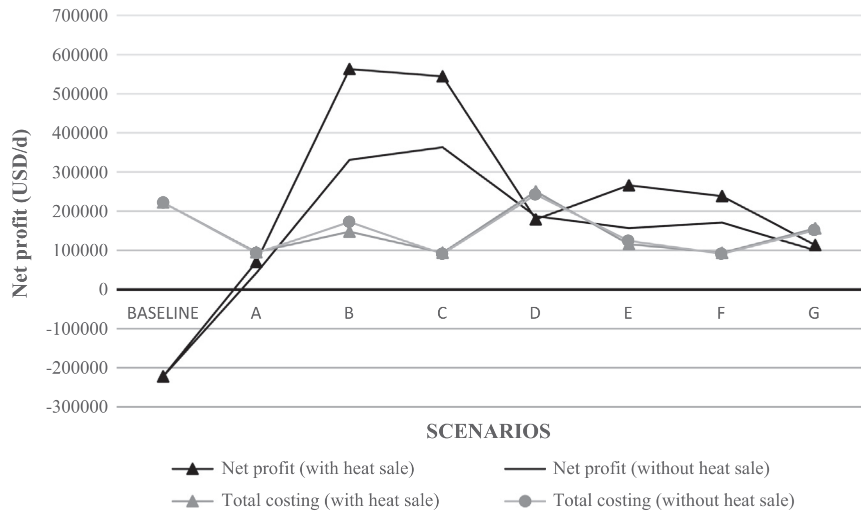

Fig. 10. Comparison of economic profitability for different AD scenarios with heat sale and without heat sale in Taman Beringin.

require different pre-treatment before they can be digested, also different organic wastes will result in different gas yields. For example, Mata-Alvarez [22] concluded that pre-treatment of the MSW can enhance the solubility of the organic matter prior to AD which lead to faster rates of degradation of MSW, reduces retention time of AD and increases biogas production. Shahriari et al. [33] studied the effect of the pre-treatment for AD of the organic MSW in the presence or absence of hydrogen peroxide at different temperatures. Kondusamy and Kalamdhad [19] reviewed different pre-treatment processes, such as mechanical, thermal, chemical, and biological pre-treatment to enhance the bio-methane production of AD from food waste. Finally, a sustainability assessment study by Ariunbaatar et al. [4] concluded that thermal pre-treatment of organic solid waste with low temperatures and two-stage AD systems provides more advantages in term of efficiency, economical cost, and environmental impact as compared to the other pre-treatment methods.

6.2.2. Waste availability

The sustainability of the waste resource is also very important to keep the WTE technology operating. In the case of an incinerator, a fluctuating waste resource (MSW) would greatly reduce efficiency, which could lead to technical and economic issues. As for the AD system, apart from organic food waste from MSW, the AD system could also use agricultural crop residue [5], tropical forestry waste [14], pulp and paper mill waste [24], palm oil residue [32], algae [8], and animal manure [15], reducing its susceptibility to fluctuating waste resources (MSW).

6.2.3. Marketability

The marketability of the produced utility resources is also very important to ensure the economic potential of WTE. As previously discussed, an incinerator is superior to AD due to its higher heat generation and the subsequent profit from the sale of heat energy. While this evaluation applies in locations with high heat demand, in Malaysia heat demand is generally low because Malaysians do not require heat energy for space heating. A comparison of incineration and AD, without considering the sale and utilisation of heat, is shown in Fig. 10. Overall, the total costs both with and without the sale of heat do not vary significantly. However, the total profit without the sale of heat is lower than it is with the sale of heat. A contract observation can be seen in AD (scenarios C and F). When the production and sale of heat from AD are implemented, the net profit reduction is comparable to the cases without heat sale. The explanation for this phenomenon is that AD is more favourable for electricity production compared to heat production. On the other hand, for AD other than generating electricity, a purified biogas could also be utilised as fuel for vehicles and cooking, thus increasing its marketability. One of the best practices of biogas utilisation for vehicular fuel is found in Stockholm, Sweden where the utilisation of biogas to fuel public transport began around the year 2000 [27]. Approximately 19% of biogas production in Sweden was used as fuel for vehicles in 2007 [10]. On the other hand, in some developing countries, the utilisation of biogas from MSW is common for household cooking – currently, there are more than 30 million household digesters in China [16] and 3.8 million in India [29].

6.2.4. Pollution

Other than carbon emission, it is also important to consider the emission of SO_x and NO_x. An incinerator generally produces higher amounts of pollutants compare to AD. Depending on the distance of the waste treatment facility from the nearest community, a health hazard for the surrounding community may arise.

Overall, AD would be the best option for implementation mainly due to the high moisture content of MSW and low demand for heat energy. AD also has better environment prospects and more options for future expansion, such as the generation of fuel for vehicles and cooking gas. Although AD does not solve the issue of inorganic waste, segregation practices induced through the project could be extended to the segregation of inorganic waste, which could be reused or recycled, and simulating the growth of an industrial eco-town.

7. Conclusion

An assessment of the 3E impacts of WTE, including LFGRS, incineration, AD, and gasification for a case study in Malaysia was performed in this study. It was found that incinerator could provide the best results for solid waste management in terms of economic and environmental impact (GHG mitigation) considering both electricity and heat production; however if heat production was not preferred, AD becomes the most sustainable option for Malaysian scenario. It is recommended that the final outcome for waste management in Taman Beringin focuses on the AD of organic waste and the recycling of inorganic waste. However, in order to achieve the mentioned goal, development should be done in phases. Beginning with LFGRS and slowly developing better waste treatment facility for inorganic waste recycling and organic waste recycling through AD.

Acknowledgements

The authors gratefully acknowledge the research grant and financial support provided by the Ministry of Higher Education (MOHE) and University Teknologi Malaysia (UTM), under the GUP research grant number Q.J130000.2544.07H95 and the Ministry of Higher Education R.J130000.7301.4B145. This research is also supported by the Japan International Cooperation Agency (JICA), under the SATREPS (Science and Technology Research Partnership for Sustainable Development) Scheme, for the project entitled *Development of a Low Carbon Scenario for the Asian Region.* This paper is dedicated to MyPhD Scholarship from the Malaysian Ministry of Education and the EU Erasmus Mundus-IDEAS Project for providing a scholarship to the first author.

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