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Optimal waste-to-energy strategy assisted by GIS For sustainable solid waste management

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Abstract. Municipal solid waste (MSW) management has become more complex and costly with the rapid socio-economic development and increased volume of waste. Planning a sustainable regional waste management strategy is a critical step for the decision maker. There is a great potential for MSW to be used for the generation of renewable energy through waste incineration or landfilling with gas capture system. However, due to high processing cost and cost of resource transportation and distribution throughout the waste collection station and power plant, MSW is mostly disposed in the landfill. This paper presents an optimization model incorporated with GIS data inputs for MSW management. The model can design the multi-period waste-to-energy (WTE) strategy to illustrate the economic potential and tradeoffs for MSW management under different scenarios. The model is capable of predicting the optimal generation, capacity, type of WTE conversion technology and location for the operation and construction of new WTE power plants to satisfy the increased energy demand by 2025 in the most profitable way. Iskandar Malaysia region was chosen as the model city for this study.

1. Introduction

Rapid urbanization, population growth and industrialization contribute significantly to the increased waste generation and changes of waste characteristics in. The municipal solid waste (MSW) in Malaysia increased from 16,200 t/d in year 2001 to 19,100 t/d in year 2005 with an average rate of 0.8 kg/capita/d. Due to rapid population growth, it is estimated that the daily solid waste generated will be 31,000 t/d by year 2020 [1]. Management of MSW follows the waste management hierarchy of: reduce, reuse, recycling and disposal. Depending on the characteristic of the MSW, it can be processed by different approaches. Currently, waste management method in Malaysia is very depending on landfilling as only 5.5% of the MSW is recycled and 1.0% is composted while the remaining 94.5% of MSW is disposed on landfilling sites [2]. To date, solid waste management in Malaysia is at the stage of transition and planning towards sustainable and effective approaches. Among various waste treatment methods, waste-to-energy (WTE) is recognized as a promising alternative for waste management as well as a potential source for the production of renewable energy [3-5]. WTE is considered an attractive waste management strategy as the approach includes all three factors for sustainable development: economy, environment, and social. In terms of the preferred hierarchy of waste management, WTE has higher priority as it involves the recovery of resources prior to the ultimate waste disposal in landfill. Besides, Malaysian Government has promoted the generation of renewable energy (RE) from waste source since 2001 under the 8th Malaysia Plan (8 MP). The latest 10th Malaysia Plan (10 MP) has targeted to increase the share of RE for up to 11% (2080 MW) in its energy mix by 2020 while the RE from MSW is one of the promising options to achieve the target [6]. The WTE technique included landfill gas recovery system (LFG) and waste incineration. Landfilling

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incorporates methane gas recovery system is considered the cheapest WTE recovery method yet it has low energy recovery efficiency. Waste incineration, on the other hand, serves as the primary approach of waste treatment technology that converts biomass to electricity and allows huge volume reduction of MSW (approximately 80-90%), however the capital cost and maintenance cost are high. Both landfilling and waste incinerator requires different criteria of site sitting. Sitting decisions of waste management technologies are governed by the pre-existing land use dynamics as well as the nature potential interaction of technology with the pre-existing environment, geologic, hydrological, and social-economic parameters in the areas.

Several key questions need to be answered along the decision making process of WTE management: a) which WTE technology should be used to produce electricity with minimum cost while achieved the targeted energy demand? b) For a long term planning period, when should the decision makers build the technology with desired capacity? c) For a planning region, where is the best sitting site of WTE technology with minimum transportation cost? In response to these concerns, the economic trade-off variable in WTE management system can be assisted by the use of an optimization model which addresses both the considerations of technology selection and site selection. This study aims to address the limitation of previous WTE study by synthesising a multi period (year 2012-2025) cost-effective processing network for MSW. The model preferentially utilizes the waste to produce energy to meet the targeted demand with the best mix of WTE technology, types of waste, power plant capacity, location and annual planning of WTE power plant construction for up to year 2025. Figure 1 explains the framework of the current WTE system as proposed. It incorporated two modeling tools. Firstly, Geographic information system (GIS) is used to analyse the land-use change of case study areas and selects the potential sitting location for WTE power plant. Generic Algebraic Modelling System (GAMS) was used to simulate the waste related data and to generate an optimal cost effective solution for the WTE system.

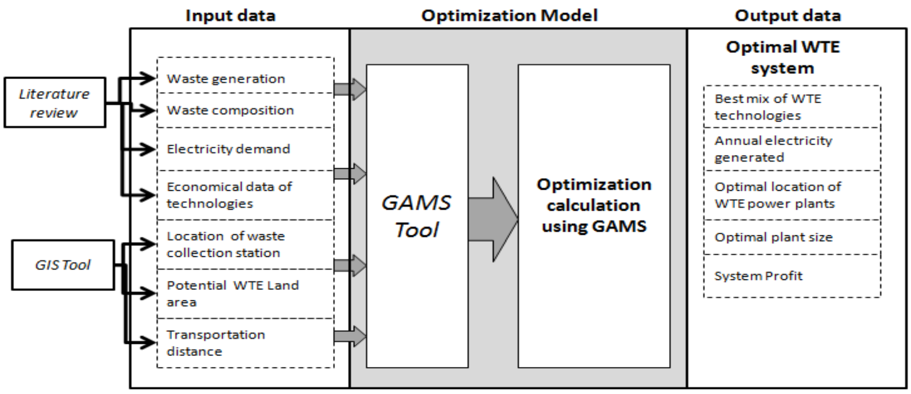

Figure 1. The proposed framework of the WTE system.

2. Methodology

As depicted in Figure 1, the primary step of this research involved data collection from various reliable sources. A superstructure is then constructed to represent the entire concept of the integrated waste management by connecting each element that covers waste generation, waste treatment technologies, storage capacity and location to the corresponding end products. Based on the designed superstructure, a mathematical model comprises of two important components is developed: the objective function and constraints. The model was then coded in General Algebraic Modeling System (GAMS), an optimization software, in a structural manner.

2.1 Input data

The input data are collected through literature review, interview or simulated through modeling tools (GAMS and GIS).

2.1.1 Study area and waste generation

Iskandar Malaysia (IM) was selected as the study area. IM covers an area of about 2,217 km^2 with five main flagship zones: Zone A (JB city center), Zone B (Nusajaya), Zone C (Western Gate Development), Zone E (Senai-Skudai), and Zone E (Eastern Gate Development). IM serves as the southern economic region in the southern Malaysia with the aims to be transformed into a metropolitan by 2020. Inspired to become a low carbon society, IM set out a target to increase the share of RE from MSW, from 8% (25MW) in year 2015 and up to 12% (50 MW) in its energy mix by 2025. [7]. MSW was considered as the only type of waste in this study. The annual waste generation and waste composition in IM from year 2012 to year 2025 are listed in Table 1.

Table 1 Annual waste generation in IM from year 2012 to 2025.

Types of waste	**Composition, %**	**Annual waste generation (tonnes)**							
		2012	**2014**	**2016**	**2018**	**2020**	**2022**	**2024**	**2025**
Food	0.493	377,855	423,651	474,998	532,568	590,786	669,486	750,628	777,660
Yard	0.182	139,492	156,399	175,354	196,607	218,100	247,153	277,108	287,087
Paper	0.171	131,061	146,946	164,756	184,724	204,918	232,215	260,360	269,736
Plastic	0.097	131,061	83,355	93,458	104,785	116,240	131,724	147,690	153,008
Glass	0.037	28,358	31,795	35,649	39,970	44,339	50,245	56,335	58,364
Metal	0.02	15,329	17,187	19,270	21,605	23,967	27,160	30,451	31,548
Total		766,440	859,333	963,485	1,080,260	1,198,349	1,357,984	1,522,573	1,577,403
					7,475,567				

2.1.3 Location of waste collection station and potential power plant

Geographical Information Systems (GIS) is used to identify the locations of the current waste transfer station and potential WTE plants. Currently, there is only one waste transfer station in IM region, i.e. the Taruka transfer station (TS1) located in zone A. Two other transfer stations (TS2 and TS3) are identified in this study by GIS. For new locations of independent WTE plants, the potential site identification was conducted using GIS based on several criteria [8].

WTE plants should be located in the land-use zones dedicated to medium or heavy industry. Other criteria for the sites includes:

- It should take no longer than one hour to drive a truck from the waste generation area to the plant.
- MSW incineration plants should be at least 300 to 500 meters from the residential zones.
- MSW incineration plants should be located near to the intended energy consumers.
- The WTE plant should be located at 0-500m from sea level as the elevation of plants location altitudes will account for the increased transport cost or fossil fuel consumption.

Ten potential WTE sites are selected based on the GIS analysis. The distance between waste transfer stations and locations to build the WTE power plants are tabulated in Table 2. The location of the transfer stations and ten potential WTE sites are illustrated in Figure 2.

Table 2. Land price for the ten potential WTE sites (S1 to S10) and the distance (in Km) between the waste transfer stations (TS1 to TS3), to the corresponding site locations (S1 to S10).

Potential WTE Site	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
Land price (RM/km2)	8	20	15	25	15	100	50	23	19	40
Available area (km2)	0.490	0.763	0.635	0.508	0.451	0.196	1.736	0.962	1.794	2.718
TS1	27.56	27.65	26.99	21.53	14.28	20.28	18.85	24.59	31.86	27.89
TS2	5.96	1.49	1.08	8.11	12.66	29.49	34.79	42.62	49.68	44.75
TS3	44.02	46.55	46.92	38.44	34.28	19.20	11.93	5.30	23.66	21.81

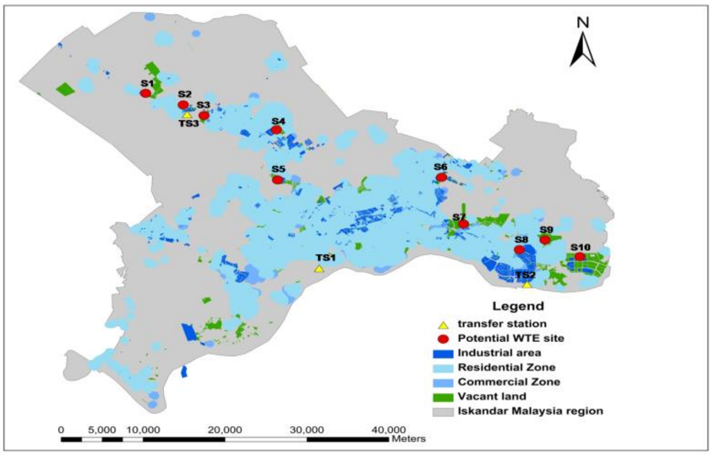

Figure 2. Locations for the transfer stations and the potential sites for WTE plant in IM.

2.1.5 Power Plant economical data

The objective function of the model is to minimize the cost of electricity generation. The costs of WTE for incineration and LFG considered in the model is taken from the U.S. Energy Information Administration, 2010 and tabulated in Table 3 [9].

Table 3. The Costs for Incineration and LFG Power Plants [13].

Power Plant	**Capital Cost ($/MW)**	**Fixed O&M ($/MW)**	**Variable O&M ($/MW)**	**Fuel Price, ($/MW)**	**RE Availability (MW)**
Incineration	3,860,000	100,500	43,800	0	717.17
LFG	8,232,000	373,760	72,970.8	0	717.17

2.2 Mathematical Formulation

The optimization model for the WTE strategy consists of an objective function and several constraints. The objective function of the WTE model is to minimize the total cost of electricity generation. The objective function includes annualized capital cost, fixed operation and maintenance (O&M) cost, variable O&M cost of the new plants, the cost of land to build the new plants, and the transportation cost, as shown in Eq. 1:

$$\min \text{cost} = \underbrace{\sum_w \sum_p \sum_s \sum_l \sum_c \sum_t Ccost^w_{p,c,t}\ Z^w_{p,s,t,c}}_{\text{Capital cost}} + \underbrace{\sum_w \sum_p \sum_{ts} \sum_l \sum_c \sum_t Fcost^w_{p,c,t}\ TR_{p,tc,t}\ Z^w_{p,s,t,c}}_{\text{Fixed O\&M cost}}$$
$$+ \underbrace{\sum_w \sum_p \sum_l \sum_c \sum_t Vcost^w_{p,c,t}\ E^w_{p,l,t,c}\ \text{OPT}}_{\text{Variable O\&M cost}}$$
$$+ \underbrace{\sum_w \sum_p \sum_s \sum_l \sum_c \sum_t F^w_{p,ts,l,t}\ Tcost^w_{p,s,t,c}\ LOC_{s,l}}_{\text{Transportation cost}}$$
$$+ \underbrace{\sum_p \sum_l \sum_c Lcos_l\, CAPArea_p\ Z^w_{p,s,t,c}}_{\text{Land cost}} \qquad (1)$$

In order to define the relationship among the variables and parameters in this model, several linear inequality and matrix manipulation constraints are developed based on: resource availability constraint, capacity demand constraint, construction lead time, and location constraints.

3.0 Result and discussion

The results shows that the waste provided by MSW as a RE resources are sufficient to satisfy the localized power generation with the capacity of 50 MW as projected in the IM blueprint. From the results obtained from the modeling using GAMS, the minimum total cost for the WTE strategy is USD 21.41 million/yr with a total electricity generation of 50MW/y when both the incineration and LFG power plants were considered for the planning year of 2012-2025. The optimization results indicated that LFG recovery system is the most preferable type of waste-to-energy (WTE) conversion technology due to higher cost constraints as compared to the incineration. Up to year 2025, two LFG power plants and two waste incinerators can be built in IM as illustrated in Figure 3 where the optimal site for WTE plant in IM is selected. The power plants are suggested in S1 and S10 area due to cheaper transportation cost and land cost. The capacity distribution for all locations is summarized in Figure 4.

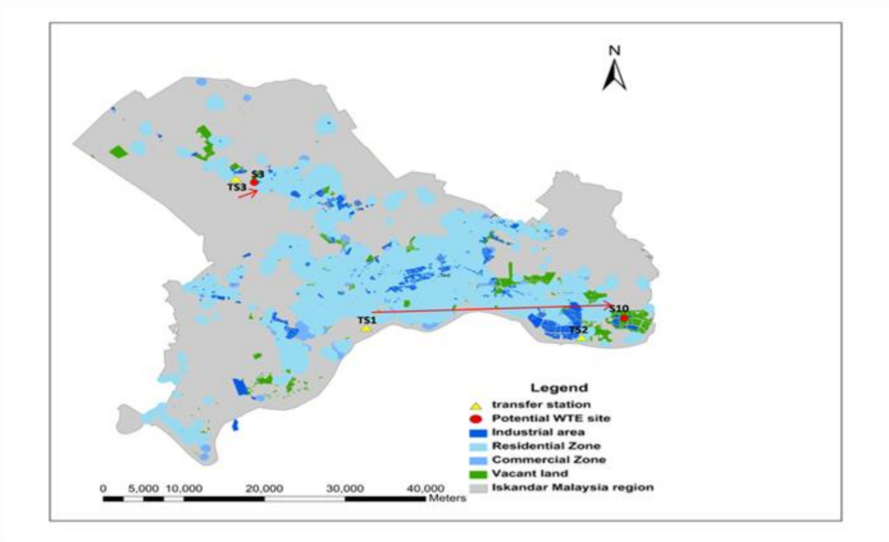

Figure 3 Optimal location selection for waste transfer stations and WTE sites.

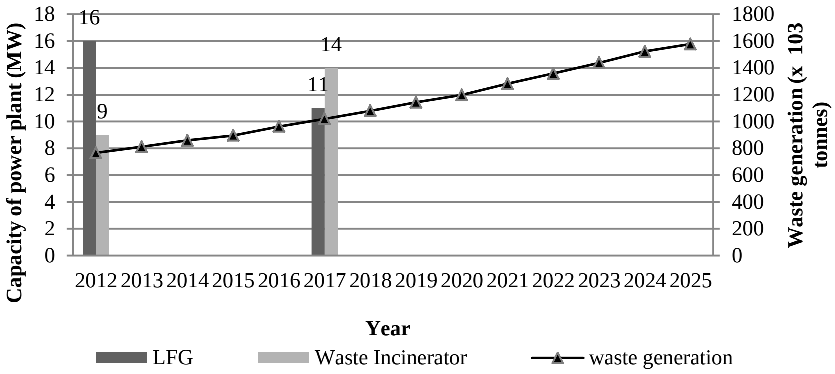

Figure 4 Optimal solutions for WTE strategy with capacity distribution.

4.0 Conclusion

A multi-period planning for WTE strategy has been successfully carried out to minimize the total cost of WTE strategy based on the power generation for IM by selecting the potential location as assisted by the GIS tool, capacity, and type of WTE conversion technology. Technology selection is dictated by capital cost, operation cost and heat rate of the system while location selection is dictated by land availability and price, transportation cost of waste resource. The optimization results indicated that LFG recovery technology is more favorable for WTE conversion with larger capacity suggested to be constructed in IM. Two potential WTE sites have been selected to satisfy the localized projected electricity requirement in IM until 2025. This study illustrates the application of GIS tool to assist the modeling work for optimal planning of WTE strategy for sustainable solid waste management.

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