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OPTIMIZATION APPROACH FOR GREENHOUSE GAS TO GREEN ENERGY FOR A LOW CARBON REGION OF ISKANDAR MALAYSIA

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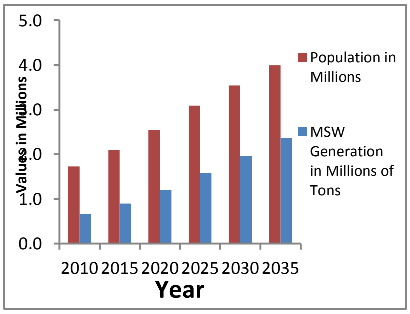
Graphical abstract



Abstract

Landfill gas (LFG) like any other greenhouse gases (GHG) is a threat to the environment; hence its mitigation through effective utilization is necessary. The objective of this study is to estimate the amount of LFG captured using IPCC methodology and then develop optimization model for the LFG utilization for green energy production for Iskandar Malaysia. Of the three MSW Scenarios considered, the most appropriate was Scenario MIX, giving projection of MSW to landfill ranging from 600,000 tons in 2010 to 711,000 tons in 2035 for Iskandar Malaysia. From this, a mean annual LFG capture of 21,672 tons was estimated. The Mixed Integer Programing model considered Scenario ST as the more appropriate of the two LFG Scenarios, favoring combined heat and power generation with steam turbines over other options. The optimal result yielded a mean annual electricity and steam generation of 20,588 MWh (2.3 MW) and 150 million MJ respectively. The mean electricity generation represents 0.16% and 0.02% of the maximum electricity demand for Iskandar Malaysia and Peninsular Malaysia respectively. Additionally, GHG emission reduction of 12,000 tons CO_2 equivalent was achieved. The findings revealed the potentials in LFG capture from the case study in terms of green energy and GHG emission reduction for sustainable development.

Keywords: Landfill gas; greenhouse gas; green energy; Iskandar Malaysia; Optimization

Abstrak

Gas tapak pelupusan (LFG) seperti mana-mana gas rumah hijau lain (GHG) merupakan ancaman kepada alam sekitar; oleh itu penggunaan berkesan adalah diperlukan untuk mengurangkan GHG. Objektif kajian ini adalah untuk menentukan jumlah LFG yang ditangkap dengan menggunakan kaedah IPCC dan kemudian membangunkan model optimasi yang berkaitan dengan penggunaan LFG untuk penjanaan tenaga hijau untuk Iskandar Malaysia. Daripada tiga Senario MSW yamg dipertimbangkan, Senario MIX adalah paling sesuai, memberi unjuran MSW ke tapak pelupusan yang terdiri daripada 600,000 tan pada tahun 2010 kepada 711,000 tan pada tahun 2035 untuk Iskandar Malaysia. Dari ini, min penangkapan LFG tahunan sebanyak 21,672 tan telah dianggarkan. *Mixed Integer Programing Model* menentukan Senario ST sebagai senario yang paling sesuai daripada dua senario LFG, memihak kepada penjanaan gabungan haba dan kuasa dengan turbin stim berbanding dengan pilihan lain. Keputusan optimum memberi min penjanaan elektrik dan stim tahunan sebanyak 20,588 MWh (2.3 MW) dan 150 juta MJ masing-masing. Penjanaan elektrik mewakili 0.16% dan 0.02% daripada permintaan elektrik maksimum bagi Iskandar Malaysia dan Semenanjung Malaysia masing-masing. Selain itu, pengurangan pelepasan GHG sebanyak 12,000 tan-bersamaan CO_2 telah dicapai. Kes kajian menunjukkan potensi dalam menangkap LFG dari segi tenaga hijau dan pengurangan pelepasan GHG bagi pembangunan.

Kata kunci: Gas tapak pelupusan; gas rumah hijau; tenaga hijau; Iskandar Malaysia; Optimization

1.0 INTRODUCTION

Greenhouse gases (GHGs) are gaseous substances which prevent the dispersion of heat from the earth's surface and thereby resulting in global temperature rise [1]. This global temperature increase is one of the significant factors responsible for various environmental problems including flood, typhoon, tsunami and most importantly climate change. The most important GHGs are carbon dioxide and methane, which constitutes 9 % – 26 % and 4 % – 9 % respectively of the total [2]. These GHGs are also the main constituent of landfill gas (LFG); making landfills sources of GHG emission. According to IPCC [3], landfills constitute approximately 3 – 4 % of anthropogenic GHG emission.

Landfills are indispensable because they play a great role in waste disposal in both developed and developing economies. In USA and UK, landfills serve as cheap source of green energy [4]. In addition, due to its cheapness and simplicity, it is the main source of waste disposal in developing economies such as Malaysia, Indonesia, Nigeria etc. [5]. One of the problems of landfills lies in the management of the LFG produced. The amount of this GHG, which is produced from biodegradation of municipal solid waste (MSW) in landfills, can be estimated from a number of methods which include Intergovernmental panel on climate change (IPCC), LandGEN, Belgium, Scholl Canyon, TNO and German EPER models [3, 6, 7].

It is a well-known fact that LFG, like any other GHGs, is a threat to our planet; on the other hand, it can be utilized as a resource for green energy production. This gives two advantages – reducing GHG emission and reducing dependence on fossil fuel utilization. This is essential particularly for a low-carbon region which is the major motivation for this study.

LFG can be utilized as a low/medium grade fuel which entails basically the removal of moisture from the captured LFG; this is the common form in which the gas is utilized as a cheap fuel. High grade LFG requires complete removal of moisture, carbon dioxide and other minor component, making the utilization of the gas in this form very expensive. Low/medium LFG can be utilized for electricity/steam generation (or both i.e. combined heat and power, CHP), using gas engines (GEs), gas turbines, (GTs), steam turbines (STs), or boilers or the combination of these equipment. Other utilization options include hydrogen/methanol production, or direct LFG supply to industries or residents via pipelines for heating purposes [8, 9].

Electricity generation from LFG was studied to be viable with a payback period of 1 – 3 years when internal combustion engines (such as GEs) are used; and 9 years with fuel cells [10]. Using Long-range Energy Alternative Planning System (LEAP), Shin *et al.*[9] studied the economic and environmental impact of LFG utilization for electricity generation in South Korea. In their study, they partially substituted fossil fuel based power generation with LFG, which resulted in cost and GHG emission reduction. Jafar *et al.* [11] also studied the environmental impact of electricity generation from LFG in terms of carbon dioxide, sulfur dioxide and oxides of nitrogen emission. Additionally, in previous studies [12-15], investigations on LFG emission and electricity generation from Malaysian landfills have been carried out. However, the aforementioned studies and many others not mentioned herein studied electricity generation only without considering other options. These other options include; (1) other green energy such as combined heat and power, CHP, hydrogen or methanol production, LFG use or its partial blending with natural gas for direct heating purpose; (2) equipment options such as GEs, GTs, STs, boilers etc. The big question here is "Can an optimization tool be developed to combine all these options and at the same time striking a balance between financial and environmental impact of each option"?

The objectives of this study are: (1) projection of the amount of municipal solid waste (MSW) generated by the case study and the amount that should be disposed in landfill for 20 years, (2) projection of LFG capture using IPCC methodology in the life span of the landfill and (3) development of optimization tool that plans the utilization of the estimated LFG for green energy production over the life span of the landfill taking into consideration equipment types, green energy option/options and simultaneously balancing the economic and environment benefits of the options.

The study considers Iskandar Malaysia as the case study and considers two sets of scenarios – MSW Scenario and LFG Scenario. Scenario MSW consists of three sub-scenarios, which determine the amount of MSW that should be disposed in landfills, while Scenario LFG consists of two other scenarios which determine the best LFG utilization option(s) for green energy production. The LFG collection projection can be determined using IPCC methodology and the green energy plan involves the development of mixed integer programing models (MIP) executed in General Algebraic Modeling System (GAMS). These methodologies are preferred due to their versatility, effectiveness, accuracy, flexibility and ease of application [3, 7, 16].

The significance of this study is in two folds, it determines the potential in LFG (a dreadful GHG) as a resource for green energy production for a low-carbon region and second, it develops a tool for the planning of LFG utilization which determines the green energy option(s) and equipment option(s) to adopt. In addition, the tool forecasts profit, GHG emission reduction and type(s) as well as amount of green energy produced throughout the life span of the landfill considered. Due to the parameters and variables in the optimization tool, it makes the model applicable to other case study beyond this.

2.0 METHODOLOGY

2.1 IPCC Model Description

The IPCC methodology was used to estimate amount of LFG generated which is based on first order decay model. It implies that the degradation of the reactive component of the waste is a first order reaction. The most important factor in the model is the amount of reactive material – decomposable degradable organic material, DDOC, remaining in the landfill at any time. The amount of this DDOC in the waste was calculated as follows [3]:

$$DDOC_{m,t} = MSW_{m,t} * DOC * DOC_f * MCF \qquad (1)$$

where, $DDOC_{m,t}$ is the amount of decomposable degradable organic material in year t in tons, $MSW_{m,t}$ is the quantity of MSW deposited in the landfill in year t in tons, DOC is the amount of degradable organic carbon in the waste in tons carbon per ton MSW, DOC_f is the fraction of DOC that can degrade under anaerobic condition in the landfill, MCF is the methane correction factor, i.e. the fraction of waste which is not affected by the aerobic process preceding the main anaerobic reaction. This is taken as 1 for a deep and managed landfill. The amount of $DDOC_m$ accumulates with time given as follows:

$$DDOC_{ma,t} = DDOC_{m,t} + (DDOC_{ma,t-1} * e^{-k}) \qquad (2)$$

where; $DDOC_{ma,t}$ and $DDOC_{ma,t-1}$ are the amounts of DDOC that have accumulated at the end of year t and year t-1 respectively. 'k' is the waste degradation rate constant (rate of reaction) in year^{-1}, given by k = ln(2)/$T_{1/2}$, and T is the half-life (in years). In addition, the $DDOC_{ma,t}$ responsible for LFG generation is actually the amount that decomposed, which was calculated as:

$$DDOC_{m,decomp} = DDOC_{ma,t-1} * (1 - e^{-k}) \qquad (3)$$

The amount of LFG generated is directly dependent on the amount of methane generated; the methane generated was thus calculated as:

$$Methane_{generated} = DDOC_{m,decomp} * F * 16/12 \qquad (4)$$

where; F is the proportion of methane in LFG, and 16/12 is the ratio of molecular mass of methane to carbon.

The amount of LFG captured is dependent on the landfill's efficiency and amount of gas generated. In this study, LFG capture efficiency of 50% was assumed. Therefore, for methane proportion of 50% in LFG, the amount of LFG captured can be estimated as follows:

$$LFG_{capture} = Methane_{generated} * 2 * 50\% \qquad (5)$$

The application of Equations (1 – 5) to the hypothetic landfill for the case study is shown in the result and discussion section.

2.2 MIP Model Development

The Mixed Integer Programing, MIP, model considered 7 LFG utilization technologies/options, denoted by the letter t which are: gas engines (GEs), gas turbines (GTs), steam turbines (STs), boilers (for electricity/heat or CHP generation); direct LFG supply; hydrogen and methanol production. The MIP model consists of the objective function and the constraints.

2.2.1 Objective Function

The objective function maximizes the profit in US$ from the LFG utilization technologies/options as follows:

$$MAX.PROFIT = Annual\ Revenue - Annual\ Totalcost \qquad (6)$$

The annual revenue and cost were modeled for the life span of the landfill considered. The revenue and cost are described in Equations (7) and (8) as follows:

$$Annual\ Revenue_y = \left(\textstyle\sum_i Price_i \times PRO_{i,y} \right) + \left(\textstyle\sum_{tm} ER_{tm} \times PRES_{tmy} \right) \times CCPT \quad \forall y \qquad (7)$$

$$Annual\ TotalCost_y = \left(\textstyle\sum_{itm} UPCost_{tm} \times MAT_{itmy} \right) + \left(\textstyle\sum_i URAWLFGCOST_{iy} \right) + \left(\left(\textstyle\sum_{itmz} AnnualCapCost_{tmz} \right) \times \right.$$

$$BV_{tmz}) \times 3\ ) \qquad \forall y \tag{8}$$

where: Annual Revenue$_y$ and AnnualTotalCosty are the revenue and total cost for year y respectively in US$. Price$_i$ is the price of product i in US$, PRO$_{iy}$ is the product i produced in year y in tons, ERtm is the emission reduction of technology t in mode m and PRES$_{tmy}$ is the corresponding processing material in tons, CCPT is the carbon credit per ton in US$. The revenue is from product sale and carbon credit while the total cost is for the processing cost (UPCost x MAT), cost of raw LFG (URAWLFGCOST) and capital cost (AnnualCapCost). BV is a binary variable which selects equipment cost based on technology t, mode m and size, z.

2.2.2 Constraints

The constraints are conditions imposed on the system. Equation (9) constrains the system to select only one mode and one equipment size for each technology selected as follows:

$$\sum_{mz} BV_{tmz} = 1 \qquad \forall t \tag{9}$$

And Equation (10) indicates that resource, RES, can be utilized as input material, i, into technology t, under mode m, in period y, or sold as product PRO$_{iy}$.

$$RES_{iy} = \sum_{tm} MAT_{itmy} + PRO_{iy} \qquad \forall i, \forall y \tag{10}$$

Equations (11) and (12) govern the materials in and out of system respectively. MAT in tons is expressed in terms of material conversion matrix, MCM and PRES in Equation (11). And Equation (12) gives the resources generated from the system SGRES, in terms of resource-product conversion matrix RPCM and PRES in tons. MCM and RPCM are two important parameters – which are essentially input material composition and output material conversion respectively.

$$MAT_{itmy} = PRES_{tmy} \times MCM_{itm} \qquad \forall i\ \ \forall t\ \ \forall m \tag{11}$$

$$SGRES_{itmy} = PRES_{tmy} \times RPCM_{itm} \qquad \forall i\ \ \forall t\ \forall m\, \forall y \tag{12}$$

3.0 THE CASE STUDY – ISKANDAR MALAYSIA

The case study for this research is Iskandar Malaysia which is a region in Johor Bahru, the capital of Johor state in southern Peninsular Malaysia. In 2006, the Malaysian Prime Minister, in his 9th Malaysian plan established Iskandar Malaysia as one of the nation's special economic corridor. One of the objectives for the establishment is the integration with Singapore's economy and to modernize Johor's economic and urban infrastructure [17]. Iskandar Malaysia is the second largest metropolitan and economic corridor after the Multimedia Super Corridor in Kuala Lumpur, the nation's capital. Iskandar Malaysia is an industrial and commercial center with an airport and seaport. As a measure to promote a climate-friendly environment, the area was planned to become a low-carbon region, i.e. to reduce energy consumption especially from fossil fuel sources and to minimize GHG emission to the minimum level possible.

As a measure to achieve the low carbon vision, the quantity of waste to be disposed in landfills ought to be reduced and landfills standardized for effective LFG utilization. In this regard, the study assumed a hypothetical landfill for Iskandar Malaysia, where the MSW intended for landfill should be disposed of. The reasons for the hypothetical landfill in spite of the existing three is because those existing ones lack the capacity for utilizing the LFG for renewable energy production moreover, they are operating beyond their capacity; two of them are supposed to have been closed (Pekan Nenas in 2006 and Tanjung Langsat in 2012) and the third will be closed in 2018[12].

The hypothetical landfill is assumed to have the following characteristics shown in Table 1. In addition, Figure 1 shows the population and MSW generation of Iskandar Malaysia.

Table 1 Parameters for the Iskandar Malaysia hypothetical landfill [12, 18]

Parameter	Description
Total landfill area	366 ha
Expected opening date	2015
Expected closure date	2035
Number of Cells	40
Landfill liner material	High-density polyethylene
Landfill depth, well diameter and type	5 meters, 500 millimeters, Vertical
Landfill type	Managed
Waste type	Municipal solid waste (MSW)
Values for DOC, DOCf, k, and MCF3	0.17 ton carbon per ton MSW, 0.5, 0.09 per year, 1
Waste composition 13	Food (37%), Garden waste (3%), Paper (17%), wood (4%), Textile (3%), Nappies (5%), Other (31%)
LFG properties	CH4 (44–56%), CO2 (40–50%), Other constituent (5%), Calorific Value (27,765kJ/kg), Temperature (25°C), Density (1.3 kg/m3)
LFG treatment	Condensate removal
LFG utilization	Energy production
Flare efficiency, temperature	99%, >1000°C

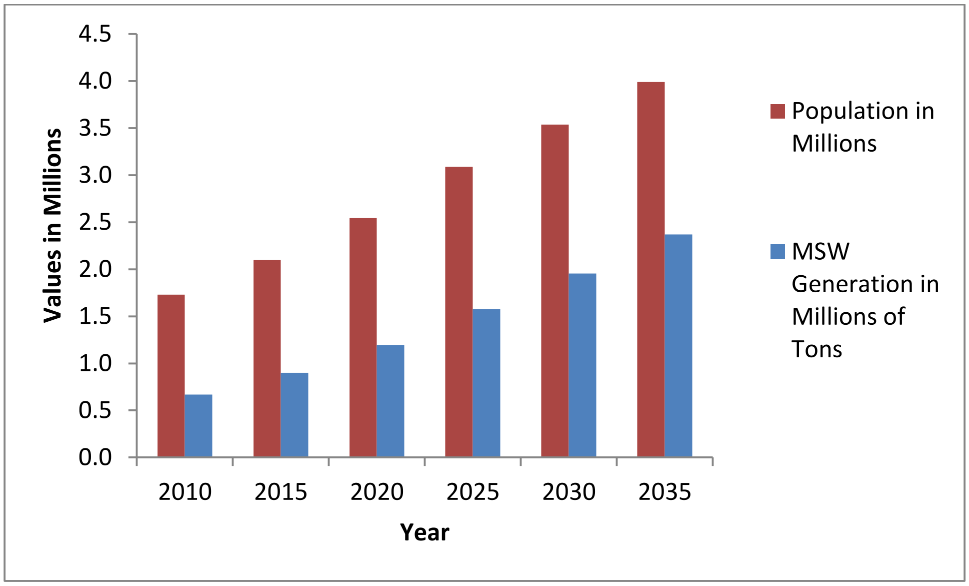


Figure 1 Population projection and MSW generation for Iskandar Malaysia. Adopted from [18]

The amount of MSW generated from Iskandar Malaysia as shown in Figure 1 cannot all go to the landfill. This is not wise in terms of environmental sustainability, especially in a bid to achieve the goal of a low-carbon region. In this respect, the policy makers of Iskandar Malaysia came out with a blue print for the proportion of the generated MSW that should go to the landfill. This blue print is considered in this study together with other MSW plans derived from other low carbon regions in Asia, and Europe. These MSW plans (MSW Scenario) are grouped into three other scenarios covering years 2010 to 2035 as follows, which gives rise to Figure 2:

i. Scenario BAU – based on the normal Malaysian practice in which 90% of MSW generated goes to landfill [13].
ii. Scenario IMBP – based on Iskandar Malaysia blue print, and is divided into 5 phases; phase 1, years 2010 – 2015, 98% of MSW goes to landfill, phase 2, 2015 – 2020, 59% of MSW goes to landfill, phase 3, 2020 – 2025, 31% goes to landfill and phase 4 2025 – 2035, 10% goes to landfill[18].
iii. Scenario MIX – based on a combination of current Malaysian practice and practices in Turkey, South Korea, UK, Finland and France. This is divided into 5 phases: phase 1, year 2010 - 2015, Malaysian practice 90% goes to landfill; phase 2, 2015 – 2020, Turkish practice 80% goes to landfill; phase 3, 2020 – 2025 South Korean & UK practice, 55% goes to landfill; phase 4, 2025 – 2030, Finnish practice 40% goes to landfill and phase 5, 2030 – 2035 French practice 30% goes to landfill [13, 19].

These 3 Scenarios are shown in Figure 2 together with the amount of MSW generation.

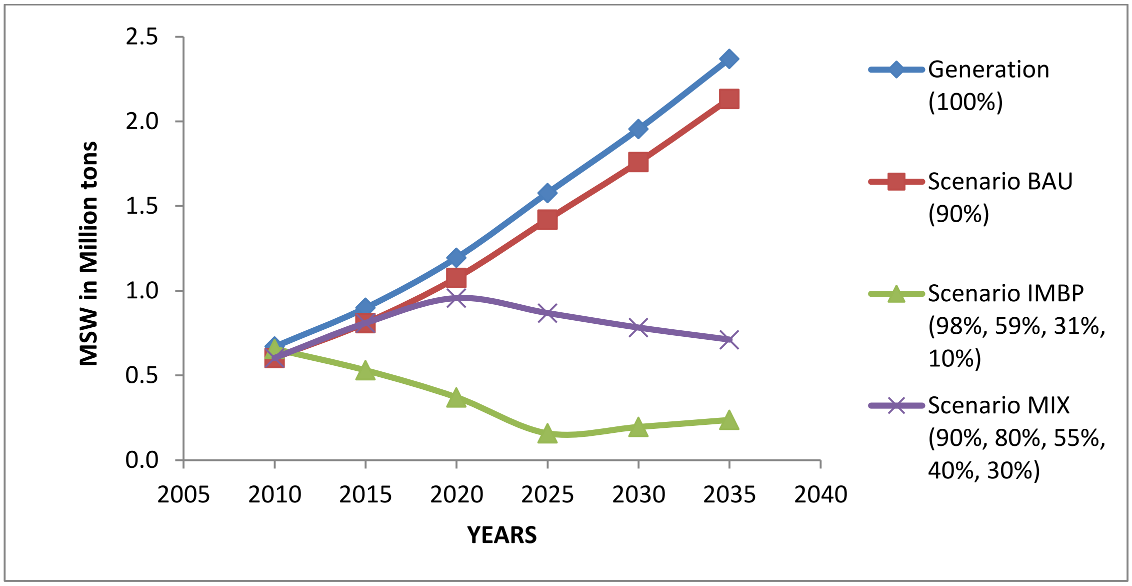


Figure 2 Total MSW generation and the amount to be landfilled based on Scenarios

Figure 2 shows four curves for MSW Scenarios. MSW generation curve (taken from Figure 1), and one curve for each of the 3 MSW Scenarios explained above. The generation is the total amount generated for the Iskandar Malaysia, and is not environmentally wise to be sent to landfill as explained above. Scenario BAU which is based on 90% of generated waste to be landfilled, is the current practice in Malaysia; and is similarly not favorable both economically and environmentally due to high cost of land, high level of emission and other problems [20]. Scenario IMBP is not realizable due to the fact that the immediate target for 2015 (59% of MSW generation to landfill) cannot be achieved because in the first quarter of 2014, at least 90% of MSW generated went to the landfill, which indicates the unlikelihood of meeting the 59% target for 2015. Scenario MIX – the combination of a number of practices makes the most sense of all the scenarios due to the fact that, (1) it combines the practices of other low-carbon regions, and (2) the changes in the proportion of MSW going to landfill is gradual – from 90% to 80% to 55% to 40% and lastly to 30%. This gives enough time for the system to adapt to the new change; i.e. enough time for facilities construction and expansion to cater for the new change. Therefore, Scenario MIX was adopted for the MSW that goes to the hypothetical landfill for Iskandar Malaysia. This amount of MSW and other information in Table 1 were used as presented in the results section, to estimate the amount of LFG captured using the IPCC methodology.

4.0 RESULTS AND DISCUSSION

This section comprises of two parts: output from the application of IPCC methodology for LFG estimation and the application of MIP models to the case study – Iskandar Malaysia.

4.1 Application of IPCC methodology to Iskandar Malaysia

This sub-section shows and discusses the output from the IPCC methodology applied to Iskandar Malaysia. Here, a step-by-step estimation of all the components of the IPCC methodology, Equations (1) – (5), is shown for easy understanding and adoption (Table 2).

Table 2 LFG estimation using IPCC methodology

Year	$MSW_{m,t}$ (tons)	$DDOC_{m,t}$ (tons)	$DDOC_{ma,t}$ (tons)	$DDOC_{m,decomp,t}$ (tons)	Methane generated (tons)	LFG captured (tons)
2015	808938.1	68759.74	68759.74	0	0	0
2016	838371.9	71261.62	134103.3	5918.069	3945.379	3945.379
2017	867805.8	73763.5	196324.7	11542.11	7694.74	7694.74
2018	897239.7	76265.38	255692.6	16897.43	11264.95	11264.95
2019	926673.6	78767.26	312452.7	22007.16	14671.44	14671.44
2020	956107.5	81269.14	366829.4	26892.43	17928.29	17928.29
2021	938400.1	79764.01	415020.9	31572.57	21048.38	21048.38
2022	920692.8	78258.89	457559.4	35720.35	23813.57	23813.57
2023	902985.4	76753.76	494931.6	39381.59	26254.4	26254.4
2024	885278.1	75248.64	527582	42598.17	28398.78	28398.78
2025	867570.7	73743.51	555917.2	45408.36	30272.24	30272.24
2026	850437.9	72287.22	580357.3	47847.13	31898.09	31898.09
2027	833305.1	70830.93	601237.5	49950.66	33300.44	33300.44
2028	816172.2	69374.64	618864.4	51747.8	34498.53	34498.53
2029	799039.4	67918.35	633517.8	53264.92	35509.95	35509.95
2030	781906.6	66462.06	645453.7	54526.13	36350.75	36350.75
2031	767698	65254.33	655154.6	55553.44	37035.62	37035.62
2032	753489.3	64046.59	662812.8	56388.38	37592.25	37592.25
2033	739280.7	62838.86	668604.2	57047.51	38031.68	38031.68
2034	725072	61631.12	672689.3	57545.97	38363.98	38363.98
2035	0	0	614791.8	57897.57	38598.38	38598.38
2036	0	0	561877.4	52914.4	35276.26	35276.26
2037	0	0	513517.2	48360.12	32240.08	32240.08
2038	0	0	469319.4	44197.82	29465.21	29465.21
2039	0	0	428925.7	40393.77	26929.18	26929.18
2040	0	0	392008.5	36917.12	24611.41	24611.41
2041	0	0	358268.8	33739.71	22493.14	22493.14
2042	0	0	327433	30835.77	20557.18	20557.18
2043	0	0	299251.3	28181.77	18787.85	18787.85
2044	0	0	273495.1	25756.2	17170.8	17170.8
2045	0	0	249955.7	23539.4	15692.93	15692.93
2046	0	0	228442.3	21513.39	14342.26	14342.26
2047	0	0	208780.5	19661.76	13107.84	13107.84
2048	0	0	190811	17969.49	11979.66	11979.66
2049	0	0	174388.2	16422.88	10948.59	10948.59
2050	0	0	159378.8	15009.38	10006.25	10006.25
2051	0	0	145661.2	13717.54	9145.028	9145.028
2052	0	0	133124.3	12536.89	8357.926	8357.926
2053	0	0	121666.5	11457.85	7638.57	7638.57
2054	0	0	111194.8	10471.69	6981.127	6981.127
2055	0	0	101624.4	9570.404	6380.27	6380.27

Table 2 shows the amount of LFG captured during the life span (2015 – 2055) of the hypothetical landfill for Iskandar Malaysia, assuming 50% LFG collection efficiency. The second column in the table is the amount of MSW deposited in the landfill (values from Figure 2, Scenario MIX) and the values in the third to seventh column were estimated from Equations (1) – (5) respectively. The values for DOC, DOC_f and MCF are shown in Table 1.

The table shows that no LFG will be captured in 2015, the year the landfill is expected to be opened, and this is because, although there will be MSW in the landfill, no gas or significant amount of the gas will be formed – this is called the delay time [3]. In 2016, the LFG captured will begin to increase from 3,945 tons to a maximum value of 38,598 tons in 2035 (a year after the closure of the landfill); and will fall to 6,380 tons in 2055 (20 years after closure). Taking an average value, approximately LFG capture is 21,672 tons per year (or 0.05 tons LFG per ton of MSW). This is equivalent to LFG generation of 0.10 tons per ton MSW (for 50% collection efficiency considered) or methane generation of 0.05 tons per ton MSW. These values correspond with values of 0.045 – 0.15 tons methane per ton MSW or 0.09 – 0.30 tons LFG per ton MSW observed by previous studies [12, 22-25].

4.2 Application of MIP to Iskandar Malaysia

The Mixed Integer Programing, MIP, models developed earlier was solved using the optimizer, General Algebraic Modeling System (GAMS). The models were applied to Iskandar Malaysia using the results in Sub-section 4.1 and other input data obtained from previous studies [13, 16, 21]. GAMS optimized the system by selecting the LFG utilization options (from options, which include; power, heat, CHP generation, direct LFG supply, hydrogen and methanol production) and equipment type(s) (such as GEs, GTs, STs and boilers) which gave maximum profit. This profit was based on economics and environmental grounds. The economic factors considered include revenue from green energy sale, carbon credit and equipment cost; and the environmental factor includes GHG emission reduction. In addition, a profitability index – the Net Present Value (NPV) was applied to analyze the maximized profit (Figure 3) based on two LFG Scenarios as follows:

1. Scenario Flaring – the captured LFG is considered for flaring only, and no green energy production is considered.
2. Scenario ST – the captured LFG is utilized for green energy production using only steam turbines for combined heat and power generation (CHP).

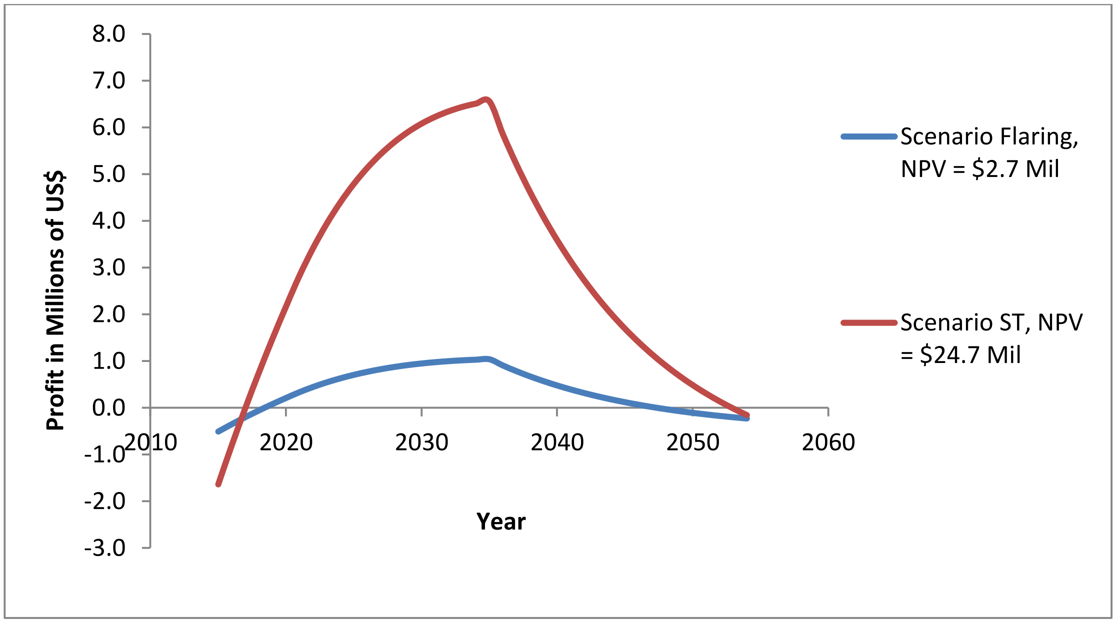


Figure 3 Profitability curves and NPV for the 2 LFG utilization scenarios

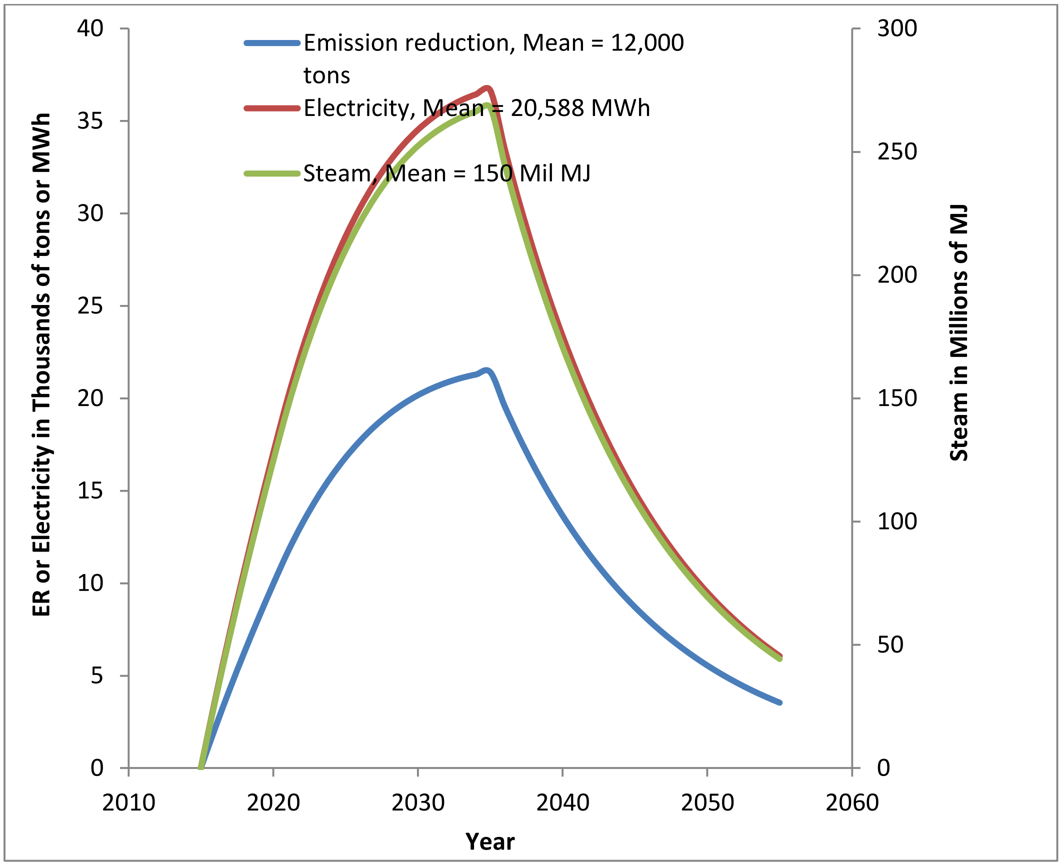


Figure 4 Emission reduction, Electricity and steam generation for the chosen option

Figure 3 shows two curves for the LFG utilization scenarios for the 40-year life span of the landfill (2015 – 2055). Initially, the 2 Scenarios show negative profits (losses) for two years or so. This is due to lack (or insignificant amount) of LFG captured in this period (see Table 2), in which the revenue accruable cannot offset the cost of production. The profit curve then increases steadily reaching its peak value in year 2035, after when it will begin to decline to the least value around year 2055. The decline in profit between years 2035 to 2055 is because of the decline in the amount LFG captured due to the closure of the landfill. The profitability analysis shows that Scenario ST has higher NPV of the 2 scenarios and therefore the better. Its NPV of US$24.7 million indicates how much the future profits are worth in the present (assuming 10% interest rate), and the higher this value is, the better [16, 26]. Therefore, Scenario ST is better for the case study – Iskandar Malaysia. This indicates that LFG captured from the landfill should be utilized for combined heat and power generation using steam turbines. The CHP is preferred over other options such as electricity/heat generation with GEs, GTs, boilers or hydrogen/methanol production etc. This is due to high efficiency and high production due to waste heat re-utilization associated with STs. These inferences are also shared by previous studies [8, 9, 25]. The amounts of power (electricity), steam generation and GHG emission reduction for this chosen option are shown in Figure 4 for the 40-year life span of the landfill.

The three curves in Figure 4 take the same pattern as the profitability curve (Figure 3) because both figures depend on the captured LFG (Table 2). For the electricity generation curve, the peak value is 37,000 MWh in 2035 (4.2 MW), which is 0.30% and 0.04% of the present maximum electricity demand for Iskandar Malaysia and Peninsular Malaysia respectively. The mean value of 20,588 MWh per year (2.3 MW) accounts for 0.16% and 0.02% of the maximum electricity demand for Iskandar Malaysia and Peninsular Malaysia respectively. In addition to the electricity generation, the optimizer output of Figure 4 resulted in a mean steam generation of 150 million MJ per year worth US$3 million. Furthermore, the outcome yielded GHG emission reduction averaging to 12,000 tons CO_2 equivalent (or 0.027% of the regions emission's rate in year 2025) with revenue generation from Carbon credit of US$141,000 per year.

5.0 CONCLUSIONS

The study estimated MSW generation and population projection for the case study – Iskandar Malaysia for years 2010 to 2035. The population ranged from 1.7 million people (2010) to approximately 4 million people while the MSW ranged from 670,000 tons in 2010 to 2.4 million tons in 2035. This MSW amount was analyzed based on three MSW Scenarios in order to arrive at a reasonable value that should be sent to the landfill. Scenario MIX, which is the combination of MSW practice based on other low-carbon regions of Asia and Europe was found to be the most appropriate. Based on this scenario, MSW to landfill ranged from 600,000 tons in 2010 to 711,000 tons in 2035.

A hypothetic landfill was proposed for the low-carbon region of Iskandar Malaysia, where the estimated MSW should be disposed of and hence LFG captured for green energy production. From the IPCC methodology, LFG capture was estimated from 2015 to 2055 and a mean LFG capture of 21,672 tons per year was arrived at. MIP model was developed and solved using GAMS software as a tool to plan the LFG captured for green energy production for the life-span of the landfill. Of the two LFG Scenarios considered, Scenario ST was found to be better due to the higher NPV of US$24.7 million obtained. The optimal results indicated that the LFG captured should be utilized for combined heat and power generation, CHP, using steam turbine, STs. Mean annual electricity and steam generation of 20,588 MWh per year (2.3 MW) and 150 million MJ per year have been achieved respectively. The mean electricity generation represents 0.16% and 0.02% of the maximum electricity demand for Iskandar Malaysia and Peninsular Malaysia respectively. Additionally, GHG emission reduction of 12,000 tons CO_2 equivalent (or 0.027% of the region's emission rate in year 2025), with revenue generation from Carbon credit of US$141,000 per year has been predicted.

The findings revealed the potentials in LFG capture from the case study in terms of green energy and GHG emission reduction. Furthermore, the optimal model developed is applicable beyond this case study due to some parameters and variables which makes it flexible for application elsewhere as LFG planning tool. However, the model does not include upstream MSW activities involving generation and tipping; and also other LFG grades and multi-period LFG utilization cases. Therefore, work is in progress to expand the model to address these shortcomings.

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