Waste Management 32 (2012) 890–900

Contents lists available at SciVerse ScienceDirect

Waste Management

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

Projecting the environmental profile of Singapore's landfill activities: Comparisons of present and future scenarios based on LCA

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ARTICLE INFO

Article history:
Received 14 June 2011
Accepted 8 December 2011
Available online 16 January 2012

Keywords:
Life cycle assessment
Landfill
Incineration ashes
Transport emissions
Land use
Lifespan

ABSTRACT

This article aims to generate the environmental profile of Singapore's Semakau landfill by comparing three different operational options associated with the life cycle stages of landfilling activities, against a 'business as usual' scenario. Before life cycle assessment or LCA is used to quantify the potential impacts from landfilling activities, an attempt to incorporate localized and empirical information into the amounts of ash and MSW sent to the landfill was made. A linear regression representation of the relationship between the mass of waste disposed and the mass of incineration ash generated was modeled from waste statistics between years 2004 and 2009. Next, the mass of individual MSW components was projected from 2010 to 2030. The LCA results highlighted that in a 'business as usual' scenario the normalized total impacts of global warming, acidification and human toxicity increased by about 2% annually from 2011 to 2030. By replacing the 8000-tonne barge with a 10000-tonne coastal bulk carrier or freighter (in scenario 2) a grand total reduction of 48% of both global warming potential and acidification can be realized by year 2030. Scenario 3 explored the importance of having a Waste Water Treatment Plant in place to reduce human toxicity levels – however, the overall long-term benefits were not as significant as scenario 2. It is shown in scenario 4 that the option of increased recycling championed over all other three scenarios in the long run, resulting in a total 58% reduction in year 2030 for the total normalized results. A separate comparison of scenarios 1–4 is also carried out for energy utilization and land use in terms of volume of waste occupied. Along with the predicted reductions in environmental burdens, an additional bonus is found in the expanded lifespan of Semakau landfill from year 2032 (base case) to year 2039. Model limitations and suggestions for improvements were also discussed.

1. Introduction

The small island state of Singapore, spanning about 710 km^2 in total land area, is densely populated with about 5 million people in 2010 (Statistics Singapore, 2011). With its robust industries and active economy, the nation faces limited land available for the disposal of municipal solid wastes (MSW). This makes sustainable waste management especially important. Singapore has experienced a steady increase in the amount of MSW generated since the 1970s. Between 2000 and 2009, total mass of MSW generated in Singapore has increased by 31%, from 4.6 million tonnes in 2000 to 6.1 million tonnes in 2009 (MEWR, 2010). MSW in Singapore can be classified into two primary categories according to the National Environmental Agency (NEA, 2010a) of Singapore:

(i) Incinerable waste materials.
(ii) Inert, non-incinerable MSW.

The only landfill in the country's size-constrained land area is situated 30 km offshore south of its mainland. Inert, non-incinerable MSW, which is sent to the offshore landfill located on Semakau island, comprises mainly of construction and demolition (C&D) debris, treated sludge, and used slag (MEWR, 2010). Presently, trucks collect ash from incineration plants and inert waste from the main island to transfer them to Tuas Transfer Marine Station (TMTS). From there a barge is used to ferry the waste materials to Semakau landfill. The landfill has a capacity of 63 million m^3.

1.1. Incinerable and non-incinerable waste materials

Incinerable waste materials, which comprise of various types of plastics, wood, cardboard, textiles, organic wastes and other substances are sent to incineration plants. The incineration of MSW in turn produces bottom and fly ash which is redirected to Semakau landfill. In order to forecast the amounts of wastes sent to the landfill, ultimate and proximate analyses are used to identify the amount of ash generated by each specific MSW components

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doi:10.1016/j.wasman.2011.12.010

(Niessen, 2002). MSW incineration residues can be classified according to the stage of incineration during which they were retrieved. They can include bottom ash and grate siftings (20–30%), boiler and economizer ash (approximately 10%), fly ash (1–3%) and air pollution control (APC) residues (2–5%) (e.g., Sabbas et al., 2003). Bottom ash and grate siftings have been collectively classified as bottom ash since their differences are generally undistinguishable.

1.2. Leachate generation

Currently, Semakau landfill is classified as an inert landfill, the definition of which stipulates a strict barring of all organic and hazardous waste materials. Incinerable MSW, containing mostly organic substrate from the residences, is incinerated to ensure the removal of a large percentage of organic contents before landfilling. However, even in well confined landfills, leachate generation is a natural consequence of fluid seeping through piles of stacked landfilled material (Qasim and Chiang, 1994). As the landfill material breaks down due to the anaerobic environment, coupled with exposure to elements of nature, such as extreme heat and high humidity, soluble toxic chemicals are produced (Qian et al., 2006).

In this article, long term leachate generation behavior is taken to emulate those from a well-controlled predominantly inorganic landfill in Europe (van der Sloot et al., 2003). As a conservative measure, we further assume that the amounts of toxic substances from incineration ash are 10% below UK Waste Acceptance Criteria (WAC) for inert landfill and US EPA Acceptance criteria; and also 10% below NEA's TCLP test for wastes from industries. A Waste Water Treatment Plant (WWTP) is being planned on Semakau to start removing toxic substances from leachate for years 2011 onwards.

This article aims to generate the environmental profile of Semakau landfill by comparing a few options associated with the life cycle stages of landfilling activities, against a 'business as usual' scenario or base case. A 'business as usual' scenario of landfilling management indicates unchanged activities including: (i) no expansion in landfill size; (ii) zero increase in recycling rates; and, (iii) no efforts on waste minimization.

2. Materials and methods

Before assessing the environmental profile of Singapore's Semakau landfill, an attempt to incorporate localized and empirical information into the amounts of ash and MSW sent to the landfill for the forthcoming years was made by performing a linear regression model of the relationship between mass of waste disposed and the mass of incineration ash generated.

2.1. MSW component projection

Landfill models are often compromised by inherent methodological uncertainty since primary landfill statistics are usually scarce (Doka, 2007; Doka and Hischier, 2005). Since MSW is either incinerated or landfilled directly in Singapore, the mass of incineration ash can be expressed as an autonomous function of the mass of MSW disposed:

$$\text{Mass}_{\text{ash}} = f(\text{MSW}_{\text{disposed}}, \text{MSW}_{\text{landfilled}}) \quad (1)$$

The waste management department of NEA has provided a fixed list of incinerable and non-incinerable materials (NEA, 2011). Based on this set of guidelines, the resultant linear projection of incineration ash amounts is directly dependant on the incinerable and non-incinerable fractions of MSW generated. This simply means that ash materials increase linearly with more waste materials being incinerated. From the MSW statistics available between 2004 and 2009 (displayed in Table A.1, Appendices), individual MSW components were expressed as percentages of total MSW disposed. A trendline for each MSW component can be established as a proportion of the total MSW disposed within that year. A second set of linear regression was performed on the total mass of MSW disposed. By combining the two sets of correlation established for each individual MSW components and the total MSW disposed, the projected mass of individual MSW components from 2010 to 2030.

The projections of MSW trends were assumed to be linear. This was accomplished with the objective to present an averaged trend that has accounted for year-to-year fluctuations, based on historical MSW statistics. It is acknowledged that scenarios of non-linearity can exist. For instance, the possibility of tapering MSW percentage figures as it approaches zero, due to constrains such as peak recycling rates and various other inertia forces such as public reluctance resulting in difficulties with waste management policies being reinforced.

The results of the correlations are shown in Table 1. The specific volume parameters which were obtained through least square approximation were based on the waste statistics provided by NEA (1994–2010). The resultant graphs were further projected till 2030.

An estimation of the mass of total MSW disposed, incineration ash and non-incinerable MSW was performed. The period of projection was determined to encompass the projected operational lifespan of Semakau landfill. The densities of landfilled MSW exhibit a great and direct influence on their final volume occupied in situ. While post-landfilling compression effects, attributable to gravitational slide and compaction, are generally acknowledged in literature (e.g., Manfredi and Christensen, 2008), the exact dynamics and mathematical modeling of such effects are beyond the scope of this work.

The results of the projected amount of landfill material till year 2030 are shown in Table 2. These projected waste amounts will be used as inventory input for the LCA investigation. Verification of the fitted parameters for specific volumes was conducted through the comparison of the lifespan calculated by the model with official landfill lifespan reported by Singapore's National Environmental Agency (NEA). The results displayed in Table 3 demonstrate that there exists a reasonable agreement between the projected results and the official NEA figures of Semakau lifespan.

Table 1
Sets of equations correlating MSW component percentages with total MSW disposed.

MSW component	Percentage correlation equation (Y = %, A = Year)
Non-incinerables	
Sludge	$Y = -0.0258A + 55.85$
Slag	$Y = -0.2939A + 590.87$
Construction & demolition waste	$Y = -0.0772A + 155.94$
Others (non-incinerables)	$Y = 0.1078A - 215.35$
Incinerables	
Ferrous metals	$Y = -0.1131A + 229.44$
Scrap tyres	$Y = -0.0345A + 69.464$
Non-ferrous metals	$Y = -0.0357A + 72.194$
Wood	$Y = -0.6672A + 1343.3$
Paper	$Y = 0.3862A - 751.49$
Horticultural waste	$Y = 0.3644A - 726.31$
Glass	$Y = -0.1051A + 213.13$
Food	$Y = 0.1429A - 266.94$
Textiles	$Y = -0.0754A + 154.98$
Plastics	$Y = 0.1729A - 323.16$
Others (incinerables)	$Y = 1.0892A - 2177.6$
MSW component	Correlation equation (A = year, X = mass of MSW disposed in million tonnes)
Total MSW disposed	$X = (-16.903A + 36497)/1000$

Table 2
Projected amount of wastes landfilled till 2030.

Year	Million tonnes		Year	Million tonnes	
	Mass Ash	Total MSW non-incinerable		Mass Ash	Total MSW non-incinerable
	According to statistics			Projected	
1999	0.433	0.309	2010	0.550	0.157
2000	0.433	0.245	2011	0.561	0.153
2001	0.446	0.236	2012	0.572	0.152
2002	0.560	0.200	2013	0.582	0.151
2003	0.510	0.190	2014	0.592	0.150
2004	0.520	0.220	2015	0.602	0.149
2005	0.483	0.231	2016	0.611	0.148
2006	0.501	0.218	2017	0.621	0.147
2007	0.516	0.174	2018	0.630	0.146
2008	0.542	0.170	2019	0.639	0.145
2009	0.561	0.156	2020	0.648	0.145
			2021	0.657	0.145
			2022	0.666	0.146
			2023	0.674	0.147
			2024	0.682	0.148
			2025	0.690	0.149
			2026	0.698	0.149
			2027	0.705	0.150
			2028	0.713	0.151
			2029	0.720	0.151
			2030	0.727	0.152

Table 3
Comparison of modeled landfill lifespan against NEA official landfill lifespan.

Year	Modeled landfill lifespan (years)	Official NEA landfill lifespan (years)
2004	37.7	35–40
2005	40.5	
2006	39.1	
2007	38.1	
2008	36.3	
2009	35.1	35–45
2010	35.8	

2.2. Life cycle assessment

Life Cycle Assessment is an objective-driven scientific tool applied to assist in the evaluation of system performance by investigating the process transformation of products from cradle to grave. LCA can be applied to evaluate various parameters within different waste management or treatment systems and their associated generation of by-products (Obersteiner et al., 2007; Khoo et al., 2010). LCA models have become the principal decision support tools for decision and policy makers at all levels for waste management strategies (Khoo, 2009; Manfredi and Christensen, 2008) and can also be effectively utilized in support of waste management planning (Thomas and McDougall, 2004; Özeler et al., 2006).

Landfill models for LCA study are still in its infant stages of development, despite the potential pollution from landfills that can affect human health and the natural environment (e.g., Damgaard et al., 2011). Moreover, land use impacts in LCA, especially for landfills, are yet to be well established or standardized (Obersteiner et al., 2007). Therefore the scope of 'land use' in the present investigation is limited to the volumetric space occupied.

2.2.1. LCA goal and scope

The goal of the LCA is to quantify the annual impacts arising from the landfilling process of MSW in Singapore, taking into account the number of road trips and sea transportation necessary in an annual basis, as well as, the pollution from these transport modes. Energy used for landfill operations and their associated air emissions, and potential leachate generation and its level of toxicity will also be analyzed. The impact of land use will be estimated according to Semakau's landfill capacity. Impacts of biodiversity and marine ecosystem will be excluded from the study.

The amounts of waste landfilled from Table 2 (years 1999–2009; and 2010–2030) are used as input to the LCA model. The LCA objectives in this research are to quantify the potential environmental profile of landfilling activities of four simulated scenarios with different operating conditions.

2.2.2. Functional unit

The functional unit for this LCA model, in accordance with ISO 14040 regulations, has been defined as:

> Per year of Singapore-generated landfill material, comprising a mixture of both incineration ash and non-incinerable MSW in variable proportions.

The composition of millions of tonnes of MSW on an annual basis is according to historical waste statistics available from NEA for the period 2004–2009, and subsequently modeled projections for 2010–2030 based on correlations of MSW components.

2.2.3. System boundary

The LCA system boundary for Semakau landfill is illustrated in Fig. 1. The stages associated with the life cycle of MSW landfilling system begin with the transportation of MSW by trucks from various incineration plants and MSW sorting and handling facilities to Tuas Marine Transfer Station (TMTS). Barges facilitate the transport of MSW to Semakau island. Landfilling operations include loading/unloading, filling and compacting of wastes. Energy demands from diesel power generators were accounted as they were necessary to power the activities on Semakau landfill. In the LCA model, the amounts and components of waste material flow are simulated according to the amounts shown in Table 2 for all cases except for changes in increased recycling rates.

Based on discussions with waste disposal personnel, the following are modeled in the LCA system:

- Scenario 1 (base case). The first scenario refers to 'business as usual' where the following operating conditions are applied:

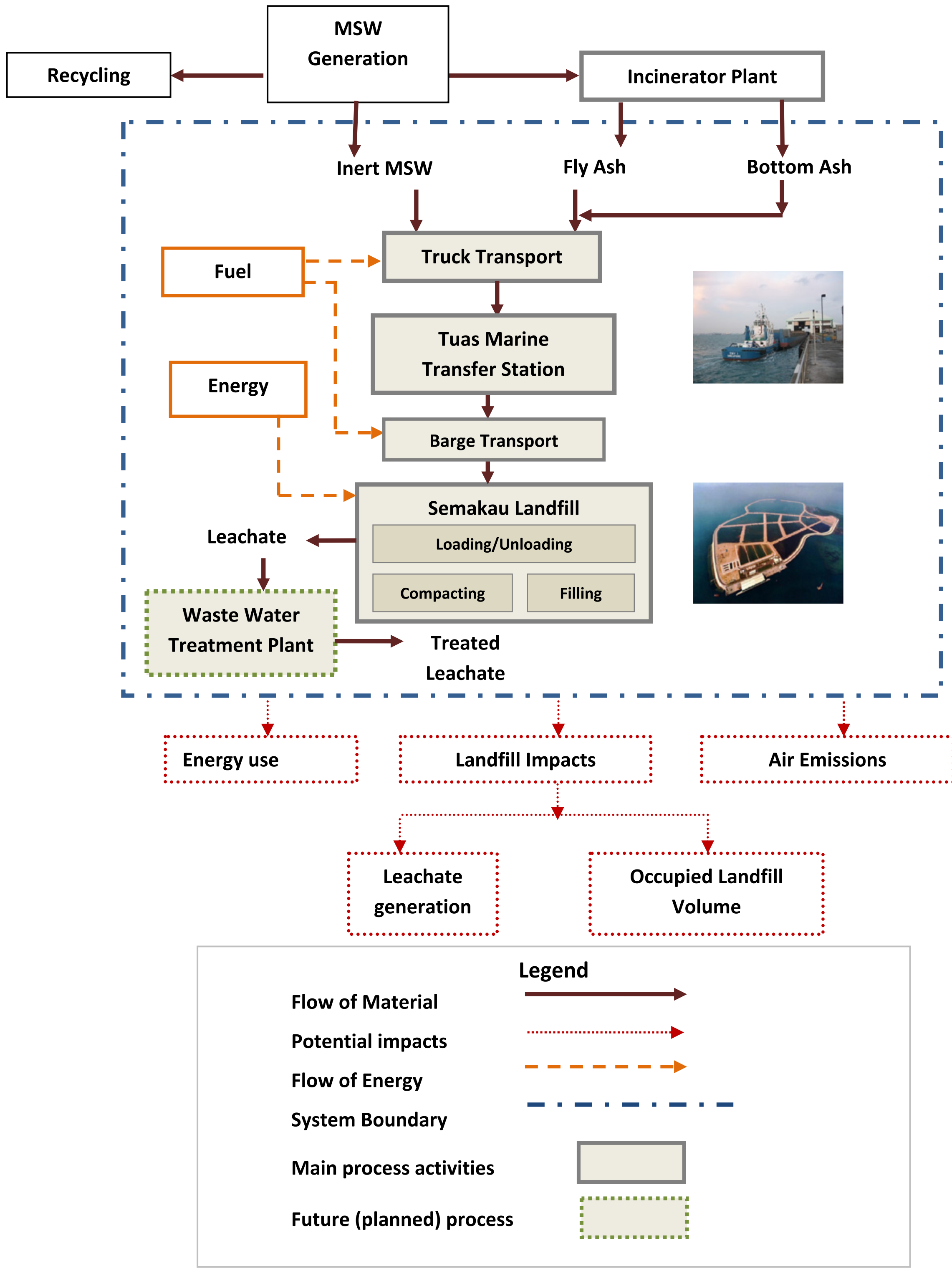

Fig. 1. LCA system boundary for Semakau landfill.

i. Energy requirements and their associated emissions to operate Semakau landfill processes are all diesel generated.
ii. Truck emissions are modeled according to the latest Euro models (Euro II in 1999; Euro III in 2004; Euro IV in 2005 and Euro V in 2009 onwards); the exact timing and routes for road truck transportations are not considered as they are expected to have a negligible effect on the overall impacts.
iii. A diesel-powered barge with a carrying capacity of 8000 tonnes is used to ferry waste from TMTS to Semakau.
iv. The amounts of toxic substances from incineration ash are 10% below UK Waste Acceptance Criteria (WAC) for inert landfill and US EPA Acceptance criteria; and also 10% below NEA's TCLP test for wastes from industries.

- Scenario 2. In the second case, the barge is replaced by a fuel oil-powered coastal bulk carrier or freighter with a carrying capacity of 10,000 tonnes in year 2011 onwards to ferry waste across the sea to Semakau. Apart from that, all other operating conditions on Semakau landfill remain unchanged.

- Scenario 3. In the third case, a Waste Water Treatment Plant (WWTP) is implemented to remove an additional 70% of toxic substances from leachate for years 2011 onwards. All other conditions remain unchanged.
- Scenario 4. In the last scenario, the recycling target of 70% set by the Singapore Green Plan 2012 is incorporated into the LCA model. Out of 70%, an estimated 26% of the waste mixtures are classified as non-incinerables. Therefore by year 2030, 26% of non-incinerables (C&D, slag and sludge) are redirected away from landfills, and the remaining 44% are the incinerable materials (plastics, cardboards, paper, etc.) that will be redirected away from Singapore's incineration plants. Hence, in the final simulation, the waste materials from 2011 onwards are adjusted to take into account a linear increase in recycling rates from 57% in 2009 and 59% in 2010 to reach 70% in 2030. Apart from that, all other operating procedures (i–iv) remain unchanged.

2.2.4. Life cycle inventory

Due to unavailable on-site data from the landfill and NEA, the following was adopted:

- Euro emission standards are extracted from DieselNet (2011) and Spielmann et al. (2010).
- Generation of emissions from marine transportation and use of diesel for energy are extracted from SimaPro (2008a,b) and Gabi life cycle engineering database (2006).

2.2.4.1. Transport emission. It is assumed that all road vehicles used for delivering waste materials and ash to Tuas Marine Transfer Station (TMTS) are operating according to Euro standards for a 40-tonne truck (DieselNet, 2011; Spielmann et al., 2010). Vehicle emission standards are established in Singapore by the Ministry of Environment's Pollution Control Department (PCD) that enforces stringent actions against road transport pollution. Based on this criteria, the latest Euro models are applied for truck transportation. The sample emissions of the latest Euro V are shown in Table 4. The shortest reasonable routes was assumed to be that adopted by collection trucks in their routine plying between incineration plants, MSW sorting facilities and TMTS. The estimated average distance is taken as 20 km for the transfer of MSW to TMTS. The number of road trips (or trucks) in a year is estimate as: (*tonnes of waste per year*)/(*truck carrying capacity*). Based on a full vehicle carrying capacity of 40 tonnes, the projected number of road trips estimated. The results are compiled in Table B.1 (Appendices).

The vehicle emissions (in total kg of pollutant/year) are calculated as:

$$\text{No. of } \frac{\text{trips}}{\text{year}} \times \frac{\text{kg pollutant}}{\text{km}} \times \text{distance travelled(km) per trip} \quad (2)$$

The nautical mileage from TMTS to Semakau landfill is around 25–30 km. The barge's carrying capacity was estimated at 8000 tonnes. Barge emissions, expressed on a basis of tonne-km are extracted from SimaPro (2008a) database for waterway barge transportation. Emissions from the 10,000-tonne coastal bulk carrier are extracted from Gabi life cycle engineering (2006). The data are presented in Tables 5 and 6. It was assumed that both marine transport vessels operated in an efficient manner and adopted the shortest and most conventional route to Semakau landfill, translating into a nautical mileage of 30 km each trip. The weather and sea conditions were assumed to exhibit negligible effects on marine transportation.

Table 4
Euro V emission standards.

Emissions	CO	CO_2	NO_X	SOx	HC	PM
(kg/km)	0.00227	0.8	0.00264	n.a.	0.00016	0.00003

Table 5
Barge transport emissions (SimaPro database, 2008a).

Barge transport emissions	Amount (kg/tonne-km)
CO_2	0.02814
CO	3.53×10^{-5}
NO_X	3.575×10^{-4}
SO_X	6.198×10^{-6}
PM	8.865×10^{-6}
HC	n.a.

Barge 8000-tonne carrying capacity.

Table 6
Coastal bulk carrier/freighter (GaBi database, 2006).

Coastal carrier/freighter	Amount (kg/tonne-km)
CO_2	0.016
CO	1.87×10^{-5}
NO_X	1.38×10^{-5}
SO_X	1.05×10^{-6}
PM	4.60×10^{-7}
HC	n.a.

Coastal bulk carrier/ocean freighter 10,000-tonne carrying capacity.

In the same manner as road transport vehicle, the number of trips by barge/bulk carrier necessary are estimated as: (*tonnes of waste per year*)/(*marine transport carrying capacity*).

Based on a carrying capacity of 8000-tonnes and 10,000-tonnes, the estimated number of trips for each year is projected. The results are compiled in Table C.1 (Appendices). Marine transportation emissions (in total kg/year) for both barge and coastal bulk carrier are calculated as:

$$\text{No. of } \frac{\text{trips}}{\text{year}} \times \text{pollutant in} \frac{\text{kg}}{\text{tonne} \cdot \text{km}} \times \text{waste(tonne)} \times \text{distance travelled(km)per trip} \quad (3)$$

2.2.4.2. Leachate generation. The leaching test acceptance criteria for landfill disposal of industrial waste set by NEA (2010b) is shown in Table 7. As a secondary safeguard, the acceptance criteria for toxic metals contained in incineration ash follow from the strictest of UK WAC (Waste Acceptance Criteria) for inert landfill and USEPA TCLP Acceptance criteria for incineration ash are displayed in Tables D.1 and E.1 (Appendices).

After performing stringent TCLP tests, the mixture of materials sent to Semakau are predominantly inert. Based on a three-year study of a predominantly inorganic landfill, van der Sloot et al. (2003) demonstrated that, despite the heterogenous mix of materials, leachate characteristics met very stringent EU landfill criteria in The Netherlands. Since the parameters of Semakau landfill matches the conditions of a well-governed inorganic landfill in Europe, the leachate generated from the island was assumed to display the same characteristics. In addition, a conservative estimation of 10% below the limits set by Tables D.1 and E.1 are applied for the ash materials sent to Semakau (for scenarios 1, 2 and 4).

In scenario 3 alone, the planned Waste Water Treatment Plant (WWTP) is estimated to remove another 70% of toxic levels from

Table 7
Leaching test acceptance criteria for landfill disposal of industrial waste (NEA, 2008b).

Substrate	Acceptance limit (mg/L)
Arsenic	5
Barium	100
Cadmium	1
Chromium	5
Copper	100
Cyanide (total)	10
Fluoride	150
Iron	100
Lead	5
Manganese	50
Mercury	0.2
Nickel	5
Phenolic compounds (as phenol)	0.2
Selenium	1
Silver	5
Zinc	100

Table 8
Pollutants in kg/kg diesel (SimaPro, 2008b).

Pollutant	CO_2	CO	HC	NOx	SOx	PM
kg/kg diesel	0.505	0.00087	0.000021	0.00265	0.00276	0.000202

Diesel = 0.84 kg/L; calorific value = 42.9 MJ/kg.

leachate. Therefore with the WWTP in operation, a total of 80% toxic substances from leachate are removed (for years 2011 onwards).

2.2.4.3. Energy utilization. The electrical energy required for building and facilities are estimated as 0.2 kWh/tonne waste (McDougall et al., 2004); as for landfill operations including loading, unloading, filling and compacting, the energy required is rated as 0.38 MJ/tonne wastes handled in all cases. The emissions for the usage of diesel-generated energy are shown in Table 8. The emission data was extracted from SimaPro (2008b).

3. Results

The environmental profile for scenarios 1–4 are presented as normalized results combining the total impacts of global warming potential, acidification and human toxicity.

The selection of the impact categories is considered taking into account the unique environmental circumstances of Singapore. The set of local impact categories that are relevant to the country include acidic gases, toxic substances and land use. Energy security is another challenge faced by the nation due to the lack of natural resources (Chan et al., 2012). Climate change impacts are also included due to rising concerns of global greenhouse gas emissions, along with the threats faced by small island-nations due to sea level changes.

A separate comparison of scenarios 1–4 is also carried out for:

- Energy utilization. Due to lack of natural resources, the nation depends on the import of fossil fuels from other countries. Therefore a comparison of energy use is regarded as an important element in waste management.
- Landfill occupation. Since there is no standard model for land use, these impacts are projected according to volume occupied (m^3/year). The justification for this comparison basis is due to the fact that Singapore faces land constraint and the operational lifespan of Semakau is of utmost importance.

3.1. Normalized results

The normalization for global warming and acidification potential were carried out based on the national inventory of pollutants in Singapore as the reference system. The emission inventories are extracted from Ohara et al. (2007) and Singapore's National Greenhouse Gas Inventory (2010). No local data is available for human toxicity levels and the European EDIP normalized value (Potting and Hauschild, 2003) is adopted based on the robust industrial activities and population densities found in parts of Europe that matches Singapore country profile. The normalized values are displayed in Table 9.

The first normalized results – for scenario 1 (base case) – are displayed in Fig. 2. It is shown in the graphs that the normalized impacts are distributed quite evenly between global warming potential (mostly by GHGs from barge transportation), acidification (by NOx emissions, also from barges) and human toxicity. According to the MSW statistics (NEA, 2010b), the waste material amounts from years 1999 to 2009 does not give a well-defined pattern therefore the same projection of the environmental burdens can be observed.

Incineration fly ash and bottom ash typically shows some substantial levels of toxic substances (Qian et al., 2006). Although the types of waste sent to Semakau are restricted to non-reactive, inert, inorganic and no-corrosive materials, the human toxicity results in Fig. 2 look as dominant as the results of global warming potential. It should also be highlighted that these toxicity results are estimated according to the discount of 10% below UK Waste Acceptance Criteria (WAC) for inert landfill, US EPA Acceptance criteria; and NEA's TCLP test for wastes from industries.

Assuming that there are no efforts spent to minimize MSW, nor any plans to redirect MSW away from landfills, the simulated trend of total impacts (global warming, acidification, and human toxicity) shows a steady uphill climb from year 2010 onwards. The total impacts after year 2011 increase by about 2% annually to nearly 40% in 2030.

Figs. 3–5 display the total normalized impacts of scenarios 2, 3 and 4 respectively. For all three graphs, the normalized impacts of scenario 1 are embedded in the background for comparing various waste management options against the backdrop of 'business as usual'.

Although the nautical mileage to Semakau is only 30 km, the accumulated emissions of exhaust gases and particles from marine

Table 9
Applied normalized values.

Impact category	Normalized values	Unit	Reference
Global warming	7569.9	CO_2 kg/capita/year	Singapore's National Greenhouse Gas Inventory (2010)
Acidification potential	1289	UES m^2/capita/year	Ohara et al. (2007)
Human toxicity	1.70×10^8	m^3/capita/year	Adopted from EDIP 2003

Based on Singapore population of 5.08 million in 2010 (Statistics Singapore, 2011).

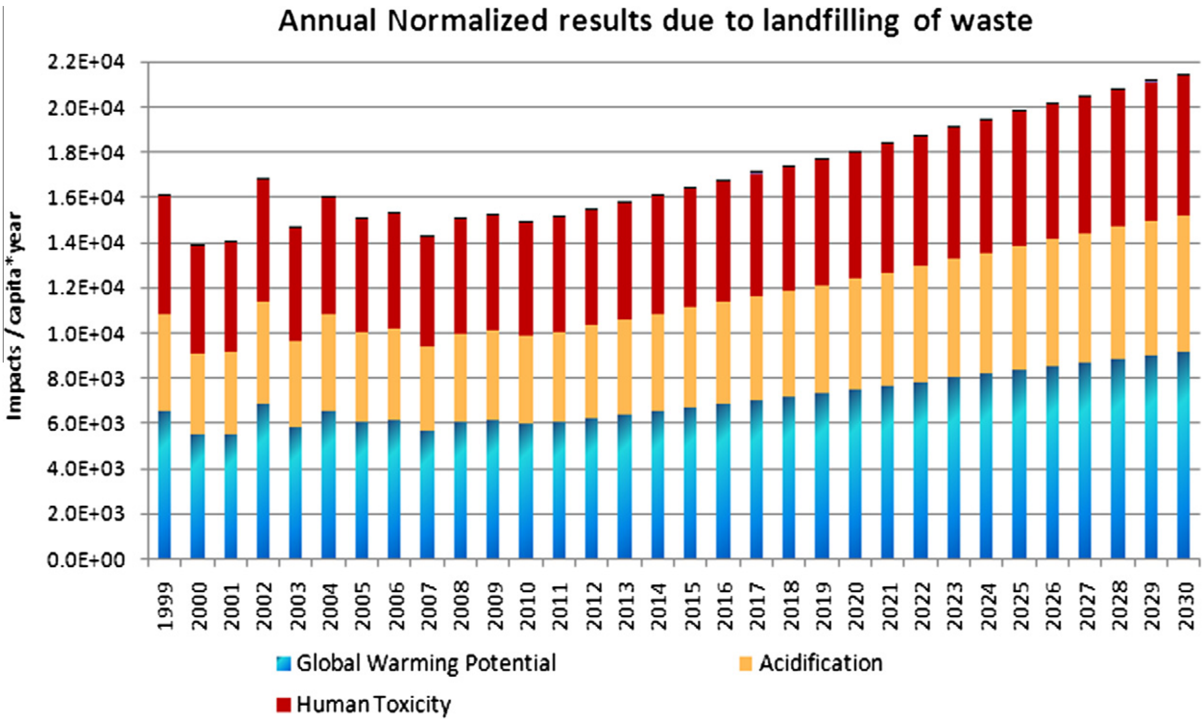

Fig. 2. Normalized results (scenario 1: base case).

transportation over a year can be rather significant. Research on pollution from sea transport has already been done extensively as a call for marine emission exhaust reductions (e.g., Eyring et al., 2010). In scenario 2 (Fig. 3), the diesel-powered barge with a carrying capacity of 8000-tonne is replaced by a heavy fuel-powered coastal carrier with a carrying capacity 10,000-tonne to transfer wastes from TMTS to Semakau. A higher capacity carrier reduces the trips required to ferry waste from the mainland to Semakau island. Apart from the less occurrence of pollution from the number of trips made, this option also reduces the amount of air emissions released from marine exhaust engines. Fig. 3 shows that the potential global warming impacts decreased by around half, and acidification impacts by at least 90%. By year 2020, the total normalized impacts are 48% lower than scenario 1; and by 2030, a 50% reduction can be realized.

As anticipated, the results in scenario 3 show that human toxicity impacts dropped uniformly each year by 70% with the WWTP in operation (Fig. 4). The resultant total normalized impacts from years 2011 to 2030 are approximately 24% lower than those of scenario 1.

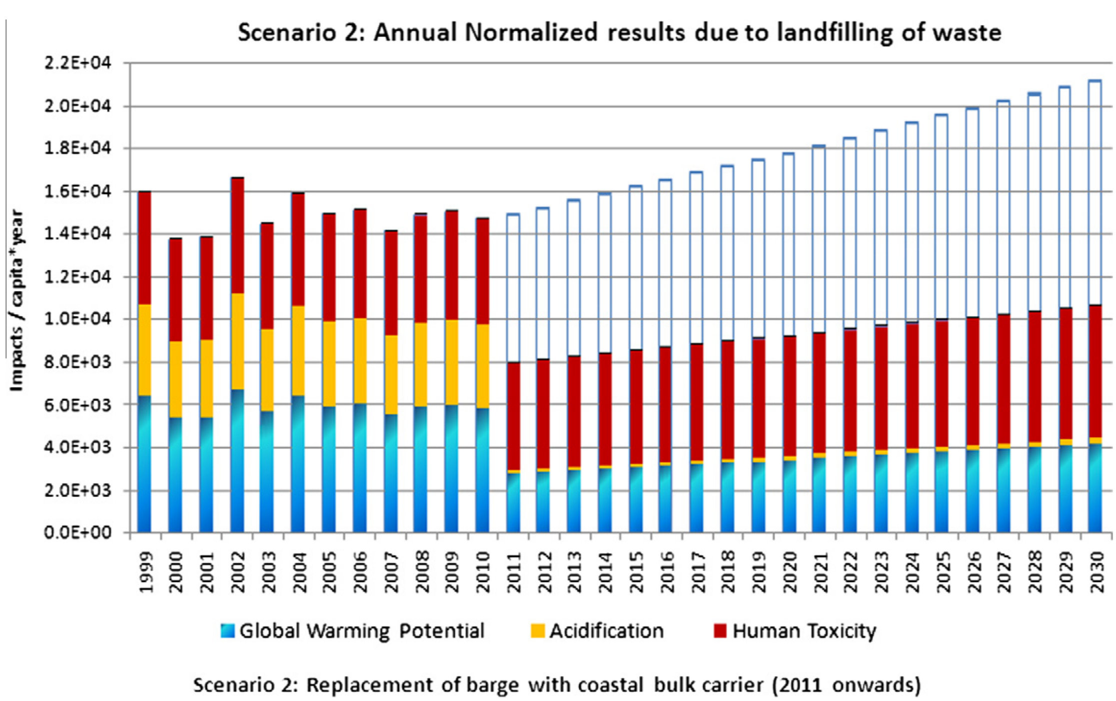

Fig. 3. Normalized results (scenario 2).

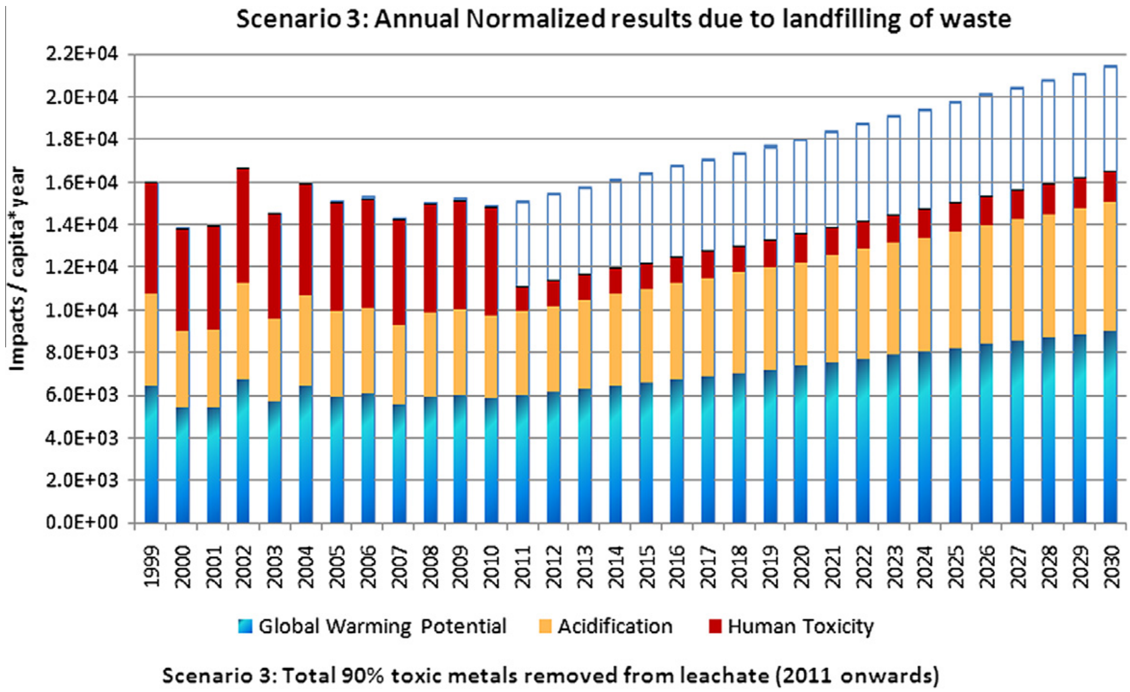

Fig. 4. Normalized results (scenario 3).

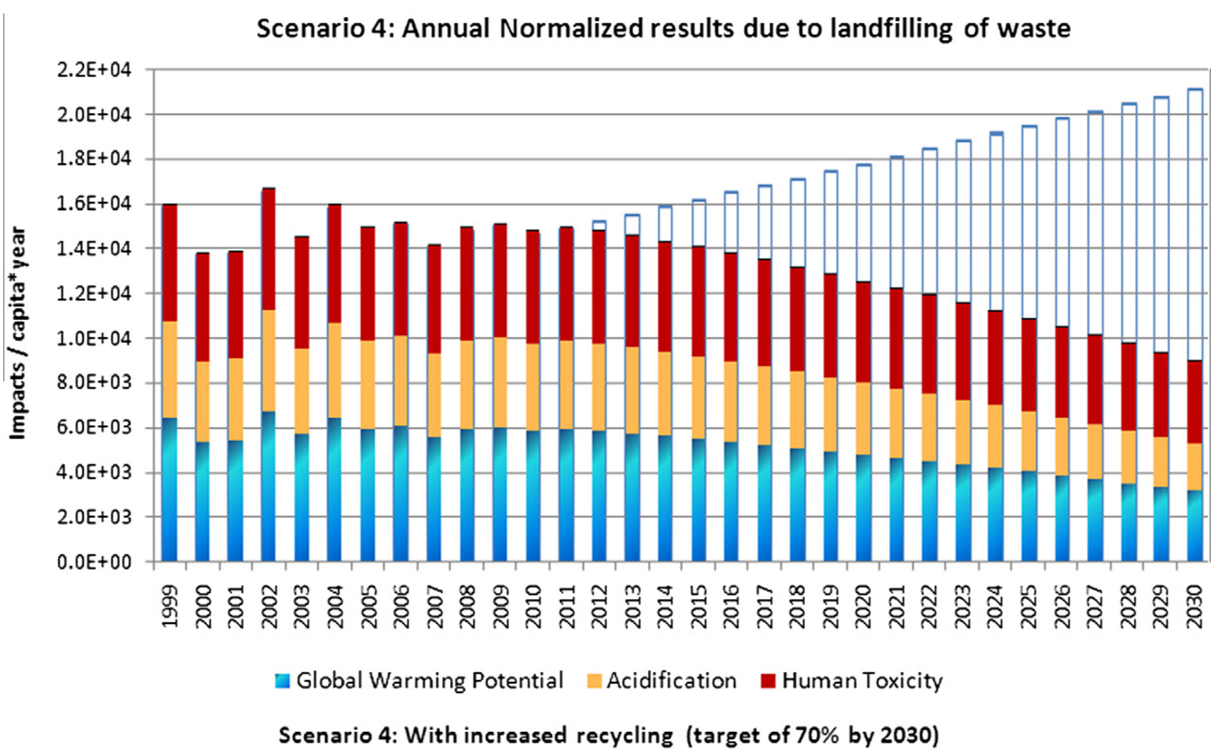

Fig. 5. Normalized results (scenario 4).

Finally, for scenario 4 (Fig. 5), a steady downward trend of all combined main impacts (global warming potential, acidification and human toxicity) can be clearly observed. Although the environmental benefits observed are initially shown as small gradual reductions (compared to scenarios 2 and 3), the benefits increases substantially with time. At the year end of 2030 where the 70% recycling target is met, the overall normalized impacts are reduced by around 58%, as compared to the base case 1.

Normalization for land use and energy use are not usually included in normalization and are therefore presented separately.

3.2. Energy utilization

3.2.1. Scenarios 1, 2 and 3

Energy security is one of the main challengers for the small island nation as Singapore lacks natural resources (Chan et al., 2012).

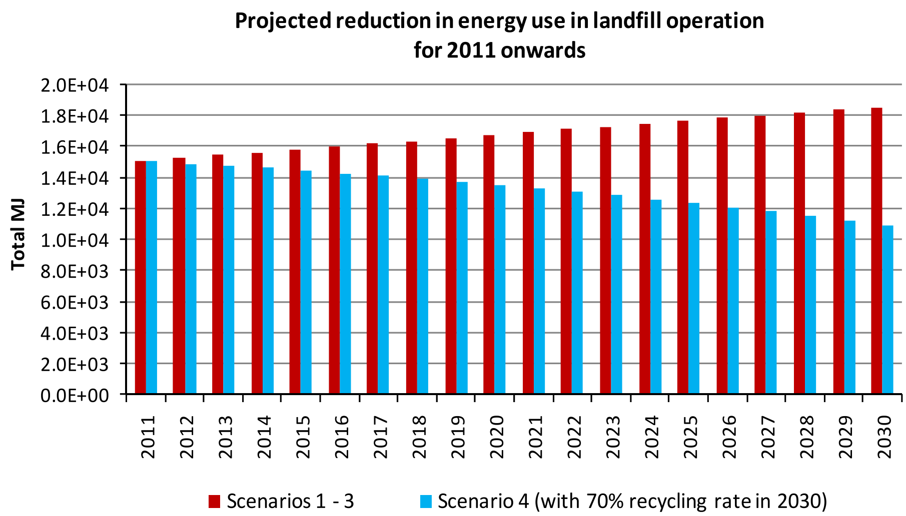

Fig. 6. Comparison of energy utilization with increased recycling rate.

Assuming that no measures are taken to reduce the nation-wide waste disposal rates, a steady uphill climb of energy utilization can be anticipated for the projected years of 2011–2030. This upward trend is expected in Semakau as a result of increased activity necessary to handle a corresponding higher MSW landfill load. Based on the pattern of waste generation over the years, the annual increase in energy demands is predicted at approximately 1% per annum. If the trend of MSW continues to climb, the total energy consumed is expected to be over 18,000 MJ per year in 2030.

3.2.2. Energy utilization in scenario 4 (70% recycling rate by 2030)

A comparison between scenarios 1 and 3 with scenario 4 for energy utilization is displayed in Fig. 6. As the recycling rates were gradually increased year-by-year, the potential energy savings increased from around 2% in 2012 to 19% in year 2020 and finally to 40% in 2030.

3.3. Landfill occupation

3.3.1. Scenarios 1, 2 and 3

Land use impact can be characterized by the percentage of decreasing volume of landfill available. The computation of volumetric impact is performed through a summation of mass–volume conversion after accounting for the densities of incineration ash, ρ_{ash}, and non-incinerable MSW, $\rho_{\text{landfilled}}$, listed in Eq. (4). Specific volumes, $1/\rho_{\text{ash}}$ and $1/\rho_{\text{landfilled}}$, were obtained through a simultaneous *least-square approximation* parameter fitting with MATLAB based on the NEA statistics available in 2003 and 2004. They corresponded to: 3161.9 m^3/kg for incineration ash and 124.3 m^3/kg for non-incinerable MSW.

$$\text{Volume of landfill material} = \frac{63\times10^6 m^3}{L} = \frac{1}{\rho_{\text{ash}}}(\text{Mass}_{\text{ash}}) + \frac{1}{\rho_{\text{landfilled}}} \times (Mass_{\text{landfilled}}) \quad (4)$$

Where

L = landfill lifespan, dated from 1999 63 × 106 m^3 = total landfill capacity.

Since the amount of environmental burdens are directly linked to the amounts of wastes that have to be handled, it has to be highlighted that the linear regression modeling of MSW (from Section 2.1) form the basis of the environmental impacts for years 2011 till 2030. Assuming that the landfilled waste amounts maintain the same uphill trend as those projected in Table 2, the estimated volume occupied will increase by approximately 3% per year. It is deduced that by the year 2030, only 3.33% of the landfill capacity remains available, which translates into a remaining lifespan of approximately 2 years. This implies that the continuous uphill trend of annual waste generation by a population size of 5 million will unfortunately cause Semakau's lifespan to end around year 2032.

In order to prolong the lifespan of the landfill, recycling rates have to be significantly increased. This action requires nation-wide efforts to involve active participation from both households and industry. Another option, waste minimization, is not explored here due to lack of supporting data on the exact types of MSW that can be reduced in Singapore Green Plan 2012 (MEWR, 2006).

3.3.2. Landfill occupation in scenario 4 (70% recycling rate by 2030)

In scenario 4, the recycling target of 70% set by the Singapore Green Plan 2012 is incorporated into the LCA model. Out of 70%, an estimated 26% of the waste mixtures are classified as non-incinerables. Therefore by year 2030, 26% of non-incinerables (C&D, slag and sludge) are redirected away from landfills, and the remaining 44% are the incinerable materials (plastics, cardboards, paper, etc.) that are redirected away from Singapore's incineration plants.

Fig. 7 displays the comparison between the cumulative landfill volume occupied and the remaining volume capacities for both normal vs. increased recycling cases. Inevitably, increased recycling activities will cause fewer amounts of waste materials and ash transferred to Semakau. In the simulated results for scenario 4, the remaining landfill volume in year 2030 increased from 3.33% (scenarios 1, 2 and 3) to around 18.5%, which means having a remaining lifespan of about 9 years, therefore enabling the landfill lifespan to last till year 2039.

NEA's projection of Semakau landfill lifespan, starting from 2009 onwards, is 30–45 years. Taking a conservative value of 30 years, the lifespan of the landfill is planned to last till the year 2039, which is in agreement with the projected values displayed in Fig. 7. It has to be highlighted however, that the goal of 2039 lifespan can be only realized with the recycling target of 70% by 2030 in place. Another accompanying solution is to expand the landfill beyond its present capacity of 63 million m^3. This scenario also assumes that the mass of MSW generated is not reduced but follows the linear trend projected earlier in Section 2.1.

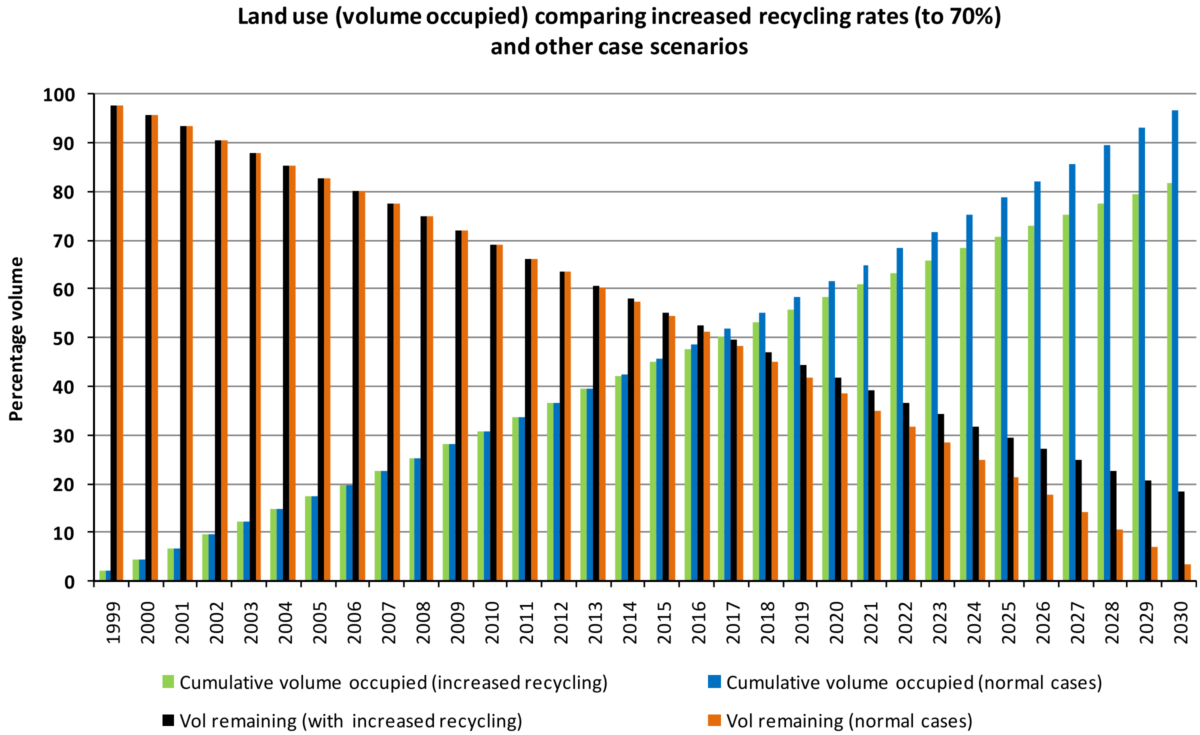

Fig. 7. Comparison of percentage landfill volume capacity (scenarios 1, 2 and 3) with increased recycling (scenario 4).

4. Discussions

4.1. Model limitation

Semakau landfill is a tightly regulated landfill for the disposal of inert, inorganic wastes. Due to lack of information, the characteristics of leachate generated from Semakau is expected to comply with a tightly-controlled inorganic landfill found in The Netherlands (van der Sloot et al., 2003). It is suggested, however, that more realistic results can be obtained if on-site data is available from Semakau landfill.

The trend lines generated in the article are modeled to give an overall pattern of waste disposal amounts – consisting of mixtures of fly ash, bottom ash, and inert MSW – that are fated to be landfilled each year. In the model, each volumetric amounts of ash projected from each specific or individual waste types are dissolved in the accumulated total. Another limitation is found in the linear nature of the projections; the influence of waste generation due to changes in economic trends, population growth and any other social indicators were not factored in any of the cases. Such dynamism (if proven necessary) would require a highly in-depth study using a highly sophisticated waste management model.

Despite these few limitations, the resultant graphs displayed an overall trend that that is in reasonably good agreement with the official estimated lifespan of Semakau landfill. Moreover, it was anticipated that despite fluctuations caused by the waste generation behavior of 5 million people, an uphill trend will still be observed in the graphs, and its associated environment results, if no strategic changes are introduced into Singapore's waste disposal activities.

4.2. Implications for waste management

With limited land available (710 km^2) for the disposal of wastes, sustainable waste management becomes especially important. Overall, the LCA results highlight that the major environmental impacts of landfilling activities. In the LCA model, different operating options are explored and compared. In a 'business as usual' scenario the emissions of GHG from barge transportation to transfer waste from TMTS to Semakau are rather high, followed by acidic gases. Based on linear projection of waste amounts, the combined total impacts of global warming, acidification and human toxicity increased by about 2% annually from 2011 to 2030.

By replacing the 8000-tonne barge with a 10,000-tonne coastal bulk carrier or freighter (in scenario 2) a grand total of both global warming potential and acidification can be realized by year 2030. Scenario 3 explored the importance of having the WWTP in place to reduce human toxicity levels – however, the overall long-term benefits were not as significant as scenario 2.

The final environmental benefits of scenario 4 championed all other cases and highlighted the importance and benefits of having increased recycling activities across the nation. The target materials for recycling should include construction and demolition waste, plastics, cardboards, and various types of metals. Along with the predicted reductions in environmental burdens, an additional bonus is found in the projected expanded lifespan of Semakau landfill. One of the examples of high rates of success in recycling is demonstrated by Taiwan (Li et al., 2006). Public education, along with mandatory participation in recycling efforts nation-wide has already been proven to be successful in Taiwan. Such practices can also be emulated in Singapore. The nation has already started recycling schemes and efforts that are spearheaded by NEA, as illustrated by Zhang et al. (2010).

Generally in LCA, potential environmental impact are quantified and assessed based on input–output flow of material. In this manner, the benefits of operating alternatives can be compared against a base case. However, it is noted that for landfilling, no there is yet to be a standardized model for land use. Although presented as two separate results, the impacts of energy use and land use both emulate the steady decrease of the total (normalized) environmental impacts of scenario 4, thereby reinforcing the option of recycling over the options of the other suggested operational changes in scenarios 2 and 3.

Another suggestion is to find uses for incineration ash instead of disposing them at landfills. Two such examples are found in The Netherlands and Germany. In The Netherlands, over 90% of the country's annual bottom ash from waste incinerators are recycled as embankments and road applications; and fly ash is also reused as admixture in asphalt fillers (van der Sloot et al., 2001). And in Germany, approximately 60% of the bottom ash from incinerators is utilized in road construction (Vehlow, 1996). However, as ash materials are expected to meet specifications similar to construction materials used for the same purpose, some quality control of incineration ash has to be implemented. Van der Sloot et al. (2001) suggested that one way to achieve this is to have more stringent criteria for waste materials sent to incinerators. The authors also introduced the treatment of incineration residues as another form of leachate control.

5. Conclusion

As Singapore advances its economic development plans and joins the ranks of other developed countries like the US and other developed nations across Europe, the country is likely to face increasing expectations to contribute to setting good sustainable environmental plans, along with tighter climate change targets that are in line with the rest of the advanced economies. In a country faced with spatial constraints, Singapore continues to struggle for outward development within a confined geography. As the economical development of the nation continues to rise, so does the burden of Municipal Waste Generation or MSW. For years, the disposal of incinerable MSW has pre-dominantly depended on incineration.

From the LCA results, it can be clearly observed the most favored option for a long-term sustainable waste management system is to redirect waste away from incinerators and landfill by fulfilling the goal of 70% recycling rate by 2030. This goal is part of Singapore Green Plan 2012, which was drafted out to provide a blueprint for the nation's holistic and long-term view of the environment with an attempt to underpin economic activities with the principle of sustainable development (MEWR, 2006). As shown in scenario 4, the option of increased recycling championed over all other three scenarios in the long run, resulting in a total 58% reduction in year 2030 for the total normalized results.

The option of increased recycling championed over all other operating scenarios in the long run, resulting in a total 58% reduction in year 2030 for the total normalized results. A separate comparison of scenarios 1–4 is also carried out for energy utilization and land use in terms of volume of waste occupied. Along with the predicted reductions in environmental burdens, an additional bonus is found in the expanded lifespan of Semakau landfill from year 2032 (base case) to year 2039.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.wasman.2011.12.010.

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Update

Waste Management

Volume 52, Issue , June 2016, Page 395

DOI: https://doi.org/10.1016/j.wasman.2016.03.014

Waste Management 52 (2016) 395

Contents lists available at ScienceDirect

Waste Management

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

Corrigendum

Corrigendum to "Projecting the environmental profile of Singapore's landfill activities: Comparisons of present and future scenarios based on LCA" [Waste Manage. 32 (2012) 890–900]

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In Section 3.3.1 of the published article, the last sentence of the first paragraph: "They correspond to: 3161.9 m^3/kg and for incineration ash and 124.3 m^3/kg for non-incinerable MSW."

Should be corrected to "They correspond to: 0.003162 m^3/kg and for incineration ash and 0.00124 m^3/kg for non-incinerable MSW. Both values translate to around 316 kg/m^3 and 806 kg/m^3, which is reasonably close to those reported in literature (Hosetti, 2006; Xu, 2008)".

The author would like to apologise for any inconvenience caused.

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DOI of original article: http://dx.doi.org/10.1016/j.wasman.2011.12.010
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http://dx.doi.org/10.1016/j.wasman.2016.03.014