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Greenhouse Gas Emissions Reductions from In-Situ Aeration in a Landfill: A Multi-Parameter Sensitivity Analysis Approach

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ABSTRACT. In this study, estimates of greenhouse gas (GHG) emissions (for methane, carbon monoxide and nitrous oxide) following the potential installation of an aerated bioreactor landfill system at the Mare Chicose landfill in Mauritius have been determined based on procedures outlined in the Approved Baseline and Monitoring Methodology AM0083, "Avoidance of landfill gas emissions by in-situ aeration of landfills" from the UNFCCC/CCNUCC CDM, and compared to the baseline emissions (flaring method) for a credit period of 10 years to compute emissions reductions (ERs). The second part of this study has employed a combined multi-parameter sensitivity analysis (MPSA) and response surface methodology (RSM) approach to assess the relative importance of 5 selected parameters in influencing the amount of ERs. This technique of data analysis is reportedly novel in this field of research in environmental engineering for GHG emissions quantification. The parameters tested were the monitored methane content in venting well/header k during in-situ aeration in the year y ($MC_{CH4,v,k,q}$), monitored methane content from surface emissions during in-situ aeration in zone i in the quarter q ($MC_{CH4,s,i,q}$), total volume of surface emissions in zone i in quarter q ($SG_{s,i,q}$), potential methane generation capacity ($L_{0,i}$) of the waste in landfill zone i as determined by sampling and lab analysis and fraction of degradable waste ($f_{dg,i}$) in landfill zone i. Results from the MPSA and mesh plots from the RSM showed that $L_{0,i}$ had the most influence on the ERs. The largest ERs amounted to 835,104.61 tCO_{2e} obtained from the variations in $L_{0,i}$ whereas 189,343.30 tCO_{2e} was the lowest predicted ERs. The best working values for the five parameters with respect to a better environmental performance for minimal GHG emissions and maximum ERs were: 0.077-0.134 ton CH_4/ton waste for $L_{0,i}$, 0.713-0.8 for $f_{dg,i}$, 688,829.30-972,916.67 m^3 for $SG_{s,i,q}$, 1.01×10^{-5} to 1.75×10^{-5} tCH_4/m^3 for $MC_{CH4,v,k,q}$ and 6.70×10^{-8} to 5.16×10^{-7} tCH_4/m^3 for $MC_{CH4,s,i,q}$. The results of this study present a novel tool of optimized parameter values and ERs data which can be used to decide on how to better design and operate the landfill in Mauritius under the Clean Development Mechanism.

Keywords: greenhouse gas emissions, bioreactor landfill, multi-parameter sensitivity analysis

1. Introduction

Global warming has gained increasing attention to such an extent that, nowadays, it can be considered as a single largest threat to the Earth, even comparable or more serious to another world war or an incurable plague (Jaworowski, 2004; Hulme, 2005). Due to anthropogenic activities, greenhouse gases (GHGs) are released into the atmosphere, preventing heat energy in the form of infrared to escape into the space and reflect it back to the Earth's surface. GHGs have been as carbon dioxide (CO_2), methane (CH_4) and nitrous oxides (NO_x), being the most significant. CH_4 is regarded as the highest contributor of greenhouse effect due to its potential being 21 times that of CO_2 over a hundred-year time horizon (Figueroa et al., 2009). Waste landfills have been recognized to be the third largest source of anthropogenic methane emission, representing about 3 to 20% of the global methane emissions (Goldstein et al., 2007; Mudhoo and Mohee, 2009).

There is nowadays an increasing interest to quantify and also reduce the surficial emissions from landfills due to the production of significant amounts of CH_4 (Bogner et al., 2007; Figueroa et al., 2009). As a direct impact of increasingly affluent lifestyles, continuing industrial and comercial growth together with population growth and increased urbanization, municipal solid waste (MSW) is expected to rise and thus will result in increasing amount of methane emanating from dumping sites and landfills (Renou et al., 2008). With this rise in view, several strategies have been developed to divert wastes from landfills as a means to mitigate the emissions of GHGs; including source reduction of the wastes, recycling of certain materials, composting of kitchen and yard wastes, waste to energy plants, and anaerobic digestion plants for the production of energy in the form of biogas (Renou et al., 2008). However, the sanitary landfill, also known as municipal solid

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waste landfill, remains the ultimate disposal option for solid waste materials due to its economic advantages (Ritzkowski and Stegmann, 2005).

The solid waste generation rate in Mauritius is about 1200 ~ 1300 tons daily, composed mainly of 60 to 80% of organic matter (Mohee, 2002). Methods for the disposal of wastes, earlier discarded in dumping grounds have considerably changed due to an increase in environmental and health awareness and therefore since 1997, the Mare Chicose Sanitary Landfill in Mauritius became operational. Due to little diversion of the wastes, except for a recently commissioned national composting plant (which process around 100000 tonnes of wastes yearly to final compost), these wastes are transported and compacted in the only landfill at Mare Chicose, which has already accommodated more than one million tonnes of wastes to date. These wastes are decomposed by a series of chemical, physical and biological processes with anaerobic biological decomposition being the dominant process to produce CH_4 gas in two phases (Mohee, 2002).

The prime criteria for landfill design involve the safe disposal of waste. Therefore, the main advantage is to keep the processing of refuse to a minimum. Landfills are developed with the aim of getting disposed of waste and at some point, some provision is made to handle and harness gases generated as a result of decomposition of the waste. The Clean Development Mechanism (CDM) and Joint Implementation (JI), two of the Kyoto Protocol mechanisms, are helping developing countries to increase the recovery of landfill gases mainly methane as well as reduce its emission to the atmosphere (Bogner et al., 2007). Landfill gas (LFG) generation and leachate releases are normally the main issues associated with sanitary landfills, giving rise to environmental and health and safety problems and therefore require a means to reduce their impacts. Landfill behavior and decomposition processes of MSW are being understood and this knowledge has gradually produced an optimization of existing landfills operation. Currently, a new and promising trend which is operating landfills as bioreactors to enhance the biodegradation and stability of waste (Berge et al., 2005; Kumar et al., 2011).

Engineered bioreactor landfills are controlled systems which can significantly reduce emission of GHGs while providing a means to control odor and CH_4 migration from landfill to the immediate surroundings, buffer zones and ultimately the atmosphere (Benson et al., 2007). These new generation landfills have the objective of providing an environment capable of decomposing the organic fractions of waste through the addition of moisture and injection of air within a shorter period of time compared to sanitary landfill (Kumar et al., 2011). Different types of landfills exist namely aerobic, anaerobic, facultative and hybrid systems (Berge et al., 2005); whereby it has been shown that aerobic processes enhance degradation of wastes (Kumar et al., 2011). As this technological advance is gradually gaining popularity, more attention must be paid to the *in-situ* processes due to several factors differing from the conventional landfill (Onay and Pohland, 1998). The choices that we make today to investigate the potential of emission reduction from anthropogenic sources, more specifically landfills will determine the extent or limitation of environmental impacts in the forthcoming years.

From the literature, it appears that there is to date no published data which have specifically investigated and reported the carbon footprint of bioreactor landfills from a 'Clean Development Mechanism' assessment perspective. In Mauritius, there is in point of fact no systematic and comprehensive study so far initiated until this one. In this respect, there is a need to take off with this part of research gap and propose reasonable quantification methods of the potential greenhouse gas emissions reduction from a future retrofit bioreactor landfill technology with aeration. Keeping both the need to meet up with this knowledge gap and the potential and promise of this novel technology, the present study has been conducted to estimate the amount of GHG (CH_4, CO_2 and N_2O) emissions generated in terms of carbon dioxide equivalent from baseline activities. These activities comprise conventional landfilling giving rise to the decomposition of biodegradable MSW fractions in landfills from predominantly anaerobic processes and from a potential CDM project activity in the form of in-situ aeration systems installed to constitute a bioreactor landfill in lieu of the conventional landfill set up.

2. Methodology

The approved baseline and monitoring methodology, *AM0083 - Avoidance of landfill gas emissions by in-situ aeration of landfills* has been prepared by Perspectives Climate Change GmbH, Gockhausen, Switzerland. This methodology is applied for future climate protection projects in economically developing countries, in accordance with the given CDM modalities. For this study, values for the parameters involved have to be identified and used for a first run of calculations to estimate CO_2 emissions for the activity. Mid-interval values of these parameters for the identified ranges or default values wherever applicable have been used. Emissions reductions (ERs) were then calculated with the difference of baseline and project emissions. The last section of this work dealt with the multi-parameter sensitivity analysis of the whole exercise for 5 selected parameters.

2.1. Applicability and Project Activity Scope

This methodology is applicable for the avoidance of partial or total atmospheric LFG emissions from closed landfills or landfill cells is based on the conversion of formerly anaerobic into aerobic conditions by means of the application of either air venting or low pressure aeration technique. Closed cells of operating or closed landfills might be eligible as long as they are physically independent from the remaining parts of the landfill. However, this methodology is not applicable to semi-aerobic landfill concepts or landfill aeration by means of the high-pressure impulse methodology.

The project activity proposed and investigated in this work comprises two phases, air-injection phase and a subsequent post-aeration phase. During the initial active aeration phase, the landfilled waste will be aerated leading to an enhanced degradation and might be terminated once the remaining methane generation potential has reached a limit value of 11 m^3 CH_4 per ton waste (dry), corresponding to 0.0077 Mg/Mg dry matter aerated. In-situ aeration would be provided by means of air injection wells. During the post-injection phase, methane emissions would be further monitored and accounted for as project emissions. The maximal duration of both phases is limited by one crediting period (i.e. 7 or 10 years, according to the eventual project provisions) as the major share of biodegradation will be completed at that time. As a consequence of the treatment (air-injection and monitoring), an after-use of landfill site might be feasible and might lead to revenues. Finally, this methodology is only applicable if the application of the procedure to identify the baseline scenario results in that the partial or total atmospheric release of LFG from the closed landfill or the closed landfill cells is the most plausible baseline scenario (Ritzkowski, 2010).

2.2. Baseline Methodology Procedure

The gas collection and flaring system of Mare Chicose landfill may capture only around 20 ~ 30% of the total gas yield. The CDM, established under the Kyoto Protocol, allows for higher recovery of LFG in excess of 50%, thereby reducing emissions of GHGs through the funding of measures. In point of fact, in October 2010, Sotravic Ltée and the Bilfinger Berger Group which are the present joint venture managing the operation and maintenance of the Mare Chicose landfill, have come into an agreement with the Central Electricity Board (CEB) of Mauritius to implant an electric power station under a 'Gas-to-Energy' CDM project. This power station comprising 3 generators each of a capacity of 1MW normally burns LFG captured at the Mare Chicose landfill (40 ~ 60% CH_4) for producing electricity. The total 3MW of 'green' electric power thus produced shall correspond approximately to 1 ~ 1.2% of the daily energy production for the National Grid of the CEB and will be able to meet the energy demand of around 20,000 households. In order to further enhance the capture of LFG and optimize the generation of LFG-derived green power, it is planned to install a further 50 vertical tubes to collect more LFG by 2016. This project is expected to achieve an emissions reduction of 300,000 tCO_{2e} by 2016.

This study investigates the impact of in-situ aeration on landfill gas emissions, mainly in terms of CH_4, N_2O and CO_2 to compare its emissions reduction potential with the 'Gas-to-Energy' project. This methodology is applicable since the most plausible baseline scenario has been identified as business-as-usual, that is, no or partial collection and combustion of LFG from the landfill, after following the steps for the identification of the baseline scenario as detailed in AM0083.

2.2.1. Additionality

The final approval of a CDM project is bounded to an ex-ante demonstration of its additionality. Herein project proponents will have to verify that the intended project would not have been realized without its consideration as a CDM measure, both in terms of economical and technological value. For landfill aeration projects, a potential economical additionality might be considered through an after-use generating economic value. If this is the case, it has to be verified that the potential economic benefit does not exceed the total costs required for the conduction of the aeration project. In terms of the technological additionality, it has to be demonstrated that landfill aeration is beneficial in terms of LFG emissions avoidance in comparison with the status quo in the host country. However, as dump sites in economically developing countries are generally not subjected to active aftercare measures, this requirement should be easily met (Ritzkowski, 2010) for this potential project activity.

2.2.2. Project Boundary

The spatial extent of the project activity boundary encompasses the site of the project activity where the waste is treated. This includes the landfill or the treated landfill cell, on-site electricity consumption, and on-site fuel use. For landfill aeration projects the following greenhouse gases are of concern: CO_2, CH_4 and nitrous oxide (N_2O) and those included in and excluded from the project boundary are shown in Table 1.

2.3. Project Emissions

Project emissions were calculated as follows (Equation (1)):

$$PE_y = PE_{EC,y} + PE_{FC,j,y} + PE_{ia,y} \quad (1)$$

where PE_y is project emissions in year y (tCO_2/yr), $PE_{EC,y}$ is project emissions from electricity consumption in year y (tCO_2/yr), $PE_{FC,j,y}$ is project emissions from fossil fuel combustion in year y (tCO_2/yr) and $PE_{ia,y}$ is project emissions from in-situ aeration of the landfill in year y (tCO_2/yr). The following detailed calculations were performed to estimate project emissions.

2.3.1. Determination of Project Emissions from Electricity Consumption ($PE_{EC,y}$)

Project emissions from electricity consumption ($PE_{EC,y}$) were calculated following the latest version of the "*Tool to calculate baseline, project and/or leakage emissions from electricity consumption*" available from UNFCCC/CCNUCC CDM website (http://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-05-v1.pdf). The scenario where electricity consumption is from the grid was found to be most appropriate for the study. Project emissions were calculated based on the quantity of electricity consumed, an emssions factor for electricity generation and a factor to account for transmission losses as follows (Equation (2)):

Table 1. Emissions Sources Included in or Excluded from the Project Boundary

Source		Gas	Considered in calculations	Justification
Baseline	Emissions from decomposition of waste at the landfill site	CO_2	No	CO_2 emissions from the decomposition of organic waste are not accounted.
		CH_4	Yes	The major source of emissions in the baseline.
		N_2O	No	N_2O emissions are small compared to CH_4 emissions from landfills. Exclusion of the gas is conservative.
Project activity	On-site fossil fuel consumption due to the project activity	CO_2	Yes	May be an important emission source. It includes vehicles used on-site etc.
		CH_4	No	Excluded for simplification. This emission source is assumed to be very small.
		N_2O	No	Excluded for simplification. This emission source is assumed to be very small.
	Emissions from on-site electricity use	CO_2	Yes	May be an important emission source.
		CH_4	No	Excluded for simplification. This emission source is assumed to be very small.
		N_2O	No	Excluded for simplification. This emission source is assumed to be very small.
	Direct emissions from the in-situ aeration of landfill	CO_2	No	CO_2 emissions from the decomposition of organic waste are not accounted.
		CH_4	Yes	The aerobic process may not be complete and result in anaerobic decay. CH_4 may be emitted by the venting pipes and the landfill surface.
		N_2O	Yes	May be an important emission source for aerobic landfill operation.

*Source: Approved Baseline and Monitoring Methodology AM0083 'Avoidance of landfill gas emissions by in-situ aeration of landfills' from the UNFCCC/CCNUCC CDM.

$$PE_{EC,y} = \sum_j EC_{PJ,j,y} \times EF_{EL,j,y} \times \left(1 + TDL_{j,y}\right) \quad (2)$$

where $EC_{PJ,j,y}$ is the quantity of electricity consumed by the project electricity consumption source j in year y (MWh/yr), $EF_{EL,j,y}$ is emissions factor for electricity generation for source j in year y (tCO_2/MWh), $TDL_{j,y}$ is average technical transmission and distribution losses for providing electricity to source j in year y and j is sources of electricity consumption in the project. A default value of 1.3 tCO_2/MWh was chosen for $EF_{EL,j,y}$ among the options provided by the "*Tool to calculate baseline, project and/or leakage emissions from electricity consumption*".

2.3.2. Determination of Project Emissions from Fossil Fuel Combustion ($PE_{FC,j,y}$)

Project emissions from fossil fuel combustion ($PE_{FC,j,y}$) were calculated using Equation (3) following the latest version of the "*Tool to calculate project or leakage CO_2 emissions from fossil fuel combustion*" available from UNFCCC/CCNUCC CDM website (http://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-03-v2.pdf/history_view). For this purpose, the processes j in the tool corresponded to all fossil fuel combustion on-site for the purposes of the project activity:

$$PE_{FC,j,y} = \sum_i FC_{i,j,y} \times COEF_{i,y} \quad (3)$$

where $FC_{i,j,y}$ is the quantity of fuel type i combusted in process j during the year y (mass or volume unit/yr), $COEF_{i,y}$ is the CO_2 emission coefficient of fuel type i in year y (tCO_2/mass or volume unit) and i is the fuel type(s) combusted in process j during the year y. The CO_2 emission coefficient $COEF_{i,y}$ was calculated based on net calorific value (Equation (4)):

$$COEF_{i,y} = NCV_{i,y} \times EF_{CO2,i,y} \quad (4)$$

where $NCV_{i,y}$ is the weighted average net calorific value of the fuel type i in year y (GJ/mass or volume unit) and $EF_{CO2,i,y}$ is the weighted average CO_2 emission factor of fuel type i in year y (tCO_2/GJ).

2.3.3. Determination of Project Emissions from In-situ Aeration of the Landfill ($PE_{ia,y}$)

The project activity may lead to residual methane and nitrous oxide emissions due to incomplete aeration (including downtime of aeration equipment), incomplete degradation and as a consequence of the aerobic degradation process itself. Residual methane emissions were estimated using Equation (5):

$$PE_{ia,y} = PE_{CH4,ia,y} + PE_{N2O,ia,y} \quad (5)$$

where $PE_{CH4,ia,y}$ is CH_4 emissions from in-situ aeration of the

landfill in year y (tCO_2/yr) and $PE_{N2O,ia,y}$ is N_2O emissions from in-situ aeration of the landfill in year y (tCO_2/yr). CH_4 emissions from in-situ aeration of the landfill in year y were calculated from Equation (6) where $PE_{CH4,emissions,y}$ is monitored CH_4 emissions from in-situ aeration of the landfill in year y (tCO_2/yr) and calculated from Equation (7). During air injection phase, we have:

$$PE_{CH4,ia,y} = PE_{CH4,emission,y} \tag{6}$$

$$PE_{CH4,emissions,y} = \sum_{k}(GWP_{CH4} \times MC_{CH4,v,k,y} \times SG_{v,k,y}) + \sum_{i}\sum_{q}(GWP_{CH4} \times MC_{CH4.s,i,q} \times SG_{s,i,q} \times CF) \tag{7}$$

where GWP_{CH4} is Global Warming Potential (GWP) of methane, valid for the relevant commitment period (tCO_2/t CH_4), $MC_{CH4,v,k,y}$ is monitored methane content in venting well/ header k during in-situ aeration in the year y (tCH_4/m^3), $SG_{v,k,y}$ is volume of captured emissions in venting well/header k in year y (m^3/yr), $MC_{CH4,s,i,q}$ is monitored methane content from surface emissions during in-situ aeration in zone i in the quarter q (tCH_4/m^3), $SG_{s,i,q}$ is total volume of surface emissions in zone i in quarter q (m^3), k is the number of venting wells/headers (monitoring of vented emissions might require measuring at different sampling points, e.g., several headers that are not interconnected), i is approximate number of surface zones (cells) and CF is the conservativeness factor. Due to the high degree of uncertainty of surface measurements, a factor of 1.37 has applied as deduced from AM0083 UNFCCC/CCNUCC CDM. During downtime of the aeration equipment during the air injection period, project emissions have been assumed to be equal to baseline emissions. System Downtime (DT) is defined when less than the minimum number of blowers required to aerate the landfill is operational. For these cases, a different value of the methane generation rate (k_{CH4}) was estimated and was for baseline conditions.

For the post-injection phase, the annual methane emissions were calculated from Equation (8):

$$PE_{ia,y} = Max(PE_{CH4,emisions,y}, PE_{CH4,FOD,y}) \tag{8}$$

where $PE_{CH4,emissions,y}$ is the monitored methane emissions of the landfill (tCO_{2e}/yr) and $PE_{CH4,FOD,y}$ is methane emissions of the landfill, calculated based on an adjusted first order decay model (FOD), using the analyzed waste quality and an adjusted methane correction factor (MCF_{adj}). The $PE_{CH4,emissions,y}$ was estimated as follows:

$$PE_{CH4.emissions,y} = \sum_{i}(GWP_{CH4} \times MC_{CH4.s,i,y} \times SG_{s,i,y}) \tag{9}$$

where $MC_{CH4,s,i,y}$ is the monitored methane content from surface emissions in zone i in the year y (t/m^3), $SG_{,s,i,y}$ is the volume of surface emissions in zone i in year y (m^3) and i is here the number of surface zones (number of cells). $PE_{CH4,FOD,y}$ was estimated using Equation (10):

$$PE_{CH4,FOD,y} = \varphi \times (1 - f) \times GWP_{CH4} \times (1 - OX) \times MCF_{adj} \times \sum_{i} A_{lf,i} \times L_{0,i} \times e^{-k_{CH4}(y-x)} \times (1 - e^{-k_{CH4}}) \tag{10}$$

where

φ = default model correction factor to account for model uncertainties (1.1),

f = Fraction of methane captured and flared. As no methane will be captured and flared during the project activity, f is set to 0 for project emission calculation,

GWP_{CH4} = Global Warming Potential (GWP) of methane, valid for the relevant commitment period (tCO_2/tCH_4)

OX = oxidation factor (reflecting the amount of methane from the landfill that is oxidized in the soil or other material covering the waste); if the landfill cover is not changed due to project activity, the OX value chosen has to be equal for baseline and project emission calculation,

MCF_{adj} = adjusted methane correction factor. MCF values according to the latest version of the "*Tool to determine methane emissions avoided from disposal of waste at a solid waste disposal site*" (http://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-04-v4.pdf) have to be applied,

$A_{lf,I}$ = amount of landfilled waste in landfill zone i (tonnes); estimated as per Equation (16) below,

$L_{o,I}$ = potential methane generation capacity of the waste in landfill zone i as determined by sampling and lab analysis (ton CH_4/ton Waste) once after the end of the air-injection phase as per the monitoring methodology described below. Alternatively, the value of L_0 determined before the start of the project activity can be used instead, since this is conservative,

k_{CH4} = methane generation rate (yr^{-1}),

y = year for which the methane emissions are calculated since the stop of the air injection phase. In case a L_o value is determined since the start of the project activity, y is the year since start of air injection,

x = the year of stopping of air injection (yr). In case an L_o value is determined before the start of the air injection is used, x is the year of start of air injection, and,

i = landfill zone category (index). Depending on the characteristics and tipping history of the landfill, the landfill is subdivided into different zones with different characteristics and methane generation potential and landfilled waste quantities determined separately for each zone (cell).

In the post-injection phase, air injection would be stopped and therefore injection and venting wells be no longer be operational. All residual emissions would then be from the surface such that vented emissions will have a value of 0 (AM0083, UNFCCC/CCNCC).

Bioreactor landfill, viewed as an accelerated composting system, will have a slow methane potential generation, L_o after the air injection phase, whereby this generation rate will have been significantly reduced through aerobic decomposition of the waste and environmental conditions (Haight, 2005). During post-injection phase, L_o would not increase and may hence can be assumed to be slow; thereby it is conservative to assume a fixed value for L_o.

2.3.4. Nitrous Oxide Emissions from In-situ Aeration of Landfills ($PE_{N2O,ia,y}$)

Emissions of N_2O were estimated from Equation (11):

$$PE_{N2O,ia,y} = \frac{\sum_i A_{lf,i} \times EF_{ia,N2O} \times GWP_{N2O}}{a} \quad (11)$$

where $A_{lf,i}$ is the amount of landfilled waste in landfill zone i (tonnes), i is the landfill zone category (index), $EF_{ia,N2O}$ is the emission factor for N_2O emissions from the in-situ aeration and stabilization (t N_2O/t treated waste). Based on the findings of Schenk et al. (1997a), N_2O emissions of 0.027 kg N_2O per tonne of treated waste can be expected for the complete composting process, and a is the scheduled minimum duration of in-situ aeration and stabilization (years). The actual number of years used for stabilization may be used for ex post determination of N_2O emissions.

2.4. Baseline Emissions

Baseline emissions were calculated as follows:

$$BE_y = (MB_y - MD_{reg,y}) \quad (12)$$

where BE_y is baseline emissions in year y (tCO_2/yr), MB_y is methane that would be produced in the landfill in the absence of the project activity in year y (tCO_2/yr) and $MD_{reg,y}$ is the methane that would be destroyed in the absence of the project activity in year y (tCO_2/yr). In cases where regulatory or contractual requirements do not specify $MD_{reg,y}$ (Equation (13)) an Adjustment Factor (AF) is normally used taking into account the project context. In doing so, the project participant should take into account that some of the methane generated by the landfill may be captured and destroyed to comply with other relevant regulations or contractual requirements, or to address safety and odor concerns:

$$MD_{reg,y} = MB_y \times AF \quad (13)$$

where AF is the adjustment factor for MB_y (%). As mentioned earlier, around 25% of the total landfill gas is collected and flared. The 'Adjustment Factor' shall be revised at the start of each new crediting period taking into account the amount of GHG flaring that occurs as part of common industry practice and/or regulation at that point in the future. In cases where there would be a regulation which mandates the collection and treatment of landfill gas from closed landfills or closed landfill cells and which is not being enforced, the baseline scenario is identified as a gradual improvement of waste management practices to the acceptable technical options expected over a period of time to comply with the regulation. The adjusted baseline emissions ($BE_{y,a}$) were calculated as follows:

$$BE_{y,a} = BE_y * (1 - RATE^{Compliance}{}_y) \quad (14)$$

where $RATE^{Compliance}{}_y$ is the state-level compliance rate with the regulation in that year y. The compliance rate shall be lower than 50%; if it exceeds 50%, the project activity shall receive no further credits. There is presently no such compliance rate deemed relevant in Mauritius. However, the compliance ratio $RATE^{Compliance}{}_y$ would be monitored *ex post* based on official reports (e.g. instance annual reports provided by municipal bodies). Consequently, $RATE^{Compliance}{}_y$ was fixed 0.

2.4.1. Methane Generation from the Landfill in the Absence of the In-situ Alternative Treatment (In-situ Aeration of Landfills) (MB_y)

At the start of the project activity, project proponents in principle have to do a statistically significant sampling and analysis of the existing wastes to determine the methane genetion potential. Then, baseline emissions are recalculated with the analytically determined value for the methane generation potential (L_o) before the start of the project as per following equation (Equation (15)):

$$MB_{y,ad} = \varphi \times (1 - f) \times GWP_{CH4} \times (1 - OX) \times MCF_{adj} \times \sum_i A_{lf,i} \times L_{0,i} \times e^{-k_{CH4}(y-x)} \times (1 - e^{-k_{CH4}}) \quad (15)$$

where φ is default model correction factor to account for model uncertainties (0.9), f is fraction of methane captured and flared (0.25), OX is oxidation factor (reflecting the amount of methane from the landfill that is oxidized in the soil or other material covering the waste), MCF_{adj} is adjusted methane correction factor (MCF values were determined according to the latest version of the "*Tool to determine methane emissions avoided from disposal of waste at a solid waste disposal site*" have to be applied), $A_{lf,i}$ is the amount of landfilled waste in landfill zone i (in tones and estimated as per Equation (16) and $L_{o,i}$ is the potential methane generation capacity of the waste in landfill zone i as determined by sampling and laboratory analysis (ton CH_4/ton Waste) once before start of the project activity. With increasing landfill age, a clear separation of waste components becomes very difficult. Therefore, the same samples taken to determine L_o have to be classified into degradable and non degradable materials (by

mass). The fraction of degradable waste has to be determined and applied to the total waste quantities in the closed landfill or closed cell to determine the value of $A_{lf,i}$ as per Equation (16):

$$A_{lf,i} = f_{dg,i} \times A_{T,i} \quad (16)$$

where $A_{lf,i}$ is the amount of landfilled waste in landfill zone i (tonnes), $f_{dg,i}$ is the fraction of degradable waste in landfill zone i, and $A_{T,i}$ is the total waste quantities in landfill zone i (tonnes).

2.4.2. Baseline Campaign

Methane emissions would also have to be measured prior the start of the aeration of the landfill to check the validity of the FOD model. This baseline campaign will last for at least 3 months. Measurements shall only start a week after the wells have been installed. The ratio between the actual methe measured and the methane estimated using the FOD model were adjusted using the FOD model and Equation (17), (18) and (19):

$$R = \frac{ME_{CH4,bl\_campaign}}{MB_{bl\_campaign,ad}} \quad (17)$$

where

R = Ratio between the actual methane measured and the methane estimated using the FOD model. If R is greater than 1, a value of 1 shall be used,

$ME_{CH4,bl\_campaign}$ = Methane produced in the landfill in the baseline campaign measured and calculated as per equation (18) below. (tCO_2/bl_campaign),

$MB_{bl\_campaign,ad}$ = Methane produced in the landfill in the baseline campaign estimated as per equation 19 below. (tCO_2/bl_campaign).

$$ME_{CH4,bl\_campaign} = \sum_k (GWP_{CH4} \times MC_{CH4,v,k,bl\_campaign} \times SG_{v,k,bl\_campaign}) + \sum_i (GWP_{CH4} \times MC_{CH4,s,i,bl\_campaign} \times SG_{s,i,bl\_campaign}) \quad (18)$$

where

$MC_{CH4,v,k,bl\_campaign}$ = Monitored methane content in venting well/header k during the baseline campaign (tCH_4/m^3),

$SG_{v,k,bl\_campaign}$ = Volume of emissions in venting well/header k in the baseline campaign (m^3/bl_campaign),

$MC_{CH4,s,i,bl\_campaign}$ = Monitored methane content from surface emissions in zone i during the baseline campaign (tCH_4/m^3),

$SG_{s,i,bl\_campaign}$ = Volume of surface emissions in zone i in the baseline campaign (m^3/yr),

k = Number of venting wells/headers (monitoring of vented emissions might require measuring at different sampling points, e.g. several headers that are not interconnected).

$$MB_{bl\_campaign,ad} = \varphi \times (1-f) \times GWP_{CH4} \times (1-OX) \times MCF_{adj} \times \sum_i A_{lf,i} \times L_{0,i} \times e^{-k_{CH4}(m-x)} \times (1-e^{-k_{CH4}}) \quad (19)$$

where

m = Month for estimating methane emission during baseline campaign (months),

i = Landfill zone category (index). Depending on the characteristics and tipping history of the landfill, the landfill is subdivided into different zones with different characterristics and methane generation potential and landfilled waste quantities determined separately for each zone (cell).

2.5. Leakage

No leakage would occur due to the project activity.

2.6. Emission Reductions

Emission reductions were calculated as follows:

$$ER_y = (R \times BE_y) - PE_y \quad (20)$$

where

ER_y = Emission reductions in year y (tCO_{2e}/yr),

BE_y = Baseline emissions in year y (tCO_{2e}/yr),

R = Ratio between the actual methane measured and the methane estimated using the FOD model,

PE_y = Project emissions in year y (tCO_2/yr).

If PE_y is smaller than 1% of BE_y in the first year after air-injection stops, the project participants would normally assume a fixed percentage of 1% for PE_y combined for the remaining years of the crediting period. Based on the above equations, the values used for each parameter to evaluate a first estimate of emissions reductions are indicated in Table 2.

2.7. Multi-Parameter Sensitivity Analysis (MPSA)

Due to the high complexity of engineering, physical, environmental, social and economic phenomena, mathematical models are often employed for approximation, usually consisting of several logical steps to determine a set of parameters which depicts a process, considered to be the most influential on model results. This technique has been employed to address a number of environmental processes from carbon sequestration or fossil fuels substitution of forests (Marland and Schlamadinger, 1997), to the assessment of performance criteria in wastewater treatment plant (Flores Alsina et al., 2008; Sin et al., 2011) and also in investigating the effects of emissions corridors on climate change (Kriegler and Bruckner, 2004).

Table 2. Summary of Values Used for the Different Parameters in Eq. (1) to Eq. (20)

Parameter	Unit	Values		Reference	Default value	Value used
$EC_{PJ,j,y}$	MWh	0.35		Ramnauth et al. (2012)	–	0.35
$EF_{EL,j,y}$	tCO_2/MWh	1.3		IPCC (2006)	1.3	1.3
$TDL_{j,y}$	%	20		Annex 7, version 01, UNFCCC/CCNUCC	–	20 %
NCV_i	GJ per tonne	42 – 44		Nwafor (2002); Treanton (2004); IPCC (2006)	–	43
EF_{CO2i}	tCO_2e/GJ	0.0741		IPCC (2006)	–	0.0741
$FC_{i,j,y}$	Tonne/yr	23.88		Ramnauth et al. (2012)	–	23.88
GWP_{CH4}	–	–		IPCC (2006)	21	21
k (Venting wells)	–	–		Calculated	–	255
$MC_{CH4,v,k,q}$	tCH_4/m^3	1.34×10^{-5} – 2.01×10^{-5}		Heyer et al. (2001), Cossu et al. (2003)	Calculated	1.34×10^{-5}
$SG_{v,k,y}$	m^3/yr	91,568.63 – 173,980.39		Calculated	–	137,352.94
$MC_{CH4,s,i,q}$	tCH_4/m^3	6.70×10^{-8} – 2.01×10^{-6}		Hupe et al. (2003)	Calculated	1.005×10^{-6}
$SG_{s,i,q}$	m^3	97,291.72 – 972,916.67		Calculated	–	486,250
i (cells)	–	6		–	–	6
CF	–	–		AM0083/Version01	1.37	1.37
φ	–	–		AM0083/Version01	0.9	0.9
OX	–	–		IPCC (2006)	0.1	0.1
MCF_{adj}	–	0.5		IPCC (2006)	–	0.5
$L_{0,i}$	ton CH_4 / ton waste	0.004154 – 0.067 (For post–aeration phase)		Firmo et al. (2011)	–	0.0255
		0.067 – 0.134		IPCC (2006)	–	0.0757
		0.0858		Surroop and Mohee (2011)	–	0.0858
k_{CH4}	$year^{-1}$	≤ 2 yr	0.170	IPCC (2006)	0.170	0.170
		>2 yr ≤ 10 yr	0.100		0.100	0.100
		> 10 yr	0.050		0.050	0.050
GWP_{N2O}	–	–		IPCC (2006)	310	310
f	Fraction of methane captured and flared	–		Mudhoo and Mohee (2009)	–	0.25
$MC_{CH4,v,k,bl\_campaign}$	tCH_4/m^3	3.33×10^{-4}		Calculated	–	3.33×10^{-4}
$SG_{v,k,bl\_campaign}$	m^3/bl_campaign	91,568.63 – 173,980.39		Calculated	–	137,352.94
$MC_{CH4,s,i,bl\_campaign}$	t CH_4 / m^3	7.705×10^{-5}		Calculated	–	7.705×10^{-5}
$SG_{s,i,bl\_campaign}$	m^3 / yr	97,291.72 – 972,916.67		Calculated	–	486,250
a	years	5.5 – 10		–	–	5.5
$EF_{ia,N2O}$	t N_2O/t treated waste	–		Schenk et al. (1997b)	0.000027	0.000027
AF	%	25		Mudhoo and Mohee (2009)	–	25
$RATE^{Compliance}_{y}$	%	0		–	–	0
$f_{dg,i}$	Fraction	0.60 – 0.80		Mohee (2002)	–	0.7057

2.7.1. Features of the MPSA

The MPSA approach allows not only a validation of the model through the assessment of each input parameter with different settings of the other input parameters (Parker, 1997) but also guides the research to a more realistic picture and to future efforts than standard analyses (Xi et al., 2005).

Standard analyses can only investigate effects of each input parameter at default values of other parameters as compared to MPSA where a pairwise evaluation of the parameters is performed to assess the development of three dimensional response curves (Rabinowitz and Steinberg, 1991; Hamby, 1994). To study a given pair of parameters denoted as primary parameters while the rest is known as secondary ones, the model or set of equations defining the system analysis is evaluated for all combinations of the secondary parameters. A visual assessment of the model sensitivity, plotted as a three-dimensional surface which is obtained through the results of the matrix, helps to identify input parameters which influence the model's response the most. The mesh plot generated provides an indication of the potential for obtaining a significant response for a given combination of the primary parameters (Mudhoo and Mohee, 2006). An elevated value in the plot would indicate a combination that will result in a potential "hot-spot" (Parker, 1997). The mesh plot can also be employed to identify areas of rapid change in the plot surface, as these are indicative of regions of model sensitivity, and decide on the optimum range(s) of parameters that satisfy the criterion. It must be noted that the results of this technique may not necessarily indicate the results that wastes might be obtained from the model for any given solid waste disposal matrix or combination of techniques, but will effectively indicate the fraction of the population of values that will exceed a given criterion (Ramnauth et al., 2012).

2.7.2. Parameter Identification and Discretisation

Given the large number of parameters ($EC_{PJ,j,y}$, $EF_{EL,j,y}$, $TDL_{j,y}$, NCV_i, $EF_{CO2,i}$, $FC_{i,j,y}$, GWP_{CH4}, k, q, $MC_{CH4,v,k,q}$, $SG_{v,k,y}$, $MC_{CH4,s,i,q}$, $SG_{s,i,q}$, i, CF, φ, OX, MCF_{adj}, $L_{0,i}$, k_{CH4}, GWP_{N2O}, f, $MC_{CH4,v,k,bl\_campaign}$, $SG_{v,k,bl\_campaign}$, $MC_{CH4,s,i,bl\_campaign}$, $SG_{s,i,bl\text{-}campaign}$, a, $EF_{ia,N2O}$, AF, $RATE^{Compliance}$, and $f_{dg,i}$) used in this study, it is not possible evaluate all of the parameters due to the high computational power requirements. This drawback was verified when a minimum of 10 parameters was analysed and the computational system failed down to 6 parameters. In this respect, only $MC_{CH4,v,k,q}$, $MC_{CH4,s,i,q}$, $SG_{s,i,q}$, $L_{0,i}$ and $f_{dg,i}$ have been used for the MPSA. The discretisation of the range of each parameter into individual values must span the endpoints and also reflect the relative distribution of values that may be encountered in practice (Mudhoo and Mohee, 2006). In this respect, and in order to eliminate any bias during the model assessment, the logarithmic approach developed by Parker (1997) was used to determine the discretized values. In this method, a multiplier was determined (Equation (21)):

$$\varphi = \left(\frac{P_f}{P_0} \right)^{\frac{1}{n}} \tag{21}$$

where

P_f and P_0 = high and low endpoints of the parameter range, respectively,

n = number of intervals in range,

φ = multiplier.

The parameter values were then calculated from:

$$P_i = \varphi^i P_0 \tag{22}$$

where i = 0, n. This technique was employed to calculate discretized parameter values. In this study, five intervals (n = 5) were employed for each parameter, resulting in a total of five values for each parameter assessed. The actual values evaluated for each parameter are presented in Table 3.

Table 3. Discretised Parameter Values Tested in MPSA

Discretised parameter				
$MC_{CH4,v,k,q}$*	$MC_{CH4,s,i,q}$**	$SG_{s,i,q}$***	$L_{0,i}$	$f_{dg,i}$
1.01×10^{-5}	6.70×10^{-8}	97,291.667	0.067	0.600
1.15×10^{-5}	1.32×10^{-7}	319,992.292	0.077	0.636
1.33×10^{-5}	2.61×10^{-7}	515,859.875	0.088	0.673
1.52×10^{-5}	5.16×10^{-7}	688,124.500	0.102	0.713
1.75×10^{-5}	1.02×10^{-6}	839,646.542	0.117	0.755
2.01×10^{-5}	2.01×10^{-6}	972,916.667	0.134	0.800

***** Based on % methane in wells; ** Based on % methane from surface; *** Based on efficiency of venting wells.

Table 4. Primary Parameter Pairs Tested in MPSA

$MC_{CH4,v,k,q} - MC_{CH4,s,i,q}$	$MC_{CH4,s,i,q} - SG_{s,i,q}$
$MC_{CH4,v,k,q} - SG_{s,i,q}$	$MC_{CH4,s,i,q} - L_{0,i}$
$MC_{CH4,v,k,q} - L_{0,i}$	$MC_{CH4,s,i,q} - f_{dg,i}$
$MC_{CH4,v,k,q} - f_{dg,i}$	$SG_{s,i,q} - L_{0,i}$
$L_{0,i} - f_{dg,i}$	$SG_{s,i,q} - f_{dg,i}$

The ten primary parameter pair combinations tested in the MPSA are summarized in Table 4. Selecting a pair of primary parameters leaves out three secondary parameters. The total number of combinations tested for the sensitivity analysis by the mathematical equations above amounted to $3000\,(5! \times 5 \times 5)$. The results for the primary parameters have been presented on mesh plots generated using the SigmaPlot Version 11 software (Copyright 2008 SYSTAT Software, Inc).

4. Results and Discussion

MPSA is a decision tool for parameters to be optimized or determined more accurately through further modeling or experimental studies for a given process (Drews et al., 2003).

In this study, MPSA was used to quantify emissions reductions (ERs) of CO_2 as a result of several interactions of the different parameters involved. The mesh (surface) plots for the comparison of $MC_{CH4,v,k,q} - MC_{CH4,s,i,q}$, $MC_{CH4,v,k,q} - SG_{s,i,q}$, $MC_{CH4,v,k,q} - L_{0,i}$, $MC_{CH4,v,k,q} - f_{dg,i}$, $MC_{CH4,s,i,q} - SG_{s,i,q}$, $MC_{CH4,s,i,q} - L_{0,i}$, $MC_{CH4,s,i,q} - f_{dg,i}$, $SG_{s,i,q} - L_{0,i}$, $SG_{s,i,q} - f_{dg,i}$ and $L_{0,i} - f_{dg,i}$ are presented below along with the discussions.

3.1. $MC_{CH4,v,k,q} - MC_{CH4,s,i,q}$

Figure 1 presents the mesh plot of $MC_{CH4,v,k,q} - MC_{CH4,s,i,q}$ together with its respective ERs. It may be observed that the model has the highest ERs at 387,560.07 tCO_{2e} when $MC_{CH4,v,k,q}$ and $MC_{CH4,s,i,q}$ are both at their minimum (1.01×10^{-5} and 6.70×10^{-8} tCH_4/m^3, respectively). The surface of the mesh plot shows a linear decrease in the ERs for $MC_{CH4,v,k,q} > 1.33 \times 10^{-5}$ tCH_4/m^3 and $MC_{CH4,s,i,q} > 5.16 \times 10^{-7}$ tCH_4/m^3. The values of ERs range from 343,314.44 to 387,560.07 tCO_{2e}. Both $MC_{CH4,v,k,q}$ and $MC_{CH4,s,i,q}$ favored higher ERs for 1.01×10^{-5} $tCH_4/m^3 < MC_{CH4,v,k,q} < 1.75 \times 10^{-5}$ tCH_4/m^3. The values that affected the ERs mostly were those of $MC_{CH4,v,k,q}$ due to a higher percentage of methane content in the venting wells compared to that on the landfill surface, causing only a slight decrease for ERs with increasing methane content. This is due to the fact that methane emitted through the surface is further oxidized by the atmosphere compared to that emitted through venting wells which is from the bulk of the waste, without no more oxidation occurring. Hupe et al. (2003) also proposed a similar explanation for the lower methane content on the surface of land-fills.

3.2. $MC_{CH4,v,k,q} - SG_{s,i,q}$

All ERs showed a favorable response for values of $MC_{CH4,v,k,q} < 1.52 \times 10^{-5}$ tCH_4/m^3 and $SG_{s,i,q} > 390{,}586.24$ m^3. A sudden decrease in ERs was observed from 370,294.76 to 324,960.72 tCO_{2e} for $MC_{CH4,v,k,q}$ at 2.01×10^{-5} tCH_4/m^3 and 97,291.67 $m^3 < SG_{s,i,q} < 972{,}916.67$ m^3. The fluctuations in ERs for this parameter pair comparison could be explained as follows: as the amount of venting emissions decreases, the methane content in these emissions also tend to decrease. Therefore, the surface emissions with a fixed methane content which is much lower than in that prevailing in venting wells (Heyer et al., 2005) tend to increase the ERs.

3.3. $MC_{CH4,v,k,q} - L_{0,i}$

For the comparison of $MC_{CH4,v,k,q}$ and $L_{0,i}$, the model response was *apparently* insensitive. The model was most favorable for values of $L_{0,i} > 0.077$ ton CH_4/ton waste. Fluctuations of values of $L_{0,i}$ mostly influenced the ERs at a fixed value of $MC_{CH4,v,k,q}$. For a fixed value of 1.15×10^{-5} tCH_4/m^3, a notable increase in ERs range from 240,250.36 to 737,590.17 tCO_{2e} was recorded. A higher value of $L_{0,i}$ corresponds to higher production rate of methane. However due to aeration of waste, conditions similar to that of composting are generated. Therefore, methane production can be avoided or oxidized, resulting in higher ERs.

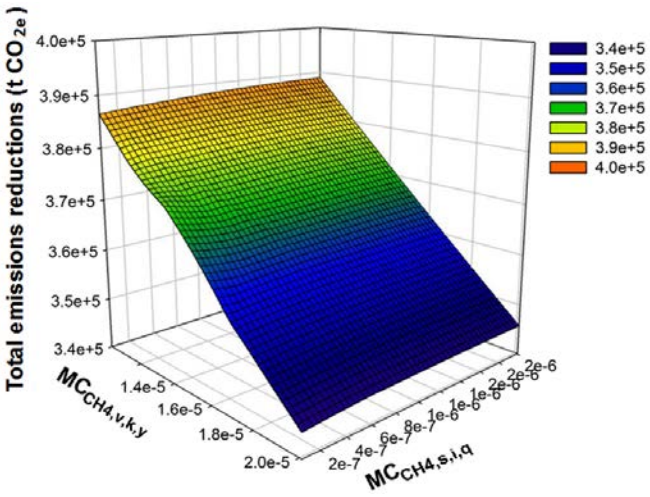

Figure 1. Mesh plot comparing $MC_{CH4,v,k,q}$ and $MC_{CH4,s,i,q}$.

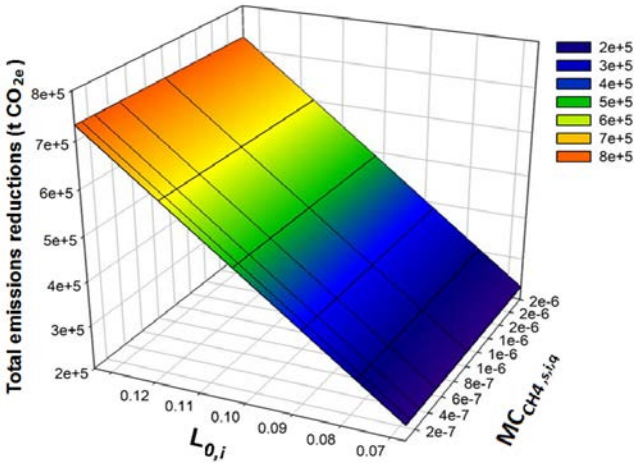

Figure 2. Mesh plot comparing $MC_{CH4,s,i,q}$ and $L_{0,i}$.

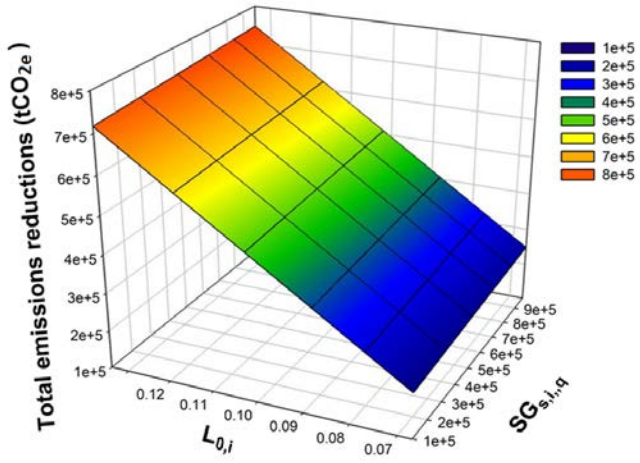

Figure 3. Mesh plot comparing $SG_{s,i,q}$ and $L_{0,i}$.

3.4. $MC_{CH4,v,k,q} - f_{dg,i}$

The comparison of $MC_{CH4,v,k,q}$ and $f_{dg,i}$ illustrated a model response which fluctuated only slightly from the variations of the values of $MC_{CH4,v,k,q}$ for fixed $f_{dg,i}$. For a fixed value of 0.713, the ERs were 369,330.41 and 360,115.05 tCO_{2e} for values of $MC_{CH4,v,k,q}$ of 1.52×10^{-5} and 1.75×10^{-5} tCH_4/m^3, respectively. For fixed value of $f_{dg,i}$, ERs have showed a decreasing trend for $MC_{CH4,v,k,q} > 1.33 \times 10^{-5}$ tCH_4/m^3. Increases in ERs were most pronounced for $f_{dg,i} > 0.713$. With an increase in the biodegradable fraction of waste, it is expected that methane generation be higher. However, with methane oxidation due to aeration, the excessive generation and emission of methane are curbed. In general, in this parameter pair comparison, values of $MC_{CH4,v,k,q} < 2.01 \times 10^{-5}$ tCH_4/m^3 and values of $f_{dg,i} > 0.713$ were seen to have increased the ERs.

3.5. $MC_{CH4,s,i,q} - SG_{s,i,q}$

When comparing $MC_{CH4,s,i,q}$ and $SG_{s,i,q}$, an increasing trend in the values of ERs was observed. The highest ERs were 391,953.65 tCO_{2e} for $MC_{CH4,s,i,q}$ equal to 6.70×10^{-8} tCH_4/m^3 and $SG_{s,i,q}$ equal to 972,916.67 m^3. For a fixed value of $SG_{s,i,q}$ at 688,124.50 m^3 and within the range 6.70×10^{-8} $tCH_4/m^3 < MC_{CH4,s,i,q} < 2.01 \times 10^{-6}$ tCH_4/m^3, the ERs were shifted from 381,444.69 to 376,367.69 tCO_{2e}. The influence of this couple of parameters can be explained based on a similar scenario reported by Hupe et al. (2003). With higher surface emissions, the emissions in venting wells tend to be less. As a result, methane escaping through the surface is much lower due to atmospheric oxidation compared to that in the venting wells which is being pumped from the bulk of the landfill.

3.6. $MC_{CH4,s,i,q} - L_{0,i}$

Figure 2 represents the mesh plot for the comparison of $MC_{CH4,s,i,q}$ and $L_{0,i}$, together with estimated ERs. A shift in sensitivity was observed from 232,698.34 to 730,038.17 tCO_{2e} for $MC_{CH4,s,i,q}$ at 1.02×10^{-6} tCH_4/m^3 and for $0.067 < L_{0,i} < 0.134$. As can be observed from Figure 2, with a fixed value of $L_{0,i}$ at 0.117 and 6.70×10^{-8} $tCH_4/m^3 < MC_{CH4,s,i,q} < 2.01 \times 10^{-6}$ tCH_4/m^3, the ERs varied from 605,605.08 to 602,015.58 tCO_{2e}. The ERs are affected mostly by variations of $L_{0,i}$. The contribution of $MC_{CH4,s,i,q}$ may be considered as negligible in affecting the values of ERs compared to the influence of $L_{0,i}$. This is due to the fact that $MC_{CH4,s,i,q}$ varies through a range of very small values. As can be observed from Figure 2, the fluctuations of $L_{0,i}$ can influence ERs values enormously. This is because higher methane generation potential produces higher methane contents in emissions for baseline activities as compared to aeration projects which induce the oxidation of methane.

3.7. $MC_{CH4,s,i,q} - f_{dg,i}$

For the comparison of $MC_{CH4,s,i,q}$ and $f_{dg,i}$, the variations recorded in ERs showed that the influence of $MC_{CH4,s,i,q}$ was small on the values of ERs. However, values of $f_{dg,i}$ from 0.6 to 0.8 caused ERs to increase from 309,429.01 to 430,942.83 tCO_{2e} with $MC_{CH4,s,i,q}$ fixed at 2.61×10^{-7} tCH_4/m^3. A slight decrease was noted in ERs values (from 378,443.25 to 374,853.79 tCO_{2e}) for 6.70×10^{-8} $tCH_4/m^3 < MC_{CH4,s,i,q} < 2.01 \times 10^{-6}$ tCH_4/m^3 at a fixed value for $f_{dg,i}$ at 0.713. Due to the variations of smaller values, $MC_{CH4,s,i,q}$ does not influence the ERs values much as is the case with $f_{dg,i}$. With an increase in the amount of biodegradables of the waste, a higher amount of methane is expected in the baseline emissions. However, through in-situ aeration of the wastes, the waste is degraded aerobically (Haight, 2005) and this results mostly in the generation of stabilized waste and carbon dioxide. Also, the oxidation of methane produced in anaerobic pockets, considerably reduces the amount of methane entering the atmosphere.

3.8. $SG_{s,i,q} - L_{0,i}$

Figure 3 presents the mesh plot for the comparison of $SG_{s,i,q} - L_{0,i}$. A shift in ERs was observed from 239,354.13 to 736,671.45 tCO_{2e} for values $SG_{s,i,q}$ at 688,124.50 m^3 and $0.067 < L_{0,i} < 0.134$. The influence of $SG_{s,i,q}$ on ERs values was quite small with ERs ranging from 375,623.14 to 404,694.71 tCO_{2e} at a fixed $L_{0,i}$ of 0.088 and 97,291.67 $m^3 < SG_{s,i,q} < 972,916.67$ m^3. This demonstrates that fluctuations in $L_{0,i}$ affected ERs most. The results agree with the other mesh plot results (not reported here) in the sense that values for $L_{0,i} > 0.102$ and $SG_{s,i,q} > 319,992.29$ m^3 should be set as design criteria for both the aerated bioreactor landfill project and baseline activity to increase ERs. With an increase in the emissions to the surface, methane emissions are reduced by atmospheric oxygen. However, $L_{0,i}$ greatly increased the ERs. With increasing $L_{0,i}$, methane production is in principle higher. Thus, during the aeration period, carbon dioxide is the main product as a result of aerobic waste degradation (Haight, 2005).

3.9. $SG_{s,i,q} - f_{dg,i}$

For the comparison of $SG_{s,i,q} - f_{dg,i}$, along its ERs, it was observed that the model equations were sensitive to both the variations in both parameters. The model responses were more favorable for values of $f_{dg,i}$ as compared to those of $SG_{s,i,q}$. With $SG_{s,i,q}$ fixed at 515,859.88 m^3 and for $0.6 < f_{dg,i} < 0.8$, the ERs were ranged from 308,968.74 to 430,482.54 tCO_{2e}. Fluctuations in $f_{dg,i}$ have influenced ERs the most, with the highest ER at 445,657.91 tCO_{2e}. The shift in ERs increased for $f_{dg,i} > 0.713$ and $SG_{s,i,q} > 319,992.29$ m^3. Increasing $f_{dg,i}$ has produced higher ERs. This is because a higher $f_{dg,i}$ implies higher biodegradable contents of wastes and hence higher methane production. With a fixed methane content in the surface emissions following atmospheric oxidation $SG_{s,i,q}$ contributed less in reducing methane release to the atmosphere.

3.10. $L_{0,i} - f_{dg,i}$

The influence of $L_{0,i} - f_{dg,i}$ produced a large increase in ERs from 189,343.30 to 835,104.61 tCO_{2e} for a $f_{dg,i}$ equal to 0.8 and $0.067 < L_{0,i} < 0.134$. However, there was a less marked increase in ERs for $0.6 < f_{dg,i} < 0.8$. ERs were mostly affected by fluctuations in $L_{0,i}$ values. The results agree with

results obtained from the other parameter pair comparisons in the sense that the higher values of both parameters should be preferably set as design criteria for producing higher ERs$L_{0,i}$ influenced ERs much more than $f_{dg,i}$. With increasing $f_{dg,i}$, methane production generally tends to increase.

3.11. Summary of Results for MPSA

All the parameters evaluated using the MPSA have in some way influenced the values of ERs, with a decreasing order for the parameters as follows:

$$L_{0,i} > f_{dg,i} > SG_{s,i,q} > MC_{CH4,v,k,q} > MC_{CH4,s,i,q}$$

As demonstrated by the results, it was observed that $L_{0,i}$ had more influence on the ERs than any other parameters while $MC_{CH4,s,i,q}$ had the least effect on ERs. It was also observed that ERs varied from 189,343.30 to 835,104.61 tCO_{2e} for $f_{dg,i}$ varying from 0.6 to 0.8 and for $0.067 < L_{0,i} < 0.134$. 835,104.61 tCO_{2e} is the highest ERs computed from the present set of mathematical analyses. Based on the above results, the range of values for the parameters tested in the MPSA which would be most favorable as design criteria for achieving high ERs are given in Table 5.

3.12. Carbon Credit Analysis

CDM provides a means to mitigate GHGs emissions in developing countries (including Mauritius) in return of financial benefits and contribution to the sustainable development of the host country offered by industrialized countries. Solid waste disposal management is a sector considered to be relatively easier to develop than projects in other sectors due to a number of reasons as discussed in Table 6. Moreover, the carbon credit market continues to evolve and mature with rising prices and increase in the number of trades per month reaching 2.5 million tons of carbon per month for the last quarter of 2004 (Lee et al., 2005). During the last decade, both the buyers and sellers for the majority of transactions were from industrialized countries. However, the contractual emissions reductions from developing countries with transition economies has increased from 38% in 2001 to 60% in 2002, 88% in 2003 and 93% in the first months of 2004 (Bogner et al., 2004; Lee et al., 2005). With several countries like Sweden, Finland, Denmark, Austria and Canada anticipated to become more active, this transaction economy is expected to increase further. With the need to meet Kyoto emissions targets, developed countries are buying CERs with intention to sell or award credits to industries within their borders; thereby their increased interest in ERs in developing countries (Bogner et al., 2004; Lee et al., 2005).

Table 5. Best Working Range for Higher ERs as per MPSA

Parameters	Range of values
$L_{0,i}$	0.077 – 0.134 ton CH_4 / ton waste
$f_{dg,i}$	0.713 – 0.8
$SG_{s,i,q}$	688,829.30 – 972,916.67 m^3
$MC_{CH4,v,k,q}$	$1.01\times 10^{-5} – 1.75 \times 10^{-5}$ tCH_4/m^3
$MC_{CH4,s,i,q}$	$6.70 \times 10^{-8} – 2.01 \times 10^{-6}$ tCH_4/m^3

Table 6. Reasons for Increased Interest in Solid Waste Management

Reasons	Explanation
Requirement of additionality	The host country's environmental regulations is required to have venting only with any captured, flared or used for energy LFG constituting a reduction in baseline emissions scenario, therefore easily meeting this test.
Technology for LFG recovery	Landfill technologies are proven and reliable due to their use since 1975.
Approved methodology by Executive Board (EB)	A number of methodologies have been approved for the calculation of baseline scenario and establishment of additionality to landfill CDM projects. Following an approved methodology increases the chance for approval by the Executive Board.

*Adapted from: Lee et al. (2005) and Bogner et al. (2004)

Table 7. Estimates of Carbon Trading Values Based on Predictions Made by MSPA for Emissions Reduction from In-Situ Aeration at the Landfill in Mauritius

	Estimates of Carbon trading values			
	US$ 1 – 4 (Bogner and Lee, 2004)	US$ 3.5 – 5.5 (NSWAI ENVIS, 2007)	US$ 8.20 / tCO_{2e} (SCS Engineers, 2009)	€ 15 – 18 US$ 19.9 – 23.9 (Baxter et al., 2007)
Place of project	South Africa	India	United States	Canada
Type of project under reference	Landfill gas recovery	Municipal solid waste management	In-situ aeration of landfills	Aerobic Bioreactor landfill
Carbon trading for minimum tCO_{2e}	183,343.30 to 733,373.20	641,701.55 to 1,008,388.15	1,503,415.06	3,648,531.67 to 4,381,904.87
Carbon trading for maximum tCO_{2e}	835,104.61 to 3,340,418.44	2,922,866.14 to 4,593,075.36	6,847,857.80	16,618,581.74 to 19,959,000.18

In this study, the values of the parameters tested in the MPSA yielded in a minimum and maximum ER. Carbon credit values were selected after a thorough literature review of projects related to aerobic bioreactor landfilling or emissions reduction in landfills. These projects are nonetheless still very limited in number (Table 7). However, being a recent innovation in the field of sustainable solid waste management, the aerobic bioreactor landfill is now being investigated in more detail for implementation at full-scale in view to obtain substantial CERs. As a result, little information is available regarding the value or range of values for carbon credit trading from which more refined estimates of carbon emissions trading could be presently proposed. Therefore, the present figures for ERs and carbon emissions trading constitute a novel pool of data in this field of research in scenario analysis for solid waste management. With the least amount of ERs at 189,343.30 tCO_{2e} the aerobic bioreactor landfill is expected to yield carbon emissions trading in the range of US$ 183,343.30 to 4,381,904.87 while the highest predicted ERs which amounted to the tune of 835,104.61 tCO_{2e} it is expected to generate between US$ 835,104.61 and 19,959,000.18 in a CDM context. As indicated in Table 7, the financial benefit in terms of CERs that can be obtained depends much on the ERs value and carbon credit value(s) that could be agreed upon after negotiations between the host country and the buyer country.

5. Conclusions

New strategies are being developed for bringing in higher GHG emissions reduction in landfill operations and in-situ aeration can be a potential technology towards this end. The aerated bioreactor landfill concept is a novel approach to sustainable waste management and thereby requires a preliminary assessment before its integration and adaptation, and in particular to the Mauritian context. In this study, the approved Baseline and Monitoring Methodology AM0083 of the UNFCCC/CCNUCC CDM, '*Avoidance of landfill gas emissions by in situ aeration of landfills*' was employed to assess the quantum of GHG emissions reduction from the potential implementation of a bioreactor landfill with in-situ aeration at the Mare Chicose landfill in Mauritius. The results of this study strongly advocate the merit of such a bioreactor design in the landfill as regards an improved environmental performance with very high GHG emissions reductions. Aeration systems in landfill may be hence expected to effectively contribute to climate protecttion. However, the potential of integrating an aerated bioreactor landfill in Mauritius may be economically difficult in the beginning. New financial drivers from developed countries can here be of help in supporting and providing the necessary financial incentives primarily in the form of carbon credit trading which can considerably aid in the establishment of such project in developing countries like Mauritius. Such financial assistance would be secured most logically after the technical reliability and potential improvements in environmental stewardship of such major undertakings be demonstrated. The results of this study, in point of fact, strongly support the latter argument. Following the MPSA approach in analyzing the performance of the bioreactor landfill with aeration units, it has been found that an integrated and well designed aeration system would favor higher degradation rates of the wastes within a relatively shorter period of time with a net positive impact on the environment as a result of large reductions in emissions of GHGs as compared to the baseline operation, i.e. flaring of methane.

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