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TITLE:

LIFE-CYCLE ASSESSMENT OF MUNICIPAL SOLID WASTE MANAGEMENT ALTERNATIVES WITH CONSIDERATION OF UNCERTAINTY: SIWMS DEVELOPMENT AND APPLICATION.

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Abstract

This paper describes the development and application of the Stochastic Integrated Waste Management Simulator (SIWMS) model. SIWMS provides a detailed view of the environmental impacts and associated costs of municipal solid waste (MSW) management alternatives under conditions of uncertainty. The model follows a life-cycle inventory approach extended with compensatory systems to provide more equitable bases for comparing different alternatives. Economic performance is measured by the net present value. The model is verified against four publicly available models under deterministic conditions and then used to study the impact of uncertainty on Sydney's MSW management 'best practices'. Uncertainty has a significant effect on all impact categories. The greatest effect is observed in the global warming category where a reversal of impact direction is predicted. The reliability of the system is most sensitive to uncertainties in the waste processing and disposal. The results highlight the importance of incorporating uncertainty at all stages to better understand the behaviour of the MSW system.

Keywords: LCA, uncertainty, Municipal solid waste, Decision support

1. Introduction

Since the early nineties, researchers have come to realize the need for a dedicated decision support tool to aid waste managers and decision makers in the planning, design and selection of appropriate waste management strategies. Several models have since been developed. Early models such as SWAP (Ossenbrugen and Ossenbrugen, 1992), Chang and Wang (1996) and MacDonald (1996) have focused on cost analysis of the waste management alternatives. However, increased awareness of the need to estimate the environmental impacts of the solid waste system has paved the way for a new generation of models. For example, the SWIM system considers CO_2 emissions from the vehicles used to collect and transport the waste (Wang et al., 1996).

Earlier models have usually ignored the interaction between different processes and stages of the waste management system. However, by the late nineties, the concept of integrated waste management had gained popularity. Most recently, life cycle analysis (LCA) use in waste management modelling has emerged as an effective technique for accounting for the environmental burdens of the integrated waste system.

Several models based on LCA have since been developed. IWM (Haight, 2004), IWM-2 (McDougall et al., 2001), WARM (EPA, 2002), WASTED (Diaz and Warith, 2006), ISWM DST (Solano et al., 2002), ORWARE (Dalemo et al., 1997; Eriksson et al., 2002), WIZARD which was developed by Ecobilan and EASWASTE

(Hansen et al., 2006) are some of the most commonly mentioned models in the literature.

LCA modelling requires large amount of data, some of which are site specific. The quality of data will usually have great impact on the credibility of the model's output (Kaplan et al., 2005; Diaz and Warith; 2006, De Feo, Malvano, 2009). Therefore, calculating the environmental emissions based on deterministic estimates may lead to erroneous results. For example, two waste management alternatives may have similar greenhouse gas emissions (GHGE) under deterministic conditions. However, when considering conditions of uncertainty, one of the alternatives may emerge as a more robust solution. Kaplan et al. (2005) illustrated the use of Latin Hypercube Sampling (LHS) to extend the capability of ISWM DST to incorporate factors of uncertainty in the design of waste management systems. However, a limited set of parameters was considered in their uncertainty analysis. None of the other models which are publicly available provided a facility to directly incorporate uncertainty in the modelling exercise.

The objective of this article is to demonstrate the importance of systematically incorporating uncertainty at all stages when modelling municipal solid waste management (MSW) systems. The Stochastic Integrated Waste Management Simulator (SIWMS), a new integrated waste management model based on LCA methodology which allows a systematic consideration of uncertainty, is presented. The model is validated under deterministic conditions by comparing its results to four other models that are publicly available, and then is used to estimate the emissions from the 'best practices' of MSW management in metropolitan Sydney.

2. Model description

2.1. Model overview

SIWMS is designed to evaluate the effects of solid waste management alternatives, maximizing the flexibility of the model. It is capable of running 5 simultaneous waste management scenarios at a time. It allows the user to change most parameters to match their local conditions. It explicitly takes into consideration the effect of uncertainty on the robustness of the results.

SIWMS addresses the typical aspects of downstream MSW management starting from the moment a waste item enters the waste stream to the point of its ultimate disposal. It relies on process sub-models to calculate the emissions and energy consumption from each waste management operation.

SIWMS applies a streamlined life cycle inventory (LCI) approach, following waste from ‘cradle to grave’. A waste item is an input to the system from the point it is collected. It is then followed through the different processes it undergoes until it eventually exits the system as an output in the form of recovered material, refuse or destroyed material along with the energy consumed or produced at all stages (ISO, 2006). The system boundaries are further expanded by introducing upstream and downstream compensatory systems to account for displaced emissions that result from recycling and energy generation. This expansion allows the comparison of different alternatives to be made on more equitable baselines (Eriksson et al., 2002).

A brief description of the different sub-models follows.

2.2. Waste generation

Reliable predictions of the quantity and type of waste generated during the simulated period will improve the quality of the modelling exercise.

In our model, we calculate waste quantities generated throughout the simulation period based on a per capita generation rate allowing uncertainty in the population growth and waste generation rates. The following equations are used

$$WQ = Pop \times WGR \tag{1}$$

where

$$Pop = Pop_{initial} \times (1 + pgr)^n \tag{2}$$

$$WGR = WGR_{initial} \times (1 + wggr)^n \tag{3}$$

$$pgr = pgr_{\min} + (pgr_{\max} - pgr_{\min}) \times \Delta_{pgr} \tag{4}$$

$$wggr = wggr_{\min} + (wggr_{\max} - wggr_{\min}) \times \Delta_{wggr} \tag{5}$$

where

WQ: waste quantity.

Pop: population.

WGR: Waste generation rate.

$Pop_{initial}$: Initial population at the beginning of the first year.

pgr: annual population growth rate drawn from a restricted range between prg_{min} and prg_{max}.

$wggr$: Waste generation growth rate drawn randomly from a restricted range between $wggr_{min}$ and $wggr_{max}$.

n: year of simulation

Δ: randomly drawn sample from the probability density function

2.3. Solid waste collection

Two modes of collection are considered in our model; (a) separate collection of refuse and recyclables and (b) co-collection of refuse and recyclables.

Total travelled distance is estimated based on average collection route distance (d), collected waste quantity (WQ_i) and truck-load capacity as follows:

$$NTours_i = \frac{WQ_i}{TruckLoadCap_i} \quad (6)$$

$$D_i = NTours_i \times d_i \quad (7)$$

$$d_i = d_i^{\min} + (d_i^{\max} - d_i^{\min}) \times \Delta_{di} \quad (8)$$

d: the route distance drawn randomly from the restricted range between a lower and upper bounds.

i: stream of collection (e.g., recyclables, refuse, …etc).

The total distance *D* is used to calculate the total fuel consumption based on the vehicle fuel type and fuel consumption.

$$F_i = D_i \times f_i \quad (9)$$

F_i: amount of fuel (*l*) consumed by the collection trucks

f_i: average fuel consumption of the collection truck (*l/km*).

2.4. Transfer station and waste transport

SIWMS allows for two modes for transporting waste streams. First, direct delivery is made to the waste disposal or processing center. Second, collected waste is delivered to a transfer station, and then reloaded on transport trucks. To calculate the amount of fuel used by the transport trucks we use equation (9). The amount of energy consumed at the transfer station is estimated using the following equations:

$$E_{TS} = El_{TS} \times QW_{TS} \qquad (10)$$

$$F_{TS} = f_{TS} \times QW_{TS} \qquad (11)$$

where

El_{TS}: the electricity usage at the transfer station per Mg of waste received (*kWh/Mg*)

f_{TS}: the fuel consumption at the transfer station per Mg of waste received (*l/Mg*)

QW_{TS}: the amount of waste sent to transfer station (*Mg*)

However, due to the large variation in El_{TS} and f_{TS} published in the literature we calculate them as follows:

$$El_{TS} = El_{TS}^{\min} + (El_{TS}^{\max} - El_{TS}^{\min}) \times \Delta_{El} \qquad (12)$$

$$f_{TS} = f_{TS}^{\min} + (f_{TS}^{\max} - f_{TS}^{\min}) \times \Delta_{fTS} \qquad (13)$$

2.5. Recycling

Two options for recycling are considered: (a) source-separated recyclables and (b) co-mingled collection of recyclables.

Recyclables are either a) delivered to a material recovery facility (MRF) where different recyclables are separated, b) sorted according to their quality and prepared for shipping to the processor or c) sent directly to the processor.

Literature surveyed shows great variation in the fuel and energy consumption of MRF operations. To account for this, equations (10) through (13) are used to estimate the amount of energy and fuel consumed. Another source of uncertainty is the percentage of material captured and recovered for recycling. To accommodate the high level of variability we estimate the percentage as follows:

$$R_z = R_z^{\min} + (R_z^{\max} - R_z^{\min}) \times \Delta_z \qquad (14)$$

R_z: the percentage of material z recovered

R_z^{min}: the minimum expected recovery rate for material z

R_z^{max}: is the maximum expected recovery rate for material z, and

z = {Aluminum, Ferrous metals, Paper, Plastic, Glass}

The un-captured material is sent to landfills or incinerators depending on the waste management scenario.

Another source of uncertainty is the percentage of recycled material in the collected recyclables streams. This is important when calculating emission credits. The percentage of recycled material is estimated in a similar manner to equation (14).

Technology used for processing recyclable and virgin material is yet another contributor to uncertainty as the emissions will vary significantly (Merrild et al, 2008;

McMillan and Keoleian, 2009). To accommodate these variations, we allow the emission factors presented in tables 1-4 to change randomly by 10%.

2.5.1. Metals recycling

Aluminum and ferrous metals are the only metals available in quantities viable for recycling in MSW. Therefore, they are the only metals considered in our model. Emission factors used in our modeling exercise are presented in table 1.

2.5.2. Paper recycling

Paper enters the municipal solid waste stream in different forms (e.g., newspaper, cardboard, fine paper…etc.). Emission factors used for paper recycling are presented in table 2. However, a source of uncertainty is the credit awarded for carbon sequestration by trees; for more details, the Environmental Services Inc. (2009) presents a discussion on estimating the tree sequestration from tree planting efforts. Carbon sequestration credits are estimated as follows:

$$CO_2^{seq} = \min CO_2^{seq} + (\max CO_2^{seq} - \min CO_2^{seq}) \times rand \qquad (15)$$

2.5.3. Plastics recycling

Plastics found in MSW usually comprise a wide range of polymers. The most common form of plastics are the polyethylene in its different forms (HDPE, LDPE and LLDPE) and polyethylene terephthalate (PET). Other novel plastics such as polyvinyl chloride (PVC), polystyrene (PS) as well as other resins are also found in small quantities. The model allows the user to define the percentage of each plastic resin expected in the recycling stream. Table 3 presents the emission factors for each type of plastic.

2.5.4. Glass recycling

Glass enters the MSW mainly in the form of food containers and beverage bottles. Both coloured and clear glass are considered. The process of glass recycling is relatively simple. Collected glass is cleaned and sorted according to colours and then crushed for recycling. Emission factors for glass recycling are shown in table 4.

2.6. Composting

Composting is an aerobic biological process, in which the organic fraction is stabilized. As a result of the process, CO_2 will be released to the atmosphere. However, since it originates from biotic source, it does not add to the GHGE inventory. Moreover, the compost is usually reduced in volume and may have a sale value as a soil amendment. Nevertheless, the process requires energy input (EPA, 1994).

There are various methods of composting; however, they can be broadly classified into two classes: (a) windrow composting and (b) in-vessel composting. SIWMS consider only food waste, green waste and paper to be suitable for composting. Other waste streams are treated as non bio-degradable and therefore will not undergo aerobic degradation and will not reduce in volume. Hence, CO_2 emissions from the composting process are completely biotic. Emission factors for composting are presented in table 5.

Amlinger et al. (2008) reported a large variation in the CH_4 and NO_x emissions from composting facilities as shown in table 5. To account for this we estimate the emission factor, by randomly drawing a value between the lower and the upper limits reported. The amount of diesel consumed by in-vessel composting varies depending on the technology used. Therefore, we estimate the amount as being a random value between the lower and upper limits as presented in table 5.

2.7. Anaerobic digestion (AD)

Anaerobic digestion is a biological process in which micro-organisms decompose the organic fraction of the municipal solid waste in the absence of oxygen, producing biogas. Methane and carbon dioxide form the major portion of the biogas, other gases such as non-methane organic compounds and sulfur gases also form in small amounts.

The amount of available degradable carbon is a key factor in estimating the amount of CH_4 produced. To estimate the amount of organic carbon, we use the ultimate analysis of waste (table 6). Furthermore, to allow for seasonal variability in moisture content we estimate the moisture content of each waste fraction by randomly drawing a value in a restricted range between the lower limit of the dry period and the upper limit of the wet period as reported in the literature. Only food waste, green waste and paper are considered suitable for anaerobic digestion by SIWMS.

Total degradable carbon is estimated using the following equation

$$C_T = \sum (1 - MC_x) \times C_x \times W_x ,\ \ x = \{FW, GW, PprW\} \qquad (16)$$

MC_x: moisture content of the waste stream as described earlier

C_x: the percentage of carbon in the waste stream as in table 6.

W_x: Quantity of waste stream x in Mg

FW: food waste

GW: green waste

$PprW$: paper waste

However, not all degradable carbon is available for decomposition. Some of the carbon is locked up in complex cellular structures that are hard to bio-degrade. The biodegradation degree of organic waste during the typical residence time of waste in a bio-digestion reactor is in the range of 35% to 65% (Themelis and Ulloa, 2007). The proportion of carbon available for biodegradation is estimated as follows (Bingemer and Crutzen, 1987):

$$C_e / C_0 = 0.014T + 0.28 \tag{17}$$

where:

C_e / C_0: is the ratio of available carbon to the total biodegradable carbon

T: is the average temperature in ^{o}C.

Anaerobic digesters are operated at optimal temperatures in the mesophilic range between 35 and 37 ^{o}C or in the thermophilic range of 55 to 56 ^{o}C with the earlier range being more popular. Therefore, we estimate the actual temperature by randomly drawing a value within the operation range. If the digester is operated at the thermophilic range then it is assumed that 100% of the degradable carbon is available.

Themelis and Ulloa (2007) conducted an ultimate analysis and estimated the production of CH4 in the biogas under complete anaerobic biodigestion as 54%, assuming that the average molecular structure of organic waste is that of $C_6H_{10}O_4$. However, actual reported values range from 50-70% (Verma, 2002). Therefore, we estimate the percentage of CH4 in the biogas by random sampling from the reported range.

Anaerobic digesters are highly engineered units; nevertheless, some methane still escapes in the process. We assume methane capture efficiency to be between 98% and 99.9%. The calorific value of the biogas collected is often reported in the range of 30 – 55 GJ/Mg (Verma, 2002; Arena et al., 2003, Haight, 2005). Electricity generation efficiencies of between 20% and 30% are commonly reported in the literature (e.g., Haight, 2004; Haight, 2005; Diaz and Warith, 2006).

2.8. Incineration

Incineration is the controlled process of combusting MSW in an oxygen rich environment. The heat generated from the process can be used to generate power and/or to heat water for the purpose of district heating. Typical emissions from a waste incineration facility are listed in table 7. As evident from table 7, the range for the emission factor of incineration is wide.

In order to estimate the GHGE from an incinerator we use the ultimate analysis method to calculate the amount of carbon available for combustion. All carbon from plastic is considered non-biotic and textiles usually contain between 5% to 25% synthetic material of hydrocarbon origin. The ‘Other’ waste stream is composed of a wide range of waste material of both organic and non-organic origins (e.g., nappies, rubber, dirt, ash … etc). While it is difficult to give an accurate estimate of the amount of organic carbon present in this waste stream we assume that it is in the range of 15% to 35% with the rest being anthropogenic.

The calorific value of different waste streams depends on its moisture content and actual composition. Typical ranges for each stream are presented in table 8. The electricity generation efficiency is another contributing factor of uncertainty with reported rates between 18% and 35% found in the literature; however, the actual energy recovery rate depends on the local circumstances such as the incinerator technology and generation; co-combusting of waste along with other fuel; air/fuel mixture... etc. (Hackl and Mauschitz, 2008). The above mentioned range is used as the default values in SIWMS. Nevertheless, SIWMS allows the user to modify these values to match the expected energy generation efficiency of the incinerator being designed.

2.9. Landfilling

Landfilling is the most common practice of MSW management. Modern landfills are highly engineered facilities that are specifically designed to stabilize the waste and minimize its hazards to the public. Several countries around the world have issued directives to minimize the amount of waste sent to landfills. Nevertheless, it is impossible to eliminate the need for landfills because some materials are thermodynamically impossible to recycle (Diaz and Warith, 2006).

The starting point of the landfill module is waste characterization. This includes waste sent to landfill after collection including waste sent from transfer stations; MRF residue; composting residue; incineration ash and slag as well as residue from anaerobic digestion.

Two types of landfills are considered in this model: traditional landfill and bio-reactor landfill.

A traditional landfill is one in which waste is entombed for the purpose of containment and stabilization. Under this category we consider two distinct types of landfilling practices: engineered lined landfill with landfill gas collection systems and landfill without gas collection.

A bio-reactor landfill is a highly engineered sanitary landfill designed to enhance the biodegradation of the biomass in the waste. This is typically achieved through recirculation of leachate to enhance the retention period of micro-organisms and to increase the moisture content of waste. This would typically lead to faster degradation of the biomass. Although, this will have no effect on the total amount of released biogas as LCA does not have temporal dimension; it will affect the amount of biogas recovered for electricity generation.

Themelis and Ulloa (2007) reported that the bulk of the landfill gas (LFG) is released within the first year with the rest being released over an extended period of time. To estimate the amount of LFG that can be collected for electricity generation, we calculate annual release of methane using the first degree decay equation (NPI, 2005):

$$Q_{CH} = L_0 \times R \times (e^{-kc} - e^{-kt}) \qquad (18)$$

where:

Q_{CH4}: methane generation rate at time t, m^3/yr

L_0: methane generation potential as calculated from the equations above (m^3/Mg of MSW)

R: annual amount of waste deposited in the landfill (Mg/yr) e: base log

k: methane generation rate constant, y^{-1}

c: time since landfill closure (0 if active)

t: time since the initial waste deposited (yr)

L_0 can be estimated using the ultimate analysis as described in the anaerobic digestion section. The methane content in the biogas is in the range of 40% to 60% (Hester and Harrison, 2002; Vesilind et al., 2002; Arena et al., 2003; Haight, 2005).

VOCs are a complex array of organic compounds that constitute up to 5% of the LFG; the amount released is highly dependent on the nature of the waste deposited, however they are estimated to be in the range of 520 – 2620 mg/Nm^3 of LFG (NPI, 2005; Diaz and Warith, 2006). Table 9 shows typical emission factors from a sanitary landfill. Methane collection efficiencies are in the range of 45% - 75% with the higher collection efficiencies usually achieved by bio-reactor landfills (NPI, 2005). Collected LFG can be either flared or used to generate electricity. In case of electricity generation, we assume that LFG is captured for electricity generation during the operational time of the landfill plus 10 years after closure. The remaining gas which is emitted after 10 years from closure up to 30 years is flared. LFG emitted beyond 30 years from closure is released to the atmosphere untreated. Electricity generation efficiency is assumed to be in the range of 20% - 30%. However, the user can adjust these parameters to better reflect their local conditions.

Table 10 shows typical emission factors from the combustion of LFG (NPI, 2005).

2.10. Economic module

The economic cost of the MSW alternatives play, of course, a vital role in the decision making process. There are different methods to estimate the cost of an environmental system; however, their review is beyond the scope of this paper. A review of different methods can be found on the National Oceanic and Atmospheric Administration website (NOAA, 2009). In our modeling exercise we use the net present value (NPV) of the system as a measurement of its economic performance. The costs and revenues calculated here do not take into consideration the 'total social cost' of the system as it is beyond the scope of the model. Nevertheless, in conjunction with the environmental impacts, NPV is a good estimate of the potential benefits/burdens of the system. A further and more detailed study of the 'total social cost' of the selected alternatives could be conducted at a later stage.

The system cost is calculated as the net present value of revenues less costs as follow:

$$SysCost = NPV(Cost - Revenue) \qquad (19)$$

where

$$Cost = f(FCC, FOC, OC, CC, PC) \qquad (20)$$

$$Revenue = f(CTR, ESR, RSR) \qquad (21)$$

FCC: Value of the facility's capital costs

FOC: Value of the facility's operational costs

OC: Value of the overheads and administration costs associated with the system.

CC: Value of the collection cost
PC: Value of the processing cost
CTR: Value of carbon trading revenue
ESR: Value of the electricity sale revenue
RSR: Value of recyclables sale revenue

3. Model Validation and Application

3.1. Model implementation

The model described above is implemented in a VBA Excel© program. First we validate the model by comparing its results under deterministic conditions with results obtained from the following models which are publically available: (a) WARM, (b) IWM, (3) IWM-2 and (4) WASTED.

3.2. Model limitations

The purpose of SIWMS is to provide engineers, researchers as well as decision makers with a tool to assess the potential environmental and economic impacts of MSW alternatives under conditions of uncertainty. However, SIWMS is not meant to be used as the sole tool in the decision-making process, nor does it aim to be as comprehensive as WRATE or EASWASTE. SIWMS is built on the principles of life cycle inventory; hence it carries all the limitations that come with LCI modeling such as the lack of temporal, social and spatial considerations. It is therefore, unable to determine the optimal waste management strategy. An optimal strategy depends on many factors beside the economic and environmental considerations such as geographic, social and political factors (Diaz and Warith, 2006). Furthermore, SIWMS does not apply a full LCA methodology to categories emissions. Although it tallies all emissions, it only employs the IPCC (2006) methodology to estimate the global warming potential of the modeled strategies.

3.3. Validation of the model

To validate the model we run SIWMS model without consideration of uncertainty. We estimate the GHGE, acidification and smog precursor pollutants release from the MSW management activity in Sydney for the coming 20 years. Best waste management practices in Sydney as described in table 11 are used in the modeling exercise. The following assumptions are made and used in all models:

(a) Garbage collection route 65 km long.
(b) Recyclables collection route 70 km long.
(c) All recycling and composting residue sent to landfill
(d) The distance of recycling /composting facility to landfill is 15 km.
(e) Diesel collection vehicles are used.
(f) Co-mingled collection of recyclables.
(g) Transfer stations are used for garbage collection only.
(h) Distance from transfer station to landfill is 45 km.
(i) Windrow composting is used.
(j) Electricity consumed is drawn from the main grid
(k) Surplus electricity produced by the system is sold to the main grid.

Unless otherwise stated, default values of each model are used.

Energy production in Sydney is heavily dependant on coal; table 14 describes the grid mix.

Figures 1, 2 and 3 show the results obtained from the modeling exercise. Fig.1 shows that IWM-2 gives the most conservative results followed by IWM while WARM gives the most optimistic results followed by WASTED. This is consistent with the findings of Diaz and Warith (2006). SIWMS estimates lie between WASTED and IWM.

Results were also compared for the acidification and smog precursor category. Since WARM only gives estimates of global warming potential; it is excluded at this stage.

All models followed the same general trend of predicting net avoided burdens in the acidification category. Once again, SIWMS predictions fell between WASTED (most optimistic) and IWM (most conservative) results.

Figure 3 shows that, although models differed significantly in estimating the amount of VOCs emissions; all models predicted the same trend of increased burdens. SIWMS and IWM were the most and the least conservative respectively. When considering particulate matter (PM), SIWMS agreed with WASTED and IWM-2 on a net avoided burdens and only IWM predicted an increased burden of PM.

Overall, the above comparisons show that SIWMS gives reasonable results well within the range of other models.

3.4. Estimated burdens under conditions of uncertainty

Having established the validity of the model, we now run SIWMS with 10000 simulations to estimate the emissions under uncertainty conditions. Table 12 shows the parameters used in the simulation.

Mean values of emissions for each pollutant are presented in fig 4, fig 5 and fig 6. Data analysis reveals that the results are widely scattered around their mean values. Therefore, mean values presented in the graphs are only indicative values for comparison. To obtain realistic estimates of credits/burdens for each pollutant, we perform a statistical analysis. We assume that a realistic estimate is a value with a likelihood of meeting or exceeding the credit value for the pollutant emission or meeting and not exceeding the estimated burden value 90% of the time. The results for each pollutant are presented in table 13.

Taking into account conditions of uncertainty has significant impacts on the modeling outcome in all categories, particularly the GWP category where a reversal of the impact direction is predicted. The model predicts that the system will result in a credit instead of an added burden. Despite the fact that the values are very widely spread around the mean, as evident from the standard deviation (3.70×10^6), 99.9% of the time a lesser amount of GHGE is predicted than that under deterministic conditions, with a 99.6% probability of the system resulting in a net credit in GHGE rather than an added burden. This is particularly important when estimating GHGE for the purpose of carbon trading credits. The results also highlight the importance of taking into consideration the ‘net energy saving’ as an effective measure of GHGE reduction rather than the ‘green electricity’ approach currently adopted by the federal government. As evident here, the bulk of the GWP impact reduction is not due to the high ‘green energy’ production, but rather to the avoided energy consumption resulting from recycling practices.

Acidification and smog precursors did not change their general trend. Nevertheless, the results obtained under deterministic conditions were optimistic compared to those under conditions of uncertainty. Further analysis show that there is 85.6% probability that the results obtained under deterministic conditions are over estimating the credits for NO_x, while SO_x credits have a 99.1 % probability of being overestimated. The probability of VOCs burdens exceeding the deterministic estimate is 98.8% and the probability of credits for PM being overestimated is 75.3%. This is not surprising given the fact that the energy grid in Sydney is highly dependent on coal-fired power plants. Therefore, an over-estimation of ‘green electricity’ production from the MSW system would lead to erroneous predictions of better performance in most impact categories as observed in the results.

Overall, the results above highlight the importance of a systematic consideration of uncertainty in both input and compensatory systems when assessing the impacts of waste management strategies.

3.5. Sensitivity analysis

In an effort to determine which component of the waste management system contributes most to the overall uncertainty, we divide the waste management system into four distinct sub-systems: a) collection and transport, b) waste composition, c) waste processing and disposal and d) compensatory system.

The waste collection and transport sub-system covers the processes of waste and recyclable collection, transfer station and long-haul transport of waste. The effect of uncertainty in parameters such as garbage and recyclables collection truck load, transport truck capacity, collection route distances and transfer station parameters are studied.

The waste composition sub-system determines the waste chemical and physical composition. The impact of uncertainty in carbon and moisture content, recycled material content, waste stream percentage of the total waste and waste generation rate are investigated.

Waste processing and disposal is the sub-system that covers recycling, landfilling and composting. The impact of uncertainty in recovery rate, LFG composition, LFG collection efficiency, methane oxidation rate, electricity generation efficiency, energy consumption in the process and process emissions are studied.

The compensatory sub-system deals with the downstream and upstream processes. Here we study the impact of uncertainty in electricity generation emissions, material production emissions, displaced energy sources as well as credits awarded for tree sequestration and carbon storage.

We run SIWMS 10000 simulations allowing the parameters of the sub-system under consideration to change randomly while the parameters of all other sub-systems are kept at default values. To compare the impact of uncertainties on the reliability of the whole system, we calculate the coefficient of variation (COV) for each emission resulting from each run. The results are presented in fig 7.

The results show that uncertainties in the waste processing and disposal sub-system have the highest impact on the reliability of the overall waste management strategy, followed by waste composition. Waste collection and transport uncertainties have the least impact .Uncertainties in the compensatory sub-system have significant impacts on certain emission such as GHGE, lead, acid gases and smog precursor while its impact on other emissions is negligible. This is mainly due to the nature of the electricity grid mix in Sydney.

4. Conclusions

A new flexible waste management decision support model based on LCA methodology that takes into consideration conditions of uncertainty has been introduced. The model has been successfully validated against four publicly available models under deterministic conditions. The model then has been used to demonstrate the effect of uncertainty on the results of waste management practices.

The analysis clearly shows the importance of taking into account the impact of uncertainty when performing LCA of waste management alternatives. Uncertainty conditions have highest impacts on GWP estimates. This could be particularly important when estimating the GHGE for the purpose of carbon trading and credits. The results also show that despite the high level of uncertainty, 'best waste management practices' as described in table 11 are likely to result in significant savings in avoided emissions in the GWP and acidification impact categories.

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Table 1.

Emission factors for metal recycling adapted from Haight (2004)

Emissions (kg/Mg)	**Al**		**Fe**	
	Virgin	**Recycled**	**Virgin**	**Recycled**
CO_2	5126	518	1820	595
CH_4	6.53	2.71	0.0097	1.29
NO_x	17.3	0.62	2.76	1.77
VOCs	24.5	0.3	0.23	0.02
SO_x	47.6	2.88	5.11	2.98
PM	10	0	1.31	7.22
Pb	10.0×10^{-3}	0.38	7.60×10^{-4}	6.59×10^{-4}
Energy (GJ/Mg)	140	11.7	25.2	9.4

Table 2.

Emission factors for paper recycling adapted from Haight (2004) and EPA (2002)

Emissions (kg/Mg)	**Virgin**	**Recycled**
CO_2	1304	-1300 to -2900
CH_4	0.02	0.01
NO_x	7.94	5.44
VOCs	6.86	23.89
SO_x	11.23	9.99
PM	4.89	3.25
Pb	$3.05x10^{-4}$	$2.69x10^{-4}$
Energy (GJ/Mg)	36.8	26.2

Table 3.

Emission factors for plastics adapted from Haight (2004) and EPA (2002)

Emissions (kg/Mg)	**PET**		**PE**		**PP**		**PS**		**PVC**	
	Virgin	Re	Virgin	Re	Virgin	Re	Virgin	Re	Virgin	Re
CO_2	2363	163	2400	163	2100	942	2200	942	2000	942
CH_4	25	0.016	28	0.016	28	0.016	24	0.016	22	0.016
NO_x	9.5	0.081	6.5	0.081	6.4	0.081	6.9	0.081	6.3	0.081
VOCs	7.2	6.95	7.8	6.95	7.7	6.95	5.9	6.95	5.8	6.95
SO_x	14	-	4.9	-	5.4	0	5.2	0	5.3	-
PM	4.6	-	1.5	-	1.7	0	2.4	0	1.4	-
Pb	-	-	-	-	-	-	-	-	-	-
Energy (GJ/Mg)	107.2	46.07	79.76	19.94	76.42	19.87	84.8	11.63	59.8	9.13

Table 4.

Emission factors from glass recycling (Haight, 2004)

Emissions (kg/Mg)	**Virgin**	**Recycled**
CO_2	632	278
CH_4	1.11	0.83
NO_x	2.73	1.69
VOCs	0.24	0.17
SO_x	4.37	3.11
PM	0.89	0.43
Pb	5.0×10^{-6}	1.15×10^{-6}
Hg	1.30×10^{-6}	3.00×10^{-7}
Cd	1.35×10^{-5}	2.95×10^{-6}
Energy (GJ/Mg)	14.1	9.4

Table 5.

Emission factors from composting adapted from Amlinger et al. (2008)

Emissions (kg/Mg)	**Windrow**	**In-Vessel**
CH_4	0.05 – 0.295	50% of windrow
NO_x	0.027 – 0.266	10% of windrow
VOCs	1.4	1.4
SO_x	n/a	n/a
CO_2	n/a	n/a
Pb	n/a	n/a
Hg	n/a	n/a
Cd	n/a	n/a
Electricity (GJ/Mg)	0	50.4
Diesel (l/Mg)	0.05	1.95 - 2.20

Table 6.

Typical chemical composition of each waste fraction adapted from Tchobanoglous et al. (1993), Pichtel (2005) and Reinhart (2006).

Waste fraction	**Carbon**	**Hydrogen**	**Oxygen**	**Nitrogen**	**Sulfur**	**Ash**
Food	48.0	6.4	37.6	2.6	0.4	5.0
Paper	43.5	6.0	44.0	0.3	0.2	6.0
Cardboard	44.0	5.9	44.6	0.3	0.2	5.0
Plastic	60.0	7.2	22.8	-	-	10.0
Textiles	55.0	6.6	61.2	4.6	0.15	2.5
Garden waste	47.8	6.0	38.0	3.4	0.3	4.5
Wood	49.5	6.0	42.7	0.2	0.1	1.5
Other (dirt, ash, etc.)	26.3	3.0	2.0	0.5	0.2	68.0

Table 7.

Typical emissions from municipal solid waste incinerator adapted from EPA (2000) and Porteous (2005).

Emission (kg/Mg)	**European mean**	**US EPA**
NO_x	0.162	2.134
VOCs	0.056	0.0275
SO_x	0.040	0.110
PM	0.012	0.385
Pb	-	2.0×10^{-5}
Cd	5.6×10^{-6}	2.2×10^{-4}
Hg	5.6×10^{-6}	2.59×10^{-3}
HCl	0.112	0.341
TCDD eq. (ng/Mg)	56	2255.00

Table 8.

Typical calorific values of waste adapted from Giugliano et al. (2008); Diaz and Warith (2006).

Waste fraction	**LHV (GJ/Mg)**
Organic waste	1.7 – 3.4
Paper and Cardboard	11.27
Wood	16.34
Plastic	22.82 – 33.5
Glass and inert material	-0.05 - 0
Metals	-0.05 – 0
Others	1.49

Table 9.

Typical emission factors from a sanitary landfill adapted from NPI (2005); Diaz and Warith (2006) and Arena et al. (2003).

Pollutant	**Emission factor (kg/Mg)**
CO	119
NO_x	107
VOCs (mg/Nm^3)	520 – 2620

Table 10.

Typical emission factors from combustion of LFG at sanitary landfill adapted from NPI (2005)

Emission factor (mg/ N m^3)	**Flaring**	**Electricity generation***
CO	12000	7500
NOx	650	4000
PM	270	770
VOC destruction (%)	90 - 99	94 – 99

* Internal combustion engine

Table 11.

Waste composition and best practices management scenario in Sydney

Waste stream	**Percentage (%wt)**	**Management practice**
Food waste	21	Landfill
Green waste	18	Composting
Paper	26	Recycling
Glass	11	Recycling
Film plastic	3.5	Landfill
Rigid plastic	3.6	Recycling
Textile	4	Landfill
Ferrous metals	2.5	Recycling
Aluminum	0.2	Recycling
Wood	1	Landfill
Others	9.2	Landfill

Table 12.

Parameter ranges used in the simulation

Parameter	**Unit**	**Range**
Population growth rate	%	0.7 – 1.0
Waste generation growth rate	%	(-0.3) – 0.5
Collection route length	km	60 - 70
Recyclables collection route length	km	70 - 85
Distance from MRF to LDF	km	10 - 20
Paper recycling recovery rate	%	40 – 60
Recycled material in paper stream	%	20 – 30
Tree sequestration credit	kg CO_2	(-1308) – (-2900)
Glass recovery rate	%	35 - 54
Recycled material in glass	%	5 - 10
Aluminum recovery rate	%	85 – 98
Recycled material in Aluminum	%	10 – 20
Ferrous metal recovery rate	%	70 – 90
Recycled material in ferrous metal	%	10 – 20
Plastic recovery rate	%	30 – 50
Recycled material in plastic	%	20 – 25
MRF electricity consumption	kWh/Mg	25 – 35
Collection truck fuel consumption	l/km	0.7 – 0.9
Composting facility fuel consumption	l/Mg	0.05 – 0.08
Compost residue	%	5.0 – 9.0

CH_4 emissions from composting	kg/Mg	0.05 – 0.295
NO_x emissions from composting	kg/Mg	0.027 – 0.266
Compost yield	kg/Mg	400 – 600
Food waste moisture content	%	65 – 75
Green waste moisture content	%	40 – 60
Paper waste moisture content	%	4 – 30
‘Others’ waste stream moisture content	%	10 - 30
‘Others’ waste stream biogenic carbon content	%	10 – 20
Methane generation rate constant (k)	yr^{-1}	0.04 – 0.058
LFG collection efficiency	%	50 – 75
LFG methane content	%	40 – 60
Methane oxidation	%	5 - 10
LFG heat content	GJ/Mg	49 - 55
Landfill temperature	^oC	23 – 28
Electricity generation efficiency from biogas	%	20 – 30

Table 13.

Values corresponding to 90% cumulative frequency vs. values obtained under deterministic conditions for each pollutant.

Category	Value corresponding to 90% cumulative frequency	Deterministic value
GHGE	-3.41×10^{6}	1.96×10^{6}
NO_x	-8.93×10^{3}	-1.34×10^{4}
SO_x	-1.27×10^{4}	-2.49×10^{4}
VOCs	9.89×10^{4}	5.62×10^{4}
PM	-3.35×10^{2}	-1.48×10^{3}

Table 14

Electricity grid mix in NSW adapted from DECC (2006)

Source	Percentage (%)
Coal	90.5
Gas	1.40
Renewable	1.30
Hydro	6.8

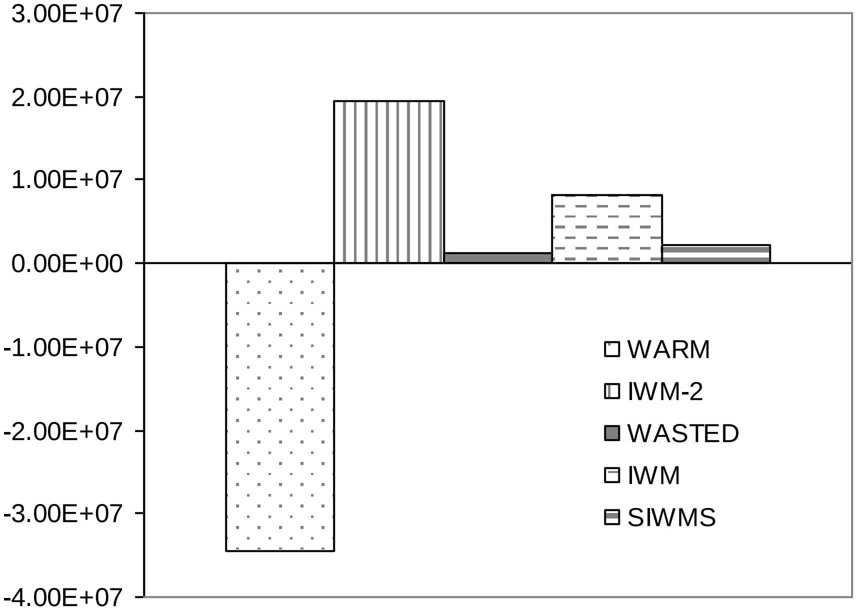
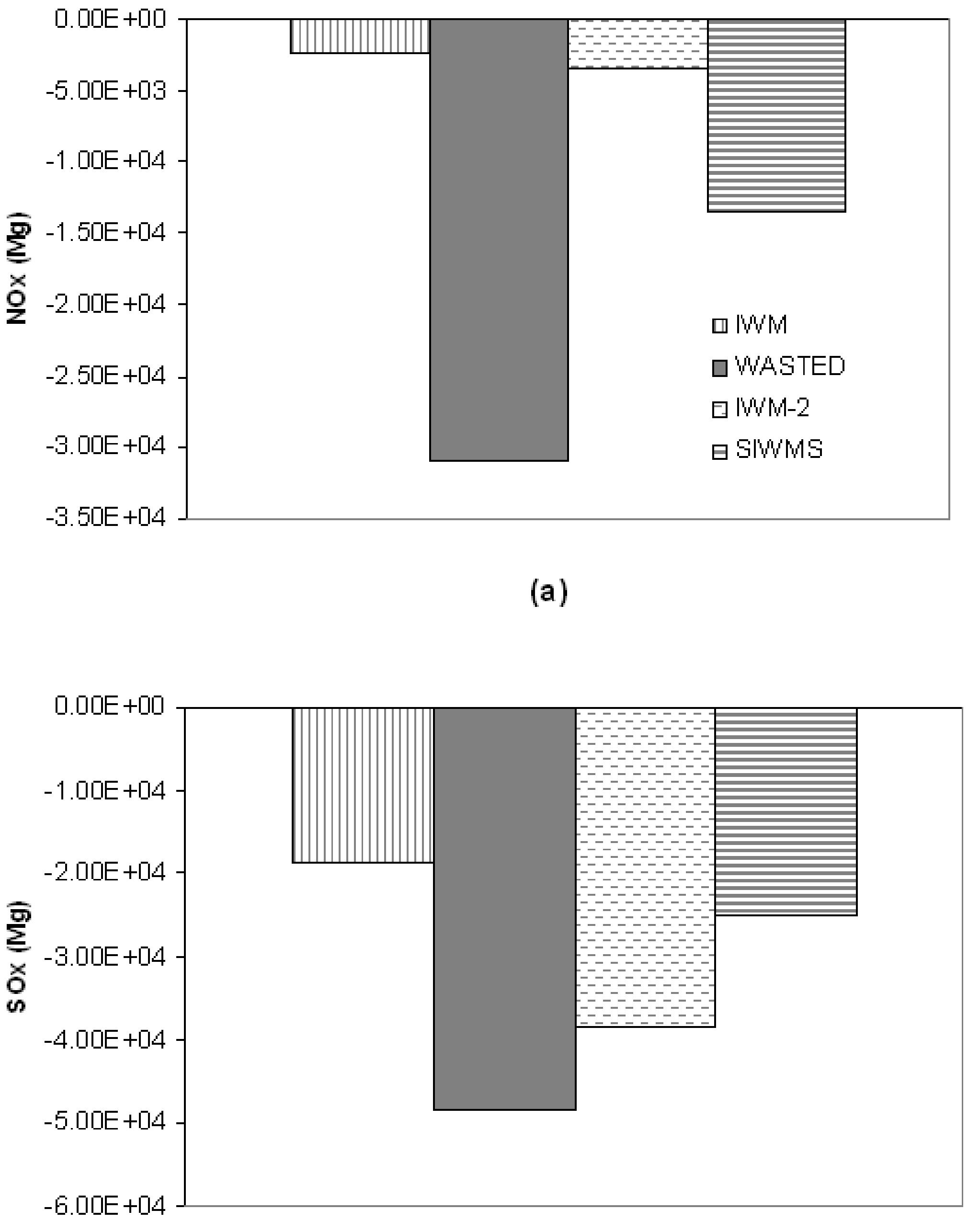


Fig. 1. GHGE (Mg CO_2 equivalent) predicted by different models.



(a)

(b)

Fig. 2. Acidification emissions as predicted by different models.

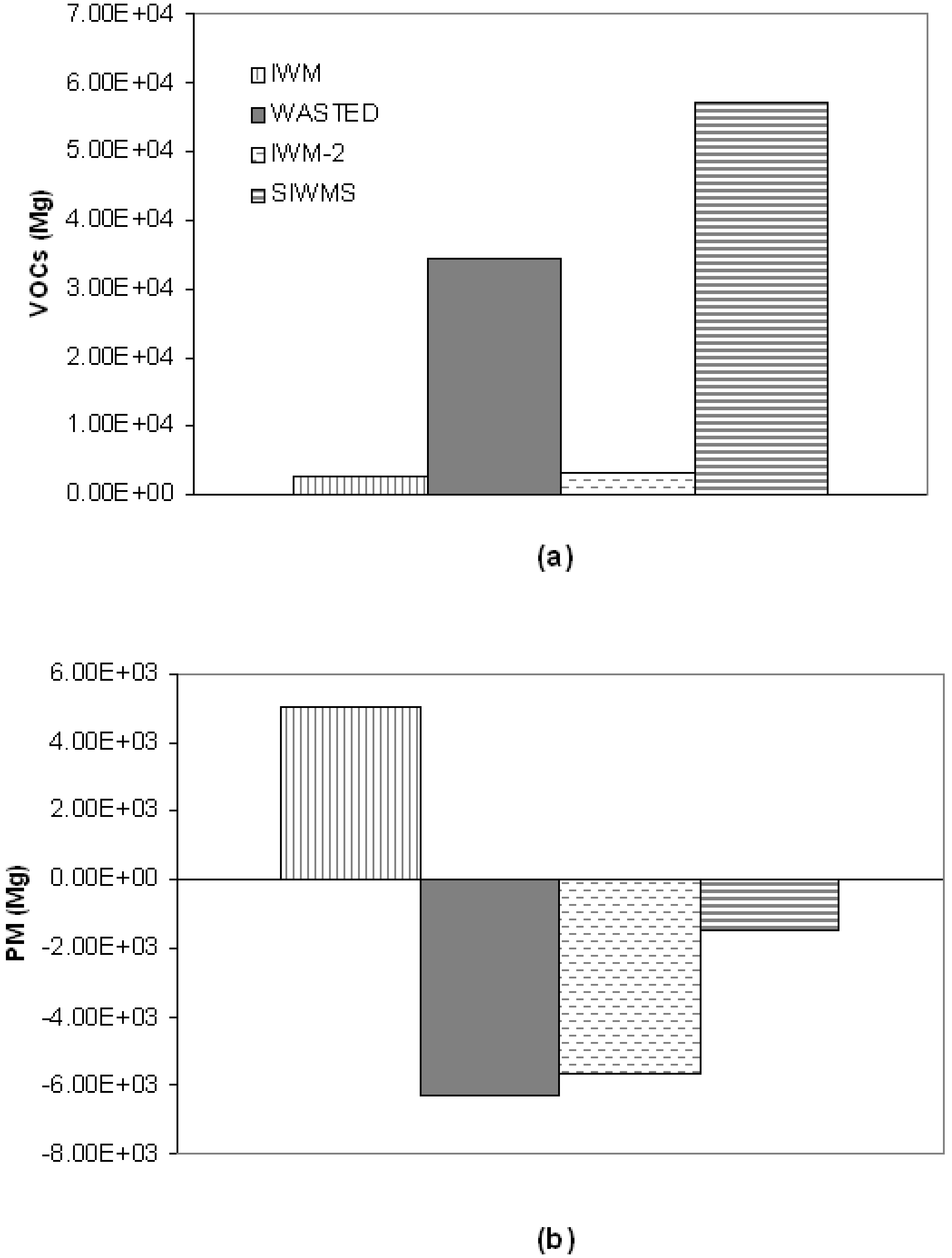


Fig. 3. Smog precursors as predicted by different models.

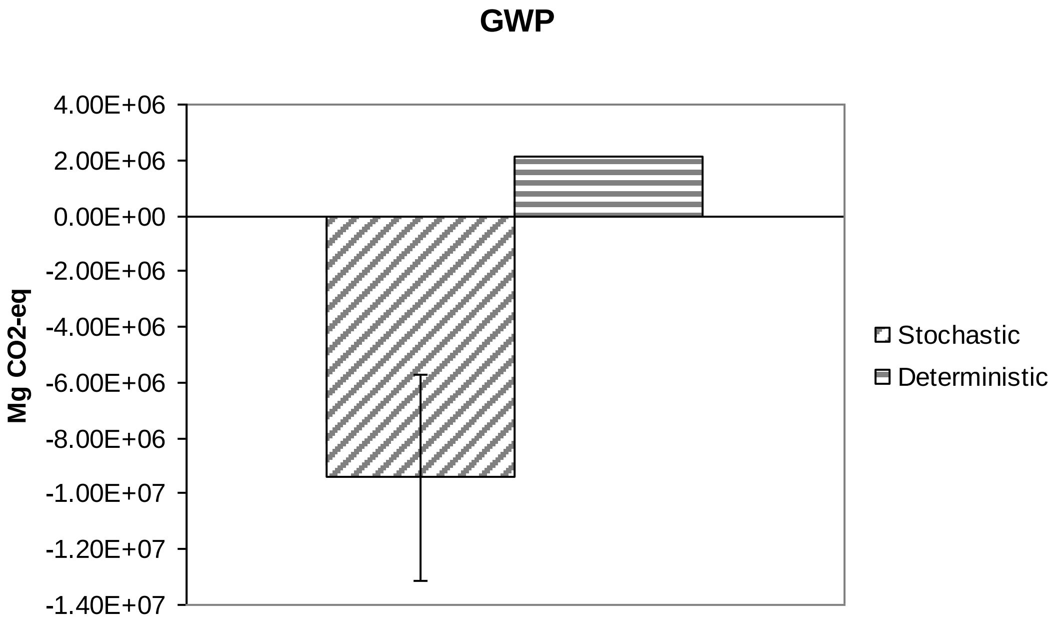


Fig. 4. Mean value of GHGE as estimated by SIWMS.

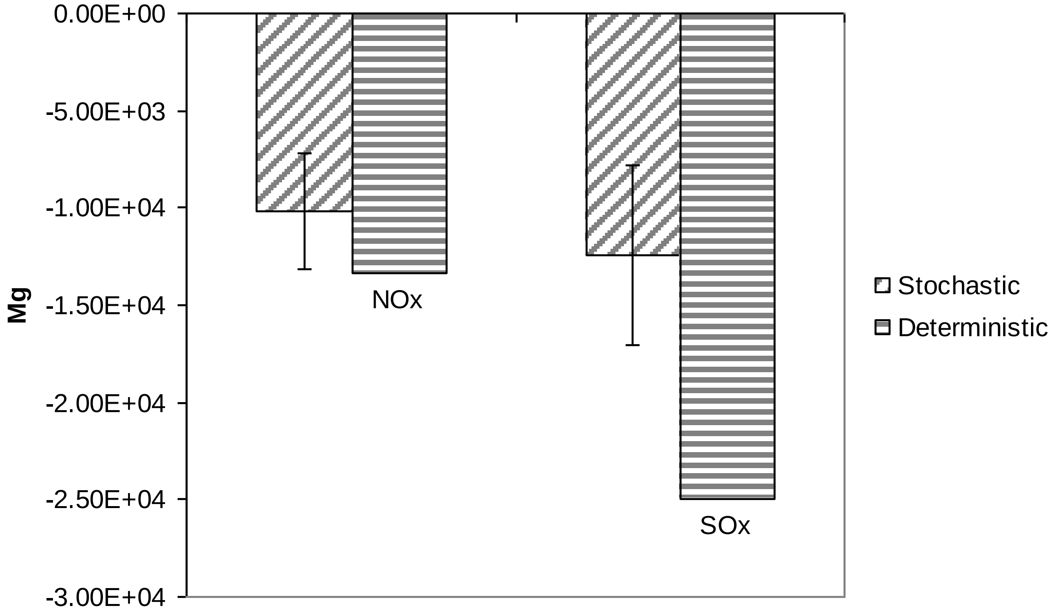
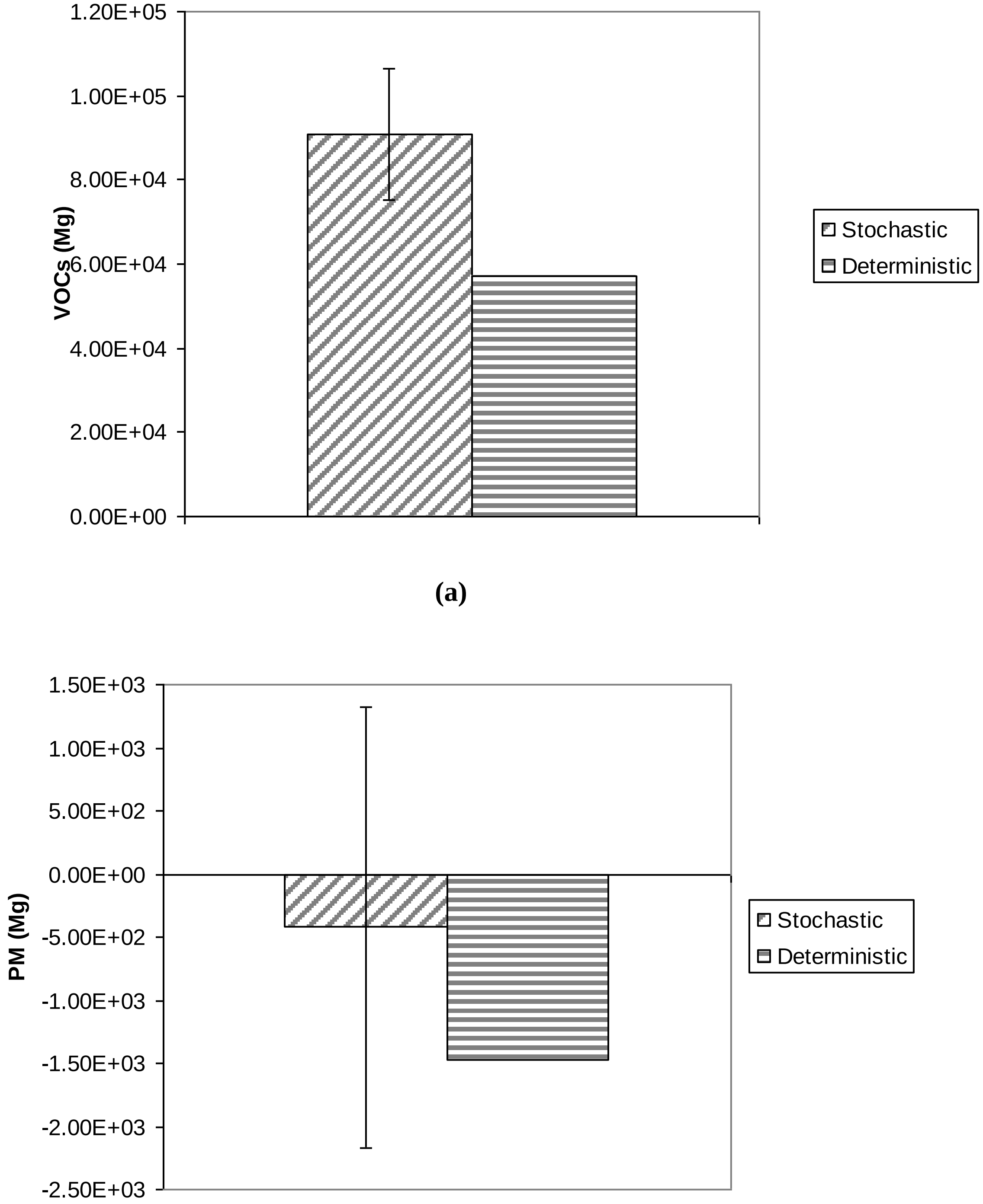


Fig. 5. Mean values of acidification burdens as predicted by SIWMS.



(a)

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Fig. 6. Mean values of smog precursors as estimated by SIWMS.

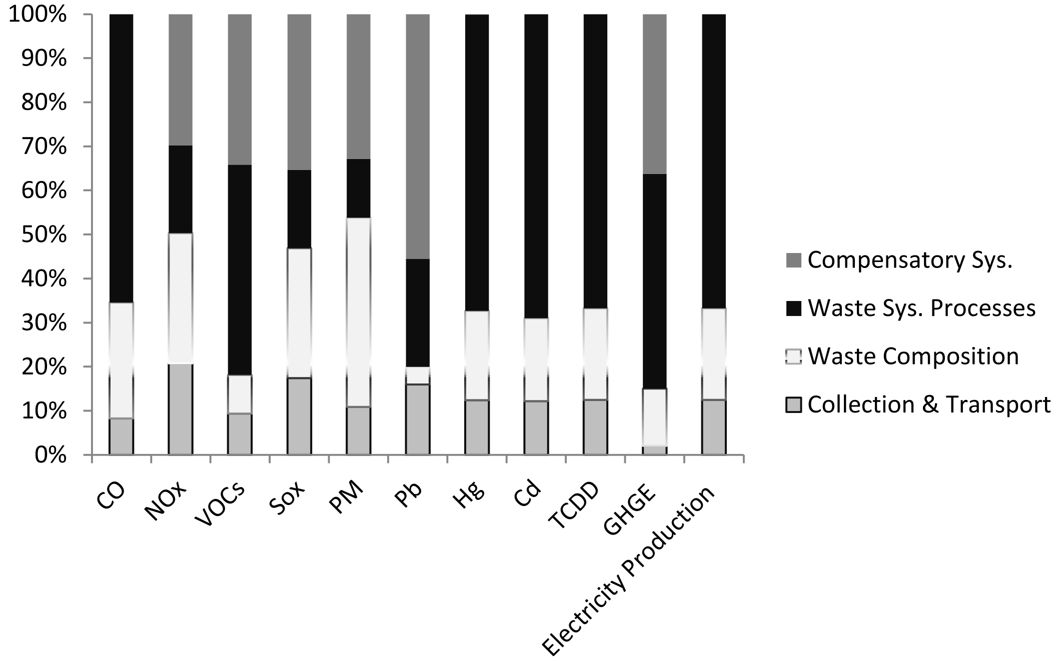

Fig 7. Impact of uncertainty of different sub-systems on the overall reliability of the waste management system measured by the coefficient of variation (COV) for each pollutant