



**Life-cycle assessment of municipal solid waste management alternatives with consideration of uncertainty: SIWMS development and application**

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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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1 **Abstract**

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

16

17 **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<sub>2</sub> 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

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

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

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

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## 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

$$WQ = Pop \times WGR \quad (1)$$

where

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

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

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

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

where

*WQ*: waste quantity.

*Pop*: population.

*WGR*: Waste generation rate.

*Pop<sub>initial</sub>*: Initial population at the beginning of the first year.

*pgr*: annual population growth rate drawn from a restricted range between *pgr<sub>min</sub>* and *pgr<sub>max</sub>*.

*wggr*: Waste generation growth rate drawn randomly from a restricted range between *wggr<sub>min</sub>* and *wggr<sub>max</sub>*.

*n*: year of simulation

1  $\Delta$ : randomly drawn sample from the probability density function

2

### 3 2.3. Solid waste collection

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

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

$$8 \quad NTours_i = \frac{WQ_i}{TruckLoadCap_i} \quad (6)$$

$$9 \quad D_i = NTours_i \times d_i \quad (7)$$

$$10 \quad d_i = d_i^{\min} + (d_i^{\max} - d_i^{\min}) \times \Delta_{di} \quad (8)$$

11

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

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

15

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

18

$$19 \quad F_i = D_i \times f_i \quad (9)$$

20

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

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

1

## 2 2.4. Transfer station and waste transport

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

$$8 \quad E_{TS} = El_{TS} \times QW_{TS} \quad (10)$$

$$9 \quad F_{TS} = f_{TS} \times QW_{TS} \quad (11)$$

10 where

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

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

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

16

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

$$19 \quad El_{TS} = El_{TS}^{\min} + (El_{TS}^{\max} - El_{TS}^{\min}) \times \Delta_{El} \quad (12)$$

$$20 \quad f_{TS} = f_{TS}^{\min} + (f_{TS}^{\max} - f_{TS}^{\min}) \times \Delta_{fTS} \quad (13)$$

21

## 22 2.5. Recycling

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

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

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

$$11 \quad R_z = R_z^{\min} + (R_z^{\max} - R_z^{\min}) \times \Delta_z \quad (14)$$

12  $R_z$ : the percentage of material z recovered

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

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

15  $z = \{Aluminum, Ferrous\ metals, Paper, Plastic, Glass\}$

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

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

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

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

3

#### 4 2.5.1. Metals recycling

5 Aluminum and ferrous metals are the only metals available in quantities viable  
6 for recycling in MSW. Therefore, they are the only metals considered in our model.

7 Emission factors used in our modeling exercise are presented in table 1.

8

#### 9 2.5.2. Paper recycling

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

16

$$17 \quad CO_2^{seq} = \min CO_2^{seq} + (\max CO_2^{seq} - \min CO_2^{seq}) \times rand \quad (15)$$

18

#### 19 2.5.3. Plastics recycling

20 Plastics found in MSW usually comprise a wide range of polymers. The most  
21 common form of plastics are the polyethylene in its different forms (HDPE, LDPE and  
22 LLDPE) and polyethylene terephthalate (PET). Other novel plastics such as polyvinyl  
23 chloride (PVC), polystyrene (PS) as well as other resins are also found in small

1 quantities. The model allows the user to define the percentage of each plastic resin  
2 expected in the recycling stream. Table 3 presents the emission factors for each type of  
3 plastic.

4

#### 5 2.5.4. Glass recycling

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

10

#### 11 2.6. Composting

12 Composting is an aerobic biological process, in which the organic fraction is  
13 stabilized. As a result of the process, CO<sub>2</sub> will be released to the atmosphere. However,  
14 since it originates from biotic source, it does not add to the GHGE inventory. Moreover,  
15 the compost is usually reduced in volume and may have a sale value as a soil amendment.  
16 Nevertheless, the process requires energy input (EPA, 1994).

17 There are various methods of composting; however, they can be broadly classified  
18 into two classes: (a) windrow composting and (b) in-vessel composting. SIWMS  
19 consider only food waste, green waste and paper to be suitable for composting. Other  
20 waste streams are treated as non bio-degradable and therefore will not undergo aerobic  
21 degradation and will not reduce in volume. Hence, CO<sub>2</sub> emissions from the composting  
22 process are completely biotic. Emission factors for composting are presented in table 5.

1 Amlinger et al. (2008) reported a large variation in the CH<sub>4</sub> and NO<sub>x</sub> emissions  
2 from composting facilities as shown in table 5. To account for this we estimate the  
3 emission factor, by randomly drawing a value between the lower and the upper limits  
4 reported. The amount of diesel consumed by in-vessel composting varies depending on  
5 the technology used. Therefore, we estimate the amount as being a random value  
6 between the lower and upper limits as presented in table 5.

7

## 8 2.7. Anaerobic digestion (AD)

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

13 The amount of available degradable carbon is a key factor in estimating the  
14 amount of CH<sub>4</sub> produced. To estimate the amount of organic carbon, we use the ultimate  
15 analysis of waste (table 6). Furthermore, to allow for seasonal variability in moisture  
16 content we estimate the moisture content of each waste fraction by randomly drawing a  
17 value in a restricted range between the lower limit of the dry period and the upper limit of  
18 the wet period as reported in the literature. Only food waste, green waste and paper are  
19 considered suitable for anaerobic digestion by SIWMS.

20 Total degradable carbon is estimated using the following equation

$$21 \quad C_T = \sum (1 - MC_x) \times C_x \times W_x, \quad x = \{FW, GW, PprW\} \quad (16)$$

22  $MC_x$ : moisture content of the waste stream as described earlier

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

1  $W_x$ : Quantity of waste stream  $x$  in  $Mg$

2  $FW$ : food waste

3  $GW$ : green waste

4  $PprW$ : paper waste

5

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

$$12 \quad C_e / C_0 = 0.014T + 0.28 \quad (17)$$

13 where:

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

15  $T$ : is the average temperature in  $^{\circ}C$ .

16

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

22 Themelis and Ulloa (2007) conducted an ultimate analysis and estimated the  
23 production of  $CH_4$  in the biogas under complete anaerobic biodigestion as 54%,

1 assuming that the average molecular structure of organic waste is that of  $C_6H_{10}O_4$ .  
2 However, actual reported values range from 50-70% (Verma, 2002). Therefore, we  
3 estimate the percentage of CH<sub>4</sub> in the biogas by random sampling from the reported  
4 range.

5 Anaerobic digesters are highly engineered units; nevertheless, some methane still  
6 escapes in the process. We assume methane capture efficiency to be between 98% and  
7 99.9%. The calorific value of the biogas collected is often reported in the range of 30 –  
8 55 GJ/Mg (Verma, 2002; Arena et al., 2003, Haight, 2005). Electricity generation  
9 efficiencies of between 20% and 30% are commonly reported in the literature (e.g.,  
10 Haight, 2004; Haight, 2005; Diaz and Warith, 2006).

11

## 12 2.8. Incineration

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

18 In order to estimate the GHGE from an incinerator we use the ultimate analysis  
19 method to calculate the amount of carbon available for combustion. All carbon from  
20 plastic is considered non-biotic and textiles usually contain between 5% to 25% synthetic  
21 material of hydrocarbon origin. The ‘Other’ waste stream is composed of a wide range of  
22 waste material of both organic and non-organic origins (e.g., nappies, rubber, dirt, ash ...  
23 etc). While it is difficult to give an accurate estimate of the amount of organic carbon

1 present in this waste stream we assume that it is in the range of 15% to 35% with the rest  
2 being anthropogenic.

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

12

### 13         2.9. Landfilling

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

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

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

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

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

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

$$18 \quad Q_{CH_4} = L_0 \times R \times (e^{-kc} - e^{-kt}) \quad (18)$$

19 where:

20  $Q_{CH_4}$ : methane generation rate at time t, m<sup>3</sup>/yr

21  $L_0$ : methane generation potential as calculated from the equations above (m<sup>3</sup>/Mg  
22 of MSW)

23 R: annual amount of waste deposited in the landfill (Mg/yr)

- 1 e: base log
- 2 k: methane generation rate constant,  $y^{-1}$
- 3 c: time since landfill closure (0 if active)
- 4 t: time since the initial waste deposited (yr)

5

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

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

22 Table 10 shows typical emission factors from the combustion of LFG (NPI,  
23 2005).

1

2           2.10. Economic module

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

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

16           
$$SysCost = NPV(Cost - Revenue) \quad (19)$$

17           where

18           
$$Cost = f(FCC, FOC, OC, CC, PC) \quad (20)$$

19           
$$Revenue = f(CTR, ESR, RSR) \quad (21)$$

20           FCC: Value of the facility’s capital costs

21           FOC: Value of the facility’s operational costs

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

1 CC: Value of the collection cost  
2 PC: Value of the processing cost  
3 CTR: Value of carbon trading revenue  
4 ESR: Value of the electricity sale revenue  
5 RSR: Value of recyclables sale revenue

6

### 7 **3. Model Validation and Application**

#### 8 3.1. Model implementation

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

13

#### 14 3.2. Model limitations

15 The purpose of SIWMS is to provide engineers, researchers as well as decision  
16 makers with a tool to assess the potential environmental and economic impacts of MSW  
17 alternatives under conditions of uncertainty. However, SIWMS is not meant to be used  
18 as the sole tool in the decision-making process, nor does it aim to be as comprehensive as  
19 WRATE or EASWASTE. SIWMS is built on the principles of life cycle inventory;  
20 hence it carries all the limitations that come with LCI modeling such as the lack of  
21 temporal, social and spatial considerations. It is therefore, unable to determine the  
22 optimal waste management strategy. An optimal strategy depends on many factors  
23 beside the economic and environmental considerations such as geographic, social and

1 political factors (Diaz and Warith, 2006). Furthermore, SIWMS does not apply a full  
2 LCA methodology to categories emissions. Although it tallies all emissions, it only  
3 employs the IPCC (2006) methodology to estimate the global warming potential of the  
4 modeled strategies.

5

### 6 3.3. Validation of the model

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

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

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

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

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

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

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

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

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

20

21 3.4. Estimated burdens under conditions of uncertainty

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

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

12           Taking into account conditions of uncertainty has significant impacts on the  
13 modeling outcome in all categories, particularly the GWP category where a reversal of  
14 the impact direction is predicted. The model predicts that the system will result in a  
15 credit instead of an added burden. Despite the fact that the values are very widely spread  
16 around the mean, as evident from the standard deviation ( $3.70 \times 10^6$ ), 99.9% of the time a  
17 lesser amount of GHGE is predicted than that under deterministic conditions, with a  
18 99.6% probability of the system resulting in a net credit in GHGE rather than an added  
19 burden. This is particularly important when estimating GHGE for the purpose of carbon  
20 trading credits. The results also highlight the importance of taking into consideration the  
21 ‘net energy saving’ as an effective measure of GHGE reduction rather than the ‘green  
22 electricity’ approach currently adopted by the federal government. As evident here, the

1 bulk of the GWP impact reduction is not due to the high ‘green energy’ production, but  
2 rather to the avoided energy consumption resulting from recycling practices.

3           Acidification and smog precursors did not change their general trend.

4 Nevertheless, the results obtained under deterministic conditions were optimistic  
5 compared to those under conditions of uncertainty. Further analysis show that there is  
6 85.6% probability that the results obtained under deterministic conditions are over  
7 estimating the credits for NO<sub>x</sub>, while SO<sub>x</sub> credits have a 99.1 % probability of being  
8 overestimated. The probability of VOCs burdens exceeding the deterministic estimate is  
9 98.8% and the probability of credits for PM being overestimated is 75.3%. This is not  
10 surprising given the fact that the energy grid in Sydney is highly dependent on coal-fired  
11 power plants. Therefore, an over-estimation of ‘green electricity’ production from the  
12 MSW system would lead to erroneous predictions of better performance in most impact  
13 categories as observed in the results.

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

17

### 18           3.5. Sensitivity analysis

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

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

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

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

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

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

22           The results show that uncertainties in the waste processing and disposal sub-system have  
23 the highest impact on the reliability of the overall waste management strategy, followed

1 by waste composition. Waste collection and transport uncertainties have the least impact  
2 .Uncertainties in the compensatory sub-system have significant impacts on certain  
3 emission such as GHGE, lead, acid gases and smog precursor while its impact on other  
4 emissions is negligible. This is mainly due to the nature of the electricity grid mix in  
5 Sydney.

6

#### 7 **4. Conclusions**

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

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

20

21

## 1 References

- 2
- 3 Amlinger, F., Peyr, S., Cuhls, C., 2008. Green house gas emissions from composting  
4 and mechanical biological treatment. *Waste Management & Research* 26, 47-  
5 60.
- 6 Arrena, U., Mastellone, M. L., Perugini, F., 2003. The environmental performance of  
7 alternative solid waste management options: a life cycle assessment study.  
8 *Chemical Engineering Journal* 96, 207-222.
- 9 Bingemer, H. G., Crutzen, P.J., 1987. The production of methane from solid waste.  
10 *Journal of Geophysical Research* 92, 2181-2187.
- 11 Bjorklund, A., Dalemo, M., Sonesson, U., 1999. Evaluating a municipal waste  
12 management plan using ORWARE. *Journal of Cleaner Production* 4, 271-  
13 280.
- 14 De Feo, G., Malvano, C., The use of LCA in selecting the best MSW management  
15 system. *Waste Management* (2009), doi:10.1016/j.wasman.2008.12.021.
- 16 DECC (Department of Environment, Climate Change and Water), 2006. New South  
17 Wales State of the Environment Report (SoE 2006). Retrieved from  
18 <http://www.environment.nsw.gov.au/soe/soe2006/index.htm> (accessed on  
19 13/12/2009).
- 20 Diaz, R., Warith, M., 2006. Life-cycle assessment of municipal solid wastes:  
21 Development of WASTED model. *Waste Management* 26, 886-901.
- 22 Environmental Services, Inc., 2009. Sustainable harvest international study:  
23 Estimation of carbon sequestration potential from planting efforts. North  
24 Lawrence, Ohio 44666, USA.
- 25 EPA (US Environmental Protection Agency), 1994. Composting of yard trimmings  
26 and municipal solid waste. US Environmental Protection Agency, EPA530-R-  
27 94-003.
- 28 EPA (US Environmental Protection Agency), 2000. Standards of performance for  
29 new stationary sources and emissions guideline: Commercial and industrial  
30 solid waste incinerator units; final rule. US Environmental Protection Agency,  
31 Washington, DC.
- 32 Eriksson, O., Frostell, B., Bjorklund, A., Assefa, G., Sundqvist, J.-O., Granath, J.,  
33 Carlsson, M., Baky, A., Thyselius, L., 2002. ORWARE – a simulation tool  
34 for waste management. *Resources, Conservation and Recycling* 36, 287-307.
- 35 Giugliano, M., Grosso, L., Rigamonti, L., 2008. Energy recovery from municipal  
36 waste: A case study for a middle-sized Italian district. *Waste Management* 28,  
37 39-50.
- 38 Haarstrick, A., Mora-Naranjo, N., Meima, J., Hampel, D.C., 2004. Modeling  
39 anaerobic degradation in municipal landfills. *Environmental Engineering*  
40 *Science* 21, 471-484.
- 41 Hackl, A., Mauschwitz, G., 2008. Role of waste management with regard to climate  
42 protection: a case study. *Waste Management and Research* 26, 5-10.
- 43 Haight, M., 2004. Integrated solid waste management model and supporting technical  
44 documents. <http://www.iwm-model.uwaterloo.ca> (accessed on 10 March  
45 2009).

- 1 Haight, M., 2005. Assessing the environmental burdens of anaerobic digestion in  
2 comparison to alternative options for managing the biodegradable fraction of  
3 municipal solid wastes. *Water Science & Technology* 52, 533-559.
- 4 Hansen, T. L., Christensen, T. H., Schmidt, S., 2006. Environmental modelling of use  
5 of treated organic waste on agricultural land: a comparison of existing models  
6 for life cycle assessment of waste systems. *Waste Management Research* 24,  
7 141 - 152.
- 8 Hester, R.E.; Harrison, R.M. (editors), 2002. Environmental and health impact of  
9 solid waste Management activities. The Royal Society of Chemistry, Thomas  
10 Graham House, Science Park, Milton Road, Cambridge CB4 0WF, UK.  
11 Retrieved from [www.knovel.com](http://www.knovel.com) (accessed on 10/04/2009).
- 12 IPCC (Inter governmental panel on climate change), 2006. Guidelines for  
13 National Greenhouse Gas Inventories, Volume 1, General Guidance and  
14 Reporting. Retrieved from [http://www.ipcc-](http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol1.html)  
15 [nggip.iges.or.jp/public/2006gl/vol1.html](http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol1.html) (accessed on 24/08/2009).
- 16 ISO (International Organization for Standardization), 2006. ISO 14044.  
17 Environmental management: life cycle assessment; requirements and  
18 guidelines. International Organization for Standardization, Geneva,  
19 Switzerland.
- 20 Kaplan, P. O., Barlaz, M. A., Ranjithan, S. R., 2005. A procedure for life-cycle based  
21 solid waste management with consideration of uncertainty. *Journal of*  
22 *Industrial Ecology* 5, 155-172.
- 23 MacDonald, M. L., 1996. Multi-attribute spatial decision support system for solid  
24 waste planning. *Computers, Environment and Urban Systems* 20, 1-17.
- 25 McDougall, F., White, P. R., Franke, M., Hindle, P., 2001. Integrated solid waste  
26 management: A lifecycle inventory. Second edition. Oxford, UK: Blackwell  
27 Science.
- 28 McMillan, C. A., and Keoleian, G. A. 2009. Not all primary aluminum is created  
29 equal: Life cycle greenhouse gas emissions from 1990 to 2005. *Environmental*  
30 *Science and Technology* 43, 1571-1577
- 31 Merrild, H., Damgaard, A., & Christensen, T., 2008. Life cycle assessment of waste  
32 paper management: The importance of technology data and system boundaries  
33 in assessing recycling and incineration. *Resources, Conservation and*  
34 *Recycling* 52, 1391-1398.
- 35 NOAA (National Oceanic and Atmospheric Administration), 2009. Environmental  
36 valuation: <http://www.csc.noaa.gov/coastal/economics/envvaluation.htm>  
37 (accessed on 1/04/2009).
- 38 NPI (National Pollutant Inventory), 2005. Emission estimation technique manual for  
39 municipal solid waste (MSW) landfills, version 1.2. Environment Australia,  
40 Canberra, Australia.
- 41 Ossenbruggen, P. J., Ossenbruggen, P. C., 1992. SWAP: A computer package for  
42 solid waste management. *Computers, Environment and Urban Systems* 16,  
43 83-100.
- 44 Pichtel, J., 2005. Waste management practices: municipal, hazardous, and industrial.  
45 CRC Press. Retrieved from [http://books.google.com.au/books?id=vKW-](http://books.google.com.au/books?id=vKW-Imcs6FAC&pg=PA7&dq=chemical+composition+of+plastics+ultimate+analy)  
46 [Imcs6FAC&pg=PA7&dq=chemical+composition+of+plastics+ultimate+analy](http://books.google.com.au/books?id=vKW-Imcs6FAC&pg=PA7&dq=chemical+composition+of+plastics+ultimate+analy)

1                   sis&source=gbs\_selected\_pages&cad=0\_1#PPP1,M1 (accessed on  
2                   05/03/2009).

3       Porteous, A., 2005. Why energy from waste incineration is an essential component of  
4                   environmentally responsible waste management. *Waste Management* 25, 451-  
5                   459.

6       Reinhart, D., 2006. MSW Learning Tool. Retrieved from <http://msw.cecs.ucf.edu>  
7                   (accessed on 05/03/2009).

8       Solano, E., Ranjithan, R., Barlaz, M. A., Brill E. D., 2002. Life-cycle-based solid  
9                   waste management I: Model development. *Journal of Environmental*  
10                  *Engineering*, 981-992.

11       Tchobanoglous, G., Theisen, H., Vigil, S., 1993. *Integrated solid waste management*.  
12                  McGraw-Hill, New York.

13       Themelis, N. J., Ulloa, P. A., 2007. Methane generation in landfills. *Renewable*  
14                  *Energy* 32, 1243-1257.

15       Verma, S., 2002. Anaerobic digestion of biodegradable organics in municipal solid  
16                  wastes. Master of Science thesis. Department of Earth and Environmental  
17                  Engineering. Columbia University, New York. Retrieved from  
18                  <http://www.seas.columbia.edu/earth/vermathesis.pdf> (accessed on  
19                  10/04/2009).

20       Vesilind, P. A., Worrell, W., Reinhart, D., 2002. *Solid waste Engineering*.  
21                  BROOKS/COLE, 511 Forest Lodge Road, Pacific Grove, CA 93950, USA.

22       Wang, F. S., Richardson, A. J., Roddick, F. A., 1996. SWIM - a computer model for  
23                  solid waste integrated management. *Computers, Environment and Urban*  
24                  *Systems* 20, 233-246.

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26

1 **Table 1.**

2 Emission factors for metal recycling adapted from Haight (2004)

| Emissions (kg/Mg) | Al                    |          | Fe                    |                       |
|-------------------|-----------------------|----------|-----------------------|-----------------------|
|                   | Virgin                | Recycled | Virgin                | Recycled              |
| CO <sub>2</sub>   | 5126                  | 518      | 1820                  | 595                   |
| CH <sub>4</sub>   | 6.53                  | 2.71     | 0.0097                | 1.29                  |
| NO <sub>x</sub>   | 17.3                  | 0.62     | 2.76                  | 1.77                  |
| VOCs              | 24.5                  | 0.3      | 0.23                  | 0.02                  |
| SO <sub>x</sub>   | 47.6                  | 2.88     | 5.11                  | 2.98                  |
| PM                | 10                    | 0        | 1.31                  | 7.22                  |
| Pb                | 10.0x10 <sup>-3</sup> | 0.38     | 7.60x10 <sup>-4</sup> | 6.59x10 <sup>-4</sup> |
| Energy (GJ/Mg)    | 140                   | 11.7     | 25.2                  | 9.4                   |

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**Table 2.**

2

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

| <b>Emissions (kg/Mg)</b> | <b>Virgin</b>         | <b>Recycled</b>       |
|--------------------------|-----------------------|-----------------------|
| CO <sub>2</sub>          | 1304                  | -1300 to -2900        |
| CH <sub>4</sub>          | 0.02                  | 0.01                  |
| NO <sub>x</sub>          | 7.94                  | 5.44                  |
| VOCs                     | 6.86                  | 23.89                 |
| SO <sub>x</sub>          | 11.23                 | 9.99                  |
| PM                       | 4.89                  | 3.25                  |
| Pb                       | 3.05x10 <sup>-4</sup> | 2.69x10 <sup>-4</sup> |
| Energy (GJ/Mg)           | 36.8                  | 26.2                  |

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**Table 3.**

2

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

| Emissions (kg/Mg) | PET    |       | PE     |       | PP     |       | PS     |       | PVC    |       |
|-------------------|--------|-------|--------|-------|--------|-------|--------|-------|--------|-------|
|                   | Virgin | Re    |
| CO <sub>2</sub>   | 2363   | 163   | 2400   | 163   | 2100   | 942   | 2200   | 942   | 2000   | 942   |
| CH <sub>4</sub>   | 25     | 0.016 | 28     | 0.016 | 28     | 0.016 | 24     | 0.016 | 22     | 0.016 |
| NO <sub>x</sub>   | 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 <sub>x</sub>   | 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  |

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**Table 4.**

2

Emission factors from glass recycling (Haight, 2004)

| <b>Emissions (kg/Mg)</b> | <b>Virgin</b>         | <b>Recycled</b>       |
|--------------------------|-----------------------|-----------------------|
| CO <sub>2</sub>          | 632                   | 278                   |
| CH <sub>4</sub>          | 1.11                  | 0.83                  |
| NO <sub>x</sub>          | 2.73                  | 1.69                  |
| VOCs                     | 0.24                  | 0.17                  |
| SO <sub>x</sub>          | 4.37                  | 3.11                  |
| PM                       | 0.89                  | 0.43                  |
| Pb                       | 5.0x10 <sup>-6</sup>  | 1.15x10 <sup>-6</sup> |
| Hg                       | 1.30x10 <sup>-6</sup> | 3.00x10 <sup>-7</sup> |
| Cd                       | 1.35x10 <sup>-5</sup> | 2.95x10 <sup>-6</sup> |
| Energy (GJ/Mg)           | 14.1                  | 9.4                   |

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**Table 5.**

2

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

| <b>Emissions (kg/Mg)</b> | <b>Windrow</b> | <b>In-Vessel</b> |
|--------------------------|----------------|------------------|
| CH <sub>4</sub>          | 0.05 – 0.295   | 50% of windrow   |
| NO <sub>x</sub>          | 0.027 – 0.266  | 10% of windrow   |
| VOCs                     | 1.4            | 1.4              |
| SO <sub>x</sub>          | n/a            | n/a              |
| CO <sub>2</sub>          | 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      |

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**Table 6.**

2

Typical chemical composition of each waste fraction adapted from

3

Tchobanoglous et al. (1993), Pichtel (2005) and Reinhart (2006).

| <b>Waste fraction</b>   | <b>Carbon</b> | <b>Hydrogen</b> | <b>Oxygen</b> | <b>Nitrogen</b> | <b>Sulfur</b> | <b>Ash</b> |
|-------------------------|---------------|-----------------|---------------|-----------------|---------------|------------|
| 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       |

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1           **Table 7.**  
 2           Typical emissions from municipal solid waste incinerator adapted from EPA  
 3 (2000) and Porteous (2005).

| <b>Emission (kg/Mg)</b> | <b>European mean</b> | <b>US EPA</b>         |
|-------------------------|----------------------|-----------------------|
| NO <sub>x</sub>         | 0.162                | 2.134                 |
| VOCs                    | 0.056                | 0.0275                |
| SO <sub>x</sub>         | 0.040                | 0.110                 |
| PM                      | 0.012                | 0.385                 |
| Pb                      | -                    | $2.0 \times 10^{-5}$  |
| Cd                      | $5.6 \times 10^{-6}$ | $2.2 \times 10^{-4}$  |
| Hg                      | $5.6 \times 10^{-6}$ | $2.59 \times 10^{-3}$ |
| HCl                     | 0.112                | 0.341                 |
| TCDD eq. (ng/Mg)        | 56                   | 2255.00               |

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1           **Table 8.**

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

3           Warith (2006).

| <b>Waste fraction</b>    | <b>LHV (GJ/Mg)</b> |
|--------------------------|--------------------|
| 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               |

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**Table 9.**

2

Typical emission factors from a sanitary landfill adapted from NPI (2005); Diaz

3

and Warith (2006) and Arena et al. (2003).

| <b>Pollutant</b>           | <b>Emission factor (kg/Mg)</b> |
|----------------------------|--------------------------------|
| CO                         | 119                            |
| NO <sub>x</sub>            | 107                            |
| VOCs (mg/Nm <sup>3</sup> ) | 520 – 2620                     |

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**Table 10.**  
Typical emission factors from combustion of LFG at sanitary landfill adapted  
from NPI (2005)

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

\* Internal combustion engine

1

**Table 11.**

2

Waste composition and best practices management scenario in Sydney

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| <b>Waste stream</b> | <b>Percentage (%wt)</b> | <b>Management practice</b> |
|---------------------|-------------------------|----------------------------|
| 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                   |

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1           **Table 12.**  
 2           Parameter ranges used in the simulation

| <b>Parameter</b>                     | <b>Unit</b>        | <b>Range</b>      |
|--------------------------------------|--------------------|-------------------|
| 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 <sub>2</sub> | (-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 <sub>4</sub> emissions from composting     | kg/Mg            | 0.05 – 0.295  |
| NO <sub>x</sub> 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 <sup>-1</sup> | 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                          | °C               | 23 – 28       |
| Electricity generation efficiency from biogas | %                | 20 – 30       |

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1           **Table 13.**  
 2           Values corresponding to 90% cumulative frequency vs. values obtained under  
 3 deterministic conditions for each pollutant.

| <b>Category</b> | <b>Value corresponding to<br/>90% cumulative<br/>frequency</b> | <b>Deterministic<br/>value</b> |
|-----------------|--|--------------------------------|
| GHGE            | $-3.41 \times 10^6$  | $1.96 \times 10^6$             |
| NO <sub>x</sub> | $-8.93 \times 10^3$  | $-1.34 \times 10^4$            |
| SO <sub>x</sub> | $-1.27 \times 10^4$  | $-2.49 \times 10^4$            |
| VOCs            | $9.89 \times 10^4$   | $5.62 \times 10^4$             |
| PM              | $-3.35 \times 10^2$  | $-1.48 \times 10^3$            |

4  
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 6

1      **Table 14**

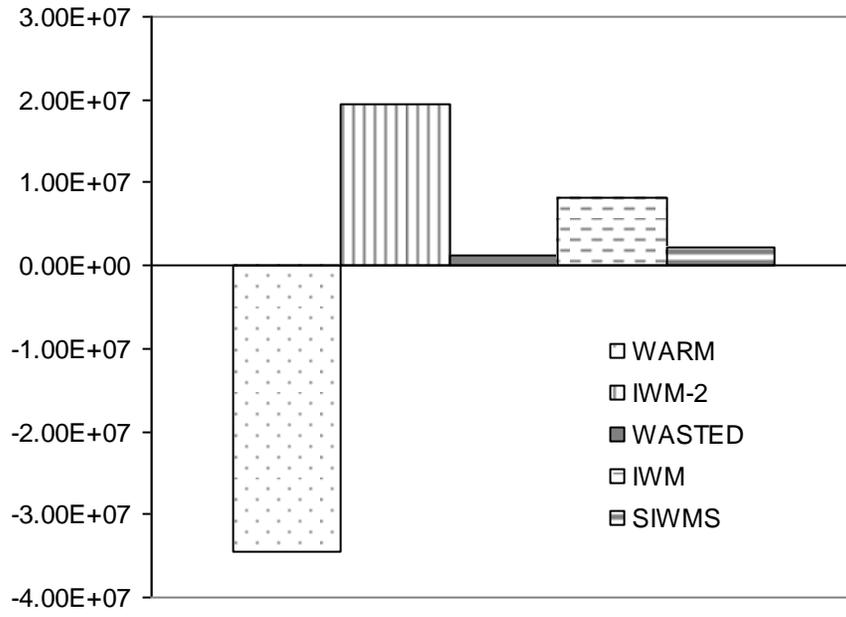
2      Electricity grid mix in NSW adapted from DECC (2006)

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

3

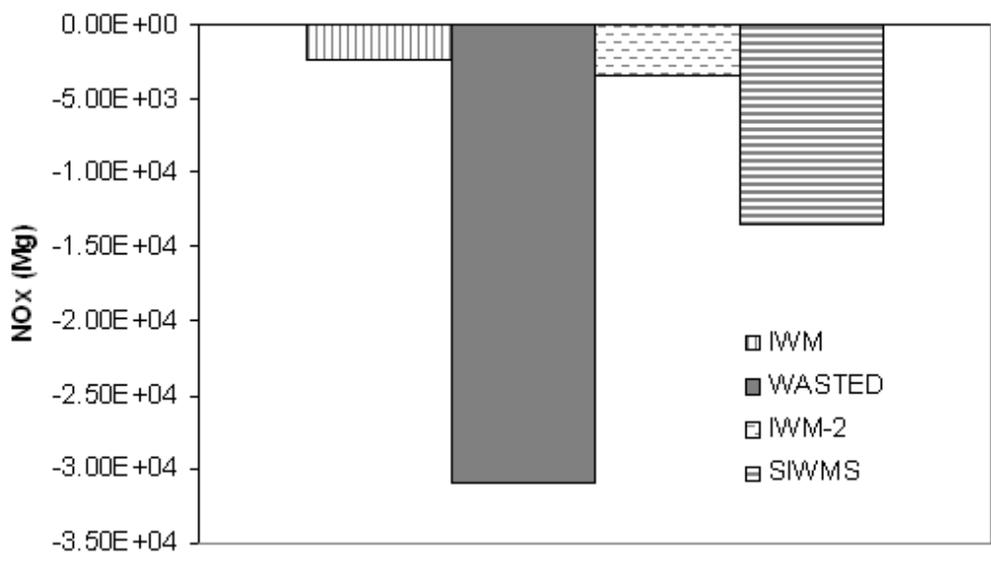
4

1

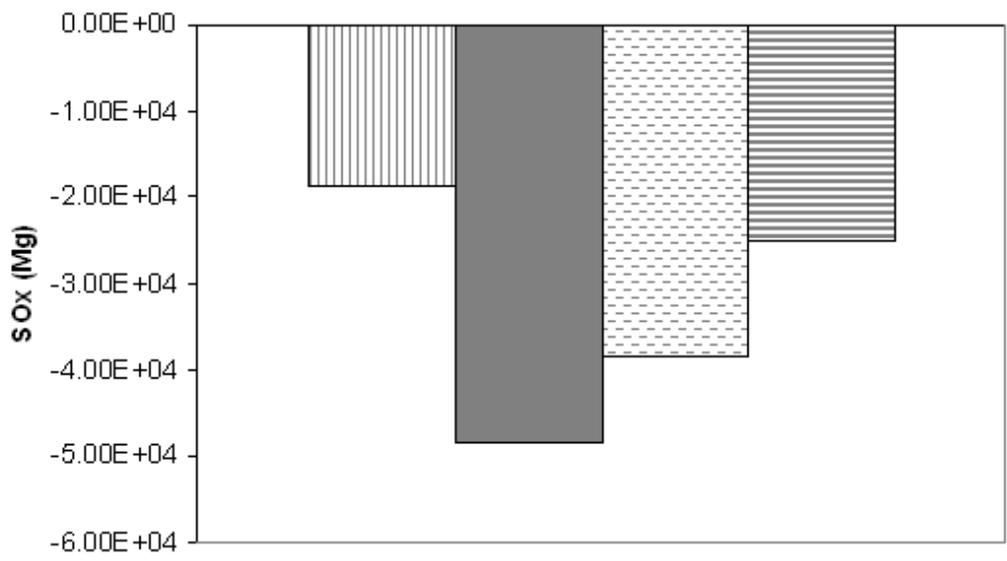


2

3 **Fig. 1.** GHGE (Mg CO<sub>2</sub> equivalent) predicted by different models.

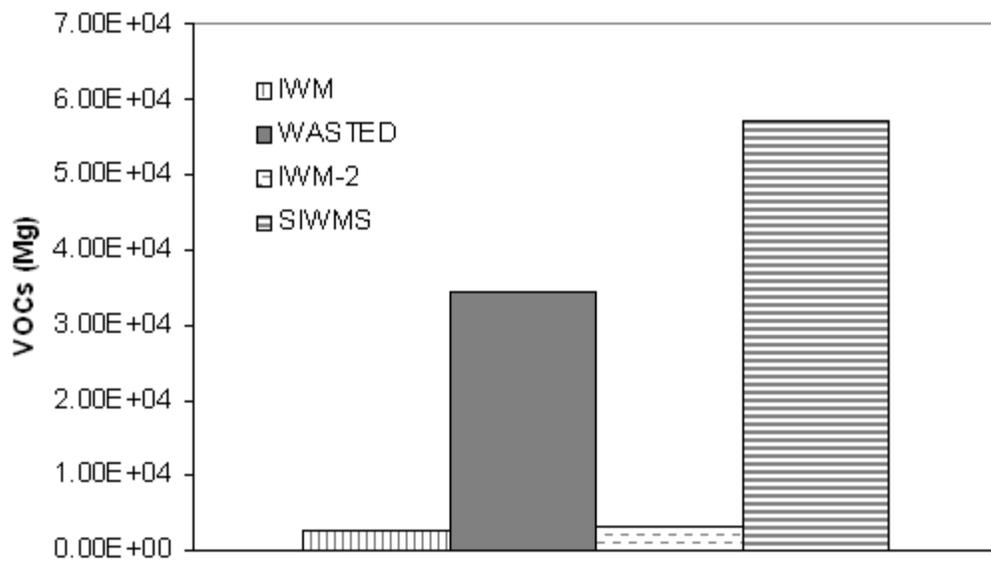


(a)

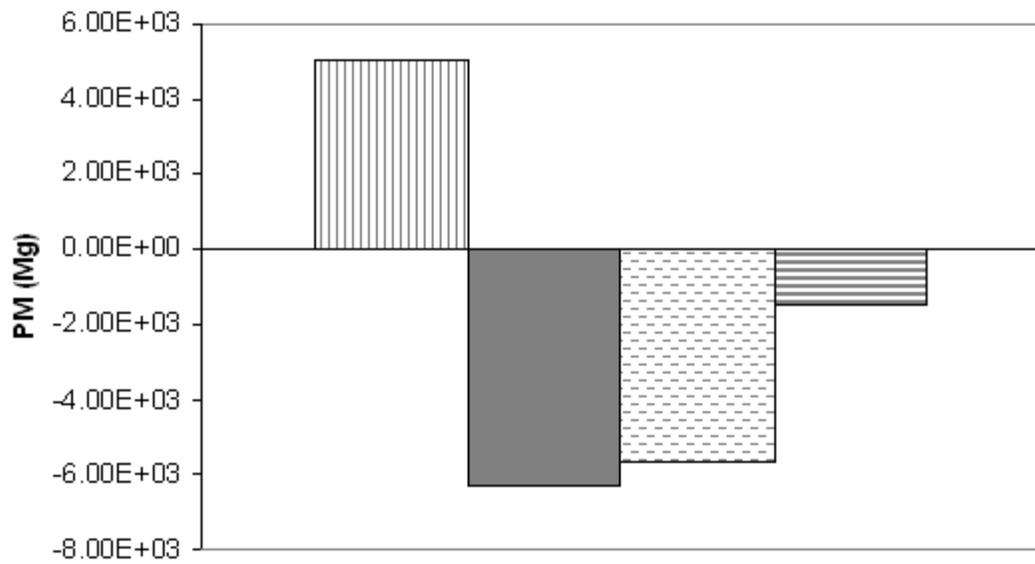


(b)

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

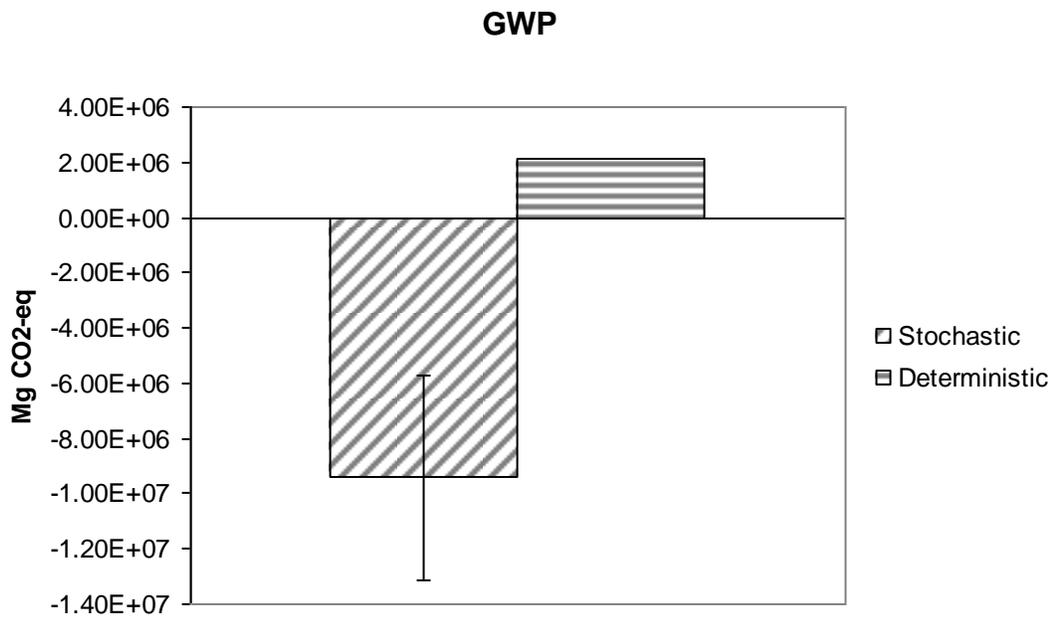


(a)

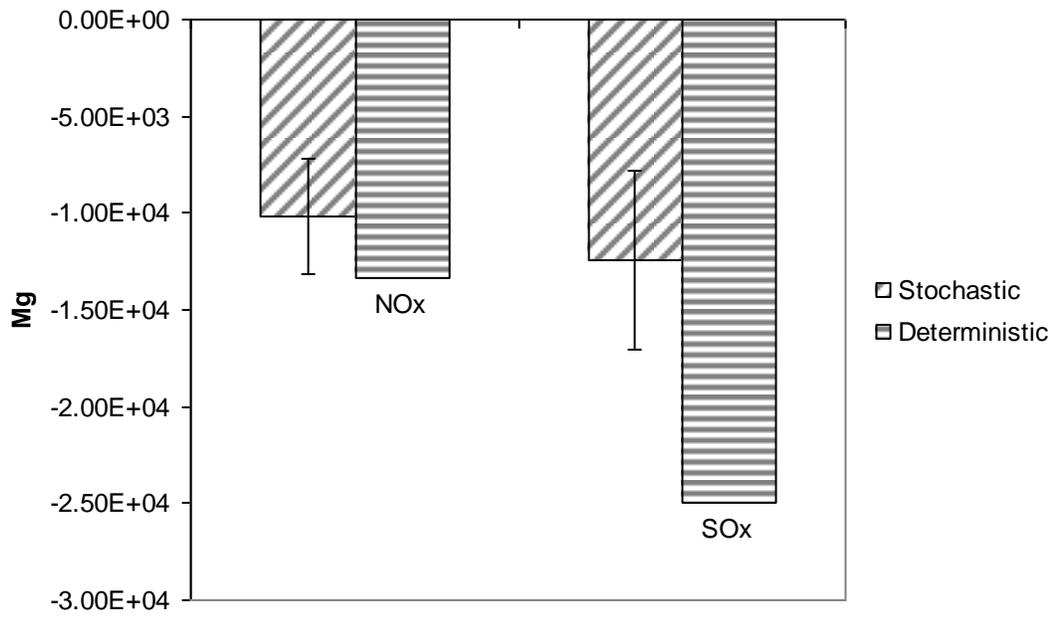


(b)

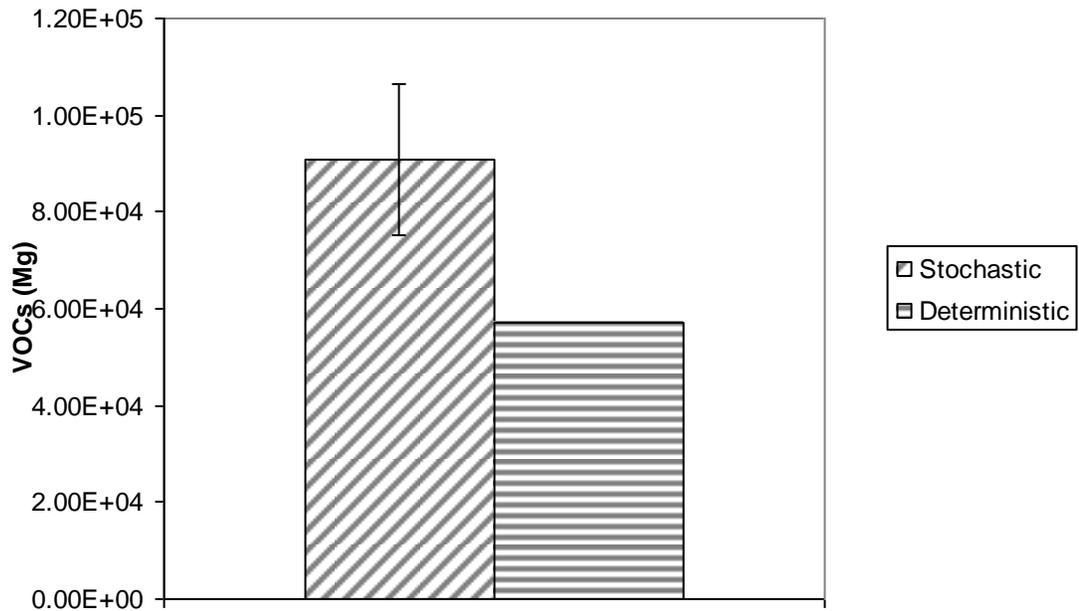
**Fig. 3.** Smog precursors as predicted by different models.



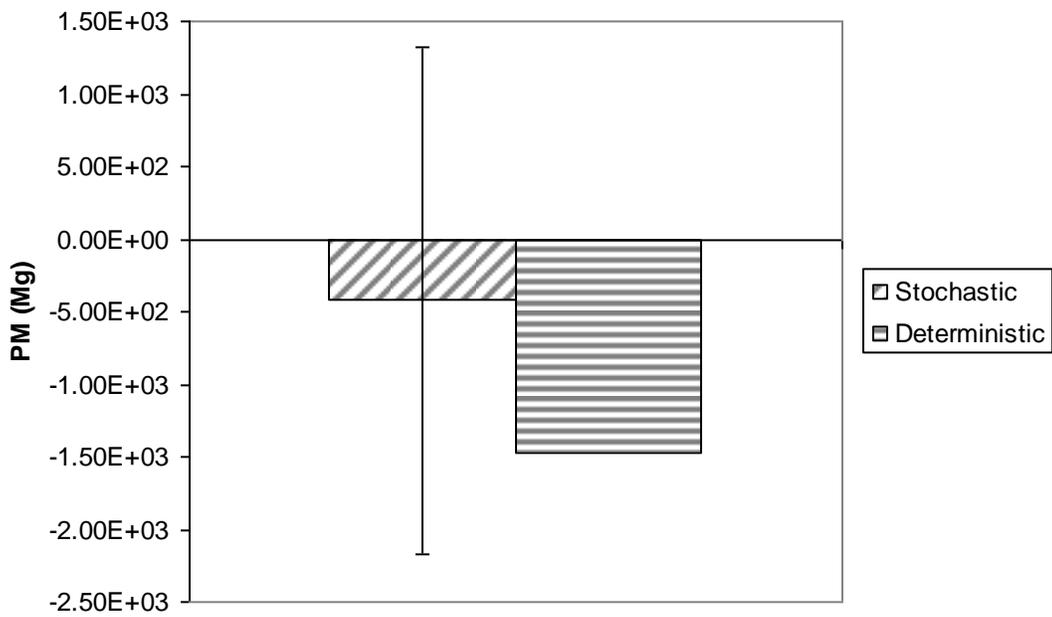
**Fig. 4.** Mean value of GHGE as estimated by SIWMS.



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



(a)



(b)

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

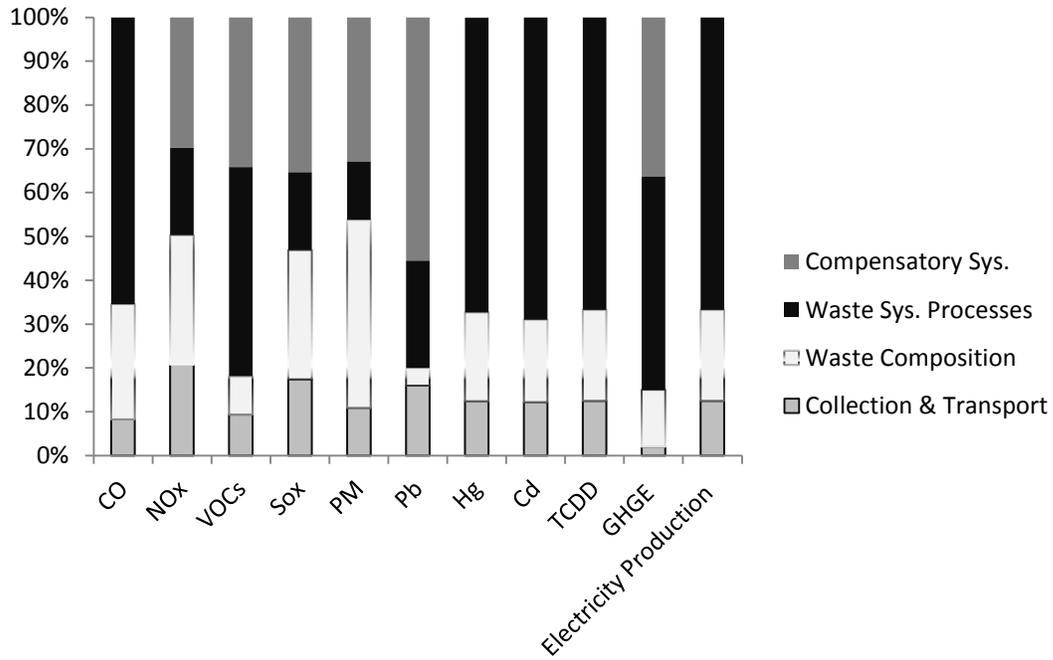


Fig 7. Impact of uncertainty of different sub-systems on the overall reliability of the waste management system measured by the coefficient of variation (COV) for each pollutant