1	Title:
2	Are the aims of increasing the share of green electricity generation and reducing GHG
3	emissions always compatible?
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## Abstract

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2 Energy from waste (EfW) has been identified as a source of 'green electricity' and has 3 been used as a way of reducing greenhouse gas (GHG) emissions. Nevertheless, selecting 4 an EfW strategy for municipal solid waste management is a challenging task not least 5 because of the uncertainty involved in quantifying the potential economic and environmental 6 impacts. This paper analyses five alternatives for managing the municipal solid waste of 7 Sydney for their 'green electricity' and GHG savings potential under conditions of 8 uncertainty. The impact of paper recycling on the ranking of alternatives was investigated, 9 too. Our analysis shows that maximizing EfW generation potential does not result in greater 10 GHG saving. A combination of food and green waste composting, recycling of metals, paper. 11 glass and plastics while only landfilling waste fractions that are not recyclable may result in the best GHG savings. Furthermore, recycling of paper does not always achieve the best 12 13 outcome; anaerobic digestion or composting may yield better results from an environmental and energy generation perspective. 14 15 16 **Keywords:** Energy from waste, green energy targets, LCA, Greenhouse gas emissions reduction, climate change. 17

## 1. Introduction

	2	1.1.	Background
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Life-cycle analysis (LCA) of municipal solid waste management practices is a powerful tool for assessing the overall environmental impact of these practices. However, LCA is a data-extensive exercise. The quality of data will usually have great impact on the credibility of the modelling output [1, 2, 3]. Inaccurate data, data gaps and unrepresentative data are sources of uncertainty in LCA [4].

The waste management sector accounts for about 3 - 5% of the GHG emissions worldwide [5]. Accounting for greenhouse gases (GHG) and other emissions from solid waste management practices has received increasing attention in the last few years [6]. New available technologies, if adopted properly, can contribute significantly to the mitigation of global warming. However, accounting for the global warming potential (GWP) of solid waste management is complicated due to inherent uncertainties in all stages of waste management processes such as transportation, system boundaries, upstream and downstream processes (e.g., [6 - 11]).

## 1.2. Waste generation in Sydney

Sydney is the largest metropolitan area in Australia with a total population of 4.1 million and an average population growth rate of 0.82% [12]. Sydneysiders are among the highest generators of solid waste in Australia. Each Sydneysider contributes on average 565 kg of municipal solid waste per year [13]. Table 1 shows the typical composition of waste in Sydney.

{Table 1 here}

- 1 The municipal solid waste of Sydney is highly dependent on landfills. However, landfill
- 2 space is fast diminishing and it is expected that within the next 10 years, the four landfills
- 3 close to the city will exhaust their capacity leaving the city with one landfill some 250 km
- 4 away [14]. This, combined with stringent criteria imposed on establishing new landfill sites,
- 5 targets set for diverting waste away from landfills and increased emphasis on climate
- 6 change, places pressure on the municipal solid waste system to explore new options.
- 7 Alternative waste technology (AWT), such as anaerobic digestion (AD), bioreactor landfill,
- 8 material recovery, composting, has gained popularity in the past few years.
- 9 Municipal solid waste contains a large biodegradable fraction and therefore is a good
- source of 'carbon neutral' energy. Energy from waste (EfW) has been identified as a source
- of renewable energy under the Renewable Energy Target scheme (RET) in Australia and
- 12 qualifies for Renewable Energy Certificates (REC) [15].
  - 1.3. Renewable Energy Target Scheme (RET)
- Australia derives most of its electricity from coal-fired power stations. These power
- stations contribute significantly to Australian greenhouse gas emissions. According to the
- 16 International Energy Agency, 0.89 kg CO<sub>2</sub>-equivellant is released per kWhe produced in
- 17 Australia [16]. In 2009, the Australian government implemented the Renewable Energy
- 18 Target scheme (RET) which is an extension of the Mandatory Renewable Energy Target
- 19 (MRET). The RET aims at reducing Australia's dependence on fossil fuel for electricity
- generation by increasing the share of electricity generation from renewable and green
- 21 sources to 20% by the year 2020. The scheme employs a mechanism for issuing
- 22 Renewable Energy Certificates (REC) to generators of 'green electricity'. Starting in 2011,
- the RET will be restructured under two main categories: the Small-scale Renewable Energy
- 24 Scheme (SRES) and the Large-scale Renewable Energy Target (LRET). A wide range of
- renewable sources has been identified under the scheme including solar, wind and energy
- 26 from waste [15].

- The purpose of this paper is to establish whether the focus on increasing the share of
- 2 green electricity generation as a strategy for reducing GHG emissions will always be optimal.
- 3 Clearly, competition for organic resources between waste management options affects the
- 4 EfW output. In particular, the impact of improved resource recovery rate on the
- 5 effectiveness of EfW as a greenhouse reduction measure will be assessed. LCA of five
- 6 different alternatives of EfW are compared for GHG savings potential taking into account the
- 7 inherent uncertainties in the municipal solid waste system. The case of Sydney is used in
- 8 this study but the results may be applicable to other countries with similar waste
- 9 composition.

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# 2. Methodology

# 11 2.1. LCA scope

- The functional unit for our study is one megagram (Mg) of municipal solid waste collected and delivered to the waste management facility(ies). GHG emissions that occur as a result of collection, transportation, handling of waste at transfer station and waste management facility, disposal and electricity generation are accounted for. GHG and electricity used in the manufacturing of collection and transportation vehicles, construction of the waste management and disposal facilities are not included in the inventory as they are usually insignificant [17]. Electricity presented is the net electricity generation after taking into account any electricity used onsite. In this study we assume that electricity generated displace electricity from the main grid.
- 21 2.2. Modeling
  - The SIWMS decision support tool is used to simulate the emissions from 5 alternatives for managing the municipal solid waste. SIWMS is an Excel© based program which employs life-cycle approach. It allows the modeller to incorporate uncertainty, through the implementation of Monte Carlo simulations, in almost all waste management parameters and is capable of running up to 5 scenarios simultaneously [11].

- 2.3. Waste management alternatives
- 2 Five waste management alternatives, described in table 2, are designed keeping in mind
- 3 the following three key objectives:
- 4 (a) increase green electricity generation;
- 5 (b) reduce greenhouse emissions from waste management activities;
- 6 (c) reduce landfilled waste.
- While designing the alternatives we kept in mind the currently available and socially
- 8 acceptable technologies. As a result, waste incineration has been excluded because it is not
- 9 a commonly used method for treating municipal solid waste in Australia. Alternative S0
- represents the current 'best practices'. The parameters of uncertainty used in this simulation
- are presented in table 3, a normal distribution is assumed.
- 12 {Table 2 here}

- 14 {Table 3 here}
  - 3. Results and discussion
- SIWMS was run 10,000 simulations using the parameters presented in table 3. To
- investigate the impact of higher paper recycling rates on the performance of alternatives,
- 18 SIWMS was rerun with the same parameters but varying the paper recycling rate to 55-80%
- 19 which is in par with the leading recycling rates in Europe. Results are presented in the
- 20 following sections.
- 3.1. Greenhouse gas emissions savings
- Figure 1 and figure 2 show the performance of the five alternatives in the greenhouse gas
- 23 saving criteria assuming the current recycling rates and higher paper recycling rates,
- respectively. The results show that regardless of the recycling rate value, composting of the
- organic components including paper is the better choice (S4). On the other hand,

- 1 alternatives that included recycling of paper (S2, S3) can realise less environmental benefits,
- 2 respectively. Anaerobic digestion of organics (S1) comes in the second place regardless of
- the recycling rate; however, higher paper recycling rate has significant impact on the 'current'
- 4 best practices' (S0). Table 4 shows the mean, standard deviation and coefficient of variation
- of each alternative with respect to GHG savings.
- 6 {figure 1 here}
- 7 {figure 2 here}
- 8 {Table 4 here}
- 9 3.2. Electricity generation
- The performances of the alternatives in term of the electricity generation potential at the
- current and higher recycling rates are shown in figures 3 and 4, respectively. S1 performs
- best and S3 performs the poorest, regardless of the paper recycling rates. In fact, recycling
- rates do not have effect on the ranking of the alternatives. Table 5 shows summary statistics
- of the performance of each alternative from electricity generation perspective.
- 15 {figure 3 here}
- 16 {figure 4 here}
- 17 {Table 5 here}
- 19 3.3. Discussion

- Our results show that the maximum avoided GWP does not always correspond to the
- 21 maximum electricity generation alternative as evident from figures 1 through 4 even when
- 22 displaced fossil fuel by 'green electricity' is accounted. This is a simple yet important
- observation especially that many policy makers focus on setting targets for 'green electricity'
- 24 as a way of reducing GWP impacts. A number of countries around the world have adopted
- 25 measures to increase 'green electricity' supply to comply with their commitments to Kyoto

1 protocol or to meet conditions for joining the EU. In Romania, for example, mandatory

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quotas and 'green electricity' certificates are used [28]. In Australia, renewable energy

3 certificates (RECs) through the Renewable Energy Target scheme (RET) are issued to

4 operators of 'green electricity' including energy from biogas such as landfill gas [29]. While it

is generally true that 'green electricity' will result in lower GHG emissions than electricity

generated from fossil fuel, the GHG emissions are more dependent on the total energy

savings. For example, in an LCA study, Morris [30] concluded that recycling will result in

lesser environmental burdens than landfilling or incineration even after considering the

displacement of energy that may be recovered. Bearing this in mind and considering the

global nature of GHG pollution, policy makers may consider setting targets for the total

energy savings of the system to better achieve their targets of reducing GHG emissions.

Our study confirms the benefits of recycling in general. However, under the conditions studied, the results show that recycling may not always be the optimal solution, especially in the case of paper, as evident from figures 1 and 3. The results further show that anaerobic digestion of organics, including paper, is a better option than the 'current best practices' option (S0) which is consistent with the findings reported by Haight [31] that anaerobic digestion of organics is likely to outperform landfilling in terms of GHG savings and energy generation. Bearing in mind that the scope of our study does not include possible land use gains resulting from paper recycling, performances of alternatives S1 and S2 provide evidence that anaerobic digestion of paper may be a better option than recycling. This can be attributed to the higher capture rate of methane in the anaerobic digestion process and the credits earned through the generation of 'green electricity'. The European Topic Centre on Waste and Material Flows (ETC) studied options for managing paper waste and concluded that paper recycling is a superior option to landfilling [32]. This, however, does not contradict our findings, the ETC report only considered landfilling and incineration and explicitly stated that its findings do not rule out that there might exist conditions under which paper recycling benefits are less evident [32]. On the other hand, comparing the results of

- 1 alternatives S3 and S4, one may conclude that recycling of paper has greater environmental
- 2 benefit than composting, regardless of the recycling rate. This observation is more evident
- when examining table 4. Average GHG savings expected from S4 has gone up from 0.4 to
- 4 0.55 Mg CO<sub>2</sub> equivalent/Mg MSW. This is mainly due to the credits earned for carbon
- 5 sequestration in the paper recycling process.
- 6 Higher paper recycling rates would have significant impact on the performance of the
- 7 'current best practice'. S0 is likely to result in higher GHG saving at higher paper recycling
- 8 rates but the electricity generation potential are likely to be insignificantly affected. At higher
- 9 rates, GHG savings from S0 are expected to be higher than those of the current recycling
- rates in 99% of the time (fig 1 and fig 2). This is mainly because the unrecovered paper from
- the recycling programs will usually end up in landfills and contribute to the fugitive methane
- release from the landfills. Therefore, trends of stakeholders recycling habits should be
- 13 considered when designing waste management alternatives.
- Referring to figures 1 through 4, we can easily exclude alternative S3 for its poor
- 15 performance in the GWP criteria and electricity generation potential. Alternative S2, despite
- its reasonable performance in the electricity generation criteria, it will result in added burdens
- in the GWP criteria. Therefore, an argument can be made for excluding this alternative in
- favour of S1 or even S0. Like S2, S1 utilises anaerobic digestion but is a simpler option from
- an operational point of view and yet achieves better results in both GWP and electricity
- 20 generation potential categories. S0 has a significantly lower electricity generation potential
- 21 than S2 but it has 75% likelihood of yielding GHG savings at the current recycling rates (fig.
- 1) and 99% likelihood of producing GHG savings if recycling rates were to improve in the
- future (fig 2). This is in addition to the fact that it requires no change in current practices
- which makes it technically and operationally feasible.
- 25 While it was easy to exclude S2 and S3 based on the argument presented in the previous
- paragraph, choosing between the remaining alternatives is a matter of compromise between
- their performances in term of GWP and 'green electricity' generation potential, on the one

1 hand and the 'expert judgment' of the future recycling trends, on the other. However, we

2 argue that the outcome depends on the rationale behind setting 'green electricity' targets. If

the policy that demands increase in 'green electricity' generation is based on the objective of

reducing GWP then the actual amount of electricity generated by each alternative should not

matter and the focus should be on the GHG emissions savings potential of the system. On

the other hand, if the rationale behind the policy is reducing demand for global resources

then the argument becomes less straightforward. If the policy were designed with the

8 intention of achieving multiple objectives, the case becomes even more complex. Therefore,

it is very important to be transparent with regards to the philosophy followed in policy setting

as this will have significant impacts on the design and selection of alternatives that best meet

the objective.

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The result suggest, as evident from figures 1 to 4, that the current 'best practices' do not exploit the resources efficiently. Diverting the 'kitchen waste' stream to aerobic composting (S4) instead of landfill (S0) will result in significant improvement in the system's performance and reliability in the GWP category, at a small cost of reduced electricity generation. The benefits of pre-treating organic waste via composting before landfilling is further evidenced by the reduced amount of waste landfilled resulting in significant savings in landfill space.

## 4. Conclusions

LCA was used to compare five alternatives for municipal solid waste management based

on their electricity generation and GHG savings potentials under conditions of uncertainty.

The impact of paper recycling rates on the performance of the alternatives was also

investigated. The results highlighted the importance of incorporating uncertainty in the

process of LCA modeling of municipal solid waste as it adds a further dimension to the

information available to the decision maker. The decision maker can, in addition to

quantifying the impacts of an alternative, consider the risks associated with the possibility of

26 failure.

- 1 The philosophy behind adopting strategies is a very important factor in the decision
- 2 making process. This brings into question the validity of setting universal legislative targets
- 3 (say at a federal level) without properly considering local conditions.
- 4 Composting of organic waste, as a pre-treatment, before landfilling can be an effective
- 5 measure to mitigate GWP and reduce demand on landfill.

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1 Figures

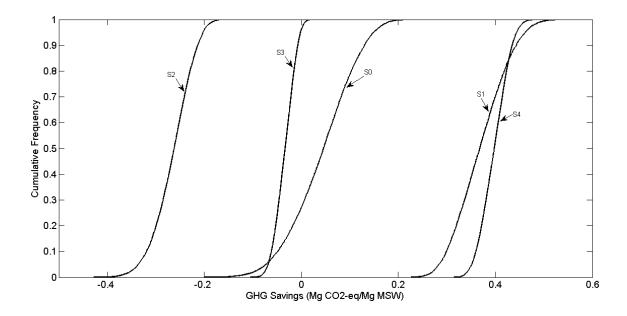


Fig.1. GHG savings at current recycling rates

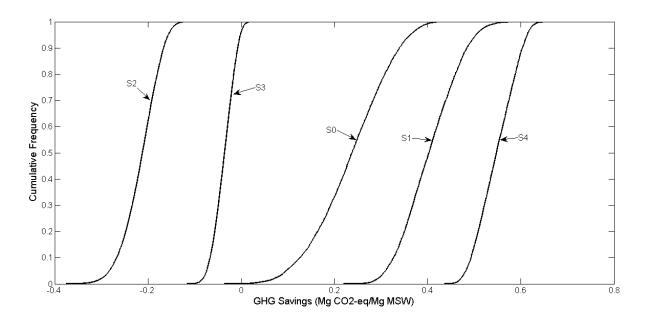


Fig.2. GHG savings at higher paper recycling rates

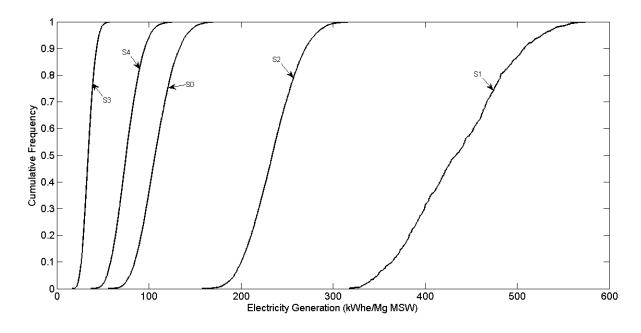


Fig. 3. Electricity potential at current recycling rates



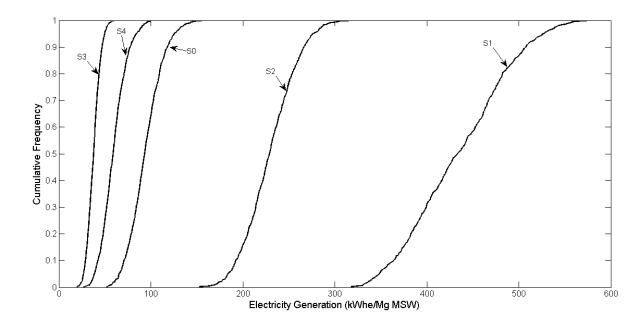


Fig. 4. Electricity potential at higher paper recycling rates

1 Tables

# 1 Table 1: Municipal solid waste composition of Sydney adapted from [13]

Waste stream	Percentage (%wt)
Food waste	35
Green waste	17
Paper	13
Glass	10
Plastics	7
Ferrous metals	2.5
Aluminum	0.2
Wood	1
Others	14.3

Table 2: Waste management alternatives

Waste fraction	Alternative						
	S0	<b>S</b> 1	S2	S3	S4		
Food waste	LDF	AD	AD	COMP	COMP		
Green waste	COMP	AD	AD	COMP	COMP		
Paper	RE	AD	RE	COMP	RE		
Metals	RE	RE	RE	RE	RE		
Glass	RE	RE	RE	RE	RE		
Plastic	RE	RE	RE	RE	RE		
Other	LDF	LDF	LDF	LDF	LDF		

2 LDF: Landfill with landfill gas collection and electricity generation. COMP: windrow composting. RE: recycling. AD: anaerobic digestion.

Table 3: Parameter ranges used in the simulation

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Parameter Parameter Parameter	Unit	Range	Source
Population growth rate	%	0.7 – 1.0	[12]
Waste generation growth rate	%	(-0.3) - 0.5	[18]*
Collection route length	km	120-150	Estimated
Recyclables collection route length	km	150-180	Estimated
Distance from MRF to LDF	km	10 – 20	Estimated
Paper recycling recovery rate	%	40 – 60	[19, 20]
Plastic recovery rate	%	30 - 50	19, 20]
Ferrous metal recovery rate	%	70 – 90	[19, 20]
Aluminum recovery rate	%	85 – 95	[19, 20]
Glass recycling recovery rate	%	35 – 54	[19, 20]
Recycled material in paper stream	%	10 – 20	Estimated
Recycled material in glass	%	5 – 10	Estimated
Recycled material in Aluminum	%	10 – 25	Estimated
Recycled material in ferrous metal	%	10 – 25	Estimated
Recycled material in plastic	%	10– 20	Estimated
Tree sequestration credit	kg CO <sub>2</sub>	(-1308) – (-	[2]
		2900)	
MRF electricity consumption	kWh/Mg	25 – 35	[20]
Collection truck fuel consumption	l/km	0.7 - 0.9	[9]
Composting facility fuel consumption	I/Mg	0.05 - 0.08	[21]
Compost residue	%	5.0 - 9.0	[2]
CH₄ emissions from composting	kg/Mg	0.05 - 0.295	[21]
NO <sub>x</sub> emissions from composting	kg/Mg	0.027 - 0.266	[21]
Compost yield	kg/Mg	400 – 600	[22]
Food waste moisture content	%	65 – 75	[23]
Green waste moisture content	%	40 - 60	[23]
Paper waste moisture content	%	4 - 30	[23]
Methane generation rate constant	yr <sup>-1</sup>	0.04 - 0.058	[24]
(k)			
LFG collection efficiency	%	50 – 75	[24]
LFG methane content	%	40 – 60	[25]
Methane oxidation rate	%	5 – 10	Estimated
LFG heat content	GJ/Mg	49 – 55	[26,27]
Electricity generation efficiency from	%	20 – 30	[28]
biogas			

<sup>\*</sup> Estimated from the historical data in the report.

# Table 4: Descriptive statistics of GHG savings (Mg CO<sub>2</sub>/Mg MSW)

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		Alternative				
	•	S0	S1	S2	S3	S4
Typical	Ave	0.04	0.37	-0.26	-0.03	0.40
paper <sub></sub>	Stdev	0.07	0.05	0.04	0.02	0.03
recycling rate	Cov	1.59	0.15	-	-	0.07
Higher	Ave	0.24	0.37	-0.21	-0.03	0.55
paper <sub></sub>	Stdev	0.08	0.06	0.04	0.02	0.04
recycling rates	Cov	0.34	0.16	-	-	0.08

Ave: average, stdev: standard deviation and Cov: coefficient of variation

Table 5: Summary statistics of electricity generation (kWhe/Mg MSW)

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		Alternative				
		S0	S1	S2	S3	S4
Typical	Ave	107.08	403.81	234.33	34.39	75.69
paper recycling	Stdev	19.01	50.32	26.06	6.62	14.37
rate	Cov	0.18	0.12	0.11	0.19	0.19
Higher	Ave	94.31	403.81	229.63	34.39	59.73
paper	Stdev	18.10	50.32	28.10	6.62	13.55
recycling rates	Cov	0.19	0.12	0.12	0.19	0.23

2 Ave: average, stdev: standard deviation and Cov: coefficient of variation