Greenhouse gas mitigation cost of energy from waste via biogas: A techno-economic analysis of co-digestion of three types of waste in Cape Town

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Abstract
This paper investigates, in the context of Cape Town the emission reduction potential (ERP) of energy from biogas and related cost. Two project-scale models and a city-scale model were developed. Substrates for project model 1 were organic fraction of municipal solid waste (OFMSW) and primary sludge (PS) from sewage works. Project model 2 considered waste paper sludge (WPS) and PS. For the city-scale model, substrates for project model 1 were extended to include total amounts of OFMSW and PS generated in Cape Town. Financial results show that at the REFIT tariff model 1 would have a higher internal rate of return (20.5%) than model 2 (5.6%). The landfill ERP of the project-scale models is 98 600 CO_2 equivalent tons per year, corresponding to a weighted average capital investment of R372 per CO_2 equivalent ton saved in year 1. The results for the city-scale model indicate that a landfill ERP of 458 000 CO_2 equivalent tons per year can be expected at an investment cost of R287 per CO_2 equivalent ton saved in year 1. Energy emissions from fossil fuels at city-scale are most effectively mitigated if coal rather than other fossil fuel based power and heat generation are replaced.

Keywords: biogas, emissions, mitigation

1. Introduction
Sources of GHG emissions are categorised into emissions from the energy sector, industrial processes, agriculture, forestry and other land use as well as waste disposal (DEA, 2009). DEA (2009) estimated that in 2000, 78.9% of GHG emissions were from the energy sector. This high contribution reveals South Africa's dependence on fossil fuels (coal, oil and gas) (DME, 2003). The landfill disposal of waste was responsible for approximately 2% of South Africa's GHG emissions (DEA, 2009). Although this is a small contribution relative to the energy sector, there is potential for energy recovery (and thus a "double dividend" for mitigation) and improved waste management practice. Municipal governments (who are responsible for waste management) are increasingly challenged to reduce and manage the quantities of municipal solid waste (MSW) that arrive at their landfill sites (LFS). They have also started to include 'low-carbon development' into their strategic decision-making (SEA & ERC, 2010).

Waste can be diverted from LFS and treated through various technologies, with those yielding excess energy, usually referred to as energy-from-waste (EfW) technologies. Anaerobic digestion (AD) is an example of an EfW technology which provides solutions to energy supply, climate change, waste management and agriculture. AD produces biogas and a digestate (by-product) (Monnet, 2003). The biogas can be used as an energy source whilst the digestate can potentially serve as an agricultural fertilizer.

A very recent study, *Energy Scenarios for Cape Town,* included modelling the contribution of electricity from biomass and municipal waste. Although energy-from-waste was considered, the quantity and cost of energy from biogas was not considered. The quantity of GHG emissions that can be avoided by diverting organic waste from LFS for biogas production and ultimately energy generation is also unknown. The objectives of this paper are to make a contribution to a better integration of municipal responses to issues of energy and climate change with waste management planning, specifically by estimating, in the context of Cape Town, firstly the emission reduction potential associated with energy from biogas, and secondly the corresponding cost.

2. Waste from Energy via Anaerobic Digestion

AD is a complex process in which organic matter is decomposed by the action of bacteria into biogas (Deublein & Steinhauser, 2008; Wilkie, 2008). The produced biogas typically has a composition as presented in Table 1 (Deublein & Steinhauser, 2008).

Table 1. Typical biogas composition

Biogas constituent	Volume %
Methane (CH_4)	55-75
Carbon Dioxide (CO_2)	25-50
Water (H_2O)	1-5%
Hydrogen Sulphide (H_2S)	0-0.5%
Nitrogen (N_2)	<2
NH_3	0-0.05%

Source: (Deublein & Steinhauser, 2008)

The success of AD depends on several parameters which include digester temperature, hydraulic and solids retention times, degree of decomposition, type of waste being digested and C/N ratio (Dennis & Burke, 2001). The types of waste suitable for AD and available in Cape Town can be classified into municipal wastes, industrial wastes and wastewater. Examples of municipal waste are municipal solid waste (MSW) and sewage sludge from wastewater treatment plants (WWTP). Food and green wastes contained in MSW represent the biodegradable fraction of MSW (OFMSW) which is usually 30-45% of household waste depending on household income (Deublein & Steinhauser, 2008). Conventional disposal of OFMSW is purely by landfilling (Sosnowski et al., 2003). OFMSW is facing challenges from environmental legislation concerning its landfill disposal (Cuetos et al., 2008). Numerous studies have shown that the anaerobic digestion of OFMSW is technically feasible (Sosnowski et al., 2003; Demirekler & Anderson, 2010; Cuetos et al., 2008).

Concerning sewage sludge, primary sludge (PS) is the major contributor to the total amount of sewage sludge produced from a WWTP (Mamabolo, 2006). PS is putrescible as it is characterised by a high content of organic compounds (Sosnowski et al., 2003). Thus the sludge should be stabilized prior to ultimate disposal. In relation to Cape Town, only a few WWTPs use AD for sludge treatment. Athlone WWTP is an example of a Cape Town plant that utilizes this technology to stabilize sludge (CoCT, 2008). The use of AD in the Athlone WWTP generates biogas that could potentially be used to generate 6.9 GWh_e/year (AgamaEnergy, 2008).

Organic industrial wastes include a very wide range of waste materials such as waste paper sludge (WPS), food processing waste, slaughterhouse waste (SHW), fish oil and fish processing residues (Klass, 1998; Monnet, 2003). WPS is generated in large quantities from the Pulp and Paper industry. Cape Town has three paper manufacturers namely Nampak, Mondi and Sappi. Approximately 800 ton per month of WPS are landfilled at Vissershok (Baloyi, 2011). This figure indicates that WPS in the city is in abundance and landfilling it is costly due to the high disposal charge of R264 per ton which is destined to increase (Nontangana, 2011). WPS might be banned from disposal at LFS in the near future (Nontangana, 2011). OFMSW, PS and WPS are also suitable for anaerobic co-digestion.

Anaerobic co-digestion is the simultaneous digestion of carbon-rich and nitrogen-rich organic material (Zamudio Canas, 2010). The primary advantage is the improvement of the rate of biogas yield. This means that shorter HRT (~21 days) in the case of co-digestion can be expected compared to a HRT of 30 days used for mono-digestion (Luste

& Luostarinen, 2010). This is achieved as co-digestion offers an improved C/N ratio, increased load of biodegradable organic matter, dilution of potential toxic compounds such as ammonia and synergistic effects resulting from complementary microbial consortia coming from different wastes (Sosnowski et al., 2003; Zamudio Canas, 2010). From an economical perspective the benefit of co-digestion results from sharing and a more intensive use of equipment (Zamudio Canas, 2010).

3. Research methodology

3.1. Characteristics of OFMSW, WPS and PS

The waste types included in the study are PS, OFMSW and PS due to their abundance and disposal problems, as well as these being representative of high-nitrogen, mixed C:N and high-carbon waste sources. Table 2 shows their characteristics. The biogas yield of WPS is lower than the 400ml/g VS obtained by Dalwai (2011). Two possible installations were considered at the project scale. Project Model 1 analyses the co-digestion of OFMSW with PS from the Athlone WWTP and Model 2 focuses on WPS and PS from the Bellville WWTP.

Table 2. Available quantities of OFMSW, WPS and PS for the project models

	M_{waste}	Biogas yield	TS	VS	C/N
Substrates:	t/day	ml/g VS	%	%	
OFMSW	78.7	218.7	18	82	21.31
WPS	25.81	140.9	32	98.5	125.5
PS-Athlone	111.8	558	4.5	66.7	6.94
PS-Bellville	67.57	558	4.5	66.7	6.94

Sources: (Jeffares&Green & IngeropAfrica 2004; Baloyi, 2011; Munganga et al., 2010; Luste & Luostarinen, 2010)

The theoretical biogas production and composition can be determined based on the chemical formula for the feedstock and Buswell's stoichiometric equation (Sosnowski et al., 2003):

$$C_nH_aN_dO_b + [n - a/4 - b/2 + 3d/4]H_2O \longrightarrow [n/2 + a/8 - b/4 - 3d/8]CH_4 + [n/2 - a/8 + b/4 + 3d/8]CO_2 + dNH_3$$

The composition of the biogas can be determined using Equation 1 based on the subscripts of the chemical formula (Sosnowski et al., 2003). For gas utilization in a Combined Heat and Power (CHP) unit the minimum composition of CH_4 in the biogas is 60% (Deublein & Steinhauser, 2008).

$$\%CH_4 = \left(4 + {}^{a}/_{n} - {}^{2b}/_{n} - {}^{3d}/_{n}\right) * 100\% \qquad \textbf{Equation 1}$$

Figure 1 is a schematic representation used to estimate the biogas production and energy generation. The raw biogas from the digester is upgraded to 60% of CH_4 depending on the outcome of Equation 1. It was assumed that the energy content of the biogas is 6 kWh/m^3 and the electric and thermal efficiencies of the CHP are 30% and 50% respectively (Deublein & Steinhauser, 2008).

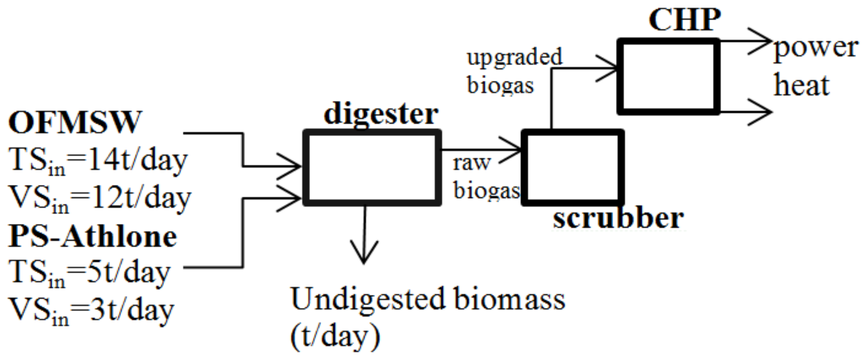

Figure 1. Simplified schematic representation of biogas and energy generation from feedstock

3.2. Estimating landfill emissions and emissions related to biogas production at project scale

3.2.1. Landfill emissions from OFMSW, WPS and PS

The landfill disposal of organic wastes produces significant amounts of methane (CH_4), a GHG with a global warming potential (GWP) that is 21 times that of carbon dioxide (CO_2) (IPCC, 2006). The potential amount of methane emissions can be estimated depending on the degradable organic carbon (DOC) content of each waste. Equation 2 estimates the amount of degradable organic carbon (DOC) contained in waste *i* (IPCC, 2006):

$$CH_{4generated} = DOC * F * 16/12 \qquad \textbf{Equation 2}$$

$CH_{4generated}$: the amount of CH_4 emissions generated within the landfill (ton of methane/ton of waste).
DOC: Fraction of degradable organic carbon (ton of carbon/ton of waste).
F: composition of CH_4 in landfill gas.
16/12: molecular ratio of CH_4 to C

Some of CH_4 generated may be oxidized in the material covering the waste. An oxidation factor (OX) is used to estimate the amount of CH_4 oxidized (IPCC, 2006). In Cape Town, OFMSW and WPS are currently disposed of at Vissershok (CoCT, 2011). On a site visit to Vissershok waste was being covered with soil thus by IPCC's definition this is a managed LFS and has an OX value of 0.1. Alcock (2009) reported that sewage sludge (a mixture of primary and secondary sludge) generated in Cape Town is either stockpiled on site, used for agricultural purposes or disposed of at dedicated landfill sites. The sludge produced from Bellville WWTP in Cape Town is applied on agricultural land whereas the Athlone WWTP disposes its sludge at a dedicated LFS. In the case of PS applied on agricultural land, CO_2 is formed instead of CH_4. However, this CO_2 is of biogenic origin and thus generally not included under landfill emissions (IPCC, 2006). The amount of CH_4 emitted from the LFS is shown in Equation 3 (IPCC, 2006):

$$CH_{4-emitted} = (1 - OX) * M_{waste} CH_{4generated} \quad \textbf{Equation 3}$$

3.2.2. Emissions from biogas production

Biogas facilities have unintentional CH_4 leakages due to process disturbances. IPCC (2006) suggested that the amount of CH_4 leaking from the facility is generally 0 to 10% of the amount of CH_4 generated. A default value of 5% can be used in the absence of further information (IPCC, 2006). The quantities of GHG emissions associated with project activity were estimated by adding the amount of CH_4 leakages and the amount of CO_2 generated as a result of combusting biogas via CHP for energy generation. The CO_2 generated from combustion should be included in the GHG emissions for the project. CO_2 emissions associated with energy generation via CHP can be estimated using Equation 4 which requires the energy activity (EA, kW) and Emission Factor (EF) values:

$$CO_{2-emissions} = EA * EF \qquad \textbf{Equation 4}$$

Then the amount of emissions reduced by diverting OFMSW, WPS and PS from LFS is the difference between the project activity emissions and the landfill emissions.

3.3. Energy emissions and landfill emissions at city-scale

At city-scale, the impact of energy from biogas was evaluated using the LEAP software. This simulation software was developed by the Stockholm Environment Institute (SEI) (Esri, 2011). It was used in this study as it is an integrated modeling tool that helps analyse energy supply and consumption. This was done by assuming that in Cape Town, all the OFMSW generated was co-digested with PS from all the WWTPs. The total available quantities (Table 3) of OFMSW and PS generated in Cape Town were sourced from Wright-Pierce (1999) and Jeffares&Green and IngeropAfrica (2004).

Table 3. Quantities of OFMSW and PS generated in Cape Town

	M_{waste} (t/year)	Biogas yield ml/g VS	VS %
OFMSW	398074	218.7	82
PS	245200	558	66.7

3.3.1. Emissions from use of fossil fuels for power and thermal energy

In order to estimate emissions associated with electricity use, it was assumed that a significant portion of Cape Town's electricity supply is generated by coal-fired stations (95%) (SEA & AMATHEMBA, 2007). Letete et al (2009) presents an average emission factor (EF) specific to South Africa's coal-generated electricity which was calculated by Eskom. The emissions were then estimated from Equation 4. In Cape Town, fossil fuels such as diesel, heavy fuel oil (HFO), coal, LPG and paraffin are often used to meet industrial thermal energy demand (Winkler et al., 2005; SEA & ERC, 2010). This contributes to the city's emissions. These emissions can be mitigated by replacing fossil fuels with the thermal component of energy derived from biogas (Junfeng et al., 1997; Bhattacharya et al., 1996). Emissions from these fuels can be computed using Equation 4 based on the EF provided by the IPCC.

3.3.2. Landfill Emissions at city-scale

Emissions associated with the landfill disposal of the quantities indicated in Table 3 were estimated as outlined in Section 3.2.1.

3.4. Financial analysis of project models 1 and 2

The investment costs can be divided into three major pieces of equipment namely; digester, scrubber and the CHP unit. The capital costs for the digesters of both project models were calculated based on order of magnitude formula (Amigun & von Blottnitz, 2010):

$$C_1 = \left(\frac{Q_1}{Q_2}\right)^n * C_2 \qquad \textbf{Equation 5}$$

Equation 5 assumes economies of scale and C_1 and C_2 indicate the capital cost of the current project (Model 1 or 2) and the reference project respectively. For digesters larger than $20m^3$, *n* (cost capacity factor) is 0.8 (Amigun & von Blottnitz, 2010). Table 4 contains a summary of the cost items used for the project models.

Table 4. Summary of the cost figures

Type of cost	
$FCI_{digester}$ distribution:	
Concrete works (x_B)	63%
Technical equipment (x_T)	37%
FCI_{CHP}:	4424R/kWel
$FCI_{scrubber}$:	12.9R/kWel (model 1), 13.7R/kWel (model 2)
Consumption-bound costs/year:	
Cost of electricity:	
Service Charge	14.35R/day
Electricity Charge	0.7766R/kWh
Cost of heat	0.05R/kWh
Maintenance for concrete works (y_B)	0.5% of $x_B \cdot FCI_{digester}$ R/year
Maintenance for technical equipment (y_T)	3% of $x_T \cdot FCI_{digester}$ R/year
Maintenance for CHP	4% of FCI_{CHP} R/year
Operational cost: scrubber	
Avoided cost of waste disposal	264R/ton
Labour cost (single personnel per model)	80316 R/year
Other costs/year:	
Insurance per model	0.5% of $FCI_{digester}$/year
Revenue:	
Sales of electricity (from REFIT scheme, 2011)	0.96R/ kWh
Sales of heat	0.05 R/kWh
Sales of fertilizer:	7019R/year

The Internal Rate of Return (IRR) was used to evaluate the profitability of the project models. For IRR values that are greater than the discount rate [r(%)] the project is deemed feasible and can be accepted. A discount rate of 8% was used consistent with that used in the IRP2 process (IRP, 2011).

4. Results

4.1. C/N ratio: mono-digestion versus co-digestion

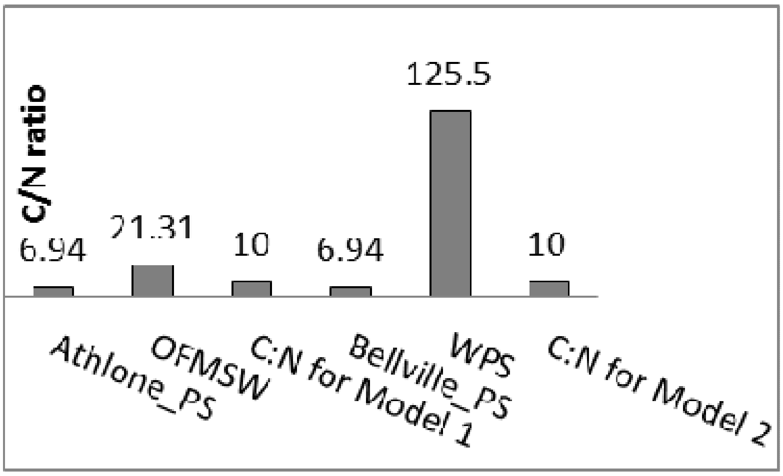

Figure 2. Comparing C/N ratio of co-digestion and mono-digestion

Figure 2 illustrates the effect that co-digesting primary sludge (PS) with carbon-rich OFMSW or WPS would have on the C/N ratio. Figure 2 indicates that OFMSW is relatively carbon rich compared to PS. WPS has the highest C/N ratio of 125.5 (Myréen et al., 2010). Scott and Smith (1995) also reported a C/N ratio of WPS of 243.5. This observation indicates that this waste is a good carbon source. A highlight from Figure 2 is that individual C/N ratios for PS (Athlone and Bellville WWTPs) and WPS are outside the desired range (20-30) (Parkin & Owen, 1986). Co-digestion is expected to offer an improved C/N ratio. Based on the quantities of materials available at the Athlone and Bellville works, co-digestion would change the C/N ratios slightly and as indicated they are below the optimal C/N ratio range. This indicates that additional quantities of carbon rich wastes are required in order to improve the C/N ratio for the co-digestion models. Nonetheless, it is noted that the addition of OFMSW and WPS to Athlone_PS and Bellville_PS would improve their C/N ratio. Sosnowski et al (2003) presented a case where co-digestion of sewage sludge with OFMSW increased the C/N ratio from 9.26 to 14.19.

4.2. Influence of co-digestion on estimated biogas production

Table 5 contains results for the mass balance calculations which were calculated on a dry matter/total solids basis.

Table 5. Mass Balance (MB) results for Model 1 and Model 2 on a total solids basis

	Model 1	**Model 2**
TS (t/day)	19.1	11.3
VS (t/day)	14.9	10.2
VS conversion (%)	33.4	25.4
$VS_{decomposed}$ (t/day)	5.6	2.58
undigested biomass (t/day)	13.5	9
m_{biogas} (t/day)	4.98	2.58
v_{biogas} (m^3/day)	4400	2277

The estimated biogas potential of Model 1 is higher than that of Model 2. This is due to the differences in quantities of total solids (TS) and volatile solids (VS) contained in the feedstock and thus indicating that for Model 1 more organic matter is available for degradation to form biogas. The conversions [VS (%)] of VS that correspond to the amount of biogas estimated in Model 1 and 2 are approximately 33.4% and 25.4% respectively. Model 1 has a higher conversion rate than Model 2, justifying its higher biogas potential. The theoretical composition CH_4 in the raw biogas for project Model 1 and 2 was determined to be 51.6% and 53.8% respectively.

Model 1:

$C_{11}H_{18}N_1O_7 + 3.63H_2O \longrightarrow 5.67CH_4 + 5.32CO_2 + NH_3$

$\%CH_4 = 51.6\%$

Model 2:

$C_{10}H_{16}N_1O_5 + 3.75H_2O \longrightarrow 5.19CH_4 + 4.45CO_2 + NH_3$

$\% CH_4 = 53.8\%$

The CH_4 compositions are low due to the high oxygen content; other studies have recorded biogas with methane compositions as high as 70% (Sosnowski et al., 2003). The use of biogas in a CHP unit requires the composition of CH_4 to be 60% (at minimum) on a volume basis. As the compositions calculated from this study are less than 60%, calculations for upgrading the biogas in a scrubbing unit were performed using the estimated biogas output from Table 5. It was assumed that the biogas quantity after the scrubber unit contains 60% of CH_4 (Deublein & Steinhauser, 2008). Table 6 shows the biogas production after upgrading the CH_4 content through a scrubber unit.

Table 6. Estimated biogas production after upgrade

Model	**CH_4 composition**	**upgraded biogas**
1	60 %	3785 m^3/day
2	60 %	2042 m^3/day

4.3. Energy Supply and Consumption

Table 7 shows the calculated digester volumes and CHP nominal capacities for each model. As shown, the thermal component of the CHP unit constitutes a higher fuel share than the electrical component; this is the case for both models due to the differences in the electrical and thermal efficiencies which are 30% and 50% respectively.

Table 7. Estimated sizes of main plant units for each model

	Model 1	Model 2
Volume of digester, m^3	4710	2178
CHP electrical and thermal:		
Electrical capacity (E_el, kW)	284	153
Thermal capacity (E_th, kW)	473	255
Nominal capacity, kW	369	199

Table 8 contains the parasitic energy demand and the surplus energy potential for each model. For each model, surplus energy is the difference between the estimated energy generated and the parasitic energy demand.

Table 8. Energy generated and consumed in Model 1 and 2

	Model 1	Model 2
Energy generated, kW	**757**	**408**
E_el, kW	284	153
E_th, kW	473	255
Heat consumed:		
Qs, kW	**171**	**84**
Cp, kJ/kg ^oC	4.18	4.18
Surplus Heat, kW	**303**	**172**
Electricity consumed:	**161**	**87**
E_consumed, kW	43	23
E_scrubber, kW	118	64
Surplus Electricity, kW	**123**	**66**
Total surplus energy, kW	**426**	**238**
Energy consumed,%	**44%**	**42%**

For both models, this study assumed a specific heat capacity of water for the substrates due to unavailability of their Cp values. This assumption is consistent with Murphy and Power (2009). The scrubber unit consumes a significant amount of the electricity generated. In Model 1, it was calculated that 161 kW of electrical energy is consumed by the biogas production process and approximately 118 kW of this consumption was attributed to the scrubber unit (assuming 0.75 kWh_{el}/m^3), in percentage terms this is 73%. This result suggests that upgrading biogas is an energy intensive process. Murphy and Power (2009) also indicate that scrubbing the biogas generated the largest electricity consumption. This indicates the importance of biogas quality which is highly dependent on the composition of the feedstock (Sosnowski et al., 2003). Table 8 shows that the energy consumption for Model 1 and 2 was roughly the same. Model 1 consumed 44% of its total energy (electrical and thermal) output whereas Model 2 consumed approximately 42%. These figures are within the range found in literature sources. Karellas et al (2010) estimated that the biogas production process consumed about 39% of the energy produced.

4.4. Financial Analysis

Table 9 contains the calculated investment costs, consumption and operational-bound costs for Model 1 and 2.

Table 9. Cost comparison between Model 1 and 2

	Model 1	Model 2
Investment Costs per unit R/m^3	**4456**	**7244**
Investment Costs(R):	**20,989,226**	**15,776,360**
Digester (R)	14,392,138	10,328,294
CHP (R)	1,683,743	908,358
Scrubber (R)	4,913,344	2,807,625
Consumption-bound costs	**-6,421,606**	**-1,863,048**
Electricity (R/year)	1,084,629	587,556
Heat (R/year)	73,655	36,106
Avoided Disposal tariff (R/year)	-7,579,889	-2,486,710
Operational-bound costs	**1,634,059**	**1,160,531**
Concrete works (R/year)	71,961	38,826
Technical equipment (R/year)	431,764	232,957
CHP (R/year)	67,350	36,334
Labour costs (R/year)	80,316	80,316
Scrubber (R/year)	982,669	772,097
Other Costs (R/year)	**104,946**	**57,406**

The larger the facility the lower the capital cost per unit (Murphy & Power, 2009). Such an assumption was also made in this analysis, with a value of n=0.8 used for Equation 5. The digester is the most capital intensive unit. For each model, the avoided disposal cost under the consumption-bound cost is shown as a negative cost to indicate a cost saving. This is due to the diversion of OFMSW and WPS from LFS to a biogas producing facility. This significant cost saving makes the economics of biogas production from the waste considered in this study more attractive as it avoids the municipality's disposal charge of R 264 per ton which currently applies only to OFMSW and WPS and not PS (Nontangana, 2011).

Table 10. Results for the financial analysis of the models

Model	**Electricity**	**Heat**	**IRR**
	R/kWh	R/kWh	%
1	0.96	0.05	21
2	0.96	0.05	5.61

Table 10 presents the financial feasibility results for Model 1 and 2 using the cost figures indicated in Table 9. As the discount rate (r = 8%) is less than the IRR for Model 1 it can be stated that Model 1 is financially feasible and that selling electricity from biogas at a REFIT of 96 c/kWh is profitable based on the assumptions considered in this study. However for Model 2, at 96 c/kWh the IRR is less than the set discount rate, indicating that the project is not profitable. Relative to the *Energy Scenarios for Cape Town* study, the cost of electricity from biogas for Model 1 is higher than electricity from Municipal waste [R0.44/kWh] (SEA & ERC, 2010). Details about the technology used to convert municipal waste to electricity are not clear thus cannot be fairly compared to the project-scale models. The selling price of electricity in Model 1 is lower relative to electricity from solar thermal, wind and gas turbines.

4.5. GHG emissions for landfill disposal of OFMSW, WPS and PS from the Athlone WWTP

Table 11 shows the estimated amount of CH_4 emissions as a result of the landfill disposal of OFMSW, WPS and PS from the Athlone sewage works. The amount of CO_2-equivalent was calculated at a GWP of 21.

Table 11. Estimated CH_4 emissions from disposal of OFMSW, WPS and PS from Athlone WWTP

	DOC (ton Carbon/ton waste)	CH_4-emitted(ton/year)	CH_4-emitted (tons of CO_2-equivalent/year)
OFMSW	0.06	1005	21110
WPS	0.4	2478	52040
Athlone PS	0.05	1318	27670

WPS has the highest DOC value and also the emissions from the disposal of WPS are higher than the sum of emissions for OFMSW and PS although WPS has a lower waste quantity (M_{waste}, 25.8 ton/day). Due to the high carbon content in WPS, the study expected higher biogas yield from Model 2. The inconsistency is due to the low biogas yield for WPS obtained from Munganga et al (2010). The total amount of GHG emissions is 100 820 CO_2 equivalent ton per year. This figure signifies the amount of carbon emissions released to the atmosphere due to the landfill disposal of OFMSW, WPS and PS based on quantities used for Models 1 and 2.

4.6. Estimated GHG emissions from biogas production

The GHG emissions due to the production of biogas and energy generation are shown in Table 12.

Table 12. Estimated GHG emissions from biogas production

	Model 1	Model 2	Total
CH_4-leak (m^3/year)	77720	37271	114990
CO_2-equivalent CH_4-leak (ton/year)	1175	564	1739
CO_2-emissions (ton/year)	296	142	438
Total CO_2 (ton/year)	1471	706	2177

As shown in Table 12, the potential amount of GHG emissions from biogas production is significantly lower than the calculated amount of GHG emissions generated as a result of landfilling wastes (OFMSW, WPS, and PS). The emissions resulting from the land application of PS (from the Bellville WWTP) were not included because the CO_2 emitted is of biogenic origin. Thus the emission reduction potential (ERP) of biogas from Models 1 and 2 is:

$$ERP = 100\,820-2177$$

$$ERP = 98\,643\ CO_2 \text{ equivalent tons per year}$$

This value indicates that 98 600 CO_2 equivalent tons per year could be mitigated by generating energy from biogas with the two modelled projects. Table 13 reports the ERP per model. The cost below the ERP value is the total investment cost obtained from Table 9 for each model. As shown, the cost of mitigation for Model 2 is slightly lower than for Model 1. This was expected given the larger ERP for Model 2. The results from Table 13 indicate that it is cost-effective to divert waste from the LFS in order to mitigate emissions.

Table 13. The emission reduction potential of biogas

	Model 1	Model 2	Total
Landfill emissions (tons of CO_2 equivalent/year)	48780	52040	100820
Biogas production emissions (tons of CO_2 equivalent/year)	1308	705	2013
ERP (tons of CO_2 equivalent/year)	47472	51335	98807
Investment Cost (R'million)	21	16	37
R/ t CO_2	442	307	

The weighted average of the cost of mitigation of Model 1 and 2 is R372 per CO_2-equivalent ton saved in year 1 [R37million/98807ton].

4.7. Results for city-scale modeling on LEAP

LEAP was set up to include energy from biogas (heat and electricity) from 2012 to 2050.

Table 14. Input parameters for LEAP modeling

Parameters	Model inputs
Model Period	2012-2050
Capacity, MW	7.51
Capital cost, R/MW	1.32E+08
Fixed O&M, R/MW	2.49E+05
Variable O&M, R/MWh	828

The results show that the amount of energy that can be generated from biogas via co-digestion from the total amount of OFMSW and primary sludge (PS) available in Cape Town is 49 GWh per model year and the emissions associated with this are 416.2 CO_2-equivalent tons per model year. The study estimated the emissions associated with energy use that could be avoided by using energy from biogas. According to the electrical (30%) and thermal efficiency (50%) of CHP, the output energy share of electricity and heat from the CHP unit are 37.5% and 62.5% respectively.

That is, 18.4GWh/year and 30.6GWh/year of electricity and heat respectively are potentially available via co-digestion of OFMSW with PS using their total amounts available in Cape Town. It was assumed that the electricity component (18.4GWh/year) of energy from biogas would replace 18.4GWh/year of coal-derived electricity. As coal accounts for 95% of the city's electricity supply (SEA, 2007; SEA & AMATHEMBA, 2007). For thermal energy, 30.6GWh/year of heat from biogas can replace fuels that are usually used to meet industrial heat demand. These fuels are diesel, LPG, paraffin, coal and heavy fuel oil (SEA & ERC, 2010).

Table 15 contains the emission factors for electricity generated from coal by Eskom, diesel, LPG paraffin, coal and Heavy fuel oil.

Table 15. Emission factors and quantities of emissions from fossil fuels

	Emission factor	ton CO_2-equivalent
Electricity source	kg CO_2-equivalent/kWhr	
For Eskom-generated electricity (coal)	1.015	1898
Heat source	kg CO_2-equivalent/GJ	ton CO_2-equivalent
Diesel	20.2	2225
LPG	17.2	1895
Paraffin	20	2203
Coal	26	2864
Heavy Fuel Oil	21.1	2324
Total		**13410**

The contribution of each fuel (diesel, LPG, paraffin, coal and HFO) to industrial heat in Cape Town is unknown because the sale and use of fuels within Cape Town is not well monitored. The study developed a scenario analysis to estimate the quantity of CO_2-equivalent emissions from coal-derived electricity and each industrial thermal energy fuel. Table 16 contains a list of scenarios (1 to 5) with each corresponding CO_2-equivalent emissions.

Table 16. Emission factors and quantities of emissions from fossil fuels

Scenario number	Scenario description	Ton CO_2-equivalent per model year
1	Coal-derived power and diesel	4123
2	Coal-derived power and LPG	3793
3	Coal-derived power and paraffin	4101
4	Coal-derived power and coal	4762
5	Coal-derived power and HFO	4222

For scenario 1 in which industrial electricity (18.7GWh/year) and thermal (30.6GWh/year) energy demands are met from coal (Eskom) and diesel respectively, the total amount of CO_2-equivalent emissions are presented in the table. These quantities of emissions are significantly higher than the emissions produced (416.2 tons CO_2-equivalent per year) with energy from biogas. Table 17 contains the total amount of emissions for each scenario over the entire modeling period. The corresponding emission reduction potential (ERP) of biogas is also shown:

Table 17. The *total* ERP of biogas energy and cost *over the model period (2012-2050)*

Scenario	Emissions (tons of CO_2-equivalent)	ERP (tons of CO_2-equivalent)	Cost, R/ton
1	157000	140 900	934
2	144 200	128 400	1026
3	155 900	140 000	940
4	181 000	165 150	797
5	160 500	144 700	910

Table 17 also contains the cost associated with reducing emissions for each scenario over the model period (2012-2050). The investment cost given in Table 14 was used to estimate the cost in Rand per ton basis for scenarios 1 to 5. The study expected larger ERP values. However, these results show that energy from biogas production has the potential to mitigate GHG emissions associated with energy utilization from fossil fuels. The potential of biogas to mitigate emissions was expected as biogas is a renewable energy source.

The amount of landfill emissions released to the atmosphere as a result of landfill disposal of OFMSW and PS was calculated and is shown in Table 18:

Table 18. The quantities of methane generated and emitted from landfill disposal of OFMSW and PS at city-scale

	OFMSW	PS	Total
CH_4-generated (ton of CH_4/year)	15480	8795	24275
CH_4-emitted(ton/year)	13930	7915	21845
CH_4-emitted (tons of CO_2-equivalent/year)	292500	166000	458500

The results in Table 18 show the total potential of CH_4 released over a long time period due to the annual landfill deposit of OFMSW and PS. The ERP of biogas [458500-416.2] is then 458 084 CO_2 equivalent tons per year. The total cost of mitigation is R287/ton CO_2-equivalent based on the investment cost from Table 14 [R1.32E+08/458 084]. This mitigation cost is lower than the weighted mitigation cost of the project models. This is an expected outcome as the city-scale model avoids higher quantities of landfill emissions.

5. Conclusions and recommendations

Biogas production from organic wastes could reduce dependency on waste disposal by landfill thus reducing landfill emissions. Furthermore, it could be an attractive option as it relies on available waste sources and currently existing technology at some of the city's wastewater treatment plants (WWTPs). Although energy-from-waste has been considered in Cape Town studies, the quantity and cost of energy from biogas was not considered.

Bottom-up project feasibility modelling indicates that energy production from organic wastes in the city could be financially rewarding for larger centralised facilities, if electricity prices similar to those of the REFIT were used. Relative to the *Energy Scenarios for Cape Town* study, the cost of electricity from biogas was estimated to be less than electricity from Solar Thermal Electricity, wind and gas turbines for one of the two possible projects modelled.

The study determined that biogas production processes also have their associated GHG emissions but are significantly lower than the emissions from the landfill disposal of OFMSW, WPS and PS. This strongly suggests that landfill emissions can be reduced by diverting wastes to a biogas facility. The combined ERP of biogas of project models 1 and 2 is approximately 98 600 CO_2 equivalent tons per year.

The landfill emissions at city-scale were higher for OFMSW than PS. The combined ERP of biogas from co-digestion of OFMSW and PS was 458 084 084 CO_2 equivalent ton per year.

The cost of mitigating energy emissions associated with fossil fuel use was lowest in the case of substituting coal with energy from biogas. For the landfill emissions of OFMSW and PS, the total cost of mitigation is R287 per CO_2 equivalent ton based on the investment cost.

The accuracy of estimating the biogas output from co-digestion can be improved by incorporating and modeling the reaction kinetics of anaerobic digestion. This would assist with mimicking the behaviour of the microorganisms involved in the digestion process. Therefore the study recommends that a detailed design of a biogas plant should be completed in order to develop a financial analysis of the plant. Regular waste composition database should be developed and updated by the municipalities as it affects the accuracy of biogas production and related energy.

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