GHG benefits of using municipal solid waste as a fuel in a thermal treatment plant

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1 SUMMARY

In this study the greenhouse gas (GHG) benefits of generating energy from the thermal treatment of municipal solid waste (MSW) was compared with two landfill options; 1) with minimal gas flaring, 2) with gas recovery for electricity production. The lifecycle analysis conducted encompassed GHG emissions and removals from four main areas, transportation, process, disposal/use of by-products, and displaced emissions for a 30 year design life which would result in the disposal of 6 million tonnes of MSW.

The results listed in Table 1 indicate that thermal treatment with electricity recovery results in a small net reduction in terms of atmospheric GHG emissions compared with both landfill scenarios. If demand for heat from thermal treatment could be found the GHG benefit would increase considerably.

Table 1: Summary of Results (t CO_2eq. / t waste)

	Thermal Treatment	**Landfill 1**	**Landfill 2**
Transportation	0.004	0.005	0.005
Process emissions	0.33	1.17	0.44
Disposal/Use	-0.03	-0.32	-0.32
Displaced Emissions (Electricity Only)	-0.37	0	-0.04
Total	**-0.06**	**0.85**	**0.09**

The key assumptions that influenced the results were associated with the waste composition; the subsequent calorific value for the waste thermal treatment (WTT) process; the methane generation parameters and the gas extraction efficiency in the landfill scenarios. The results for the landfill and landfill gas flaring scenarios were quite robustness with uncertainty in the estimates of approximately 10%, however a larger uncertainty was associated with the second landfill scenario which involved gas recovery and electricity production due to the large range in the gas extraction efficiency.

While the waste composition available for thermal treatment is likely to change with the implementation of national recycling targets, it was shown that the implication on the GHG balance was such that it remained significantly lower than the best landfill scenario.

2 INTRODUCTION

Ireland produces over 2.3 million tonnes of municipal solid waste (MSW) each year. The treatment of MSW in the past has predominately been disposal in landfills with little or no pre-treatment. Currently more than 80% of MSW in Ireland is landfilled without pre-treatment [1], approximately 70% of which is putresible waste, or from biomass sources.

Under the EU Landfill Directive (1999/31/EC) Ireland is committed to reducing the amount of biodegradable waste in landfill to 35% by 2016. This is to be achieved through an integrated waste management (IWM) approach focused on the recovery of waste and its conversion into a new resource rather than disposal.

Ireland's IWM plan outlines a combination of recycling and landfill pre-treatment processes, which includes waste thermal treatment (WTT) with energy recovery. Local waste management plans throughout the country have provision for the development of WTT plants capable of processing almost 2 million tonnes of MSW. Sustainable Energy Ireland's (SEI) bioenergy strategy group predicts that this technology will feature strongly in reaching the reduced landfill targets (Pearse Buckley, personnel communication 2005) and subsequently make a contribution to the current national energy mix.

Energy generated as a result of the thermal treatment of the biodegradable component of MSW is considered renewable in terms of its impact on atmospheric greenhouse gas (GHG) concentrations as it comes from a biomass source [2]. Where this energy offsets the use of fossil fuels it can have a positive contribution to reducing GHG concentrations.

With the planning of Irelands first municipal WTT plant in its final stages the GHG impact of diverting waste from landfill is of interest to the national greenhouse gas inventory.

2 SCOPE

The primary focus of this study is the operational GHG impact of the proposed WTT plant with energy recovery in Carronstown, Co. Meath, Ireland.
The study assesses the GHG benefits of WTT approach through a lifecycle analysis comparison of replacing current waste disposal scenarios with WTT, those being

L1 Landfill disposal of the same quantity of waste with gas collected at the periphery and flared and there is no onsite treatment of leachate[1].

L2 Landfill disposal of the same quantity of waste according to best practice where the gas is collected efficiently and used to generate electricity. Includes the onsite treatment of leachate.[2]

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[1] Only 5 out of the total 40 Irish landfill operations recover gas to generate electricity [3].

[2] L2 describes typical best practice site operations which is required for new landfill sites and the most reasonable 'comparison' to the new WTT plant.

A lifecycle approach is taken to produce estimates of the impact of each scenario on atmospheric GHG concentrations over a 30 year design life encompassing;

- *Transportation* of the waste and any by-products arising from the treatment
- Direct emissions and energy used in the waste *treatment process* including any onsite operations
- Influences on atmospheric GHG through the *disposal or use* of by-products including any materials recycled or materials sequestered in landfill
- *Displaced Emissions* from energy recovered where that energy would have been generated by fossil fuels

The study does not take into consideration the construction and decommissioning of the waste treatment facilities as many other studies report its insignificance compared with the operation of the facilities [4].
Emissions from transportation excludes those associated with the door- to door collection of waste. This exclusion was considered to have only a small influence on the absolute level of emissions and relative results would not be affected as the collection element is the same for all three cases.

3 METHODOLOGY

3.1 Systems and their boundaries

3.1.1 Thermal Treatment

WTT is currently the most widely practiced waste management alternative to landfill in Europe [4]. The net climate change impact of WTT is dependant on a number of factors including the waste composition and the resulting CO_2 released from materials of fossil carbon (C) origin (i.e. plastics and some textiles). The other key factor is the percentage of energy recovered and utilised from the WTT plant, and the energy mix which it displaces
The WTT process typically has limited materials recycling capabilities with no waste separation procedures being undertaken prior to incineration. Ferrous materials are generally collected from the bottom ash following the incineration process..

The waste management facility proposed for Carranstown will service an area which generates approximately 500,000 tonnes of waste / yr. The plant will have the capacity to treat 200,000 tonnes of waste / yr or 40% of total waste generated in the region and will operate on average 7500 hr/annum. The plant design has a thermal capacity of 70MW and is designed to recover this heat to generate 16 MW of electricity. 3MW will be used to operate the plant and the remaining 13 MW will be exported to the national grid. There is no market for the excess heat at this stage.

The daily plant operation (Figure 1) involves the delivery of waste by road from as far as 100km. The trucks are weighed on entry from where they then proceed to an enclosed waste reception hall. The waste is tipped into the waste bunker with a holding capacity of 16, 000 m^3, or approximately 1 weeks fuel supply. The area is enclosed and maintained under negative air pressure to contain odour and litter. The waste is mixed in this bunker to produce a relatively uniform feedstock to the furnace.

From the bunker the waste is automatically lifted into a furnace feed hopper by the bunker grab and crane system. The ‘grate’ type furnace continually moves waste from the entrance side to the ash discharge side. The furnace retention time is 1 hour to ensure complete combustion in excess oxygen conditions. Following complete burnout the bottom ash is removed from the furnace via a water bath to the ash bunker where ferrous metals are removed and sent for recycling.

Residual ash represents 20% of the original weight (40,000 tonnes) and consists of inert bottom ash (30,000 tonnes) and a smaller quantity of hazardous waste arising from flue gas cleaning process (10,000 tonnes) [5]. Although the inert ash is a suitable raw material for use as road fill or the daily cover in landfill sites, following treatment in an ash recycling plant, no such plant is proposed and the ash will be sent to landfill. Hazardous ash will be transported off site for disposal in an appropriate landfill in Ireland or abroad.

The hot combustion gases leaving the furnace enter a boiler to recover the generated heat from the waste incineration process at an efficiency of 75%. The gas temperature at the inlet to the boiler is a minimum of 850°C with a residence time of at least two seconds (EU Directive on Incineration of Waste (2000/76/EC)). Steam leaves the boiler at a pressure of 40 bar, a temperature of 400°C and is expanded through a electricity generating turbine with a conversion efficiency of 20%. The stream leaves the turbine at 0.15bar and 50°C. The plant has an operating demand of 3MW. Currently there is no demand for excess heat from the process and is therefore not utilised.

3.1.2 Landfill Scenarios

Landfilling of biodegradable waste leads to the creation of anerobic conditions which in turn leads to the breakdown of biodegradable components (i.e. food and garden waste, paper and paper products, some textiles), and the release of landfill gas. This gas is typically 50% CH_4 and 50% CO_2 [6]. In landfill, municipal solid waste is broken down by either aerobic or anaerobic fermentation. Degradable organic matter is broken down into a stabilised organic residue (or compost), and water and carbon dioxide, the latter contributing to the composition of landfill gas.

The waste quickly becomes anoxic due to the high oxygen demand for bacterial respiration in sanitary landfills. Anaerobic fermentation of organic matter will take place if sufficient moisture is present. With the complete absence of oxygen, true anaerobic microorganisms, including methanogens, become established. Organic acids and hydrogen in the waste are then metabolised forming methane and carbon dioxide. If the methane migrates to areas of the landfill, which are operating under aerobic conditions, it may be oxidised to CO_2 by methanotrophic bacteria.

The CO_2 component of landfill gas is considered carbon neutral [6]. Methane however is not. Where this landfill gas is collected for energy generation it can offset fossil fuels and subsequently have both a direct (through conversion of CH_4 to CO_2[3])

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[3] CO_2 has a global warming potential 23 times less than CH_4. Once the CH_4 in the landfill gas is converted to CO_2, the CO_2 is considered carbon neutral, like the CO_2 component of landfill gas

and indirect (offset energy generated from fossil fuels) positive impact on atmospheric GHG concentrations.

Landfill gas is generated during the waste acceptance lifetime of the landfill and for some considerable time after waste has ceased being accepted. While this study considers an operational lifetime when the landfill is accepting waste for 30 years, landfill gas production will go on once the landfill has finished accepting waste. To accommodate this, it is normal practice in life cycle analysis to take account of all the gas which is emitted over a 100 year period in the analysis, not just that which is emitted while the landfill is operational.

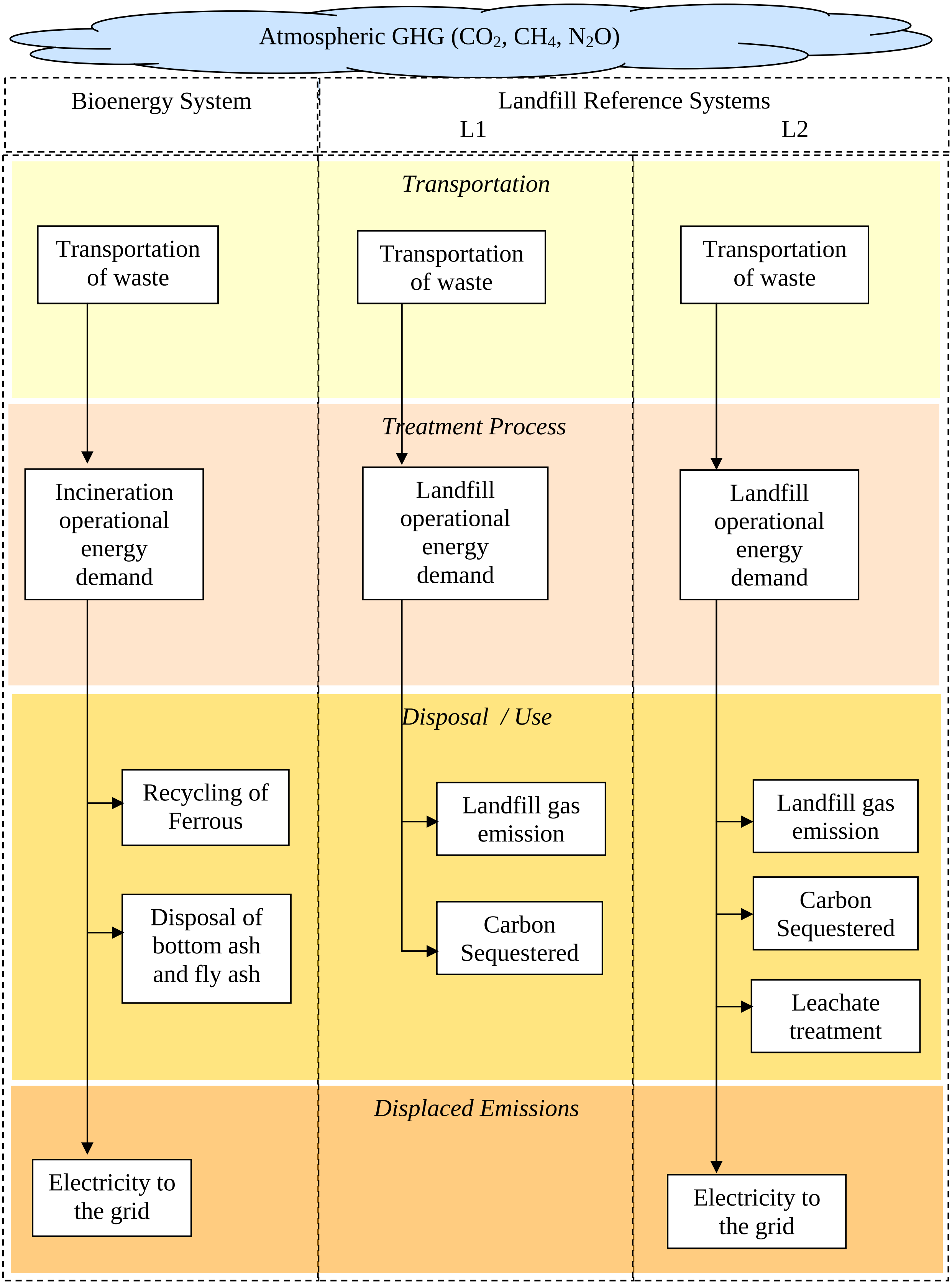

Figure 1: Lifecycle system boundary of the bioenergy system and the two landfill reference systems. The carbon sequestered in landfill contains both fossil (plastics) and biogenic carbon (unrotten wood, boards, paper etc).

Operational assumptions for reference system landfill were made as follows. Waste delivery to the site was considered the same as the incineration process where the landfill would service an area of up to 100km. The waste enters the site and is taken to a working area where it is tipped out. It is then spread and compacted using a large machine such as a bulldozer. Soil is also spread and compacted over the working area daily to minimise odour and wind blown litter. As areas reach the required depth a final cover of soil is spread and compacted. In addition to these machinery intensive operations, on sites managed for best practice electricity is required to operate its leachate and gas collection pumps.

In the case where a landfill has no gas control measures, the landfill gas migrates to the surface and is released through cracks and at the landfill edges. A small proportion (10%) of this gas is oxidised to CO_2 by microbial action as it passes though the soil . Alternatively where a gas collection system is in place the landfill is fitted with a low permeability liner and cover that prevents the release of gas in combination with a system of wells and pumps used to extract the gas for flaring or combustion in a gas engine.

The two landfill scenarios explored in this study had the following operational characteristics;

L1 – Limited gas collection, typical of the majority of existing landfills in Ireland. Gas collection occurs at site periphery with an efficiency of 20% and is subsequently flared with no energy recovery. The oxidation rate of the remaining CH_4 is assumed to be 10% [6].

L2 – Best practice in accordance with new EU Landfill Directive. Gas collection efficiency is assumed at 70% and as with L1 the oxidation rate of the remaining CH_4 is 10%.. Of the collected gas, 60% is used for energy production (with an energy conversion efficiency of 30%) and the remaining 40% of the collected gas is flared.

3.2 Calculations and Emission Factors

3.2.1 Transportation

The transportation of waste to the WTT plant was calculated based on distances travelled by each truck provided by the plat operators (Appendix 1) and typical CO_2 emissions expected from each vehicle (Table 2). Nitrous oxide emissions from a diesel heavy goods vehicle account for approximately 1% of the global warming impact of CO_2 emitted from such vehicles [7], and were also estimated.

Removal of non-hazardous waste from the WTT plant was assumed to be undertaken by empty trucks leaving the site on their return journey and thus was incorporated in the above calculations. Daily operational transport requirements for the WTT are expected to be 4 ML trucks per day [5]. It was assumed that Dublin would be the source of materials meaning each truck would travel approximately 40km per day.

The same waste collection and transportation scenario applies to landfill as to incineration as it was assumed that the location of the landfill would be in the vicinity of the WTT plant and that waste from a similar region would be collected and transported there.

Table 2. Greenhouse gas emissions by vehicle type

Vehicle Type	Capacity (t)	Emissions (kg CO_2 / km)
Small Lorry (SL)	3.5 – 7.5	0.45
Medium Lorry (ML) and Refuse collection vehicle (RCV)	7.5 – 20	0.71
Large Lorry (LL)	>20	0.84

Adapted from [4]

On site operations such as spreading and compaction of the waste are very site specific and can range between 0.44 l diesel fuel per tonne of waste disposed [4] to 0.81 l diesel fuel per tonne of waste disposed [4, 7]. The value used in this analysis was 0.44 l diesel fuel per tonne of waste disposed, which was based on practices in the UK and is likely to be closest to the techniques used in Ireland. A GHG emission factor for diesel of 2.7 kg CO_2/lt was applied [4].

3.2.2 Treatment Process

Throughout all calculations the waste was assumed to have the composition as reported in the National Waste Database (Table 3) [1]. Waste from electrical and electronic equipment (WEEE) was separated into its major components based on percentages reported by the Irish Environmental Protection Authority [1][4].

Table 3. Composition of Irish Waste Stream

Components	**Household**		**Commercial**		**Total**	
	%	*kt*	*%*	*kt*	*%*	*kt*
Paper	19	233	35	213	25	446
Glass*	4	46	2	9	3	55
Plastic*	14	169	12	73	13	242
Ferrous Metals*	2	23	1	7	2	30
Aluminium*	1	17	1	4	1	21
Other Metals*	0	6	1	8	1	13
Textiles	11	133	2	14	8	147
Organics	36	440	38	227	37	667
Wood*	1	11	1	3	1	15
Other*	11	136	8	46	10	182
Total	**100**	**1214**	**100**	**604**	**100**	**1818**

It should be noted that Ireland has very low recycling rates. While there is a curb side collection and recycling centres across the country, all glass, paper, and metal that is recovered is taken offshore for processing as there are no facilities operating in Ireland, subsequently internal demand for recyclable material is low.

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[4] WEEE was assumed to contain 48% Ferrous Metals, 4% Aluminium, 9% Other Metals, 21% Plastic, 5% Glass, 3% Wood and 10% Other [8].

Based on this data the waste was found to consist of 70 % biogenic material[5], 17 % fossil material[6] and 13 % inert material[7].

3.2.2.1 Thermal Treatment

IPCC Guidelines state that only CO_2 emissions from the incineration of C of fossil origin (i.e. plastics, certain textiles, rubber, liquid solvents and waste oil) need be reported according to Equation 1 [2].

$$CO_2 emission(t/yr) = IW \times CCW \times FCF \times EF \times 44/12 \qquad (1)$$

where;

IW = Amount of incinerated waste (200 000 tonnes/yr)
CCW = Fraction of C content in fossil based waste (0.56)[8]
FCF = Fraction of fossil carbon in waste (0.17)[9]
EF = burn out efficiency of incinerator (0.95)[10]

N_2O emissions from combustion are estimated as 0.05 kg / tonne waste [4].

3.2.2.2 Landfill Scenarios

The landfill gas emission model LandGEM [9] was used to estimate CO_2 and CH_4 emissions. This US developed model was chosen due to the lack of a relevant Irish model. This model is designed to simulate gas production in landfills accepting MSW with a high biogenic C content [10] The model has some limitations in its application to site specific conditions, however it is a simple model requiring a few inputs that are dependant on readily available data. It also produces comparable values with models developed in the UK [10], which experiences similar climatic conditions to Ireland, using less input data.

LandGem is a first order decomposition model (Equation 2) that estimates the landfill gas generation rate based on the potential methane generation capacity of the refuse, L_o (Mg CH_4 / Mg waste) and the methane generation decay rate, k.

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} kL_o \left(\frac{M_i}{10} \right) e^{-kt_{ij}} \qquad (2)$$

where;

Q_{CH4} = annual methane generation in the year of the calculation (m^3 / yr)
i = 1 – year time increment
n = (year of calculation) – (initial year of waste acceptance)
j = 0.1 – year time increment
k = methane generation rate (yr^{-1})
L_o= potential methane generation capacity (m^3 / Mg)

The selection of an appropriate methane generation rate (k) was based on guidance provided by the Intergovernmental Panel on Climate Change (IPCC) inventory

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[5] Made up from 100% Paper, Organics and Wood, 50% Textiles, and 40% Other
[6] Made up from 100% Plastics and WEE, 50% Textiles
[7] Made up from 100% Glass, Ferrous, Aluminium, Other Metals and 60% Other
[8] Based on 0.61 for plastic component and 0.39 for textiles component [4]
[9] Based of results reported in Table 3
[10] Taken from [3]

guidelines [2]. The range expected for k is reportedly between 0.03 and 0.2 and is dependant on waste composition and decay rates which are influenced by site moisture conditions. Given the annual rainfall in Ireland is high and the relatively high biodegradable fraction of the waste stream, a value of 0.1 applied.

According to international inventory reporting guidelines [2] L_o is calculated as follows;

$$L_o = (MCF \times DOC \times DOC_F \times F \times (16/12) \qquad (3)$$

where;

MCF = methane correction factor (default =1)
DOC = degradable organic C fraction (Mg C / Mg MSW)
DOC_F = fraction of DOC dissimilated (default = 0.55)
F = fraction by volume of CH_4 in landfill gas (default = 0.5)

and

$$DOC = (0.4A) + (0.16B) +(0.3C) \qquad (4)$$

where;

A = fraction of paper and the biogenic component of textiles and other in MSW stream (33 % from Table 3)
B = fraction of organic waste in MSW stream (37 % from Table 3)
C = fraction of wood in MSW (1 % from Table 3)

Therefore, DOC = 0.194, and subsequently,

$L_o = (1 \times 0.194 \times 0.55 \times 0.5 \times (16/12) = 0.0714$ (Mg CH_4 / Mg waste), or

$L_o = 105\ m^3$ / Mg waste

Applying these figures in the LandGEM model produced an emissions graph for methane and carbon dioxide (Figure 2), which was used as the basis of calculations.

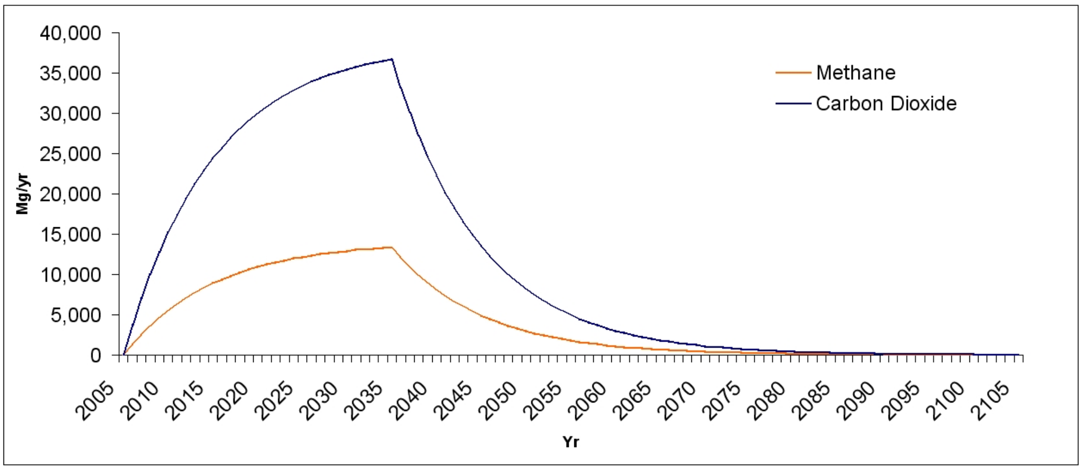

Figure 2. Annual CH_4 and CO_2 emissions from the landfill over 100 year design life

For scenario L1, 20% of the methane is collected and flared converting it to CO_2. A further 10% of the methane is assumed to be oxidise in the surface layer leaving the remaining methane emitted to the atmosphere.

For scenario L2, gas extraction efficiency is assumed to be 70% and this gas is then flared or combusted in an engine. Under this scenario 10% of the remaining methane is again assumed to be oxidised and the remainder emitted.

On site landfill operations require approximately 0.1 kWh of electricity per tonne of land filled waste [11]. Under scenario L1 this was assumed to be sourced from the national grid. Under scenario L2 it was assumed that the energy requirements would be met by onsite electricity generation and is accounted for by discounting the reduction associated with displaced emissions (see below).

3.2.3 Disposal / Use

Each option generates or recovers by-products that are either reused/recycled or disposed of. These can have both positive and negative GHG implications.

3.2.3.1 Thermal Treatment

Following the incineration process, the collection and transportation and disposal or further treatment of by-products such as bottom ash, fly ash and ferrous metals was included in the analysis.

Bottom ash is non hazardous material and was assumed to be transported off site to a nearby landfill in Drogheda, approximately 6km away.

All fly ash requiring hazardous waste disposal requires off shore transportation by specialist trucks due to the lack of a suitable facility in Ireland. The company running the incinerator has a suitable landfill in Antwerp and it is assumed that the ash would be transported here via truck (and ferry) for disposal. The total distance by road is 488.2 km and the quantity of ash generated requires 455 trucks with a capacity of 22 t per year. The contribution of emissions arising from ferry travel were considered negligible and therefore only the road distance was applied in calculations.

The collection of ferrous metals is undertaken from the bottom ash following incineration. These metals constitute 2% of the waste stream being equivalent to 4000 t / yr and it is assumed that all of this metal is steel and that it will all be recycled. Recycling steel avoids emissions of 1.49 t CO_2 eq / t of metal recovered compared to the production of virgin steel [4]. This includes all associated GHG emissions from transportation, treatment processes, and the disposal/use of any by-products.

3.2.3.2 Landfill

Leachate from landfills can pose an environmental risk to the surrounding water quality. Sites that operate to best practice collect this leachate and treat it onsite, which requires energy inputs. In this analysis we assumed that 1% of the C in biodegradable waste is emitted as chemical oxygen demand (COD) to the leachate and that 1 gram of C is equivalent to 3 grams of COD [11]. COD recovery rates for treatment were assumed to be 70%. The treatment process involves biological treatment, precipitation, chemical oxidation, sand filtration, activated C adsorption and sludge treatment resulting in an energy demand of 215 kWh / t COD treated [11]. Assuming that the 140,000 t of biogenic waste disposed of annually has an average carbon content of 25%, approximately, 1050 t of COD annually would require treatment resulting in an energy demand of 30kW. As such leachate treatment plants are installed in sites operating to best practice this process was only included in the L2 scenario and the energy required came from the onsite generation from landfill gas.

Landfill of material can also lead to the long term sequestration of biogenic C which is calculated as;

$$LongtermC_{biogenic} = DOC \times (1 - DOC_F) \times 44/12 \qquad (5)$$

Therefore;
0.194 x (1- 0.55) x 44/12 = 0.320 t CO_2 / t waste, which is equivalent to 1920600 t CO_2 over the life of the landfill.

Fossil C (i.e. plastic material and fossil fuel based textiles) can also be sequestered in landfill however its inclusion in any GHG lifecycle analysis would be double counting. This is because the C in such materials was already ‘locked up’ in fossil fuels and then in plastic, for example, so there is no change in its status. Alternatively, biogenic C, locked up in landfills, can be considered to have been removed from the natural carbon cycle and should therefore receive a credit for reducing CO_2 emissions.

3.2.4 Displaced Emissions

4.2.4.1 Thermal Treatment

Currently the plant is designed to generate electricity only from the heat produced during the process. There are no plans for a combined heat and power plant (CHP) at this stage. Nonetheless the potential savings from capturing this heat are of interest and the calculations are included for comparisons.

Displaced emissions were calculated on the basis of the net calorific value of the waste in 2000 (Table 4), electricity (20%) and heat (50%) conversion efficiencies according to Equation 6.

$$DE = CV \times ECE \times EF \times 277.8 \quad (7)$$

where;
DE = displaced emissions (kg CO_2 /tonne of waste)
CV = calorific value of waste (GJ / tonne of waste)
ECE = energy conversion efficiency (%)
EF = national energy emission factor (kg CO2 / kWh)

The onsite operational energy demand of 3MW was subtracted from the potential energy generation capacity with the rest being exported to the grid.

The average Irish emissions factor for grid generated electricity of 0.624 kg CO_2 / kWh [12] was applied in calculations for displaced emissions for both incineration and landfill scenarios.

Displaced CO_2 emissions arising from the utilisation of surplus heat were calculated based on replacing an oil fired boiler, with a heat conversion efficiency of 50%. The emission factor of heating oil was assumed to be 74.9 kg CO_2/ GJ[11].

Table 4: Net Calorific Value (NCV) of MSW in Ireland in 2000

Component	CV (GJ/tonne of waste component)[a]	% contribution by weight to WTT	Calorific values contribution (GJ/tonne MSW)
Paper/Cardboard	11.5	24.5	2.82
Organics	3.98	36.7	1.46
Plastics	31.5	13.2	4.16
Glass	0	3.7	0
Metals	0	3.1	0
Textiles	14.6	8.1	1.18
Other	8.4	11.4	0.96
Total			**10.58**

a. Taken from [4]
b. Taken from SEI bioenergy strategy group, data supplied by Pearse Buckley SEI, April, 2005

3.2.4.1 Landfill

Displaced emissions are only relevant to the energy generated from landfill gas under scenario L2. The assumptions for gas recovery of 70%, collection and energy conversion efficiencies of 60% and 30% respectively and a calorific value for landfill gas of 16 MJ / m^3, were applied to the methane production estimates from LandGem to calculate a generation capacity of 5.73MW.
After meeting the onsite energy demands approximately 4.6 MW of excess electricity is available for export to the grid.

3.2.5 Unceratainty and Sensitivity Analysis

An uncertainty and sensitivity analysis was conducted using the Monte Carlo based software package Crystal Ball© [13]. Each parameter was assigned an uncertainty range (Table 5) and the simulation run with 10,000 iterations. The total uncertainty

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[11] Sourced from http://www.aie.org.au/melb/material/resource/fuels.htm

associated with the total estimates of GHG impact of each scenario were calculated based these possible parameter ranges.

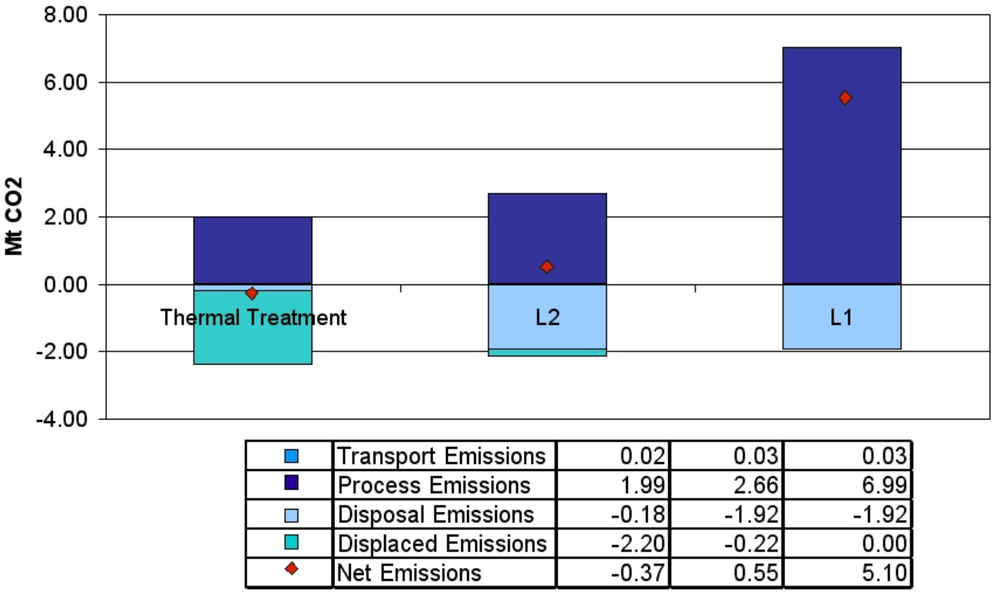
Table 5: Parameters and applied uncertainty

Parameter	**Value**	**Uncertainty / Range**
Transporation		
Small Lorry (SL) (kg CO_2 / km)	0.45	10 %
Medium Lorry (ML) and Refuse collection vehicle (RCV) (kg CO_2 / km)	0.71	10 %
Large Lorry (LL) (kg CO_2 / km)	0.84	10 %
Total distance travelled (km)	various	2%
National energy emission factor (kg CO_2 / kWh)	0.624	5 %
Process		
Quantity of waste (t)	200000	180000 - 200000
C content of fossil component (%)	0.58	10%
Fossil waste in MSW stream (%)	0.18	5%
Incinerator burn out efficiency (%)	0.95	0.95 - 0.99
L_o	105	8%
Fraction of CH_4 in landfill gas (%)	0.5	0.4 – 0.60
Methane generation rate, k (yr^{-1})	0.1	0.07 - 0.12
Gas extraction efficiency (%)	0.7	0.6 – 0.9
% landfill gas flared	0.2	10 %
% landfill gas oxidised at surface	0.1	2 %
Disposal/Use		
Recycling of ferrous material (t)	4000	10%
Ferrous recycling emission factor (kg CO_2 / t)	-1490	10%
DOC	0.194	5%
DOC_F	0.55	0.5 – 0.6
Displaced Emissions		
Electricity generation efficiency (%)	0.20	0.18 – 0.22
Heat recovery efficiency (%)	0.50	0.44 – 0.55
Calorific value of MSW (GJ / t)	10.58	10.00 – 12.50
GHG emission factor heating oil (kg / GJ)	74.9	5%
Irish emission factor for grid generated electricity (kg / kWh)	0.624	5%
Energy utilisation efficiency (%)	0.6	10 %
Energy conversion efficiency	0.3	5 %
Calorific value of landfill gas (MJ / m^3)	16	12-18

1 Influenced by reduction in composition % of fossil waste in MSW stream following implementation of national waste management targets including increased recycling rates.

4 RESULTS

The results of the full lifetime of each project (i.e. 30 years) indicate that incineration of MSW provided the best option in terms of GHG emissions (Figure 3). In all scenarios investigated the process emissions dominated the GHG balance, however the displaced emissions provided by the generation of electricity from the thermal treatment of waste more than offset this resulting in a net reduction in GHG emissions. In all cases the impact of waste transportation had no significant effect.



■	Transport Emissions	0.02	0.03	0.03
■	Process Emissions	1.99	2.66	6.99
■	Disposal Emissions	-0.18	-1.92	-1.92
■	Displaced Emissions	-2.20	-0.22	0.00
◆	Net Emissions	-0.37	0.55	5.10

Figure 3: Total lifecycle greenhouse gas flux (Mt CO_2) of each waste treatment scenario. Thermal treatment balance does not take into consideration the utilisation of process heat.

The break down of each sector for each scenario is provided in Tables 6, 7and 8 and then recalculated on a tCO_2 / t waste basis for the process lifetime (Figure 4).

4.1 Incineration

Table 6. GHG balance of incineration process (t CO_2eq)

	CO_2	CH_4	N_2O	Total
Transportation				
Waste to site[a]	21,500		200	22,000
Consumables from operation	200		2	200
Process				
Emissions from fossil C incineration	1,989,700		300	1,990,000
Disposal/Use				
Recycling of Ferrous material	-178,800			-178,800
Ash Disposal[b]	200		2	202
Displaced Emissions				
Electricity	-2,200,000			-2,200,000
Heat	-2,377,000			-2,377,000
Total (Electricity only)	**-367,200**		**502**	**-366,400**
Total (CHP)	**-2,744,200**		**502**	**-2743,400**

a. Takes into account the return journey of empty truck.

b. 68% attributed to transportation to hazardous waste landfill in Antwerp and 32% to transportation to local MSW landfill.

4.2 Landfill Scenarios

Table 7. GHG balance of L1 landfill process (t CO_2eq)

	CO_2	CH_4	N_2O	Total
Transportation				
Waste to site	21,500		260	21,700
On site operations[a]	7,200		90	7,300
Process				
Methane emitted[b]		7,000,000		7,000,000
On site electricity demand[c]	400			400
Disposal/Use				
Sequestration[d]	-1,920,000			-1,920,000
Displaced Emissions				
Total	**-1,890,000**	**7,000,000**	**350**	**5,109,000**

a. Onsite operations were assumed to occur for 30 years while waste is transported to site.
b. Result following flaring 20% and 10% surface oxidation to CO_2
c. Accounts for annual demand of 2000kWh for 30 year operational life
d. Includes non dissimilated C and fossil C in plastics

Table 8. GHG balance of L2 landfill process (t CO_2eq)

	CO_2	CH_4	N_2O	Total
Transportation				
Waste to site	21,500		260	21,700
On site operations[a]	7,200		90	7,300
Process				
Methane emitted[b]		2,656,000		2,656,000
On site electricity demand[c]	6,000			6,000
Disposal/Use				
Sequestration[d]	-1,921,000			-1,921,000
Displaced Emissions				
Electricity production	-217,000			-217,000
Total	**-2,103,000**	**2,656,000**	**350**	**553,000**

a. Onsite operations were assumed to occur for 30 years while waste is transported to site.
b. Result following 70% efficiency in landfill gas collection and 10% surface oxidation to CO_2. Assuming that remaining landfill gas is 50% CH_4.
c. Includes energy demand for general operation as with L1 and leachate treatment
d. Includes non dissimilated C and fossil C in plastics

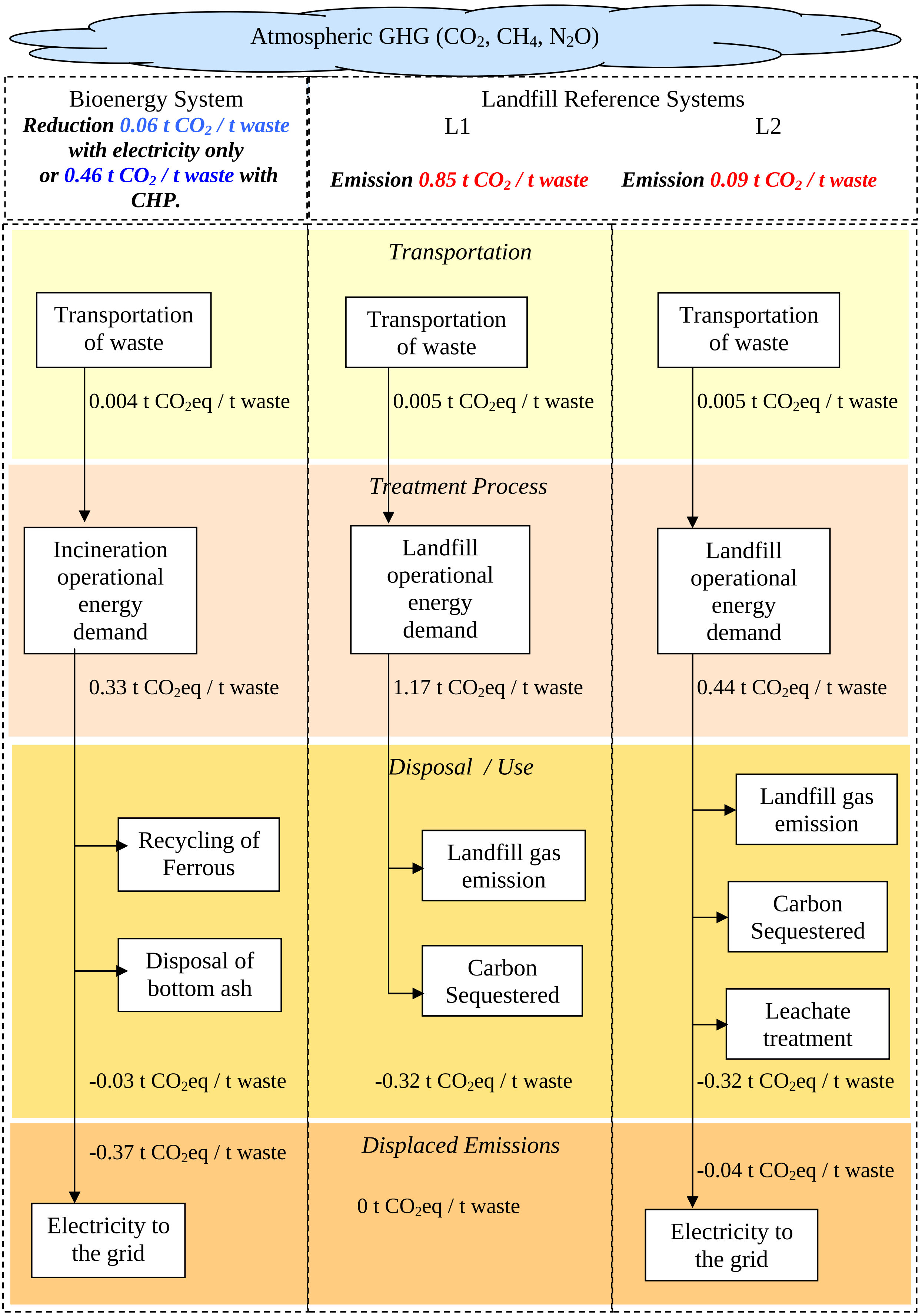


Figure 4: Comparison between bioenergy and references systems of emissions or reductions in CO_2 eq / t waste for each stage in the lifecycle analysis.

4.3 Uncertainty and Sensitivity Analysis

Uncertainty in the estimates generated for the WTT scenarios were 11% for both the heat and electricity options. A total uncertainty of 10% was calculated for the L1 option, which was increased significantly to 42% for the L2 scenario. This uncertainty assessment indicated that the GHG lifecycle estimates were significantly different and that the ranking of treatment option in terms of their GHG benefit was not altered.

The large uncertainty associated with the L2 scenario estimates was driven by the extraction efficiency of the gas for use in energy conversion, which was responsible for approximately 55% of the variance from the mean estimate following a sensitivity analysis (Figure 5). The other key parameters identified in the sensitivity analysis are not surprising given that most of the relationships in the model developed for this lifecycle analysis are linear. However, it was identified that the waste composition and resulting calorific waste make a significant contribution to the end estimate.

Given that the composition of MSW waste is very likely to change due to the recycling target outlined in the national waste management plan [14], the impact on the potential GHG budget calculated in this analysis is of interest. Increased recycling rates will impact on GHG balance of the WTT plant by altering both the calorific value of the waste and the amount of recovered metals collected from the bottom ash for recycling.

Applying the national target for 2010 and 2020 resulted in the calorific value of waste available for WTT reducing to 8.95 by 2020 (Table 9). Additionally the amount of ferrous material collected from the bottom ash fell from 4000 t in 2005 to 600 t in 2010 and 2020.

Table 9: Change in NCV of waste available for WTT following the implementation of national recycling targets in 2010 and 2020.

		Waste Composition for WTT			Component NCV Contribution		
Component	NCV (GJ / t)	2004	2010	2020	2004	2010	2020
Paper	11.50	0.25	0.21	0.17	2.82	2.42	1.96
Organics	3.98	0.37	0.50	0.54	1.46	1.99	2.15
Plastic	31.50	0.13	0.12	0.10	4.16	3.78	3.15
Glass	0.00	0.03	0.01	0.01	0.00	0.00	0.00
Metals	0.00	0.03	0.00	0.00	0.00	0.00	0.00
Textiles	14.60	0.08	0.03	0.03	1.18	0.44	0.44
Other	8.40	0.11	0.14	0.15	0.96	1.18	1.26
	Average Net Calorific Value (GJ / t waste)				**10.58**	**9.80**	**8.95**

When the GHG emission per tonne of waste was recalculated based on these assumptions, the balance showed a reduction in GHG emissions of 0.01 t CO_2 / t waste in 2010 however in 2020 the plant emitted 0.02 t CO_2 / t waste. Even though the plant become a net contributor to atmospheric GHG under the 2020 waste composition assumptions, the WTT plant emissions still remained significantly lower than the best landfill scenario.

Figure 5: Contribution to variation in the mean estimates by model input parameters for A)WTT with electricity production only. B)WTT with combined heat and power recovery, C)Landfill with no electricity generation, D) Landfill with gas recovery for electricity generation

5 DISCUSSION AND CONCLUSIONS

The incineration of waste resulted in the reduction of GHG emissions by 0.06 t CO_2 eq. / t waste compared to emissions of between 0.09 and 0.83 t CO_2 eq. / t waste for the landfill scenarios. If the heat from the incineration process could be utilised the benefits would be greatly increased to a reduction of 0.46 t CO_2 eq / t waste. Should Ireland meet its thermal treatment capacity as outlined by the EPA [1] a GHG reduction potential could be created equivalent to 180,000 t CO_2 eq per year. If the full CHP potential of these operations could be realised, the GHG reduction potential could be increased to 920,000 t CO_2 eq. per year.

While incineration is new to Ireland and features strongly in the long term management of MSW [14], materials recycling is the preferred option in the waste management hierarchy. It is been shown that materials recycling generally results in the lowest net GHG flux [4, 15].
Although Ireland includes recycling of materials in its waste management plan, and has in various collection options in place (i.e. kerbside and recycling centres), all materials collected are transported off shore for processing as there are no recycling plants located in the country. Therefore internal demand for recyclable materials is low and exporting for processing results in added cost both economically and environmentally. More importantly any benefits from recycling materials would be accounted for in the country where the process took place. Therefore under current processing conditions, any GHG benefits of recycling Irish waste would not appear in the national GHG inventory.

The GHG balance calculated for the landfill scenarios should also be discussed in the context of national GHG inventories. While avoided CO_2 emissions from sequestration of some of the carbon in the biogenic waste in the landfill should be calculated in this type of comparison, these avoided emissions would not be reflected in Irelands national greenhouse inventory. If the results are considered in this context then the emissions from the landfill scenarios are significantly increased to 0.41 t CO_2 eq / t waste under L2 and 1.17 t CO_2 eq. / t waste under L1.

The results if this work show that changing waste management option from landfill to thermal treatment with energy recovery will reduce the net GHG flux associated with MSW disposal, however increased recycling rates are likely to have an impact on the GHG balance of the plant in the future.

6 APPENDIX 1

Town	Distance to Facility (km)	Number of truck loads annually	
		ML	LL
Carronstown	0.5	18	
Drogheda	6	2737	
Ardee	31.4	350	
Duleek	2.7	222	
Dunleer	0.5	91	
Navan	29.4	1713	
Dundalk	39.9	2868	
Kingscourt	54.5		76
Kells	45.3	613	
Carrickmacross	56.0		221
Laytown	10.0	495	
Ashbourne	19.2	562	
Dunshaughlin	38.4	271	
Ratoath	32.5	235	
Athboy	47.8	210	
Enfield	78	228	
Bailiebourogh	67.9	75	96
Trim	44.4	286	
Castleblaney	100.7		169
Dunboyne	42.0	499	
Coothill	98.5		111
Virginia	64.0	261	63
Monaghan	87.6		341
Cavan	93.5		351
Clones	107.1		112
Belturbet	107.8		75

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