

**THE ADDITION OF BIOMETHANE
TO GHGENIUS**

Prepared For:

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EXECUTIVE SUMMARY

The GHGenius model has been developed for Natural Resources Canada over the past ten years. It is based on the 1998 version of Dr. Mark Delucchi's Lifecycle Emissions Model (LEM). GHGenius is capable of analyzing the energy balance and emissions of many contaminants associated with the production and use of traditional and alternative transportation fuels.

GHGenius is capable of estimating life cycle emissions of the primary greenhouse gases and the criteria pollutants from combustion sources. The specific gases that are included in the model include:

- Carbon dioxide (CO₂),
- Methane (CH₄),
- Nitrous oxide (N₂O),
- Chlorofluorocarbons (CFC-12),
- Hydro fluorocarbons (HFC-134a),
- The CO₂-equivalent of all of the contaminants above.
- Carbon monoxide (CO),
- Nitrogen oxides (NO_x),
- Non-methane organic compounds (NMOCs), weighted by their ozone forming potential,
- Sulphur dioxide (SO₂),
- Total particulate matter.

The model is capable of analyzing the emissions from conventional and alternative fuelled internal combustion engines or fuel cells for light duty vehicles, for class 3-7 medium-duty trucks, for class 8 heavy-duty trucks, for urban buses and for a combination of buses and trucks, and for light duty battery powered electric vehicles. There are over 200 vehicle and fuel combinations possible with the model.

There is increased interest in bio-methane in the transportation sector. This term means different things to different people but would typically include landfill gas and the output from anaerobic digestion. The production of landfill gas is already included in GHGenius as a feedstock for methanol production but for this work its use is expanded to compress the gas and use it as CNG or liquefy it to produce LNG.

Anaerobic digestion of biological waste and agricultural residues is a rapidly expanding industry in Europe. Part of the drive there is a result of significant government incentives but there will be situations in Canada where environmental requirements drive the application of this technology and we will likely see some further expansion of the availability of bio-methane in Canada.

Anaerobic digestion (AD) is applied using mostly waste materials (manure, food and beverage wastes, etc.) rather than AD involving feedstocks grown specifically to produce biogas. It is unlikely that this later option will be adopted in North America unless the value of the biogas approaches that in the very heavily subsidized European markets. Hay, as a substitute for silage, as a feedstock for the AD process is modelled so that some sensitivity to non-waste products can be accessed. The structure of the model has been set so that any of the four agricultural residues can be used as a feedstock, either alone or in combination with manure.

The gas from the landfill or the digester will be cleaned up and either compressed or liquefied so that it can be used as a transportation fuel for light and heavy-duty applications.

The necessary changes have been made to the macros to ensure that the sensitivity solvers, Monte Carlo simulator, and other macros all function with the additional sheet in the model. The version of the model that accompanies this report is 3.15.

Two distinct biomethane pathways, upgrading landfill gas and using anaerobic digestion, have been added to the GHGenius model. Each can be compared to gasoline and diesel fuel as well as to fossil natural gas on an energy balance basis and a GHG emissions basis. The total and fossil energy balances are shown in the following tables. Not surprisingly the landfill gas option has a better total and fossil energy balance since less inputs are required to operate a landfill compared to an anaerobic digestion system.

Table ES- 1 Total Energy Balance Comparison – Gasoline and Natural Gas

Fuel	Gasoline	CNG	CNG	CNG
Feedstock	Crude Oil	Fossil NG	Landfill Gas	AD Gas
2009				
Joules consumed/joule delivered				
Fuel dispensing	0.0024	0.0227	0.0227	0.0227
Fuel distribution, storage	0.0068	0.0307	0.0000	0.0000
Fuel production	0.1708	0.0249	0.0659	0.2886
Feedstock transmission	0.0132	0.0000	0.0000	0.0053
Feedstock recovery	0.1126	0.0263	0.0000	0.0114
Ag. Chemical manufacture	0.0000	0.0000	0.0000	0.0117
Co-product credits	-0.0013	0.0000	0.0000	0.0000
Total	0.3044	0.1046	0.0886	0.3397
Net Energy Ratio (J delivered/J consumed)	3.2855	9.5622	11.2894	2.9442

Table ES- 2 Fossil Energy Balance Comparison – Gasoline and Natural Gas

Fuel	Gasoline	CNG	CNG	CNG
Feedstock	Crude Oil	Fossil NG	Landfill Gas	AD Gas
2009				
Joules consumed/joule delivered				
Fuel dispensing	0.0006	0.0060	0.0060	0.0060
Fuel distribution, storage	0.0056	0.0299	0.0000	0.0000
Fuel production	0.1608	0.0234	0.0175	0.0506
Feedstock transmission	0.0105	0.0000	0.0000	0.0053
Feedstock recovery	0.1014	0.0226	0.0000	0.0112
Ag. Chemical manufacture	0.0000	0.0000	0.0000	0.0112
Co-product credits	-0.0012	0.0000	0.0000	0.0000
Total	0.2777	0.0819	0.0235	0.0843
Net Energy Ratio (J delivered/J consumed)	3.6011	12.2147	42.6105	11.8676

The GHG emission comparisons for the two biomethane pathways are compared in the following table using the diesel heavy-duty vehicle option as a basis for comparison. There is a relatively small difference in the GHG emissions between these two biomethane pathways

when the default values for the input assumptions are used but the AD systems provides a slightly larger GHG emission benefit. The GHG emission reductions provided by these systems is significant. In the AD system, the emission reduction provided by the reduced mass of digestate spread on the land compared to manure provides a GHG emission credit that offsets the better energy balance of the landfill gas system.

Table ES- 3 Comparison of GHG Emissions - Diesel and Natural Gas - HDV

Fuel	Diesel	CNG	CNG	CNG
Feedstock	Crude Oil	Fossil Natural Gas	Landfill Gas	AD Gas
Year	2009			
	g CO ₂ eq/km			
Vehicle operation	1,112.0	972.5	972.5	972.5
C in end-use fuel from CO ₂ in air	0.0	0.0	-926.4	-926.4
Net Vehicle Operation	1,112.0	972.5	46.1	46.1
Fuel dispensing	1.8	20.0	20.0	20.0
Fuel storage and distribution	7.6	36.5	0.0	0.0
Fuel production	132.5	25.5	58.2	192.5
Feedstock transport	16.7	0.0	0.0	7.6
Feedstock and fertilizer production	128.0	31.6	0.0	35.6
Land use changes and cultivation	0.0	0.0	0.0	32.9
CH ₄ and CO ₂ leaks and flares	30.1	77.6	27.3	0.0
Emissions displaced by co-products	-1.9	0.0	0.0	-233.1
Sub total (fuelcycle)	1,426.7	1,163.9	151.7	101.7
% Changes (fuelcycle)		-18.4	-89.4	-92.9
GHG Reductions g CO ₂ eq/kg of natural gas		722	3,605	3,783

TABLE OF CONTENTS

EXECUTIVE SUMMARY	I
TABLE OF CONTENTS	V
LIST OF TABLES.....	VI
LIST OF FIGURES.....	VI
1. INTRODUCTION	1
1.1 SCOPE OF WORK	3
2. LANDFILL GAS.....	5
2.1 LANDFILL GAS SYSTEMS.....	5
2.1.1 Gas Collection Wells	6
2.1.2 Condensate Collection and Treatment.....	6
2.1.3 Blower/Compressor	6
2.1.4 Gas Treatment Systems	6
2.1.5 Landfill Gas Process Energy Requirements.....	7
2.1.5.1 Scrubbing Systems	7
2.1.5.2 Membrane Systems	8
2.1.5.3 PSA Systems	8
2.2 COMPRESSION AND DISPENSING SYSTEMS.....	8
2.3 REFERENCE SYSTEM.....	9
3. ANAEROBIC DIGESTION	10
3.1 SYSTEM BOUNDARIES	11
3.2 FEEDSTOCKS	12
3.2.1 Agricultural Residues	13
3.2.2 Manure.....	13
3.3 PROCESS PARAMETERS	13
4. NATURAL GAS USE	16
4.1 HEAVY DUTY SPARK IGNITED ENGINES.....	16
4.2 HEAVY DUTY COMPRESSION IGNITED ENGINES.....	16
5. LIFECYCLE RESULTS.....	18
5.1 LANDFILL GAS.....	18
5.1.1 Energy Balance.....	18
5.1.2 GHG Emissions	19
5.2 ANAEROBIC DIGESTION.....	22
5.2.1 Energy Balance.....	22
5.2.2 GHG Emissions	23
6. DISCUSSION.....	26
6.1 COMPARISON OF THE BIOMETHANE PATHWAYS.....	26
6.2 SENSITIVITY ANALYSIS.....	27
6.3 CRITERIA AIR CONTAMINANTS.....	29

7. REFERENCES	30
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LIST OF TABLES

TABLE 2-1	LANDFILL GAS TREATMENT EFFECTIVENESS	7
TABLE 2-2	ENERGY REQUIREMENTS FOR GAS TREATMENT	8
TABLE 3-1	MANURE PROPERTIES	13
TABLE 3-2	PERFORMANCE OF EUROPEAN AD SYSTEMS	14
TABLE 3-3	ENERGY YIELD OF VARIOUS SUBSTRATES.....	14
TABLE 3-4	ANAEROBIC DIGESTION MASS AND ENERGY BALANCE	15
TABLE 4-1	LNG RELATIVE EFFICIENCY	17
TABLE 5-1	TOTAL ENERGY BALANCE COMPARISON – GASOLINE AND NATURAL GAS	18
TABLE 5-2	FOSSIL ENERGY BALANCE COMPARISON – GASOLINE AND NATURAL GAS	19
TABLE 5-3	COMPARISON OF GHG EMISSIONS - GASOLINE AND NATURAL GAS - LDV	19
TABLE 5-4	COMPARISON OF GHG EMISSIONS - DIESEL AND NATURAL GAS – HDV	20
TABLE 5-5	COMPARISON OF GHG EMISSIONS - GASOLINE AND NATURAL GAS - LDV	21
TABLE 5-6	COMPARISON OF GHG EMISSIONS - DIESEL AND NATURAL GAS - HDV	21
TABLE 5-7	TOTAL ENERGY BALANCE COMPARISON – GASOLINE AND NATURAL GAS	22
TABLE 5-8	FOSSIL ENERGY BALANCE COMPARISON – GASOLINE AND NATURAL GAS	23
TABLE 5-9	COMPARISON OF GHG EMISSIONS - GASOLINE AND NATURAL GAS - LDV	23
TABLE 5-10	COMPARISON OF GHG EMISSIONS - DIESEL AND NATURAL GAS – HDV	24
TABLE 5-11	COMPARISON OF GHG EMISSIONS - GASOLINE AND NATURAL GAS - LDV	25
TABLE 5-12	COMPARISON OF GHG EMISSIONS - DIESEL AND NATURAL GAS - HDV	25
TABLE 6-1	TOTAL ENERGY BALANCE COMPARISON – GASOLINE AND NATURAL GAS	26
TABLE 6-2	FOSSIL ENERGY BALANCE COMPARISON – GASOLINE AND NATURAL GAS	26
TABLE 6-3	COMPARISON OF GHG EMISSIONS - DIESEL AND NATURAL GAS - HDV	27
TABLE 6-4	IMPACT OF FEEDSTOCK ON AD EMISSION PERFORMANCE	29
TABLE 6-5	CRITERIA AIR CONTAMINANT COMPARISON.....	29

LIST OF FIGURES

FIGURE 1-1	LIFECYCLE STAGES	3
FIGURE 2-1	LANDFILL GAS TREATMENT	7
FIGURE 3-1	ANAEROBIC DIGESTION SYSTEM SCHEMATIC.....	10
FIGURE 3-2	N ₂ O EMISSION RATE COMPARISON - RAW VS. DIGESTED MANURE	12
FIGURE 6-1	IMPACT OF ELECTRIC POWER CONSUMED ON GHG EMISSIONS REDUCED	28

1. INTRODUCTION

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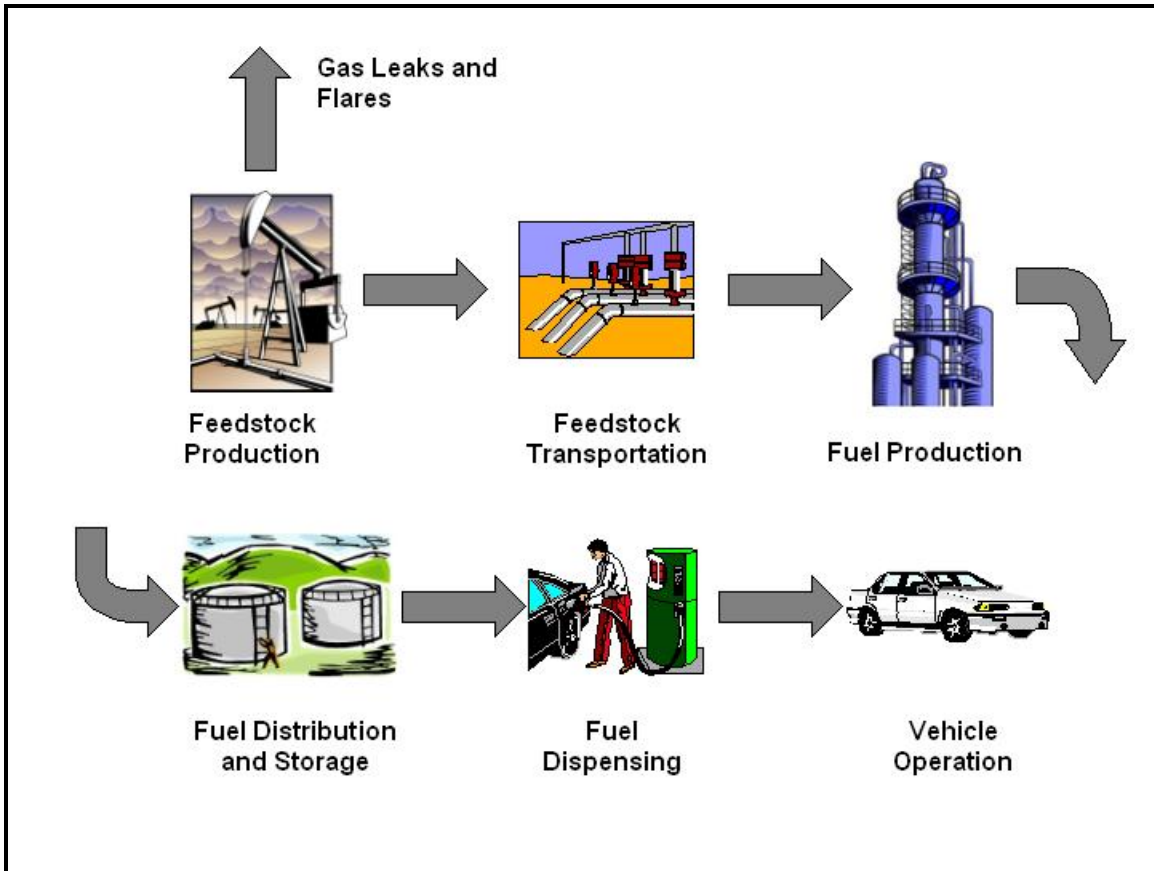
GHGenius can predict emissions for past, present and future years through to 2050 using historical data or correlations for changes in energy and process parameters with time that are stored in the model. The fuel cycle segments considered in the model are as follows:

- Vehicle Operation
Emissions associated with the use of the fuel in the vehicle. Includes all greenhouse gases.
- Fuel Dispensing at the Retail Level
Emissions associated with the transfer of the fuel at a service station from storage into the vehicles. Includes electricity for pumping, fugitive emissions and spills.
- Fuel Storage and Distribution at all Stages
Emissions associated with storage and handling of fuel products at terminals, bulk plants and service stations. Includes storage emissions, electricity for pumping, space heating and lighting.
- Fuel Production (as in production from raw materials)
Direct and indirect emissions associated with conversion of the feedstock into a saleable fuel product. Includes process emissions, combustion emissions for process heat/steam, electricity generation, fugitive emissions and emissions from the life cycle of chemicals used for fuel production cycles.
- Feedstock Transport

- Direct and indirect emissions from transport of feedstock, including pumping, compression, leaks, fugitive emissions, and transportation from point of origin to the fuel refining plant. Import/export, transport distances and the modes of transport are considered. Includes energy and emissions associated with the transportation infrastructure construction and maintenance (trucks, trains, ships, pipelines, etc.)
- Feedstock Production and Recovery
Direct and indirect emissions from recovery and processing of the raw feedstock, including fugitive emissions from storage, handling, upstream processing prior to transmission, and mining.
 - Fertilizer Manufacture
Direct and indirect life cycle emissions from fertilizers, and pesticides used for feedstock production, including raw material recovery, transport and manufacturing of chemicals. This is not included if there is no fertilizer associated with the fuel pathway.
 - Land use changes and cultivation associated with biomass derived fuels
Emissions associated with the change in the land use in cultivation of crops, including N₂O from application of fertilizer, changes in soil carbon and biomass, methane emissions from soil and energy used for land cultivation.
 - Carbon in Fuel from Air
Carbon dioxide emissions credit arising from use of a renewable carbon source that obtains carbon from the air.
 - Leaks and flaring of greenhouse gases associated with production of oil and gas
Fugitive hydrocarbon emissions and flaring emissions associated with oil and gas production.
 - Emissions displaced by co-products of alternative fuels
Emissions displaced by co-products of various pathways. System expansion is used to determine displacement ratios for co-products from biomass pathways.
 - Vehicle assembly and transport
Emissions associated with the manufacture and transport of the vehicle to the point of sale, amortized over the life of the vehicle.
 - Materials used in the vehicles
Emissions from the manufacture of the materials used to manufacture the vehicle, amortized over the life of the vehicle. Includes lube oil production and losses from air conditioning systems.

The main lifecycle stages for crude oil based gasoline or diesel fuel are shown in the following figure.

Figure 1-1 Lifecycle Stages



1.1 SCOPE OF WORK

There is increased interest in bio-methane in the transportation sector. This term means different things to different people but would typically include landfill gas and the output from anaerobic digestion. The production of landfill gas is already included in GHGenius as a feedstock for methanol production but for this work, its use is expanded to compress the gas and use it as CNG or liquefy it to produce LNG.

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The gas from the landfill or the digester will be cleaned up and either compressed or liquefied so that it can be used as a transportation fuel for light and heavy-duty applications.

The necessary changes have been made to the macros to ensure that the sensitivity solvers, Monte Carlo simulator, and other macros all function with the additional sheet in the model. The version of the model that accompanies this report is 3.15. Version 3.15 also included changes to the model to allow easier set up of Provincial versions of the model. Those changes are described in a separate report.

2. LANDFILL GAS

Disposal and treatment of industrial and municipal wastes can produce emissions of most of the important greenhouse gases (GHG). Solid wastes can be disposed of through landfilling, recycling, incineration or waste-to-energy.

The most important gas produced from industrial and municipal wastes is methane (CH₄). Approximately 5-20 per cent (IPCC, 1992) of annual global anthropogenic methane produced and released into the atmosphere is a by-product of the anaerobic decomposition of waste. Two major sources of this type of methane production are solid waste disposal to land and wastewater treatment. In each case, methanogenic bacteria break down organic matter in the waste to produce methane.

In addition to methane, solid waste disposal sites can also produce substantial amounts of carbon dioxide and non-methane volatile organic compounds (NMVOCs). Decomposition of organic material derived from biomass sources (e.g., crops, forests), which are regrown on an annual basis, is the primary source of carbon dioxide released from waste. Hence, these carbon dioxide emissions are not treated as net emissions from waste in the IPCC Methodology (IPCC, 1996).

Organic waste in landfills is broken down by bacterial action in a series of stages that result in the formation of methane and carbon dioxide (termed biogas or landfill gas) and further bacterial biomass. In the initial phase of degradation, organic matter is broken down to small soluble molecules including a variety of sugars. These are broken down further to hydrogen, carbon dioxide, and a range of carboxylic acids. These acids are then converted to acetic acid, which, together with hydrogen and carbon dioxide, forms the major substrate for growth of methanogenic bacteria.

Landfill gas consists of approximately 50 per cent carbon dioxide and 50 per cent methane by volume. However, the percentage of carbon dioxide in landfill gas may be smaller because of decomposition of substrates with a high hydrogen/oxygen ratio (e.g., fats, hemicellulose) and because some of the carbon dioxide dissolves in water within the site.

In Canada, methane emissions from landfills are estimate at 1.16 million tonnes per year (Environment Canada, 2008). Approximately 28% of the CH₄ generated in Canadian MSW landfills in 2006 was captured and combusted (either for energy recovery, or flared).

2.1 LANDFILL GAS SYSTEMS

Typical landfill gas collection systems have three central components: collection wells, a condensate collection and treatment system, and a compressor. Depending on the end application of the gas there may be a need to treat the gas to remove all trace contaminants typically found in landfill gas, particularly if the gas is used directly for vehicle fuel or further chemical processing. In addition, most landfills with energy recovery systems will have a flare for the combustion of excess gas and for use during equipment down times. Most LCA work on alternate use of LFG assumes that the gas is flared if it is not utilized. This assumption provides a very conservative emission profile for the reference system since it would appear from the Environment Canada data that less than one third of the LFG in Canada is captured for flaring or utilization. The assumption also simplifies the issue of methane leaks and any flaring that would be present in the operation of the collection and upgrading systems, since these would generally also occur in the reference system. The combustion efficiency of flaring is generally assumed to be greater than 99.9%.

Each of these central components of the landfill gas system is described below.

2.1.1 Gas Collection Wells

Gas collection typically begins after a portion of a landfill (called a cell) is closed. There are two collection system configurations: vertical wells and horizontal trenches. Vertical wells are by far the most common type of well used for gas collection. Trenches may be appropriate for deeper landfills, and may be used in areas of active filling. Regardless of whether wells or trenches are used, each wellhead is connected to lateral piping, which transports the gas to a main collection header. Ideally, the collection system should be designed so that the operator can monitor and adjust the gas flow if necessary.

2.1.2 Condensate Collection and Treatment

An important part of any gas collection system is the condensate collection and treatment system. Condensate forms when warm gas from the landfill cools as it travels through the collection system. If condensate is not removed, it can block the collection system and disrupt the energy recovery process. Condensate control typically begins in the field collection system, where sloping pipes and headers are used to allow drainage into collecting ("knockout") tanks or traps. These systems are typically augmented by post-collection condensate removal as well. Some of the methods for disposal of condensate are discharge to the public sewer system, on-site treatment, and recirculation to the landfill. The best method for a particular landfill will depend upon the characteristics of the condensate (which may vary depending on site-specific waste constituents), regulatory considerations, and the cost of treatment and disposal.

2.1.3 Blower/Compressor

A blower is necessary to pull the gas from the collection wells into the collection header, and a compressor may be required to compress the gas before it can enter the energy recovery system. The size, type, and number of blowers and compressors needed depend on the gas flow rate and the desired level of compression, which is typically determined by the energy conversion equipment.

2.1.4 Gas Treatment Systems

After the landfill gas has been collected, and before it can be used in a conversion process, it must be treated to remove any condensate that is not captured in the knockout tanks, as well as particulates and other impurities. Treatment requirements depend on the end use application.

Three types of technologies are being utilized to upgrade the landfill gas to pipeline quality, scrubbing systems, membrane systems, and pressure swing adsorption systems.

One gas treatment system that has been proposed for use with a landfill gas is the one designed by Acrion Technologies, Inc. (<http://www.acrion.com/>). This system utilizes liquid carbon dioxide as a washing agent for the landfill gas and can produce both carbon dioxide for the market as well as gas suitable for methanol production. This system is shown in the following figure. The effectiveness of this technology is shown in the following table.

Figure 2-1 Landfill Gas Treatment

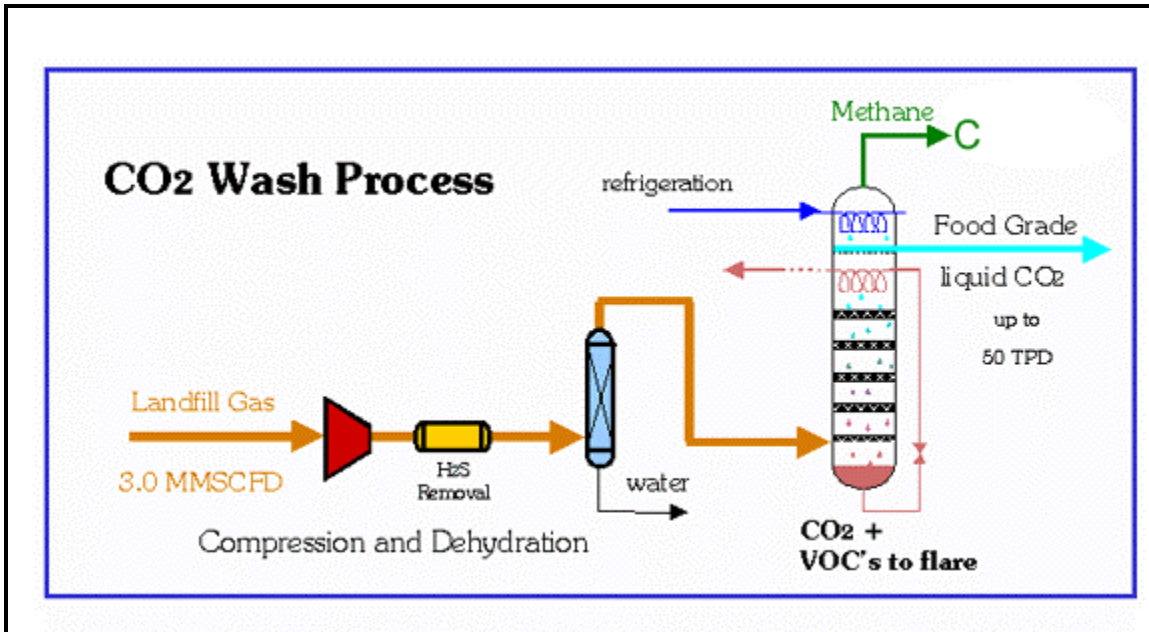


Table 2-1 Landfill Gas Treatment Effectiveness

	Raw Gas	Methane Product
Methane	49.6%	62.6%
Carbon dioxide	35.0%	25.7%
Ethylene	3 ppm	3 ppm
Ethane	2 ppm	2 ppm
Propane	41 ppm	14 ppm
Isobutane	13 ppm	nd
n-Butane	8 ppm	nd
Isopentane	2 ppm	nd
n-Pentane	2 ppm	nd
Hexanes	200 ppm	nd
Dimethyl sulphide	4 ppm	nd
Carbonyl sulphide	1.1 ppm	0.1 ppm
Freon 12	2.8 ppm	nd
Ethyl benzene	14 ppm	nd
Toluene	38 ppm	nd

2.1.5 Landfill Gas Process Energy Requirements

The efficiencies and energy requirements of each system vary slightly. Data on examples of each system is summarized below.

2.1.5.1 Scrubbing Systems

Acron designed a landfill gas treatment system for a landfill in Romania (US DOE, 1998). The process description for that project is described below.

Raw landfill gas is compressed to 3,500 kPa in three stages of compression with intercooling and water knockout between stages. Final gas dehydration to a -60°C dew point is with molecular sieves. The dehydrated, compressed landfill gas leaving the final compressor is cooled in a heat exchanger with cold recycle gas, medium quality product gas and contaminant rich absorber bottoms. The cooled gas enters the bottom of the absorber column where it is contacted with liquid carbon dioxide. The liquid carbon dioxide washes the volatile organic compounds from the gas. At the top of the absorber, liquid carbon dioxide is condensed from the upward flowing gas by heat exchange with the methane stripper reboiler, with evaporating VOC enriched carbon dioxide and with pure carbon dioxide. The vapour and liquid are separated in a reflux drum. The vapour, enriched in methane, is warmed by heat exchange with compressed feed gas to produce VOC free medium MJ fuel gas for subsequent processing. The system can also further process and purify the carbon dioxide stream so that it can be sold.

The system requires energy to compress the raw landfill gas and to compress and refrigerate the carbon dioxide used in the washing process. The energy consumption for the Romania project is shown in the following table.

Table 2-2 Energy Requirements for Gas Treatment

	Romania Landfill	Parameters for 1 GJ
Raw gas flow	113,267 m ³ /d	49.9 m ³
Raw gas composition	53% methane	53% methane
Methane recovery	99.9%	99.9%
Carbon dioxide recovery	56.2%	56.2%
Power required	791 kW	8.4 kWh/GJ

2.1.5.2 Membrane Systems

TIAX analyzed the emissions from a landfill gas system for the California Air Resources Board (2008) and chose a membrane system to model. The electricity requirements for landfill and membrane operation were 19.82 kWh/GJ. This is higher than the scrubbing system shown previously but that would be expected given the different technologies.

2.1.5.3 PSA Systems

QuestAir Technologies Inc. has sold a number of PSA systems for upgrading landfill gas. Detailed energy requirements for a system for a proposed landfill in British Columbia are publicly available (Sperling Hansen Associates). This system used 14 kWh/GJ of upgraded natural gas produced.

The default input value in GHGenius will be changed from 9 to 14 kWh/GJ (Input sheet AU217), as this is the middle value for the three technologies. Users can change this value to model the specific technology that interests them.

2.2 COMPRESSION AND DISPENSING SYSTEMS

The compression and dispensing energy requirements and emissions are calculated the same for both fossil and biogenic methane. The user must specify the input and output pressures of the compression system or the liquefying parameters. The same parameters are applied to both types of natural gas.

It has been assumed that the compressed LFG is used at the landfill site and is not transported through the existing natural gas grid. Accordingly the fuel distribution and storage energy requirements and emissions are set to zero.

2.3 REFERENCE SYSTEM

An important part of an LCA is the comparison of the results to the reference system. In most cases this means the comparison the fossil reference fuel, gasoline or diesel. In the case of landfill gas this is still appropriate but some discussion of the alternate utilization of the landfill gas is also necessary.

In the reference system landfill gas could be either vented to the atmosphere or combusted in a flare. According the 2006 Canadian National Emissions Inventory Report (Environment Canada, 2008) there are still significant emissions of methane from landfills in Canada. It was estimated that 1.16 million tonnes of methane were released and that only 28% of the landfill gases were captured for either use of combustion. If the reference system were the release of land fill gas methane into the environment, then with the use of the methane as a transportation fuel about 450,000 g CO₂eq/GJ of methane would be avoided by the captured and use of the gas. This is a very large number and would make the use of landfill gas the best GHG emission reduction option in the transportation sector.

Since the reduction of methane emissions from landfills is such an attractive GHG mitigation strategy, many landfill operators, particularly the large municipal landfills, practice the capture and flaring of the gas. Flaring of the methane in landfill gas is typically expected to be at least 99.7% efficient and thus the methane emissions from a system that is flared is expected to be 1,350 g CO₂eq/GJ of methane flared. In the modelling we do not have an estimate for methane leaks from a landfill gas capture and upgrading system (just from the compression and dispensing), so if we assume that these emissions are in both the reference system and the NG from LFG system then the reference system can be assumed to be emission free and no formal expansion of the system boundaries are required beyond the use of gasoline or diesel fuel as the reference systems.

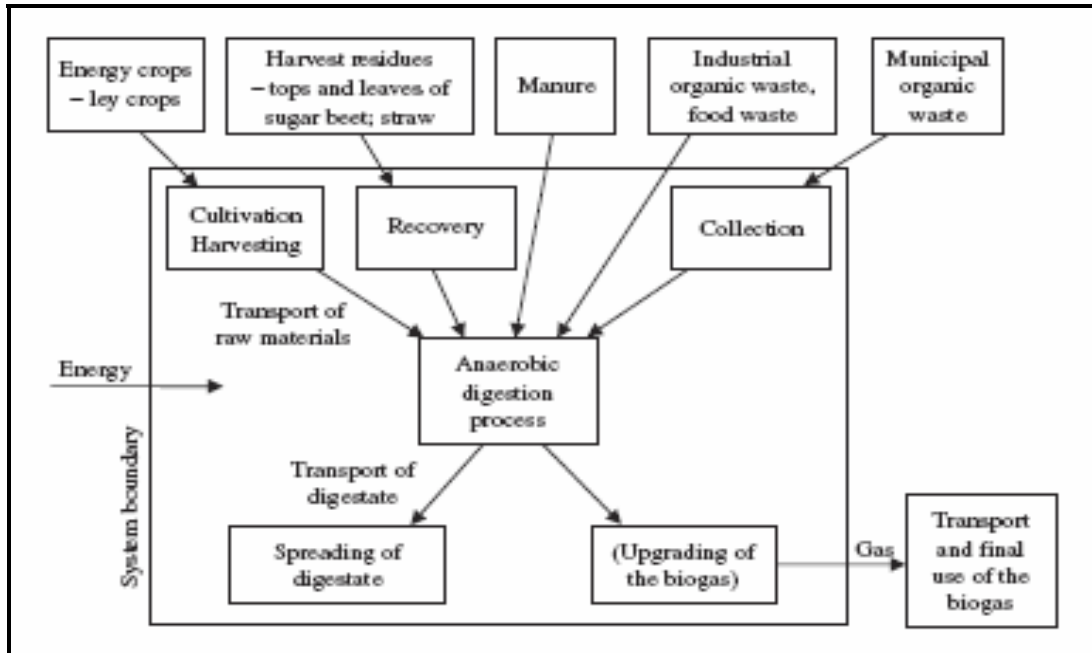
3. ANAEROBIC DIGESTION

Almost any organic material can be processed with anaerobic digestion. This includes biodegradable waste materials such as waste paper, grass clippings, leftover food, sewage and animal waste. The exception to this is woody wastes that are largely unaffected by digestion as the anaerobes are unable to degrade lignin. Anaerobic digesters can also be fed with specially grown energy crops such as silage for dedicated biogas production. In Europe, these facilities are referred to as biogas plants.

These biogas systems have traditionally been used to produce heat and power but there is also the potential to concentrate the methane that is produced and produce pipeline quality natural gas. Natural gas is used as a transportation fuel in many regions of the world but it requires engines designed for the fuel or converted gasoline engines.

A schematic of the potential anaerobic digestion systems is shown in the following figure.

Figure 3-1 Anaerobic Digestion System Schematic



In the digestion process, bacteria decompose organic matter in the absence of oxygen, producing methane (biogas) and other by-products. The digestion process begins with bacterial hydrolysis of the input materials in order to break down insoluble organic polymers such as carbohydrates and make them available for other bacteria. Acidogenic bacteria then convert the sugars and amino acids into carbon dioxide, hydrogen, ammonia, and organic acids. Acetogenic bacteria then convert these resulting organic acids into acetic acid, along with additional ammonia, hydrogen, and carbon dioxide. Methanogenic bacteria finally are able to convert these products to methane and carbon dioxide.

Variables affecting anaerobic digestion include temperature, retention time, pH, chemical composition of the influent, competition of methanogens with sulphate-reducing bacteria, and the presence of toxicants. Operation at the mesophilic range requires temperatures from 25°C to 40°C and is optimized at approximately 36°C. Thermophilic digestion operates at

temperature ranges of 50°C-65°C. Thermophilic operation more completely digests the influent. In temperature-phased anaerobic digestion, thermophilic and mesophilic digestion occurs in sequence, and can produce as much as 25 percent more biogas than single-phase digestion.

3.1 SYSTEM BOUNDARIES

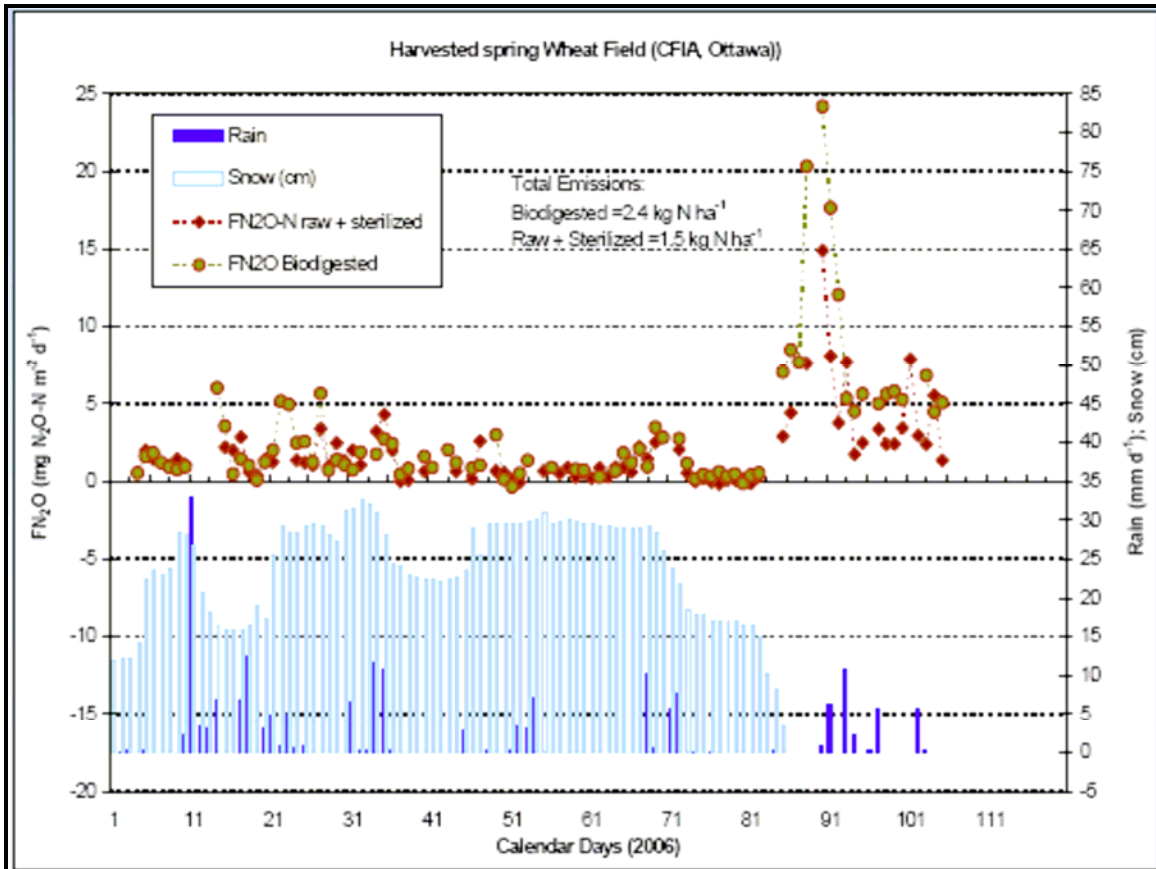
The system boundaries in GHGenius are relatively well defined for most of the fuel production and utilization pathways in the model. Like the collection of landfill gas, the utilization of the feedstocks in an anaerobic digester, particularly manure, raises the issue of what would the emissions be from the alternative means of utilization of the feedstock?

For agricultural residues this issue is already addressed in the model. These feedstocks, wheat straw and corn stover, would decompose on or in the soil, the nutrients would be returned to the soil, and some N₂O emissions would be created from the nitrogen in the residue. When these residues are removed from the system, some energy is expended to collect and transport them and the nutrients are replaced by synthetic fertilizer. There is no change in N₂O emissions since the emissions are the same whether they come from the nitrogen in the agricultural residues or from synthetic fertilizer.

Manure is a new feedstock in the model. It has a high nitrogen and other nutrient content. Depending on how it is generated and stored, it may also create methane emissions as it anaerobically decomposes in storage or when applied to the soil. There are also N₂O emissions generated when it is applied to the soil, and this soil application is the predominant method of disposal.

The nutrient content of the manure is not altered when it is anaerobically digested and the solids that remain after digestion (the digestate) are also typically applied to the soil for their nutrient content. The IPCC guidelines no longer have different emission factors for synthetic fertilizer compared to manure. Since these N₂O emissions will be in both the reference system (manure application to ground) and the study system (digestate application to ground) they can be ignored for the purposes of modelling. This was confirmed in a presentation by Crolla (2007) in a Canadian environment and shown in the following figure, where the N₂O emission rate for raw manure was compared to the emission rate from digested manure. It can be seen that there is very little difference in the N₂O emission rate from the two different treatments.

Figure 3-2 N₂O Emission Rate Comparison - Raw vs. Digested Manure



The other potential issue is the change in methane emissions between the storage and application of raw manure and the system that includes anaerobic digestion. Crolla reported about a 75% reduction in methane emissions for one dairy farm with an anaerobic digester compared to when the same digester was disabled. Unfortunately the emission reduction was expressed on the basis of head of dairy cows rather than a per unit of feed to the digester or the rate of production of the gas. Thyo and Wenzel (2007) report similar reductions of about 75% in the methane emissions between raw and digested swine and cattle manure. They report that the reduction in methane between land application and digestion is about equal in magnitude to the GHG emission reduction achieved from the displacement of fossil fuel by the biogas produced. We will assume a methane emissions saving of 0.015 kg methane/kg of solids if the storage of manure can be avoided through the application of anaerobic digestion.

3.2 FEEDSTOCKS

The model has been set up so that manure and/or agricultural residues (corn stover, wheat straw, hay, or switchgrass) can be used as feedstocks for anaerobic digestion. Each of the feedstock families is described below.

3.2.1 Agricultural Residues

The model is set up for the user to choose one of four (or a combination of four) agricultural residues. This includes two residues (corn stover and wheat straw) and two lignocellulosic feedstocks (switchgrass and hay). The two feedstocks would be typical of the production of silage, which is used in Europe to augment manure in anaerobic digestion systems. Each of these feedstocks can be used in the anaerobic digestion pathway using the same set of user inputs on the input sheet (cell B48 set to zero for “grass” and the choice of which feedstock in cells B54 to E54).

3.2.2 Manure

For this work we have added manure as a feedstock in the model. Manure can vary widely in terms of its properties and typical values have been chosen. The manure is a waste product so no emissions are attributed to it up to the point of production, as is the case with almost all LCA work. The typical properties are shown in the following table. These properties are included on sheet E (row 140).

Table 3-1 Manure Properties

	Dairy manure	Swine manure	Feedlot manure	Used for Modelling
Moisture content	89%	90%	40%	90
HHV, Mj/kg (dry)	15.6	14.5	10	15
Carbon	41%	37%	24%	38%
Hydrogen	4.2%	4.3%	3.6%	4.2%
Oxygen	28.5%	25.4%	20%	25%
Nitrogen	2.5%	3.5%	2.0%	3%
Sulphur	0.7%	0.6%	0.9%	0.7%

3.3 PROCESS PARAMETERS

World-wide, there are now more than 130 large AD plants operating that digest the organic fraction of the municipal solid waste stream and/or organic industrial wastes. All but approximately five of these installations are located in Europe. A recent survey of European anaerobic digestion systems was undertaken (R.W. Beck, 2004) to determine their performance. The results are summarized in the following table. It is believed that the weights in this table are on a wet basis.

Table 3-2 Performance of European AD Systems

Location	Waste Type	Waste tonnes/Year	Digester M ³	Gas Production M ³	M ³ Biogas /Tonne	M ³ Gas/ M ³ Digester/Day
Aarburg	Yard	11,025	1,500	809,983	67	1.479
Baar	Yard	4,009	480	379,992	86	2.169
Bachenbülach	Yard & Food	8,620	520	849,983	90	4.478
Baden-Baden	Food & Kitchen	6,515	6,000	1,449,970	202	0.662
Braunschweig	Kitchen	16,036	1,680	1,699,965	96	2.772
Buchen	MSW	100,227	4,000	3,999,918	36	2.740
Geneva	Yard	12,027	1,000	1,199,975	91	3.288
Grindsted	Biosolids & Food	34,578	2,800	649,987	17	0.636
Holsworthy	Manure & Food	146,332	8,000	3,899,920	24	1.336
Karlsruhe	Yard & Kitchen	8,018	1,350	875,982	99	1.778
Lemgo	Yard & Kitchen	34,077	2,550	3,799,922	101	4.083
München	Yard & Kitchen	25,057	2,380	1,499,969	54	1.727
Niederuzwil	Yard	10,023	900	869,982	79	2.648
Otelfingen	Yard	12,528	840	1,099,977	80	3.588
Rümlang	Yard & Food	7,016	460	799,984	104	4.765
Samstagern	Yard & Food	7,717	520	819,983	97	4.320
Average		27,738	2,186	1,544,093	51	1.935

It can be seen that there is a wide variation in the productivity of the commercial systems. Part of this is caused by a variation in the feedstocks. In the following table the energy production for various substrates is shown (BBI, 2008). Agricultural residues were not included in this reference but other studies have indicated that energy production from silage is about the same as it is for manure. It is therefore important that the user choose an appropriate energy production rate for the feedstock being modelled.

Table 3-3 Energy Yield of Various Substrates

Substrate	Percent Solids			Energy Yield MJ/kg
	TS%	VS%	VS*TS%	
Fats, Oils & Grease	90	90	81	33
Animal Fats	20	85	17	27
Food Waste	40	95	38	21
Poultry Manure (dry)	5	80	4	13.5
Swine Manure (Dry)	5	80	4	13.5
Cattle Manure	8	80	6.4	13.1
MSW	30	85	25.5	6.5

The process parameters for the default case in GHGenius have been taken from a recent draft LCA review (Thyo, et al). This system included the digestion of manure and silage. The mass and energy balance for the system modelled is summarized in the following table.

Table 3-4 Anaerobic Digestion Mass and Energy Balance

	Inputs	Net Output
Feedstock	67 kg (dry)	
Electric Power	25.5 kWh	
Natural Gas		1 GJ
Digestate fertilizer		~0.038 kg NPK fertilizer

The manure and agricultural residue inputs can be entered separately on the input sheet (manure in cell AL223 and agricultural residues in AL222). The default values are set to 50% each.

The biogas systems have very high efficiencies; approaching 90% of the energy in the feedstock is found in the produced gas. The system inputs are electric power, some thermal energy, and sometimes nutrients to aid in the digestion.

The gas that is produced will contain 50% to as much as 70% methane with most of the rest being carbon dioxide. It will still need to be cleaned and concentrated before it can be used for transportation purposes. We will use the same 14 kWh of electricity used for the LFG cleanup system. The total power requirements will therefore be modelled as 40 kWh/GJ of gas produced.

4. NATURAL GAS USE

A key aspect of the natural gas lifecycle is how the fuel is used in engines. There are commercial heavy-duty natural gas engines available that operate on a spark ignited cycle and a compression ignited cycle. The two types of engines have different efficiencies and emission profiles. The modelling parameters are discussed below.

No changes to the light duty natural gas engine performance have been made in this version of the model. There are very few light duty natural gas vehicles that are being offered for sale by the original vehicle manufacturers. In Canada, most light duty natural gas vehicles are now after market conversions. In the United States, the Honda Civic GX is the only OEM vehicle currently available. The Honda Civic GX gets the same relative efficiency (0.965) compared to gasoline that the model currently projects (US EPA, 2009). No detailed information is available on the relative efficiency of the after market conversions.

4.1 HEAVY DUTY SPARK IGNITED ENGINES

Heavy-duty natural gas engines changed significantly in 2007. In North America, CumminsWestport (CWI), a Cummins joint venture company, is the only manufacturer of 6 to 9 litre heavy-duty natural gas engines. CWI changed their combustion philosophy from that of a lean burn spark ignited engine to a stoichiometric with cooled EGR spark ignited engine. At the same time diesel engines have lost some efficiency due to the use of particulate traps to control PM emissions to the 2007 engine standards. These two changes have resulted in an improvement in the relative efficiency of the natural gas engines.

Real world experience that quantifies the magnitude of the change is not yet available but emissions certification data for the engines is available. This data indicates that in 2007, the efficiency of the natural gas engine was 0.8577 relative to a diesel engine, a 5.14 percentage point improvement over the value previously predicted by GHGenius for 2008. For model years 2007 and higher, the model will add this incremental efficiency. It is assumed that the historical trends in efficiency improvement will continue into the future and will not apply to this one time jump in relative efficiency.

This change was first incorporated into version 3.13 of the GHGenius.

4.2 HEAVY DUTY COMPRESSION IGNITED ENGINES

Westport Innovations Inc. offers a 15 litre engine that utilize compression ignition. Their HPDI system directly injects LNG and a small amount of diesel fuel into the cylinder. When LNG is selected as the fuel in GHGenius, the model then uses the performance parameters of this engine rather than the spark ignited engines, which is assumed if CNG is the fuel for the heavy-duty natural gas pathway.

The data in the model for the HPDI duty cycle is based on estimates made about ten years when the engine was in an early stage of development. The engine is now offered commercially and there have been several well documented field tests of the engine in recent year.

A test of five trucks in Canada (Westport, 2006) found that the fuel economy of the HPDI trucks were 4.2% less than those of diesel trucks. In a test in California (Los Angeles County Sanitation Districts, 2008) it was found that there was no difference in fuel economy between the two engines in terms of fuel economy.

Based on these two sets of test results the parameters for calculating the relative efficiency in the model have been changed slightly. The old and new parameters are summarized in the following table. The new values result in a small increase in lifecycle GHG emissions of about 1% over the previous values.

Table 4-1 LNG Relative Efficiency

	Old Values	New Values
City cycle 1995 (BV)	0.99	0.99
Highway cycle 1995 (BV)	0.99	0.99
Input maximum value (MV) for city cycle	1.10	1.05
Input maximum value (MV) for highway cycle	1.10	1.05
City cycle k exponent	-0.02	-0.02
Highway cycle k exponent	-0.02	-0.02
City cycle (2009)	1.01	1.00
Highway cycle (2009)	1.01	1.00

No changes have been made to the criteria air emission rates for natural gas. A limited amount of data is available on heavy-duty LNG engines (Environment Canada, 2006) and the data is directionally the same as that used in the model. That is the methane emissions are higher for the natural gas engine, the CO, NOx, and PM are reduced and the N₂O emissions are similar.

5. LIFECYCLE RESULTS

The modelling results for the two processes are presented in this section based on the default process parameters. In the next section of the report some sensitivity analysis will be undertaken on some of the key parameters.

5.1 LANDFILL GAS

The default process conditions the new landfill gas pathway produce the following results.

5.1.1 Energy Balance

In the following table the total energy balance for gasoline, compressed fossil natural gas, and compressed landfill gas is shown. The landfill gas system is slightly more energy efficient than the fossil natural gas system, but that is due to the lack of transmission energy being modelled. It was also noted earlier that there is a significant range in terms of the energy requirements for the clean-up of landfill gases and some systems may have energy efficient performances that is not as good as modelled here. Both the natural gas systems are more energy efficient than the gasoline system.

Table 5-1 Total Energy Balance Comparison – Gasoline and Natural Gas

Fuel	Gasoline	CNG	CNG
Feedstock	Crude Oil	Fossil NG	Landfill Gas
	2009		
	Joules consumed/joule delivered		
Fuel dispensing	0.0024	0.0227	0.0227
Fuel distribution, storage	0.0068	0.0307	0.0000
Fuel production	0.1708	0.0249	0.0659
Feedstock transmission	0.0132	0.0000	0.0000
Feedstock recovery	0.1126	0.0263	0.0000
Ag. Chemical manufacture	0.0000	0.0000	0.0000
Co-product credits	-0.0013	0.0000	0.0000
Total	0.3044	0.1046	0.0886
Net Energy Ratio (J delivered/J consumed)	3.2855	9.5622	11.2894

The fossil energy balance for the three fuels is shown in the following table. Since the primary energy input for the landfill gas systems is electricity, the fossil energy balance will vary by region. The data shown in the following table is the average for Canada. The landfill gas system is significantly better than the fossil natural gas system on this basis.

Table 5-2 Fossil Energy Balance Comparison – Gasoline and Natural Gas

Fuel	Gasoline	CNG	CNG
Feedstock	Crude Oil	Fossil NG	Landfill Gas
	2009		
	Joules consumed/joule delivered		
Fuel dispensing	0.0006	0.0060	0.0060
Fuel distribution, storage	0.0056	0.0299	0.0000
Fuel production	0.1608	0.0234	0.0175
Feedstock transmission	0.0105	0.0000	0.0000
Feedstock recovery	0.1014	0.0226	0.0000
Ag. Chemical manufacture	0.0000	0.0000	0.0000
Co-product credits	-0.0012	0.0000	0.0000
Total	0.2777	0.0819	0.0235
Net Energy Ratio (J delivered/J consumed)	3.6011	12.2147	42.6105

5.1.2 GHG Emissions

The GHG emissions for natural gas (on a g/GJ basis) are summarized in the following table and compared to gasoline. The combustion emissions for a light duty vehicles have also been added to get an accurate comparison between the fossil fuels and the biofuel. This is a common comparison being used in policy discussions around low carbon fuel standards but it ignores any differences in the engine efficiency between the two fuels.

Table 5-3 Comparison of GHG Emissions - Gasoline and Natural Gas - LDV

Fuel	Gasoline	CNG	CNG
Feedstock	Crude Oil	Fossil Natural Gas	Landfill Gas
Year	2009		
	g CO ₂ eq/GJ (HHV)		
Fuel dispensing	112	1,081	1,081
Fuel distribution and storage	558	1,968	0
Fuel production	12,268	1,376	3,136
Feedstock transmission	1,031	0	0
Feedstock recovery	7,899	1,704	0
Land-use changes, cultivation	16	0	0
Fertilizer manufacture	0	0	0
Gas leaks and flares	1,903	3,540	1,472
CO ₂ , H ₂ S removed from NG	0	642	0
Emissions displaced	-120	0	0
Sub-Total	23,668	10,310	5,689
Combustion emissions	63,814	52,786	4,410
Grand Total	87,482	63,096	10,099
% Reduction		27.9	88.5

The landfill gas option produces significant reductions in GHG emissions as a result of being a biofuel. Unlike the thermal utilization of municipal solid waste, where some of the energy

may be derived from the energy contained in plastics, the energy produced by the micro-organisms active in a landfill can only act of biomass and so all of the energy that is released as landfill gas meets the requirement of being produced from biomass.

The comparison of the results for heavy-duty vehicles is shown in the following table. It is assumed that the engine is a CWI natural gas engine.

Table 5-4 Comparison of GHG Emissions - Diesel and Natural Gas – HDV

Fuel	Diesel	CNG	CNG
Feedstock	Crude Oil	Fossil Natural Gas	Landfill Gas
Year	2009		
	g CO ₂ eq/GJ (HHV)		
Fuel dispensing	115	1,081	1,081
Fuel distribution and storage	478	1,968	0
Fuel production	8,373	1,376	3,136
Feedstock transmission	1,053	0	0
Feedstock recovery	8,072	1,704	0
Land-use changes, cultivation	16	0	0
Fertilizer manufacture	0	0	0
Gas leaks and flares	1,900	3,540	1,472
CO ₂ , H ₂ S removed from NG	0	642	0
Emissions displaced	-120	0	0
Sub-Total	19,888	10,310	5,689
Combustion emissions	70,277	52,410	2,486
Grand Total	90,065	62,720	8,175
% Reduction		30.4	90.9

Looking at the lifecycle emissions using the distance driven as the functional unit incorporates any differences in combustion efficiency resulting from the change in fuel. These results are shown in the following table. Due to the lower assumed efficiency of the natural gas emissions the GHG emission reductions for the natural gas systems are slightly lower than when they reported on a g/GJ basis in the previous tables. The emission reductions available from the landfill gas are still very significant.

Table 5-5 Comparison of GHG Emissions - Gasoline and Natural Gas - LDV

Fuel	Gasoline	CNG	CNG
Feedstock	Crude Oil	Fossil Natural Gas	Landfill Gas
Year	2009		
	g CO ₂ eq/km		
Vehicle operation	211.6	185.9	185.9
C in end-use fuel from CO ₂ in air	0.0	0.0	-170.3
Net Vehicle Operation	211.6	185.9	15.5
Fuel dispensing	0.4	3.8	3.8
Fuel storage and distribution	1.8	6.9	0.0
Fuel production	40.7	4.8	11.0
Feedstock transport	3.4	0.0	0.0
Feedstock and fertilizer production	26.3	6.0	0.0
Land use changes and cultivation	0.0	0.0	0.0
CH ₄ and CO ₂ leaks and flares	6.3	14.7	5.2
Emissions displaced by co-products	-0.4	0.0	0.0
Sub total (fuelcycle)	290.1	222.2	35.6
% Changes (fuelcycle)		-23.4	-87.8
GHG Reductions g CO ₂ eq/kg of natural gas		990	3,792

The change in the emissions reductions for the heavy-duty fuel cycles are larger than for the light duty cycles due to the lower relative efficiency of the heavy-duty engines compared to the gasoline spark ignited engines.

Table 5-6 Comparison of GHG Emissions - Diesel and Natural Gas - HDV

Fuel	Diesel	CNG	CNG
Feedstock	Crude Oil	Fossil Natural Gas	Landfill Gas
Year	2009		
	g CO ₂ eq/km		
Vehicle operation	1,112.0	972.5	972.5
C in end-use fuel from CO ₂ in air	0.0	0.0	-926.4
Net Vehicle Operation	1,112.0	972.5	46.1
Fuel dispensing	1.8	20.1	20.1
Fuel storage and distribution	7.6	36.5	0.0
Fuel production	132.5	25.5	58.2
Feedstock transport	16.7	0.0	0.0
Feedstock and fertilizer production	128.0	31.6	0.0
Land use changes and cultivation	0.0	0.0	0.0
CH ₄ and CO ₂ leaks and flares	30.1	77.6	27.3
Emissions displaced by co-products	-1.9	0.0	0.0
Sub total (fuelcycle)	1,426.7	1,163.9	151.7
% Changes (fuelcycle)		-18.4	-89.4
GHG Reductions g CO ₂ eq/kg of natural gas		722	3,605

5.2 ANAEROBIC DIGESTION

In the default case a blend of 50% manure and 50% hay is provided as the feedstock to the anaerobic digester. In the discussion section the impact of other feedstocks will be evaluated.

5.2.1 Energy Balance

In the following table the total energy balance for gasoline, compressed fossil natural gas, and compressed natural gas from an anaerobic digester is presented. In this case, the energy balance for the digester is about the same as it is for gasoline and not as good as the fossil natural gas system.

Table 5-7 Total Energy Balance Comparison – Gasoline and Natural Gas

Fuel	Gasoline	CNG	CNG
Feedstock	Crude Oil	Fossil NG	AD Gas
	2009		
	Joules consumed/joule delivered		
Fuel dispensing	0.0024	0.0227	0.0227
Fuel distribution, storage	0.0068	0.0307	0.0000
Fuel production	0.1708	0.0249	0.2886
Feedstock transmission	0.0132	0.0000	0.0053
Feedstock recovery	0.1126	0.0263	0.0114
Ag. Chemical manufacture	0.0000	0.0000	0.0117
Co-product credits	-0.0013	0.0000	0.0000
Total	0.3044	0.1046	0.3397
Net Energy Ratio (J delivered/J consumed)	3.2855	9.5622	2.9442

The fossil energy balance for the three fuels is shown in the following table. Since a significant primary energy input for the anaerobic digestion gas systems is electricity, the fossil energy balance will vary by region. The data shown in the following table is the average for Canada. The energy balance of the AD gas system is significantly better than gasoline and about the same as the fossil natural gas system on this basis.

Table 5-8 Fossil Energy Balance Comparison – Gasoline and Natural Gas

Fuel	Gasoline	CNG	CNG
Feedstock	Crude Oil	Fossil NG	AD Gas
	2009		
	Joules consumed/joule delivered		
Fuel dispensing	0.0006	0.0060	0.0060
Fuel distribution, storage	0.0056	0.0299	0.0000
Fuel production	0.1608	0.0234	0.0506
Feedstock transmission	0.0105	0.0000	0.0053
Feedstock recovery	0.1014	0.0226	0.0112
Ag. Chemical manufacture	0.0000	0.0000	0.0112
Co-product credits	-0.0012	0.0000	0.0000
Total	0.2777	0.0819	0.0843
Net Energy Ratio (J delivered/J consumed)	3.6011	12.2147	11.8676

5.2.2 GHG Emissions

The GHG emissions for natural gas (on a g/GJ basis) are summarized in the following table and compared to gasoline. The combustion emissions for a light duty vehicles have also been added to get an accurate comparison between the fossil fuels and the biofuel. This is a common comparison being used in policy discussions around low carbon fuel standards but it ignores any differences in the engine efficiency between the two fuels. The emissions displaced for the AD system is the reduction in methane emissions resulting from the land application of the digestate compared to manure. The emission reductions are very significant.

Table 5-9 Comparison of GHG Emissions - Gasoline and Natural Gas - LDV

Fuel	Gasoline	CNG	CNG
Feedstock	Crude Oil	Fossil Natural Gas	AD Gas
Year	2009		
	g CO ₂ eq/GJ (HHV)		
Fuel dispensing	112	1,081	1,081
Fuel distribution and storage	558	1,968	0
Fuel production	12,267	1,376	10,375
Feedstock transmission	1,031	0	412
Feedstock recovery	7,899	1,704	1,243
Land-use changes, cultivation	16	0	1,773
Fertilizer manufacture	0	0	676
Gas leaks and flares	1,903	3,540	0
CO ₂ , H ₂ S removed from NG	0	642	0
Emissions displaced	-120	0	-12,563
Sub-Total	23,668	10,310	2,997
Combustion emissions	63,814	52,786	4,410
Grand Total	87,482	63,096	7,407
% Reduction		27.9	91.5

The AD gas option produces significant reductions in GHG emissions as a result of being a biofuel.

The comparison of the results for heavy-duty vehicles is shown in the following table.

Table 5-10 Comparison of GHG Emissions - Diesel and Natural Gas – HDV

Fuel	Diesel	CNG	CNG
Feedstock	Crude Oil	Fossil Natural Gas	AD Gas
Year	2009		
	g CO ₂ eq/GJ (HHV)		
Fuel dispensing	115	1,081	1,081
Fuel distribution and storage	478	1,968	0
Fuel production	8,373	1,376	10,375
Feedstock transmission	1,053	0	412
Feedstock recovery	8,072	1,704	1,243
Land-use changes, cultivation	16	0	1,773
Fertilizer manufacture	0	0	676
Gas leaks and flares	1,900	3,540	0
CO ₂ , H ₂ S removed from NG	0	642	0
Emissions displaced	-120	0	-12,563
Sub-Total	19,888	10,310	2,997
Combustion emissions	70,277	52,410	2,486
Grand Total	90,064	62,720	5,482
% Reduction		30.4	93.9

Looking at the lifecycle emissions using the distance driven as the functional unit incorporates any differences in combustion efficiency resulting from the change in fuel. These results are shown in the following table for the light duty vehicle application.

Table 5-11 Comparison of GHG Emissions - Gasoline and Natural Gas - LDV

Fuel	Gasoline	CNG	CNG
Feedstock	Crude Oil	Fossil Natural Gas	AD Gas
Year	2009		
	g CO ₂ eq/km		
Vehicle operation	211.6	185.9	185.9
C in end-use fuel from CO ₂ in air	0.0	0.0	-170.3
Net Vehicle Operation	211.6	185.9	15.5
Fuel dispensing	0.4	3.8	3.8
Fuel storage and distribution	1.8	6.9	0.0
Fuel production	40.7	4.8	36.5
Feedstock transport	3.4	0.0	1.5
Feedstock and fertilizer production	26.3	6.0	6.8
Land use changes and cultivation	0.0	0.0	6.2
CH ₄ and CO ₂ leaks and flares	6.3	14.7	0.0
Emissions displaced by co-products	-0.4	0.0	-44.2
Sub total (fuelcycle)	290.1	222.2	26.1
% Changes (fuelcycle)		-23.4	-91.0
GHG Reductions g CO ₂ eq/kg of natural gas		990	3,970

The results for the heavy-duty vehicle application are shown in the following table. The reductions are still very large but the emission reduction from each unit of natural gas used as a fuel is not as large as it is for the light duty application due to the reduced relative efficiency of natural gas in the diesel fuel replacement sector.

Table 5-12 Comparison of GHG Emissions - Diesel and Natural Gas - HDV

Fuel	Diesel	CNG	CNG
Feedstock	Crude Oil	Fossil Natural Gas	AD Gas
Year	2009		
	g CO ₂ eq/km		
Vehicle operation	1,112.0	972.5	972.5
C in end-use fuel from CO ₂ in air	0.0	0.0	-926.4
Net Vehicle Operation	1,112.0	972.5	46.1
Fuel dispensing	1.8	20.0	20.0
Fuel storage and distribution	7.6	36.5	0.0
Fuel production	132.5	25.5	192.5
Feedstock transport	16.7	0.0	7.6
Feedstock and fertilizer production	128.0	31.6	35.6
Land use changes and cultivation	0.0	0.0	32.9
CH ₄ and CO ₂ leaks and flares	30.1	77.6	0.0
Emissions displaced by co-products	-1.9	0.0	-233.1
Sub total (fuelcycle)	1,426.7	1,163.9	101.7
% Changes (fuelcycle)		-18.4	-92.9
GHG Reductions g CO ₂ eq/kg of natural gas		722	3,783

6. DISCUSSION

The two biomethane options investigated both can provide very large GHG emission reductions when the gas is processed to natural gas that can be used in transportation applications. The resource base for these fuel production pathways, while large, has some limitations since they are based on processing waste products.

6.1 COMPARISON OF THE BIOMETHANE PATHWAYS

Two distinct biomethane pathways, upgrading landfill gas and using anaerobic digestion, have been added to the GHGenius model. Each has been compared to gasoline and diesel fuel as well as to fossil natural gas on an energy balance basis and a GHG emissions basis. The total and fossil energy balances are shown in the following tables. Not surprisingly the landfill gas option has a better total and fossil energy balance since less inputs are required to operate a landfill compared to an anaerobic digestion system.

Table 6-1 Total Energy Balance Comparison – Gasoline and Natural Gas

Fuel	Gasoline	CNG	CNG	CNG
Feedstock	Crude Oil	Fossil NG	Landfill Gas	AD Gas
2009				
Joules consumed/joule delivered				
Fuel dispensing	0.0024	0.0227	0.0227	0.0227
Fuel distribution, storage	0.0068	0.0307	0.0000	0.0000
Fuel production	0.1708	0.0249	0.0659	0.2886
Feedstock transmission	0.0132	0.0000	0.0000	0.0053
Feedstock recovery	0.1126	0.0263	0.0000	0.0114
Ag. Chemical manufacture	0.0000	0.0000	0.0000	0.0117
Co-product credits	-0.0013	0.0000	0.0000	0.0000
Total	0.3044	0.1046	0.0886	0.3397
Net Energy Ratio (J delivered/J consumed)	3.2855	9.5622	11.2894	2.9442

Table 6-2 Fossil Energy Balance Comparison – Gasoline and Natural Gas

Fuel	Gasoline	CNG	CNG	CNG
Feedstock	Crude Oil	Fossil NG	Landfill Gas	AD Gas
2009				
Joules consumed/joule delivered				
Fuel dispensing	0.0006	0.0060	0.0060	0.0060
Fuel distribution, storage	0.0056	0.0299	0.0000	0.0000
Fuel production	0.1608	0.0234	0.0175	0.0506
Feedstock transmission	0.0105	0.0000	0.0000	0.0053
Feedstock recovery	0.1014	0.0226	0.0000	0.0112
Ag. Chemical manufacture	0.0000	0.0000	0.0000	0.0112
Co-product credits	-0.0012	0.0000	0.0000	0.0000
Total	0.2777	0.0819	0.0235	0.0843
Net Energy Ratio (J delivered/J consumed)	3.6011	12.2147	42.6105	11.8676

The GHG emissions for the two biomethane pathways are compared in the following table using the heavy-duty vehicle option as a basis for comparison. There is a relatively small difference in the GHG emissions between these two biomethane pathways when the default values for the input assumptions are used but the AD systems provides a slightly larger GHG emission benefit. The emission reduction provided by the reduced mass of digestate spread on the land compared to manure provides a GHG emission credit that offsets the better energy balance of the landfill gas system.

Table 6-3 Comparison of GHG Emissions - Diesel and Natural Gas - HDV

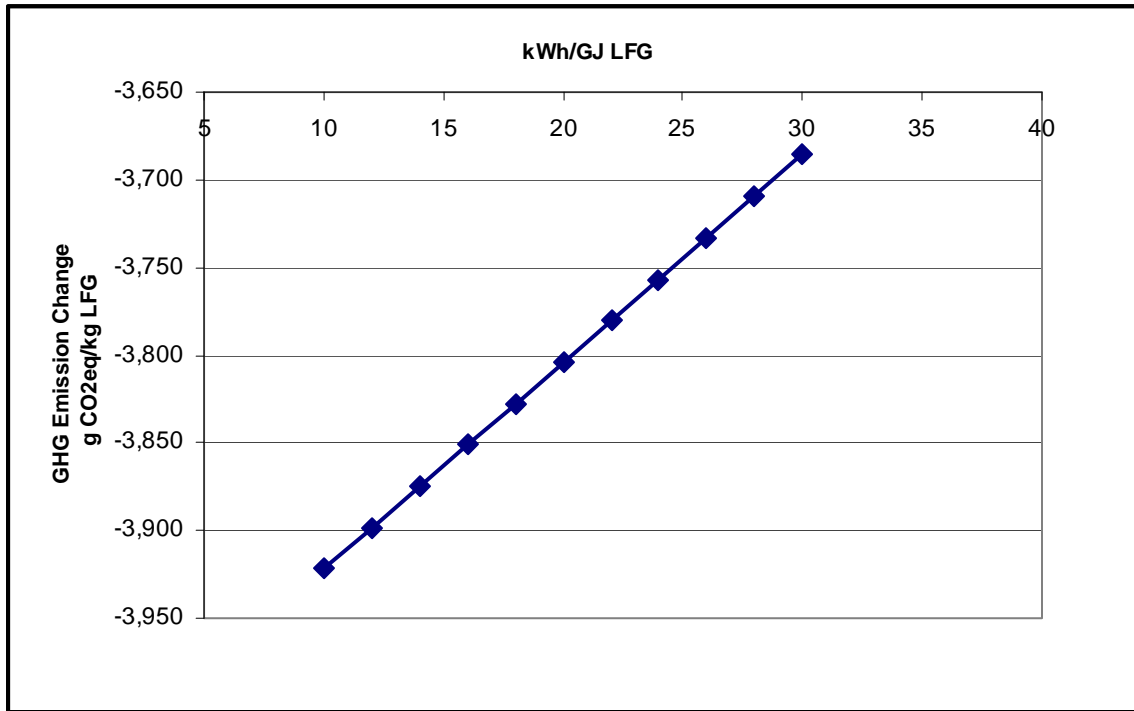
Fuel	Diesel	CNG	CNG	CNG
Feedstock	Crude Oil	Fossil Natural Gas	Landfill Gas	AD Gas
Year	2009			
	g CO ₂ eq/km			
Vehicle operation	1,112.0	972.5	972.5	972.5
C in end-use fuel from CO ₂ in air	0.0	0.0	-926.4	-926.4
Net Vehicle Operation	1,112.0	972.5	46.1	46.1
Fuel dispensing	1.8	20.0	20.0	20.0
Fuel storage and distribution	7.6	36.5	0.0	0.0
Fuel production	132.5	25.5	58.2	192.5
Feedstock transport	16.7	0.0	0.0	7.6
Feedstock and fertilizer production	128.0	31.6	0.0	35.6
Land use changes and cultivation	0.0	0.0	0.0	32.9
CH ₄ and CO ₂ leaks and flares	30.1	77.6	27.3	0.0
Emissions displaced by co-products	-1.9	0.0	0.0	-233.1
Sub total (fuelcycle)	1,426.7	1,163.9	151.7	101.7
% Changes (fuelcycle)		-18.4	-89.4	-92.9
GHG Reductions g CO ₂ eq/kg of natural gas		722	3,605	3,783

6.2 SENSITIVITY ANALYSIS

Each biomethane situation is also likely to be unique and it is therefore appropriate to investigate the sensitivity of the emission reductions to some of the assumptions that have been made for the modelling.

The landfill gas is a relatively simple system with some uncertainty about the amount of electric power required to upgrade the gas to transportation fuel quality. In the following figure the quantity of electricity used for the gas clean-up is varied from 10 to 30 kWh/GJ of landfill gas produced and the impact on the GHG emissions reduced per kg of CNG used in a light duty vehicle is shown. While the quantity of electricity used does have some impact on the emission performance, the GHG reductions are significant even in the highest power case modelled.

Figure 6-1 Impact of Electric Power Consumed on GHG Emissions Reduced



The performance of AD systems is very dependent on the feedstocks being processed as was shown earlier in the report but even for feedstocks that have similar AD performance the lifecycle GHG emissions can be very different. In the following table the upstream emission performance is shown for the various feedstock options available with the model. The quantity of manure has an obvious impact on the emissions due to the fact that it is a waste, and thus emissions burden free at the point of production, and the large emission credit available for spreading the digestate on the field instead of the raw manure.

Table 6-4 Impact of Feedstock on AD Emission Performance

Fuel	CNG	CNG	CNG	CNG	CNG	CNG
Feedstock	Manure/ Hay	100% Manure	Hay	Switch grass	Wheat Straw	Corn Stover
	2009					
	g CO ₂ eq/GJ					
Fuel dispensing	1,081	1,081	1,081	1,081	1,081	1,081
Fuel distribution and storage	0	0	0	0	0	0
Fuel production	10,375	10,278	10,471	10,471	10,471	10,471
Feedstock transmission	412	0	824	824	824	824
Feedstock recovery	1,243	0	2,486	2,627	579	2,825
Land-use changes, cultivation	1,773	0	3,546	3,112	0	0
Fertilizer manufacture	676	0	1,351	1,973	1,505	2,072
Gas leaks and flares	0	0	0	0	0	0
CO ₂ , H ₂ S removed from NG	0	0	0	0	0	0
Emissions displaced	-12,563	-25,125	0	0	0	0
Total	2,997	-13,766	19,759	20,089	14,460	17,273

6.3 CRITERIA AIR CONTAMINANTS

The criteria air contaminants for the fossil natural gas system and the two biomethane fuel production pathways are summarized in the following table. These are shown for the upstream portion of the lifecycle only as the emissions from the combustion of the fuel would be same in each case. The different emissions profiles are a function of the different quantities of inputs into each system. For example, the high N₂O emissions for the hay system are a function of the application of nitrogen fertilizer in that case.

Table 6-5 Criteria Air Contaminant Comparison

Fuel	CNG	CNG	CNG	CNG
Process		LFG	AD	AD
Feedstock	NG	MSW	Hay	Manure
	2009			
	g/GJ			
Carbon dioxide (CO ₂)	5,925	3,960	14,579	9,547
Non methane organic compounds (NMOCs)	4	1	6	4
Methane (CH ₄)	173	66	28	-986
Carbon monoxide (CO)	8	2	66	53
Nitrous oxide (N ₂ O)	0	0	15	4
Nitrogen oxides (NO ₂)	40	10	202	96
Sulphur oxides (SO _x)	13	21	68	62
Particulate matter (PM)	1	1	33	26
HFC-134a (mg)	0	0	1	0
CO ₂ -equivalent GHG emissions	10,310	5,687	19,756	-13,769

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