

# Potential Production of Methane from Canadian Wastes

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## **EXECUTIVE SUMMARY**

This report evaluates the role wastes can play in producing energy from waste biomass by generating methane from Canadian wastes, which can then be used as a renewable natural gas (RNG) source.

The objective of this project is to conduct a literature based study whose aim will be to assess the technical potential for methane generation from Canadian wastes, and the relative greenhouse gas (GHG) impacts of capturing the generated methane. The project also looks at the economic viability of different scenarios involving the production of RNG. While the work does not attempt to quantify the useful potential of RNG in Canada, which would need factoring in infrastructure and economic constraints, it will assist in determining the resource base for methane from waste.

We define technical feasibility as the potential to realize a product based on the availability of resources and the prior knowledge and experience of using similar processes for producing similar products. Production of RNG from Canadian wastes was shown to arise from the application of two well used and understood processes: anaerobic digestion and gasification. With the main focus of this report the production of methane from waste biomass, we have concentrated our discussion of cleaning and upgrading of anaerobic digestion produced raw biogas and gasifier produced raw biosyngas. Based on our findings, it is envisioned that anaerobic digestion process will be the main source of RNG in the next 5 to 10 years with gasification contributing afterwards. This is based on the availability of the technologies, prior use and acceptance by industry and the need for further technology development activities.

Canadian wastes that are amenable to producing RNG are those containing significant amounts of biomass and are mostly generated by the agricultural, forestry and municipal sectors.

Agricultural wastes containing significant biomass are mostly made up of crop residues and animal manures. These wastes can be converted to biogas and syngas through anaerobic digestion and gasification. The produced biogas can be cleaned up of potential contaminants and separated into CH<sub>4</sub> and CO<sub>2</sub> both of which can be sold as

RNG and industrial grade CO<sub>2</sub>. Syngas can be cleaned up, methanated and then separated into CH<sub>4</sub> and CO<sub>2</sub>.

Data shows that the greatest potential for producing RNG from crop residues is through gasification as it consumes most of the biomass while anaerobic digestion is limited to about 20% of that biomass.

Manure production on Canadian farms varies according to the type of animals and the animal population numbers, but is amenable for producing RNG. Data shows that the potential for producing RNG from manure residues is slightly higher through gasification than that for anaerobic digestion.

Forestry residues are made up of forest operation residues and mountain pine beetle (MPB) residues. Forest residue data shows that the potentially available residues are to be found mostly in BC (33%), Quebec (27%) and Ontario (17%). Potential production of RNG from these residues through gasification shows a similar pattern as the residue distribution.

Canadian municipal wastes considered as potential sources for RNG production included solid wastes collected from homes and businesses by municipalities (MSW), landfill gas recovered from closed landfills (LFG), wastewaters (WW) collected through municipal sewer systems, and the municipal biosolids which are the solid materials collected (through settling) of the wastewaters.

Data of the contributions of each municipal waste to the total municipal potential RNG production shows that the largest sources of potential RNG are from solid wastes (MSW) and Landfills. This is understandable considering the much larger solid production of wastes from the above two sources. Anaerobic digestion contributes slightly more RNG than gasification due to the production of LFG. Total potential RNG production shows a distribution similar to population size.

This municipal waste source is significant for the large contribution of anaerobic digestion to RNG production allowing for the use of established technologies with much easier technology uptake and adaptation. Another attractive aspect for using this waste is the lower cost of production due to the absence of waste collection and transportation costs as they are usually incurred by the municipalities. The most significant costs are



those associated with gas cleaning and separation. Challenges exist in adapting gasification to municipal wastes as few gasification plants exist and those usually use the syngas only to produce power. Most thermal treatments of municipal wastes, have up until now tended to favour incineration.

All potential RNG that can be produced from the total Canadian wastes reviewed, shows that a potential total of 24.9 Mt/yr of RNG can be produced. Forestry seems to have the potential to produce 12.9 Mt/yr (51% of total), followed by 8.8 Mt/yr (36%) from agriculture and 3.2 Mt/yr (13%) from municipal wastes. The use of gasification seems to have the potential to produce most of the RNG in Canada as we estimated that 21 Mt/yr (84% of total) can be produced by this process. Anaerobic digestion has the potential to produce 3.9 Mt/yr (16% of total); while this process seems to be significantly less than gasification, it is still significant because of the technology availability and lower cost.

We compared the relative size of our potential RNG estimates to the current natural gas use for the residential and commercial sectors. The potential Canadian generation of 24.9 Mt/yr of RNG corresponds to an energy value of 1.4 TJ/yr or 389,528 GWh of electricity. RNG production can account for a significant amount of the natural gas use. Nationally, our estimate of the technical potential is that 130% of current NG residential and commercial use can be replaced by the produced RNG.

We developed several scenarios using proprietary spreadsheets developed within the Alberta Research Council, to highlight the complexity around the economics issue. Our analysis shows that to lower the cost of RNG, then the technology costs for cleaning the biogas needs to be reduced. At the moment, there is very little data on the cost to clean gas to a pipeline grade. However, the economic models which have been presented evaluated different scenarios which included examples of RNG used to produce pipeline grade natural gas, or RNG used in power production. The economics underlines the need to develop biogas cleaning technologies that lower capital costs by an order of magnitude over the current state of the art.

The production and capture of RNG from Canadian wastes contributes to GHG reduction through two processes: emission reduction and fuel substitution. Emission

reduction can be achieved through the capture of the emitted methane from landfills and the anaerobic digestion of animal manures. Fuel substitution applies to the use of RNG to replace any natural gas produced from fossil fuels.

Total GHG reductions were estimated as 107 Mt CO<sub>2</sub> eq/yr for Canada with the largest amounts found for Quebec, Ontario and BC. Fuel substitution seems to contribute more GHG reductions than emission reduction except for those provinces with large forestry wastes such as BC. Almost 33% of the Canadian GHG reductions arise from emission reduction, while the rest (67%) from fuel substitution.

The potential RNG production from wastes can contribute a significant amount of GHG reductions and thus carbon credits, which may alleviate the cost of RNG production if factoring in the sale of the CO<sub>2</sub> produced and the value of its carbon credit.

On a going forward basis, there is a need to engage appropriate stakeholders and various levels of government to get a better handle on the useful potential of RNG considering spatial infrastructure and economic factors, initiate policy development as well as undertaking additional technical development that will provide more operating and cost data.

## RÉSUMÉ

Ce rapport évalue le rôle que peuvent jouer les déchets dans la production d'énergie (le méthane) à partir de la biomasse des déchets canadiens, ce qui devient une source de gaz naturel renouvelable (GNR).

Le projet vise à évaluer, en se fondant sur les connaissances publiées, le potentiel technique de production de méthane à partir de déchets au Canada, ainsi que l'impact relatif de la capture du méthane ainsi produit sur les émissions de gaz à effet de serre (GES). Il se penche également sur la viabilité économique des différents scénarios de production de GNR. Cette étude ne cherche pas à quantifier le potentiel utile du GNR au Canada, ce qui nécessiterait de tenir compte des contraintes structurelles et économiques, mais elle aidera à déterminer les ressources disponibles en méthane provenant des déchets.

Nous définissons la faisabilité technique comme étant le potentiel de créer un produit basé sur la disponibilité des ressources, ainsi que sur les connaissances et l'expérience antérieures dans l'utilisation de procédés similaires pour créer des produits similaires. L'étude a démontré que la production de GNR à partir de déchets canadiens est possible grâce à l'application de deux procédés bien utilisés et compris : la digestion anaérobie et la gazéification. Ce rapport portant principalement sur la production de méthane à partir de biomasse des déchets, nous avons concentré notre propos sur le nettoyage et la valorisation du biogaz brut provenant de la digestion anaérobie et du gaz de synthèse brut produit par gazogène. D'après nos constatations, on estime que la digestion anaérobie sera la source principale de GNR pour les 5 à 10 prochaines années, après quoi la gazéification ajoutera sa contribution. Cette opinion se fonde sur la technologie disponible, l'usage antérieur, l'acceptation au sein de l'industrie, ainsi que le besoin de poursuivre le développement des techniques.

Les déchets canadiens se prêtant à la production de GNR contiennent des quantités importantes de biomasse; ce sont surtout des déchets agricoles, forestiers et municipaux.

Les déchets agricoles qui contiennent beaucoup de biomasse sont surtout les résidus de récoltes et le fumier. Ces déchets peuvent être convertis en biogaz et gaz de synthèse par digestion anaérobie et gazéification. On peut débarrasser le biogaz ainsi produit de ses contaminants potentiels et le séparer en CH<sub>4</sub> et CO<sub>2</sub>, qui pourront être vendus ensuite comme GNR et CO<sub>2</sub> industriel. Le gaz de synthèse peut être nettoyé, méthanisé, puis séparé en CH<sub>4</sub> et CO<sub>2</sub>.

Selon les données obtenues, la gazéification offre le plus grand potentiel pour produire du GNR à partir de résidus de récoltes, puisqu'elle utilise la majeure partie de la biomasse, alors que la digestion anaérobie n'en utilise qu'environ 20 %.

La production de fumier dans les fermes canadiennes varie selon le type et le nombre d'animaux, mais elle peut se prêter à la production de GNR. Selon les données obtenues, la gazéification offre un potentiel légèrement supérieur à la digestion anaérobie pour produire du GNR à partir de fumier.

Les résidus forestiers sont constitués de résidus d'exploitation forestière et de résidus du dendroctone du pin ponderosa (DPP). Selon les données sur les résidus forestiers, les résidus potentiellement disponibles se trouvent principalement en Colombie-Britannique (33 %), au Québec (27 %) et en Ontario (17 %). La production potentielle de GNR à partir de ces résidus par gazéification affiche une tendance similaire à la distribution de ceux-ci.

Les déchets municipaux canadiens qui représentent une source potentielle de GNR comprennent les déchets solides collectés dans les résidences et entreprises (DSM), le gaz d'enfouissement récupéré des sites d'enfouissement fermés (GEF), les eaux usées (EU) que recueillent les égouts municipaux, ainsi que les biosolides municipaux, soit les matières solides collectées (par décantation) dans les eaux usées.

Selon les données sur l'importance relative de chacun de ces déchets municipaux dans le potentiel de production de GNR municipal, les déchets solides (DSM) et les sites d'enfouissement constituent les sources les plus importantes. Ce sont aussi les deux sources de déchets solides les plus abondantes, par une forte marge. La digestion anaérobie fournit un peu plus de GNR que la gazéification, en raison de la production de

GEF. La production potentielle totale de GNR se répartit suivant la taille de la population.

Cette source de déchets municipaux compte grandement dans l'apport important de la digestion anaérobie à la production de GNR, ce qui permet d'utiliser des techniques bien établies, à l'aide de technologies plus accessibles et adaptables. Autre aspect qui avantage ce type de déchet : son coût de production plus faible, puisque les municipalités en défraient déjà la cueillette et le transport. Les coûts les plus importants sont liés au nettoyage et à la séparation du gaz. Par ailleurs, l'adaptation de la gazéification aux déchets municipaux ne se ferait pas sans heurts, puisqu'il existe peu d'usines de gazéification et que celles-ci utilisent habituellement le gaz de synthèse pour produire de l'électricité. Jusqu'à présent, on a favorisé l'incinération pour traiter les déchets municipaux.

Pour l'ensemble des déchets canadiens étudiés, on peut s'attendre à une production totale potentielle de 24,9 millions de tonnes (Mt) de GNR par année. Pour les déchets forestiers, on parle d'un potentiel de 12,9 Mt/an (51 % du total), 8,8 Mt/an (36 %) pour les déchets agricoles et 3,2 Mt/an (13 %) pour les déchets municipaux. La gazéification produirait la majeure partie du GNR au Canada, puisque nous estimons la production potentielle à l'aide de ce procédé à 21 Mt/an (84 % du total). La digestion anaérobie pourrait produire 3,9 Mt/an (16 % du total). Bien qu'il semble moins important que la gazéification, ce procédé demeure intéressant en raison de la disponibilité des techniques et de son moindre coût.

Nous avons comparé la taille relative de nos estimations de GNR potentiel à l'utilisation actuelle du gaz naturel dans les secteurs résidentiel et commercial. La production potentielle de GNR au Canada de 24,9 Mt/an correspond à une valeur énergétique de 1,4 TJ/an ou 389 528 GWh d'électricité. La production de GNR peut donc représenter une part importante de la consommation de gaz naturel. À l'échelle nationale, selon notre estimation du potentiel technique, 130 % de la consommation actuelle résidentielle et commerciale de GN peut être remplacée par du GNR.

Nous avons élaboré plusieurs scénarios à l'aide de feuilles de calcul exclusives qu'à conçues l'Alberta Research Council pour souligner la complexité de l'aspect

économique de cette question. Selon notre analyse, pour abaisser le coût du GNR, il faut réduire le coût technique lié au nettoyage du biogaz. À l'heure actuelle, il existe très peu de données sur ce qu'il en coûterait pour raffiner le gaz à une qualité gazoduc. Toutefois, les modèles économiques présentés ont évalué différents scénarios qui comptent des exemples de GNR utilisé pour produire du gaz naturel de qualité gazoduc ou du GNR utilisé dans la production d'électricité. L'analyse économique souligne la nécessité de développer des techniques de nettoyage du biogaz qui réduisent les coûts en capital d'un facteur 10 par rapport à la fine pointe technologique actuelle.

Produire et capturer le GNR à partir de déchets canadiens contribue à réduire les GES de deux manières : en réduisant les émissions et substituant le carburant. La réduction des émissions s'effectue par la capture du méthane qu'émettent les sites d'enfouissement et la digestion anaérobie du fumier. La substitution de carburant s'applique à l'utilisation du GNR en remplacement du gaz naturel d'origine fossile.

On évalue les réductions possibles de GES à 107 Mt d'équivalent CO<sub>2</sub> par année pour le Canada; les plus grandes quantités se trouveraient au Québec, en Ontario et en Colombie-Britannique. La substitution de carburant semble contribuer à diminuer beaucoup plus les GES que la réduction des émissions, sauf dans les provinces ayant beaucoup de résidus forestiers, comme la C.-B. Près de 33 % des réductions de GES du Canada proviennent de la réduction des émissions, le reste (67 %) étant dû à la substitution de carburant.

La production potentielle de GNR à partir des déchets peut contribuer grandement à réduire les GES et donc entraîner des crédits de carbone qui pourraient alléger le coût de production du GNR, si on tient compte de la vente du CO<sub>2</sub> produit et de la valeur de ses crédits de carbone.

Sur une base prospective, il est nécessaire d'impliquer les intervenants appropriés et les divers paliers de gouvernement afin : d'obtenir une meilleure connaissance du potentiel utile du GNR, compte tenu des infrastructures spatiales et des facteurs économiques; d'initier l'élaboration de politiques; enfin, de développer plus avant les techniques qui fourniront de plus amples données quant à l'exploitation et aux coûts.

## 1. **INTRODUCTION**

The use of biomass resources for energy production started early in human history, and continued to be the major source of energy until overtaken by coal then oil in the 19<sup>th</sup> and 20<sup>th</sup> centuries. Biomass supplies 5.9% of Canadian primary energy sources, 15% of the world's energy and 35% of the developing countries needs (Holmes and Edwards, 2003). The rest of the energy needs are supplied by fossil fuels. Concern about the use of fossil fuels and the resulting atmospheric buildup of carbon dioxide has led to a reevaluation of biomass resources for energy production.

The new efforts to use biomass for energy production centre on increasing efficiency, promoting sustainability of this resource and lowering carbon dioxide atmospheric levels by replacing fossil fuels.

This report evaluates the role wastes can play in producing energy from waste biomass by generating methane from Canadian wastes, which can then be used a renewable natural gas (RNG) source. This path to energy production offers the advantages of new previously untapped sources of biomass and a solution to mounting waste problems.

### **1.1. OBJECTIVE**

The objective of this project is to conduct a literature based study whose aim will be to assess the technical potential for methane generation from Canadian wastes, and the relative greenhouse gas (GHG) impacts of capturing the generated methane. The project also looks at the economic viability of different scenarios involving the production of RNG. While the work does not attempt to quantify the useful potential of RNG in Canada, which would need factoring in infrastructure and economic constraints; the study will enable the CGA to determine (with coarse granularity) the resource base for methane from waste.

In particular the following sub-objectives will be addressed:

- The sources of wastes that are or can be potentially converted into methane (e.g. Municipal and Agricultural)

- The total resource potential nationally with provincial breakdown where possible/feasible (the technically feasible potential methane generation)
- Expressed as percent of domestic gas consumption or any other unit that relates it to current gas use
- The economic viability of different scenarios involving the production of RNG.
- The potential for GHG management (impact of capturing methane, turning it to CO<sub>2</sub> and claiming the benefit).

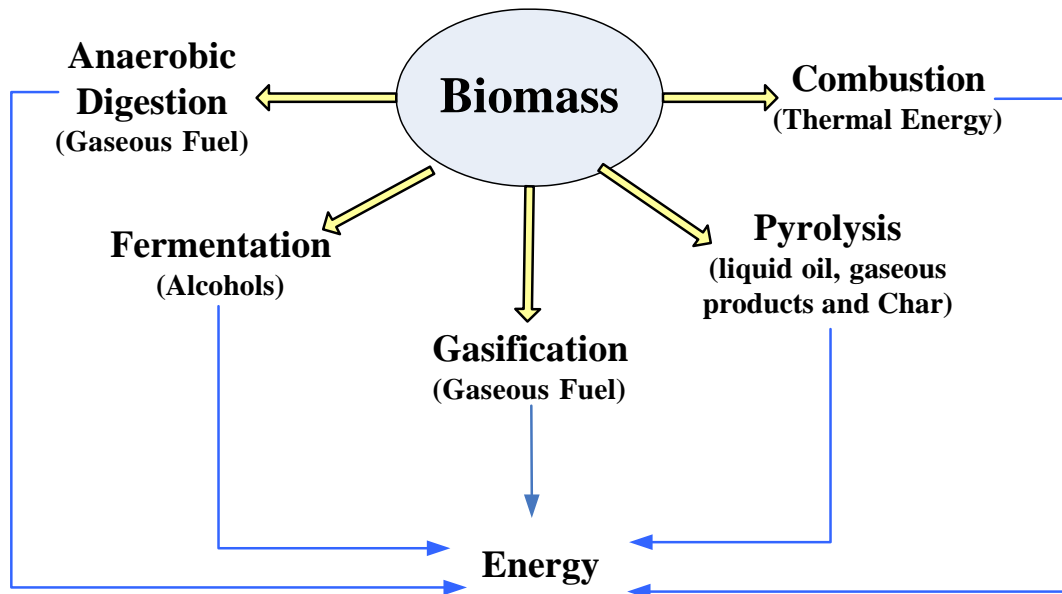
## **1.2. APPROACH**

We reviewed the literature with respect to the available processes for converting waste into renewable natural gas (RNG) and the results will be discussed in the following chapters. Furthermore, we collected data related to the source and quantities of wastes produced in Canada, organized by province and for the whole country. We used the waste information to calculate potential quantities of RNG that can be produced from these wastes using assumptions about the conversion pathways and yields. These values were based on the scientific literature and our own experience and will be explained later in this report. The potential RNG production values are discussed for each province and the country in terms of RNG production pathways and their technical and economic feasibilities. Similar discussion is also included for the potential reduction in greenhouse gases realized from the production of RNG from waste.



2.  **BIOGAS, SYNGAS AND RENEWABLE NATURAL GAS PRODUCTION PROCESSES FROM WASTES**

Biomass can be converted to fuel for production of energy, i.e. electrical and thermal or raw materials for the synthesis of chemicals, liquid fuels, gaseous fuels such as hydrogen and methane. There are five different technological routes by which energy can be produced from biomass. These five processes are shown in Figure 1 and can be grouped into thermochemical (biomass combustion, gasification and pyrolysis) and non-thermal (anaerobic digestion and fermentation) processes. Though the diagram in Figure 1 has shown energy production but the chemicals produced by digestion, fermentation, gasification and pyrolysis can be used as feedstocks for producing other useful chemicals.



**Figure 1.** Potential Pathways for Energy Production from Biomass.

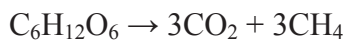
## **2.1. ANAEROBIC DIGESTION**

Anaerobic digesters are commonly used for effluent and sewage treatment or for managing animal wastes. Anaerobic digestion is a simple process that can greatly reduce the amount of organic matter which might otherwise end up in landfills or waste incinerators. In developing countries simple home and farm-based anaerobic digestion systems offer the potential for cheap, low cost energy from biogas. Environmental pressure on solid waste disposal methods in developed countries has increased the application of anaerobic digestion as a process for reducing waste volumes and generating useful byproducts. Anaerobic digestion may either be used to process the source separated fraction of biodegradable waste, or alternatively combined with mechanical sorting systems, to process mixed municipal waste. Almost any biodegradable 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. Anaerobic digesters can also be fed with specially grown energy crops or silage for dedicated biogas production. After sorting or screening to remove physical contaminants, such as metals and plastics, from the feedstock the material is often shredded, minced, or hydrocrushed to increase the surface area available to microbes in the digesters and hence increase the speed of digestion. The material is then fed into an airtight digester where the anaerobic treatment takes place. There are four key biological and chemical stages of anaerobic digestion:

1. The first is the chemical reaction of hydrolysis, where complex organic molecules are broken down into simple sugars, amino acids, and fatty acids with the addition of hydroxyl groups.
2. The second stage is the biological process of acidogenesis where a further breakdown by acidogens into simpler molecules, volatile fatty acids (VFAs) occurs, producing ammonia, carbon dioxide and hydrogen sulfide as byproducts.

3. The third stage is the biological process of acetogenesis where the simple molecules from acidogenesis are further digested by acetogens to produce carbon dioxide, hydrogen and mainly acetic acid.
4. The fourth stage is the biological process of methanogenesis where methane, carbon dioxide and water are produced by methanogens.

A simplified generic chemical equation of the overall process is as follows:



## **2.2. GASIFICATION**

Gasification is a process that converts carbonaceous materials, such as coal, petroleum, or biomass, into carbon monoxide, hydrogen and methane by the reaction of the raw organic feedstock at elevated temperatures with a controlled amount of oxygen at a deficit condition. The resulting gas mixture is called synthesis gas or syngas and is itself a fuel. Gasification is a very efficient method for extracting energy from many different types of organic materials. The advantage of gasification is that using the syngas is more efficient than direct combustion of the original raw feedstock; more of the energy contained in the raw feedstock is extracted. Syngas may be burned directly in internal combustion engines, used to produce methanol and hydrogen, converted via the Fischer-Tropsch process into synthetic fuel, or converted to methane through catalytic methanation. Gasification can also begin with materials that are not otherwise as useful fuels, such as biomass or organic waste. In addition, the high-temperature combustion refines out corrosive ash elements such as chloride and potassium, allowing clean gas production from otherwise problematic fuels. Gasification of coal is currently widely used on industrial scales to generate electricity. However, almost any type of organic material can be used as the raw material for gasification, such as wood, biomass, or even plastic waste. Thus, gasification may be an important technology for renewable energy. Gasification relies on chemical processes at elevated temperatures, 700°C-1800°C, which distinguishes it from biological processes such as anaerobic digestion that produce biogas.

### **2.3. OTHER ENERGY PRODUCTION PROCESSES FROM WASTES**

Three other processes commonly used for energy production from wastes are fermentation, combustion and pyrolysis. These processes will be discussed briefly here.

#### **2.3.1. Fermentation**

Fermentation is the biochemical conversion of carbohydrates into energy in the form of alcohols. This process uses microorganisms and/or enzymes to convert biomass feedstocks (including wastes) into fuel alcohols, most notably ethanol. Ethanol is used in liquid fuel blends and its most common use is currently found in Brazil and increasingly in the US and EU. Most ethanol today is produced from grains, corn, sugar beets and sugar cane.

The process includes the physical breakdown of the biomass tissues through grinding to expose their starches then adding water and heat to cook the mixture. The resulting mix is then treated with enzymes that transform the starches into sugars, which is followed by fermentation of the sugars to alcohols using added yeast microorganisms. The resulting alcohol (ethanol) is then distilled and dehydrated before readying for use (Holmes and Edwards, 2003).

#### **2.3.2. Combustion**

Combustion is a complex sequence of exothermic chemical reactions between a fuel and oxidant (oxygen; air-a source of oxygen) to produce thermal energy. It is the major chemical energy conversion technique and key to humankind's existence. Combustion includes thermal, hydrodynamic, and chemical processes. It starts with the mixing of fuel and oxidant, and sometimes in the presence of other species or catalysts. The fuel can be gaseous, liquid, or solid (biomass) and the mixture may be ignited with a heat source. During combustion, new chemical substances are created, i.e., carbonaceous materials of the feedstock react with oxygen and produce gaseous product. Combustion process operates in excess oxygen. When ignited, chemical reactions of feedstock and oxidant take place and the heat release from the reaction creates a self-sustained process. For combustion to occur three things must be present: a fuel to be burned, a source of

oxygen, and a source of heat. As a result of combustion, exhausts are created and heat is generated. One can control or stop the combustion process by controlling the amount of the fuel available, the amount of oxygen available, or the source of heat.

### **2.3.3. Pyrolysis**

Pyrolysis is a chemical decomposition induced in organic materials by thermal energy in the absence of oxygen. But in real world application, it is not possible to achieve a completely oxygen-free atmosphere. Pyrolysis transforms organic materials into gaseous components, liquid, and a solid residue (coke) containing fixed carbon and ash. Pyrolysis of organic materials produces combustible gases, including carbon monoxide, hydrogen and methane, and other hydrocarbons. If the off-gases are cooled, liquids condense producing an oil/tar residue and contaminated water. Pyrolysis typically occurs in the temperatures range between 350°C-550°C. In general it is a simple, low-cost technology capable of processing a wide variety of feedstocks producing gases, a bio-oil, bio-chemicals, and charcoal. An ancient industrial use of anhydrous pyrolysis is the production of charcoal through the pyrolysis of wood. In more recent times, pyrolysis has been used on a massive scale to turn coal into coke for metallurgy, especially steelmaking.

*Slow pyrolysis* is a thermochemical decomposition of organic material at elevated temperatures in the absence of oxygen. The feed material is dried and fed into a stirred, heated kiln. As the material passes through the kiln, a combustible gas is evolved and is continuously removed from the reactor. Approximately 35% by weight of the dry feed material is converted to a high-carbon char material that is collected on the discharge of the reactor. Typical yield is 30% liquid (mostly water), 35% gaseous product and 35% char.

Anhydrous pyrolysis can also be used to produce liquid fuel similar to diesel from solid biomass. The most common technique uses very low residence times (<2 seconds) and high heating rates using a temperature between 300 and 500 °C and is called either *fast*

*or flash pyrolysis*. Fast pyrolysis of biomass achieves high yields of liquids. Rapid heating means that the biomass must be ground into fine particles and that the insulating char layer that forms at the surface of the reacting particles must be continuously removed. Typically it yields 60-75% oil, 10-25% gaseous product and 10-15% chars.

### 3. **METHANE PRODUCTION PROCESSES FROM BIOGAS AND SYNGAS**

As it is already stated in the earlier section, the main focus of this report is production of methane from waste biomass. Therefore, we would be concentrating our discussion of cleaning and upgrading of anaerobic digestion produced raw biogas and gasifier produced raw biosyngas where gasifier operation temperature is  $<1000^{\circ}\text{C}$ . The anaerobic digestion produced raw biogas consists of 40-80 % methane ( $\text{CH}_4$ ) and 15-50 % carbon dioxide ( $\text{CO}_2$ ). Therefore, methane is the major constituent of the anaerobic digestion produced biogas. Here 'Biosyngas' term is used to distinguish it from the 'Syngas' produced by gasification technology from fossil fuel. Gasifier produced raw biosyngas mainly consists of hydrogen and carbon monoxide. Therefore, here a methanation step has to be included.

#### 3.1. **CLEANUP**

##### 3.1.1. **Biogas Cleaning**

Typically, anaerobic digestion produced raw biogas consists of 40-80% methane ( $\text{CH}_4$ ) and 15-50% carbon dioxide ( $\text{CO}_2$ ), with the exact proportions depending on the production conditions and processing techniques. In addition, hydrogen sulphide ( $\text{H}_2\text{S}$ ), ammonia ( $\text{NH}_3$ ), siloxanes, water vapor and nitrogen gas ( $\text{N}_2$ ) may be present in small amounts. In order to upgrade the biogas to a natural gas quality, a multi-stage cleaning and upgrading treatments are needed to obtain desired biomethane. The cleaning and upgrading processes depends on the feedstock, anaerobic digestion process and the end use of the biomethane. Flowchart in Figure 2 shows the typical biogas cleaning stages. Excellent review of biogas cleaning is provided in NRCan document on Biogas Treatment (Conestoga-Rovers & Associates, 2007), and the following references (IEA Bioenergy, 2000; Schmack Biogas AG; and Persson et al. 2006) are recommended for further reading.

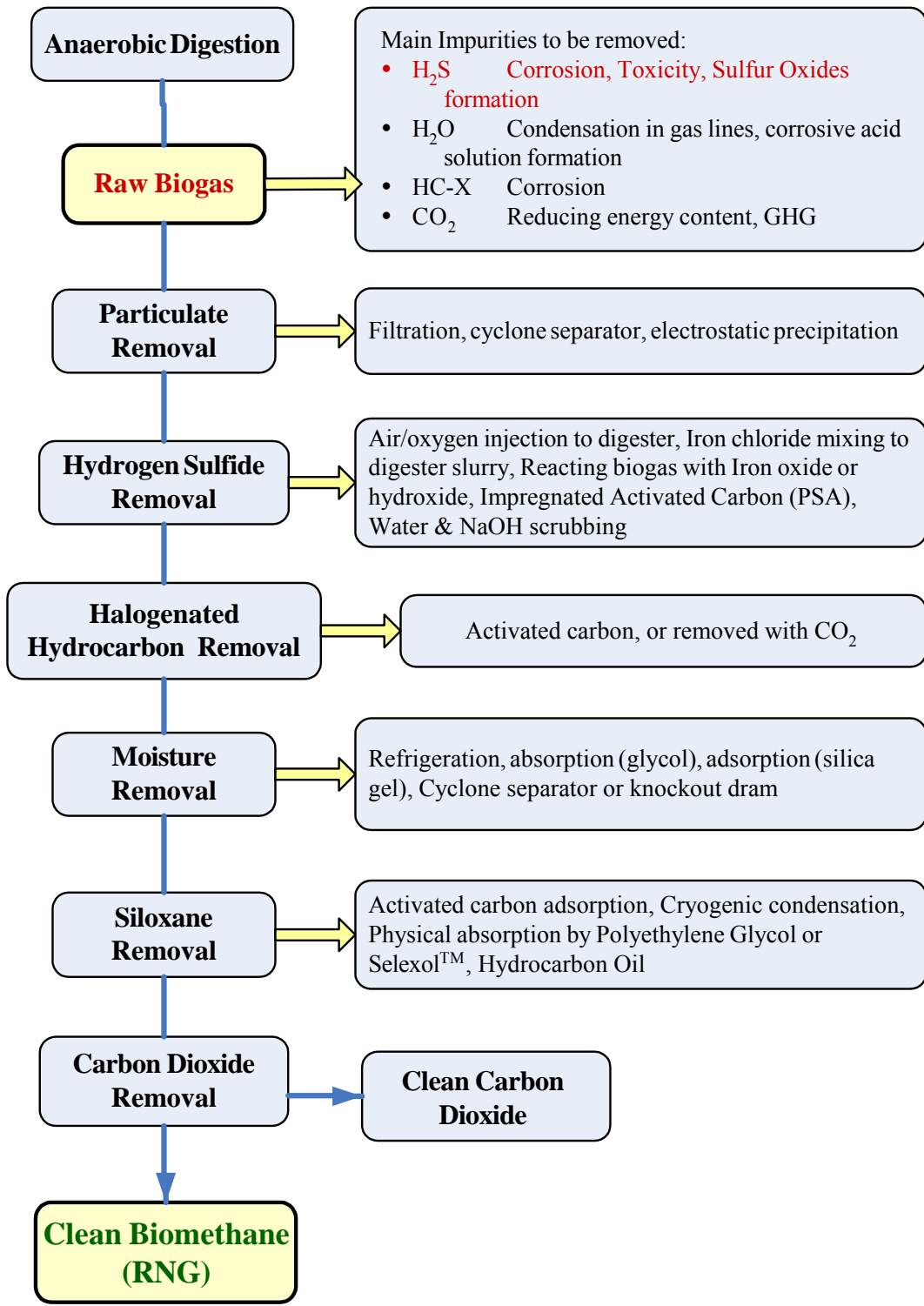


Figure 2. Flowchart of the Biogas Cleaning Process.

**Particle Removal:** Some moisture removing techniques also remove particles as well as some particle removal techniques also remove moisture. Filtration is a simple way to remove particles. Just passing the biogas through stainless steel mesh filter or filter pad can remove particles as well as some of the moisture. Cyclone separator can be very effective to remove larger particles as well as some moisture from the biogas. Here centrifugal force is used for separating the particles from the biogas stream. Electrostatic precipitator can be used to remove particles from biogas.

**Hydrogen Sulfide Removal:** Hydrogen sulfide is needed to be removed in order to avoid corrosion in compressors, pipeline, gas storage tank and other metallic parts. On the top of its corrosiveness it is also toxic. Due to all these potential problems with hydrogen sulfide, it is generally removed at the early stages of cleaning process. There are number of ways hydrogen sulfide can be removed as listed below:

- Air/Oxygen injection to digester biogas
- Iron chloride mixing to digester slurry
- Iron oxide or iron hydroxide
- Impregnated activated carbon
- Water scrubbing
- Sodium hydroxide scrubbing

Air/or oxygen injection is a biological method of removing of hydrogen sulfide. Oxygen promotes sulphur oxidizing bacteria in the digester and the bacteria converts hydrogen sulfide to yellow cluster of sulphur. Though air injection is simple and a low cost solution, it introduces nitrogen in the biogas which is difficult to remove.

Iron chloride in digester slurry reacts with hydrogen sulfide and forms iron sulfide. This method is very effective in reducing high hydrogen sulfide levels but less effective in attaining low and stable levels. Iron oxide or iron hydroxide can be used for removal of hydrogen sulfide, here iron oxide/hydroxide react with hydrogen sulfide of the biogas and form iron sulfide. In this case biogas is passed through iron



oxide/hydroxide bed. This reaction is slightly endothermic, optimum reaction temperature is between 25°C and 50°C. Iron oxide can be recovered by reacting iron sulfide with air. This regenerative process is highly exothermic.

With pressure swing adsorption (PSA) systems hydrogen sulfide is removed by potassium iodide impregnated activated carbon. For this process small amount of air is needed to be added in the biogas. Hydrogen sulfide is catalytically converted to sulphur and water. This reaction occurs at a pressure of 7 to 8 bar and a temperature of 50°C-70°C. The sulphur is adsorbed by activated carbon.

Hydrogen sulfide is soluble in water; therefore, water scrubbing can be used to remove hydrogen sulfide. Contaminated water must be regenerated before reuse. Hydrogen sulfide can be desorbed from water and the result is a fugitive emission. Water solution of sodium hydroxide has higher hydrogen sulfide absorption capacity than pure water. Sodium hydroxide reacts with hydrogen sulfite and form sodium sulfide. Major problem here is the disposal of sodium sulfide contaminated water.

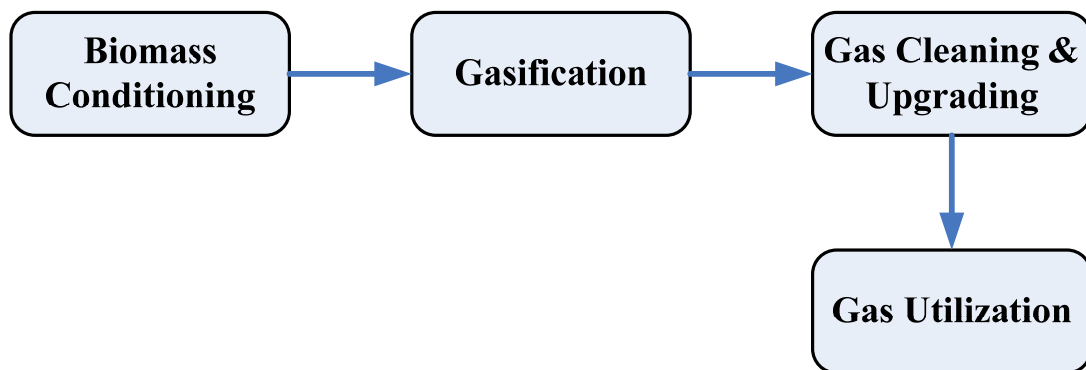
***Halogenated Hydrocarbon Removal:*** Halogenated hydrocarbon including hydrochloric acid, hydrofluoric acid and chlorinated aromatics are difficult to remove in low concentration. Generally halogenated hydrocarbons are simultaneously removed with carbon dioxide. Activated carbon can be used for removing halogenated hydrocarbon.

***Siloxane Removal:*** Siloxane form siliceous deposit on engine and enhances the wear and as a result reduces the lifespan of the engine or engine parts. It can be removed by several ways. Activated carbon can remove siloxane by adsorption. Cryogenic condensation can be used for removing it. It is possible to remove 99% of siloxane by cooling the biogas at -70°C. Polyethylene glycol or Selexol™, a commercially available solvent can be used for siloxane removal. Here physical absorption is the mechanism. This chemicals are not selective to siloxane removal, it also remove carbon dioxide, hydrogen sulfide and water vapor. Hydrocarbon oil can be effective in removing siloxane and the oil can be regenerated by vacuum treatment.

Raw biogas is normally saturated with moisture and it must be removed to avoid corrosion of piping and the equipments and freezing problems in winter. Moisture should be removed close to the downstream process unit. Multiple moisture taps can be installed in the vital location of the piping network. There are multiple ways to remove moisture, such as refrigeration, here biogas is cooled below its dew point to condense water and remove it. It can be removed using absorption technique such glycol or some salt absorbed moisture. Absorbing chemical can be regenerated by drying at high temperature.

### **3.1.2. Bio Syngas Cleaning and Treatment**

A biomass gasification system can be divided into four major steps, as shown in the process flowchart they are raw biomass conditioning, gasification, crude biosyngas cleaning and gas utilization. Depending on the biomass feedstock and the type of gasifier, the raw biomass must be conditioned (sized, dried etc.). Achieving a good continuous and reliable biomass conditioning is often one of the most important points in operation of a gasification plant.



**Figure 3.** Flowchart of the Four Main Steps in a Biomass Gasification System.

There are several different types' gasifier technologies available, each of them has there own characteristics:

- Fluidized bed gasifiers
- Fixed bed gasifiers
- Entrained flow gasifiers
- Indirect gasifiers

If gasification is performed at high temperature (e.g., entrained flow gasification) i.e.,  $>1200^{\circ}\text{C}$ , biomass is completely converted into  $\text{H}_2$ ,  $\text{CO}$ ,  $\text{CO}_2$  &  $\text{H}_2\text{O}$ . This biosyngas is free from tar and is chemically similar to syngas derived from fossil fuels and can be used for the same applications such as Fisher Tropsch diesel production, Methanol/DME production, Ammonia production, Hydrogen source etc. The advantages of entrained flow gasification are that there is a lot of experience with large scale plants using coal & refinery waste. Feeding “raw” biomass into such a plant is often not possible and the low energy density of biomass favors smaller scale plants for which this entrained flow gasifier is not suitable.

Low temperature gasification (fluidized bed, fixed bed gasifier), i.e.,  $<1000^{\circ}\text{C}$  is the other option and commonly used for biomass gasification. The quality and pureness of the biosyngas always differ between different gasifiers. Impurities in a raw syngas are tar, particulates, halogens, alkali metals, S-compounds, N-compounds, heavy metals, calcium etc. Typically most all the cleaning processes operates at lot lower temperature that the gasifier itself. Therefore, raw syngas need to be cooled for cleaning treatment. In most cases, it is desirable to utilize the sensible heat in the gas, for example raising steam.

In some cases first step in this process is a water scrubber that utilizes water trays to wash and cool the syngas. The water scrubber removes the fine solids, as well as ammonia, chlorides, and other trace components that are water soluble. The acid gas removal (AGR) system is designed to remove greater than 99% of the total sulfur from the raw syngas. Primary sulfur compounds in the syngas are hydrogen sulfide ( $\text{H}_2\text{S}$ ) and carbonyl sulfide ( $\text{COS}$ ). Because  $\text{COS}$  is not readily captured by the AGR, a hydrolysis

unit is utilized upstream of the AGR to react COS with water vapor in the presence of a catalyst to form H<sub>2</sub>S and CO<sub>2</sub>.

Solids particulates can be removed by cyclone separators, barrier filters, electrostatic filters, and wet scrubbers. Cyclone separators are a primary means of removing bulk particulates from gas streams. They rely on centrifugal force to separate solids from the gas by directing the gas flow into a circular path. Cyclone separators are employed as an initial gas cleanup step in most gasifier systems because they are effective and relatively inexpensive to operate. Cyclone separators are effective at removing larger particles and can operate over a wide range of temperatures, limited primarily by the material of construction. They can remove >90% of particulates above about 5 microns in diameter at minimal pressure drops of 0.01 atm. Since cyclone separators can operate at elevated temperatures, the sensible heat in the product gas can be retained. Cyclone separators also remove condensed tars and alkali material from the gas stream; although the vaporized forms of those constituents remain in the gas stream. Barrier filters include a range of inorganic porous membranes that allow gases to penetrate but prevent the passage of particulates. Barrier filters membranes can be designed to remove almost any size of particulate, including those in the sub-micron range, but the pressure differential across the filter will increase as the pore size decreases. As a result, there are technical and economic constraints that effectively limit particulate removal to about 0.5 $\mu$ m in systems such as gasifiers that must handle large gas volumes. Filters are cleaned by periodically passing pulsing clean gas through the filter in the reverse direction of normal gas flow. To reduce the overall particulate load, these filters are typically placed downstream from cyclone separator. Electrostatic filters have also been used extensively in a variety of gas cleaning operations. In these systems, the product gas flows past high-voltage electrodes that impart an electric charge to particulates, but do not affect the permanent gases. The particulates are then collected as the gas stream passes collector plates of the opposite polarity. The electrically charged particulates migrate to the collector plate and deposit on the surface. Particulates are removed from the scrubber plates by either wet or dry methods. Dry scrubbers use

mechanical action to periodically remove material from the surface and can operate at temperatures of 500°C or more.

The presence of tars in the product gas is seen as the biggest problem in the smooth application of biomass product gas as source of sustainable energy. Tar is formed in the gasifier and comprises a wide spectrum of organic compounds, generally consisting of several aromatic rings. Heavy tars condense out as the gas temperature drops and cause major fouling. The tar dew point is a critical factor. Light tars like phenol or naphthalene have limited influence on the tar dew point, but are not less problematic. Light tars like phenol chemically pollute the bleed water of downstream condensers and aqueous scrubbers. Naphthalene is important as it is known to crystallize at the inlet of gas engines causing a high service demand. Tar can be removed few different ways as follows:

***Thermal tar cracking:*** A thermal tar cracker heats up the product gas to a temperature of 1200°C. At this temperature the tars are removed almost completely leading to a very low tar concentration (<100 mg/m<sup>3</sup>) and tar dew point (<10°C). Thermal cracking take place in the gasifier which operates  $\geq 1200^{\circ}\text{C}$ , such as entrained-flow slagging gasifiers. It is not practical to set up thermal cracking outside the gasifier.

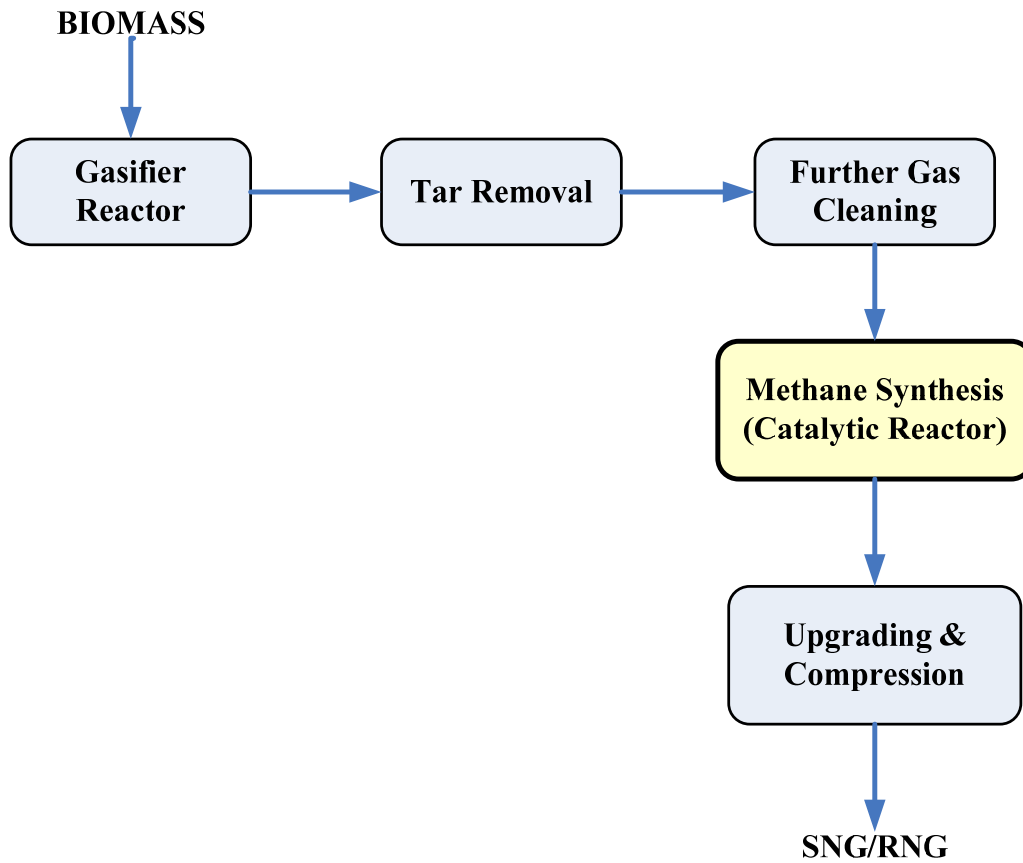
***Catalytic tar cracking:*** A catalytic tar cracker does not heat up the product gas and thus eliminates the disadvantages of a thermal cracker. There are a large number of different catalysts that have been used to eliminate the tars in the product gas from the gasification process. The two most researched groups are Ni-based catalysts and dolomites. When Ni-based catalysts are used, tar concentration in the product gas can be reduced significantly by means of reforming but since this process is endothermic, a part of the chemically bound energy of the gas has to be burned to sustain this process. This effect leads to a decreased efficiency of the gasification process. In contrast, when so called tar cracking catalysts such as dolomite are used, the only thing that is reformed is the tar itself while low hydrocarbons e.g. methane, ethane and propane are left intact. Tar cracking can be defined as a process that breaks down the larger, heavier and more complex hydrocarbon molecules of tar into simpler and lighter molecules by the action of

heat and aided by the presence of a catalyst but without the addition of hydrogen. Two well known tar cracking catalysts are naturally occurring minerals: dolomite and olivine.

***Tar removal by aqueous scrubbers:*** Aqueous tar removal systems cool down the product gas and remove the tars by condensation. In most aqueous systems dust and tars are collected simultaneously. The product gas is cooled down and aerosols of dust and tars are collected. To avoid tar condensation and fouling of piping the gas should not cool down. In the aqueous scrubber system a tar/water problem is created. Mixing (heavy) tars with water will lead to operational difficulties in the scrubber and huge maintenance costs. The most important disadvantage is formed by waste water handling. Waste water handling is often so expensive that the plants economical feasibility is at stake.

ECN and Dahlman Filter Technology developed the oil based tar removal system OLGA. In OLGA the tars are removed by condensation and by absorption. The temperature remains above the water dew point to avoid mixing of dust and tar with water. Due to the absorption step in OLGA the tar dew point is decreased far below the operating temperature of OLGA, typically below 10°C. The total tar concentration is reduced to 200 mg/m<sup>3</sup>. Tars downstream (OLGA process) are composed of light compounds like Xylene and Indene. These compounds do not cause fouling problems in the downstream system. Phenols are almost completely removed in OLGA to avoid the production of hazardous condense water and expensive wastewater cleaning.

Raw bio-product gas or biosyngas can be converted to methane/renewable natural gas. ECN is extensively working in this area. The flowchart of the process of making renewable methane from biomass via gasification is given in Figure 4. After raw product gas cleaning a catalytic methanation step is included to convert hydrogen and carbon monoxide to methane. The last step of gas upgrading involves the removal of water, CO<sub>2</sub> to meet the natural gas specifications. It also might include compression. Biosyngas cleaning/treatment information are available from ECN (van Ree, 2003 and ECN) and the book on Gasification by (Higman and van der Burg, 2003) is an excellent basic book on this subject.



**Figure 4.** Process Flowchart of the Synthetic/Renewable Natural Gas (SNG/RNG) Production from Biomass.

### 3.2. SEPARATION

Separation technologies can be considered to belong to one of these four categories (Kohl and Riesenfeld, 1985; Yang, 1987; and Wong et al., 2002):

- Liquid absorption - chemical and physical absorption
- Solid physical adsorption - pressure swing and temperature swing adsorption
- Membrane separation
- Cryogenic separation.

### **3.2.1. Liquid Absorption**

Liquid absorption is a method commonly used to remove or separate gas components by a chemical solvent which selectively reacts or physically bonds with some gas components. By dissolving the reacted gas components in the liquid phase and the un-reacted gas components remaining in the gas phase, the gas stream can be separated efficiently.

The main advantages of liquid absorption processes are:

- Availability of many different solvents for required gas stream separations, including alkanolamines, alkaline salt solutions and many other tailor-made solvents for different gas separations.
- Gas separation efficiency is high. By selecting a suitable absorbing liquid and gas separation column; the gas separation efficiency can be as high as 99.9%. The most common liquid absorption process is using alkanolamine solvents to remove CO<sub>2</sub> and H<sub>2</sub>S from natural gas. The CO<sub>2</sub> and H<sub>2</sub>S level in the final gas produced must meet the regulatory and industry requirements. Typically the H<sub>2</sub>S level is less than 4 ppm and CO<sub>2</sub> level is less than 2% (v/v).

The process relies on conventional pack columns to provide the gas liquid surface contact area. The solvent regeneration cycle consumes large amounts of energy. Therefore the high capital and operational costs become its disadvantage when compared with other gas separation technologies. This process is more economically suitable to large scale gas separation and purification (Mimura et al., 2001; Idem et al., 2001; Rochelle et al., 2002; and Mariz, 1998).

Although the liquid absorption process is the most mature technology for gas separation, the ongoing research and developments includes:

- Improving the solvent formulation to boost reaction kinetics and reduce regeneration energy.
- Column pack to provide bigger surface to improve the mass transfer and reduce operational related problems such as flooding, channeling.
- Improving the process control.



### **3.2.2 Solid Physical Adsorption**

The solid physical adsorption is based on the concept of using micro-porous materials as sorbents for gas purification and separation. Most commonly used materials are activated carbon, synthetic and natural zeolites, silica gel and activated alumina (Yang, 1987). The past two decades have seen a large growth in adsorption separation processes. Most of these processes employ pressure-swing adsorption cycles. Using PSA for gas separation will continue to increase with the development of new adsorbents and improved process configurations (Kohl and Riesenfeld, 1985 and Gas Processes, 1998). For production of oxygen or nitrogen from air, it is already shown that it is more economical to use PSA than cryogenic means for a production rates below 30 metric tons per day. A similar situation also exists for hydrogen production. High-purity (99.9999%) hydrogen can be produced by the PSA separation of steam reformer products. PSA can be used for bulk gas separation or gas purification depending on the selection of different adsorbents and process cycles. New applications will also emerge as new or improved adsorbents are developed (Natcogroup). Separation of carbon dioxide from methane or from hydrocarbons is also possible with the development of new adsorbents.

The main advantage of physical adsorption over chemical or physical absorption is its simple and energy efficient operation and regeneration, which can be achieved with a pressure swing or temperature swing cycle. The concerns over this technology are scale up and the need for further development and improvement of the selectivity of the adsorbent for different gas separation which includes the adsorbent specific for CO<sub>2</sub> removal from the post combustion flue gas, landfill gas and biogas streams.

### **3.2.3 Membrane Separation**

Membrane technology, as applied to gases, involves the separation of individual components on the basis of the difference in their rate of permeation through a thin membrane barrier. The rate of permeation for each component is determined by the characteristics of the component, the characteristics of the membrane and the partial pressure differential of the gaseous component across the membrane. Since separation is

based on a difference in the rate of permeation rather than on an absolute barrier to one component, the separated component that flows through the membrane (the permeate) is never 100% pure. Also, since a finite partial pressure differential is required as the driving force, some portion of the permeating component remains in the residue gas, and 100% recovery is not possible. As these generalizations would suggest, the process is particularly suitable for bulk removal operations rather than for the removal of trace impurities from gas streams. It is possible to reach high purity recovery gas with the help of membrane module configurations and/or combined with other technology, such as liquid absorption process (Mulder, 1996; Echt, 2002; and Srikanth).

The membrane based processes for gas separation competes with technology alternatives such as adsorption, cryogenic and liquid absorption processes in niche application areas. Membrane gas separation technology has its own advantages that make it attractive to many industries and some large gas supply companies as well. Based on the concept of membrane gas separation the following four key factors can influence the membrane separation performance:

- membrane selectivity towards the gases separated
- membrane flux or permeability
- the life of the membrane
- maintenance and replacement costs

The membrane gas separation process has been used for hydrogen separation and recovery, ammonia purge gas separation, refinery hydrogen recovery, syngas separation in petro-chemical industry, CO<sub>2</sub> enhanced oil recovery and natural gas processing.

A commercial process for CO<sub>2</sub> removal from natural gas stream uses a combination of membrane and liquid absorption processes. The membrane process is used to remove bulk CO<sub>2</sub> to reduce the CO<sub>2</sub> level in the gas stream, while the liquid process is used after the membrane process to further remove CO<sub>2</sub> to the required level. NATCO Group started initial application of this system in 1983 including two membrane process plants of 50 mmscfd and 25 mmscfd capacities to remove a bottleneck in the Benfield process, a conventional liquid absorption process. The plants were designed to reduce the CO<sub>2</sub>

content in the produced gas from a range of 45% to 65% down to about 30%. This was sufficient to keep the Benfield plant within its process limitations. Change in field production and development in membrane technology have changed the plant considerably. By the year 2006, membranes have replaced the Benfield process and the plant is currently processing up to 180mmscfd of produced gas from 85% down to 10% CO<sub>2</sub>. The downstream cold plant has been replaced with a more efficient cryogenic plant and a small amine unit processes the hydrocarbon stream of 10% CO<sub>2</sub> coming from the membrane unit into sale gas. Now owned by Kinder Morgan, SACROC can recover 150 mmscfd of CO<sub>2</sub> for reinjection while also producing sale gas and recovering NGL liquids. The membrane unit itself has been online 97.9% of time and process ready for 99% of its nearly 20 years in service. The most important factor in project success is the life cycle of Cynara membrane element with properly designed pretreatment. Careful process design keeps cost well below other CO<sub>2</sub> removal technologies (Parro, 1985).

Gas purification and separation by membrane permeation has many advantages including:

- Low capital investment
- Ease of operation, process can be operated unattended
- Good weight and space efficiency
- Ease of scale up
- Minimal associated hardware, no moving parts
- Ease of installation
- Flexibility and module design
- Minimal utility requirement
- Low environmental impact
- Reliability
- Ease of incorporation of new membrane development. User can install the next generation of membranes into existing equipment at the scheduled membrane replacement time.

The main disadvantages are:

- A clean feed is required. Particulates and entrained liquids must be removed. Filtration to remove particles down to one micron in size is preferred.
- Because membrane uses pressure as the driving force of the process, there may be a considerable energy requirement for gas compression.

Using the mechanism of polymeric membrane permeation to the separation of gases started as early as 1831. Early industrial membrane processes were using rubber membrane for the separation of O<sub>2</sub> from air and recovery of helium from natural gas. However, the selectivity and production rates of the membranes available at the time were poor, and the need for the required large membrane areas made membrane permeation economically unattractive. Improvements in manufacturing methods have resulted in improved membrane performance and economics. The developmental and commercial successes of the early 1980s and the existing large market attracted many large companies into this field.

The application area includes air separation, hydrogen separation, and CO<sub>2</sub> H<sub>2</sub>S and water separations from methane and other hydrocarbons in different processes from the Oil & Gas and Petrochemical industries. CO<sub>2</sub> removal from landfill gas was successively demonstrated in 1986. The landfill collection gas had to be compressed to 525 psi and the organics and condensed liquids had to be removed before the gas was sent to the membrane unit for separation of CO<sub>2</sub> and methane. Advantages of this membrane system for landfill gas separation are claimed to be low capital and operating cost, simplicity of operation and maintenance, compact size and modular construction.

There are many future improvements related to membrane performance that are available for research and development (Carolan et al., 2002; and Vu et al., 2002). These include the following areas:

- Reduction of the membrane operation pressure would all for better economics for many gas streams that are generated at low or ambient pressures, such as

post combustion flue gases, landfill gas and biogas generated from anaerobic digesters.

- Increase in the membrane operation temperature would allow for the separation of high temperature gas streams without a significant temperature drop or heat loss. The development of inorganic based ceramic and carbon fiber membranes might be germane for these types of applications.
- Increase in the membrane selectivity would increase the separation efficiency. Many research groups are active in the areas of selecting and developing different type of membrane materials and in improving the physical and chemical properties of the membranes.

#### **3.2.4 Cryogenic Gas Separation**

Cryogenic separation involves cooling the gases to very low temperatures so that some gas components can be liquefied and thus separated from the gas phase. The most popular applications that are using this technology are in the production of liquid oxygen and liquid nitrogen. The technology requires a large plant to cool air to several hundred degrees below zero in order to separate the component gases. Nitrogen and oxygen are then distributed to customers in liquid form using tanker trucks. Compared with other separation technologies, cryogenic separation tend to use more energy unless the concentration of easy liquefied gases are much higher which avoids cooling large amounts of un-liquefied gas components. This method is worth considering where there is a high concentration of CO<sub>2</sub> gas streams. The advantage is that it produces a liquid CO<sub>2</sub> ready for transportation by pipeline. The disadvantage is that it requires high energy inputs to reach cryogenic temperatures. Cryogenics are normally used for high pressure gases such as pre-combustion decarbonization processes (Wong et al., 2002).

#### **3.2.5 Summary**

The above stated four main technologies for gas separation and purification are all actively used by many different industries. They all have their own advantages and disadvantages. Sometimes a combination of these technologies can be used, for example,

a membrane process and a liquid absorption process can be used together to economically remove CO<sub>2</sub> from natural gas stream. How to select a suitable technology for each gas stream is dependent on the composition of the gas stream, the temperature and pressure of the gas stream, the separation and purification requirements, and most importantly the economic viability based on the capital and operating costs and other market related factors.

Among these technologies, the membrane technology is relatively new and there is great potential for research and development in terms of membrane materials and improvement of membrane fabrication and membrane module design. For pressure-swing adsorption technology, the development of the new adsorbent material would also have high potential to become a great candidate for the demanding gas separation and purification market.

#### 4. **PRODUCTION OF BIOGAS, SYNGAS AND RENEWABLE NATURAL GAS FROM CANADIAN WASTES**

Canadian wastes that are amenable to producing RNG are those containing significant amounts of biomass and are mostly generated by the agricultural, forestry and municipal sectors.

##### **4.1. AGRICULTURAL WASTES**

Agricultural wastes containing significant biomass are mostly made up of crop residues and animal manures. These wastes can be converted to biogas and syngas through anaerobic digestion and gasification. The produced biogas can be cleaned up of potential contaminants and separated into CH<sub>4</sub> and CO<sub>2</sub> both of which can be sold as RNG and industrial grade CO<sub>2</sub>. Syngas can be cleaned up, methanated and then separated into CH<sub>4</sub> and CO<sub>2</sub>.

##### **4.1.1. Crop Residues**

Canadian crop residues amenable for producing RNG vary between provinces and regions and are made up of the unused part of the crops. We estimated crop production (e.g. grain) for the major crops grown in Canada using Statistics Canada data (Statistics Canada, 2007a) for each province and for the whole country (Tables 1 to 11). Dry matter content of the reported crops were estimated from assumed water contents as recommended by Ralevic and Layzell (2006) and reported in Tables 1 to 11. The unused parts of the plants were estimated from the harvest index for each crop (Ralevic and Layzell, 2006) and the amount of removable residues was assumed to be 50% of the unused biomass (Tables 1 to 11). The harvest index is defined as the ratio of crop production over the total biomass (crop production and unused part of the plant).

Crop	Area <sup>1</sup>	Crop Production <sup>1</sup>	Water Content <sup>2</sup>	Dry Matter Production <sup>3</sup>	Harvest Index <sup>4</sup>	Total Residue <sup>5</sup>	Removable Residue <sup>6</sup>
	(1000ha)	(kt)	(%)	kt(dry)	(%)	kt(dry)	kt(dry)
<b>Wheat</b>	8,636	20,054	16%	16845	50%	16845	8423
<b>Oats</b>	1,816	4,696	16%	3945	50%	3945	1972
<b>Barley</b>	3,998	10,984	16%	9226	50%	9226	4613
<b>Grain Corn</b>	1,369	11,649	16%	9785	50%	9785	4892
<b>Mixed Grains</b>	96	263	16%	221	50%	221	110
<b>Canola</b>	5,911	8,751	16%	7351	50%	7351	3675
<b>Soybeans</b>	1,172	2,696	16%	2264	50%	2264	1132
<b>Flaxseed</b>	524	634	16%	532	50%	532	266
<b>Rye</b>	109	233	16%	196	50%	196	98
<b>Tame Hay</b>	7,468	30,245	32%	20566	95%	1082	541
<b>Fodder Corn</b>	230	8,137	70%	2441	95%	128	64
<b>Total</b>	<b>31328</b>	<b>98340</b>		<b>73372</b>		<b>51576</b>	<b>25788</b>

1 Statistics Canada. 2007a. Field crop reporting series. Catalogue no. 22-002-XIE, Vol. 86, no. 8  
2 Assumed values (Ralevic and Layzell, 2006)  
3 Calculated as Production X (1-water content)  
4 Assumed values (Ralevic and Layzell, 2006). This is the ratio of production (e.g. grain) over total biomass  
5 Calculated as (DM production/harvest index)-DM production  
6 Assumes 50% of total residue can be removed as a bioenergy feedstock (Ralevic and Layzell, 2006)

Crop	Area <sup>1</sup>	Crop Production <sup>1</sup>	Water Content <sup>2</sup>	Dry Matter Production <sup>3</sup>	Harvest Index <sup>4</sup>	Total Residue <sup>5</sup>	Removable Residue <sup>6</sup>
	(1000ha)	(kt)	(%)	kt(dry)	(%)	kt(dry)	kt(dry)
<b>Wheat</b>							
<b>Oats</b>							
<b>Barley</b>							
<b>Grain Corn</b>							
<b>Mixed Grains</b>							
<b>Canola</b>							
<b>Soybeans</b>							
<b>Flaxseed</b>							
<b>Rye</b>							
<b>Tame Hay</b>	6.1	27.2	32%	18.5	95%	0.97	0.49
<b>Fodder Corn</b>			70%	0	95%	0	0
<b>Total</b>	<b>6.1</b>	<b>27.2</b>		<b>18.5</b>		<b>0.97</b>	<b>0.49</b>



Crop	Area <sup>1</sup>	Crop Production <sup>1</sup>	Water Content <sup>2</sup>	Dry Matter Production <sup>3</sup>	Harvest Index <sup>4</sup>	Total Residue <sup>5</sup>	Removable Residue <sup>6</sup>
	(1000ha)	(kt)	(%)	kt(dry)	(%)	kt(dry)	kt(dry)
<b>Wheat</b>	10.5	33	16%	28	50%	28	14
<b>Oats</b>	4.7	12.1	16%	10	50%	10	5
<b>Barley</b>	32.8	93.5	16%	79	50%	79	39
<b>Grain Corn</b>							
<b>Mixed Grains</b>	3.8	8.8	16%	7	50%	7	4
<b>Canola</b>							
<b>Soybeans</b>	4.5	11.1	16%	9	50%	9	5
<b>Flaxseed</b>							
<b>Rye</b>							
<b>Tame Hay</b>	61.1	301.2	32%	204.8	95%	10.78	5.39
<b>Fodder Corn</b>	2.4	70.8	70%	21	95%	1	1
<b>Total</b>	<b>119.8</b>	<b>530.5</b>		<b>359.2</b>		<b>145.04</b>	<b>72.52</b>

1 Statistics Canada. 2007a. Field crop reporting series. Catalogue no. 22-002-XIE, Vol. 86, no. 8  
2 Assumed values (Ralevic and Layzell, 2006)  
3 Calculated as Production X (1-water content)  
4 Assumed values (Ralevic and Layzell, 2006). This is the ratio of production (e.g. grain) over total biomass  
5 Calculated as (DM production/harvest index)-DM production  
6 Assumes 50% of total residue can be removed as a bioenergy feedstock (Ralevic and Layzell, 2006)

Crop	Area <sup>1</sup>	Crop Production <sup>1</sup>	Water Content <sup>2</sup>	Dry Matter Production <sup>3</sup>	Harvest Index <sup>4</sup>	Total Residue <sup>5</sup>	Removable Residue <sup>6</sup>
	(1000ha)	(kt)	(%)	kt(dry)	(%)	kt(dry)	kt(dry)
<b>Wheat</b>	1.5	5	16%	4	50%	4	2
<b>Oats</b>	2	4.5	16%	4	50%	4	2
<b>Barley</b>	2.6	6.9	16%	6	50%	6	3
<b>Grain Corn</b>	3.8	27.8	16%	23	50%	23	12
<b>Mixed Grains</b>							
<b>Canola</b>							
<b>Soybeans</b>							
<b>Flaxseed</b>							
<b>Rye</b>							
<b>Tame Hay</b>	72.8	375.6	32%	255.4	95%	13.44	6.72
<b>Fodder Corn</b>	4	72.6	70%	22	95%	1	1
<b>Total</b>	<b>86.7</b>	<b>492.4</b>		<b>314.3</b>		<b>51.72</b>	<b>25.86</b>

Crop	Area <sup>1</sup>	Crop Production <sup>1</sup>	Water Content <sup>2</sup>	Dry Matter Production <sup>3</sup>	Harvest Index <sup>4</sup>	Total Residue <sup>5</sup>	Removable Residue <sup>6</sup>
	(1000ha)	(kt)	(%)	kt(dry)	(%)	kt(dry)	kt(dry)
Wheat	1.8	5.4	16%	5	50%	5	2
Oats	8.5	24	16%	20	50%	20	10
Barley	13.2	45.3	16%	38	50%	38	19
Grain Corn	2.6	19.2	16%	16	50%	16	8
Mixed Grains							
Canola							
Soybeans							
Flaxseed							
Rye							
Tame Hay	72.8	375.6	32%	255.4	95%	13.44	6.72
Fodder Corn	2.8	58.1	70%	17	95%	1	0
<b>Total</b>	<b>101.7</b>	<b>527.6</b>		<b>351.7</b>		<b>93.24</b>	<b>46.62</b>

1 Statistics Canada. 2007a. Field crop reporting series. Catalogue no. 22-002-XIE, Vol. 86, no. 8  
2 Assumed values (Ralevic and Layzell, 2006)  
3 Calculated as Production X (1-water content)  
4 Assumed values (Ralevic and Layzell, 2006). This is the ratio of production (e.g. grain) over total biomass  
5 Calculated as (DM production/harvest index)-DM production  
6 Assumes 50% of total residue can be removed as a bioenergy feedstock (Ralevic and Layzell, 2006)

Crop	Area <sup>1</sup>	Crop Production <sup>1</sup>	Water Content <sup>2</sup>	Dry Matter Production <sup>3</sup>	Harvest Index <sup>4</sup>	Total Residue <sup>5</sup>	Removable Residue <sup>6</sup>
	(1000ha)	(kt)	(%)	kt(dry)	(%)	kt(dry)	kt(dry)
Wheat	56.2	173.7	16%	146	50%	146	73
Oats	109	280	16%	235	50%	235	118
Barley	94.5	308	16%	259	50%	259	129
Grain Corn	449	4100	16%	3444	50%	3444	1722
Mixed Grains	23.5	70	16%	59	50%	59	29
Canola	9	19	16%	16	50%	16	8
Soybeans	175.5	472	16%	396	50%	396	198
Flaxseed							
Rye							
Tame Hay	833	4,039.70	32%	2747.0	95%	144.58	72.29
Fodder Corn	46.5	1,879.70	70%	564	95%	30	15
<b>Total</b>	<b>1795.7</b>	<b>11341.6</b>		<b>7865.6</b>		<b>4728.91</b>	<b>2364.45</b>

Crop	Area <sup>1</sup>	Crop Production <sup>1</sup>	Water Content <sup>2</sup>	Dry Matter Production <sup>3</sup>	Harvest Index <sup>4</sup>	Total Residue <sup>5</sup>	Removable Residue <sup>6</sup>
	(1000ha)	(kt)	(%)	kt(dry)	(%)	kt(dry)	kt(dry)
<b>Wheat</b>	313.6	1,442.40	16%	1212	50%	1212	606
<b>Oats</b>	36.4	87.9	16%	74	50%	74	37
<b>Barley</b>	66.8	217.7	16%	183	50%	183	91
<b>Grain Corn</b>	831.6	6,985.30	16%	5868	50%	5868	2934
<b>Mixed Grains</b>	50.6	147	16%	123	50%	123	62
<b>Canola</b>	14	27.8	16%	23	50%	23	12
<b>Soybeans</b>	900.4	2,000.30	16%	1680	50%	1680	840
<b>Flaxseed</b>							
<b>Rye</b>	20	43.2	16%	36	50%	36	18
<b>Tame Hay</b>	1015.8	5,216.30	32%	3547.1	95%	186.69	93.34
<b>Fodder Corn</b>	121.4	3,991.60	70%	1197	95%	63	32
<b>Total</b>	<b>3371.0</b>	<b>20159.5</b>		<b>13943.9</b>		<b>9449.06</b>	<b>4724.53</b>

1 Statistics Canada. 2007a. Field crop reporting series. Catalogue no. 22-002-XIE, Vol. 86, no. 8  
2 Assumed values (Ralevic and Layzell, 2006)  
3 Calculated as Production X (1-water content)  
4 Assumed values (Ralevic and Layzell, 2006). This is the ratio of production (e.g. grain) over total biomass  
5 Calculated as (DM production/harvest index)-DM production  
6 Assumes 50% of total residue can be removed as a bioenergy feedstock (Ralevic and Layzell, 2006)

Crop	Area <sup>1</sup>	Crop Production <sup>1</sup>	Water Content <sup>2</sup>	Dry Matter Production <sup>3</sup>	Harvest Index <sup>4</sup>	Total Residue <sup>5</sup>	Removable Residue <sup>6</sup>
	(1000ha)	(kt)	(%)	kt(dry)	(%)	kt(dry)	kt(dry)
<b>Wheat</b>	1,173.50	3,211.40	16%	2698	50%	2698	1349
<b>Oats</b>	398.6	1,204.50	16%	1012	50%	1012	506
<b>Barley</b>	380.4	1,195.30	16%	1004	50%	1004	502
<b>Grain Corn</b>	78.9	493.5	16%	415	50%	415	207
<b>Mixed Grains</b>	4	4.3	16%	4	50%	4	2
<b>Canola</b>	1,141.20	1,714.60	16%	1440	50%	1440	720
<b>Soybeans</b>	91.1	212.3	16%	178	50%	178	89
<b>Flaxseed</b>	78.9	105.4	16%	89	50%	89	44
<b>Rye</b>	22.3	53.9	16%	45	50%	45	23
<b>Tame Hay</b>	959.1	3,538.00	32%	2405.8	95%	126.62	63.31
<b>Fodder Corn</b>	24.3	816.5	70%	245	95%	13	6
<b>Total</b>	<b>4352.3</b>	<b>12549.7</b>		<b>9534.8</b>		<b>7023.48</b>	<b>3511.74</b>

Crop	Area <sup>1</sup>	Crop Production <sup>1</sup>	Water Content <sup>2</sup>	Dry Matter Production <sup>3</sup>	Harvest Index <sup>4</sup>	Total Residue <sup>5</sup>	Removable Residue <sup>6</sup>
	(1000ha)	(kt)	(%)	kt(dry)	(%)	kt(dry)	kt(dry)
<b>Wheat</b>	4,762.30	9,058.40	16%	7609	50%	7609	3805
<b>Oats</b>	985.4	2,401.20	16%	2017	50%	2017	1009
<b>Barley</b>	1,659.20	3,945.20	16%	3314	50%	3314	1657
<b>Grain Corn</b>							
<b>Mixed Grains</b>	6.1	8.4	16%	7	50%	7	4
<b>Canola</b>	2,913.70	3,948.50	16%	3317	50%	3317	1658
<b>Soybeans</b>							
<b>Flaxseed</b>	433	511.8	16%	430	50%	430	215
<b>Rye</b>	50.6	99.1	16%	83	50%	83	42
<b>Tame Hay</b>	1,784.70	5,511.10	32%	3747.5	95%	197.24	98.62
<b>Fodder Corn</b>							
<b>Total</b>	<b>12595.0</b>	<b>25483.7</b>		<b>20524.5</b>		<b>16974.22</b>	<b>8487.11</b>

1 Statistics Canada. 2007a. Field crop reporting series. Catalogue no. 22-002-XIE, Vol. 86, no. 8  
2 Assumed values (Ralevic and Layzell, 2006)  
3 Calculated as Production X (1-water content)  
4 Assumed values (Ralevic and Layzell, 2006) . This is the ratio of production (e.g. grain) over total biomass  
5 Calculated as (DM production/harvest index)-DM production  
6 Assumes 50% of total residue can be removed as a bioenergy feedstock (Ralevic and Layzell, 2006)

Crop	Area <sup>1</sup>	Crop Production <sup>1</sup>	Water Content <sup>2</sup>	Dry Matter Production <sup>3</sup>	Harvest Index <sup>4</sup>	Total Residue <sup>5</sup>	Removable Residue <sup>6</sup>
	(1000ha)	(kt)	(%)	kt(dry)	(%)	kt(dry)	kt(dry)
<b>Wheat</b>	2300.7	6,076.10	16%	5104	50%	5104	2552
<b>Oats</b>	250.9	627.4	16%	527	50%	527	264
<b>Barley</b>	1,728.00	5,114.30	16%	4296	50%	4296	2148
<b>Grain Corn</b>	2.8	22.9	16%	19	50%	19	10
<b>Mixed Grains</b>	8.1	24.1	16%	20	50%	20	10
<b>Canola</b>	1,804.90	2,993.70	16%	2515	50%	2515	1257
<b>Soybeans</b>							
<b>Flaxseed</b>	12	16.3	16%	14	50%	14	7
<b>Rye</b>	16	36.8	16%	31	50%	31	15
<b>Tame Hay</b>	2,260.20	9,276.00	32%	6307.7	95%	331.98	165.99
<b>Fodder Corn</b>	20.2	839.10	70%	252	95%	13	7
<b>Total</b>	<b>8404.1</b>	<b>25026.7</b>		<b>19085.2</b>		<b>12870.98</b>	<b>6435.49</b>

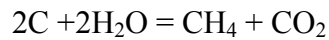
Crop	Area <sup>1</sup>	Crop Production <sup>1</sup>	Water Content <sup>2</sup>	Dry Matter Production <sup>3</sup>	Harvest Index <sup>4</sup>	Total Residue <sup>5</sup>	Removable Residue <sup>6</sup>
	(1000ha)	(kt)	(%)	kt(dry)	(%)	kt(dry)	kt(dry)
<b>Wheat</b>	16.2	48.60	16%	41	50%	41	20
<b>Oats</b>	20.2	54.7	16%	46	50%	46	23
<b>Barley</b>	20.2	57.7	16%	48	50%	48	24
<b>Grain Corn</b>			16%	0	50%	0	0
<b>Mixed Grains</b>			16%	0	50%	0	0
<b>Canola</b>	28	47.6	16%	40	50%	40	20
<b>Soybeans</b>			16%	0	50%	0	0
<b>Flaxseed</b>			16%	0	50%	0	0
<b>Rye</b>			16%	0	50%	0	0
<b>Tame Hay</b>	394.6	1,578.50	32%	1073.4	95%	56.49	28.25
<b>Fodder Corn</b>	8.1	408.20	70%	122	95%	6	3
<b>Total</b>	<b>487.6</b>	<b>2195.3</b>		<b>1371.1</b>		<b>238.16</b>	<b>119.08</b>

<sup>1</sup> Statistics Canada. 2007a. Field crop reporting series. Catalogue no. 22-002-XIE, Vol. 86, no. 8  
<sup>2</sup> Assumed values (Ralevic and Layzell, 2006)  
<sup>3</sup> Calculated as Production X (1-water content)  
<sup>4</sup> Assumed values (Ralevic and Layzell, 2006) . This is the ratio of production (e.g. grain) over total biomass  
<sup>5</sup> Calculated as (DM production/harvest index)-DM production  
<sup>6</sup> Assumes 50% of total residue can be removed as a bioenergy feedstock (Ralevic and Layzell, 2006)

The total Canadian residues for each crop available for anaerobic digestion and gasification are shown in Figure 5. The data shows that the largest available crop residues are those from wheat (34%) followed by grain corn (19%), barley (18%), canola (14%) and oats (8%). These 5 crop residues make up 93% of the available Canadian total. Any effort to harness this resource for RNG production will have to take into account the geographic distribution of these crops.

Conversion of available crop residues to methane is shown in Table 12. The data shows the potential production of methane from biogas through anaerobic digestion (AD) and from syngas through gasification of the residues not consumed in the AD process. Biogas generation from the crop residues assumes that only 20% of the material is amenable to digestion and that 300 Mm<sup>3</sup> CH<sub>4</sub>/dry Mt of residues is produced (Wiese and Kujawski, 2007). Gasification of the crop residues assumes a process conversion

efficiency of 65% according to the following reaction where 2 moles of carbon are required to produce 1 mole of CH<sub>4</sub> and 1 mole of CO<sub>2</sub>:

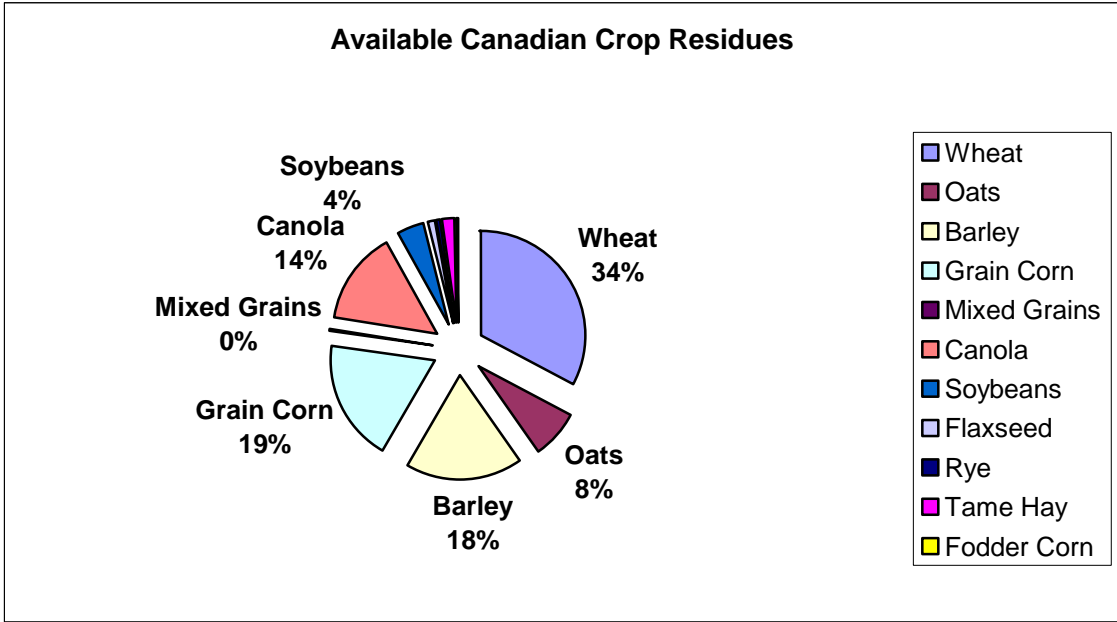


The combined gasification and methanation processes required to convert biomass to methane are reported to have efficiencies that vary from 64 to 79% (Mozaffarian et al, 2005 and Zwart and Rabou, 2006). We chose to use an efficiency of 65% as a conservative value.

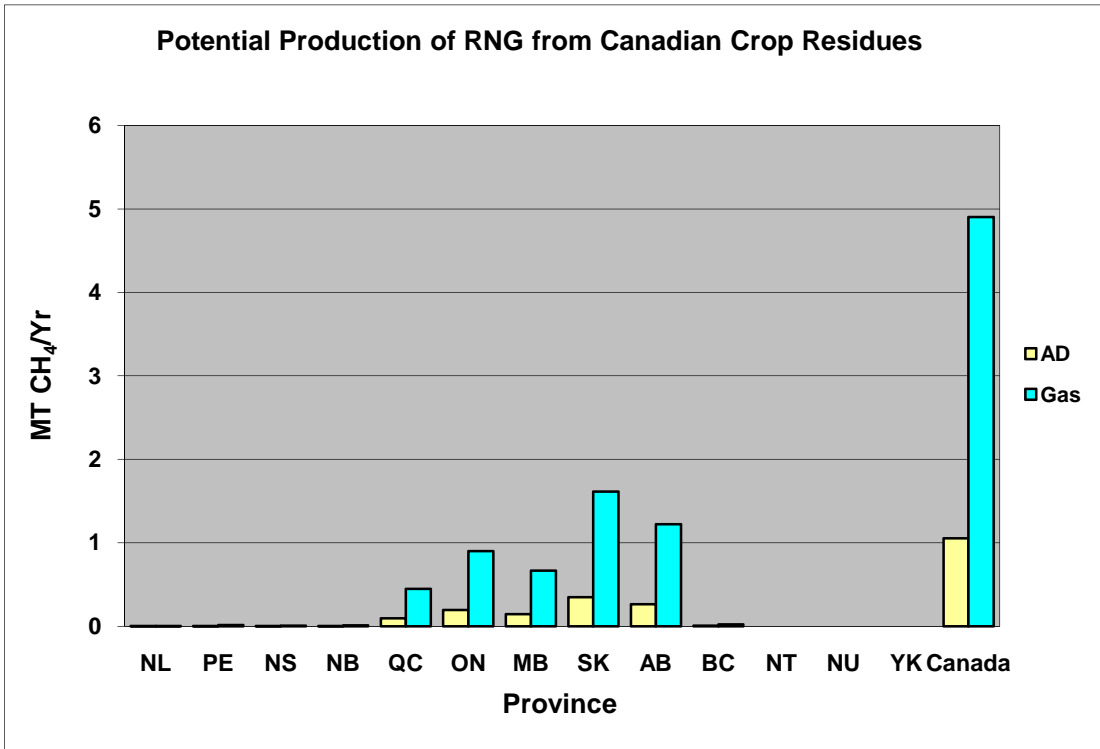
The data shows that the greatest potential for producing RNG from crop residues is through gasification (Figure 6 and Table 12) as it consumes most of the biomass while anaerobic digestion is limited to about 20% of that biomass. The largest amounts of potentially available crop residues and potential RNG produced are in the Prairie Provinces, in particular, Saskatchewan and Alberta (Figure 6) due to the large production of wheat, barley and canola. Smaller amounts are potentially available in Ontario and Quebec due to significant production of grain corn. Total Canadian potential RNG production from crop residues is estimated to be 1.05 MT CH<sub>4</sub>/yr from anaerobic digestion and 4.90 MT CH<sub>4</sub>/yr from gasification for a combined total of almost 6 MT CH<sub>4</sub>/yr. Although this potential total production of RNG is technically feasible, one needs to take into account the economic factors of this production, in particular the costs of collection and transportation of the residues to the plant(s) and the market price of natural gas derived from fossil fuel sources.

<b>Table 12. Potential Methane Production from Canadian Crop Residues.</b>				
	<b>Removable Residue<sup>1</sup></b>	<b>Methane</b>		
		<b>AD<sup>2</sup></b>	<b>Gasification<sup>3</sup></b>	<b>Total<sup>4</sup></b>
	<b>(kt dry/yr)</b>	<b>(Mt/yr)</b>		
<b>Canada</b>	25787.98	1.0521	4.9035	5.9556
<b>Newfoundland and Labrador</b>	0.49	0.0000	0.0001	0.0001
<b>Prince Edward Island</b>	72.52	0.0030	0.0138	0.0167
<b>Nova Scotia</b>	25.86	0.0011	0.0049	0.0060
<b>New Brunswick</b>	46.62	0.0019	0.0089	0.0108
<b>Quebec</b>	2364.45	0.0965	0.4496	0.5461
<b>Ontario</b>	4724.53	0.1928	0.8984	1.0911
<b>Manitoba</b>	3511.74	0.1433	0.6677	0.8110
<b>Saskatchewan</b>	8487.11	0.3463	1.6138	1.9601
<b>Alberta</b>	6435.49	0.2626	1.2237	1.4863
<b>British Columbia</b>	119.08	0.0049	0.0226	0.0275

**1** Calculated as the sum of all crop production  
**2** Calculated as crop residue (dry kt/yr)x10<sup>-3</sup> (Mt/kt)x0.2x 300 (Mm<sup>3</sup> CH<sub>4</sub>/Mt dry) x 0.00068 (Mt CH<sub>4</sub>/Mm<sup>3</sup> CH<sub>4</sub>). (Wiese and Kujawski, 2007). Assume that only 0.2 (20%) of the crop residue is amenable to AD.  
**3** Calculated as (dry kT residue/yr)x10<sup>-3</sup> (Mt/kt) x 0.5 (Mt C/Mt residue) x (16 Mt CH<sub>4</sub>/ 24 Mt C) x 0.65. Assumes a gasification conversion efficiency of waste carbon to CH<sub>4</sub> and CO<sub>2</sub> carbon of 65%  
**4** Calculated as the sum of AD and gasification methane



**Figure 5.** Availability of Canadian Crop Residues for AD and Gasification



**Figure 6.** Potential Production of RNG from Canadian Crop Residues



#### **4.1.2. Livestock Manure**

Manure production on Canadian farms varies according to the type of animals and the animal population numbers. These manures are amenable for producing RNG and tend to vary between provinces and regions. We estimated manure production for the major animal populations according to Statistics Canada data for cattle (Statistics Canada, 2007b), hogs (Statistics Canada, 2007c), sheep (Statistics Canada, 2008) and poultry (Statistics Canada, 2007d) for each province and for the whole country (Tables 13 to 15). Manure production was calculated using statistics Canada animal population numbers and a specific average daily manure production rate for each animal as suggested by Klass (1998). The average manure production rates (kg dry/head/day) varied with the animal type from a high of 4.64 for cattle to 0.0101 for turkeys (Tables 13 to 15). The manures available for RNG production are less than what is produced as some of the manures are already used for other purposes. We estimated that the availability of cattle manure was 25% of the total cattle manure produced with different availability indices for hogs (85%), sheep (10%) and poultry (85%). These indices were used according to the data published for a BC bioenergy inventory report (Ralevic and Layzell, 2006).

The total Canadian manure production from each animal type available for anaerobic digestion and gasification are shown in Table 16 and Figure 7. The data shows that the largest available manure residues are those from cattle (48%) followed by chicken (34%) and hogs (18%) with less than 1% from turkey and sheep manures. The cattle, chicken and hog manures make up almost 100% of the available Canadian total.

Conversion of available manure residues to methane is shown in Table 16 and Figure 8. The data shows the potential production of methane from biogas through anaerobic digestion (AD) and from syngas through gasification of the manures not consumed in the AD process. Biogas generation from the manures assumes that 250 Mm<sup>3</sup> CH<sub>4</sub>/dry Mt of manure is produced (Electrigaz, 2007). Gasification of the manure residues assumes a process similar to that for crop residues at a conversion efficiency of 65% and a manure carbon content of 40% (Klass, 1998).

The data shows that the potential for producing RNG from manure residues is slightly higher through gasification (Figure 8 and Table 16) than that for AD. The largest amounts of potentially available manures and potential RNG produced are in the Ontario and Quebec (large hog and chicken numbers) and the Prairie Provinces (large cattle numbers), in particular, Alberta (Figure 8). Smaller amounts are potentially available in BC due to significant chicken population numbers. Total Canadian potential RNG production from manure residues is estimated to be 1.19 MT CH<sub>4</sub>/yr from anaerobic digestion and 1.69 MT CH<sub>4</sub>/yr from gasification for a combined total of 2.88 MT CH<sub>4</sub>/yr. Although this potential total production of RNG is technically feasible, one needs to take into account the economic factors of this production, in particular the costs of collection and transportation of the residues to the plant(s) and the market price of natural gas derived from fossil fuel sources.

	Cattle			Hogs		
	Number <sup>1</sup>	Manure Production		Number <sup>2</sup>	Manure Production	
	(x1000head)	(kg dry/head/d) <sup>6</sup>	(dry Mt/yr) <sup>7</sup>	(x1000)	(kg dry/head/d) <sup>6</sup>	(dry Mt/yr) <sup>7</sup>
<b>Canada</b>	15885.0	4.64	6.726	14437.0	0.564	2.526
<b>Newfoundland and Labrador</b>	12.5	4.64	0.005	1.7	0.564	0.000
<b>Prince Edward Island</b>	90.0	4.64	0.038	110.4	0.564	0.019
<b>Nova Scotia</b>	102.0	4.64	0.043	86.0	0.564	0.015
<b>New Brunswick</b>	87.0	4.64	0.037	92.0	0.564	0.016
<b>Quebec</b>	1395.0	4.64	0.591	4070.0	0.564	0.712
<b>Ontario</b>	1953.5	4.64	0.827	3789.9	0.564	0.663
<b>Manitoba</b>	1540.0	4.64	0.652	2910.0	0.564	0.509
<b>Saskatchewan</b>	3430.0	4.64	1.452	1340.0	0.564	0.234
<b>Alberta</b>	6470.0	4.64	2.739	1910.0	0.564	0.334
<b>British Columbia</b>	805.0	4.64	0.341	127.0	0.564	0.022

1 Statistics Canada. 2007b. Cattle Statistics 2007. Catalogue no. 23-012-XIE, Vol. 6, No. 2

2 Statistics Canada. 2007c. Hog Statistics 2007, Vol 6, No 4. Catalogue no. 23-010-XIE

3 Statistics Canada. 2008. Sheep Statistics 2007, Vol 7, No 1. Catalogue no. 23-011-X

4 Statistics Canada. 2007d. Poultry and Egg Statistics, July to September 2007. Catalogue no. 23-015-X, vol. 4, no. 3

6 Klass (1998)

7 Calculated as number (h) x manure production (kg dry/h/d) x 365 (d/yr) x (kg recovered/kg) x 10<sup>-6</sup> (Mt/kg). Recovered manure was assumed as: Cattle (25%), Hogs (85%), Sheep (10%) and Chicken (85%) (Ralevic and Layzell, 2006)

	Sheep			Chicken		
	Number <sup>3</sup>	Manure Production		Number <sup>4</sup>	Manure Production	
	(x1000head)	(kg dry/head/d) <sup>6</sup>	(dry Mt/yr) <sup>7</sup>	(x1000)	(kg dry/head/d) <sup>6</sup>	(dry Mt/yr) <sup>7</sup>
<b>Canada</b>	1095.7	0.756	0.0302	621725.0	0.0252	4.861
<b>Newfoundland and Labrador</b>	4.2	0.756	0.0001		0.0252	0.000
<b>Prince Edward Island</b>	3.6	0.756	0.0001		0.0252	0.000
<b>Nova Scotia</b>	26.8	0.756	0.0007	21720.0	0.0252	0.170
<b>New Brunswick</b>	8.1	0.756	0.0002	17688.0	0.0252	0.138
<b>Quebec</b>	295.0	0.756	0.0081	164913.0	0.0252	1.289
<b>Ontario</b>	305.0	0.756	0.0084	202285.0	0.0252	1.582
<b>Manitoba</b>	70.0	0.756	0.0019	29009.0	0.0252	0.227
<b>Saskatchewan</b>	120.0	0.756	0.0033	22787.0	0.0252	0.178
<b>Alberta</b>	205.0	0.756	0.0057	53854.0	0.0252	0.421
<b>British Columbia</b>	58.0	0.756	0.0016	98010.0	0.0252	0.766

	Turkey		
	Number <sup>5</sup>	Manure Production	
	(x1000head)	(kg dry/head/d) <sup>6</sup>	(dry Mt/yr) <sup>7</sup>
<b>Canada</b>	21171.0	0.0101	0.0663
<b>Newfoundland and Labrador</b>			
<b>Prince Edward Island</b>			
<b>Nova Scotia</b>	789.0	0.0101	0.0025
<b>New Brunswick</b>	365.0	0.0101	0.0011
<b>Quebec</b>	4567.0	0.0101	0.0143
<b>Ontario</b>	8939.0	0.0101	0.0280
<b>Manitoba</b>	1413.0	0.0101	0.0044
<b>Saskatchewan</b>	802.0	0.0101	0.0025
<b>Alberta</b>	1651.0	0.0101	0.0052
<b>British Columbia</b>	2640.0	0.0101	0.0083

<sup>5</sup> Statistics Canada. 2007d. Poultry and Egg Statistics, July to September 2007. Catalogue no. 23-015-X, vol. 4, no. 3

<sup>6</sup> Klass (1998)

<sup>7</sup> Calculated as number (heads) x manure production (kg dry/head/d) x 365 (d/yr) x (kg recovered/kg) x 10<sup>-6</sup> (Mt/kg). Turkey manure that can be recovered was assumed to be 85% (Ralevic and Layzell, 2006)

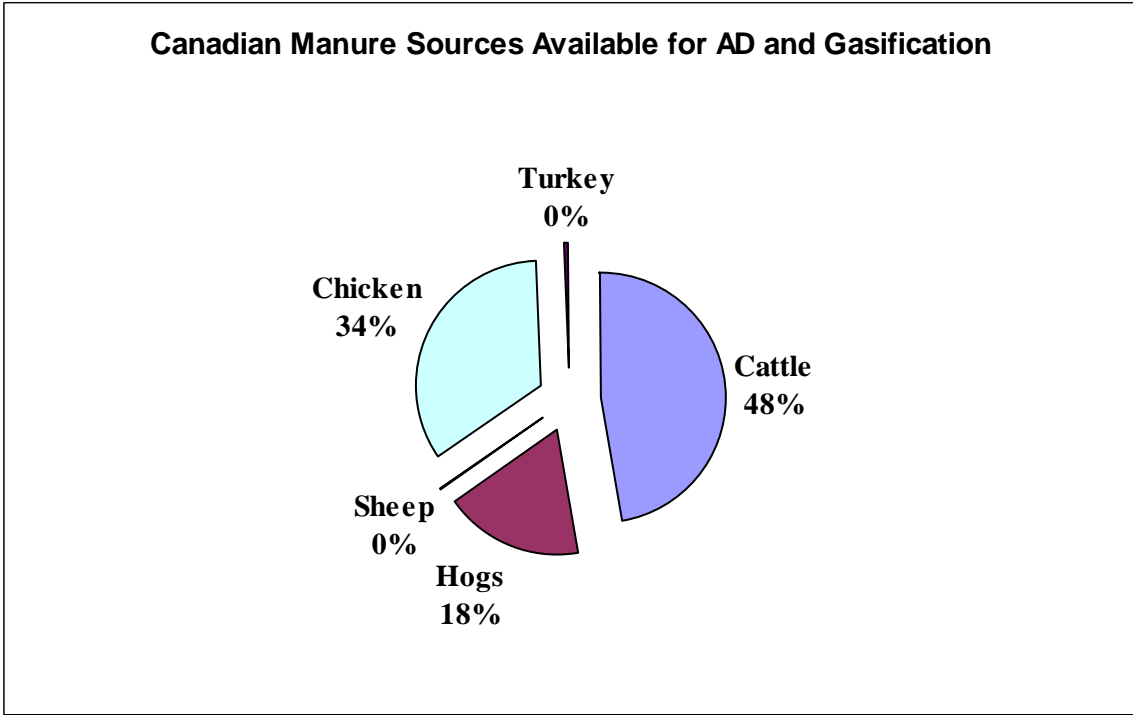
	Total	AD <sup>9</sup>	Gasification <sup>10</sup>	Total Manure <sup>11</sup>
	Manure <sup>8</sup>	Methane		
	(dry Mt/yr)	(Mt/yr)		
<b>Canada</b>	14.209	1.188	1.690	2.879
<b>Newfoundland and Labrador</b>	0.006	0.000	0.001	0.001
<b>Prince Edward Island</b>	0.058	0.005	0.007	0.012
<b>Nova Scotia</b>	0.231	0.019	0.028	0.047
<b>New Brunswick</b>	0.193	0.016	0.023	0.039
<b>Quebec</b>	2.615	0.219	0.311	0.530
<b>Ontario</b>	3.108	0.260	0.370	0.630
<b>Manitoba</b>	1.394	0.117	0.166	0.283
<b>Saskatchewan</b>	1.871	0.156	0.223	0.379
<b>Alberta</b>	3.505	0.293	0.417	0.710
<b>British Columbia</b>	1.139	0.095	0.136	0.231

<sup>8</sup> Calculated as the sum of all manures (cattle, hogs, sheep, chicken and turkey)

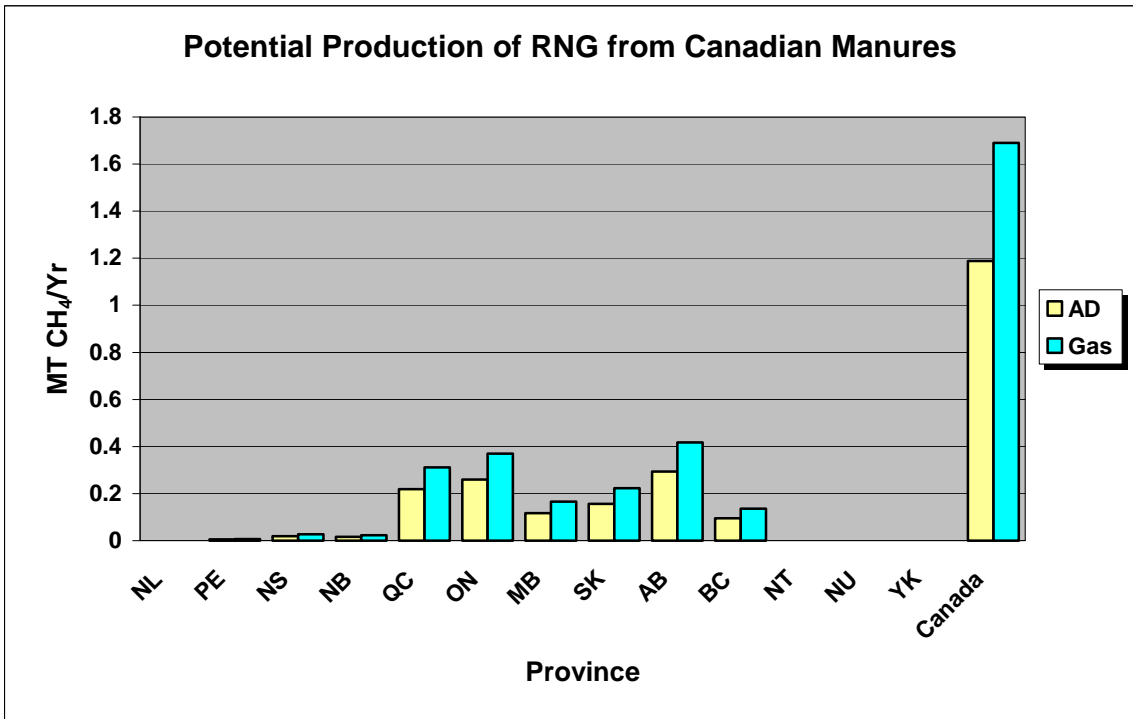
<sup>9</sup> Calculated as total manure (dry Mt/yr) x 250 (Mm<sup>3</sup> CH<sub>4</sub>/Mt dry manure) x 0.00068 (Mt CH<sub>4</sub>/Mm<sup>3</sup> CH<sub>4</sub>) (Electrigaz, 2007)

<sup>10</sup> Calculated as (dry Mt manure/yr) x 0.4 (Mt C/Mt manure) x (16 Mt CH<sub>4</sub>/ 24 Mt C) x 0.65. Assumes a gasification conversion efficiency of waste carbon to CH<sub>4</sub> and CO<sub>2</sub> carbon of 65%

<sup>11</sup> Calculated as the sum of AD and gasification methane



**Figure 7.** Availability of Canadian Manures for AD and Gasification.



**Figure 8.** Potential Production of RNG from Canadian Manures

## 4.2. FORESTRY WASTES

Forestry residues are made up of forest operation residues and mountain pine beetle (MPB) residues (due to MPB infestations of forests in BC). Forest residues are generated during harvest operations and subsequent wood treatment in either sawmills or pulp and paper plants. MPB residues are those generated from the unused part of the infested wood due to harvest operations, unsuitability as a wood source and waste materials generated during the wood treatment processes in sawmills and pulp and paper plants. Production of Forestry wastes was estimated from the data reported in the Canadian biomass inventory by Wood and Layzell (2003) for wood production in Canada. We assumed that 20% of the produced roundwood can be available for gasification into RNG; while 50% of the non-stem wood left on site can be collected and used for gasification into RNG. These estimates are similar to those suggested by Wood and Layzell (2003) for Canada and by Ralevic and Layzell (2006) for BC. We also estimated the forest residues from the MPB infestation and the extra materials it provides for gasification to RNG from the BC data reported by Ralevic and Layzell (2006). The MPB residues are estimated to last for 20 years and our data is reported as the annual residue for 20 years only. Gasification of the harvested forest residues to RNG is assumed to occur with a process efficiency of 65% as discussed in previous sections.

Forest residue data are presented in Table 17 and shows that the potentially available residues (minus MPB data) are to be found mostly in BC (33%), Quebec (27%) and Ontario (17%). Adding the MPB residues increases the BC residues to 44% of the Canadian total. Potential production of RNG from these residues through gasification (Table 17 and Figure 9) shows a similar pattern as the residue distribution. The 3 provinces of BC, Quebec and Ontario account for 81% of the total Canadian potential RNG production with BC alone making up almost half of that total. Total Canadian potential RNG production from forest residues is estimated as 12.88 Mt/yr offering a significant addition of RNG to the current Canadian NG resource inventory.

Although this potential total production of RNG is technically feasible, one needs to take into account the economic factors of this production, in particular the costs of collection and transportation of the residues to the gasification plants and the market price of natural gas derived from fossil fuel sources.

**Table 17. Potential Production of Methane from Canadian Forestry Wastes.**

	<b>Total Roundwood<sup>1</sup></b>	<b>Non-Stem Residue<sup>1</sup></b>	<b>Gasifiable Roundwood<sup>2</sup></b>	<b>Gasifiable Non-Stem<sup>3</sup></b>	<b>Mountain Pine Beetle Residues<sup>1</sup></b>	<b>Total Forest Residues<sup>4</sup></b>	<b>Total CH<sub>4</sub> Generation<sup>5</sup></b>
	(Mt C/yr)						(Mt/yr)
<b>NL</b>	0.68	0.41	0.136	0.205		0.341	0.148
<b>PE</b>	0.16	0.21	0.032	0.105		0.137	0.059
<b>NS</b>	1.47	1.64	0.294	0.82		1.114	0.483
<b>NB</b>	2.77	3.96	0.554	1.98		2.534	1.098
<b>QC</b>	10.35	11.83	2.07	5.915		7.985	3.460
<b>ON</b>	6.69	7.71	1.338	3.855		5.193	2.250
<b>MB</b>	0.52	0.38	0.104	0.19		0.294	0.127
<b>SK</b>	1.08	0.5	0.216	0.25		0.466	0.202
<b>AB</b>	5.22	1.45	1.044	0.725		1.769	0.767
<b>BC</b>	18.67	12.26	3.734	6.13	5.55	15.414	6.679
<b>NT</b>	0.01	0.01	0.002	0.005		0.007	0.003
<b>NU</b>						0	
<b>YK</b>	0.01		0.002			0.002	0.001
<b>Canada</b>	47.64	40.37	9.528	20.185		35.256	12.876

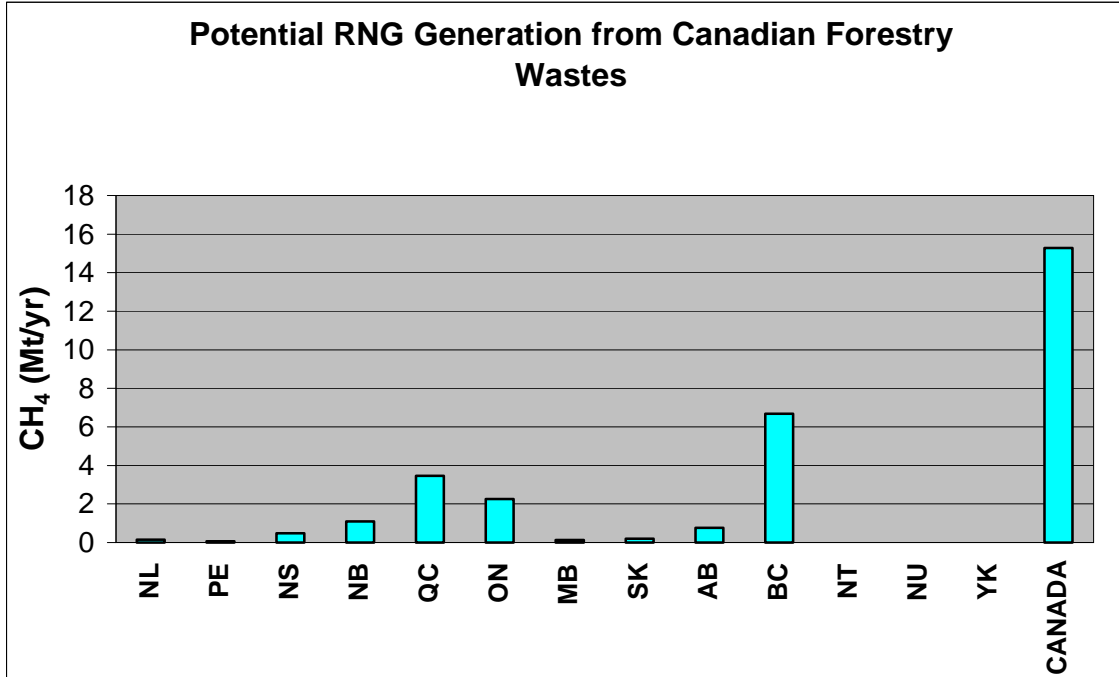
**1** Quoted from Wood and Layzell (2003) and Ralevic and Layzell (2006).

**2** Assumed that only 20% of roundwood is available for gasification. (Wood and Layzell, 2003 and Ralevic and Layzell, 2006)

**3** Assumed that only 50% of stemwood is available for gasification. (Wood and Layzell, 2003 and Ralevic and Layzell, 2006)

**4** Calculated as the sum of gasifiable roundwood (column 4), stemwood (column 5) and mountain pine beetle residues (column 6)

**5** Calculated as Column 7 (Mt C/yr) x ( 16 Mt CH<sub>4</sub>/ 24 Mt C) x 0.65. Assumes a gasification conversion efficiency of waste carbon to CH<sub>4</sub> and CO<sub>2</sub> carbon of 65%



**Figure 9.** Potential Production of RNG from Canadian Forestry Wastes.



### **4.3. MUNICIPAL WASTES**

Canadian municipal wastes considered as potential sources for RNG production included solid wastes collected from homes and businesses by municipalities (MSW), landfill gas recovered from closed landfills (LFG), wastewaters (WW) collected through municipal sewer systems, and the municipal biosolids which are the solid materials collected (through settling) of the wastewaters.

#### **4.3.1. Municipal Solid Waste**

MSW residues are made up of wastes collected from residential areas (households), industrial and commercial and institutional (ICI) wastes, and construction and demolition (CD) wastes. Some of these wastes are collected by municipalities while others are collected by private companies.

The amounts of various Canadian disposed MSW fractions are presented in Table 18 and Figure 10 for the 2005 year (Statistics Canada, 2005). The data shows that 30% to 57% of the total MSW is from household sources with higher values in the East and lower values are in Western Canada. ICI wastes makes up the highest fraction of the total MSW with values ranging from 37% to 54% with the higher values reported for Ontario and Western Canada. CD wastes are the lowest fraction and make up from 5 to 22% of the Canadian total with higher values in BC and Alberta, likely due to increased construction activity.

The amounts of MSW that are amenable to AD and gasification are reported in Table 18 and Figure 11. We estimated that only 25% of the household wastes are amenable to anaerobic digestion (Ostrem, 2004). None of the other wastes were considered to contain significant amounts of digestible wastes. This assumption unfortunately underestimates the mount of digestible waste by neglecting the amount of food wastes disposed of from restaurants and institutional cafeteria. The gasifiable waste

<b>Table 18. Annual Canadian Municipal Solid Waste (MSW) Production (2005).</b>						
	<b>Waste Disposal<sup>1</sup></b>				<b>MSW Organic Fraction Subject to</b>	
	<b>Residential</b>	<b>Industrial, Commercial &amp; Institutional</b>	<b>Construction &amp; Demolition</b>	<b>Total</b>	<b>AD<sup>2</sup></b>	<b>Gasification<sup>3</sup></b>
	<b>(kt/yr)</b>				<b>(dry kt/yr)</b>	<b>(dry kt C/yr)</b>
<b>NL</b>	216	140	20	377	18.9	55.2
<b>PE</b>						0.0
<b>NS</b>	170	177	43	389	14.8	52.9
<b>NB</b>	204	155	55	414	17.8	58.2
<b>QC</b>	2,876	2,261	407	5,544	251.7	789.2
<b>ON</b>	3,438	5,193	1,014	9,646	300.9	1,249.5
<b>MB</b>	413	406	78	897	36.1	123.5
<b>SK</b>	279	441	75	795	24.4	102.5
<b>AB</b>	866	1,380	644	2,890	75.8	363.9
<b>BC</b>	937	1,347	461	2,745	82.0	353.6
<b>NT</b>						
<b>NU</b>						
<b>YK</b>						
<b>Canada</b>	9,455	11,564	2,817	23,836	827.3	3,167.2

**1 Statistics Canada. 2005.** This is the difference between waste generated and diverted.

**2** Calculated as Column 2 (t/yr) x 0.35 (t solids/t) x 0.25 (t OFMSW subject to AD/t solids). (**Ostrem, 2004**).  
(25% of the Residential waste is amenable to Anaerobic Digestion and the wastes contains 35% solids)

**3** Calculated as the MSW biomass fraction that was not converted to biogas plus 50% of the ICI waste  
(50% solids) and 30% of the CD waste (90% solids). . Assumed the waste biomass contains 40% carbon.

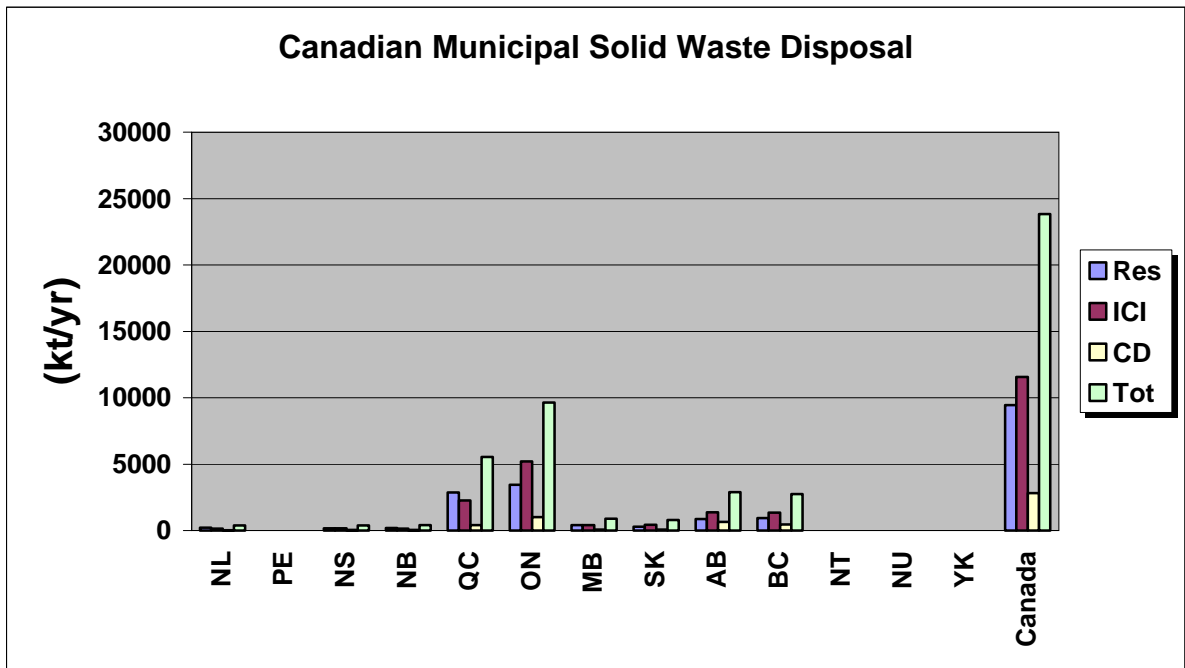
quantities were assumed to consist of the undigestible biomass from household wastes, 50% of the ICI wastes and 30% of the CD wastes (mostly wood products). The waste quantities amenable to AD ranged from 3 to 5% of the total disposed and the gasifiable amounts from 13 to 15%.

Generation of RNG from these wastes is presented in Table 19 and Figure 12 and it shows that gasification can potentially produce 1.27 Mt of RNG annually (92 to 93% of the total potential RNG) while AD can produce ~ 0.1 Mt/yr (5 to 8%).

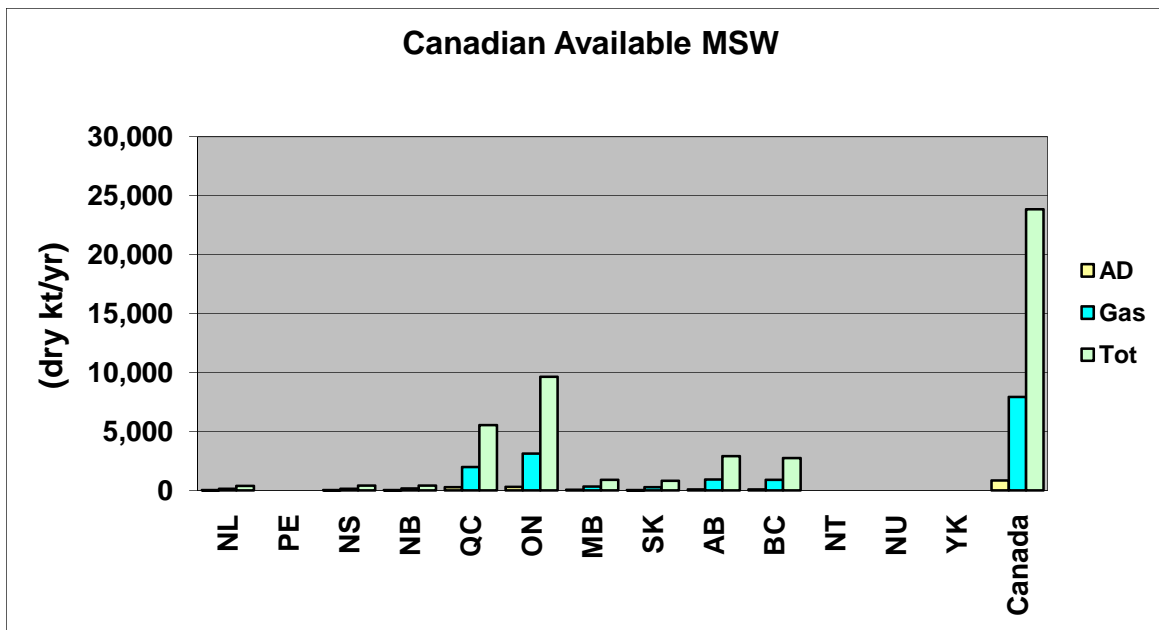
<b>Table 19. Annual Methane Production from Canadian Municipal Solid Wastes (2005).</b>			
	<b>Methane</b>		
	<b>AD<sup>1</sup></b>	<b>Gasification<sup>2</sup></b>	<b>Total<sup>3</sup></b>
	<b>(kt/yr)</b>		
<b>NL</b>	2.21	23.9	26.1
<b>PE</b>			
<b>NS</b>	1.74	22.9	24.7
<b>NB</b>	2.08	25.2	27.3
<b>QC</b>	29.43	342.0	371.4
<b>ON</b>	35.19	541.4	576.6
<b>MB</b>	4.22	53.5	57.7
<b>SK</b>	2.85	44.4	47.3
<b>AB</b>	8.87	157.7	166.6
<b>BC</b>	9.59	153.2	162.8
<b>NT</b>			
<b>NU</b>			
<b>YK</b>			
<b>Canada</b>	96.76	1,372.5	1,469.2

**1** Calculated as Column 6 (Table 18) (dry kt /yr) x 10<sup>3</sup> (dry t/kt) 172 (m<sup>3</sup> CH<sub>4</sub>)/(t dry ) x 0.00068 (t CH<sub>4</sub>/m<sup>3</sup> CH<sub>4</sub>) x 10<sup>-3</sup> (kt CH<sub>4</sub>/t CH<sub>4</sub>). (Ostrem, 2004)  
**2** Calculated as Column 7 (Table 18) (dry kt C/yr) x ( 16 kt CH<sub>4</sub>/ 24 kt C) x 0.65. Assumes a gasification conversion efficiency of waste carbon to CH<sub>4</sub> and CO<sub>2</sub> carbon of 65%  
**3** Calculated as the sum of Methane generated by Anaerobic Digestion (column 2) and Gasification (column 3)

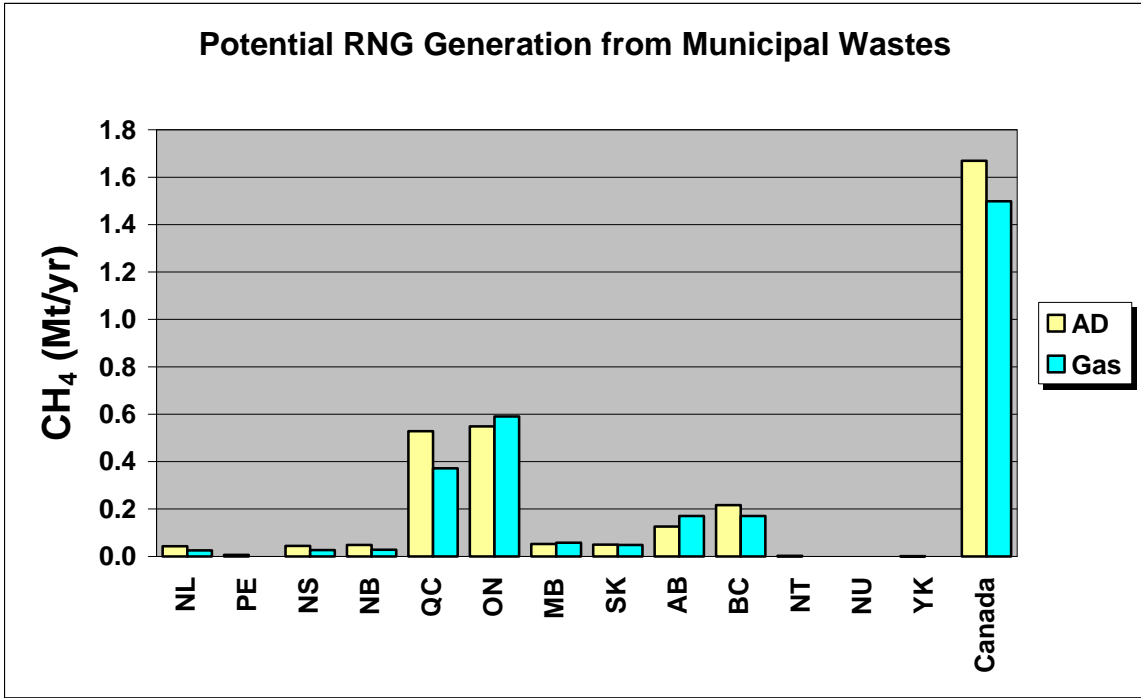
Most of the potential RNG produced correlates well with population size making Ontario and Quebec the largest potential RNG producers (Figure 12). The potential lower RNG amounts produced from MSW is offset by the fact that the cost of waste collection and transportation is borne by the municipalities. This potential source of RNG is significant because of the cost offset and high degree of technical knowledge found in municipal waste plants. Although this potential production of RNG is technically feasible, one needs to take into account the economic factors of this production, in particular the costs of gas cleaning and separation.



**Figure 10.** Canadian Municipal Solid Waste Disposal (2005).



**Figure 11.** Availability of Canadian MSW for AD and Gasification as Compared to Total Disposed MSW.



**Figure 12.** Potential Production of RNG from Canadian Municipal Solid Wastes

#### **4.3.2. Wastewater**

Wastewaters are the mixed liquid and solid wastes collected through sewers and delivered to a wastewater treatment plants. These wastes can produce RNG through anaerobic digestion in large digesters where some of the biomass solids are converted into CH<sub>4</sub> and CO<sub>2</sub>. This practice is common for larger municipalities where the original aim was to reduce the solids contents of the wastes before discharge form the plants.

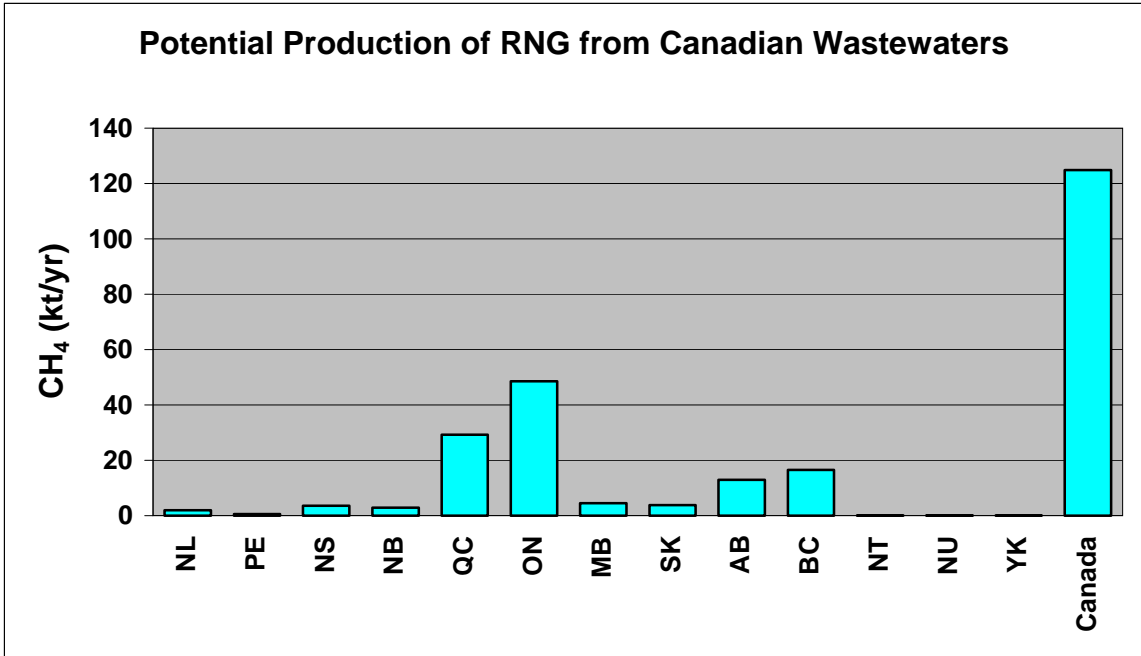
We estimated the generation for wastewaters for each province and the whole country from Environment Canada data (Environment Canada, 2001) for the Canadian generation in 1999 and the population sizes of provinces and Canada in 2006 (Statistics Canada, 2007e). Environment Canada also reported that 97% of the Canadian population is served with some form of wastewater treatment. Table 20 presents the data for wastewater generation and predictably, the highest amounts correlate with the highest populations, making Ontario and Quebec the largest producers of wastewaters in the country.

The potential RNG produced from the anaerobic digestion of these wastes is presented in Table 20 and Figure 13. We estimated the production of RNG using data reported for many Ontario wastewater anaerobic digesters by Wheeldon et al. (2005), where the specific methane production was reported as 0.0336 m<sup>3</sup> CH<sub>4</sub>/m<sup>3</sup> wastewater. The total Canadian potential RNG production from wastewaters is estimated to be ~ 0.124 Mt/yr and provincial production correlates with population size. This RNG amount does not look significant except for the fact that many of these facilities exist already and the only cost incurred to produce RNG is through cleaning of the produced biogas and separation of the CH<sub>4</sub> and CO<sub>2</sub> from this biogas. Thus the cost of producing RNG from this source is relatively cheaper and technologically easier.

Although this potential production of RNG is technically feasible, one needs to take into account the economic factors of this production, in particular the costs of gas cleaning and separation.

<b>Table 20. Annual Methane Production from Canadian Wastewaters (2006)</b>					
	<b>Population<sup>1</sup></b>	<b>Wastewater Production</b>		<b>CH<sub>4</sub> Production</b>	
	<b>(persons)</b>	<b>(m<sup>3</sup>/d)<sup>2</sup></b>	<b>(M m<sup>3</sup>/yr)<sup>3</sup></b>	<b>(M m<sup>3</sup>/yr)<sup>4</sup></b>	<b>(kt/yr)<sup>5</sup></b>
<b>NL</b>	509,677	233845	85.4	2.87	1.95
<b>PE</b>	138,519	63554	23.2	0.779	0.53
<b>NS</b>	934,405	428714	156	5.26	3.58
<b>NB</b>	749,168	343726	125.5	4.22	2.87
<b>QC</b>	7,651,531	3510599	1281	43.05	29.28
<b>ON</b>	12,686,952	5820900	2125	71.39	48.54
<b>MB</b>	1,177,765	540370	197	6.63	4.51
<b>SK</b>	985,386	452105	165	5.54	3.77
<b>AB</b>	3,375,763	1548834	565	18.99	12.92
<b>BC</b>	4,310,452	1977678	722	24.25	16.49
<b>NT</b>	41,861	19206	7.01	0.236	0.16
<b>NU</b>	30,782	14123	5.15	0.173	0.12
<b>YK</b>	31,229	14328	5.23	0.176	0.12
<b>Canada</b>	32,623,490	14967983	5463	184	124.83

**1 Statistics Canada, 2007e.**  
**2** Calculated as Column 2 (p) x 0.97 x 0.474 (m<sup>3</sup>/d/p). (In 1999, 97% of Canadians used Wastewater treatment facilities that produced 14,400,000 m<sup>3</sup>/day (population of 30,404,000) or 0.474 m<sup>3</sup>/person/day). (**Environment Canada, 2001.**)  
**3** Calculated as (Column 3 (m<sup>3</sup>/d) x 365 d/yr)/(1000000 m<sup>3</sup>/M m<sup>3</sup>)  
**4** Calculated as Methane production (at 60% of biogas) = Column 4 (M m<sup>3</sup>/yr) x 0.0336 (m<sup>3</sup> CH<sub>4</sub>/m<sup>3</sup> wastewater) (**Wheeldon et al, 2005**)  
**5** Calculated as Column 5 (M m<sup>3</sup>/yr) x CH<sub>4</sub> density (0.00068 t/m<sup>3</sup>) x 1000000 (m<sup>3</sup>/M m<sup>3</sup>)



**Figure 13.** Potential Production of RNG from Canadian Wastewaters.



### **4.3.3 Biosolids**

Biosolids are the solids collected through solid liquid separation of the wastewaters before liquid discharge from the wastewater treatment plant. Some of these wastewaters would have undergone anaerobic digestion previously. Currently, Biosolids are disposed on land, landfills or composted.

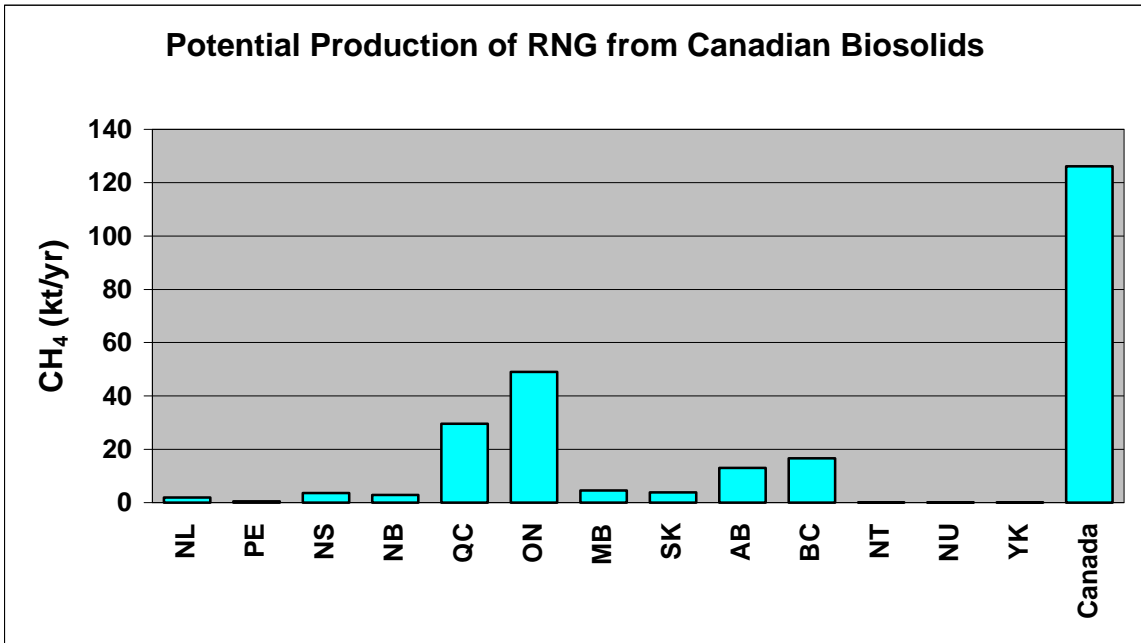
We estimated the amount of Biosolids produced in Canada from the population size and the specific Biosolids production rate of 0.063 kg (dry Biosolids)/person/day (Klass, 1998). Thus, Biosolids quantities correlate well with population size.

Production of RNG from Biosolids is through gasification of the dried Biosolids. We assumed that the carbon content of the Biosolids to be 40% according to Klass (1998) and that the gasification efficiency is 65% as discussed earlier in this report. Table 21 and Figure 14 show the data for Biosolids production and potential RNG generation from these wastes. The total Canadian potential RNG production from biosolids is estimated to be ~ 0.126 Mt/yr and provincial production correlates with population size. This RNG amount does not look significant except for the fact that many of these facilities exist already and the cost incurred to produce RNG is through gasification, cleaning of the produced syngas, methanation and separation of the CH<sub>4</sub> and CO<sub>2</sub>. Thus, the cost of producing RNG from this source is relatively cheaper due to the elimination of collection costs.

Although this potential production of RNG is technically feasible, one needs to take into account the economic factors of this production, in particular the costs of gasification, methanation, gas cleaning and separation.

<b>Table 21. Annual Methane Production from Canadian Biosolids (2006)</b>				
	<b>Population<sup>1</sup></b>	<b>Biosolids Production</b>		<b>CH<sub>4</sub> Production<sup>4</sup></b>
	<b>(persons)</b>	<b>(kt dry/yr)<sup>2</sup></b>	<b>(dry kt C/yr)<sup>3</sup></b>	<b>(kt/yr)</b>
<b>NL</b>	509,677	11.37	4.55	1.97
<b>PE</b>	138,519	3.09	1.24	0.54
<b>NS</b>	934,405	20.84	8.34	3.61
<b>NB</b>	749,168	16.71	6.68	2.90
<b>QC</b>	7,651,531	170.67	68.27	29.58
<b>ON</b>	12,686,952	282.98	113.19	49.05
<b>MB</b>	1,177,765	26.27	10.51	4.55
<b>SK</b>	985,386	21.98	8.79	3.81
<b>AB</b>	3,375,763	75.30	30.12	13.05
<b>BC</b>	4,310,452	96.15	38.46	16.67
<b>NT</b>	41,861	0.93	0.37	0.16
<b>NU</b>	30,782	0.69	0.27	0.12
<b>YK</b>	31,229	0.70	0.28	0.12
<b>Canada</b>	32,623,490	727.67	291.07	126.13

**1 Statistics Canada. (2007e).**  
**2** Calculated as Column 2 (p) x 0.97 x 0.063 (kg dry biosolids/d/p) x 365 (d/yr) x 10<sup>-3</sup> (t/kg). (**Klass, 1998**)  
**3** Calculated as Column 3 x 0.4 (kt C/kt biosolids). Assumed a 40% carbon content for the Biosolids. (**Environment Canada. 2001.**) and (**Klass, 1998**)  
**4** Calculated as Column 4 (dry kt C/yr) x ( 16 kt CH<sub>4</sub>/ 24 kt C) x 0.65. Assumes a gasification conversion efficiency of waste carbon to CH<sub>4</sub> and CO<sub>2</sub> carbon of 65%



**Figure 14.** Potential Production of RNG from Canadian Biosolids.

#### 4.3.4 Landfills

Landfills have been the traditional repositories for Canadian solid wastes. The large biomass quantities collected in these landfills after closure tends to anaerobically digest naturally to produce CH<sub>4</sub> and CO<sub>2</sub>. Most of the produced gases escape to the atmosphere but in some landfills, are collected and harnessed to produce power.

Table 22 shows the data for the estimated methane generation from Canadian landfills. The data also shows the amounts of methane captured and by difference from the generated values, the amount emitted to the atmosphere (Table 22 and Figure 15). Emitted methane gas is considered a greenhouse gas with potential activity equivalent to 21 times that of CO<sub>2</sub>. Table 22 shows the amounts of greenhouse gas emitted (as CO<sub>2</sub> eq.) due to the release of methane from landfills. Predictably, most of the generated methane is found in Ontario and Quebec, the largest provincial populations in Canada; smaller amounts are found in BC and Alberta. Most of the captured landfill methane is found in Ontario (27% of the emitted), Quebec (31%), Nova Scotia (14%), BC (15%) and Alberta (5%) with much lesser quantities (< 1%) in the other provinces.

Total potential RNG generation from Canadian landfills is estimated at 1.45 Mt/yr (Table 22) with only 21% captured. The potential exists to increase the capture of the generated methane due to the availability of established technology for landfill gas capture, cleaning and separation into CH<sub>4</sub> and CO<sub>2</sub>.

This RNG amount is significant especially when one considers that many of these facilities exist already where the cost of waste collection and placement is already incurred by municipalities. The only cost incurred to produce RNG is through cleaning of the captured landfill gas and separation of the CH<sub>4</sub> and CO<sub>2</sub> from this biogas. Thus, the cost of producing RNG from this source is relatively cheaper and technologically easier.

Although this potential production of RNG is technically feasible, one needs to take into account the economic factors of this production, in particular the costs of gas cleaning and separation.

**Table 22. Annual Methane Gas Generation and Capture from Canadian Landfills (2005).**

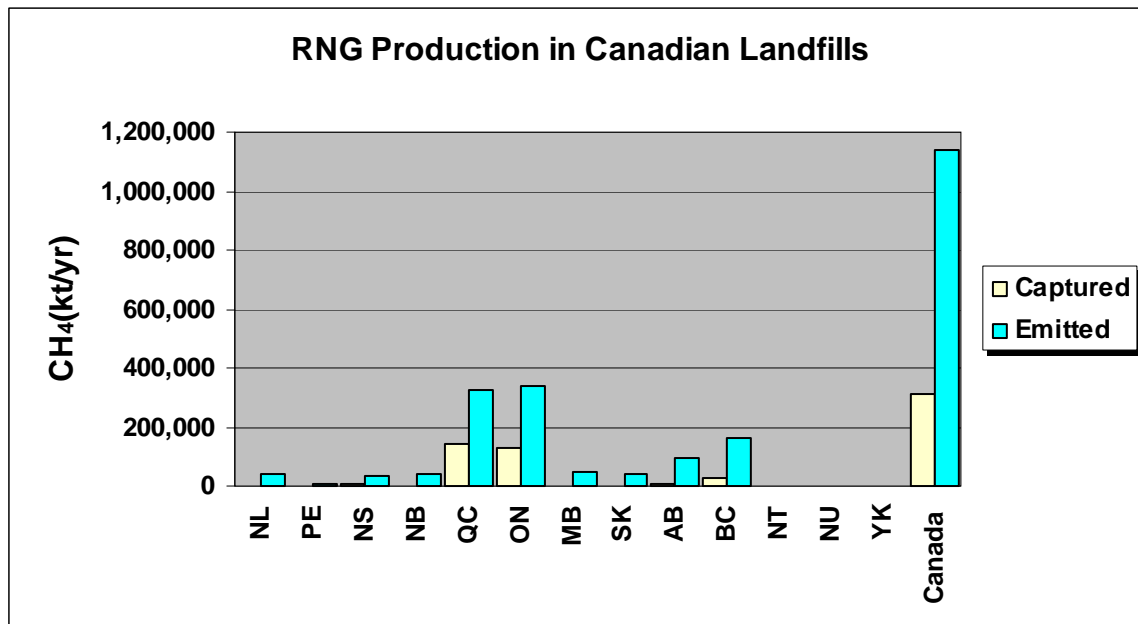
	<b>Methane Generation<sup>1</sup></b>	<b>GHG Generation<sup>2</sup></b>	<b>LFG projects<sup>3</sup></b>	<b>Methane Captured<sup>3</sup></b>	<b>Methane Emitted<sup>4</sup></b>	<b>GHG Emitted<sup>2</sup></b>
	<b>(kt CH<sub>4</sub>/yr)</b>	<b>(kt CO<sub>2</sub> eq/yr)</b>	<b>Number</b>	<b>(kt CH<sub>4</sub>/yr)</b>	<b>(kt CH<sub>4</sub>/yr)</b>	<b>(kt CO<sub>2</sub> eq/yr)</b>
<b>NL</b>	38.57	810	0	0.00	38.57	810
<b>PE</b>	6.69	141	0	0.00	6.69	141
<b>NS</b>	39.66	833	1	5.39	34.28	720
<b>NB</b>	43.34	910	0	0.00	43.34	910
<b>QC</b>	469.46	9,859	12	143.97	325.50	6,835
<b>ON</b>	465.17	9,769	19	126.09	339.08	7,121
<b>MB</b>	44.10	926	0	0.00	44.10	926
<b>SK</b>	43.71	918	0	0.00	43.71	918
<b>AB</b>	103.55	2,175	2	5.39	98.16	2,061
<b>BC</b>	189.60	3,982	13	27.89	161.71	3,396
<b>NT</b>	2.34	49	0	0.00	2.34	49
<b>NU</b>				0.00		
<b>YK</b>	1.15	24	0	0.00	1.15	24
<b>Canada</b>	1,447.35	30,394	47	308.74	1,138.62	23,911

**1** Thompson et al (2006)

**2** Calculated as methane generation x 21

**3** Environment Canada ( 2007b)

**4** Calculated as the difference between the methane generated and captured



**Figure 15.** Potential Production of RNG from Canadian Landfills.

#### **4.3.5 Total Municipal Wastes**

A summary of the contributions of each municipal waste to the total municipal potential RNG production is presented in (Table 23 and Figures 16 to 18). The data shows that the largest sources of potential RNG are from solid wastes (MSW) and Landfills. MSW contributes 1.47 Mt/yr of RNG while Landfills contribute 1.45 Mt/yr with ~ 0.13 Mt/yr each from wastewaters and Biosolids (Figure 16). This is understandable considering the much larger solid production of wastes from the above two sources. Anaerobic digestion contributes slightly more RNG than gasification (Figure 17) due to the production of LFG. Total potential RNG production is shown in Figure 18 and predictably, it shows a distribution similar to population size. The total potential RNG production for Canada is estimated at 4.6 Mt/yr, a potential significant addition to the national NG supply.

This waste source is additionally significant for the large contribution of AD to RNG production allowing for the use of established technologies with much easier technology uptake and adaptation. Another attractive aspect for using this waste is the lower cost of production due to the absence of waste collection and transportation costs as they are usually incurred by the municipalities. The most significant costs are those associated with gas cleaning and separation. Challenges exist in adapting gasification to municipal wastes as few gasification plants exist and those usually use the syngas only to produce power. Most thermal treatments of municipal wastes have up till now tended to favour incineration.

Table 23. Annual Potential Production of Methane from Canadian Municipal Wastes.							
	LFG	MSW		Total	Wastewater	Biosolids	Total
		AD	Gasification		AD	Gasification	
	(kt/yr)						
NL	38.57	2.21	23.93	26.14	1.95	1.97	94.8
PE	6.69	0.00	0.00	0.00	0.53	0.54	7.8
NS	39.66	1.74	22.93	24.67	3.58	3.61	96.2
NB	43.34	2.08	25.21	27.30	2.87	2.90	104
QC	469.46	29.43	341.97	371.40	29.28	29.58	1,271
ON	465.17	35.19	541.44	576.62	48.54	49.05	1,716
MB	44.10	4.22	53.51	57.74	4.51	4.55	169
SK	43.71	2.85	44.44	47.29	3.77	3.81	146
AB	103.55	8.87	157.70	166.57	12.92	13.05	463
BC	189.60	9.59	153.22	162.81	16.49	16.67	548
NT	2.34	0.00	0.00	0.00	0.16	0.16	2.66
NU	0.00	0.00	0.00	0.00	0.12	0.12	0.24
YK	1.15	0.00	0.00	0.00	0.12	0.12	1.39
Canada	1,447.35	96.76	1,372.47	1,469.24	124.83	126.13	4,637

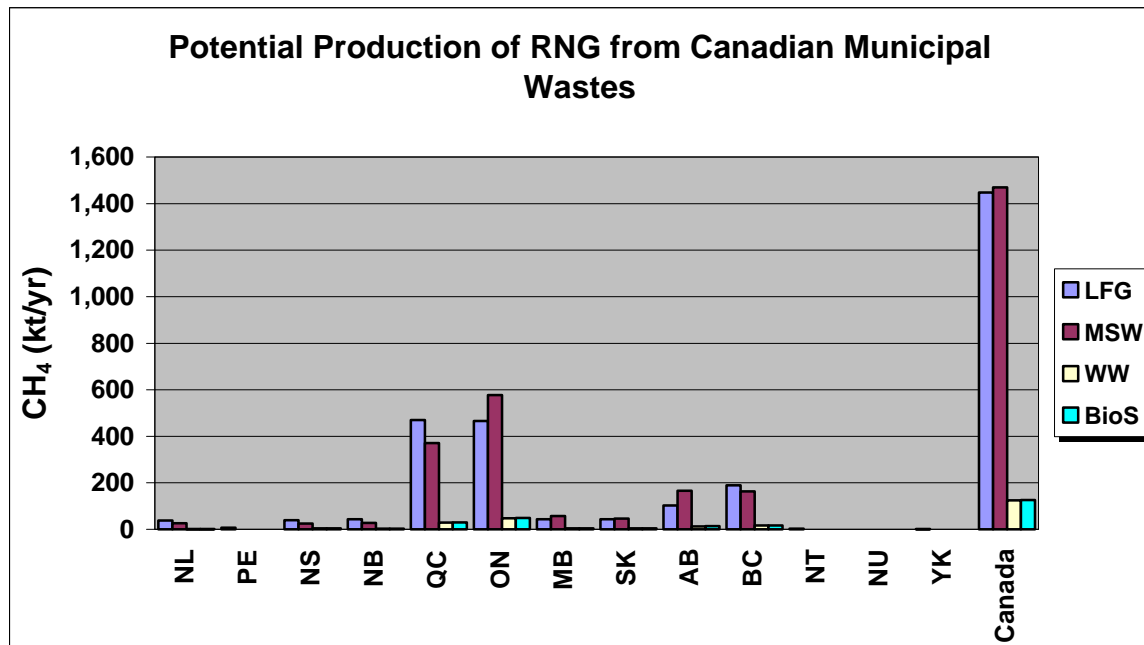
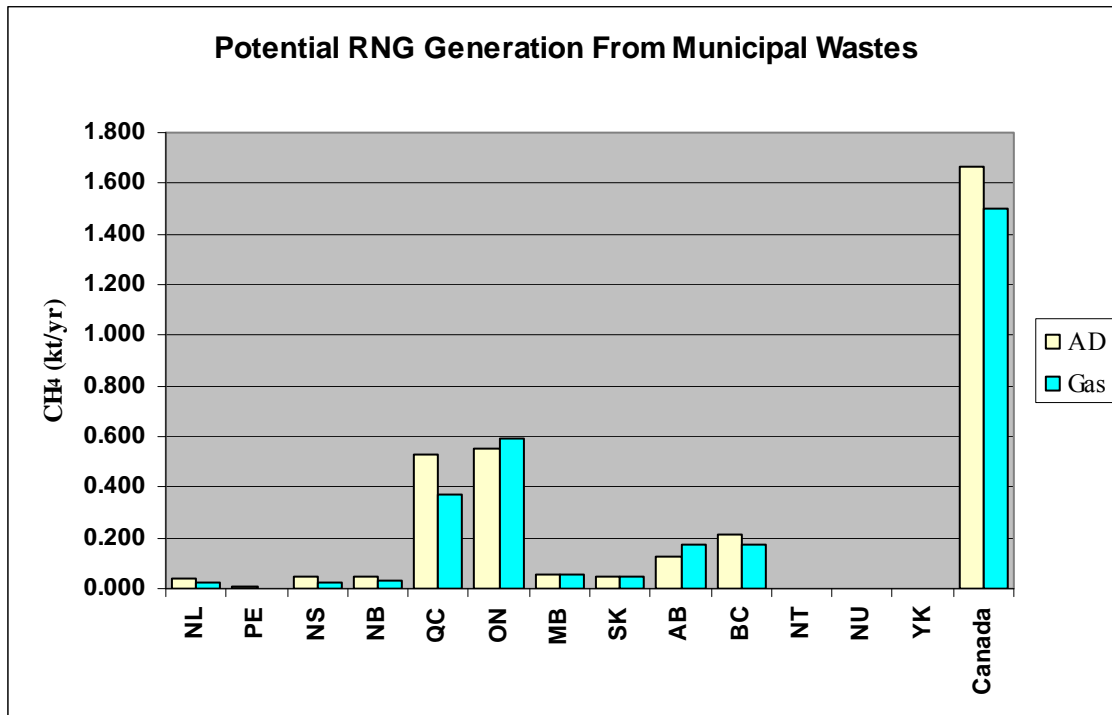
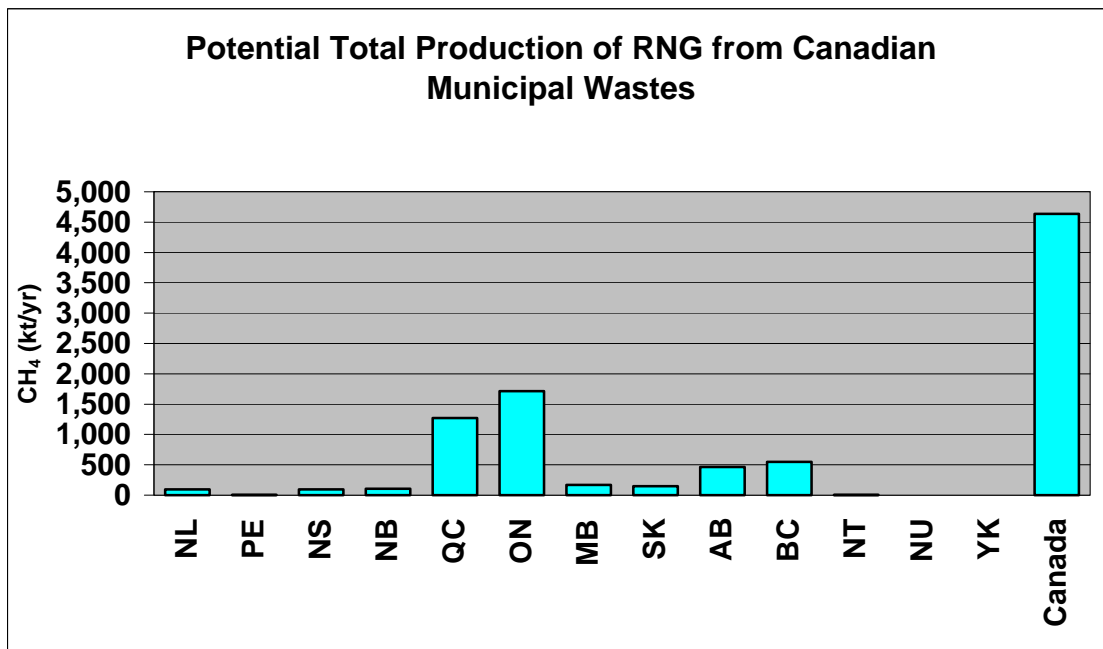


Figure 16. Potential Production of RNG from Canadian Municipal Wastes.





**Figure 17.** Potential RNG Source of Production from Municipal Wastes.



**Figure 18.** Potential Total Production of RNG from Canadian Municipal Wastes.

## **5. PRODUCTION OF METHANE FROM CANADIAN WASTES**

This section will address the technical feasibility of producing RNG from Canadian wastes and an economic analysis of it.

### **5.1 TECHNICAL FEASIBILITY**

We define technical feasibility as the potential to realize a product based on the availability of resources and the prior knowledge and experience of using similar processes for producing similar products. Production of RNG from Canadian wastes was shown to arise from the application of two well used and understood processes: Anaerobic digestion and gasification.

Anaerobic digestion is a naturally occurring process that has been used industrially to produce biogas from agricultural, municipal and industrial process (food processing). Production of RNG adds the processes of biogas cleaning and gas separation to the anaerobic digestion process.

Gasification is an old industrial process that has been used mainly to process coals into gaseous products and to further use these gases to produce energy. Gasification of coal into RNG has been demonstrated in the US and Europe. The application of the technology has until recently been limited by the low NG prices. Gasification of wastes is an established process where the produced syngas is used to produce energy. Examples of using this technology for various wastes are found mostly in Europe and to a lesser degree in North America. Syngas is made up of hydrogen, carbon monoxide and smaller amounts of methane. Production of RNG through gasification thus required the cleaning of the syngas, methanation and further separation into methane and carbon dioxide. Methanation has been industrially applied in Europe for coal but much less for waste gasification. The processes of gas cleaning and separation are common to both anaerobic digestion and gasification. Gas cleaning is dependent on the nature of contaminants to be removed and thus the source of the biogas/syngas. Most contaminants can be removed by existing processes that have been applied industrially; the challenge is to integrate these technologies into the RNG production chain. Similarly,

gas separation has been practiced for many industrial processes and the challenge is to adapt the existing technologies into the RNG production process.

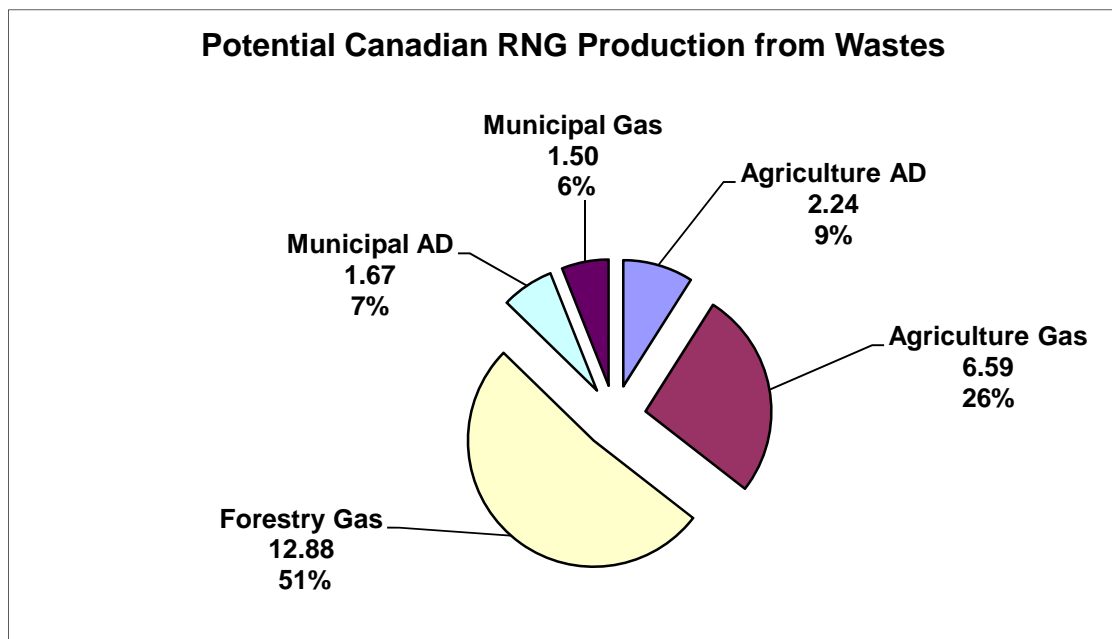
Based on our findings, it is envisioned that anaerobic digestion process will be the main source of RNG in the next 5 to 10 years with gasification contributing afterwards. This is based on the availability of the technologies, prior use and acceptance by industry and the need for further technology development activities.

A summary of all potential RNG that can be produced from Canadian wastes is presented in Table 24 and Figure 19. The data shows that a potential total of 24.9 Mt/yr of RNG can be produced Canadian wastes. Forestry seems to have the potential to produce 12.9 Mt/yr (51% of total), followed by 8.8 Mt/yr (36%) from agriculture and 3.2 Mt/yr (13%) from municipal wastes (Figure 20). This data shows the great potential of forestry wastes to produce RNG.

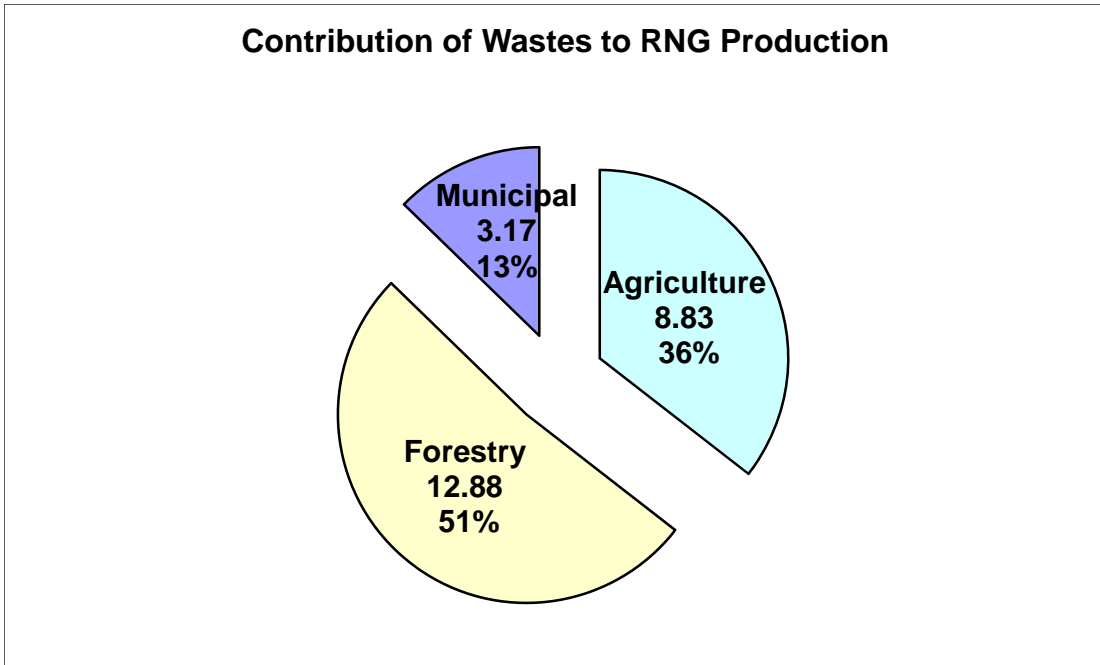
The use of gasification has the potential produce most of the RNG in Canada as we estimated that 21 Mt/yr (84% of total) can be produced by this process (Figure 21). Anaerobic digestion has the potential to produce 3.9 Mt/yr (16% of total); while this process seems to be significantly less than gasification, it is still significant because of the technology availability and lower cost.

We compared the relative size of our potential RNG estimates to the current NG use for the residential and commercial sectors and the results are presented in Table 25 and Figure 22. The potential Canadian generation of 24.9 Mt/yr of RNG corresponds to an energy value of 1.4 TJ/yr or 389,528 GWh of electricity (Table 25). RNG production can account for a significant amount of the NG use (Figure 22), whereby as little as 56% of the residential and commercial use can be produced in Ontario and as high as 336% in Quebec. Nationally, our estimate is that 130% of current NG residential and commercial use can be replaced by the produced RNG based on the technical RNG potential.

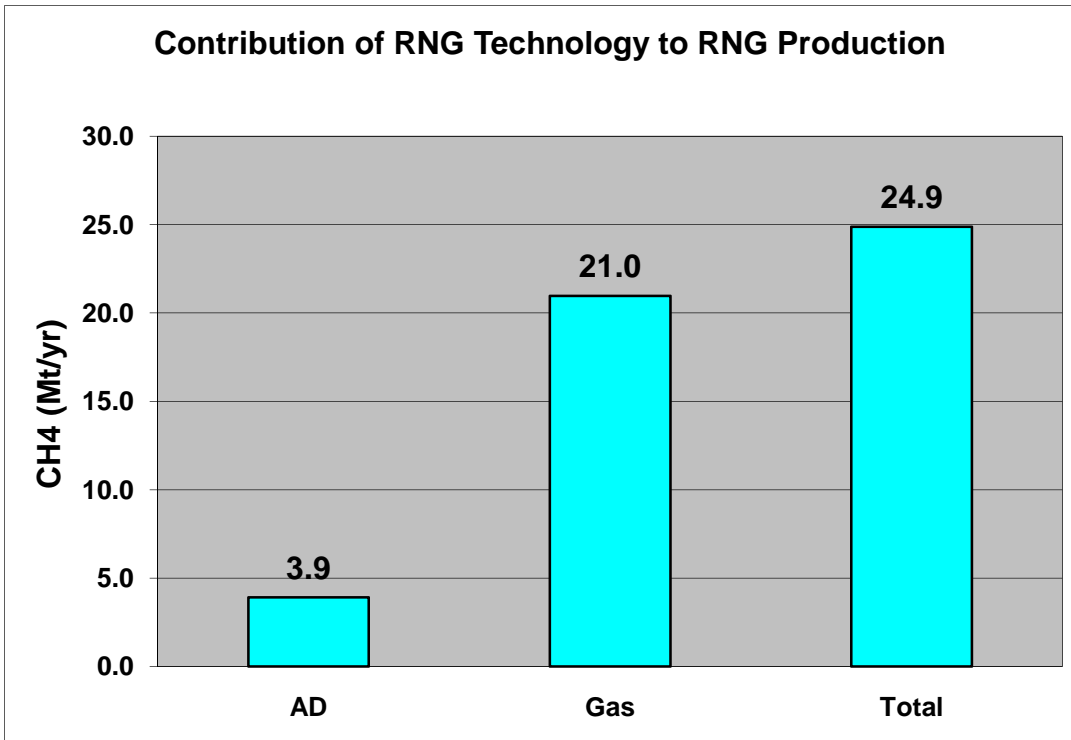
<b>Table 24. Potential Methane Production from Canadian Wastes</b>											
	<b>Agriculture Wastes</b>				<b>Forestry</b>	<b>Municipal Wastes</b>					<b>Total</b>
	<b>Manure</b>		<b>Crops</b>		<b>Residues</b>	<b>MSW</b>		<b>Landfill</b>	<b>WW</b>	<b>Biosolids</b>	
	<b>AD</b>	<b>Gas</b>	<b>AD</b>	<b>Gas</b>	<b>Gas</b>	<b>AD</b>	<b>Gas</b>	<b>AD</b>	<b>AD</b>	<b>Gas</b>	
<b>(Mt/yr)</b>											
<b>NL</b>	0.000	0.001	0.000	0.000	0.148	0.002	0.024	0.039	0.002	0.002	0.218
<b>PE</b>	0.005	0.007	0.003	0.014	0.059			0.007	0.001	0.001	0.096
<b>NS</b>	0.019	0.028	0.001	0.005	0.483	0.002	0.023	0.040	0.004	0.004	0.607
<b>NB</b>	0.016	0.023	0.002	0.009	1.098	0.002	0.025	0.043	0.003	0.003	1.224
<b>QC</b>	0.219	0.311	0.096	0.450	3.460	0.029	0.342	0.469	0.029	0.030	5.436
<b>ON</b>	0.260	0.370	0.193	0.898	2.250	0.035	0.541	0.465	0.049	0.049	5.111
<b>MB</b>	0.117	0.166	0.143	0.668	0.127	0.004	0.054	0.044	0.005	0.005	1.332
<b>SK</b>	0.156	0.223	0.346	1.614	0.202	0.003	0.044	0.044	0.004	0.004	2.640
<b>AB</b>	0.293	0.417	0.263	1.224	0.767	0.009	0.158	0.104	0.013	0.013	3.259
<b>BC</b>	0.095	0.136	0.005	0.023	6.679	0.010	0.153	0.190	0.016	0.017	7.323
<b>NT</b>					0.003			0.002	0.000	0.000	0.006
<b>NU</b>									0.000	0.000	0.000
<b>YK</b>					0.001			0.001	0.000	0.000	0.002
<b>Canada</b>	1.188	1.690	1.052	4.903	12.876	0.097	1.372	1.447	0.125	0.126	24.878



**Figure 19.** Potential Production of RNG from Canadian Wastes.

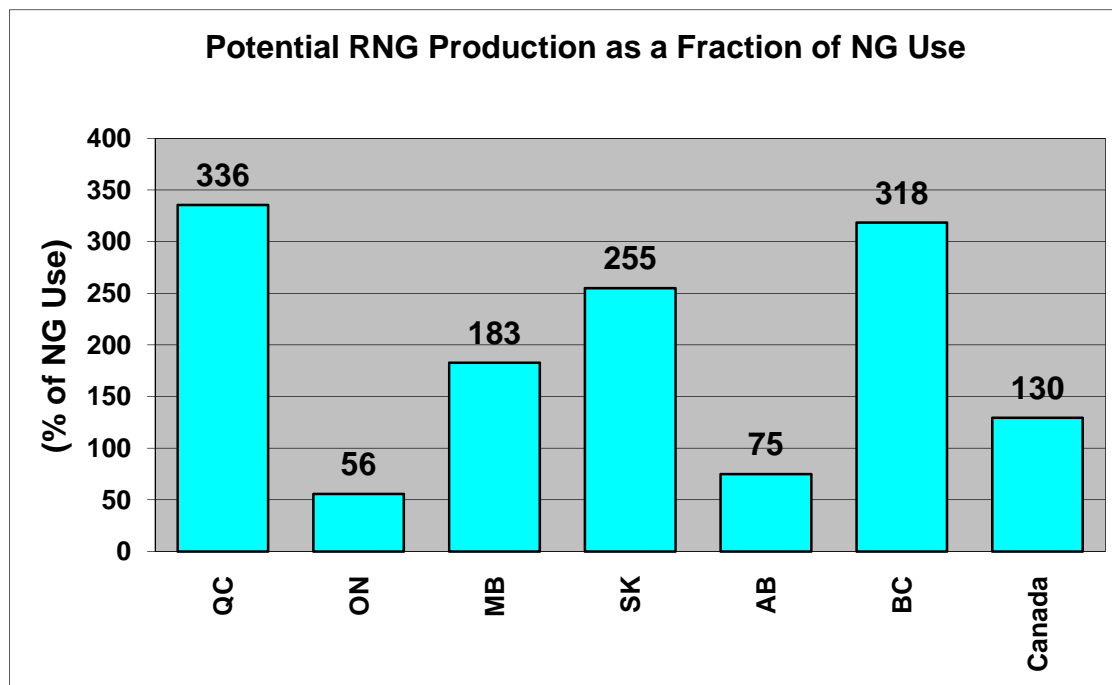


**Figure 20.** Contribution of Wastes to RNG Production.



**Figure 21.** Contribution of RNG Technology to RNG Production.

<b>Table 25. Potential RNG as a Function of Energy Production and Current NG Consumption</b>					
	<b>Total Potential CH<sub>4</sub> Generation</b>	<b>Energy</b>	<b>Electricity</b>	<b>NG Consumption</b>	<b>Total Potential CH<sub>4</sub> Generation</b>
	<b>(Mt/yr)</b>	<b>(PJ/yr)</b>	<b>(GWh)</b>	<b>(Mt/yr)</b>	<b>(% of NG)</b>
<b>NL</b>	0.218	12.27	3,408		
<b>PE</b>	0.096	5.38			
<b>NS</b>	0.607	34.22	9,505		
<b>NB</b>	1.224	69.01	19,169		
<b>QC</b>	5.436	306.40	85,110	1.62	336
<b>ON</b>	5.111	288.07	80,019	9.18	56
<b>MB</b>	1.332	75.07	20,854	0.73	183
<b>SK</b>	2.640	148.79	41,330	1.04	255
<b>AB</b>	3.259	183.71	51,031	4.35	75
<b>BC</b>	7.323	412.77	114,659	2.30	318
<b>NT</b>	0.006	0.32			
<b>NU</b>	0.000	0.01			
<b>YK</b>	0.002	0.13			
<b>Canada</b>	24.878	1,402.30	389,528	19.21	130



**Figure 22.** Potential RNG Production as a Function of NG Use.

## 5.2 ECONOMIC FEASIBILITY

We have used ARC proprietary economic models to evaluate 4 different scenarios involving the production of biogas:

1. An industrial scale anaerobic biogas plant hypothetically situated near Lethbridge processing feedlot manure from 560,000 head of cattle annually and producing pipeline grade natural gas.
2. The same plant but without upgrading the gas and producing only power.
3. A gasification plant processing forest biomass (slash, bug kill, fire kill etc) and producing power and heat for an adjacent pulp mill. This model could potentially be adapted to agricultural crop residues as well.
4. A large landfill near Edmonton producing biogas for power generation.

The models are constructed based on a series of assumptions on revenues, capital costs and operating costs to calculate EBITDA (Earnings Before Interest, Taxes, Depreciation and Amortization) as well as pre- and post-tax profit and rates of return. The models are intended to produce a “snapshot” of a typical year’s operation and are not reflective of ongoing changes to the business during a full business cycle. Our intent is to refine the information and expand the models accordingly to improve their utility as an analytical and decision making tool.

Items like depreciation are estimated based on a very rough estimate of the capital cost asset classes for each plant. It also assumes straight line depreciation versus declining balance.

The model assumes 100% debt financing for each case with interest at 6%. So a project that returns a pre-tax return of 0% is actually generating a “True” rate of return of 6%. The EBITDA value is employed so that rates of return can be compared independent of depreciation schedules and financing charges. A 40% EBITDA is considered as ideal and 30% EBITDA as being the minimum acceptable return.

### **5.2.1 Estimating the Economically Recoverable Resource**

With good assumptions about the state of technology and thereby the capital and operating costs, as well as revenue and raw material costs, we can determine the optimal plant size to exploit the available resource. While we have estimates on the total landfill gas resource, as an example, we would need to know what the optimal sized plant would be that can generate a satisfactory investor grade return for a minimal sized landfill. We can then assume that any larger landfill will generate even better returns and calculate a “recoverable reserve” value. Similarly, we will be able to assess how this economically exploitable reserve increases as gas and/or power prices change due to market forces or to changes in public policy with respect to subsidies.

### **5.2.2 Pipeline versus Power**

Developing these basic spreadsheets highlights the complexity around a fundamental question. Is it better to produce power or a pipeline grade gas? At the moment, there is very little data on the cost to clean gas to a pipeline grade. But if this capital cost is lower than the cost of installing power generation equipment, then it may be preferable to make gas rather than power subject of course to the price of “green” gas being higher than “green” power and subject to there being available customers for power.

What information we do have about gas cleaning costs suggests that the best use for biogas given the current state of the technology is for power generation. A study by Electrigaz Technologies: "Feasibility Study - Anaerobic Digester and Gas Processing Facility in the Fraser Valley, British Columbia" quotes a biogas upgrading cost of \$4.5 million for a 95,000 GJ/year plant. This is equal to \$47/GJ. A study by the USDE “Biogas Multi-Year Program” states that in the case of a forest biomass gasification plant, biogas upgrading costs are expected to be two times higher than the cost of feedstock procurement and gasification itself. In other words, converting biogas to power rather than upgrading to pipeline grade gas results in a production cost just over one third less.



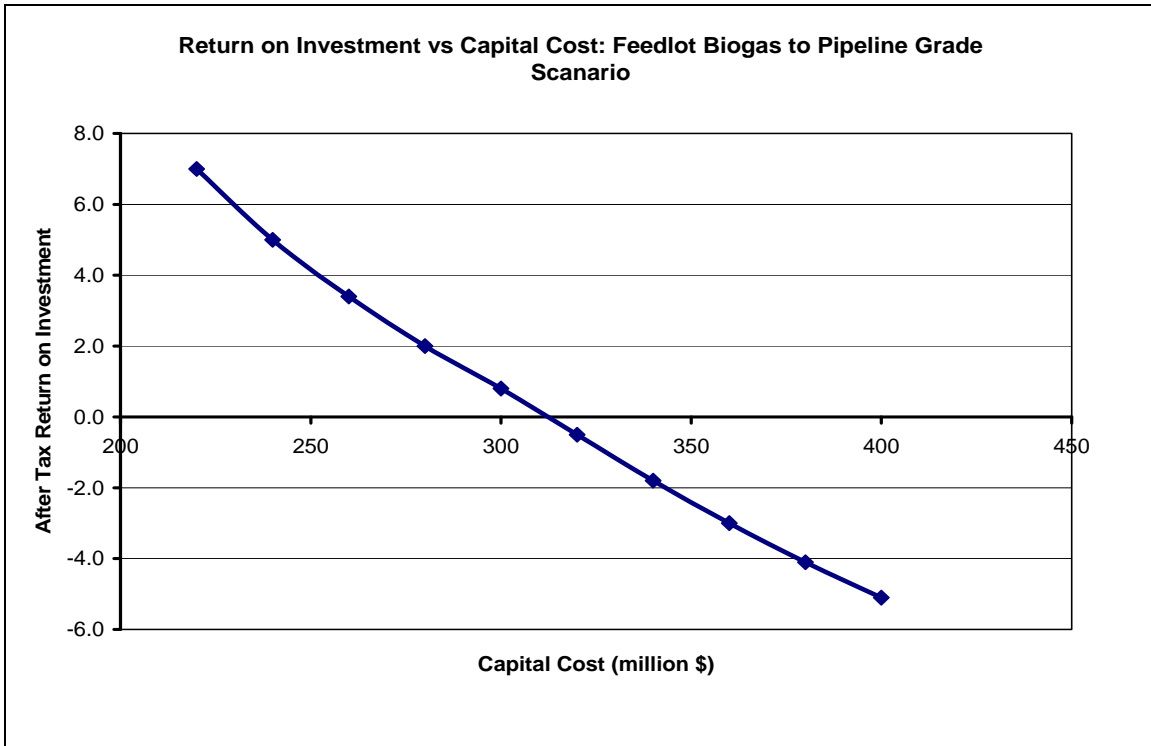
The economics around this question are critical as it will dictate whether “green” gas plants will ultimately be tied into the electrical grid or the natural gas grid.

This underlines the need to develop biogas cleaning technologies that lower capital costs by an order of magnitude over the current state of the art. Rather than effectively tripling the cost of a project, gas cleaning costs should strive to add less than 30% to the cost of a project if these projects are to be competitive with power production.

A second alternative is to look at building biogas projects adjacent to sour gas or acid gas pipelines prior to midstream natural gas cleaning plants. If the biogas is compatible with this gas line infrastructure, it can be run through this existing system at minimal cost.

We have attempted to address this question on the two largest scenarios (the industrial scale manure digester) by assuming that gas cleaning infrastructure would cost the same as electrical generating infrastructure and observe the difference in financial returns. While this particular model shows a continued preference for producing gas, this is entirely dependent on the assumptions being used. It shows that given current assumptions on price of \$0.12/kwh versus \$14/mcf that returns are twice as high for power production versus pipeline grade gas production but are adequately profitable in either case.

Additional capital costs associated with gas cleaning drives out profitability as the following chart demonstrates. A 50% increase in capital associated with cleaning biogas i.e. an increase in capital costs from \$220 million to \$330 million would drive the project to a net zero profit position.



**Figure 23.** Economic Analysis of Feedlot Biogas to Pipeline Grade RNG

### **5.2.3 Risk Sensitivity and Mitigation Analysis**

These models were helpful in exploring risk sensitivity analysis in the different scenarios. Feedlot manure plants, for example, are highly exposed to transportation costs on manure which in turn have relatively low biogas yields. This sensitivity has been tested for financial impact. Landfill gas, with no transport costs is very highly and favourably leveraged with natural gas prices.

### **5.2.4 Comparing the Four Scenarios**

Based on our assumptions, landfill gas is a clear winner due to the low raw material and capital costs involved. Rates of return are spectacular and it is easy to see why this technology has been quickly embraced. The same conclusions can be drawn from wastewater treatment plant digester gas which would have similar economics.

The forest biomass gasification to power model (which could include agricultural wastes like straw after adjusting for feedstock costs) came up with an EBITDA of 28% and an after tax return on capital of 1% (but 7% in real terms assuming 100% debt financing at 6%). This scenario assumed a power price of \$0.06/kwh. With “green” power pricing of say \$0.12/kwh, EBITDA was at 80%. Even if there are errors in the capital and raw material cost assumptions, these are interesting financials.

In comparing the two industrial scale feedlot manure biogas plants, we have assumed equivalence in capital cost for gas cleaning to achieve pipeline grade versus power generation. The model results in an EBITDA of 31% and an after tax return of 7% assuming a “green” gas price of \$14/mcf. Producing power results in an EBITDA of 33% and an after tax return of 8% assuming a “green” power price of \$0.12/kwh.

This model highlights the need to develop capital and operating cost equivalent gas cleaning technologies and to ensure that market demand and price structures can best support the investment.

The following table summarizes the economics reviewed above:

<b>Landfill Gas</b>		<b>EBITDA</b>	<b>Post Tax Return</b>
Capital Cost (million \$)	4.85	61.3%	24.4%
Power Price (\$/kwh)	0.06		
<b>Biomass Gasification</b>			
Capital Cost (million \$)	18.52	27.6%	1.1%
Power Price (\$/kwh)	0.06		
<b>Feedlot Biogas Power</b>			
Capital Cost (million \$)	220	33.1%	8.4%
Power Price (\$/kwh)	0.12		
<b>Feedlot Biogas Pipeline</b>			
Capital Cost (million \$)	220	31.1%	7.0%
Gas Price (\$/mcf)	14		

**Table 26.** Economic Analysis of RNG Scenarios

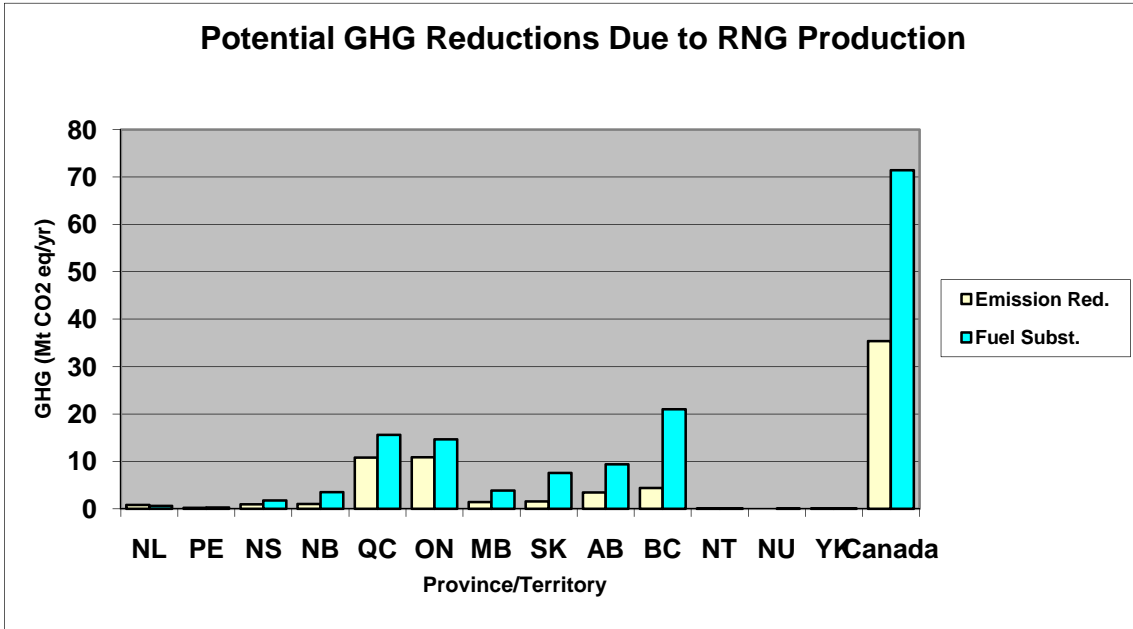
## **6. GREENHOUSE GAS IMPACT OF METHANE CAPTURE FROM CANADIAN WASTES**

The production and capture of RNG from Canadian wastes contributes to GHG reduction through two processes: emission reduction and fuel substitution. Emission reduction can be achieved through the capture of the emitted methane from landfills and the anaerobic digestion of animal manures, in particular hog manures. Fuel substitution applies to the use of RNG to replace any NG produced from fossil fuels. Table 27 shows the results of our estimates where we assigned a value of 21 times CO<sub>2</sub> for the methane emission reductions and a value of 2.87 (NG GHG intensity, t CO<sub>2</sub> eq/t) for fuel substitution. The value of 2.87 we used for fuel substitution is similar to the value of 2.79 used in a recent BC report (Electrigaz Technologies, 2008).

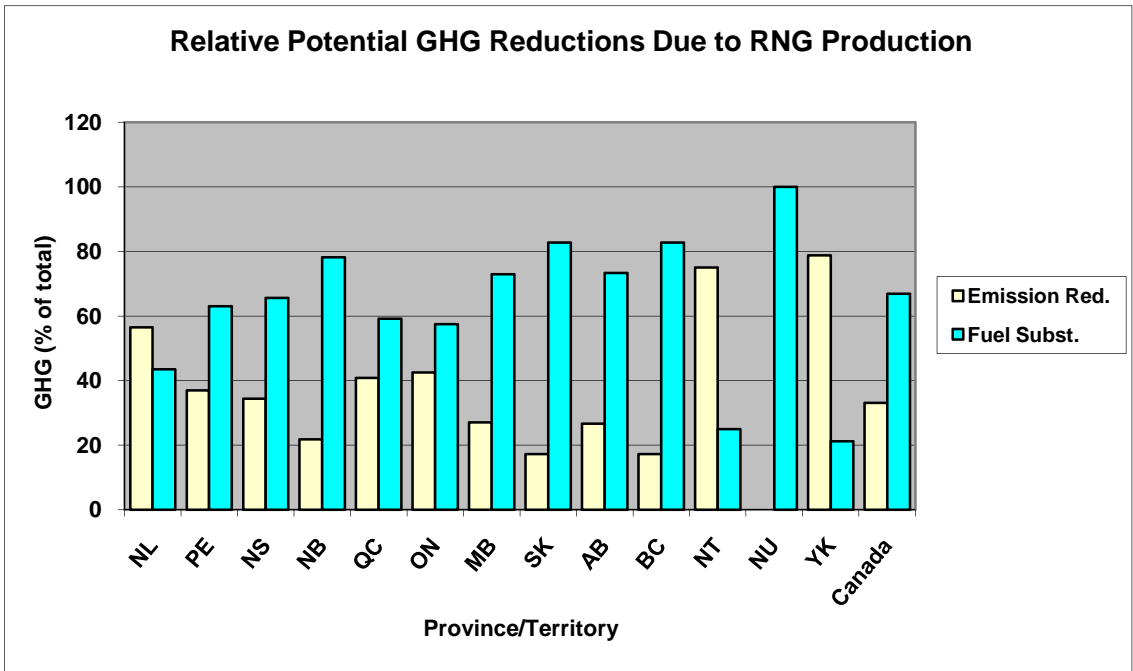
Total GHG reductions were estimated as 107 Mt CO<sub>2</sub> eq/yr for Canada with the largest amounts found for Quebec, Ontario and BC. The provincial estimated ranged from 0.43 for PEI to 26.4 Mt CO<sub>2</sub>/yr for Quebec. Fuel substitution seems to contribute more GHG reductions than emission reduction except for those provinces with large forestry wastes such as BC (Figures 24 and 25). Almost 33% of the Canadian GHG reductions arise from emission reductions, while the rest (67%) are from fuel substitution.

RNG production from wastes seems to contribute significant amounts of GHG reductions and thus carbon credits. This might alleviate the cost of RNG production if one factors in the sale of the produced CO<sub>2</sub> and its carbon credit.

<b>Table 27. GHG Reductions Due to Production of Renewable Natural Gas</b>							
	<b>Methane</b>		<b>GHG</b>				
	<b>Emission Reduction<sup>1</sup></b>	<b>Fuel Substitution<sup>2</sup></b>	<b>Emission Reduction<sup>3</sup></b>	<b>Fuel Substitution<sup>4</sup></b>	<b>Total<sup>5</sup></b>	<b>Emission Reduction<sup>6</sup></b>	<b>Fuel Substitution<sup>6</sup></b>
	<b>(Mt/yr)</b>		<b>(Mt CO<sub>2</sub> eq/yr)</b>			<b>(%)</b>	
<b>NL</b>	0.039	0.218	0.81	0.63	1.437	56.5	43.5
<b>PE</b>	0.008	0.098	0.16	0.28	0.44	36.4	63.6
<b>NS</b>	0.044	0.614	0.91	1.76	2.68	34.2	65.8
<b>NB</b>	0.047	1.230	0.98	3.53	4.51	21.7	78.3
<b>QC</b>	0.513	5.538	10.78	15.89	26.67	40.4	59.6
<b>ON</b>	0.517	5.258	10.86	15.09	25.95	41.9	58.1
<b>MB</b>	0.067	1.416	1.42	4.06	5.48	25.8	74.2
<b>SK</b>	0.075	2.803	1.57	8.04	9.62	16.4	83.6
<b>AB</b>	0.162	3.440	3.41	9.87	13.28	25.7	74.3
<b>BC</b>	0.209	7.337	4.38	21.06	25.44	17.2	82.8
<b>NT</b>	0.002	0.006	0.05	0.02	0.07	75.0	25.0
<b>NU</b>		0.000	0.00	0.00	0.00	0.0	100.0
<b>YK</b>	0.001	0.002	0.02	0.01	0.03	78.8	21.2
<b>Canada</b>	1.685	25.606	35.39	73.49	108.88	32.5	67.5
<p><b>1</b> Calculated as the CH<sub>4</sub> generated in landfills plus 20% of the CH<sub>4</sub> generated from manure through AD</p> <p><b>2</b> This is the total amount of potential CH<sub>4</sub> generated from all wastes</p> <p><b>3</b> Calculated as column 2 x 21 (GWP)</p> <p><b>4</b> Calculated as column 3 (Mt CH<sub>4</sub>/yr) x 2.87 (Mt CO<sub>2</sub> eq/Mt CH<sub>4</sub>)</p> <p><b>5</b> Calculated as the sum of columns 4 and 5</p> <p><b>6</b> Calculated as a percent of the total GHG (column 6)</p>							



**Figure 24.** Potential GHG Reductions Due to RNG Production.



**Figure 25.** Relative Potential GHG Reductions Due to RNG Production.

## 7. CONCLUSIONS

Production of RNG from Canadian wastes was shown to arise from the application of two well used and understood processes: anaerobic digestion and gasification. Based on our findings, it is envisioned that anaerobic digestion process will be the main source of RNG in the next 5 to 10 years with gasification contributing afterwards. This is based on the availability of the technologies, prior use and acceptance by industry and the need for further technology development activities.

Canadian wastes that are amenable to producing RNG are those containing significant amounts of biomass and are mostly generated by the agricultural, forestry and municipal sectors.

The analysis shows that a technical potential total of 24.9 Mt/yr of RNG can be produced from the total Canadian wastes reviewed. Forestry seems to have the potential to produce 12.9 Mt/yr (51% of total), followed by 8.8 Mt/yr (36%) from agriculture and 3.2 Mt/yr (13%) from municipal wastes. The use of gasification seems to have the potential to produce most of the RNG in Canada as we estimated that 21 Mt/yr (84% of total) can be produced by this process. Anaerobic digestion has the potential to produce 3.9 Mt/yr (16% of total); while this process seems to be significantly less than gasification, it is still significant because of the technology availability and lower cost.

We compared the relative size of our potential RNG estimates to the current natural gas use for the residential and commercial sectors. The potential Canadian generation of 24.9 Mt/yr of RNG corresponds to an energy value of 1.4 TJ/yr or 389,528 GWh of electricity. RNG production can account for a significant amount of the natural gas use. Nationally, our estimate is that 130% of current NG residential and commercial use could theoretically be replaced by the produced RNG, on a technical potential basis.

We developed several scenarios using proprietary spreadsheets developed within the Alberta Research Council, to highlight the complexity around the economics issue. Our analysis shows that to lower the cost of RNG, then the technology costs for cleaning the biogas needs to be reduced. At the moment, there is very little data on the cost to clean gas to a pipeline grade. However, the economic models which have been presented



evaluated different scenarios which included examples of RNG used to produce pipeline grade natural gas, or RNG used in power production. The economics underlines the need to develop biogas cleaning technologies that lower capital costs by an order of magnitude over the current state of the art.

The production and capture of RNG from Canadian wastes contributes to GHG reduction through two processes: emission reduction and fuel substitution. Emission reduction can be achieved through the capture of the emitted methane from landfills and the anaerobic digestion of animal manures. Fuel substitution applies to the use of RNG to replace any natural gas produced from fossil fuels.

The total technical potential GHG reductions were estimated as 107 Mt CO<sub>2</sub> eq/yr for Canada with the largest amounts found for Quebec, Ontario and BC. Fuel substitution seems to contribute more GHG reductions than emission reduction except for those provinces with large forestry wastes such as BC. Almost 33% of the Canadian GHG reductions arise from emission reduction, while the rest (67%) come from fuel substitution.

The potential RNG production from wastes can contribute a significant amount of GHG reductions and thus carbon credits, which may alleviate the cost of RNG production if factoring in the sale of the CO<sub>2</sub> produced and the value of its carbon credit.

## 8. **RECOMMENDATIONS**

On going forward, the recommendations which we offer from completing this project include several initiatives which address policy or technical development issues.

### 8.1 **POLICY DEVELOPMENT**

- Refine the analysis on the potential of RNG to become a significant energy source in Canada by estimating the useful potential of RNG, taking into account spatial infrastructure and economic constraints.
- Promote the production and use of RNG through increased interactions with and collaboration between various levels of governments, institutions and associations.
- Engage governments in discussions in order to have RNG included in a listing of approved clean energy fuel sources.
- Convene a meeting of all stakeholders to develop a deployment roadmap and strategy at the national level for the development of RNG as a renewable fuel.

### 8.2 **TECHNICAL DEVELOPMENT**

- Identify the priority waste materials which are amenable for use in RNG production by collecting more detailed data about the waste.
- Develop economically viable technologies for the cleaning and separation of biogas, with detailed costing information.
- Develop improved gasification technologies for a wider range of biomass materials.

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