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Economic and environmental assessment on the energetic valorization of organic material for a municipality in Quebec, Canada

Philippe Morin [a], Bernard Marcos [a,*], Christine Moresoli [b], Claude B. Laflamme [c]

[a] Département de génie chimique et génie biotechnologique, Université de Sherbrooke, Sherbrooke, Quebec, Canada
[b] Chemical Engineering Department, University of Waterloo, Waterloo, Ontario, Canada
[c] Laboratoire des technologies de l'énergie (LTE), Hydro-Québec – Institut de recherche, Shawinigan, Quebec, Canada

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ABSTRACT

Waste-to-energy provides a solution to two problems: waste management and energy generation. An integrated anaerobic waste valorization process is an interesting option, but because of investments cost and low energy value in the province of Quebec, it is hard for a municipality to commit to that solution. This paper investigated the economic possibilities to manage organic material, organic fraction of municipal solid waste, and municipal wastewater sludge by anaerobic digestion for a 150,000 inhabitant municipality, with consideration to energy generation and greenhouse gas emission reduction. Using the biogas to co-generation solution brings a payback time on investment (PBT) of 3.7 years with electricity price at 0.10 $Cdn/kW h. The addition of manure from surrounding farms increases the biogas production by 37%, but increases the PBT to 6.8 years unless the leftover digestate can be used for agronomic valorization; then it becomes economically advantageous. The natural gas purchasing cost is too low to promote the enrichment of biogas into renewable natural gas. However, this scenario has the lowest energetic payback time (3.3 years) and reduces the most greenhouse gas emissions (4261 tCO_2eq/a).

1. Introduction

Waste management of organic materials is the center of many environmental problems such as greenhouse gas emissions and lixiviate production associated with the biodegradation within landfills. Some communities promote composting to remedy this problem, while others rely on biogas recovery with or without energy valorization. With the increasing energy demand around the world and the heavy reliance on fossil fuel in the context of the climate change debate, the organic waste should be valorized, as it would provide energy while reducing greenhouse gas emissions. Organic materials represent unused resources that can be transformed into an opportunity to create a new supply of energy located near urban centers, turning an issue into a solution.

1.1. Energy generation: new supply

Quebec, a province in Canada, has a widely developed hydroelectricity network for its population of 7 million inhabitants. Even though hydro-electricity produces clean electricity, the province is heavily dependent on the electricity transportation network between the large dams, often located in remote regions, and the urban centers where most of the electricity is used. Since the electricity transportation network covers a large territory, the potential of new local sources of renewable electricity generation can offer an attractive solution to reduce the pressure on the electricity transportation network and to the increasing energy demand in Quebec [1]. Also, the establishment of electricity generation plants closer to the urban centers would reduce the cost of transportation and limiting extra ecological footprints around new power lines and new reservoirs. Since there is a new need for kilowatts of energy, Quebec replaced the low-price ruling (around 0.05 $Cdn/kW h) with a marginal cost of 0.10 $Cdn/kW h for extra production to the actual network [2].

1.2. Waste management issues

In the 1990s the government of Quebec established the Quebec Residual Materials Management Policy, 1998–2008 [3]. The overall objective of the policy is to recover 60% of the residual organic materials which would otherwise end up in landfills. Landfills bring many environmental problems such as soil, groundwater, and air pollution; mainly because of the uncontrolled biodegradation of the residual organic materials. The major source of residual organic materials (with the exception of wood) is municipal waste and represented 68% in 2006. The residual organic materials represented 1.3 million metric tonnes in 2007, 44% of all the residual materials produced in the municipalities. The provisional balance sheet made in 2006 indicates that the objectives of the policy

* Corresponding author.
E-mail address: bernard.marcos@usherbrooke.ca (B. Marcos).

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would certainly not be reached by 2008; only 8% of the residual organic materials were valorized [3]. Source sorted collection of the residual organic material coupled with composting was suggested in the policy, but the number of composting sites decreased by 20% [3] due to the quality of the compost (69% of B quality [4]) leading to a low selling price (5.67 $Cdn/t), and therefore high management cost (70 $Cdn/t).

1.3. Integrated waste management process by anaerobic valorization

Bringing together both issues, it is possible for municipalities to manage organic material differently, producing a valuable product: energy. Anaerobic digestion allows the use of organic materials as the primary resource for biogas production. The biogas can then be used as a fuel for usable energy generation. The waste produced in urban centers can then become a complementary local energy source. Moreover, the purified biogas can be used as a replacement for natural gas and therefore reduce the amount of greenhouse gas (GHG) released into the atmosphere, since the carbon produced by the combustion of biogas is considered biogenic and thus does not contribute to the global warming. A review of the literature was completed in 2006 compiling technical information on anaerobic digestion. This review focuses on the improved performance of thermophilic digesters and the gains associated with co-digestion of multiple organic wastes: increasing the biogas production and cost-sharing of management and energy [5]. Consequently, thermophilic digesters and co-digestion will be the focus of the scenarios analyzed in the current study.

Despite the environmental advantages, the energy generation and the avoided costs associated with anaerobic digestion as a sustainable waste management option, the characteristics of the province of Quebec make it difficult to compensate for the significant investment and operation cost and turn anaerobic digestion into a profitable option. The reason for this is the low energy cost and the lack of subsidies in the Province of Quebec to encourage anaerobic digestion. The main drawback is mostly economic, since the environmental soundness of anaerobic digestion is already proven. The present study will identify the economic elements that should be considered for the development of regional anaerobic digestion for a municipality located in the province of Quebec.

1.4. Integrated waste management scenarios

Haight assessed the anaerobic digestion of organic fraction of municipal solid waste (OFMSW) with a life-cycle analysis for a mid-sized Canadian community and concludes that the environmental burdens are reduced compared to landfilling and composting. However, he concludes that in a province where hydro-electric power is the main source of electricity, such as Quebec, the offset environmental burdens are reduced [6]. Suh and Rousseau (2001) use a composed performance index consisting of nine indicators (resource depletion, climate change, human toxicity, water ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, acidification, eutrophication and oxidant formation) for the classification of the scenarios. They show that the best scenario is independent of the weight factors assigned to the nine indicators. Anaerobic digestion of sewage sludge is more environmentally friendly than composting when used for stabilization prior to agricultural land application due to fewer emissions and reduced energy consumption [7]. Edelman et al. compute the sum of damages for each scenario with ECOINDICATOR; the damages caused by the reference substances of each impact category are weighted for causing mortality, damage to health and ecosystem impairment. However, the weight of the three categories (mortality, health, and ecosystem) is somehow subjective. Results show the environmental advantages of anaerobic digestion compared to composting and incineration because of the improved energy balance [8,9].

Murphy and Power assessed the technical and economic aspects of biogas production from energy crops in Ireland. A sensitivity analysis was conducted to determine the most critical parameters relating to the economic feasibility. The purchase cost of renewable natural gas is the primary factor, and the cost of feedstock is the secondary factor. The selling price's impact depends on the quantity of digestate generated. The overall capital and operating costs are not significant factors [10].

A study was completed in 2005 in the context of the Quebec Waste Management Policy to assess the anaerobic digestion of the OFMSW and sewage sludge from the Montréal Metropolitan Community. The evaluation of the energy potential and GHG reduction with the anaerobic digestion of a theoretical available quantity of organic wastes indicates that anaerobic digestion of the biosolids is a sustainable solution when the biogas is converted into marketable energy [11].

1.5. Focus of paper

The aim of this paper is to assess the energy generation potential of the organic material managed by a municipality of 150,000 inhabitants practising source sorted collection of their organic material. The industrial sector of the municipality is mainly composed of services. There is a lack of integrated scenario analysis that considers the process from cradle to grave. This paper focuses on the impact of the type of technology selected for the management of municipal solid organic waste. Three performance criteria are considered: the energetic, environmental and economic performances for a situation where the electricity is clean (hydro-electricity) and affordable (0.05 $Cdn/kW h). The energy generation obtained from the organic material managed by the municipality is based on mass and energy balances for an integrated anaerobic digestion process that considers the initial collection of the waste, its processing and the energy produced. It includes an extensive economic analysis based on investment and operational costs of a full scale plant. Two energy generation schemes will be investigated: energy-to-electricity using a co-generation unit, and an upgrade of the biogas into renewable natural gas as a local substitute for transportation (bus fleet) or heating.

2. Methodology

2.1. Integrated energy generation process scenarios

The integrated scenarios start with the volume and composition of the waste, the sequence of the unit operations necessary for the treatment and energy generation. Those scenarios are compared based on economic, energetic and environmental criteria. The software tool used is called MATTEUS and was developed by Hydro-Quebec, a government-owned corporation that supplies electricity for the Province of Quebec. It is an Excel-based spreadsheet and database program that calculates mass and energy balances. MATTEUS provides extensive technical and economic information about integrated processes, from the collection of any organic material to the final disposal of the waste. The investment, operation, and maintenance costs are estimated for each unit necessary for the process, with scale-up power law obtained from similar cases in literature and supplier information. It is then straightforward to compare the effect of different technologies and operation conditions on the performance of the process, and to evaluate the flow sheet chosen by the user. The scenario requires the selection of a unit for each of the steps presented in Fig. 1. An example of a completed scenario is illustrated in Fig. 2.

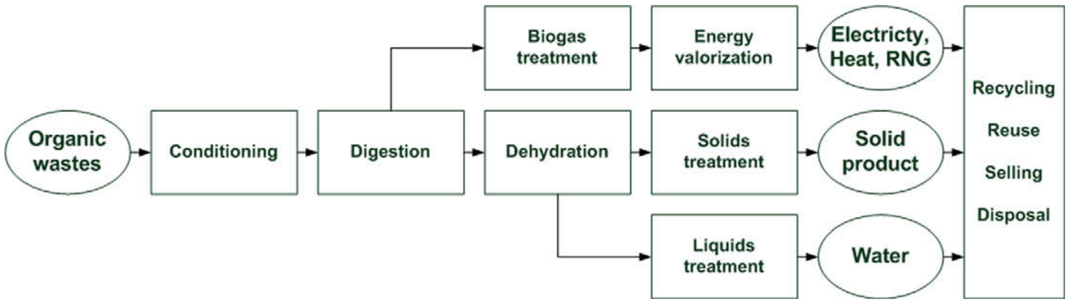

Fig. 1. MATTEUS key-steps for the waste treatment process.

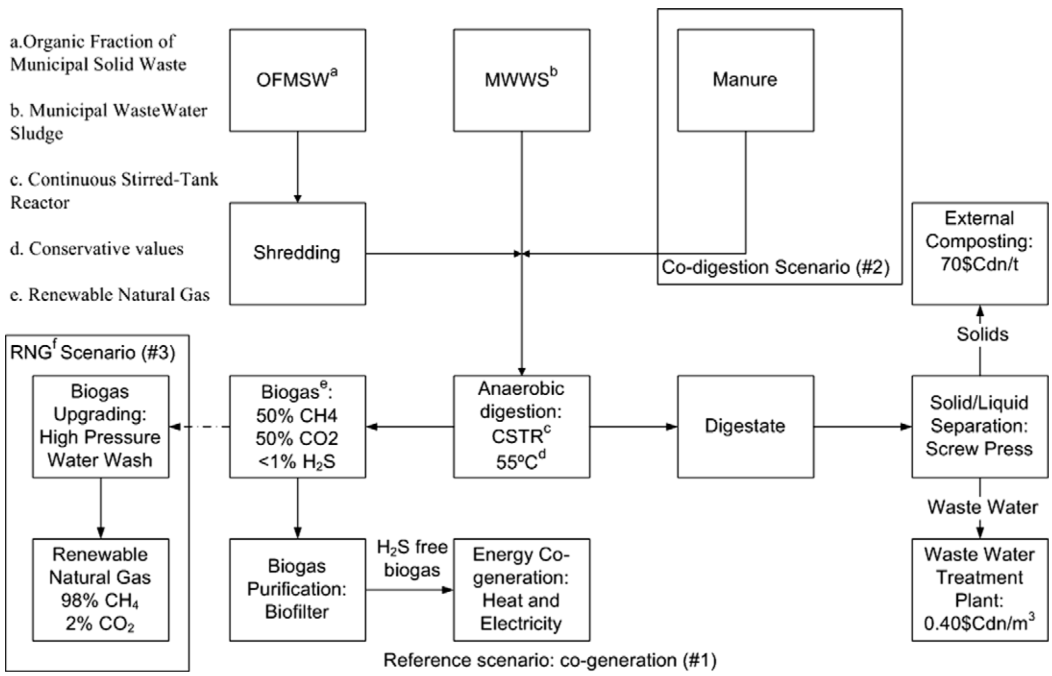

Fig. 2. Flow sheet of the proposed scenarios for the management of organic material by the selected municipality.

2.2. Biogas production stoichiometry

This is the major stoichiometric equation that calculates the amount of compounds produced (methane, carbon dioxide, ammonia, hydrogen sulphide and fresh biomass) or consumed (organic material and water) on a mass basis of 1.0 mass unit of an organic waste degraded by an anaerobic process based on its elementary mass composition (wt.%) [12]. The biogas production is only from the degraded material which is based on literature, around 67% of organic load for wastewater sludge [13] and around 70% for OFMSW [14]. The integer numbers in Eq. (1) refer to the stoichiometry and the molecular weight (decimal numbers) of the elements/molecules expressed on a mass basis:

$$\begin{aligned}
&C_\alpha H_\beta O_\gamma N_\delta S_\varepsilon + \frac{18.01}{4}\left(\frac{4(\alpha-\Phi\alpha')}{12.01} - \frac{\beta-\Phi\beta'}{1.01} - \frac{2(\gamma-\Phi\gamma')}{15.99} + \frac{3(\delta-\Phi\delta')}{14.01} + \frac{2(\varepsilon-\Phi\varepsilon')}{32.06}\right)H_2O \\
&\rightarrow \frac{16.05}{8}\left(\frac{4(\alpha-\Phi\alpha')}{12.01} + \frac{\beta-\Phi\beta'}{1.01} - \frac{2(\gamma-\Phi\gamma')}{15.99} - \frac{3(\delta-\Phi\delta')}{14.01} - \frac{2(\varepsilon-\Phi\varepsilon')}{32.06}\right)CH_4 \\
&+ \frac{43.99}{8}\left(\frac{4(\alpha-\Phi\alpha')}{12.01} - \frac{\beta-\Phi\beta'}{1.01} + \frac{2(\gamma-\Phi\gamma')}{15.99} + \frac{3(\delta-\Phi\delta')}{14.01} + \frac{2(\varepsilon-\Phi\varepsilon')}{32.06}\right)CO_2 + \frac{17.04(\delta-\Phi\delta')}{14.01}NH_3 \\
&+ \frac{34.08(\varepsilon-\Phi\varepsilon')}{32.06}H_2S + \Phi C_{\alpha'}H_{\beta'}O_{\gamma'}N_{\delta'}S_{\varepsilon'}
\end{aligned} \tag{1}$$

$\alpha, \beta, \gamma, \delta, \varepsilon$; is the mass composition (wt.%) of the organic material, $\alpha', \beta', \gamma', \delta', \varepsilon'$; the mass composition (wt.%) of the fresh biomass, Φ; is the ratio of organic material converted in fresh biomass (5%).

2.3. Economic, environmental and energetic indicators

As the aim of this study is to evaluate the economic, environmental and energetic aspects of anaerobic digestion as a waste management option, three simple indicators are used for the quantitative comparison. The economic criterion was the payback time on investment (PBT) in years.

$$\mathrm{PBT} = \frac{I}{R + C_{WM} - C_O} \tag{2}$$

where I is the total investment cost ($Cdn), R is the total revenues and avoided cost ($Cdn/a), C_{WM} is the avoided waste management cost ($Cdn/a), and C_O is the operation cost including maintenance, labour, external energy and chemicals ($Cdn/a).

The energetic investment is the embodied energy for the construction of an anaerobic digestion treatment plant. The energetic investment can be related to the capital investment. A power law was created to associate the quantity of waste treated in tonne of dry matter per hour (t_{dm}/h), with the total capital cost of the process giving an exponent of 0.6624. It was assumed that the energetic investment follows the same power law with respect to the plant capacity. According to a life-cycle analysis performed by Ishikawa, a plant with a capacity of 0.208 t_{dm}/h requires an energetic investment (EI) of 42,000 GJ [15]. These assumptions were used to extrapolate the energetic investment (EI) of any size plant, leading to Eq. (3).

$$\mathrm{EI} = 42000 \times \left(\frac{\text{Plant capacity}}{0.208}\right)^{0.6624} \quad (3)$$

The energetic payback time in year (EPBT) was used to evaluate the energetic aspect and represents the number of years required to reimburse the energetic investment according to the energy balance of the process.

$$\mathrm{EPBT} = \frac{\mathrm{EI}}{\mathrm{EG} - \mathrm{EC}} \quad (4)$$

where EI is the energetic investment (GJ), EG is the energy generation from the process (GJ/a), and EC is the energetic consumption of the process (GJ/a).

To compare the environmental performance of the scenarios, a balance of the greenhouse gas emissions (GHG) was made. All of the CO_2 coming out of the anaerobic digestion and the combustion of the associated biogas is biogenic; it results from living organisms that picked it up from the atmosphere. Thus, it is not a greenhouse gas and the biogas can replace traditional energy sources that produce greenhouse gases such as electricity and natural gas. However, since Quebec uses mostly hydro-electricity, its emissions are low and Lambert reports that the average CO_2 equivalent resulting from Hydro-Québec electricity between 1990 and 2005 is 18.54 tonnes of CO_2 equivalents per Gigawatt hour (tCO_2eq/GW h) [16]. To compare, Environment Canada calculated the average CO_2 equivalent from Canadian electricity to be 203.9 tCO_2eq/GW h [17], and the Environmental Protection Agency calculated the average CO_2 equivalent from American electricity to be 610.9 tCO_2eq/GW h [18] because of thermal power stations. For natural gas, the emission from combustion is 1902 gCO_2eq/N m^3 [19]. To estimate the total reduction between the current waste management practices of the municipality and the proposed scenarios, the current emissions are added, and the new emissions of the proposed processes are subtracted.

3. Energy scenarios development and analysis

The aim of this study is to obtain preliminary data about economic, energetic, and environmental performance of an integrated anaerobic digestion process in the context of a municipality located in the province of Quebec. The selected municipality has a population of 150,000 inhabitants on a territory of 350 km^2. Currently, the municipality is managing the wastewater sludge from its treatment plant and the municipal solid waste with a three-way collection system (wastes, recyclables, and organics collected separately). Furthermore, manure mainly from dairy cows is produced in the region. This material could be added to those managed by the municipality to increase the capacity of the anaerobic digestion process and to lessen the environmental impact of manure spreading. The OFMSW is sent to external composting site, 90% of the wastewater sludge, produced from the municipal wastewater treatment, is sent for agronomic valorization as fertilizing organic material for land spreading of cultures not related to human consumption and pasture land, and the remaining 10% is sent to landfill. The implementation of an anaerobic digestion plant managed by the municipality would enable the investment of municipal funds in an environmentally-friendly approach, producing valuable energy and managing organic wastes. An anaerobic digestion plant would also reduce the utilization of the landfill and increase its lifetime. Table 1 presents the characteristics of the municipality.

Table 1
Characteristics of the selected municipality.

Characteristics			GHG (tCO_2eq/a)
Population	Inhabitant	150,000	
Waste management cost	$Cdn/a	2,000,000	
External composting cost	$Cdn/t	70[a]	146[b]
Landfilling cost	$Cdn/t	70[a]	12[b]
Agronomic valorization cost	$Cdn/t	56[a]	410[c]
Wastewater treatment	$Cdn/m^3	0.40	
Area	km^2	350	
Average distance travelled by OFMSW	km	11	
Average distance of surrounding farms	km	11	
Distance to the composting site	km	50	

[a] The transportation is not included in the disposition costs.
[b] GHG produced by transportation.
[c] GHG produced by transportation and agronomic valorization.

Table 2 presents the municipal and agricultural organic materials that are collected by the selected municipality. The three scenarios considered in this study are shown in Fig. 2 and will be detailed in the next sections.

The anaerobic digestion plant and the municipal waste treatment plant are expected to be on the same site. The municipality shows interest in electricity and heat co-generation, as well as renewable natural gas production for their bus fleet.

3.1. Reference scenario: co-generation (#1)

The reference scenario is the anaerobic digestion of the organic material managed by the municipality with the co-generation of electricity and heat from a generator supplied by purified biogas. The integrated process uses a completely new plant and includes the transportation related to the collection of the municipal waste. Since the proposed waste treatment plant will be located on the same site as the municipal wastewater treatment plant, the transportation of the sludge is nonexistent.

The municipal wastes need to be shredded prior to being incorporated in the anaerobic digestion tank. This allows for a more efficient digestion by the consortium of microorganisms and facilitates the mixing inside the tank.

Considering the dry weight (d.w.) of the organic material mixture (9%) and the nature of the organic material, a continuous stirred-tank reactor was selected as it is an effective, easy to operate and low-cost option for the digestion operation [20–22]. The inoculation of the digester occurs naturally with the presence of activated sludge from the wastewater treatment plant. The temperature was selected to be 55 °C, which corresponds to the optimal thermophilic conditions. The major advantage of thermophilic digestion is the lower hydraulic retention time needed for an equivalent conversion (10 vs. 28 days) [23,24] of the biomass when operated at a lower temperature. Furthermore, the destruction of pathogens is more effective, which is an advantage for future agronomic valorization. However, some thermophilic installations turned out to be less stable than mesophilic ones because of ammonia inhibition [24]. In the

Table 2
Available organic materials around the selected municipality.

Organic material	Amount (t/a)	Actual management cost ($Cdn/a)
Managed by city		
OFMSW (36% d.w.[b])	16,000	1,120,000
Wastewater sludge (5% d.w.[b])	108,000	850,000
Managed by surrounding farms		
Manure (cows and bullocks) (12% d.w.[b])	30,000	N.A.[a]
Total	154,000	1,970,000

[a] N.A.: Not available.
[b] d.w.: dry weight.

end, the payback time will show what operating temperature is the most economically sound: a smaller digester with higher heating cost or a larger digester with lower heating cost.

After the anaerobic digestion, the biogas exits at the top and the digestate (inorganic compounds, undigested materials, ammonia and fresh biomass) exits at the bottom. The biogas is composed of carbon dioxide, methane, hydrogen sulphide, and water vapour. The biogas is purified in a biofilter filled with peat. In this step, most of the water and hydrogen sulphide are removed from the biogas, resulting in a fuel which has higher calorific value and is more gentle for the co-generator that produces electricity for the power grid, heating for the operation of the digester, and the heating of the nearby municipal wastewater treatment plant.

The digestate needs to be disposed. To reduce the cost of disposal, a mechanical dehydration system will be used. A screw-press allows for sludge of 30% d.w. to be obtained. This sludge will be sent to external composting since agronomic valorization requires a composting treatment when used for cultures related to human consumption and pasture land. The utilization and size of the composting site would remain the same because of the combined effect of the reduction of the organic material by anaerobic digestion and the addition of municipal wastewater sludge. The extracted water will be sent to the nearby municipal wastewater treatment plant. The annual utilization factor was estimated to be 95%. A flow sheet of the reference co-digestion scenario (#1) is presented in Fig. 2.

3.2. Co-digestion scenario (#2)

The co-digestion scenario (#2) aims for the integration of the manure generated by surrounding farms into the anaerobic digestion process. The objective is to increase the biogas production but also to reduce the amount of ultimate residual material while lowering the environmental impact. A previous study has shown that the co-digestion of OFMSW with manure is possible in thermophilic wet digestion system with stable operation, despite fluctuation in the feed volume, possibly due to seasonal changes, and similar biogas yield [25]. On the other hand, since manure has a low dry matter content, its addition to the process necessitates an increase in equipment sizing, heating, transportation, and digestate quantity, leading to a low energy output [26]. Economic and energetic assessment will demonstrate if the manure should be integrated to the process. A flow sheet of the co-digestion scenario (#2) is illustrated in Fig. 2.

3.3. Renewable natural gas (RNG) scenario (#3)

It is possible to enrich the methane composition in the biogas to obtain renewable natural gas (RNG), which can replace natural gas in any purpose. The local natural gas distributor in Quebec provides 96% methane gas. The enrichment of biogas leads to 98% methane gas. The renewable natural gas scenario (#3) requires modifications of the downstream part of the process. After the anaerobic digestion, the biogas purification unit will be replaced by a high pressure water wash for the removal of the hydrogen sulphide as well as most of the carbon dioxide. The purified gas will need to be dried before its use. The co-generation unit is no longer needed since the biogas is the end product, but a gas boiler is necessary for heating the digester, unless residual heat from the outside is available. Obviously, the cost of the system is higher than the biofilter and the CHP unit, leading to a significant increase of the investment and operation cost. The purchasing cost of the natural gas is then important for economic sustainability. The calculations of the additional investment and upgrading costs are made according to Persson [27]. Since the purchasing cost of natural gas is very volatile, an average purchasing cost of natural gas in Canada for 2008 was selected and obtained from Natural Resources Canada, 7.73 $Cdn/GJ. Since 2005 the price varied from 4.49 $Cdn/GJ (October 2006) to 12.54 S/GJ (November 2005) [28]. The effect of the purchasing cost of natural gas on the payback time on investment price is discussed in Section 4.6.

Murphy, McKeogh and Kiely investigated the best way to use biogas based on technical, economic, and environmental performance [29]. They considered the biogas from a fixed biogas plant in order to lower the gate fees of the waste and to minimize GHG production. In contrast, the present study focuses on the best integrated energy generation process scenarios to manage organic waste from a community's perspective. Murphy, McKeogh and Kiely conclude that the preferred solution is to produce RNG for transportation, with a co-generation unit to fulfill the energetic needs of the plant. However, only 53% of the biogas would then be available for transportation [29]. Since the operation of the biogas plant is the most important part of the energy needed for the system (40–80%) [26] a lower temperature for the digester could increase the energy available for transportation. A flow sheet of the RNG scenario (#3) is presented in Fig. 2.

4. Results and discussion

4.1. Estimated process technical and economic data

The results from Table 3 were obtained using MATTEUS, with the input data from Tables 1 and 2 and according to the three scenarios presented in Section 3.

4.2. Investment and operation

The investment and the operation costs of the scenarios are similar to the costs of the Dufferin Organics Processing Facility in Toronto (Canada) for OFMSW: 54 $Cdn/t OFMSW processed for the investment cost and 91 $Cdn/t OFMSW processed for the operation cost [30,31]. To compare with the reference co-generation scenario (#1), the wastewater sludge should have the same dry weight (d.w.) as OFMSW such that 108,000 tonnes at 5% d.w. is equivalent to 15,000 tonnes at 36% d.w. The total amount of organic material at 36% d.w. to be processed corresponds to 31,000 tonnes which gives an investment of 1,674,000 $Cdn and an annual operation cost of 2,821,000 $Cdn.

The difference between the investment cost of the co-generation scenario (#1) and the co-digestion scenario (#2) is due to the additional equipment required for the treatment of 30,000 t/a of manure. The same applies to the operation cost. For the RNG scenario (#3), the additional investment cost and operation cost are based on the amount of renewable natural gas produced using the relation proposed by Persson [27]. The investment cost increases by 33% and the operation cost by 18% (@20 °C) when compared to the co-generation scenario (#1).

Table 3
Technical and economical results.

Parameters	Scenario			
	Co-generation (#1)	Co-digestion (#2)	RNG (#3)	RNG (#3)
OFMSW (36% d.w.) (t/a)	16,000	16,000	16,000	16,000
Wastewater sludge (5% d.w.) (t/a)	108,000	108,000	108,000	108,000
Manure (12% d.w.) (t/a)	0	30,000	0	0
Operation temperature (°C)	55	55	55	20
Investment cost ($Cdn)	1,894,000	2,246,000	2,170,000	2,522,000
Operation cost ($Cdn/a)	2,138,000	2,620,000	2,271,000	2,526,000
Dry biogas production (Nm^3/a)[a]	4,149,000	5,691,000	4,149,000	4,149,000
Methane contents (%)	53.3	52.2	53.3	53.3
Net electricity production (kW h/a)	6,924,000	9,614,000	−977,000	−1,513,000
Net heat production (GJ/a)	8,513	14,478	0	0
RNG production (Nm^3/a)	0	0	1,068,000	1,984,000
Total income ($Cdn/a)	759,000	1,058,000	318,000	551,000
Economic payback time (PBT) (a)	3.7	6.8	N.P.[b]	N.P.[b]
Energetic payback time (EPBT) (a)	4.3	3.5	30.1	3.3
GHG reduction (tCO_2eq/a)	988	1305	2362	4261
Digestate liquid phase (m^3/a)	97,000	118,500	97,000	97,000
Digestate solid phase@30% d.w. (t/a)	21,300	25,900	21,300	21,300

[a] N m^3: Gas at normal temperature (0 °C) and pressure (1 atm).
[b] N.P.: Not profitable.

The economic payback times on investment estimated in this study are comparable to previous studies. A 5 year payback time on investment was estimated for an on-farm digester working only with manure in Minnesota; where the climate can be considered relatively similar to the province of Quebec [32]. In fact, the AgStar program in the United States of America reports 3–7 years payback time on investment for digesters in 7000 US farms [33]. A study from Thailand for a digester on a small pig farm reported a range of payback time on investment, between 4 and 11 years, according to the government subsidies and whether or not the H_2S was removed from the biogas [34]. Also, a feasibility study on anaerobic digestion plants in North America concluded that payback time on investment range from 5 to 16 years, averaging 7 years when the biogas energy is produced continuously [35]. In the State of Wisconsin (USA), it was reported that 23 communities have the potential to use anaerobic digestion for biogas co-generation with a payback time on investment less than 8 years. This study also indicates that the municipality of Appleton (Wisconsin) appears to have the lowest payback time with 4.8 years [36].

For the scenarios investigated in this study, the co-generation scenario (#1) has the shortest payback time (3.7 years). The co-digestion scenario (#2) has a payback time of 6.8 years while the RNG scenario (#3) is non profitable (no payback time). Possible adjustments to improve the economic characteristics of the scenarios are presented in the following sections. Note that the payback times for scenarios 1 and 2 were calculated with the marginal cost of electricity (0.10 $Cdn/kW h). If the cost of the electricity was the current acquisition cost in Quebec (0.05 $Cdn/kW h), the payback time for the co-generation scenario (#1) increases to 11.2 years and the co-digestion scenario (#2) becomes non profitable.

4.3. Energy production

The co-digestion scenario (#2) generates 37% more biogas than the co-generation scenario (#1) because of the manure added to the process. This leads to an increase of electricity and heat production from the combined heat and power (CHP) unit; 39% for electricity and 70% for heat. For the renewable natural gas scenario (#3), the digester has to work in psychrophilic condition (20 °C) instead of thermophilic (55 °C), for energetic reasons. It is possible to obtain good yield using psychrophilic conditions and even to reduce pathogens [37–39]. A simulation using MATTEUS showed that for thermophilic conditions, the digester needs 49% of the total biogas for heating through a gas boiler, leading to an EPBT of 30 years. If psychrophilic conditions are selected, the energy required for heating decreases to 11%, leading to an EPBT of four. Those results agree with Berglund's [26], and the psychrophilic alternative is chosen for further considerations. Without a CHP unit, the RNG scenario (#3) consumes much more electricity from the grid. The effect of the addition of a CHP unit is discussed further.

The co-generation scenario (#1) and the co-digestion scenario (#2) imply co-generation with an overall efficiency of 86%, with 36% for electricity. However, the renewable natural gas scenario (#3) produces RNG that contains 100% of the energy available in the original biogas (neglecting gas leaks). Considering the investment in energy and the energy necessary for operation of the equipment, the RNG scenario (#3) has the lowest EPBT, while the co-generation scenario (#1) has the highest.

For the co-generation scenario (#1), the residual heat available for sale after the heating of the process is small, but has an important impact on the payback time on investment. Considering the proximity of the municipal wastewater treatment plant, it is reasonable to assume that all the heat will be used, and the associated costs will be avoided. Without the value of those 8500 GJ of heat, the economic payback time increases to 4.2 years and the EPBT value increases to 5.8 years. For the co-digestion scenario (#2), the PBT and the EPBT increase to 9.5 years and 5 years, respectively.

The RNG scenario (#3) produces 1,984,000 Nm^3 of renewable natural gas in a year. Considering that 65 Nm^3 of methane are required for a bus to travel 100 km [40], there is enough gas for 3,502,000 km of bus travel. Since an average bus for the selected municipality travels around 50,000 km per year, 61 buses can use renewable natural gas instead of diesel. It represents approximately 75% of the total bus fleet of the 150,000 inhabitant municipality. The conversion cost to adjust a bus carbureting from diesel to natural gas is around 5% of the purchasing cost of the bus [41].

4.4. GHG reduction

The RNG scenario (#3) shows the most significant GHG reduction, because all the biogas is used as a replacement to natural gas. In the co-generation scenario (#1) and the co-digestion scenario (#2), the reductions come from the replacement of electricity and of natural gas for heating. As mentioned earlier, the electricity in the province of Quebec comes from hydro-electricity, while it comes mainly from thermal plant in the rest of Canada. Consequently, the average Canadian electricity generates more GHG emission (203.9 tCO_2eq/GW h) than the province of Quebec (18.54 tCO_2eq/GW h). If the electricity was produced from a municipality outside of the province of Quebec but within Canada, the reduction of GHG emission would be more important: the co-generation scenario (#1) would reduce emissions by 2270 tCO_2eq and the co-digestion scenario (#2) by 3086 tCO_2eq.

In scenarios 1 and 2, most of the GHG reduction comes from the valorization of the natural gas for heating. If the surplus heat is not valorized, the reduction decreases to 457 tCO_2eq per year for scenario 1 and to 405 for scenario 2.

The economic calculations were made by assuming no cash value for the GHG reduction also known as carbon credits. However, carbon credits are marketable. A first trade of carbon dioxide equivalent unit was made in June 2008 for 9.50 \$Cdn/tCO_2eq on the Montréal Climate Exchange [42]. The impact on scenario 1 and 2 is negligible. Even with the 40,500 \$Cdn of annual extra income, the RNG scenario (#3) would still not be profitable.

4.5. Management of the process liquid and solid residues

The quantity of wastewater and digestate produced during the treatment of the organic material is directly proportional to the quantity of input organic material digested. Consequently, there will be more liquid waste generated for the co-digestion scenario (#2) than for the co-generation scenario (#1) and the RNG scenario (#3). The liquid waste disposal cost will also have a higher impact for scenario 2. Moreover, in scenario 2, the farmers who provide the manure would still need fertilizing material for their crops. The possibility to use the digestate for agronomic valorization is considerable. However, specific provincial governmental permits will be required for the use of the digestate as fertilizing material for cultures related to human consumption if no aerobic maturation (composting) is included even though studies presented in Section 1.4 showed the advantages of the practise. The following economical comparison provides a preliminary estimate of this option. The basic price of 70 \$Cdn/t is for the composting of the digestate. After composting, the digestate can be used for any type of agronomic valorization. The municipal wastewater plant currently pays 56 \$Cdn/t for the agronomic valorization of 90% of its dehydrated sludge because the sludge cannot be used for cultures related to human consumption and pasture land. Such a decrease for the disposal cost of the digestate decreases the payback time to 2.9 years and makes the co-digestion scenario (#2) more profitable than the co-generation scenario (#1) while promoting agronomic valorization. Another advantage is the shorter distance of the surrounding farms which are on average 11 km away from the anaerobic digestion plant compared to the 50 km distance of the composting site. The extreme case for agronomic valorization where no costs are considered represents a 1 year payback time. The digestate would have to be used for cultures related to human consumption to do the agronomic valorization for free and governmental permits would also be required. The cost of transportation is included in all the scenarios for the disposal of the solid residues.

4.6. Proposed Improvement to the RNG scenario

With the initial conditions specified in this study, the RNG scenario (#3) is not profitable. The selling price of the natural gas has a significant impact on its profitability. The associated results are presented in Section 5. A price of 7.73 \$Cdn/GJ was used for the calculation, which represents the average price for year 2008. Obviously, the minimum price since 2005, 4.49 \$Cdn/GJ leads to an unprofitable process. However, the maximum price for the same period, 12.54 \$Cdn/GJ, leads to a payback time on investment of 9.6 years. The "breakeven point" for this scenario is 8.9 \$Cdn/GJ. Some modifications to the suggested process, can improve the payback time. For example, the replacement of the gas boiler for a CHP unit (CHP alternative) allows the process to be energetically self-sufficient. To respond to the electrical and heating needs of the process, 22% of the biogas is necessary for the co-generator instead of 11% solely for the heating if the electricity is purchased from the grid. The total incomes decrease by 5% with an 8% increase for the investment cost and a 4% decrease for the operation cost. With the CHP unit, the "breakeven point" goes down to 8 \$Cdn/GJ which is closer to the 2008 average price of 7.73 \$Cdn/GJ. However, the energetic payback time increases to 3.9 years, but remains lower than the 4.3 years payback time for the co-generation scenario (#1).

With respect to the natural gas purchasing cost, the addition of a CHP unit to the RNG scenario (#3) is profitable. However, as shown in Fig. 3, the gap between the payback times goes down as the natural gas purchasing cost goes up. When the RNG purchasing cost reaches 14.9 \$Cdn/GJ, a similar payback time is obtained. At higher RNG prices, the boiler alternative becomes slowly more profitable and approaches the payback times of the co-generation scenario (#1) at a price of 17.6 \$Cdn/GJ, while the CHP alternative requires a natural gas purchasing cost of 18 \$Cdn/GJ.

5. Sensitivity analysis

A sensitivity analysis of the parameters most susceptible to change was conducted. Since the order of magnitude from one parameter to another is different, the comparison was made with respect to a 10% fluctuation around a fixed operation point. The operation point was selected to be the value that was initially specified, with the exception of the natural gas purchasing cost. Because it is unprofitable at a price of 7.73 \$Cdn/GJ, the operation point was set to 12.54 \$Cdn/GJ, which corresponds to the maximum price since 2005. Results are shown in Table 4.

The quantity of available organic material has the lowest sensitivity. This means that the analysis of the scenarios presented in this study is applicable to other municipalities with a similar waste management approach.

The most sensitive parameter is the purchasing cost of the natural gas. On top of that, it is the parameter that is the most suscep-

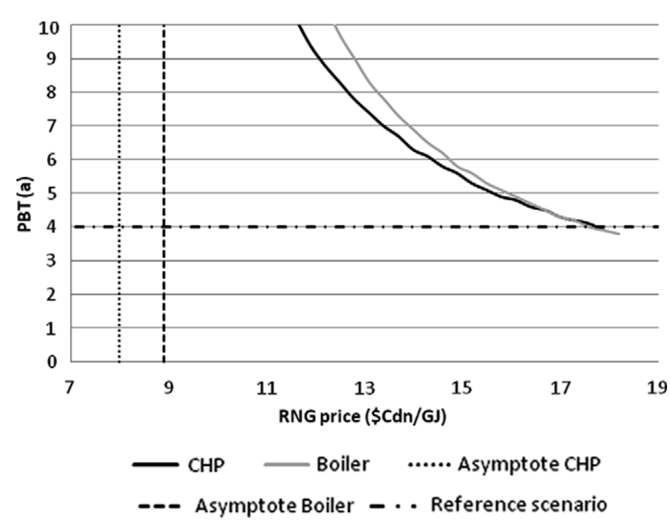

Fig. 3. Effect of the increase of natural gas purchase cost on the payback time on investment for RNG scenario and its CHP unit alternative.

Table 4
Sensitivity analysis on the reference scenario (co-generation #1) and RNG scenario (#3).

Parameters	Sensitivity on the payback time			
	−10% a	Operation point a	+10% a	a/Deviation%
Electricity price	4.2	3.7	3.2	−0.050
Natural gas purchase cost	14.5	9.6	7.2	−0.365
Waste management income	5.8	3.7	2.7	−0.155
Available organic material	3.9	3.7	3.5	−0.020
Investment cost	3.3	3.7	4	0.035
Operation cost	2.6	3.7	6.3	0.185

tible to changes considering the fluctuations of the market [28]. The second most sensitive parameter is the operation cost followed by the waste management income, the electricity price and the investment cost.

6. Conclusions

MATTEUS, an Excel-based spreadsheet and database program that calculates mass and energy balances and developed by Hydro-Quebec, was used to conduct the present study. An integrated waste management process using anaerobic digestion for energetic valorization was the focus of the study. Variations in the process gave different economic, energetic, and environmental performances:

- It is possible for a municipality of 150,000 inhabitants in Quebec, Canada to build an anaerobic digestion plant for its organic wastes with reasonable payback time on investment (3.7 years) using co-generation of heat and electricity, if the selling price of electricity follows the marginal cost (0.10 $Cdn/kW h) instead of the actual acquisition price (0.05 $Cdn/kW h with an 11.2 years payback time). If the residual heat is not used, the payback time increases to 4.2 years. The residual heat can be used for heating in the municipal wastewater treatment plant or surrounding houses during a significant part of the year (the average temperature is below 15 °C for 75% of the year in Quebec).
- The addition of manure for co-digestion increases the biogas production by 37%, but also increases the payback time on investment to 6.8 years. If the residual heat is not used, the payback time increases to 9.5 years. A lower payback time could be obtained with a lower disposal cost of the digestate.
- The production of renewable natural gas scenario has the lowest energetic payback time (3.3 years), and the highest reduction of greenhouse gas emissions (4261 tCO_2eq/a). Cashing the GHG reduction does not have a significant impact on the profitability of the scenarios. To be profitable, the renewable natural gas scenario needs a CHP unit for energetic self-sufficiency and higher natural gas purchasing cost. In this scenario, 22% of the biogas is necessary for the operation of the process (heat and electricity) when using psychrophilic conditions, and increases to 49% for thermophilic conditions. The renewable natural gas produced is sufficient to operate 75% of the bus fleet for the municipality considered in this study.
- The sensitivity analysis of the different parameters with a 10% fluctuation around the operation point in absolute value shows the following influence with the most sensitive to the least sensitive parameter: Natural gas purchasing cost, the operation cost, the waste management income, the electricity price, the investment cost and the available organic material.

The results obtained for the selected municipality could be transferable to other municipalities with similar waste management practices since the sensitivity analysis indicates that the available organic material has the lowest sensitivity on the payback time. The application of the assessment to a municipality with a different population would be worth exploring but is beyond the scope of this study. We believe that the improvement of the technology could also increase the performance of the process as the operation cost is the second most sensitive parameter. Since the composting of the digestate represents the largest component of the operation cost, further development of the agronomic valorization should be considered in order to increase the revenues and reduce the operation cost. The marketing of the digestate could also increase the revenues.

Based on its economic performance, the co-generation scenario (#1) should be selected by the municipality. However, the sensitivity to the purchasing cost of natural gas and the carbon credits, the renewable natural gas scenario (#3) could become economically competitive in the upcoming years in addition to its current positive energetic and environmental performance. The purchasing cost of natural gas was low in 2008. But according to the general trend of the previous years, the purchasing cost of natural gas should increase. The value of the carbon credits for GHG reduction should also increase in the upcoming years according to the proposed policies to be established in Canada.

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