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Energy Production Based on the Chain's Service Area Size in Biomethane Recovery

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Abstract: This article studies the chain's service area size in biomethane recovery from municipal organic waste, with a model created to study the energy generated, which may be applied to determine the optimal allocation of waste and location of the digester. This paper critically addresses the transportation energy losses, which are related to the transport distance and to the technology used for transportation. The collection and transportation of organic waste to the transfer station are studied, with us first considering the use of a 10-ton-payload truck, and the transportation to the digester then studied considering the use of trucks with different payloads: 9, 18 and 27 tons. The results show that depending on the availability of organic waste and the distances to travel, a positive impact may be derived from having many digesters in the area rather than the most common scenario today of a single digester. The results also demonstrate that in less populated regions, the energy differences created by the location of the digester are less significant than those in more populated regions. This paper presents a real-life case study in the province of Québec, Canada. However, this approach can be used in other territories and provides insights for urban planners or policymakers considering the sustainability of waste management in their territory. The novelty of this paper is the study of energy recovery based on the location of the digester and the availability of organic waste in the region. When using only one digestor in the municipality, the total energy losses in the transportation between a transfer station and the digester are between 9.8 and 13%, but when using two digesters in the municipality, the total loss from transportation is reduced to 6.6%.

Keywords: sustainable development; energy balance; biomethane recovery; transportation; collection

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1. Introduction

Waste management in an urban setting is associated with transport and material recovery. In the last decades, the focus of waste management has shifted from final disposal to the development of a circular economic approach based on resource and energy recovery [1].

The chain's service area size, the availability of organic materials and the potential energy recovered from many materials are studied [2], with researchers considering the availability of materials and the territory [3]. The potential for recovering bioenergy from municipal organic waste has gained increasing importance worldwide [4]. There are various physical and chemical processes that may play a role in this context, like adsorption, absorption, cryogenics or membrane separation, and some biological processes are applied for biogas upgrades, though the use of each process is site- and case-specific [5] and may add enzymatic catalysis [6]. Many authors have studied the process of upgrading [7,8], but in this paper, the calculations for producing methane are based on real production values of anaerobic digesters in the province of Québec. It has been proven that the nature of the substrate, the design of the digester and the upgrading process determine the composition of raw biogas [9]. Despite there being many available technologies, anaerobic digestion displays the best environmental and economic performance for methane recovery [10].

Biological treatments degrade biodegradable waste materials via controlled biological processes by living micro-organisms such as bacteria and fungi, which can take place under aerobic or anaerobic conditions [11]. An aerobic composting process needs controlled operating conditions, such as temperature, moisture and oxygen concentration, the product has to be degraded after separation of non-compostable materials [11], it is time-consuming and space is needed for the degradation of organic matter. Figure 1 presents the biomethane recovery system from municipal organic waste. The anaerobic digesters produce biogas, but to be used as biomethane, it must be upgraded through the removal of CO_2 and cleaned of contaminants [12]. This process allows biomethane to be used for different applications, like cooking, domestic heating or as alternative fuel for the shipping and road transport sectors [13]. Biomethane is essentially purified biogas that contains a certain percentage of methane, and it can either be used as fuel for vehicles running on compressed natural gas or injected into the natural gas grid [14].

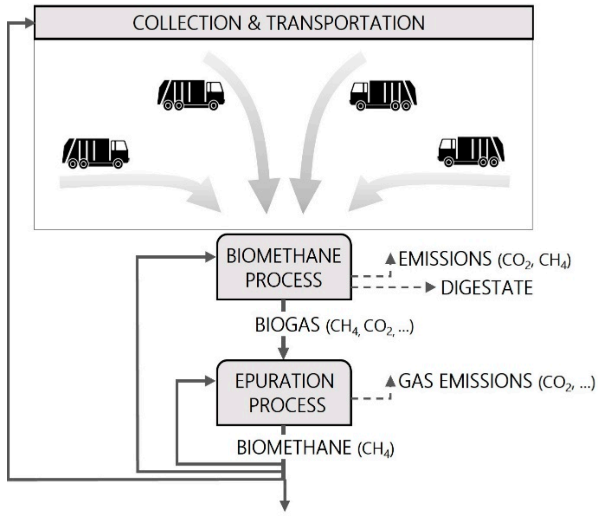

Figure 1. Biomethane recovery system (adapted from Rotunno et al., 2017 [15]).

The anaerobic digestion of municipal organic waste to produce raw biogas involves several process steps: waste pretreatment, digestion and handling of the digestate. The obtained biogas requires additional steps for its commercialization and usage as a valuable product. Biomethane can be obtained using biogas purification systems such as membranes, biofilters and water scrubbers, amongst other technologies [16].

There is a growing interest in sustainability and anaerobic digestion [17], and biogas offers important environmental benefits, like the reduction in greenhouse gas (GHG) emissions. Biogas production in Europe is estimated to output 963 PJ (9.63×10^{17} J), resulting in a 60% GHG reduction [18]. In addition, the global share of biomethane among all fuels is forecasted to rise from 2% today to 27% in 2050 [18]. In 2020, in Canada, emissions reductions were estimated at 8.2 Mt CO_2, a figure that is predicted to increase to 23.6 Mt CO_2 by 2050, accounting for both avoided methane emissions and displaced fossil fuel use [19]. In 2021, Canada had nearly 300 biogas and renewable natural gas projects, processing 2 million tons of manure, crop residues and off-farm organic material annually and generating over 20 PJ of energy from agricultural and industrial digesters, municipal and industrial treatment plants and landfills. The industry for renewable natural gas production is projected to quadruple in the coming years [19].

This study creates a model based on the energy balance of the biomethane recovery process to study the impact of the territorial aspect of the gains and losses of energy on the different steps of the process. To study the effects of different densities and different areas of the city, the territory's parameters are included in this study. It focuses on developing a systemic method for locating biomethane recovery facilities based on the energy balance of the biomethane recovery chain. This recovered energy can substitute fossil energy and can be used for many industrial and household applications; in this case, the comparison is performed considering the GHG emissions that this represents. The economic aspect of the waste management process is not studied; instead, we offer an energetic evaluation of the process. This model is based on the energy balance of the waste management process, integrating the technological challenges of biomethane recovery and the different levels of transportation. The goal of the model is to compare the energy availability of different regions at a large scale; for more accurate results, other computational tools are available, though increasing the cost of the assessment.

According to the principle of economies of scale, many municipalities attempt to mutualize their waste to benefit from the economies of scale [20]. When considering the economic impact of waste collection, the environmental impact of the transport structure and lack of adaptability to the territory are the main drawbacks [21] of the application of this principle in waste management of materials. Economic decoupling refers to a society that grows without increasing the pressure on the environment. With that in mind, territorial characteristics and details of recovery facilities must be considered to move toward a greener society that is aware of the environmental challenges presented by waste materials. Figure 2 presents the biomethane recovery process from the collection of organic waste to the transfer station and then transport to the recovery facility.

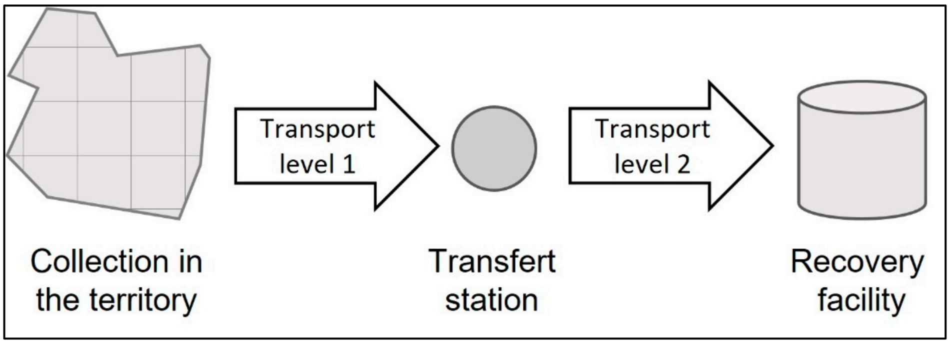

Figure 2. Biomethane recovery process.

As can be seen in Figure 2, the territorial aspect plays a double role in the recovery process: on the one hand, transport level 1, which represents the collection and transportation of the organic waste in the territory to the transfer station, and, on the other hand, transportation level 2, which represents the transportation of the organic waste from the territory to the recovery facility. The waste management system could benefit from the use of different transportation methods accounting for the territorial morphology and population density [22]. It has been established that waste collection and transportation are related to the parameters of waste generation in the territory, so the transport structures need to be adjusted to the city's structures and population distribution [23].

To reduce the noise and traffic inconveniences created by waste management in an urban setting, curbside waste collection should be replaced. Some authors tackled the location and allocation of waste management based on the spatial interaction of a model in a constrained environment, showing the impact of transport in the production chain of biomethane [24], but the energy recovered from the biomethane recovery process was neglected.

The allocation of organic waste and the distribution of resources in the supply chain for anaerobic digesters were studied to lower the total cost of supplying materials and study the biomethane production system [25]. Computational tools have been used to determine the optimal digester location [26], and in some cases, geographic information systems (GIS) were used to study the spatial distribution of waste management facilities like the transfer station [21].

The novelty of this paper is that the energy spent on collection and transportation from the household to the digester is included in our study, to shed light on the energy efficiency of the global chain of biomethane recovery. Many aspects of the waste management process are considered for a single territory, to study the energy impact of the location of the recovery facility. The chain's area service size, the allocation of municipal waste, and the number and locations of digesters are analyzed to study the losses of the biomethane recovery process. This model integrates the supply chain of biomethane recovery with the location of the digester and the characteristics of the territory.

2. Materials and Methods

The model developed is based on a systemic approach that considers the gains and losses of energy of the biomethane recovery system. The global energy of the biomethane recovery system includes the energy spent on collection and transport level 1 of municipal organic waste, the energy spent on transport level 2 of the municipal organic waste and the energy spent on the biological treatment and the energy embedded in the biogas. The data of different anaerobic digesters operated in real conditions in the province of Québec are used to calculate the volume of biomethane produced [27]. The simplicity of this approach allows for comparing different scenarios considering the location of the digester without the need for costly computational tools; the only data needed are the urban and material densities and the data associated with the collection and transportation method.

The developed model simplifies data analyses and can be coupled with a GIS system used in the waste management field [28]. The waste management computer software can process vast data of the travelled distances in a short period of time, so it can create many scenarios for the planification and associated energy recovery performances, which can be compared. That makes it possible to anticipate consequences of the changes in the territory or to identify the zones where the model generates the gain in energy recovery. It is also possible to integrate a dynamic study, for a temporal picture of the territory's evolution.

The energy recovery and the impact of the location of the recovery facility are studied and different scenarios are created. First, the losses of collection and transport level 1 and level 2 are calculated when there is only one recovery facility per region, which is considered the centralized scenario. In scenario A, the municipal organic material is sent to the digester in the MAS municipality. Then, the impact of the location of the digester is analyzed when there is one recovery facility per municipality, which is considered the scenario B or decentralized. This situation represents the maximum energy that can be recovered when there is no transport level 2 in the territory. Scenario C is the centralized scenario, but the municipal organic waste is sent to a digester situated in the ROS municipality. To study the energy losses of the centralized scenario and the impact of the location of the digester in the territory, a new scenario D is created. In scenario D, there are multiple digesters in the region and the municipal organic waste is sent to the closest one. These are presented in Table 1.

Table 1. Description of different scenarios.

Scenario	Description
A	Centralized: the organic waste is sent to the digester in the MAS municipality
B	Decentralized: the organic waste is sent to the digester in the centre of each municipality
C	Centralized: the organic waste is sent to the digester in the ROS municipality
D	Centralized to multiple digesters: the organic waste is sent to the digester in the MAS or ROS municipalities

This systemic model is based on the relation between the territory dimension and the availability of municipal organic waste generated and collected. Figure 3 presents the different levels of transport involved in the global process of organic waste collection for different municipalities, where different municipalities are represented by different colours.

$$Energy\ available = Energy_{generation\ CH4} - Energy_{collection} - Energy_{transport\ level\ 1} - Energy_{\ traansport\ level\ 2} \quad (1)$$

The gain in energy obtained by the production of biomethane is presented in Equation (2) at it represents the energy embedded in the biomethane.

$$Energy_{\ generation\ CH4} = LHV_{CH4} \times V_{CH4} \quad (2)$$

where

$Energy_{\ generation\ CH4}$: embedded energy of biomethane (MJ/period);

LHV_{CH4}: 36 MJ/Nm^3 [29];

V_{CH4}: volume of biomethane produced (Nm^3/period);

LHV_{CH4}: lower heating value of biomethane.

This considers the energy value of biomethane after the upgrade from biogas; the product can be used without the need for any changes or transformations, and it can be used in natural gas vehicles.

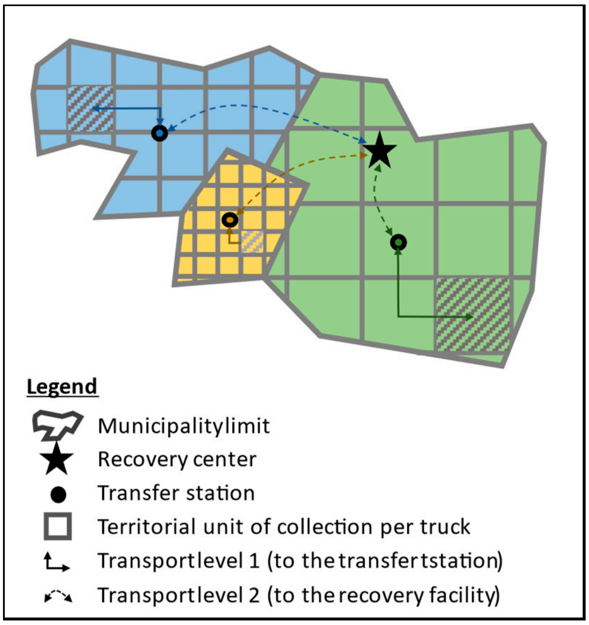

Figure 3. Different levels of collection and transport.

2.1. Energy Losses of Collection and Transport Level 1

To calculate the distances and therefore the energy spent during collection and transport, this article presents a model where the area is divided into smaller squares, where each small square represents the area of collection of one truck. The breakdown of the area is represented by a symmetrical grid, and the anaerobic digester is located at the centre of the territory. This approach allows for calculating the total collected organic waste using the variable of the dimension of the territory.

To calculate the distance travelled by the truck in the collection and transport level 1, two different configuration types are presented in Figure 4.

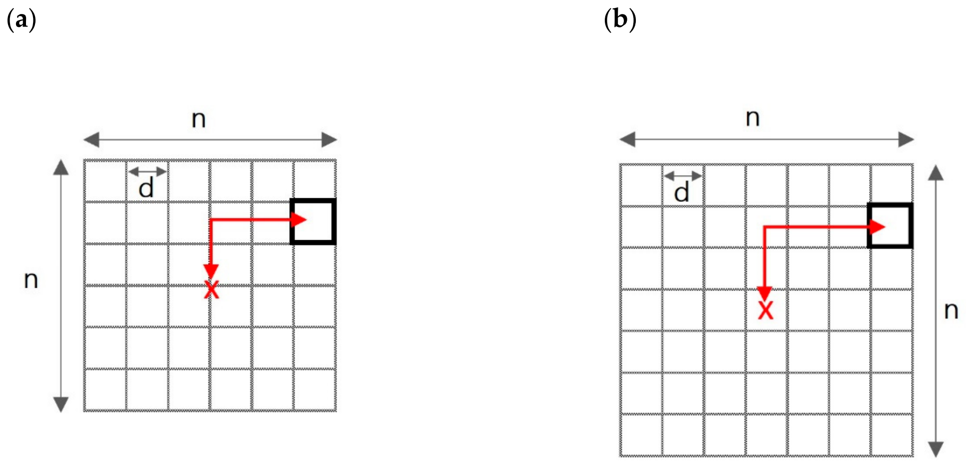

Figure 4. Configuration breakdown grid type ($n \times n$) centred on the recovery facility with the cell unit of collection represented by d2 dimensions for both configuration types: (**a**) even or (**b**) uneven number of units in the grid to travel from the unit cell to the digester.

Where

d is the dimension of each cell unit.

The model is based on a cycle of collection or a defined period, so the energy balance and all the parameters are based on that period, which can be adapted to the territorial situation. The equations that define the territorial breakdown are presented in Equations (3) and (4).

$$n_{travel} = \frac{Waste_{\ total}}{C_{truck}} \quad (3)$$

where

n_{travel}: number of journeys or collection cycles needed to collect the organic waste of the area (unit/period);

$Waste_{total}$: total collected waste of the area (t/period);

C_{truck}: payload of the truck used for the collection and transportation (t/truck).

$$n = \sqrt{n_{travel}} \quad (4)$$

where

n is the number of unit cells required to cover the entire area, and the cell unit has an area of d^2.

The area of each unit cell is calculated considering the quantity of municipal organic waste available and the density of the population in the territory, and it is presented in (5).

$$d^2 = \frac{C_{truck}}{w_{hab} \times d_{pop}} \times 1000 \quad (5)$$

where

d^2: area of each unit cell (km^2);

w_{hab}: quantity of municipal organic waste generated (kg/people/period);

d_{pop}: density (people/km^2).

The dimensions of each cell unit of the grid are represented in (6).

$$d = \sqrt{\frac{C_{truck}}{w_{hab} \times d_{pop}} \times 1000} \quad (6)$$

The distance for the collection of organic waste considers, on the one hand, the capacity of the truck, and, on the other hand, the availability of organic waste and the density of the population and roads in the area. The dimension of the cell is presented in Equation (6), and the distance of collection per cell unit dc_{truck} is presented in Equation (7).

$$dc_{truck} = \frac{C_{truck}}{w_{hab}} \times \frac{d_{road}}{d_{pop}} \times 1000 \quad (7)$$

where

dc_{truck}: distance of collection per cell unit (km/period);

d_{road}: density of routes (km/km^2).

Then, the total distance of collection for each scenario is calculated by multiplying the distance of each cell unit dc_{truck} by the number of cells considered $(n \times n)$. This total distance of collection for each scenario DC_{total} is presented in Equation (8).

$$DC_{total} = dc_{truck} \times (n \times n) \quad (8)$$

where

DC_{total}: total distance of collection (km/period).

This approach allows for relating the dimensions of the territory to the energy spent not only on municipal organic waste management but also on the biomethane recovery system. Considering the dimensions of the cell as a variable, this model calculates the distance of collection and transport level 1 and the availability of municipal organic waste to be transformed in biomethane.

The total distance travelled one way on transport level 1 represents the total distance connecting the centre of all the unit cells and the centre of the area; this distance is represented in Equations (9) and (10). In this model, the recovery facility is located in the middle of the area.

$$\text{even}: \ DT_{tot.1way} = \left(\left(\frac{n}{2}\right) \times n^2\right) \times d \quad (9)$$

$$\text{uneven}: \ DT_{tot.1way} = \left(\left(\frac{n}{2}\right) \times (n-1) \times (n+1)\right) \times d \quad (10)$$

where

$DT_{tot.1way}$ is the total distance travelled one way from the centre of each unit cell to the recovery facility (km/period).

The total distance travelled to go pick up the waste and then come back is represented in Equations (11) and (12).

$$\text{even}: \ DT_{tot,2ways} = n^3 \times d \quad (11)$$

$$\text{uneven}: \ DT_{tot,2ways} = (n \times (n-1) \times (n+1)) \times d \quad (12)$$

where

$DT_{tot,\ 2ways}$: total distance travelled from the centre of each unit cell to the centre of the grid or the recovery facility for the reference situation (km/period).

In the simplified systemic approach developed in this paper, the digester is situated in the centre of a grid-type structure, and this allows for calculating the total energy consumed for transport level 1 using $DT_{tot.2way}$ presented in (11) and (12) and $DC_{tot.2way}$ presented in (8). The total energy consumed for collection and transport level 1 includes the embedded energy of the fuel used for the truck, in this case, the fossil fuel consumption to produce 1 litre of diesel. These energies are presented in (13) and (14).

$$E_C = (FC_C \times DC_{total}) \times E_{diesel} \quad (13)$$

$$E_T = \left(FC_{T,\,i} \times DT_{tot,2way}\right) \times E_{diesel} \quad (14)$$

where

FC_C: fuel consumption of trucks based on collection modes (L/km);

$FC_{T,i}$: fuel consumption of trucks based on transportation modes (L/km);

E_{diesel}: embedded energy in 1 litre of diesel (42.6 MJ/L [30]).

Certain articles [31] include the tortuosity of the territory (τ), which represents the ratio of the road length and the length of the arc connecting two adjacent nodes of the grid to account for the lack of linearity of some roads. But that factor is not included in this paper, because the actual values of population density and roads are used; these values are based on the data of the province of Québec [32].

The values used in (13) and (14) are a fuel consumption in collection (FC_C) of 0.84 L/km and fuel consumption in transportation ($FC_{T,\,i}$) for transport level 1 of 0.61 L/km [33].

2.2. Energy Losses of Transport Level 2

The maximum energy can be recovered when there is no transport level 2 in the territory and the recovery facility is located in the municipality.

The second level of transportation of organic waste from the transfer centre to the recovery facility is studied considering transportation using trucks with different payloads. The payloads studied are 9, 18 and 27 tons, and the fuel consumptions $FC_{T,i}$ for transport level 2 are $FC_{T,9} = 0.25$ L/km, $FC_{T,18} = 0.28$ L/km and $FC_{T,27} = 0.30$ L/km [34].

In the simplified systemic approach developed, the digester is situated in the capital of the municipality, which allows for calculating the total energy consumed using this value as the distance presented in (11). The energy consumed for transportation level 2 is presented in Equation (15).

$$E_{transport\ level\ 2} = \left(FC_{T,i} \times DT_{level2,\ 2\ ways}\right) \times E_{diesel} \quad (15)$$

where

$E_{transport\ level\ 2}$ is the energy spent on transportation level 2 (MJ/period);

$DT_{level2,\ 2\ ways}$ represents the distance to the digester back and forth (km).

In this paper, the tortuosity factor (τ) is not included because the actual values of population density and roads are used; these values are based on data of the province of Québec [32].

2.3. Location of the Recovery Facility

To study the impact of the distance from the territory to the digester, the digester is situated in the centre of each of the municipalities of the region, to eliminate losses due to transport level 2.

To analyze the impact of the location of the recovery facility, two scenarios are studied. Scenario A includes only one recovery facility in the region, which represents the centralized scenario. Then, scenario B considers one recovery facility at the centre of each municipality, which is the decentralized scenario, where the energy losses of transport level 2 are avoided. The methodology used for this study is presented in Figure 5.

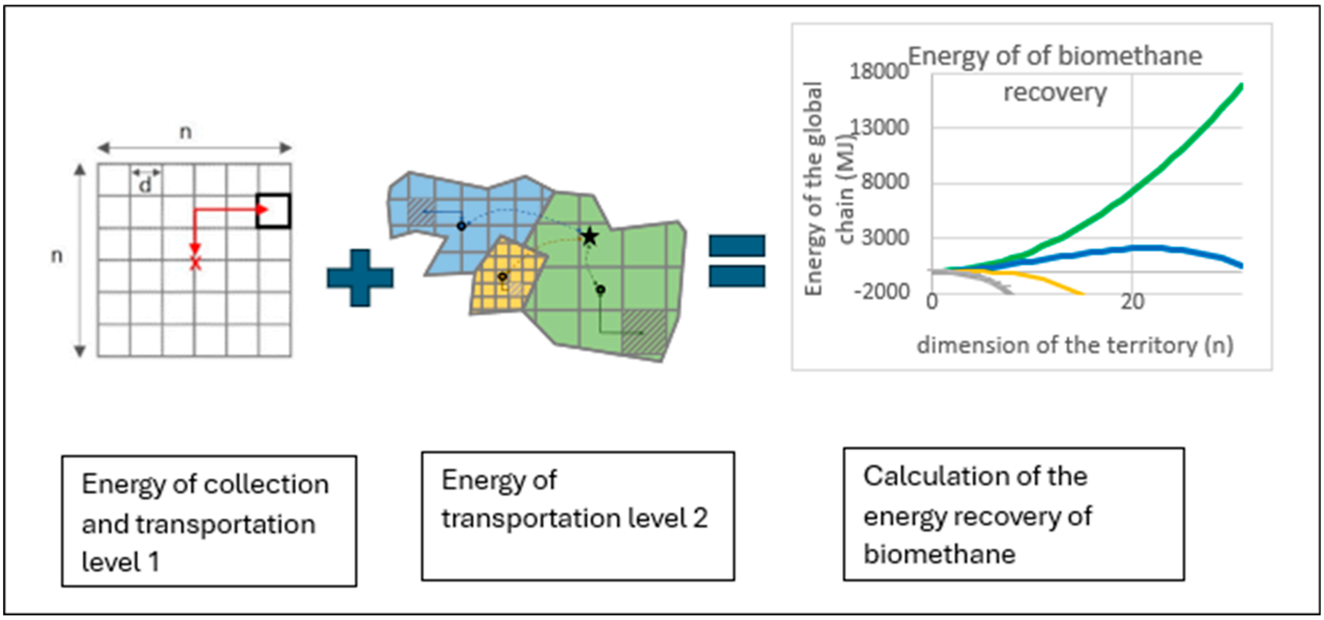

Figure 5. Methodology used for the calculations of the global chain of methane recovery.

2.4. Description of the Study Case: Montérégie, Québec, Canada

The province of Québec in Canada is divided in different administrative regions, and one of them is the Montérégie. It covers a territory of 8764 km^2 with a population of 1,433,085 people, and it is divided in 13 municipalities. Montérégie is one of the southern provinces, and it presents a large array of population densities. Figure 6 presents the geography of the Montérégie region in Québec.

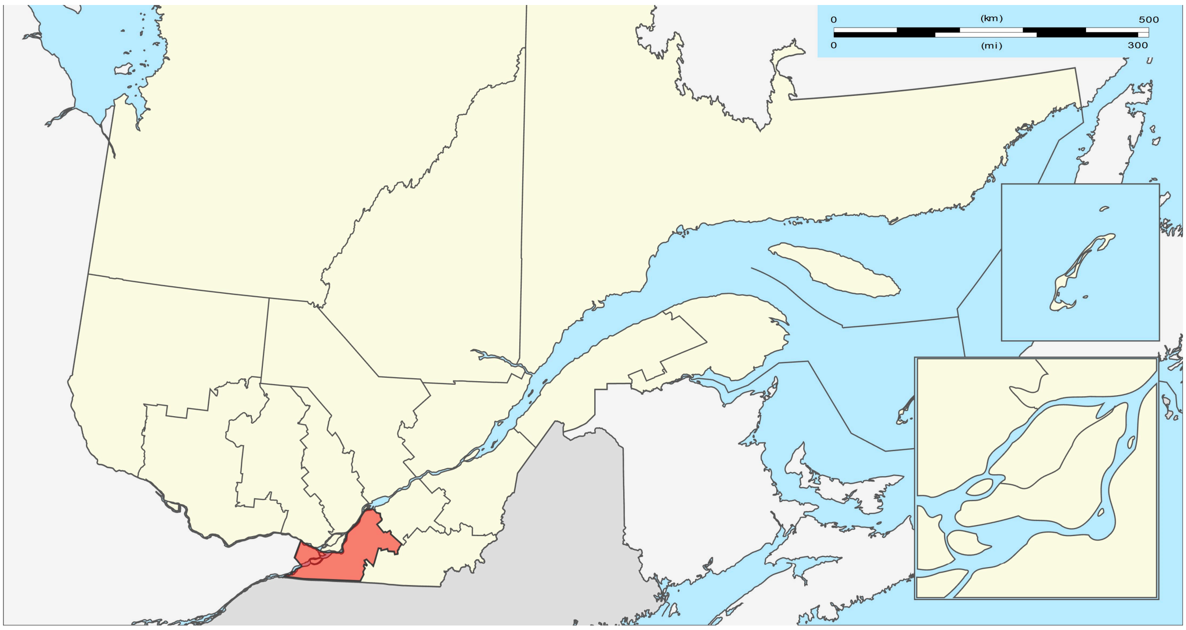

Figure 6. Location of the Montérégie region (in red) in the province of Québec, Canada (data from [35]).

The linear density of the population, which is the number of people per unit of length, as defined in (16); this represents the availability of municipal organic waste per unit of length in the territory.

$$Linear\ density\ of\ population = \frac{d_{pop}}{d_{road}} \quad (16)$$

The data of the province of Québec, Canada [27] are used to study the biomethane recovery process. There are 12 projects of biomethane recovery and composting approved in the province of Québec under the government program to process organic material. Only data from those projects are available on the government database [27], and only five of these projects produce biomethane from municipal solid organic waste, without considering composting projects or ones processing municipal slurry. The data of different anaerobic digesters for biomethane recovery operated in real conditions in the province of Québec are used to calculate the volume of biomethane produced, which is shown in Figure 7.

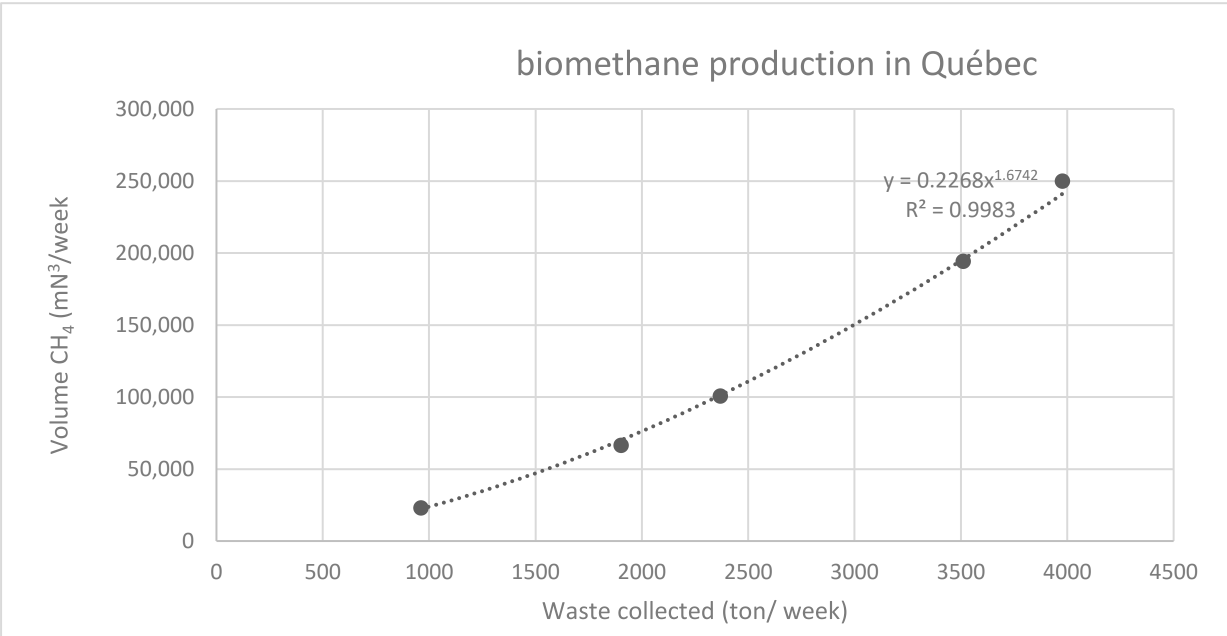

Figure 7. Production capacity of biomethanization facilities in Quebec, Canada. Data collected from [27].

In the case of collection and transportation level 1, the payload of the truck is 10 tons. In all cases, the collection cycle considered is one week. In the case of transportation level 2, the payloads of the trucks C_{truck} considered are 9, 18 and 27 tons.

3. Results

Herein, we study the energy of the chain's service area size in biomethane recovery and the impact of changes in the location of the digester on the energetic evolution. A systemic approach based on the energy balance of the process is used: first, the efficiency of the digester is calculated for scenario A where only one digester is available in the region; in scenario A, the energy losses of collection and transport level 1 and level 2 are calculated. Then, the efficiency of the digester is calculated for scenario B, where a digester is situated in each municipality, and there, the energy losses of collection and transport level 1 are the only losses to be considered. Finally, this approach is used to study the impact of the location of the digester and the use of two different digesters in the same region.

The distance of collection and transportation in the area is calculated when the collection truck has a payload of 10 tons; this distance depends on the population and road density of the territory. The territorial data, extracted from [36], are presented in Table 2.

Table 2. Municipalities and density in the administrative region of Montérégie in Québec, Canada (data extracted from [37]).

Municipality	Population (People)	Area (km^2)	Road Network (km)	Density (People/km^2)	Road Density (km/km^2)	Linear Population Density (People/km)
Acton (ACT)	15,965	579	440	28	0.76	36.3
Beauharnois-Salaberry (BSA)	67,899	468	720	145	1.54	94.2
Haut Richelieu (Le) (HRI)	122,526	936	1399	131	1.49	87.6
Haut Saint Laurent (Le) (HSL)	22,200	1157	988	19	0.85	22.5
Jardins de Napierville (Les) (JNA)	31,295	802	599	39	0.75	52.3
Longueuil (agglomération de) (LON)	434,711	282	1963	1542	6.96	221
Maskoutains (Les) (MAS)	89,575	1303	1158	69	0.89	77.4
Margueritte-D'Youveille (MYO)	80,742	348	600	232	1.72	135
Pierre-De Saurel (PDS)	51,800	594	679	87	1.14	76.3
Roussillon (ROS)	184,980	372	1120	497	3.01	165
Rouville (ROV)	37,680	482	487	78	1.01	77.3
Vallée du Richelieu (La) (VRI)	132,315	587	1070	225	1.82	124
Vaudreuil-Soulanges (VSO)	161,397	854	1518	189	1.78	106

The results in Table 2 show that the dimensions of the cell and the population density of the municipality are related with the linear density, which means that when an area has bigger dimensions, it also has a greater linear density. These data are used for the calculations of the energy spent in the transportation process to create the energy recovery model.

3.1. Losses of Energy Depending on the Different Levels of Transport

The energy losses of collection and transport levels 1 and 2 are calculated for the different municipalities and different payloads. Figure 8 shows the energy lost in collection and transportation level 1 and level 2 for scenario A, with only one digester in the region, which is situated in the municipality of MAS.

The results in Figure 8 show that the energy losses of transport level 2 diminish when transporting municipal organic waste with a truck with a bigger payload. Therefore, the percentage of energy losses for transport level 2 is calculated when using a tuck with a 27-ton payload. With the data of the energy spent in transportation in level 1 and in level 2, the energy recovery model is built for the comparison of the energy recovered for different digester locations.

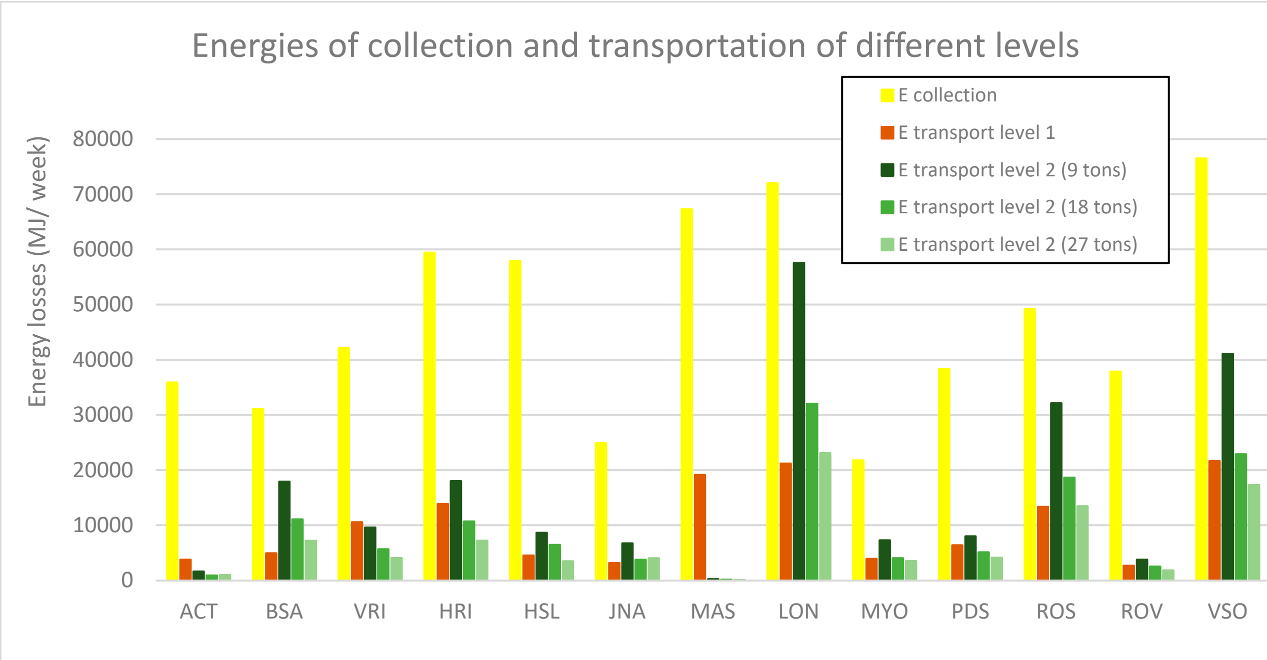

Figure 8. Energies of collection and transportation level 1 and level 2 for scenario A.

3.2. Comparison of Different Scenarios and Digester Locations

The results in Table 3 show the energy of the recovery process and the percentage of energy losses for each municipality when considering scenarios A and B. Scenario A represents the centralized scenario, which includes the energy losses of collection and transport level 1 and level 2; scenario B represents the decentralized scenario, which includes a digester in each municipality, and in that way, only the energy losses of collection and transport level 1 are considered.

Table 3. Energy losses of scenarios A and B.

Municipality	**Waste**	**Energy**			
(code)	(t/week)	Potential (MJ/week)	Collect (MJ/week)	Transport 1 (MJ/week)	Transport 2 (MJ/week)
			(% of potential)	(% of potential)	(% of potential)
				Recovery Sc.B (MJ/week)	Recovery Sc.A (MJ/week)
				(% of potential)	(% of potential)
scenarios		A (centralised) B (decentralised)	From the territory to MAS Intra territory		
Acton (ACT)	17.6	4244	35,878 >100%	3775 89.0%	983 23.2%
				−35,409 <0%	−36,392 <0%
Beauharnois-Sallaberry (BSA)	74.7	16,496	31,067	4937	7182
			>100%	29.92%	43.5%
				−19,507 <0%	−26,689 <0%

Table 3. *Cont.*

Municipality	Waste	Energy			
Haut Richelieu (Le) (HRI)	135	43,225	59,422	13,857	7220
			>100%	32.1%	16.7%
				−30,055 <0%	−37,275 <0%
Haut Saint-Laurent (Le) (HSL)	24.4	4244	57,937	4525	3471
			>100%	>100%	81.8%
				−58,219 <0%	−61,690 <0%
Jardins de Napierville (Les) (JNA)	34.4	4244	24,898 >100%	3174 74.8%	4043 95.3%
				−23,828 <0%	−27,871 <0%
Longueil (Agglom. de) (LON)	478	281,526	71,984 25.6%	21,200 7.53%	23,074 8.20%
				188,342 66.9%	165,268 58.7%
Maskoutains (Les) (MAS)	98.5	43,225	67,265	19’122	101
			>100%	44.2%	0.02%
				−43,162 <0%	−43,264 <0%
Marguerite-D’Youville (MYO)	88.8	16,496	21,761 >100%	3907 23.7%	3496 21.2%
				−9172 <0%	−12,668 <0%
Pierre-De Saurel (PDS)	57.0	16,496	38,359	6366	4127
			>100%	38.6%	25.0%
				−28,229 <0%	−32,356 <0%
Roussillon (ROS)	203	91,248	49,219	13,333	13,437
			53.9%	14.6%	14.7%
				28,696 31.4%	15,259 16.7%
Rouville (ROV)	41.4	16,496	37,860 >100%	6727 40.8%	1819 11.0%
				−28,091 <0%	−29,910 <0%
Vallée du Richelieu (La) (VRI)	146	43,225	42,088 97.4%	10,562 24.4%	4074 9.42%
				−9426 <0%	−13,499 <0%
Vaudreuil-Soulange (VSO)	178	91,248	76,488 83.8%	21,623 23.7%	17,290 19.0%
				−6862 <0%	−24,153 <0%

The results in Table 3 show that the municipalities with a greater availability of municipal organic waste and a big territory have a bigger percentage of losses from collection and transport level 1, and, in these cases, to diminish the energy losses, the option of having multiple digesters in the municipality can be considered.

In the cases of bigger municipalities with a higher availability of organic material, where the percentage of energy losses from collection and transport level 2 are important, the use of a digester in a nearby municipality should be considered.

There are two different situations to consider when allocating organic municipal waste facilities in order to diminish the energy losses of transport level 1 or level 2. Here, a comprise should be considered between the proximity of the municipality to the transfer station and that to the digester.

3.3. Allocation of Municipal Organic Waste

To diminish the energy losses of transport level 2, a new scenario is created. Scenario C represents the case where a second digester is located in the municipality of ROS, which represents a centralized scenario where organic waste is sent to the ROS digester. Then, scenario D is created, where organic waste is sent to the digester that is closer to each municipality's transfer center; this represents the mix between scenarios A and C. Figure 9 shows the energy losses for transportation level 2 when the digesters are located in different municipalities.

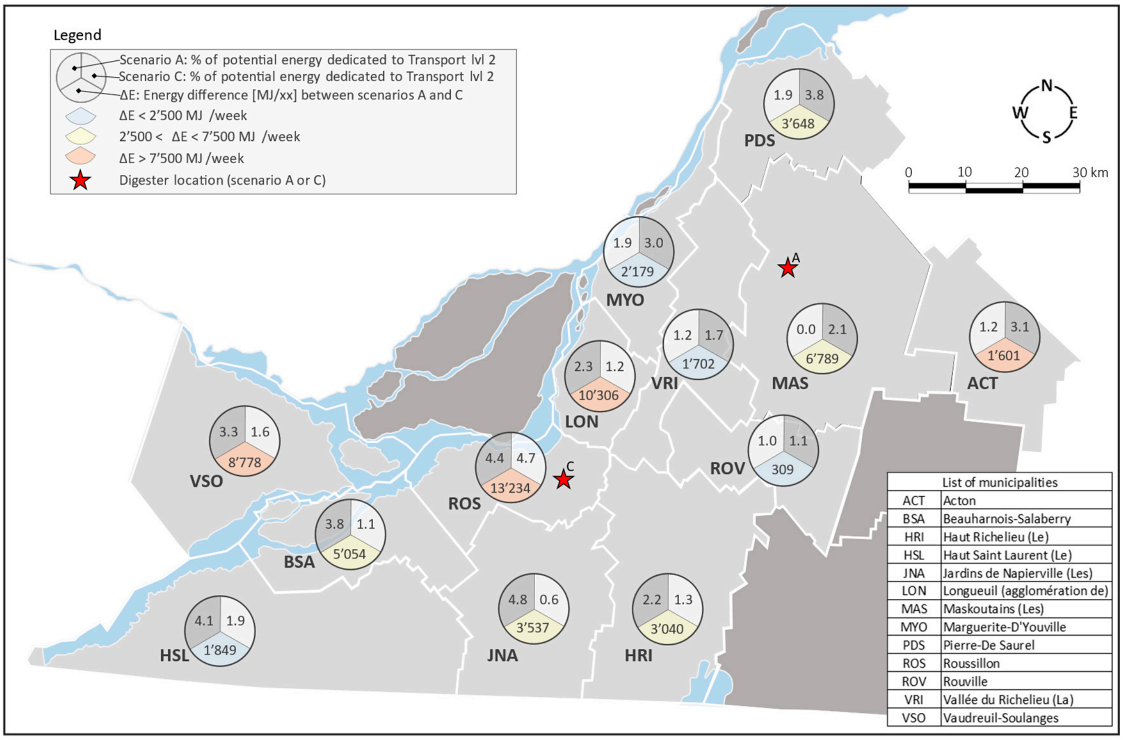

Figure 9. Study of allocation of organic waste and locations of the digesters in the Montérégie region.

The difference in energy losses between scenarios is also shown in Table 4; when this difference is small, there is not a big impact in terms of changing the digester to which the organic waste is transported. In those cases, there is no big impact depending on which of the digesters is used, and municipal organic waste can be rerouted with little energy impact. Additionally, the results in Table 4 show that there is a relationship between the availability of organic waste and the difference in energy losses of transportation level 2 between scenarios. The impact of the difference in the location of the digester on a municipality increases with the availability of organic municipal waste in the municipality.

Table 4. Results of energy losses of transport level 2 for scenarios A, C and D.

Parameters	Energy		
	Transport 2 (MJ) (% of Potential)		
	scenario A centralised to MAS	scenario C centralised to ROS	scenario D mixed MAS and ROS
Total losses transp level 2 (MJ/week) % of potential	90,317 13.4%	60,117 8.94%	44,519 6.62%
Fuel consumption (l/week)	2120	1411	1045
GHG emissions (t CO_2/year)	298	198	147

The total energy losses of transport level 2 for all scenarios are presented in Table 4.

The results in Table 4 show that the location of the recovery facility influences the energy losses of the process of energy recovery. The change in the digester from MAS to ROS for the centralised scenario with one digester represents 0.67% of the potential energy benefit, but when considering scenario D, the percentage of energy losses represent 49% of those in scenario B and 72% of those in scenario C. The fuel consumption of transport level 2 is calculated for each of these scenarios considering the embedded energy in 1 litre of diesel (42.6 MJ/L; [30]), and the GHG emissions are considered as 2.7 $kgCO_2$ per litre of diesel consumed [38]. Considering the fuel consumption and the GHG emissions per year, the economic and environmental costs of the change in the digester location can be calculated.

When considering a multiple-digester situation in the region, there is a compromise to be made between the energy losses and the investments required in order to have more than one digester per municipality, meet the cost of the industrial infrastructure in the area, and overcome disturbance of the transport.

4. Discussion

The analysis of energy production based on the chain's service area size in biomethane recovery shows that the energy recovery process is beneficial for a territory with a high population density, but distance level 2 must be considered. The energy spent on collection and transport level 1 depends on the distance travelled, population density, route density, and size of the municipality, and also on the number of trucks needed to transport the municipal organic waste available. There are two different situations to consider when allocating organic municipal waste facilities to diminish the energy losses of transport level 1 or level 2. Here, a compromise is required between the proximity of the municipality to the transfer station and that to the digester.

In the case of municipalities with higher energy losses in collection and transport level 1, the option can be considered to add another digester in the municipality, to diminish the energy losses of collection and transport level 1. In the cases of bigger municipalities with a higher availability of organic material, where the percentage of energy losses of collection and transport level 2 is important, the use of a digester in a nearby municipality should be considered. In less dense municipalities, with less organic waste available, digester location changes have a small impact on the energy of the chain's service area size in biomethane recovery. Having the digester closer to the municipality benefits denser municipalities with a greater availability of municipal organic waste.

It is a difficult task to find reliable information about the recovered energy potential, because it depends on the raw material, the territorial characteristics and the geographical situation. There are so many different pathways for methane recovery that it is not easy to calculate the exact amount of energy recovered. The calculation of the different transportation methods depends also on different conditions of the geographical territory, the quality of the roads and the style of driving.

This research considers the technological aspects of the waste management process, and future research on economic aspects of changes in the location of the biomethane recovery facilities and the transport structure should be conducted. Nonetheless, energetic analysis without including the economic aspect allows for identifying the economic cost of an environmental improvement and thus making an enlightened decision. The importance of this approach was demonstrated using the data of the Montérégie region in Québec and using plausible transportation methods. However, payloads, transportation methods and recovery technologies can be changed to suit other materials, cities or environments. Many countries have developed new technologies for smaller digesters, which can be installed [39] without compromising the efficiency of biomethane recovery. Even if the technology is available in biomethane recovery to install smaller digesters, encouraging social acceptance of the anaerobic digester is a difficult step for many territories [40].

In this case, the created conceptual model allows the planification of waste management throughout the territory. This model simplifies data analysis and can be adapted to many scales of the territory: for instance, at a provincial scale, the model can be used to gain a general picture and to compare the performances of different municipalities, while at a neighbourhood scale, being exact becomes more important, so a GIS system can be integrated.

The configuration of transport structure and digester should be chosen considering the characteristics of the territory, thus finding the compromise between many aspects, like sustainability, environmental criteria, the urgency of transportation, economic performance and energy efficiency, for the specific territory.

The developed approach studies the energy of the chain's service area and the area in size of biomethane recovery, the energy consumption in the waste management process, and the energy recovery, which is linked to energy policies to promote sustainable development, and this aligns with goal 7 of the United Nations Agenda for Sustainable Development [41]. The study of energy consumption in the collection of materials in an urban setting and the generation of biomethane promotes the production of clean energy in an affordable manner [42]; at the same time, this approach encourages biomethane recovery, which has been proven to represent a key factor for development and innovation [43]. The developed model studies the generation of waste in the territory and encourages the recovery of materials, which are necessary to fight against overconsumption and the overexploitation of natural resources, aligning with goal 12 of the United Nations Agenda for Sustainable Development [44]. The recovery process of biomethane from organic waste encourages the production of clean energy and the control of pollutants in the environment [45], moving toward independence from the use of fossil fuels.

5. Conclusions

This article examines the impact of the location of the digester in different municipalities in the Montérégie region, Canada, considering the characteristics of the territory. This highlights the fact that the size of the territory impacts the energy losses of collection and transportation to the transfer station, and the distance between the transfer station and the digester plays a key role in the energy losses of the chain of recovery.

So, municipal officers should consider the location of the transfer station and the allocation of organic materials when designing and planning the waste management process in order to study the energetic benefits of the global chain of methane recovery. By the same token, the impact of noise, traffic, and economic investment in the area should also be evaluated in guiding the location of the digester.

Future work on this topic should add GIS to assist in the calculations and accuracy of data on the distance travelled; this is particularly relevant when considering a smaller territory. Different synergies and recovery processes can be studied for the same territory, and the potential of industrial symbiosis to improve material recovery. Another topic to further investigate is the use different methods of transportation, including a unique vehicle for the collection or transportation of different materials. The use of a greener and smaller transportation method for collection should also be studied to decrease the energy spent on collection and transportation. Economic analysis of all these parameters should also be performed in future work.

The conceptual approach used for the calculations of energy spent in transport can be generalized to the rest of the territory. Other methodologies using computational tools may be more precise, but the methodology used in this article allows for comparing different scenarios. The waste management process is complex, and the specificity of each territory could profit from in-depth study.

It has been demonstrated that a compromise between the size of the territory, the distance from the territory to the recovery facility and the allocated quantity of organic waste is crucial to improve the energy recovery of the process.

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