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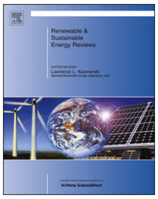

The potential of biogas production in Uruguay

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ABSTRACT

Based on a national survey of agricultural and agro-industrial production, the amount of organic waste that can be treated by anaerobic digestion was estimated. Assuming the actual possibilities of waste collection and considering the potential of methanation, the potential for methane generation from solid and liquid wastes in Uruguay was calculated. The results indicate that, in the current situation, energy generation equivalent to 1.3–2.1% of total primary energy could be achieved. Despite its low incidence in the energy matrix, biogas generation from wastes must be viewed from the standpoint of sustainable development. While generating renewable energy, biogas meets requirements related to waste treatment and minimises environmental impacts. Some industries, such as slaughterhouses and the dairy and bioethanol industries are noted for their contribution and the feasibility of implementing treatment systems for biogas generation in factories. In other cases, especially for residues of agricultural activity, uptake difficulties cause it to be a less viable choice; the installation of centralised plants that process substrates from diverse sources may be a solution. Due to changes in many productive areas, new opportunities for biogas potential may arise. The potential impact of the use of energy crops is also discussed.

Contents

1. Introduction . . . 1580
2. Fundamentals of the anaerobic digestion . . . 1581
    2.1. Liquid effluent treatment . . . 1581
    2.2. Treatment of solid substrates . . . 1582
3. Current status of the biogas in Uruguay . . . 1582
4. Methodology . . . 1583
5. Description of the available biomass . . . 1583
    5.1. Wastewaters . . . 1583
        5.1.1. Industrial processes . . . 1583
        5.1.2. Domestic sewage . . . 1584
    5.2. Agro industrial solid wastes . . . 1584
    5.3. Agricultural wastes . . . 1585
    5.4. Forest wastes . . . 1585
    5.5. Municipal Solid Waste (MSW) . . . 1586
    5.6. Energy crops . . . 1586
6. Biogas potential . . . 1586
7. Conclusions . . . 1589
Acknowledgments . . . 1589
References . . . 1589

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1. Introduction

The search of renewable sources of energy is a required task for all countries in the present time. In this context, the energetic valorization of organic wastes captivates the attention of many researchers. Specially, the anaerobic treatment of wastes with biogas production is a valuable alternative. Great effort was made to improve the technology of treatment of both liquid and solid wastes.

But, which is the impact of the biogas production in the energy matrix of a specific country? For answer this question, specific studies must be made: quantification of substrates and evaluation of the fraction that can be collected, determination of methane yield of the substrates considered, technical possibilities, economic profitability and other considerations. Due to this complexity, few examples of a complete estimation of the potential of biogas generation in a specific country are found in the literature [1–4]. Then, advances of the impact of anaerobic technologies on the current energy needs could be achieved with the application of an estimation methodology in a specific case.

Furthermore, specific wastes require specific treatment technologies. Therefore, the consideration of local experiences and specific developments of the anaerobic technology improve the estimation of the biogas production because they are based in true data and no extrapolation from other contexts is made. Then, the objectives of this paper are focused to apply a methodology of estimation of the potential of biogas production in a specific country, also using specific experiences and verified results of the use of the anaerobic technology over the main substrates. The comparison with similar data of other countries provides a generalized conceptualization about the impact of anaerobic digestion in the energy consumption.

Uruguay is a little country with an intensive use of land for agriculture and livestock. Despite his size, especially if it is compared with the neighbours, Brazil and Argentina, it can be marked its production in certain categories: beef, dairy and forest products, besides the soy production. Then, agro industrial wastes are very significant in the country and application of the anaerobic technology can be encouraged. On the other hand, the little size allows managing a relatively homogeneous country, and allowing handling the production data with an acceptable precision. Additionally, there is a solid base of academic knowledge about anaerobic processes that can provide the scientific background to technological applications. Also, in the South American context Uruguay contributes with other innovative experiences and developments in renewable energy sources, as wind energy.

The Uruguayan energy framework-According to the 2011 Census, Uruguay has 3,286,314 inhabitants [5] and a terrestrial area of 176,215 km^2. In 2012, it had a primary energy supply of 4841 ktoe (kilo tons of oil equivalent) and a final energy consumption of 3688 ktoe [6]. In addition, 41% of the primary energy was imported, corresponding to 1950 ktoe of oil and 52 ktoe of natural gas. The aggregate of three sectors accounts for 85% of the final energy consumption, which include transport (1105 ktoe), residential sector (772 ktoe) and industry (1257 ktoe). The remaining 15% is consumed by trading and services (330 ktoe) and by agriculture and fishing (224 ktoe).

The national energy matrix shows a great dependence on imported energy sources, especially hydrocarbons, as Uruguay is a country with no petroleum extraction at present. It is clear that the rise of oil prices in the near future will push the search for alternative energy sources. Moreover, environmental restrictions and the concept of sustainability compel the search for solutions that involve renewable sources, including energy valorisation of wastes. A goal of generating more than 50% of energy from renewable sources has been established for the year 2015. In particular, wind energy has contributed 140 GWh of electricity in 2013, and its contribution will soon exceed 300 GWh according to official targets. Another goal that has been achieved is the incorporation of 5% of liquid biofuels into gasoline and diesel oil [7].

The industrial and urban waste treatment systems were both developed with the primary aim of reducing pollution levels. However, given the current energy conditions, a complementary goal can be the recovery of the energy contained in the waste. In certain instances, the energetic valorisation of wastes can make a significant contribution to meeting energy demand. The possibility of a profitable use of a specific technology should be analysed and optimised for each type of waste or material to enhance energy production.

The paper is organised as follows: first, in order to introduce the reader, a brief review of the main fundamentals of the anaerobic digestion, including liquid and solid treatments, is presented. Second, a description of the current status of the biogas applications and policies in Uruguay are outlined. Third, the methodology used is described; this section depicts a general procedure that could be applied to other countries. Fourth, description of the available biomass and some specific key data available from the Uruguayan experience are presented. Finally, the estimated potential of biogas production is calculated and is compared with similar estimations in other countries and conclusions are made.

2. Fundamentals of the anaerobic digestion

Currently, global changes in the world require greater efficiency in the use of biotechnologies. In this sense, the anaerobic digestion of agro industrial organic waste is an alternative treatment with significant advantages over other process, including low operating costs and power generation from biogas [8–10]. Additionally, anaerobic technology has proven to be more favourable than the aerobic treatment of wastes from a greenhouse gas generation point of view [11] and can even compete with other biofuels [12]. In this scenario, anaerobic digestion plays a key role because the products generated (e.g., hydrogen, methane) from the different metabolic steps can be used as energy sources in boilers, internal combustion engines, fuel cells [13] or as raw material for other processing options (e.g., the production of biopolymers or other organic substances). For these reasons, anaerobic technology constitutes the core of organic waste treatment systems [14].

Anaerobic digestion involves multiple related biochemical processes, which assumes different populations of microorganisms must work together harmoniously to achieve the complete degradation of organic matter into methane and carbon dioxide. The complex molecules must first be hydrolysed to smaller molecules (sugars, lipids and proteins), which are then converted in subsequent steps into smaller molecules, including volatile fatty acids (VFA), hydrogen and carbon dioxide. Finally, the methanogenesis process converts acetic acid or hydrogen and CO$_2$ to the final product, methane. Additionally, the process can focus on hydrogen production, an energy vector that is considered to be a clean fuel with a promising future. Each individual substrate requires the adjustment of conditions for process optimisation.

2.1. Liquid effluent treatment

The most important development in anaerobic technology for wastewater treatment came from the concept of high-rate reactors such as the UASB (Upflow Anaerobic Sludge Blanket) reactor, where the cell retention time is decoupled with the hydraulic retention time in the reactor. This achieves several objectives, such as the application of a high load per unit volume, the specialisation of microorganisms and the integration of the zones of reaction and phase separation into a single unit. In many applications, the microorganisms cluster into consortiums or granules and then produce slurry with a very low sludge volume index and optimal sedimentation properties [15].

The Expanded Granular Sludge Bed (EGSB) reactors exploit the sedimentation properties of anaerobic granules and allow greater up flow velocities [16]. In a similar form, the Internal Circulation (IC) reactors generate a gas lift that allow greater up flow velocities without mechanical pumps, which allows an increase of volumetric loads and greater efficiency in the removal of organic matter [17].

2.2. Treatment of solid substrates

The microbiological processes that occur in wastewater treatment systems are the same for solid substrates [18]. However, there are important differences. First, the lysis step of the particulate material is considered to be a key step in the overall process and may even be the limiting step in the whole process. Second, mass transfer may be more difficult if sufficient mixing is not provided. Finally, because the separation of microorganisms from the solid substrate is impossible, the substrate and cell residence times in the reactor are equal. Considering the growth rate of anaerobic microorganisms, residence times of approximately 20–60 days are required to prevent the digester "wash-out" of microorganisms. Beyond these issues, the high concentration of organic matter makes the anaerobic digestion of solid materials very attractive for energetic purposes [10].

The substrates originate from a variety of sources, including solid waste generated in agro industrial activity, sludge produced in aerobic treatment plants, agricultural residues, animal wastes, municipal waste, and crops cultivated specifically to generate biogas. There are systems that operate in the mesophilic temperature range (35–37 °C) and others operating in thermophilic conditions (55 °C). Some systems operate in batches, while others operate continuously, resulting in different mixer features. Finally, there are systems that operate with either low solids content (5–10%, "wet digestion") or high solids content (20%, "dry digestion"). Some options involve the mechanical pretreatment of the waste to reduce the size of the solids. Other options involve separating the process into two phases, a hydrolytic phase which converts the organic matter into the liquid phase and then a methanogenic phase which takes place in a conventional anaerobic reactor [19].

Sludge of aerobic treatment plants–Primary and secondary sludge of aerobic wastewater treatment plants must be treated to achieve harmless characteristics. Anaerobic digestion is a typical technology that produces a stable and safe biosolid that can be used as a soil conditioner [20,21]. Sludge digestion produces methane in a sufficient amount for use in heating and mixing the reactor itself and any excess can be used for other purposes, including the specific needs of the aerobic liquid handling system [22]. Solids were reduced by between 25% to 45%. Typically, long retention times in excess of 10 days are required; thus, the reactors are relatively large.

Municipal Solid Waste (*MSW*)–Solid waste produced from urban activity (residential, commercial and certain industrial activities) contains a significant biodegradable fraction that can be treated anaerobically. Landfill disposal is the most common final destination of MSW in undeveloped countries. A landfill is an engineering technology that confines the waste to a controlled volume and minimises environment impact [23]. In the landfill process, the oxygen is consumed rapidly and leads to anaerobic conditions. Under this point of view, the landfill can be conceived as a giant bioreactor [24]. Based on modern concepts, a landfill is designed for biogas extraction. In addition to being a disposal site, waste energy can be recovered from landfills. Unfortunately, in undeveloped countries, wastes are disposed in uncontrolled forms and biogas recovery is not possible. Another alternative for the treatment and valorisation of the organic fraction of MSW is the use of digesters [25]. In this alternative the key of success is the household separation of the organic fraction. The digester performance can be improved with a pre-treatment process (chemical, enzymatic, thermal or mechanical).

3. Current status of the biogas in Uruguay

Uruguay is a country with a relative lower industrial density, mainly focused on the transformation of agricultural and livestock raw material. In the last decade a sustained economical growth has been developed, receiving considerable amounts of external investment [26]. On the other hand, old companies do not always have supported the environmental solutions with the same rate of investment as they have done in the production facilities. Due to relative availability of land, extensive solutions like lagoons were widely used in the past. However, some companies do have anaerobic reactors in the wastewater treatments plants: one of the three malting companies has a UASB reactor, two dairy industries have a modified UASB reactor accompanied with a grease digester, the main wool scouring factory has an anaerobic reactor with methane recovery, a high scale dairy farm with powder milk production has anaerobic digesters for solid wastes, and so on. Many factories have anaerobic lagoons in the wastewater treatment plant. Now, environmental restrictions, energetic improvements and new concepts as clean production, shift the companies to search more effective and optimized treatment technologies. In this context, although at the moment the number of industrial applications of anaerobic technologies is still small, the future is promissory.

The domestic wastewater is mainly aerobically treated or discharged directly to the sea. However, there is a little plant with two UASB reactors which have been working for 15 years, and a new plant for a hundred thousand inhabitants based on anaerobic reactors is now under construction.

Past experiences with indian or chinese digester types have not been sustained in rural zones because the production modality is very different to other undeveloped countries. Moreover, nowadays, rural electrification covers the whole country and consequently low income technologies for energetic purposes, including rural digesters, are less attractive.

Despite the small size of the country compared to other countries of South America, Uruguay is now characterized by its institutional stability and the orderly development of the economy. The governmental plans include the promotion of renewable energy, in order to achieve more energetic sovereignty in an environmental friendly way. Wind energy and biomass combustion are particularly encouraged, but other ways of renewable energy are also stimulated. This stimulation is provided through some tax exemptions for investments. Other tools as green certificates or subsidies are not used. The energy prices are determined by the market transactions and contracts with the national electric enterprise.

The main regulation about the environment is the General Law of Environment Protection and specific regulations determine the discharge characteristics of wastewaters as well as the solid disposal conditions [27]. The Environment National Office (DINAMA), as a division of the Ministry of Housing, Land Management and Environment, has the control of environmental issues without detriment of some local comptrollers.

There are not specific regulations about biogas promotion. Anaerobic technologies must compete with other alternatives in the efficient use of resources and in the economic aspects. However, anaerobic technologies can be applied in a variety of situations, since them constitute a very interesting alternative for the waste treatment, without energy consumption and generating methane. Government studies have not been performed, but in 2014 a pilot project founded by GEF (Global Environment Found) started, in order to implement two sets of full-scale treatment plants that can be replicated later [28].

Academic research in anaerobic technology is developed at the Chemical Engineering Department of the Universidad de la República (the single public university) and the microbiological aspects are cultivated by researchers of several microbiological departments. The academic staff gives support to technological services offered by public and private companies.

On the other hand, due the small size and the small population density, Uruguay could be considered as a real scale laboratory for the introduction of new technologies. This is the case, for example, of the "one laptop per child" project [29] or the cattle traceability [30]. Technologies based on the valorisation of natural resources and the human resources intensification, like anaerobic technologies, could be successful.

4. Methodology

The anaerobic digestion of organic substrates depends on the conditions in which the process is carried out, the type of reactor, the residence time if the system is continuous or the reaction time if it is discontinuous, the temperature, the mixing behaviour, the type of microorganisms, etc. Experiments carried out in different conditions and at different scales allow the determination of optimal conditions of degradation and, consequently, the potential for anaerobic digestion. Values for different types of waste are obtained in literature. With these values, the degradation of waste can be estimated in terms of a reduction of Chemical Oxygen Demand (COD) or Volatile Suspended Solids (VSS).

Knowing the amount of methane or biogas produced, and in this case also the methane content, per unit of waste and the overall waste generation, the maximum theoretical potential for biogas production can be calculated for each type of waste. However, it is clear that only a fraction of the total waste can be collected. There are always constraints that prevent collection or there are alternative uses for the waste. The available potential can be obtained by applying these constraints. In this way, an estimate of the minimum and maximum quantities of collected waste and the corresponding range of available potential is obtained. Then, the potential of methane production for a substrate is calculated according Ec. (1):

$$MP = Q \times RF \times SMP \tag{1}$$

where

MP: methane potential of the substrate, as standard cubic meters per year
Q: quantity of substrate (solid waste or wastewater), as kg of Volatile Solids or kg of COD (Chemical Oxygen Demand) per year
RF: recovery factor, fraction of waste effectively recovered
SMP: specific methane potential, as standard cubic meter of methane per kg of volatile solids of per kg of COD

From an energy point of view, the biogas generated will be used for electricity generation, heat generation or a combination of both. The technical potential corresponds to the electrical and thermal energy that can be produced. Technological restrictions on the conversion of energy should be considered, which depends on the equipment and overall size where a larger size tends to be more efficient.

Once the technical potential is defined, economic performance must be considered, which leads to an estimate of the economic potential, i.e., the fraction of the technical potential that it is economically feasible to produce. This depends on many factors and regional and local levels should be evaluated for each project under specific conditions; thus, economic performance is beyond the scope of this work. Although the project be economically feasible, restrictions such as legislation, logistics and other constraints could impede the effective implementation of the potential project.

There are various possibilities for the use of biogas for energy. Each situation must be analysed individually and take into consideration the facilities involved. A common use of biogas is for direct combustion in a boiler to replace natural gas or fuel oil, but this requires the presence of a boiler at the site of waste generation. Another common alternative is the transformation of biogas into electrical energy, which enables energy generation at different scales and in a distributed manner. The electrical energy can be used for domestic or industrial purposes or to feed the public network. Even in the electrical transformation of biogas, the heat recovery of the flue is determined by the characteristics of the factory and its location relative to potential users. It should also be noted that a fraction of the heat must be used for heating the digester itself in many cases. Internal combustion engines with Otto cycle are commonly used for power generation [1,31]. The engines are made in a wide power range (from tens of kW to 20 MW) and have overall yields (combination of heat and power) between 70% and 80%. The transformation of fuel into electrical energy varies between 30% and 40%; larger units tend to be more efficient.

It is also possible to construct "centralised" plants which receive waste of different types and sources for co-digestion, generating biogas and producing a digestate that can be distributed between farmers. These plants can operate as an independent company dedicated specifically to the treatment and recovery of waste by providing services and producing energy and digestate with agronomic value.

5. Description of the available biomass

5.1. Wastewaters

5.1.1. Industrial processes

There is a wide variety of industrial wastewaters that have been successfully treated in anaerobic systems, including malting, brewing, drinks, distilleries, pulp and paper, food processing, pharmaceuticals, yeasts, leachate, etc. [15,32]. We present select cases that are relevant to Uruguay in the next section.

5.1.1.1. Slaughterhouses. The slaughterhouses perform the industrialisation step in the meat chain [33]. There are 34 slaughterhouses (20 that export trade) in the country, and these slaughtered more than 2.2 million cattle in 2007. In Uruguay, approximately 70% of the cattle demand is concentrated in the top 10 slaughter plants. The origins of slaughterhouse wastewater are from the processes of bleeding, deboning, evisceration, and washing. Three types of effluents are produced, including red water, green water and sewage. The red water is mainly generated in the slaughter operations and mainly contains lipid and protein material; the green water comes from evisceration processes and washing and has a high content of lignocellulosic solids and fats; sewage comes from waste generated in toilets used by workers. The combination of the different streams generates a complex effluent containing proteins, fats and lignocellulosic materials that are in soluble and suspended solid forms [34]. Table 1 shows the characteristics of slaughterhouse wastewater from a typical factory

Considering the effluent flows and volume generated from a slaughterhouse, an average load of 23 kg COD per ton of slaughtered animal is obtained. The number of cattle slaughtered annually on average between 2008 and 2010 was 247,541 [35]. With an average weight of 485 kg per head, there is an annual COD load of 25,000 t to be treated.

Table 1
Slaughterhouse wastewater characteristics (from [34]).

Parameter	Red water	Green water	Sewage
Flow (m^3/d)	1900	800	200
Temperature (°C)	29	23	20
Total COD (mg/L)	6700	21,000	730
Soluble COD (mg/L)	2400	3600	550
TSS (mg/L)	1900	12,000	400
VSS (mg/L)	1600	10,000	200
Oil & Grease (mg/L)	1200	1700	10
COD/NTK	25	40	8
COD/P	390	310	150
pH	6.5	7.5	7.5

Table 2
Mean values for the Uruguayan dairy industry wastewater.

2.7 $m^3_{wastewater}/m^3_{milk}$
9.7 kg COD/m^3_{milk}
3.6 kg $COD/m^3_{wastewater}$
2.0 kg $BOD_5/m^3_{wastewater}$
0.49 kg $O\&G/m^3_{wastewater}$

5.1.1.2. Dairy industry. Liquid effluents from the dairy industry are mostly generated in the process of cleaning facilities, which use acids, alkalis and/or detergents to extract milk residues with water. In anaerobic reactors such as the UASB, the dairy effluent may create problems due to the high content of fatty material, which is approximately 40% of organic matter. Because this fatty material is more difficult to degrade, it accumulates in the reactor by surrounding the active biomass, which prevents the transfer of substrates from the liquid medium and, due to its low density, results in the flotation of solids. The accumulation of solids under the phase separation device or the escape of solids with liquid effluent causes the reactor to fail. To avoid these problems, a physical separation of the fat is generally carried out by dissolved air flotation, which is then followed by biological processes. Nevertheless, a successful full-scale experience has been carried out in Uruguay [36,37] with the following changes introduced in a sludge bed reactor: i) the floating material is collected under the phase separation device and is periodically extracted, ii) an auxiliary anaerobic digester for the floating materials is added and iii) an external lamella settler is used to minimise the escape of biomass in the startup period.

According to the indexes presented in Table 2, 1472 million litres of milk industrialised in 2009 would have generated approximately 4.0 million cubic meters of wastewater with approximately 1.43 million kg of COD.

Beyond is used for animal food, the whey is often considered as a residue [38] and has high COD concentration (approximately 60 gCOD/L). Due to its high concentration and because it is not typically part of the waste stream, the whey must not be treated in dairy wastewater treatment units. When whey is considered to be waste, the preferred option is to treat it in a solids digester.

5.1.1.3. Vinasse from bioethanol distillery. In 2005, government authorities decided to begin the production of bioethanol and biodiesel from domestic raw materials to diversify the national energy matrix in order to achieve the following: i) increase energy sovereignty, ii) reduce oil consumption, iii) reduce greenhouse gases emissions, iv) develop agro-business chains, and v) promote economic and social development in certain regions. In this context and considering the 2007 Act of biofuels, a sugarcane based project has been implemented in Bella Union, which is in the northern part of the country, and had a projection of 10,000 Ha of sugarcane plantations and 4000 Ha of sweet sorghum for the production of ethanol, sugar and electricity. The distillery was projected to have a capacity of 120 m^3/d of alcohol and has been in operation since 2008.

Distillation of the fermented juice produces alcohol at the top of the column and wastewater with a relatively high concentration of alcohol and other organic components called vinasse at the bottom. It can be assumed that one litre of bioethanol will generate approximately 13 to 15 l of vinasse [39,40] with variable concentrations depending on the source of material fermented and the process conditions [41].

With a production level of 120 m^3 of alcohol per day, 1800 m^3 of effluent will be generated per day. Assuming an average concentration of 54 gCOD/L (experimental value of the vinasse in Bella Union), a load of 97,000 kgCOD per day is generated during the productive months.

5.1.2. Domestic sewage

Uruguay has a population of 3,286,314 inhabitants, 94.7% of whom are urban, and 1,319,108 live in the city of Montevideo. For the rest of the country, 91.7% of the population is urban [1]. In Montevideo, the municipality is responsible for sewage, covering 91% of the urban area in 2009 [42]. There is also a non-separative system where wastewater is released into the Rio de la Plata through a sub aquatic emissary. For the rest of the country, domestic sewage is managed by the public enterprise OSE (Obras Sanitarias del Estado). Some cities along the coastline discharge directly without biological treatment. By 2008, sanitation coverage within the country was 38% of the urban population [43]. The urban areas with treatment or pretreatment facilities include 735,262 people. In two cities, one only has a pretreatment system and the other (Pando) has an anaerobic plant. In Ciudad de la Costa, which is near Montevideo, a treatment plant with anaerobic reactors is under construction.

The average values for sewage water were determined as 480 $mgCOD_{total}$/L, 230 $mgCOD_{soluble}$/L, 170 mg TSS/L and 120 mgVSS/L [44]. Considering a typical value of 200 L per inhabitant per day [45], an estimated 6.5×10^7 kgCOD per year will be discharged into the sewer system. However, excluding the cities that discharge directly into the sea with only primary treatment (Montevideo and Maldonado-Punta del Este), the load would be approximately 1.6×10^7 kg of COD per year. Approximately 92% of this load would be treated in aerobic systems and the remaining 8% in anaerobic systems.

The use of methane in anaerobic reactors for sewage is typically not economically viable because it is a very dilute effluent, where even a substantial fraction of the dissolved methane will escape into the effluent [46]. However, because there are significant energy savings compared to aerobic systems based on the cost of aeration, it can be considered an attractive option for treatment.

In aerobic systems, a significant amount of sludge purge is usually stabilised by anaerobic digesters, which generates methane. Using a yield factor of 0.4 kgVSS/kgCOD, approximately 6000 t of VSS could be treated anaerobically.

5.2. Agro industrial solid wastes

Many Uruguayan industries that process raw materials of agricultural origin generates solid wastes that can be treated anaerobically and produce biogas. A survey based on official information, including data from the Environmental Agency and other governmental offices, was conducted. Mean annual production in each industrial branch and indexes of waste generation were calculated and are presented in Table 3.

Table 3
Yearly production of the main industries processing agro industrial commodities and waste generation indexes.

Industry		**Production**		Type	**Waste generation index**			
		Quantity	Unit		Mean	Min	Max	Unit
Brewery		117,600	ton/year	Trub	106	65	120	kg/ton
				Yeast	13	8	15	
				Packing wastes	9	8	12	
Dairy		1,495,290	m^3/year	Packing wastes	1.6	2	3.1	kg/m^3 milk
				Biological sludge	0.063	0.18	0.053	
				Whey	0.85	0.68	0.94	
Fish		64,125	ton/year	Fish remains	430	270	630	kg/ton
				Packing wastes	2.5	2.4	2.7	
				Grease trap sludge	25			
Malting		231,200	ton/year	Dust	8			kg/ton
				Malting wastes	69			
				Biological sludge	2			
Oil		26,400	ton/year	Bleaching earth (rice)	78			kg/ton
				Bleaching earth (sunflower)	4			
				Packing wastes	0.5			
				Biological sludge	37			
Poultry		53,243	ton/year	Slaughter wastes	150	130	180	kg/ton
				Feather	73	71	80	
				Grease trap sludge	13			
Rice		1,320,224	ton/year	Pre-cleaning	11			
				Husk	200			
Sausage		21,584	ton/year	Process wastes	56	13	80	kg/ton sausage
				Packing wastes	41	9	98	
				Grease trap sludge	85	30	250	
Slaughterhouse	Bovine	1,752,325	head/year	Red water solids	3.9	0.8	14	kg/head
				Green water solids	37	15	50	
				Biological sludge	43	30	50	
				Packing wastes	0.8	0.2	1.3	
	Ovine	1,767,185	head/year	Red water solids	0.4	0.1	1.4	kg/head
				Green water solids	3.7	1.5	5	
				Biological sludge	0.4	3	5	
				Packing wastes	0.1	0	0.1	
	Swine	214,815	head/year	Red water solids	1.3	0.3	4.7	kg/head
				Green water solids	12	0.5	17	
				Biological sludge	14	10	17	
				Packing wastes	0.3	0.1	0.4	
	Equine	34,765	head/year	Red water solids	3.9	0.8	14	kg/head
				Green water solids	37	15	50	
				Biological sludge	43	30	50	
				Packing wastes	0.8	0.2	1.3	
Tannery	Bovine	3,071,970	skin/year	Wastes without tanning	8.7	6.5	9.4	kg/skin
				Wastew with tanning	2.4	1.9	2.8	
				Sludge	4.5			
	Ovine	1,671,430	skin/year	Wastes without tanning	1.2	0.06	1.6	
				Wastew with tanning	0.3	0.2	0.5	
				Sludge	1.2			
Wine		112,559	m^3/year	Marc	90			kg/ton grape
				Wine sludges	30			
				Pedicel	30			
Woolscouring		41,050	ton/year	Recovered grease	19	9	29	kg/ton
				Settler sludge	30	26	43	
				Decanter sludge	107			
				Wool dust	16	2.5	34	
				Packing wastes	8	1	11	

5.3. *Agricultural wastes*

Agriculture is a very dynamic sector and products and cultivated lands change drastically over time. The main agricultural production data of 2011 are presented in Table 4.

In agricultural production, the primary wastes are straw and debris after harvest. The waste is usually not collected and remains in the soil. Thus, energy production from these wastes is negligible in practice.

In the fruits sector, orange, tangerine and apple are the main products, and a fraction of the production is exported. In horticulture, potato and tomato are the main products, which are focused in domestic consumption.

5.4. *Forest wastes*

In late 1968, the first Forestry Law was adopted to promote forestation, through tax exemptions and credit lines. Because of the law, trees were planted on a large scale beginning in 1990. Between 1990 and 2000, the land was reforested at an average rate of nearly 50 thousand hectares per year, with a maximum of 83,000 established in 1998. By 2010, the forested area was 1,721,658 Ha, of which 752,158 Ha are natural forests and approximately 1 million hectares are plantations, and consisted predominantly of eucalyptus (676,096 Ha) followed by pine (274,568 Ha). In 2011, approximately 6.2 million cubic meters was extracted for pulp, approximately 2.4 million cubic meters was

Table 4
Main agricultural production.

Season	Crop	Planted area (thousands of Ha)	Production (thousands of ton)
Spring	Wheat	404	1300
	Barley	62	186
	Oats	22	34
Winter	Soy	863	1820
	Sunflower	10	9
	Corn	93	530
	Sorghum	35	138

Table 5
Review of methane yield for different types of substrates and proposed availability range of agroindustrial wastes.

Industry	Waste	Methane yield (L CH_4/kgSV)	Availability (%)		References
			MIn	Max	
Sauceries	Process waste	216	10	25	[53]
	Grease trap sludge	278	50	80	[54]
Slaughterhouses	Ruminal content, manure, other solids	540	50	80	Our studies
Poultry	Slaughter waste	550	10	25	[55]
	Grease trap sludge	278	50	80	[54]
Fish	Fish waste	390	10	25	[56]
	Grease trap sludge	278	50	80	[54]
Oil	Blanking earth	400	50	90	[57]
	Biological sludge	340	50	90	[1]
Dairy	Biological sludge	340	50	90	[1]
	Whey	424	5	30	[53]
Wine	Pressing	180	30	50	[58]
	Wine sludge	283	30	50	[58]
	Peduncle	283	30	50	[58]
Brewery and malting	Malting waste	245	70	90	[59]
	Biological sludge	340	70	90	[1]
	Yeast	560	70	90	[60]
Woolscouring	Sedimentation sludge	150	70	90	Estimated
	Recovered grease	150	70	90	Estimated
	Decanter sludge	150	70	90	Estimated

used as a direct fuel and approximately 1.9 million cubic meters was for solid wood.

The wastes generated in the forest are a potentially valuable source of energy but because it is difficult to collect, it commonly remains on the land. On the contrary, the biomass located in the processing factory is available for simple uptake. The lignin content of this type of waste prevents efficient methanation if pretreatments are not provided. Hence, thermal processes could result in a more attractive alternative.

5.5. *Municipal Solid Waste (MSW)*

The most recent studies quantifying MSW generation have been conducted in the metropolitan area of Montevideo [47]. However, values can be extrapolated for the whole country. A generation rate of 1.14 kg/inhab/d and a total production of 3070 t per day can be used to represent the country.

Table 6
Review of methane yield for different types of substrates and proposed availability range for horticultural wastes.

Culture	Waste (as % production)	Methane yield (L CH_4/kgVS)	Availability (%)		References
			Min	Max	
Orange	3	250	15	25	[61]
Tangerine	5	250	15	25	[61]
Lemon	3	250	15	25	[61]
Grapefruit	22	250	15	25	[61]
Apple	25	180	15	25	[61]
Tomato	20	300	15	25	[62]
Carrot	10	300	15	25	[62]
Potato	15	335	15	25	[53]

MSW is typically sent to landfills. In Las Rosas (Maldonado) and more recently in Montevideo, landfill biogas is being extracted. It is difficult to estimate the generation of biogas because the incidence of various factors, including composition of the waste, filling mode, operating conditions, weather conditions, etc. In Montevideo, a production rate of 0.25 Nm^3 of biogas per ton of wet waste per day was obtained, of which methane accounted for 60% [48]. According Chamy and Vivanco [1], 60 m^3 of biogas are generated per ton of waste.

5.6. *Energy crops*

Uruguay is focused on cultivating commodities for human and animal food and for producing liquid biofuels. The production of energy crops has never been considered. However, it is an alternative that has been widely accepted in the world, especially in Europe [26,49–52]. Due to the need for sources of renewable energy and considering that land suitable for cultivation is not fully used, the production of energy crops can be considered an alternative strategy. Europe has a proposal that allocates 10–30% of the total arable land to grow crops for energy production [53]. Besides, Uruguay should assess whether the cost savings from using its current land for energy crops will compensate for a reduction in fossil fuel imports.

6. Biogas potential

Tables 5 to 7 show the values obtained from the literature and the suggested availability levels used for the estimation.

Fig. 1 shows the results regarding the potential solid waste production in agro industries. A predominance of the dairy industry is observed, which is due to the inclusion of whey as a waste and assuming that a fraction must be treated in a solid digester. Because there is no clear policy on the use of whey, this result must be considered with caution. Note that we have taken a minimum 5% uptake of whey, which corresponds to a discarded fraction in the scenario of other uses, and a maximum of 40%, which corresponds to an explicit policy of energy recovery for this product.

Excluding the dairy industry, the slaughterhouse industry has the greatest potential for methane production. Considering cattle, sheep and horses, the slaughterhouse sector represents 31–47% of the methane production potential in the agro industrial sector. Because most of the production is concentrated in relatively large industries, it would be possible to implement waste methanation systems in the factories.

Fig. 2 shows the potential of anaerobic digestion of waste from horticultural crops. Typically, the waste consists of prunes and discarded fruits and is often from small and medium producers. The implementation of methanation systems does not seem to be

Table 7
Review of methane yield for different types of substrates and proposed availability range for agricultural wastes.

Culture	Waste	Methane yield (L CH_4/kgVS)	Availability (%)		References
			Min	Max	
Wheat	Straw	304	10	15	[63]
Corn	Straw	317	10	15	[64]
Barley	Straw	219	10	15	[64]
Sunflower	Straw	260	10	15	[65]
Sorghum	Straw	228	10	15	[58]
Soy	Straw	260	10	15	[65]
Sugarcane	Straw	177	10	15	[66]
Rice	Straw	226	10	15	[67]

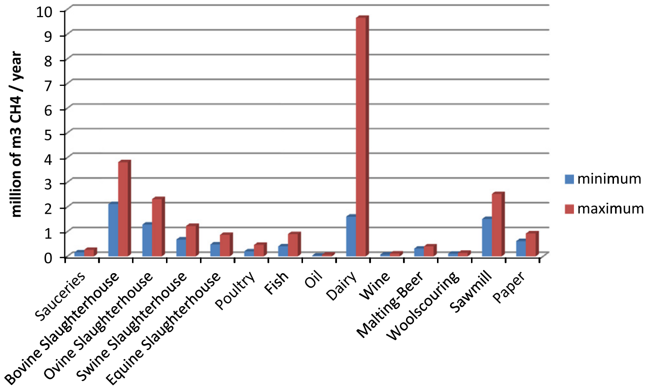

Fig. 1. Yearly methane potential of agroindustrial solid wastes.

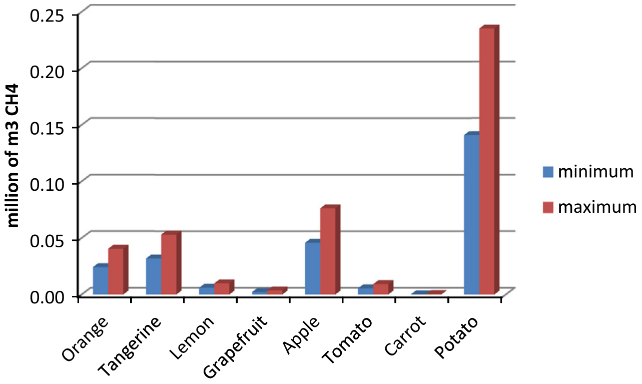

Fig. 2. Yearly methane potential of horticultural wastes.

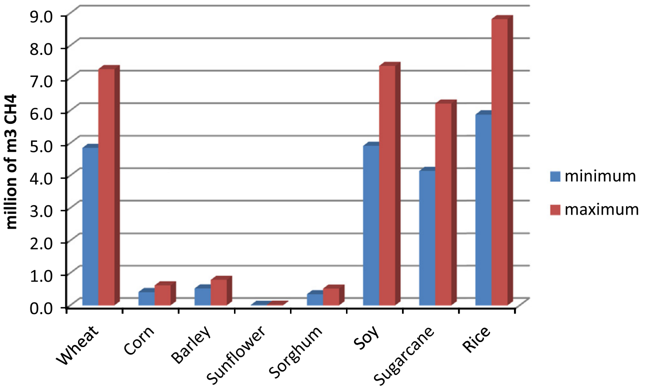

Fig. 3. Yearly methane potential of agricultural wastes.

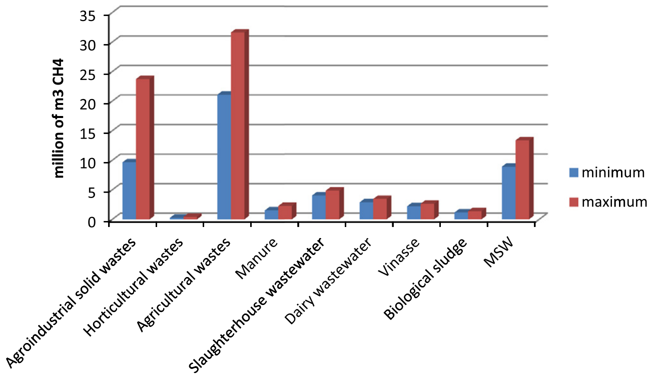

Fig. 4. Yearly methane potential of various types of wastes.

Table 8
Methane potential of the main wastes, estimated potential of electricity and heat.

	Methane (million of m^3/year)		Electricity (GW h/year)		Electric power (MW)		Heat (TJ/year)	
	Min	Max	Min	Max	Min	Max	Min	Max
Agroindustrial solid wastes	10	24	30.6	75.4	6.9	14.0	129	309
Horticultural wastes	0.3	0.4	0.8	1.3	0.1	0.1	3	5
Agricultural wastes	20	29	58.2	87.2	6.3	9.5	247	371
Manure	1.5	2.3	4.4	6.5	0.5	0.7	18	27
Slaughterhouse wastewater	4.0	4.9	13.6	16.4	1.6	1.9	49	59
Dairy wastewater	2.9	3.4	9.1	10.9	1.0	1.2	35	42
Vinasse	2.2	2.6	7.4	8.9	0.8	1.0	27	32
Biological sludge	1.1	1.4	3.9	4.7	0.4	0.5	94	113
MSW	8.9	13.3	30.0	45.0	3.4	5.1	108	162
Total	**52**	**84**	**162**	**263**	**21**	**34**	**649**	**1052**

feasible with the current infrastructure, but could be implemented if there was a centralised plant.

Fig. 3 shows the potential that is generated from crop residues of agricultural production. Waste is typically not collected and remains on the field. Collecting waste would require a change in its current practice, which may also affect agronomic and soil management. Definitely, there are few chances for using this type of residue for methanation (Fig. 4).

Table 8 shows the potential of groups of solid wastes with special wastes and liquid wastewaters of interest. The category "manure" includes manure generated on dairy farms and feedlot, considering the current situation. In traditional establishments that are based on grazing in the field, only a fraction of the excreta can be collected when cattle are in the waiting room for milking. Moreover, many feedlots currently installed have not provided a system for the regular collection of excreta, making it virtually impossible to capture fresh substrate. However, this is a category that has undergone major changes in recent years due to the emergence of establishments that have thousands of animals. Hence, the contribution of the category "manure" can grow significantly.

The slaughterhouse and the dairy industries are particularly notorious for their liquid wastewaters. Relatively concentrated effluents are usually treated by pond systems, but could be treated in reactor systems with biogas capture if certain problems are solved. The case of distillery vinasse also stands out as an effluent with a very high concentration and a high methane potential in consequence.

Currently, sewage treatment plants are primarily aerobic and generate sludge that can be digested anaerobically to produce biogas. The extension of the coverage of the sewage system could increase the amount of sludge produced.

Finally, MSW is a major substrate for methanation, which can occur in landfills with biogas capture or through treatment in digesters. Either option involves a clear proposal on MSW management and investment in infrastructure, whether it be new landfills or digesters.

Results show that the full potential for methane production is between 52 and 84 million cubic meters per year, which is equivalent to 1.3– 2.1% of total primary energy of the country. The power generation can be estimated from 21 MW to 34 MW and represents between 1.9% and 3.0% of the average electric demand.

Comparing these results with values obtained in similar studies for other countries show similar outcomes. For example, Chamy and Vivanco [1] estimate a power generation potential of approximately 3.5% of the installed capacity of Chile. Gómez et al. [2] reported that anaerobic digestion of MSW, sewage sludge and animal waste waters could represent the equivalent of 2.82% of the power generation in Spain and 2.0% of the primary energy consumed. Ribeiro and Silva [3] indicate that between 1.16% and 1.24% of the Brazilian electric power could be generated from the anaerobic digestion of vinasse, manure, sewage and MSW. According to Poeschl et al. [4], electricity generation from biogas in Germany in 2008 amounted to 1.6% of the demand and the technical potential would allow a six-fold increase in production. The projections for the European Union in 2020 are to achieve between 2% and 3% of the primary energy from wastes (1/5 animal waste, 1/5 other wastes, and 3/5 energy crops). According to NREL [68], the biogas potential for the USA (including sanitary landfills, wastewaters, animal wastes and other organic wastes) is approximately 420,000 million cubic meters per year, which is equivalent to 5% of the current consumption of gas in the electrical sector or 56% of the consumption of natural gas in transportation. Murray et al. [69] estimated that biogas generation could account for between 3% and 5% of the gas market in USA.

The comparison of results achieved in the Uruguayan estimation with similar results obtained in other countries shows that the same order of magnitude can be expected. From the point of view of the energetic demand the biogas contributes with a percentage of one digit to the global needs. These results may seem a low contribution but some remarks should be considered: while contribution is low there is an equivalent non consumption of non renewable sources. On the other hand, wastes need a treatment to avoid pollution; the anaerobic processes compete with advantages in many aspects with aerobic or physicochemical treatments [37] and additionally allow the energetic valorization of wastes.

The main barrier to implant the anaerobic technology is the need of dedicated investment in order to improve the collection of wastes and update the treatment plants. Without direct government subsidies the fitting of the old waste treatment plants to new environmental requirements constitutes an incremental cost to the companies. However, energetic valorization of wastes could be a way to diminish the treatment cost, substituting fossil fuels and consequently acting in an environmental friendly way.

The existence of technologies like anaerobic waste treatment could enable more stringent controls to the national environmental agency. But also there is a need of a cultural change in the industrial companies and agricultural enterprises, in order to include the cost associated to waste treatment in the productive plans. Production intensification requires a more efficient use of natural resources and process optimization. But the official lemma "Uruguay Natural" [70] requires the use of environmental friendly technologies. In this context, anaerobic technologies should have a higher acceptance.

These results have not considered the possibility of anaerobic digestion of energy crops, which is conducted in several European countries, especially Germany, in co-digestion with animal excreta. An important variable in this case is the agronomic crop yield. Considering a conservative value of 3 t of dry matter per hectare per year (Smyth et al. [71] considered a four times greater value of 12 t/Ha.year), 90% of SV and a methane production of 250 m3/TVS. year (Smyth et al. [71] considered average 300 m^3CH_4/TSV.year), 675 m^3CH_4 per hectare per year would be obtained. If we consider the energy requirements for the farm operation (12% of total), pretreatment and mixed waste (5%), the energy requirements of the digester (15%) and transport of digestate (3%) (following Smyth et al. [71]), the net energy is 65%, which is equivalent to 15.3 GJ or 366 koe (kilo equivalent of oil). A significant increase in potential biogas production could be achieved in function of the land allocation. Based on the total primary energy used in 2012 (3413 ktoep), approximately 100,000 Ha would be required for each percentage point of energy. For example, the equivalent to half of the land dedicated today to improve pasture could generate 11% of the country's primary energy surface. These numbers can be improved if agronomic productivity increases.

However, the use of energy crops for biogas production must be analyzed taking into account not only the energy requirements and the technical possibilities but also the policies about the land use and the food production. Probably the European framework is quite different from the Latin American framework and a lot of political discussion must be done before clarify this topic.

7. Conclusions

The application of anaerobic technology presents an interesting opportunity in Uruguay. Because of its productive matrix, anaerobic digestion is a clear choice for the treatment of liquid and solid waste with significant organic content. From an energy point of view, not only do anaerobic treatments need low amounts of energy to operate but because biogas is generated, it becomes an attractive option for energy recovery from organic matter. Two objectives are met, reducing the environmental impacts and achieving renewable energy generation.

The contribution of energy from waste through anaerobic digestion has no major impact on the Uruguayan energy matrix, potentially reaching values between 1.3% and 2.1% of total primary energy. This is not a peculiarity of the country, because the contribution is comparable to those of other regions. However, it should be noted that, generally, investments are necessary for waste treatment, and these facilities can be used to generate energy, which contributes to improving the economic equation and saving fossil fuels.

The actual implementation of anaerobic systems strongly depends on the ability to collect waste. In the agro industrial factories, such as slaughterhouses, dairy industries and bioethanol distillery, it is relatively easy to install technical solutions and internally use the energy generated as electricity or heat. In other cases, such as forest residues and agricultural activity, collection of waste is not the standard practice and the actual utilisation of the biogas potential is low. The solution will go through a centralised facility that receives waste from various sources, with the objective to generate electricity and digestate that can be used as a soil conditioner.

The actual production is continually changing in some areas; for example, the growth of feedlot establishments poses the challenge of managing large amounts of manure and may involve a significant increase in methane generation capacity. Political decisions about MSW will significantly affect the possibilities of considering this type of waste as a potential source of biogas. Finally, the consideration of energy crops from biogas production could have a significant impact on the energy matrix, but implies important decisions about the use of land and a change in the paradigms of agricultural practice.

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