Bioresource Technology 182 (2015) 208–216

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Life cycle assessment of biomethane use in Argentina

Betzabet Morero [a,*], Eduardo Groppelli [b], Enrique A. Campanella [a,c]

[a] Instituto de Desarrollo Tecnológico para la Industria Química (INTEC), Universidad Nacional del Litoral-CONICET, Güemes 3450, 3000 Santa Fe, Argentina
[b] Grupo de Energía No Convencional, Facultad de Ingeniería Química (FIQ), Universidad Nacional del Litoral, Santiago del Estero 2829, 3000 Santa Fe, Argentina
[c] Facultad de Ingeniería y Ciencias Hídricas, Universidad Nacional del Litoral, Ruta Nacional N° 168 Km 472.4, 3000 Santa Fe, Argentina

HIGHLIGHTS

- Three upgraded biogas processes are compared with LCA.
- The water upgrading process results in less environmental impact.
- The water upgrading process is also more economically feasible.
- Different sources and end uses for biogas are compared with LCA.
- Using energy from biogas can reduce the environmental impact of upgrading biogas.

ARTICLE INFO

Article history:
Received 20 November 2014
Received in revised form 15 January 2015
Accepted 19 January 2015
Available online 27 January 2015

Keywords:
LCA
Waste treatment
CO_2 capture
Biomethane
CHP

ABSTRACT

Renewable substitutes for natural gas, such as biogas, require adequate treatment to remove impurities. This paper presents the life cycle and environmental impact of upgrading biogas using absorption–desorption process with three different solvents: water, diglycolamine and polyethylene glycol dimethyl ether. The results showed that water produces a minor impact in most of the considered categories, and an economic analysis showed that water is the most feasible solvent for obtaining the lowest payback period. This analysis includes three different sources for biogas production and two end uses for biomethane. The use of different wastes as sources results in different environmental impacts depending on the type of energy used in the anaerobic digestion. The same situation occurs when considering the use of biomethane as a domestic fuel or for power generation. Using energy from biogas to replace conventional energy sources in production and upgrading biogas significantly reduce the environmental impacts of processes.

1. Introduction

Anaerobic digestion (AD[1]) is a mature technology that has been widely investigated for treating different organic wastes, as it allows the use of biogas as an energy alternative. AD is feasible from a technical point of view and convenient from an economic point of view because it is a simple process with a simple infrastructure. Argentina has passed legislation that promotes the production and use of renewable energy (Law 26.093/2006; Law 26.190/2006). However, Argentina currently faces an energy crisis due to the lack of natural gas. Biogas could be a good substitute of natural gas, if the undesired components of methane, can be removed.

The main components of biogas are methane, carbon dioxide, water and hydrogen sulfide. In the context of diversifying the energy matrix, it is important to analyze the environmental and economic variables associated with different biogas generation and purification processes and the end use of biogas to determine the most appropriate options for application.

Several Life Cycle Assessment (LCA) studies found in the literature discuss the impacts of biogas generation, purification and end use. For example, the potential impacts of biogas production from different sources were assessed using LCA by Borjesson and Berglund (2006), De Vries et al. (2012), Pertl et al. (2010) and Jury et al. (2010). In contrast, several studies have analyzed the end use of biogas (Patterson et al. (2011, 2013), Beylot et al. (2013)) and have included an analysis of the upgrading stage. Additionally, Stare et al. (2012) conducted a LCA to compare three biogas upgrading technologies and identified the factors that should be reviewed when applying those technologies. In a more comprehensive study, Poeschl et al. (2012b) performed a LCA of biogas

* Corresponding author. Tel.: +54 0342 4559174x2165; fax: +54 0342 4559174x2006.

E-mail addresses: bmorero@intec.unl.edu.ar (B. Morero), groppellieduardo@gmail.com (E. Groppelli), tquique@santafe-conicet.gov.ar (E.A. Campanella).

[1] AD: Anaerobic digestion.

http://dx.doi.org/10.1016/j.biortech.2015.01.077
0960-8524/

production and its multiple uses in Germany to identify areas where the potential environmental impacts of biogas could be mitigated. In addition, Cherubini and Stromman (2011) conducted a literature review of LCAs related to bioenergy and concluded that the wide variability in the different approaches makes it difficult to interpret the results. Therefore, as mentioned by Patterson et al. (2011), it is necessary to evaluate the life cycles of biogas systems at the regional level to guide decisions regarding infrastructure development.

This study aims to provide a life cycle assessment for upgrading biogas through the absorption–desorption process using three different solvents, water, a chemical solvent (diglycolamine) and a solvent physical (dimethyl ether polyethylene glycol), to convert biogas into a form that is equivalent to natural gas and can serve as a renewable energy alternative. Because it is important to correctly define local factors, this paper analyzes the environmental impacts using LCA by considering the technology, utilities and end use of biogas in Argentina. The midpoint-oriented CML 2001 method (Guinee, 2001) was used and included 11 impact categories. The analysis of biogas purification included three different sources (municipal solid waste, agro-industrial and brewery effluents) and two end uses (injection into the natural gas pipeline and use in combined heat and power).

2. Methods

The LCA was carried out according to ISO 14040-44 (ISO 14040:2006; ISO 14044:2006) with four phases: the goal and scope definition phase, the inventory analysis phase, the impact assessment phase and the interpretation phase.

In a first assessment, the biogas upgrading processes (with different locally available solvents) were compared. Upgrading processes aim to improve the biogas quality by removing CO_2 (the greater impurity) and convert biogas into biomethane, an equivalent to natural gas. In addition, this analysis considers the economic feasibility of these three processes. Moreover, different local sources of biogas were evaluated while considering the specific conditions of each particular case. Finally, a study regarding the end use of biomethane was performed. This analysis includes the full cycle (generation, upgrading and end use of biogas) while considering the natural gas quality standards required in Argentina (ENARGAS, 2008). In addition, this study included the end use of biogas by considering the power produced by a combined heat and power unit (CHP).

2.1. Upgrading biogas methods

2.1.1. Goal and scopes

The objective of this study is to analyze the environmental impacts of the three different solvents used for upgrading biogas to determine which solvent generates the lowest environmental impact.

2.1.1.1. Functional unit. The functional unit is the removal of 1 kg of CO_2 from the biogas. The biogas input stream to the different upgrading plants has a theoretical composition of 58.4% CH_4, 37.3% CO_2, 1% N_2, 0.1% H_2S, and 3.2% H_2O at atmospheric pressure and room temperature (25 °C) and a flow rate of 250 m^3 biogas/h. The final biogas quality is a sufficient substitute for natural gas.

2.1.1.2. System boundaries. The LCA of the biogas upgrading processes considers the reactants and the energy used in each process. A global LCA would include the transport of the reactants and the materials used for manufacturing the necessary valves, pipes and plant. However, in this study, only the supplies in each process were analyzed. The biogas generation process and the end use of biomethane are not accounted for in this study (these analyses will be performed later). The boundaries of the absorption–desorption process when using water, DEPG and DGA as solvents are detailed in Fig. 1.

2.1.2. Inventory analysis

The inventories of the inputs and emissions are summarized in Table 1. The data used in each process were obtained from the simulation carried out in the ProMax commercial simulator (ProMax, 2013). From these simulations, was determined the amounts of supplies needed for each process and energy consumption. The operating variables were optimized previously (Morero and Campanella, 2014). Flow rate of each solvent (water, amines and DEPG), shown in Table 1, are the solvent lost during the process.

Some of the data used in these processes were obtained from the NERL database (US Life Cycle Inventory Database, 2012), while other data (DEPG and DGA production) were obtained from the literature (Frischknecht, 1999; Sutter, 2007) and were loaded into the program. The flow of power was adapted to the energy matrix of Argentina. This information was obtained from the local Department of Energy (SEN, 2011a) and loaded into the program. In addition, the water treatment process was provided by the local supplier company.

2.1.3. Impact assessment

The LCA was performed using specific software (OpenLCA, 2013). The CML 2001 impact assessment method (Guinee, 2001) was used because it includes many categories for analyzing ecological and human health effects and resource depletion, among others. In addition, this method has been successfully used in previous studies of biogas processes (Patterson et al., 2011; Poeschl et al., 2012a,b; Starr et al., 2012; Rehl and Muller, 2011; Rehl et al., 2012). The 11 selected impact categories included the acidification potential (AP) [kg SO_2-Eq]; climate change, 100 years (GWP) [kg CO_2-Eq]; eutrophication potential (EP) [kg PO_4-Eq]; freshwater aquatic ecotoxicity potential, 100 years (FAETP) [kg 1,4-DCB-Eq]; freshwater sediment ecotoxicity potential, 100 years (FSETP) [kg 1,4-DCB-Eq]; human toxicity potential, 100 years (HTP) [kg 1,4-DCB-Eq]; malodorous air (MO) [m^3 air]; photochemical oxidation (summer smog) (RBEI) [kg ozone FORMED]; abiotic depletion resource (ARD) [kg antimony-Eq]; stratospheric ozone depletion, 40 years (ODP) [kg CFC-11-Eq]; and terrestrial ecotoxicity, 100 years (TAETP) [kg 1,4-DCB-Eq].

2.1.4. Economic analysis of the biogas upgrading processes

It is important to assess the economic feasibility of the upgrading process in addition to the environmental impacts of the process. For this assessment, the methodology developed by Lang (1947, 1948) and Guthrie (1970a,b) was used. The costs due to inflation are not static and increase with time. One of the best-known indexes for updating the cost of chemical plants was published in the Chemical Engineering Journal (CE). In this analysis, was used the year 2000 as the base year with an index of CE = 394 and a current index value for 2013 of CE = 584.6. The equations used to calculate the costs of the necessary equipment for the biogas upgrading processes and the estimated production costs and profitability measures were obtained from the literature (Seider et al., 2004). The production costs of each plant were divided into three stages: utility costs, labor costs and maintenance costs.

The utility costs include the costs of power, steam, cooling duty, process water and chemicals. To estimate the costs associated with labor, one operator was considered sufficient per shift (three shifts a day). Considering the local economy, a salary of US $5/h was assumed. The annual maintenance cost, *M*, can be estimated as a percentage of capital repayable investment. The maintenance

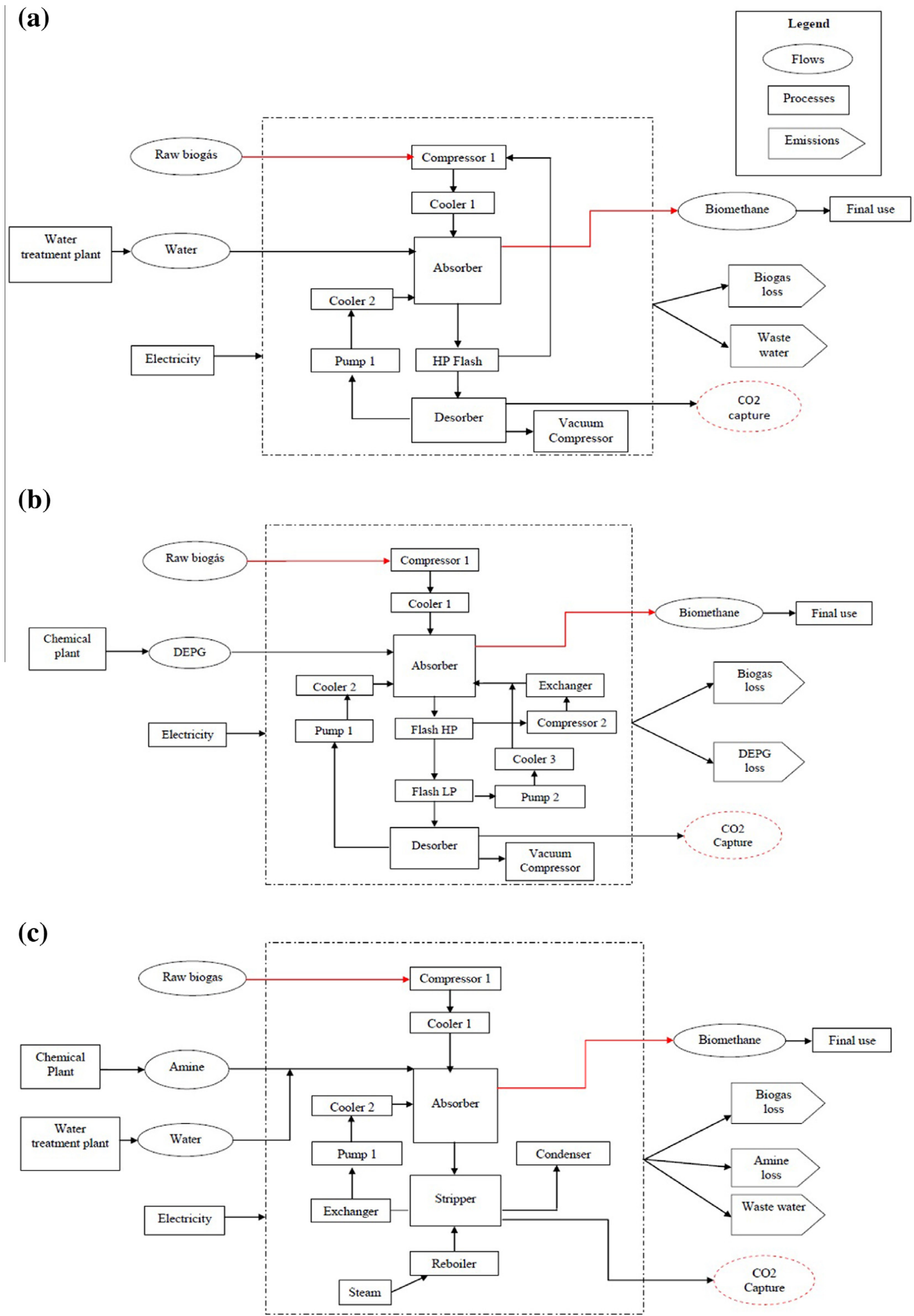

Fig. 1. System boundaries of the upgrading processes using (a) water, (b) DEPG, and (c) DGA.

wages and benefits (MW&B) were estimated as a fraction (3.5%) of the total depreciable capital, and the salaries and benefits for the engineers and supervisory personnel were estimated to be 25% of the MW&B. The materials and services for the maintenance were estimated as 100% of the MW&B, while the overhead maintenance was estimated as 5% of the MW&B (Seider et al, 2004). The annual sales revenue, S, was calculated by considering a biomethane production of 141 m^3/h or 1,173,402 m^3/year. The cost of gas was considered as US $10.50/MMBtu, which corresponded with the current import price of natural gas in the country.

To calculate the return on investment (ROI), a value of 0.35 is assumed for t (state income tax rate), which is the value that is currently used in Argentina for fuels (Decree 518/1998). In addition, the payback period (PBP) was also calculated.

Table 1
Inventory list of the biogas upgrading processes for operating a plant processing biogas at a rate of 250 m^3/h.

Flows	Unit	Processes		
		Water	DEPG	DGA
CO_2 capture	kg	172.74	184.93	185.68
Inputs				
Power required	kW	146.34	81.28	78.72
Cooling duty requirement	kW	150.25	187.63	194.92
Reboiler duty requirement	kW		104.48	229.21
Water reposition	kg	5.02		1.28
DEPG reposition	kg		2.68	
DGA reposition	kg			1.32
Outputs				
Air emissions				
H_2S	kg	0.327	0.303	0.366
CH_4	kg	5.993	4.651	0.189
N_2	kg	0.017	0.006	0.002
H_2O	kg	1.449	4.426	5.635
DEPG	kg		0.048	
DGA	kg			7.79E−13
Water effluents				
DEPG	kg		2.68	
DGA	kg			1.31

2.2. Biogas generation methods

2.2.1. Goal and scope

Different waste treatment plants (municipal solid waste [MSW[2]], agro-industrial effluents [AE[3]], and brewery effluents [BE[4]]) were compared. In each case, the amount of biogas produced and the demand for power and heat vary according to the process. The heat needed to heat the AD primarily depends on the weather conditions. This study discusses the impact generated by using a conventional energy (natural gas) or a fraction of the biogas generated in the process as the energy source to heat the AD.

2.2.1.1. Functional unit. The functional unit results in the generation of 1 m^3 of raw biogas.

2.2.1.2. System boundaries. This LCA accounts for the biogas generation process without considering the transport of the wastes to an anaerobic digestion facility. Instead, this LCA only considers the power and thermal energy required, the chemicals used, the air emissions and the water effluents. Fig. 2 shows the system boundaries for the biogas generation processes.

2.2.2. Inventory analysis

The data for each process were obtained from questionnaires and interviews conducted at the institutions that are developing these technologies. Although the company treating agro-industrial effluents uses energy from cogeneration to heat their digester, was assumed that the heat was generated from burning natural gas (AE–NG[5]) and from burning a fraction of biogas (AE–BG[6]). Likewise, it was assumed that the energy required to heat the AD fed with municipal solid wastes was generated from burning natural gas (MSW–NG[7]) and biogas (MSW–BG[8]). In the brewery process, it was not necessary to heat the digester due to the high temperature of the effluents. In Table 2, the inputs and outputs of each annual process are described.

2.2.3. Impact assessment

The LCA was performed using the OpenLCA software and the impact assessment method CML 2001 (Guinee, 2001). The 11 selected impact categories were the same as those used in the biogas upgrading analysis and included the acidification potential (AP) [kg SO_2-Eq]; climate change, 100 years (GWP) [kg CO_2-Eq]; eutrophication potential (EP) [kg PO_4-Eq]; freshwater aquatic ecotoxicity potential, 100 years (FAETP) [kg 1,4-DCB-Eq]; freshwater sediment ecotoxicity potential, 100 years (FSETP) [kg 1,4-DCB-Eq]; human toxicity potential, 100 years (HTP) [kg 1,4-DCB-Eq]; malodorous air (MO) [m^3 air]; photochemical oxidation (summer smog) (EBIR) [kg formed ozone]; abiotic resource depletion (ARD) [kg antimony-Eq]; stratospheric ozone depletion, 40 years (ODP) [kg CFC-11-Eq]; and terrestrial ecotoxicity, 100 years (TAETP) [kg 1,4-DCB-Eq].

2.3. Biogas end use comparison

2.3.1. Goal and scope

There are different ways to use the energy generated from biogas. For example, the generated energy can be used directly to generate heat through combustion, can be used to generate power from an engine generator fueled with biogas or can produce combined heat and power (CHP). In addition, after purification the biomethane obtained can be injected into the natural gas grid or can be used in vehicles. However, the facilities necessary for injecting biomethane into the grid or for transforming it into power are different, and the required energy and supply vary.

It is important to compare the above processes to consider the energy requirements and the final products of each process. For injection into the natural gas grid, it is important to consider the biogas upgrading process followed by the drying and pressure conditioning processes. The cogeneration process should include a power generator and a heat recirculation pump to heat the AD. The goal of this LCA is to compare the impacts of the process used for obtaining biomethane (for injection into the natural gas grid) and the combined generation of heat and power using conventional natural gas and power processes.

2.3.1.1. Functional unit. The functional unit for generating power is 1 kW of energy, and the functional unit for generating gas for injection into the natural gas grid is 1 m^3 of biomethane.

2.3.1.2. System boundaries. This LCA considers the effluent and the energy used in each biogas generation process, followed by upgrading with water as the solvent. Additionally, the steps necessary to achieve the required specifications for each case are considered with the emissions from the end use of the fuel (i.e., domestic use in the case of the injection into the natural gas grid). The system boundaries are shown in Fig. 3.

2.3.2. Inventory analysis

Table 3 shows the inputs and outputs of the biomethane production process for different end uses. This table shows the energy obtained by treating 250 m^3 of raw biogas per hour and details the energy generated for each process.

2.3.3. Impact assessment

As demonstrated in the biogas upgrading and generation processes, the OpenLCA software was used to conduct the LCA and the impact assessment method CML 2001 (Guinee, 2001) was used. In addition, the selected impact categories were also the same.

[2] MSW: Municipal Solid Waste.
[3] AE: Agro-industrial effluents.
[4] BE: Brewery effluents.
[5] AE–NG: agro-industrial effluents, natural gas to heat the AD.
[6] AE–BG: agro-industrial effluents, biogas to heat the AD.
[7] MSW–NG: municipal solid waste, natural gas to heat the AD.
[8] MSW–BG: municipal solid waste, biogas to heat the AD.

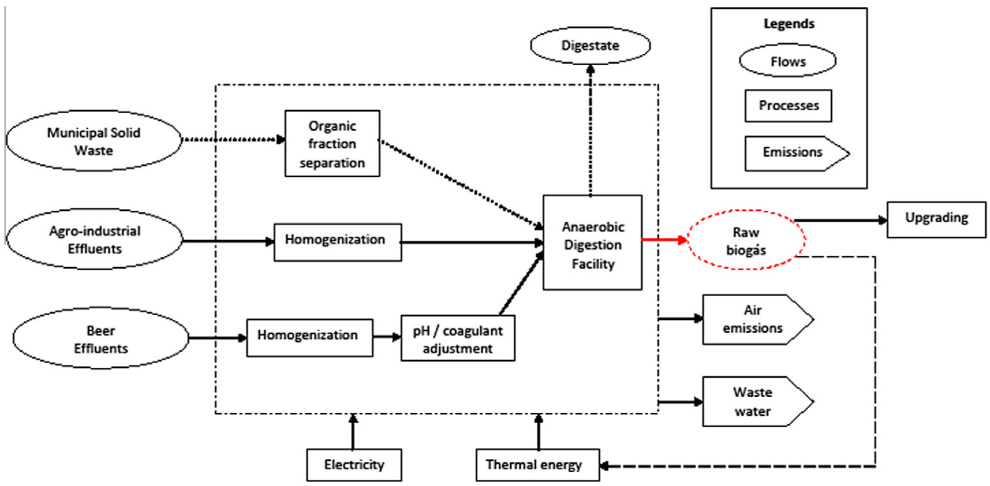

Fig. 2. System boundaries in the biogas generation processes from different sources.

Table 2
Inventory lists for generating biogas from the annual treatment of municipal solid wastes, agro-industrial effluents and brewery effluents.

Flows	Unit	Processes				
		MSW-NG[a]	MSW-BG[b]	AE-NG[c]	AE-BG[d]	BE[e]
Inputs						
Treated waste	kg	145,200	145,200	948,971	948,971	1,084,529
Power	kW	9249	9249	177,499	177,499	729,423
Caustic soda	kg					137,118
Iron trichloride	kg					8510
Natural gas	m^3	3633		182,206		
Biogas	m^3		6364		319,180	
COD[f]	kg			4,015,000	4,015,000	1,149,203
Outputs						
Biogas	m^3	20,075	13,711	1,690,932	1,371,752	371,440
Organic fertilizer	kg	8030	8030			
CO_2 emissions	kg		7788		390,569	
COD[f]	kg			81,939	81,939	171,262

[a] MSW–NG: municipal solid waste, natural gas to heat the AD.
[b] MSW–BG: municipal solid waste, biogas to heat the AD.
[c] AE–NG: agro-industrial effluent, natural gas to heat the AD.
[d] AE–BG: agro-industrial effluent, biogas to heat the AD.
[e] BE: brewery effluent.
[f] COD: chemical oxygen demand.

3. Results and discussion

3.1. Biogas upgrading processes

3.1.1. Life cycle assessment of the biogas upgrading process

Fig. 4 summarizes the results obtained when comparing the biogas upgrading processes using water, amine and DEPG as solvents. The *x*-axis shows the impact categories and the percentage of 100% impact for the process that generates the greatest impact within each category. This figure shows that the amine process generates the largest impact in nearly all categories, except for the human toxicity potential, abiotic resource depletion and climate change categories. The impacts on human toxicity are related to the production of ethylene oxide, which is required for manufacturing DEPG and DGA solvents. Thus, the water process was the least harmful regarding human health. The water process generated minor impacts in all of the studied categories, except for climate change, because of the methane losses that were generated during the biogas upgrading process. The significant environmental impact of this process with amines resulted from the high energy consumptions of the chemical amine production process and the solvent regeneration process with vapor in the upgrading process.

3.1.2. Economic analysis of the biogas upgrading processes

The results of the economic analyses obtained for the three biogas upgrading processes are summarized in Table 4. In this table, the dimensions of the pressure vessels, absorbers and strippers, the power of the pumps and compressors and the thermal duty of the reboilers, coolers and heat exchangers are specified. The investment costs of the processes involving DGA are the lowest, and both processes use water and DEPG, which requires more investment regarding the costs of the compressors and pumps.

Table 5 presents the annual sales revenue, *S*, and biomethane production costs, *C*, divided into three stages (utilities, labor and maintenance costs). The measures of profitability that were calculated for the biogas upgrading processes are also summarized in Table 5. The water upgrading process is the most profitable of the three processes, with the lowest payback period (PBP) and the highest return on investment (ROI). The higher profitability of the water upgrading process, despite being costly in terms of initial infrastructure investments, results from the low operating

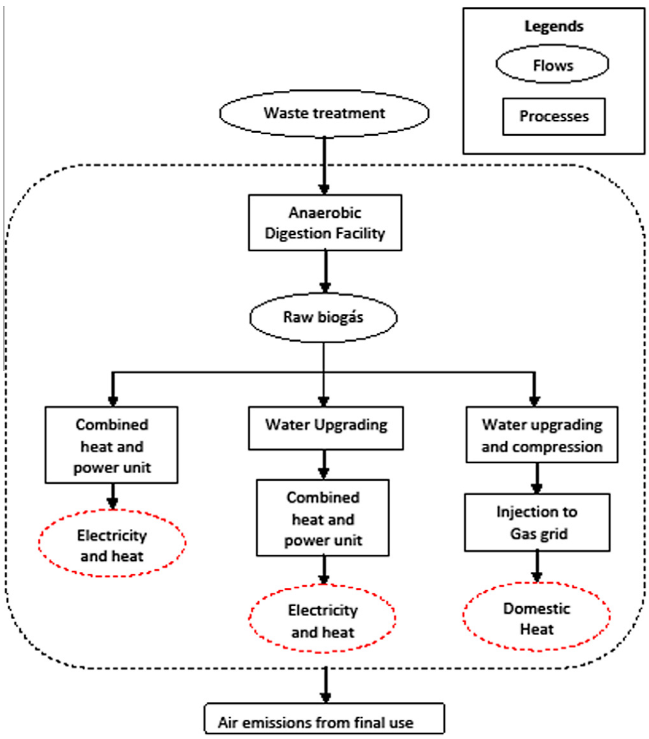

Fig. 3. System boundaries of biogas end use processes

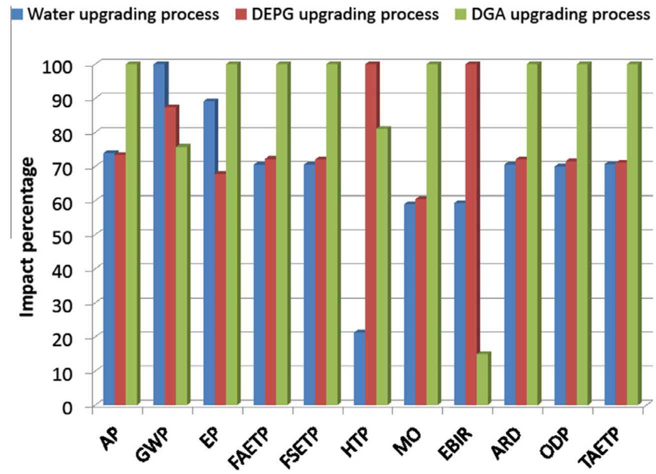

Fig. 4. Environmental impacts associated with the biogas upgrading process. Comparison of the different upgrading technologies. *Abbreviations:* AP, acidification potential; GWP, climate change; EP, eutrophication potential; FAETP, freshwater aquatic ecotoxicity potential; FSETP, freshwater sediment ecotoxicity potential; PHT, human toxicity potential; MO, malodorous air; EBIR, photochemical oxidation; ARD, abiotic resource depletion; ODP, stratospheric ozone depletion; TAETP, terrestrial ecotoxicity.

Table 3
List of the biogas inventory of a plant processing at a rate of 250 m^3/h.

Flows	Units	Injection into the gas grid	Upgrading and CHP	CHP
Input				
Power	kW	147.34	152.13	11.17
Cooling duty	kW	60.50	77.97	
Process water	kg	5.02	5.02	
Outputs				
Air emissions				
H_2S	kg	0.327	0.327	
CO_2	kg	267.09	271.51	467.57
CH_4	kg	5.99	5.99	
N_2	kg	0.02	0.02	0.625
SO_2	kg		0.074	0.131
CO	kg		0.141	0.250
NO_x	kg		0.071	0.125
Energy generated				
Power generated	kW		531	573
Thermal energy recovered	kcal		278,373	319,217
Biomethane	m^3	141	531	

costs, including the lower power consumption and lower solvent cost.

The proven reserves of natural gas in Argentina have declined in recent years (SEN, 2011b) and the country has greatly increased the imports of natural gas (since the 51% of domestic energy supply depends of natural gas). In this context, the water upgrading process is an interesting alternative not only in environmental terms but also in economic terms, considering that the PBP is close to one year. Besides, biogas upgrading projects will generate jobs and give solution to the biological waste generated in municipalities, industries, farms, as is discussed in Section 3.3.

3.2. Biogas generation methods

The results of the biogas generation processes using municipal solid waste and liquid effluents are shown in Fig. 5. When comparing the biogas generation from the organic fractions of the municipal solid waste, it was observed that the MSW–NG option (which uses natural gas for heating the AD) has the greatest impact on almost every category of the MSW–BG option (which uses a fraction of biogas for heating the AD). The MSW–BG option is just above the MSW–NG option regarding human toxicity, stratospheric ozone depletion and terrestrial ecotoxicity, and this position is related to the amount of power consumed during the process, as this process requires more power consumption to produce 1 m^3 of biogas. One advantage of the anaerobic digestion treatment of MSW is the reduction of odor. By using solids that are generated in the digester as fertilizer, the amount of fertilizer is reduced and the malodor decreases.

When generating biogas from agro-industrial effluents, the AE–NG option has greater environmental impacts than the AE–BG option for all analyzed categories, as the use of biogas to heat the digester reduces its environmental impact. The generation of biogas from the brewery effluents had a greater environmental impact for all categories because the presence of caustic soda and iron trichloride in the effluent requires the use of additional chemicals to regulate the pH and coagulation of the effluent before it enters the digester and because the process has a high energy demand. One advantage of generating biogas from liquid effluents is the reduction of the negative effects of eutrophication by reducing the COD (over 85%) through anaerobic digestion.

When comparing the different biogas generation processes, it was observed that biogas generated from the brewery effluents had the largest impact (based on the large amount of energy consumed in the plant per m^3 of biogas and by the chemical demand process). The generation from agro-industrial effluents (AE-BG option) is more environmentally friendly according to the 11 analyzed categories.

The treatment of waste streams is mandatory for industrial and municipalities. For that reason, the generation and utilization of biogas results a convenient option because reduces the environ-

Table 4
Summary of the characteristics and costs of the equipment used in the upgrading processes.

Equipment[a]	Water	Cost (US$)	DEPG	Cost (US$)	DGA	Cost (US$)
Absorber diameter (m)	0.30	$23,167	0.50	$24,206	0.28	$24,175
Flash HP diameter (m)	1.37	$18,899	1.22	$15,615	–	
Flash LP diameter (m)	–		1.22	$13,347	–	
Desorber diameter (m)	1.37	$448	0.61	$1592	–	
Stripper diameter (m)	–		–		0.35	$24,434
Pump 1 (kW)	94.61	$40,272	16.37	$21,653	0.38	$16,488
Pump 2 (kW)	–		1.27	$16,060	–	
Compressor 1 (kW)	51.67	$150,830	27.54	$91,166	13.46	$51,411
Compressor 2 (kW)	–		11.78	$61,842	–	
Vacuum compressor (kW)	1.18	$7307	1.18	$7307		
Cooler 1 (MBtu/h)	210.07	$6574	118.03	$7698	62.22	$4816
Cooler 2 (MBtu/h)	305.17	$8099	158.48	$6888	567.02	$7489
Cooler 3 (MBtu/h)	–		363.38	$7129	–	
Exchanger (MBtu/h)	–		1.88	$2842	486.42	$7462
Reboiler (MBtu/h)	–		445.60	$29,943	782.09	$52,788
Condenser (MBtu/h)	–				198.38	$4038
Total cost (US$)		$255,594		$307,287		$193,102

[a] For equipment, see Fig. 1.

Table 5
Cost sheet and annual sales of the upgrading processes using water, DEPG and DGA.

Cost factor	Water	DEPG	DGA
	Annual cost (US$)		
Utilities			
Power	58806.52	32662.25	31633.52
Refrigeration	31285.98	35106.80	36794.18
Steam	–	11742.98	26430.54
Process water	806.46		0.20
DEPG	–	111473.19	–
DGA	–	–	97345.35
Total utilities	$90898.96	$190985.22	$192203.79
Operations			
Direct wages and benefits (DW&B)	$52,000	$52,000	$52,000
Maintenance			
Wages and benefits (MW&B)	9516.02	10755.05	6758.58
Salaries and benefits	2379.00	2688.76	1689.65
Materials and services	9516.02	10755.05	6758.58
Maintenance overhead	475.80	537.75	337.93
Total maintenance	$21886.84	$24736.63	$15544.73
Annual sales (*S*)	$422077.53	$422077.53	$422077.53
Total product cost (*C*)	$164785.80	$267721.84	$259748.53
Depreciation (*D*)	$20447.51	$24582.98	$15448.18
ROI [a]	0.64	0.32	0.53
PBP [b] (years)	1.39	2.52	1.64

[a] ROI: return on investment.
[b] PBP: payback period.

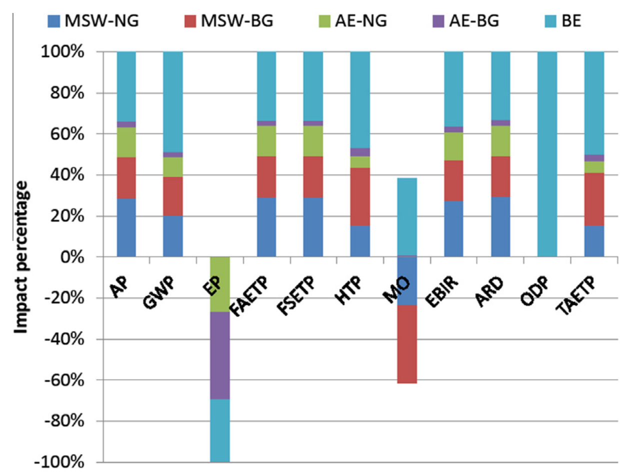

Fig. 5. Environmental impacts associated with biogas generation. Comparison of the treatment processes used for municipal solid wastes using natural gas (MSW–NG) and biogas (MSW–BG), agro-industrial effluents using natural gas (NG–AE) and biogas (AE–BG) and brewery effluents (BE) (for nomenclature impacts, see Fig. 4).

mental impact of waste and produces cleaner energy that can be used in the same place.

3.3. Biogas end use comparison

Fig. 6 shows the results of the environmental impacts when considering the end uses of the biogas, including power production and injection into the natural gas grid. The environmental impacts resulting from the production of 1 kW of power using biogas is compared with the environmental impacts of 1 kW of power from the Argentina power grid in Fig. 6a. The biogas generated from the agro-industrial effluent was used with a fraction of biogas to heat the digester (AE–BG–BM–CHP[9]). The alternatives for heating the digester include using the heat from the CHP plant when using biomethane as a fuel (AE–BM–CHP[10]), using biogas as a fuel (AE–CHP[11]), and using the CHP option without the upgrading stage and heating the digester with biogas (AE–BG–CHP[12]). The results show that the methods used for heat from the CHP (CHP–BM–AE and AE–CHP) result in a lower environmental impact than the options used to fraction the biogas for heating (AE–BG–BM–CHP and AE–BG–CHP). In addition, the processes lacking an upgrading stage (BG–AE–BG–CHP and AE–CHP) generated a significantly lower impact than the processes involving the upgrading stage (AE–BG–BM–CHP and CHP–BM-–AE). The environmental impact of energy produced in the Argentina power grid is greater in all categories.

In Fig. 6b, the environmental impacts of producing 1 m^3 of biomethane for injection into the grid are compared with those of producing 1 m^3 of natural gas. Here, the biogas generated from agro-industrial effluents (AE–NG, AE–BG) is considered. The results show that the production of biomethane results in greater impacts

[9] AE–BG–BM–CHP: agro-industrial effluents, biogas to heat the AD, biomethane to feed the CHP unit.

[10] AE–BM–CHP: agro-industrial effluents, heat from CHP to heat the AD, biomethane to feed the CHP unit.

[11] AE–CHP: agro-industrial effluents, heat from CHP to heat the AD, biogas to feed the CHP unit.

[12] AE–BG–CHP: agro-industrial effluents, biogas to heat the AD, biogas to feed the CHP unit.

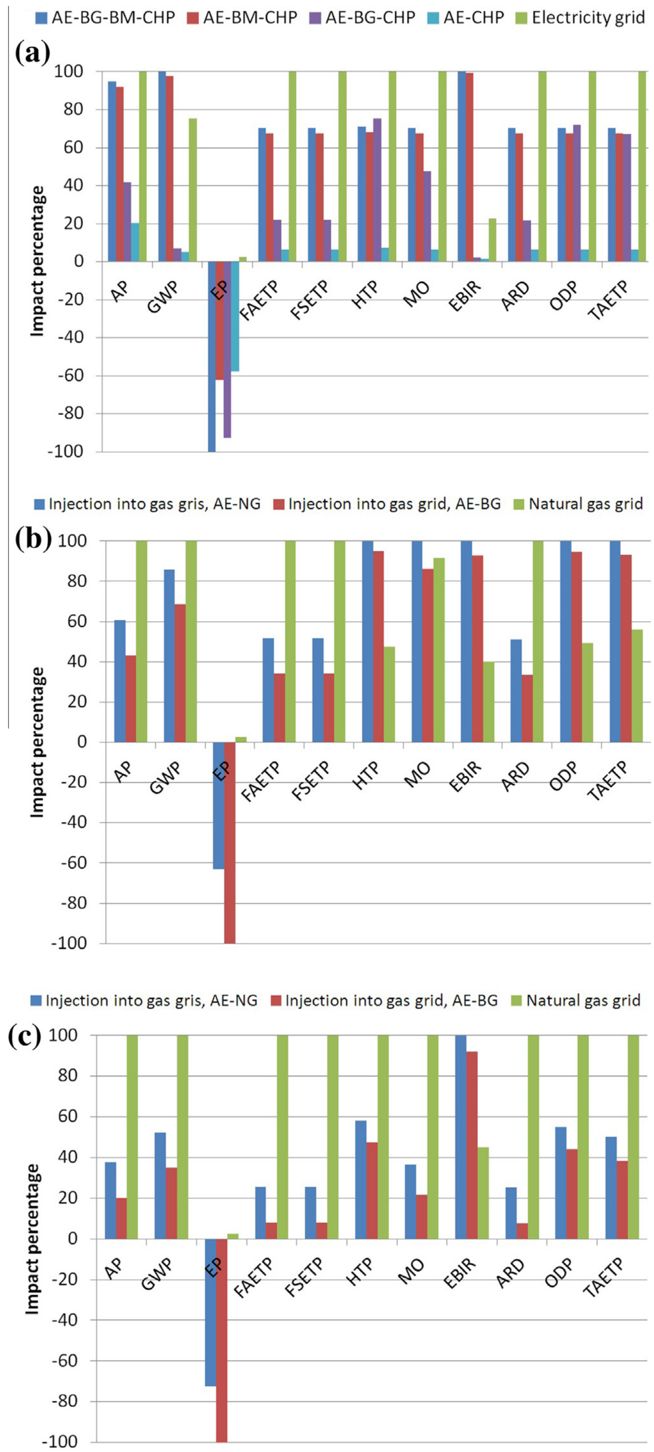

Fig. 6. Environmental impacts associated with the production of (a) 1 kW of power obtained by comparing the alternative of the Argentina power grid with the alternatives from biogas (treatment of agro-industrial effluents using: biogas for heating and biomethane for CHP (AE–BG–BM–CHP), exhaust gas for heating and biomethane for CHP (AE–BM–CHP), biogas for heating and CHP (AE–BG–CHP) and exhaust gas for heating and biogas for CHP (AE–CHP)); (b) 1 m^3 of biomethane for injection into the gas grid from the treatment of agro-industrial effluents (NG–AE, AE–BG) with the alternative of natural gas; and (c) 1 m^3 of biomethane for injection into the gas grid from the treatment of agro-industrial effluents (NG–AE, AE–BG) (using biogas for power generation) with the alternative of natural gas (for impact nomenclature, see Fig. 4 and for agro-industrial effluent nomenclature, see Fig. 5).

than the production of natural gas when considering the HTP, MO, EBIR, ODP and TAETP categories. The high environmental impacts of this process are associated with the energy consumption that is required in the upgrading stage. The environmental impacts resulting from the use of biogas as the power needed for the upgrading process are shown in Fig. 6c. In this figure, it is observed that replacing conventional power with power produced by biogas reduces the environmental impact in most cases. Less impact was observed in the climate change category, and the impact in the photochemical oxidation category was largely due to CH_4 emissions. The amount of biogas required for power production to achieve the quality specifications of natural gas is 35% of the generated biogas showing that biomethane has the potential to replace natural gas in the grid.

Therefore, the utilization of biogas to power production and injection into the natural gas grid is a feasible process for application in Argentina, as it minimizes environmental impacts, improving the socioeconomic development of the country and is energetically efficient. Further research is needed to evaluate the use of biogas in certain marginal regions (such as farm, diaries, feedlot) where there are not natural gas network or power grid and where the availability of organic matter is abundant, allowing exploit the resources of the place.

4. Conclusions

Evaluating different biogas upgrading processes allow selecting the water upgrading process as the best option for local application. The economic analysis show that the water upgrading process is more economically better feasible because it is a simple process with low impacts on the environment and human health. Analyzing the overall process (generation, upgrading and final use) allow to select a process that minimized its impact on the environment depending on the end use. Overall, biogas should be used as an energy source to make the upgrading process for injecting biomethane into the grid sustainable.

Acknowledgements

The authors acknowledge the financial support received from the Universidad Nacional del Litoral (UNL) and the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET).

References

Beylot, A., Villeneuve, J., Bellenfant, G., 2013. Life cycle assessment of landfill biogas management: sensitivity to diffuse and combustion air emissions. Waste Manage. 33 (2), 401–411.
Borjesson, P., Berglund, M., 2006. Environmental systems analysis of biogas systems – Part I: Fuel cycle emissions. Biomass Bioenergy 30 (5), 469–485.
Cherubini, F., Stromman, A.H., 2011. Life cycle assessment of bioenergy systems: state of the art and future challenges. Bioresour. Technol. 102 (2), 437–451.
De Vries, J.W., Vinken, T.M.W.J., Hamelin, L., De Boer, I.J.M., 2012. Comparing environmental consequences of anaerobic mono- and co-digestion of pig manure to produce bio-energy – a life cycle perspective. Bioresour. Technol. 125, 239–248.
Decree 518/1998, 1998. Impuesto sobre los combustibles líquidos y gas natural. Poder Ejecutivo Nacional, Argentina.
ENARGAS (Ente Nacional Regulador del Gas), 2008. Reglamentación de las especificaciones de calidad de gas natural – Resolución 259/08. Available from: <http://www.enargas.gov.ar>.
Frischknecht, R., 1999. Umweltrelevanz natürlicher kältemittel: Ökobilanzen von wärmepumpen und kälteanlagen. Schlussbericht im Auftrag des Bundesamtes für Energie (BFE).
Guinee, J., 2001. Handbook on life cycle assessment – Operational guide to the ISO standards. Int. J. Life Cycle Assess. 6 (5), 255.
Guthrie, K.M., 1970a. Capital and operating costs for 54 chemical processes. Chem. Eng. 77 (13), 140–156.
Guthrie, K.M., 1970b. Data and techniques for preliminary capital cost estimating. Chem. Eng. 76, 114–142.
ISO 14040:2006, 2006. Environmental Management – Life Cycle Assessment – Principles and Framework. International Organisation for Standardisation (ISO), Geneva, Switzerland.
ISO 14044:2006, 2006. Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Organisation for Standardisation (ISO), Geneva, Switzerland.

Jury, C., Benetto, E., Koster, D., Schmitt, B., Welfring, J., 2010. Life cycle assessment of biogas production by monofermentation of energy crops and injection into the natural gas grid. Biomass Bioenergy 34 (1), 54–66.

Lang, H.J., 1947. Engineering approach to preliminary cost estimates. Chem. Eng., 130–133

Lang, H.J., 1948. Simplified approach to preliminary cost estimates. Chem. Eng. 55 (6), 112–113.

Law 26093/2006, 2006. Régimen de regulación y promoción para la producción y uso sustentables de biocombustibles. Honorable Congreso de la Nación Argentina.

Law 26190/2006, 2006. Régimen de fomento Nacional para el uso de fuentes renovables de energía destinada a la producción de energía eléctrica. Honorable Congreso de la Nación Argentina.

Morero, B., Campanella, E.A., 2014. Comparación técnico ambiental de diferentes procesos de purificación de biogás. Avances en Energías Renovables y Medio Ambiente (ISSN 0329-5184).

OpenLCA, 2013. Professional Life Cycle Assessment (LCA) Software. GreenDelta GmbH, Berlin, Germany.

Patterson, T., Esteves, S., Dinsdale, R., Guwy, A., 2011. Life cycle assessment of biogas infrastructure options on a regional scale. Bioresour. Technol. 102 (15), 7313–7323.

Patterson, T., Esteves, S., Dinsdale, R., Guwy, A., Maddy, J., 2013. Life cycle assessment of biohydrogen and biomethane production and utilisation as a vehicle fuel. Bioresour. Technol. 131, 235–245.

Pertl, A., Mostbauer, P., Obersteiner, G., 2010. Climate balance of biogas upgrading systems. Waste Manage. 30 (1), 92–99.

Poeschl, M., Ward, S., Owende, P., 2012a. Environmental impacts of biogas deployment – Part I: Life Cycle Inventory for evaluation of production process emissions to air. J. Cleaner Prod. 24, 168–183.

Poeschl, M., Ward, S., Owende, P., 2012b. Environmental impacts of biogas deployment – Part II: Life Cycle Assessment of multiple production and utilization pathways. J. Cleaner Prod. 24, 184–201.

ProMax®, 2013. Bryan Research and Engineering, Inc. Copyright 2013 BRE Group Ltd.

Rehl, T., Muller, J., 2011. Life cycle assessment of biogas digestate processing technologies. Resour. Conserv. Recycl. 56 (1), 92–104.

Rehl, T., Lansche, J., Muller, J., 2012. Life cycle assessment of energy generation from biogas. Attributional vs consequential approach. Renew. Sustain. Energy Rev. 16 (1), 3766–3775.

Seider, W.D., Seader, J.D., Lewin, D.R., 2004. Product and Process Design Principles: Synthesis, Analysis and Design, second ed. John Wiley & Sons Inc..

SEN (Secretaría de Energía República Argentina), 2011. Informe estadístico del sector eléctrico. Available from: <http://www.energia.gov.ar>.

SEN (Secretaría de Energía República Argentina), 2011. Reservas de gas y petróleo. <http://energia3.mecon.gov.ar/contenidos/verpagina.php?idpagina=3312>.

Starr, K., Gabarrell, X., Villalba, G., Talens, L., Lombardi, L., 2012. Life cycle assessment of biogas upgrading technologies. Waste Manage. 32 (5), 991–999.

Sutter, J., 2007. Life cycle inventories of petrochemical solvents. Life Cycle Inventories of Chemicals. Final Report Ecoinvent Data V2.0.

U.S. Life Cycle Inventory Database, 2012. National Renewable Energy Laboratory.