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From Biogas to Biomethane: How the Biogas Source Influences the Purification Costs

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Often left in the background by media, biogas is a renewable energy source with a great potential for development. Its production is based on the anaerobic digestion of organic waste materials, which are usually livestock effluents, municipal and industrial sewage sludge, energy crops, agro-industrial wastes, MSW landfills, etc. To date, biogas is mainly used for the production of electrical energy, thanks to a more favorable regulatory and incentive framework. Installations may adopt a cogeneration arrangement, that allows to recover the heat produced by gas-fired engines for home or industrial reuse. In the near future, however, the biogas properly upgraded to biomethane will be used for transportation or fed into the natural gas grid directly reaching end consumers, both solutions adding value to biogas. The utilization of biogas is in line with the “20-20-20” targets to be met by the Member States of the European Union by 2020, which provide that 20 % of EU energy consumption will have to come from renewable resources and that the share of energy from renewable sources in the transport sector in 2020 will be at least 10 %. Biomethane is obtained from properly treated biogas. Biogas is a mixture of mainly methane and CO_2 with other contaminants (such as H_2S, nitrogen and oxygen), whose type and amount depend upon the biogas source and determine which cleaning technique (and, to some extent, also upgrading technique) is the most suitable for gas purification. ”Cleaning” is referred to the pretreatment that allows the removal of all pollutants but carbon dioxide, while “upgrading” consists of CO_2 removal. There are no clear guidelines for choosing among the different techniques, mainly in relation with the biomass source which affects the biogas composition. This work performs a techno-economic analysis of the biogas-to-biomethane process using three different biogases produced from sewage sludge, agro-industrial wastes and landfills, using water scrubbing and amine washing for the upgrading process. By means of process simulation with commercial software (such as Aspen Plus®), a comparison among performances, energy requirements and solvent type is carried out. In the end, an economic assessment of the two upgrading techniques for the three considered biogas sources is performed, taking into account the flow rate of the biogas to be treated.

1. Introduction

The global energy demand is growing rapidly and an important part of it is currently met by fossil fuels which are responsible for CO_2 emissions. In order to reduce climate change impacts, governments have proposed some ambitious climate and energy targets, like the so-called “20-20-20 targets” set by the European Union. One of the objectives to be reached within the year 2020 concerns raising the share of EU consumption of energy produced from renewable resources to 20 % (European Commission, 2014). In this context, the production of biogas has gained more and more attention, as proved by the latest statistics for Europe (European Biogas Association, 2013). Biogas is a versatile energy source. Firstly, it can replace fossil fuels in heat and power generation, providing a solution to environmental problems and to the energy security global challenge which has to be faced because most of the conventional oil and gas reserves are located in politically unstable regions. Secondly, methane-rich biogas (biomethane) can be used as a vehicle fuel (like in Sweden or Switzerland) or be injected into the natural gas grid (Weiland, 2010). It can also substitute natural gas as feedstock in the production of chemicals and materials. Biogas production offers many advantages including a reduction of the release of methane (which has a global warming potential 23 times higher than carbon dioxide) to the atmosphere compared to traditional manure disposal or landfill management.

The aim of the work is to perform a techno-economic analysis to compare biomethane production from three different feedstocks and considering the two most widespread technologies for biogas upgrading (i.e., water scrubbing and amine washing).

2. Biogas sources and upgrading technologies

Biogas is produced during anaerobic digestion of several organic substrates which are converted to a mixture mainly consisting of methane and carbon dioxide with traces of other gases. The type of substrate affects the methane content in biogas. Historically, anaerobic digestion has been associated with the treatment of animal manure and sewage sludge from aerobic wastewater treatment. More recently, agricultural biogas plants digest manure from different animals with the addition of co-substrates to increase the content of organic material in order to achieve a higher gas yield. Typical co-substrates are harvest residues (e.g., top and leaves of sugar beets), organic wastes from agriculture-related industries, the organic fraction of household and industrial waste and energy crops. Biogas is also formed during anaerobic degradation in landfills: in such a case the obtained biogas is referred to as landfill gas and its utilization allows to reduce the methane that would be released to the atmosphere in case of traditional landfill management (Petersson and Wellinger, 2009). When compared with biogas from other sources, landfill gas is characterized by an average methane content lower than that of “conventional” biogas (because of the heterogeneity of the disposed waste) and it usually contains nitrogen from air that naturally seeps into the landfill during recovery.

In order to increase the quality of the raw biogas for the end use, it typically undergoes a cleaning step to be purified from undesired components, such as hydrogen sulphide and water, in order to prevent damages to gas utilization equipment. The cleaning step is then followed by the upgrading step which aims at removing carbon dioxide and increasing the biogas energy density. Several technologies for biogas upgrading are commercially available (Bauer et al., 2013), including water washing or scrubbing with organic solvents, chemical scrubbing by means of alkanolamine solutions, pressure swing adsorption using activated carbon or molecular sieves and membrane technologies. Some new technologies are also being developed, such as cryogenic separation.

3. Case study definition

This work compares the costs of the biogas-to-biomethane route for three different feedstocks and for two of the most commonly used upgrading technologies (Gamba and Pellegrini, 2013): water scrubbing and chemical washing by alkanolamine solutions. Therefore, six cases have been simulated and compared.

3.1 Feedstocks

Since the substrate composition affects the yield of biogas and its content of methane, three different feedstock materials have been considered for comparison. The composition of the corresponding produced biogas is reported in Table 1. As for the landfill gas, the average composition of the biogas produced by the ‘Balançan’ municipal solid waste landfill in Le Cannet des Maures (France) has been considered (Jaffrin et al., 2003). The biogas of the Yonkers (NY) sewage processing facility owned and operated by Westchester County (Spiegel and Preston, 2003) has been taken as an example of biogas from wastewater (sewage) treatment plants. For the biogas produced by agricultural biogas plants, the composition has been taken from that reported by Herout et al. (Herout et al., 2011), which concerns a biogas produced by co-fermentation of biomass (maize silage, grass haylage and rye grain) and liquid cattle manure.

Table 1: Composition of the three analysed biogas streams

	Landfill gas	Gas from WWT	Gas from co-fermentation
Methane	0.3677	0.5774	0.5574
CO_2	0.2739	0.3856	0.4387
N_2	0.2905	0.0370	0
O_2	0.0679	0	0.0039

3.2 Simulation of the upgrading process

Water washing and chemical absorption by a 50 % wt. MDEA aqueous solution (in the following indicated as WW and MDEA, respectively) have been applied to the three biogas streams considered in this work for the removal of carbon dioxide. Both upgrading processes have been simulated in Aspen Plus® (AspenTech, 2012). The biogas fed to the upgrading section is at a temperature of 35 °C and at a pressure of 1.1 bar. The layout of the water scrubbing upgrading process (Bortoluzzi et al., 2014b) is shown in Figure 1. The inlet biogas stream is compressed to 8 bar and purified in a packed absorption column; the rich solvent is first regenerated in a flash chamber and then in a stripping column by means of an air stream.

The chemical scrubbing has been simulated considering a conventional process scheme (Gamba et al., 2014), as shown in Figure 2, and using a rate-based approach. Details about the thermodynamic modeling of CO_2 absorption with MDEA can be found in the literature (Moioli et al., 2013). The built-in method of Aspen Plus® has been used for describing heat transfer (Taylor and Krishna, 1993) and mass transfer (Onda et al., 1968) with reaction kinetics.

The raw biogas is fed to the absorption column operated at 2.7 bar, after a single-stage compression and cooling down to 35 °C. Both the absorption column and the column for regeneration of the solvent are packed columns (packing: metal Pall rings). For each of the three cases corresponding to the different feedstocks, at fixed amine flow rate, the packing height of the regeneration column has been chosen to minimize the reboiler duty whereas the packing height of the absorption column has been determined in order to obtain the maximum possible concentration of methane in the gas outlet stream. The diameters of the two columns have been adjusted from the ones used in a previous work (Gamba and Pellegrini, 2013), according to the total gas flow rate entering the upgrading section.

For each of the six studied cases, the total flow rate for the inlet biogas is such that the volumetric flow rate of methane in the gaseous stream leaving the absorption column is 500 Sm^3/h to account for the high capacities of wastewater treatment plants and landfills. This choice provides a common basis for a comparison among the six cases and implies that the gas outlet stream from the absorption column is concentrated in downstream processing for removing nitrogen and/or oxygen in the landfill and in the WWT cases.

4. Cost evaluation

In order to assess the economic feasibility of the different solutions, a preliminary sizing of the major equipment found in the upgrading process for each case has been performed according to common process engineering practice (Turton et al., 2003). For each piece of equipment the purchased equipment costs have been determined using the generalized charts provided by Ulrich (Ulrich, 2004). Then, the cost has been scaled using the six-tenths-rule to account for the effect of capacity and it has been updated from the reference year (2004) to the year 2014 using the Chemical Engineering Plant Cost Index. The resulting capital costs estimated for the upgrading section are reported in Table 2, along with the investment costs of the overall plant. These include also the cost of the biogas production section (comprising the cost of digesters or biogas captation wells and the cost of the heating system necessary to satisfy the thermal requirements of the digesters by burning a fraction of raw biogas), the cost of biomethane concentration (necessary to meet the specifications for biomethane grid injection in the two cases of biogas from water treatment plants and landfill gas) and the cost of the connection to the gas network (assumed as 300 k€). Considering the same type of feedstock, a slightly higher investment cost is needed for the MDEA case compared to the WW case.

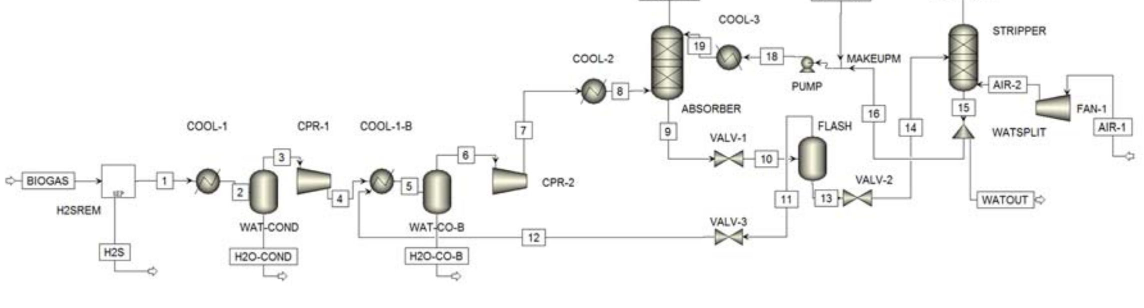

Figure 1: Process flow scheme of the water scrubbing upgrading process simulated in Aspen Plus®

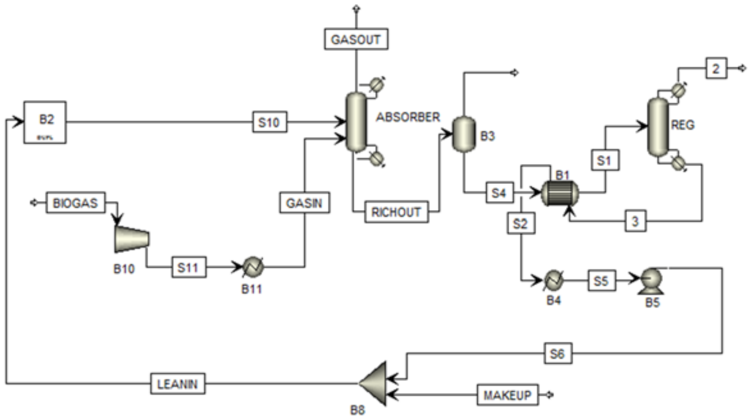

Figure 2: Process flow scheme of the chemical scrubbing upgrading process simulated in Aspen Plus®

As shown in Table 3, this is due to the thermal consumption required in addition to that for operating the digester in the biogas production section, which results in a larger plant size. Moreover, considering the same biomethane production capacity of 500 Sm^3/h, the electric specific consumption for the biogas production section is always higher in the WW option than in the MDEA one as result of the higher operating pressure of the absorber (8 bar vs 2.7 bar) and of the higher solvent circulation rate.

As for the operating expenses, the cost of the feedstock has been taken into account for the case of biogas produced by co-fermentation of biomass and liquid cattle manure, assuming a manure/biomass ratio of 0.7 and a cost of 35 €/t for biomass (cattle manure has been considered to be free of charge). The operating costs of digesters have been assumed to be 4 % of their capital cost, whereas those of the upgrading section are estimated to be 2 % of the capital costs of this section. A value of 0.11 €/kWh_e has been used for taking into account the electricity imports for both the biogas production and upgrading sections. Overheads have been set to 1 % of total plant capital costs.

Revenues are computed as the incentives for biomethane fed into the grid, considering a 10 % increase of twice the 2012 market value for natural gas (i.e., 28.52 €/MWh_{HHV}).

Table 2: Capital costs (M€) of the upgrading section and of the overall plant for the six investigated cases

Case	CAPEX upgrading section	Overall CAPEX
WW-Gas from co-fermentation	2.2	7.6
WW-Gas from WWT	2.2	11.3
WW-Landfill gas	2.9	6.1
MDEA-Gas from co-fermentation	2.3	7.8
MDEA-Gas from WWT	2.3	11.7
MDEA-Landfill gas	3.0	6.1

Table 3: Thermal and electricity consumption (kW) of the biogas production and upgrading sections for the six investigated cases

Case	Biogas production section		Biogas upgrading section	
	Thermal consumption	Electricity consumption	Thermal consumption	Electricity consumption
WW-Gas from co-fermentation	483	97	0	288
WW-Gas from WWT	468	94	0	273
WW-Landfill gas	0	4	0	415
MDEA- Gas from co-fermentation	502	100	285	89
MDEA- Gas from WWT	485	97	273	87
MDEA- Landfill gas	0	4	396	120

5. Results and Discussion

Given the capital costs of the overall plant, the operating costs and the incentives on biomethane grid injection, the annual cash flows and commonly used profitability parameters - Internal Rate of Return (IRR), Net Present Value (NPV) and Payback Time (PBT) - have been calculated based on the assumptions taken from LEAP experience on thermo-economic assessments of biogas plants (Bortoluzzi et al., 2014a). Table 4 sums up the results of the cash flow analysis for the six analysed cases for transforming biogas to biomethane.

Table 4: Economic performances of the six investigated cases

Case	IRR (%)	NPV (M€) (D.R. = 0 %)	PBT (y) (D.R. = 0 %)
WW-Gas from co-fermentation	10.6	8.6	7.3
WW-Gas from WWT	10.5	14.0	7.7
WW-Landfill gas	23.0	20.1	4.2
MDEA-Gas from co-fermentation	12.6	11.5	6.6
MDEA-Gas from WWT	11.4	16.3	7.3
MDEA-Landfill gas	26.4	24.7	3.7

The IRR of all the analyzed cases are positive, but if the three cases concerning biogas upgrading by water scrubbing are compared with the corresponding ones for which carbon dioxide removal has been performed by chemical absorption with an aqueous solution of MDEA, it turns out that chemical scrubbing should be preferred. This can be explained by the higher operating costs found in the WW option.

Considering the same upgrading technology, of the three feedstocks taken into account in this work the landfill gas is the one which shows a higher profitability, with a NPV ranging from 5 to 25 M€ for the MDEA case, depending on the discount rate as shown in Figure 3. The landfill gas turns out to be better than the biogas obtained from co-fermentation because it is not affected by feedstock costs and it performs better than the gas from wastewater treatment plants since it shows lower capital costs for the biogas production section.

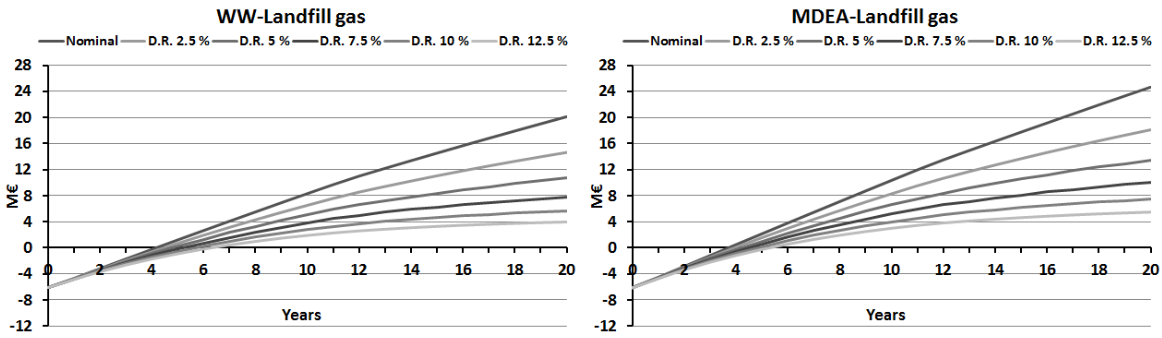

Figure 3: Cumulative discounted cash flows for the landfill gas considering the two upgrading technologies

6. Conclusions

This work presents a techno-economic analysis of biomethane production from biogas upgrading by scrubbing with water or with a MDEA aqueous solution, considering three types of feedstock (landfill gas, biogas from wastewater treatment plants and an agricultural feedstock) and a biomethane production capacity of 500 Sm^3/h. As for the upgrading technologies, the economic analysis carried out starting from the technical evaluation has demonstrated that, for the same feedstock, despite lower investment costs, upgrading by water scrubbing is less profitable when compared with upgrading by chemical absorption mainly due to a larger electricity consumption: as an example, the plant fed with the agricultural feedstock consumes 0.576 $kWh/Sm^3_{BIOMETHANE}$ in the WW option and 0.179 $kWh/Sm^3_{BIOMETHANE}$ in the MDEA case. As far as the type of feedstock is concerned, although the subsidies ensures a positive profitability in all cases, the landfill gas, which contains a lower amount of carbon dioxide than the other two biogases, guarantees better performances.

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