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Global and local emissions of a biogas plant considering the production of biomethane as an alternative end-use solution

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ABSTRACT

The conversion of biomass to energy is a complex process whose environmental sustainability must be assessed. In the present work, global and local emissions of a biogas plant are evaluated considering two alternative end uses: combustion of biogas in a combined heat and power unit or upgrading of biogas to biomethane and subsequent injection to the gas grid or use in transports. Global emissions are estimated by using the carbon footprint methodology, comparing the scenarios on the basis of the same functional unit. The results show a CO_2 reduction for biogas combustion equivalent to that of biomethane used as fuel in transports. If the thermal energy produced by the biogas cogenerator is not used, the greenhouse gas balance approaches to zero. A second part of the work considers the contribution of methane losses from the upgrading process. The equivalent CO_2 saving raises considerably if methane slip is limited to 0.05%, while the process results no longer sustainable for a methane loss of 4%. The evaluation of local impacts considers the emission of NO_x and particulate matter (PM) generated by biogas combustion and its alternative solution. A Gaussian model of dispersion is applied and ground level iso-concentration maps are generated. The results show a variable extension of the plume which may a cause non-negligible impact of these pollutants in the surroundings of the source. Adopting biomethane as the end use solution could partly or totally avoid these local impacts. In conclusion, this work points out that adopting the biomethane solution may result environmentally sustainable in terms of greenhouse gas emissions and reduction of NO_x and PM local emission.

1. Introduction

Biofuels applications are acquiring an increasing importance as a component of low-carbon and renewable energy source. The European Union pushed member states toward the development of these technologies, by the emission of energy policies, as the Directive 2009/28/EC (2009), that promote the reduction of the greenhouse gas (GHG) emission and the use of energy from renewable resources. EU countries adopted these policies by introducing local regulations and feed-in schemes, further increasing the interest in bioenergy production.

Nonetheless, there is concern on the sustainability of bioenergy chains (Cherubini, 2010; Blengini et al., 2011). The conversion of biomass to energy is a complex process that involves physical and biological transformations, with relevant mass and energy exchanges connected both to agri-forestry subsystems and to industrial processes. The environmental compatibility of biofuel chains must be assessed, in order to guarantee an efficient performance in terms of GHG saving and production of renewable energy resources. Anaerobic digestion of agricultural products (maize silage, triticale, sorghum etc.) and organic wastes from industry and agriculture is the most frequently employed bioenergy technology to this day. A survey study made by Fraunhofer Institute (2012) indicated around 10,000 biogas installations in Europe in 2012, expecting a raise to 13,500 units by 2016.

Abbreviations: AwR, alkaline with regeneration carbon mineralization; BABIU, bottom ash for biogas upgrading; CH_4, methane; CHP, combined heat and power; CO_2, carbon dioxide; CO_{2eq}, equivalent carbon dioxide; CRY, cryogenic separation; dLUC, direct land use change; GHG, greenhouse gas; GWP, global warming potential; H_2S, hydrogen sulfide; iLUC, indirect land use change; LCA, life cycle assessment; LPG, liquefied petroleum gases; MB, membrane permeation; MEA, chemical absorption with amine solutions; NG, natural gas; NH_3, ammonia; NO_x, nitrogen oxides; PM, particulate matter; $PM_{2.5}$, particulate matter $\leq$2.5 μm; PM_{10}, particulate matter $\leq$10 μm; PSA, pressure swing absorption; PWS, pressurized water scrubbing; SCR, selective catalytic removal; SO_2, sulfur dioxide; VOC, volatile organic compounds; VS, volatile solids; λ, excess air-to-fuel ratio.

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Until today, the predominant final use of biogas has been its on site combustion in endothermic engines for the co-generation of electricity and heat (Combined Heat and Power, CHP). Combustion represents an efficient destination for biogas, in particular if there is a need of thermal energy next to the production site (Patterson et al., 2011). On the other hand, biogas combustion holds back some environmental issues, that concern both global and local aspects. Local impacts are mainly represented by the formation of thermal NO_x due to the Zeldovich mechanism (Hill and Douglas, 2000), or by the generation of primary and secondary particulate matter (PM) (Tree and Svensson, 2007). Both pollutants represent a hazard to human health and ecosystems.

Research is addressing efforts to look for sustainable alternatives to biogas combustion. A possible future competition for conventional anaerobic degradation might be represented by biohydrogen, which has received significant attention from both the scientific community and stakeholders (Bakonyi et al., 2014). Anyway, to this day the most common alternative to biogas combustion consists in the production of biomethane, that is, separating methane fraction from other gaseous components by mean of a treatment process commonly referred as biogas upgrading.

Currently, the market of upgrading technologies is at the stage of development. The majority of these applications derives from the other gas separation know-how. The most frequently used technologies are pressurized water scrubbing (PWS), pressure swing absorption (PSA), chemical absorption with amine solutions (MEA), membrane permeation (MB) and cryogenic separation (CRY) (Makaruk et al., 2010). Other emerging technologies are those based on carbon mineralization. These latter may be distinguished between alkaline with regeneration (AwR) or bottom ash for biogas upgrading (BABIU) (Starr et al., 2012). The mentioned processes allow the achievement of a methane rich fraction whose energy yield is potentially nearly equal to the one of biogas, thanks to limited conversion losses. In addition, the amount of residual contaminants present in the methane fraction (H_2S, CO_2, oxygen, nitrogen, and other organic components) may be also limited, that makes biomethane adapt to be injected into the national gas transmission grid, or be employed as fuel in transports.

Although it represents a good opportunity, biomethane must be justified by an environmental perspective, since it involves additional energy consumption and emissions with respect to biogas, seen that part of the methane is lost during the upgrading process. This environmental assessment represents the object of the present study.

Environmental sustainability of biogas has been treated widely in literature, in particular employing Life Cycle Assessment (LCA) tools, and there is a growing interest addressed to biomethane. Nonetheless, since biomethane is a quite novel application, there is a substantial lack of knowledge on the environmental aspects connected to the upgrading technologies. Poeschl et al. (2010b) included the analysis of different biogas utilization pathways in their study, indicating that the most efficient solutions for small and large-scale biogas plants in terms of primary energy input to output was CHP generation with heat utilization at a relatively short transmission distance. Pertl et al. (2010) tried to identify an upgrading scenario featuring minimum overall GHG emissions. The study considered four different upgrading technologies (PWS, MB PSA and BABIU). BABIU-scenarios shown the lowest impact of GHG emissions thanks to the CO_2 sequestrated by the bottom ash. However, the authors put in evidence that the data obtained from this method are based solely on laboratory experiments. Considering the methods in practice, PWS was identified as the more “climate-friendly”. Starr et al. (2012) evaluated the LCA of four different biogas upgrading technologies (PWS, MEA, PSA, CRY) comparing them with AwR and BABIU on the basis of 1 ton of CO_2 removed (functional unit). The results still highlight that BABIU process shows the least environmental impact. Anyway the authors put in evidence that these performances go beyond any economical evaluation. This study, rather than give an insight on the different upgrading technologies, aimed to evaluate the environmental aspects of a biogas plant in terms of global (greenhouse gases) and local (NO_x and particulate matter) emissions, by comparing two alternative end-uses: the “traditional” combustion in a CHP unit and the “novel” upgrading to biomethane. The GHG contribution was calculated by using the carbon footprint methodology. A Gaussian model was employed to calculate the local dispersion and concentration of gaseous pollutants NO_x and PM. The work was organized in three separate sections, described as follows:

- Task 1: Carbon footprint of biomethane production process was compared to that generated by the direct on site combustion of biogas in a CHP unit.
- Task 2: Carbon footprint of biomethane production process was calculated for different levels of methane losses from the upgrading process.
- Task 3: Local dispersion of NO_x and PM was calculated for the combustion of the biogas and for its alternative solution.

2. Materials and methods

In the present section, the biogas producing process, the upgrading installation and the methodology employed for the environmental evaluation are described.

2.1. Biogas plant

The present study considers a biogas production through anaerobic digestion of cattle slurry and energy crops (maize silage), according to the most frequent observed technical configuration in Italy (Brizio, 2012). The data and configuration of the plant do not come from a specific existing site, but represent an average of the region. The plant works with a mesophilic process (42 °C) and a hydraulic retention time around 60 days. The anaerobic digester is fed by 47.5 t/d of maize and 48.5 t/d of cattle slurry. Biogas production is around 14,051 m^3/d, and is it assumed to be composed of 53% of CH_4 and 47% of CO_2, percentages in volume. The feedstock-to-biogas mass balance of the plant is reported in Table 1. The data presented in Table 1 were taken from the average of the commercial plants in exercise in Italy, reported by Saracco and Antonini (2014) and Brizio (2012). Biogas produced corresponds to about 2.5 MW of thermal energy available. It is desulfurized and then conveyed to an Otto engine, generating around 1 MW of electrical energy and 1 MW of thermal energy. The combustion takes place with an excess air ratio value of 40%.

The functional scheme of the process together with the relevant flows for biogas combustion is reported in Figs. 1 and 2. Biogas losses from digester were assumed to be 0.3% of total biogas produced, according to Dumont et al. (2013). Emission of unburnt methane from the engine was assumed to be 1.78% of the total methane contained in the biogas, according to Dumont et al. (2013) and van Dijk (2011). The operating time of the plant was estimated to be 8000 h/y. The amount of electricity auto-consumed by the plant was estimated to be 400 MWh/y. This value comes from field measurements made by Buratti et al. (2013) on a 1 MW biogas plant with similar working conditions of the present. Other studies show a variability in parasitic electricity demand, depending on requirements for stirring to maintain slurry homogeneity, pumping and conveying liquid feedstock and other auxiliary equipments (Poeschl et al., 2010b). The amount of thermal energy auto-

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