Algal Research 25 (2017) 237–243

Contents lists available at ScienceDirect

Algal Research

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

A comparative analysis of biogas upgrading technologies: Photosynthetic vs physical/chemical processes

Alma Toledo-Cervantes[a], José M. Estrada[b], Raquel Lebrero[a], Raúl Muñoz[a,*]

[a] *Department of Chemical Engineering and Environmental Technology, University of Valladolid, Dr. Mergelina s/n, Valladolid 47011, Spain*
[b] *Temple Group Ltd., Devon House, 58-60 St. Katharine's Way, London E1W 1LB, United Kingdom*

ARTICLE INFO

Keywords:
Activated carbon filter
Algal-bacterial photobioreactor
Bio-methane
Photosynthetic biogas upgrading
Water scrubber

ABSTRACT

Two biogas upgrading technologies, viz. an innovative algal-bacterial photobioreactor and a conventional activated carbon filter coupled with a water scrubber, were comparatively evaluated in terms of environmental, economic and social performance by using the IChemE Sustainability Metrics. The upgrading of 300 Nm^3/h of biogas generated from the anaerobic digestion of mixed sludge in a wastewater treatment plant was used as a model scenario for the comparative analysis. Despite the algal-bacterial photobioreactor entailed 1860 times higher land requirements, the two-stage physical/chemical technology exhibited × 3.8 higher energy consumptions and larger environmental impacts in terms of material and water consumption and greenhouse gas emissions (the latter by a factor of ~45). The investment cost for the algal-bacterial photobioreactor was 1.6 times higher than that of its physical/chemical counterpart due to the biomass drying unit required to produce an algae-based fertilizer. However, the operating cost of the physical/chemical technology was ~7 times higher due to the frequent replacement of the activated carbon. A further analysis of the net present value (NPV 20) revealed that photosynthetic upgrading would yield revenues from year 5 of operation mainly due to the sale of the algal bio-fertilizer produced, even without tax incentives for bio-methane.

1. Introduction

Biogas from the digestion of mixed sludge in wastewater treatment plants (WWTP) is typically composed of methane (CH_4) 55–70%, carbon dioxide (CO_2) 30–45%, nitrogen (N_2) 0–1%, oxygen (O_2) 0–0.5%, hydrogen sulfide (H_2S) 0–10,000 ppm_v, halogenated compounds $< 0.1\ mg\ Nm^{-3}$, organic silicon compounds 2–41 $mg\ Nm^{-3}$, water 5–10%, benzene, toluene and xylene (BTX) < 0.1–$5\ mg\ Nm^{-3}$, hydrocarbons 0–200 $mg\ Nm^{-3}$ and ammonia (NH_3) 0–100 ppm_v [1,2,3]. However, biogas is subject to the most rigorous quality specifications when intended to be used as a natural gas substitute. For instance, the draft of the EU regulation on bio-methane is targeting a composition of $CH_4 > 95\%$, $CO_2 < 2.5$–4%, $O_2 < 0.001$–1%, $H_2S + COS < 5\ mg\ Nm^{-3}$, $NH_3 < 10\ mg\ Nm^{-3}$, $BTX < 500\ mg\ Nm^{-3}$ and siloxanes $< 10\ mg\ Nm^{-3}$.

Current physical/chemical biogas upgrading technologies have been tailored to the composition of the raw biogas and the quality specifications required depending on the final use of biogas. Commercially available physical/chemical technologies for biogas desulfurization include in-situ chemical precipitation, adsorption, absorption and membrane separation. A wide range of physical/chemical technologies such as water, organic solvent and chemical scrubbing, membrane separation, pressure swing adsorption and cryogenic CO_2 separation is also commercially available nowadays for CO_2 removal [3]. On the other hand, conventional biological technologies such as biotrickling filtration, microaerophilic anaerobic digestion and hydrogenotrophic CO_2 reduction to CH_4 have been successfully tested at pilot and even full scale. Biological technologies are considered a low cost and environmentally friendly alternative to physical/chemical methods as a result of their lower chemicals and energy consumption and consequently lower CO_2 footprint. Despite the significant advances carried out over the past decades in the field of biogas upgrading, two-stage processes are still required for the removal of the two main biogas contaminants (CO_2 and H_2S) in both physical/chemical and biological technologies [4]. This entails high investment and operating costs that nowadays jeopardize the economic viability of bio-methane, requiring strong tax incentives in order to be employed as a viable natural gas substitute.

In this context, biogas upgrading in algal–bacterial systems constitutes a promising biotechnological alternative to conventional physi-

---

Abbreviations: AC, absorption column; ACF, activated carbon filter; EBRT, empty bed residence time; GHGs, greenhouse gases; HRAP, high rate algal pond; HRAP-AC, high rate algal pond interconnected to an absorption column; NPV, net present value; RE, removal efficiency; REs, removal efficiencies; WWTP, wastewater treatment plants

[*] Corresponding author.

E-mail address: mutora@iq.uva.es (R. Muñoz).

http://dx.doi.org/10.1016/j.algal.2017.05.006
Received 26 January 2017; Received in revised form 1 May 2017; Accepted 13 May 2017

cal/chemical and biological upgrading technologies for the removal of CO_2 and H_2S in a single-stage process [5]. This process is based on CO_2 fixation by microalgae using light energy, while sulfur-oxidizing bacteria oxidize H_2S to sulphate using the O_2 photosynthetically produced. Photosynthetic biogas upgrading has been recently optimized at laboratory and pilot scale in a high rate algal pond (HRAP) interconnected to a CO_2-H_2S absorption column (AC) via recirculation of the culture broth. The photosynthetically upgraded biogas complied with most European regulations for bio-methane injection into natural gas grids: 0.4 ± 0.1% CO_2, 0.03 ± 0.04% O_2, 2.4 ± 0.2% N_2 and 97.2 ± 0.2% CH_4 [6]. In addition, this technology can simultaneously support a partial mitigation of the eutrophication impact of anaerobic effluents, which contributes to enhance its environmental sustainability. In this sense, algal-bacterial growth in photobioreactors installed at WWTPs would be supported by the liquid fraction resulting from the dewatering of the digested sludge, which is typically composed of 500–1500 mg $N\text{-}NH_4^+\ L^{-1}$ and 60–100 mg $P\text{-}PO_4^{3-}\ L^{-1}$ [7]. In fact, a recent study has suggested that despite the main limitation of microalgae-based wastewater treatment is the large land area requirement for an efficient nutrient removal, the economic profitability of this technology might will ultimately rely on the valorization of the algal biomass [8]. Therefore, the algal biomass produced during biogas upgrading (containing the CO_2 from biogas and nutrients from centrate) can be used as an organic biofertilizer based on its high nutrient content and the presence of natural phytohormones and insecticides, which will significantly enhance the economic sustainability of the process. To the best of our knowledge, no economic and/or environmental impact assessment has been carried out to date for photosynthetic biogas upgrading despite the potential of this technology.

This study aimed at comparatively evaluating the performance of a physical/chemical technology consisting of an activated carbon filter combined with a water scrubber (ACF-WS) and a photosynthetic process consisting of a HRAP interconnected to an AC (HRAP-AC) for the production of a bio-methane suitable for injection into natural gas grids. Both technologies were assessed in terms of environmental, economic and social performance at full scale based on the IChemE Sustainability Metrics.

2. Methods

Environmental, economic and social indicators such as resource usage, generation of gas emissions, liquid effluents and solid wastes, investment an operating costs, net present value for a 20 year operation scenario and society acceptance were evaluated for the target biogas upgrading technologies.

2.1. Goal and scope definition

The treatment of a biogas stream of 300 Nm^3/h from a WWTP sludge anaerobic digester, with a composition of 65% CH_4, 34% CO_2, 0.1% O_2, 0.4% N_2, 0.5% H_2S, 2 mg Nm^{-3} BTX, 10 ppm_v siloxanes and water saturated, was selected as the reference upgrading scenario. This biogas flowrate was selected based on the current niche of cost-competitive biogas upgrading technologies at capacities $< 500\ Nm^3/h$.

The removal efficiencies (REs) of CH_4, CO_2, H_2S and BTX supported by the ACF-WS were obtained from the literature, while the performance of the HRAP-AC for these pollutants was based on the experimental results achieved in a pilot scale plant operated at the Department of Chemical Engineering and Environmental Technology at the University of Valladolid (Spain) [6,9]. Water removal is currently carried out by physical/chemical technologies such as adsorption, absorption or condensation [10], while adsorption constitutes the only technology commercially available for siloxanes removal [11]. Based on the fact that the removal of these biogas contaminants takes place in additional and independent units, and therefore would entail similar impacts on both technologies, these processes were not included in the present comparative assessment. Moreover, nitrogen is not considered as an undesirable biogas component in international bio-methane regulations, thus no N_2 removal was considered. However, this compound was taken into account in the mass balance calculation applied to estimate the final bio-methane composition in the technologies evaluated.

2.2. Process design

2.2.1. Activated carbon filter coupled with water scrubber

2.2.1.1. Activated carbon filter (ACF). Adsorption in activated carbon is a widely applied method to remove H_2S from biogas. The extensive design and operational knowledge available makes ACF the most widely applied method for biogas desulfurization. The use of impregnated activated carbons for H_2S removal allows for higher efficiencies than conventional carbons. A 1.0 m height packed bed of impregnated activated carbon (density 450 $kg\ m^{-3}$) operated at an empty bed residence time (EBRT) of 7 min was used as a model adsorption filter [4,12]. A carbon lifespan of 73 days was estimated based on the density and H_2S-adsorption capacity of the activated carbon (0.25 g-H_2S $(\text{g-carbon})^{-1}$) and the H_2S content of the raw biogas [4]. The annual activated carbon consumption was calculated based on the volume of the packed bed (35 m^3) and the adsorbent lifespan. No regeneration of the activated carbon was considered. Removal efficiencies of 100% for H_2S and BTX were assumed [13,14].

The power consumption E (kW-h) for gas circulation through the ACF was calculated considering a pressure drop ΔP (kPa) of 1.7 kPa and a compressor efficiency of 70% (Eq. (1)).

$$E_{\text{gas}} = \frac{Q_{\text{gas}}\ \Delta P}{0.7} \tag{1}$$

The operating costs of the ACF were based on those reported by Estrada et al. [16] and updated with the most recent data available, including: i) purchase of the activated carbon needed for bed replacement, with an estimated price of 4.5 € kg^{-1} [4], ii) handling, transport (30 € m^{-3}) and disposal as hazardous waste in landfills (120 € m^{-3}) of the saturated activated carbon, iii) electricity costs (0.120 € kW-$h^{-1}_{;}$ average electricity prices in the EU-28 for industrial consumers during the second half of 2014 [14]) and iv) maintenance costs accounting for 2.5% of the ACF investment cost. The investment cost for the impregnated ACF was obtained from Xiao et al. [17] (Table 1).

2.2.1.2. Water scrubber. Water scrubbing, which accounts nowadays for ~41% of the biogas upgrading market, was selected as model CO_2 removal technology [18]. A 5 m^3 water scrubber operated at an EBRT of 1 min, a water recirculation rate of 63 $m\ h^{-1}$ and a pressure of 8 bar was used as a model scrubber [19]. Water consumption in the scrubber was estimated at 0.1 $m^3\ h^{-1}$ according to Muñoz et al. [3]. A typical CO_2 removal efficiency (RE) of 98% was considered in the present study. The power consumption was calculated based on the SGC Rapport 2013:270 [20], which reported a consumption of 0.3 kW-h m^{-3} of treated biogas. The operating costs accounted for i) electricity consumption, ii) water consumption assuming a water price of 3.23 € m^{-3}, according to Eurostat [15], and iii) maintenance cost (2.5% of the investment cost). The investment cost of the water scrubber, including the flash and desorption columns, was obtained from SGC Rapport 2013:270 [20] (Table 1).

The total land required for the implementation of the ACF-WS was estimated to be 20 times the footprint of the biogas absorption column. This approach is a conservative assumption based on the area required for the installation of commodities and facilities associated to the process. The cost associated to land purchase was calculated considering a land price of 100 € per m^2 for industrial land [21]. The ACF-WS would produce 194 Nm^3/h of water saturated bio-methane with a composition of 98.8% CH_4, 0.7% CO_2, 0.1% O_2, 0.4% N_2 and negligible concentrations of H_2S and BTX. Fig. 1 shows a typical layout of the