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Techno-economic and Life Cycle Assessment of methane production via biogas upgrading and power to gas technology

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HIGHLIGHTS

- CH_4 production from Power to Gas and upgrading technologies have been assessed.
- Both environmental and economic assessments of have been done.
- We perform sensitivity analyses to identify key parameters.

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ABSTRACT

To decrease the use of fossil fuels and face the energetic demand, the integration of renewable energy is a necessary step. Part of this renewable energy can be supplied by the production of electricity from photovoltaic panels and windfarms. The massive use of these intermittent energies will lead to overproduction periods, and there is consequently a need to convert this surplus of electricity into a storable form of energy. Power-to-gas (PtG) technology consists in using electricity to convert water into hydrogen by electrolysis, and then to synthetize methane from carbon dioxide and hydrogen. Techno-economic and Life Cycle Assessment of methane production via the combination of anaerobic digestion and PtG technology have been applied to sewage sludge valorization. Process studies and equipment design have been addressed considering already available technologies. Sensitivity analyses have been done on biogas upgrading technologies, electricity prices, annual operation time and composition of the electricity mix with also a comparison between PtG and direct injection. It appears that the more the electricity is expensive, the longer the operation time of the methanation process must be to be competitive with injection of methane from biogas. Reduction of electricity consumption of the electrolysis step decreases production costs. Even if the current context does not feature adapted conditions to ensure an economically viable chain, the evolution of the energetic context in the next few years as well as the expected technological improvements will contribute to overall cost reduction. From an environmental point of view, continuous PtG generates more greenhouse gases than direct injection, but intermittent operation with use of renewable electricity can significantly reduce GHG emissions. From an endpoint impacts perspective, impact from continuous PtG are higher than biogas upgrading, but much lower than fossil energy. Future development of low electricity consumption of the electrolysis process, and integration of renewable credits from CO_2 valorization can increase the competitiveness of this technology.

1. Introduction

Even if fossils fuels accounted for 83% of total primary energy supply in 2008 [1], the use of fossil energy faces many issues: decreasing reserves, emissions of greenhouses gas (GHG) and other pollutants during their combustion, but also dependence to importations, with the associated risks. It is consequently compulsory to develop alternative energy production technologies. Renewable energy can play a central role in minimizing these issues, and can be partly supplied by electricity from renewable sources, like photovoltaic panels and windfarms. This electricity emits less GHG [2] and pollutants [3,4] than fossil fuels (except nuclear

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electricity), and can be produced almost all over the planet [5]. Nevertheless, renewable electricity production faces two major drawbacks: first its intermittency, with a production which cannot be adjusted to electricity demand, and second its substitution to high energy density fuels, especially in transport and heat [6].

While renewable electricity represents a small proportion of electricity production in Europe (24.7%) and in France (16.5%) in 2014 (http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_production_and_supply_statistics), recent publication of the European Commission on energy production forecasts a large share of renewables (between 64% and 97% depending on the scenarios) in the electricity mix in 2050 [7], and scenarios developed by the ADEME [8] go as far as to propose fully renewable electricity mix.

To fulfill the needs of electricity demand with the integration of more renewables in the electricity mix, the installed capacity should be increased. This massive electricity production from renewable energies will lead to overproduction periods, where produced electricity would not be totally employed. Therefore there is a need to store this energy. Several electricity storage technologies are available like batteries, pumped hydropower plants, compressed air energy storage or hydrogen storage technologies, with different prices, run times and storage capacities [9]. Pumped hydropower technology is the most massive storage technology available today, and is generally enough to balance the current electrical system. However it will be probably inadequate to store large amounts of overproduced electricity [10] and it has already been largely deployed. In this perspective, natural gas network offers a high storage capacity (for example 135 TW h in France, (DGEC [11])), and therefore conversion of electricity into gas would offer an interesting leverage to valorize overproduced electricity. In this perspective, production of methane (CH_4) by power-to-gas (PtG) technology can greatly increase the total production of CH_4 from biogas by combining carbon dioxide (CO_2) contained in the biogas and converted to CH_4 via methanation with CH_4 already present in the biogas [12–14]. PtG is defined here as using electricity to convert water into hydrogen (H_2) by electrolysis, and then to synthetize methane from carbon dioxide (CO_2) and H_2 through methanation (Sabatier reaction). H_2 production from electrolysis plays a key role in integrated energy system [15], as fuel for transportation for instance [16]. Furthermore, the synthesis of methane through methanation can strongly contribute to large scale energy storage, as CH_4 injection is not limited in the gas grid, contrary to hydrogen which also faces process and safety management issues.

Both economic and environmental criteria are crucial to fully assess the relevance of a new technology. In this study we propose a model for CH_4 production from PtG that evaluates these two dimensions of sustainability, by taking into account intermittent operation functioning. Economic assessment is done by calculating capital expenditures (CAPEX) and operational expenditures (OPEX) for each analyzed configuration, as in de Boer et al. [17]. Economic assessment of methane production from PtG have been proposed recently [18], with sometimes the use of time dependent optimization approach [19]. Environmental evaluation is done with Life Cycle Assessment (LCA), a standardized tool allowing to assess the environmental impacts of the whole cycle of a process, from raw extraction to final wastes management [20]. It should be noticed that it is an attributional study (and not consequential), which means that changes in the techno-economic sphere induced by large-scale production of bioCH_4 from PtG are not considered [21]. In particular, this implies that the use of long-term marginal data to characterize the electric mix is not in the scope of the study [22]. Several LCAs of H_2 production have been done in the past years [23–26], with sometimes a focus on the use of electricity from renewables [27]. Nevertheless, only a few environmental studies have been conducted on CH_4 production by PtG: GHG emissions of used electricity for electrolysis in Jentsch et al. [28] or direct carbon emissions [17], and only one Life Cycle Approach to evaluate GHG emissions [13]. To our knowledge, this is the first time that both economic and environmental assessments are performed together to evaluate the production of bioCH_4 from PtG technology with continuous and intermittent operations modes.

2. Methodology

2.1. Overview of the system

PtG consists in the conversion of electricity into H_2 and further into CH_4, which can be stored without restriction in the natural gas network. CH_4 can then be further used for different purpose: storage of electricity, heat production, raw materials for chemical industry and transportation services via NGV production. In this paper, we will focus on the production of heat from CH_4, as it is the main use of natural gas, from two different sources: from biogas upgrading, with no valorization of the CO_2, or from biogas upgrading and CO_2 conversion into CH_4 via methanation (Fig. 1). Different configurations are analyzed: CH4 from methanation after biogas upgrading, CH4 from methanation of the biogas without upgrading (direct methanation), and finally CH4 from biogas upgrading without methanation. A fossil reference system (natural gas) is also included in the LCA. The system assessed in the model includes all steps from biogas production to CH_4 combustion in a boiler: anaerobic digestion of sewage sludge, biogas upgrading and compression, electrolysis, methanation, completion, injection in the gas network, and combustion. The wastewater treatment plant of the study is designed for a population equivalent of 300,000 inhabitants. The daily quantity of sewage sludge processed is 16,440 kg of dry matter, which leads to a biogas production of 230 $m^3\ h^{-1}$. The anaerobic digestion plant, as well as the electrolysis and the methanation installations are supposed to be near the wastewater treatment plant. The inventory is based on figures derived from academic resources, internal communications with industrials and processes described in the Ecoinvent database [29]. The location of the system is in France; as a consequence the electric mix is the French one, with a low carbon content. Infrastructures are included in the economic assessment but are not considered in the LCA, in line with the assessment of renewable energy production in The Renewable Energy Directive [30].

2.2. Anaerobic digestion step

The data used for the functioning of the anaerobic digestion plant are summed up in Table 1. The heat necessary for operating the anaerobic digestion plant is provided by burning part of the produced biogas in a boiler and by the recovery of wasted heat from methanation when it is functioning. Compositions of the biogas and the digestates come from literature survey and from Suez Environment internal data. Biogenic CH_4 emissions occur during biogas production and digestates storage, and NH_3 and N_2O emissions are linked with the spreading of the digestates on the fields. Biogenic CO_2 fixation and emission are not taken into account, and it is supposed that the carbon of the digestates is entirely reemitted in the environment.

2.3. Biogas upgrading and compression steps

In the present study, the impurities contained in the biogas (especially sulphur and silicone derived compounds) are removed via activated carbon adsorption, this latter step being considered as integrated with the biogas production. Biogas is thus considered as composed of CH_4 and CO_2 and biogas upgrading focus on CO_2

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