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Life Cycle Assessment of electricity production in Italy from anaerobic co-digestion of pig slurry and energy crops

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ABSTRACT

This study aims to evaluate the environmental consequences and energy requirements of a biogas production system and its further conversion into bioenergy by means of the Life Cycle Assessment (LCA) methodology. To do so, an Italian biogas plant operating with pig slurry and two energy crops (maize and triticale silages) as feedstock was assessed in detail in order to identify the environmental *hotspots*. The environmental profile was estimated through six impact categories: abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion potential (ODP) and photochemical oxidation potential (POFP). An energy analysis related to the cumulative non-renewable fossil and nuclear energy demand (CED) was also performed, considering this indicator as an additional impact category.

According to the results, the biomass production subsystem was identified as the main environmental key issue in terms of ADP, AP, EP, ODP and CED, with contributions ranging from 26% to 61% of the total impact. Regarding ADP, ODP and CED, these results are mainly related with diesel requirements in agricultural machinery, derived combustion emissions and mineral fertilizers production. Concerning AP and EP the production field emissions derived from fertilizers application was observed as the main contributor. Concerning GWP, this step presents an environmental credit due to the uptake of CO_2 during crop growth, which contributes to offset the GHG emissions. The bioenergy production plant significantly contributes to the environmental impact in categories such as GWP (43%) and POFP (59%), mostly related with emissions produced in the gas engine and biogas losses. Emissions derived from digestate storage contribute to AP (52%) and EP (41%). The use of the digestate as an organic fertilizer has a beneficial role because this action avoids the production and use of mineral fertilizers.

A sensitivity analysis was also conducted to assess the influence of variations in important parameters of biogas systems. The environmental profile of the biogas system turned out to be highly dependent on the selection of system boundaries and the allocation method.

To sum up, this study aims to assess the environmental performance of a biogas technology available not only in Italy but also in other European countries. The environmental analysis of the process under study highlights the environmental benefits of the co-digestion processes, which not only produces biofuel but also reduces the disposal of solid wastes and produces digestate, with special value in the fertilization of agricultural soil.

1. Introduction

Nowadays, general scientific consensus believes that global warming is caused by the emission of anthropogenic greenhouse gases (GHG), mainly derived from fossil fuel combustion [1,2]. Moreover, securing energy supply is a key target [3]; since its demand has soared under the pressure of developing countries, which have increased their production schemes [4]. Therefore, the use of renewable resources, the efficient energy production and the reduction of energy use are priorities on the European political agenda towards a more sustainable future [3]. In this context, the European Commission has adopted the ambitious target to increase the ratio of renewable energy up to 20% by 2020 [5].

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Bioenergy is a renewable energy produced from biomass, including energy crops, wood, microbial biomass as well as wastes from household, agricultural, cattle, forestry and industrial activities [6]. Currently, there is a growing interest on the use of biomass for energy purposes in order to satisfy energy requirements all over Europe [7], which would imply lower dependency on imports of fossil fuels for many European Union countries where biomass is a local resource [8].

According to Holm-Nielsen et al. [9], biogas as potential renewable energy source could represent 25% of all the bioenergy in Europe in the near future. Biogas is a gaseous fuel obtained as a result of the Anaerobic Digestion (AD) of a wide range of organic feedstock [10], giving an answer to the inadequate management of industrial, agricultural and domestic wastes [11,12]. Special interest is being paid on its promotion for several reasons: security of energy supply, economic and market benefits, advantages on production and storage [9].

As a result, many agricultural biogas plants using manure and agricultural products as main feedstock have been recently built in Europe for the final transformation of biogas into electric and thermal energy [13]. The most developed facilities are located in Germany, Denmark, Austria, Sweden [9] and Italy [14]. Focusing on Italy, although the incentive framework for electricity production has been recently revisited, there is still a big interest on production of renewable energy with special emphasis on biogas [15]. In addition, Italy occupies an outstanding position in terms of pig and cattle breeding in Europe [16].

AD does not only produce biogas but also a digested substrate, commonly referred as digestate. It is a nutrient-rich stream that can be used as organic fertilizer for crop cultivation, which would return nutrients back to the soil in substitution of mineral fertilizers [17–19].

Furthermore, the AD of two or more different feedstock is known as co-digestion. According to the literature, biogas plants that perform co-digestion can achieve up to 10% higher biogas yield in comparison with those with single feedstock digestion [20], since the synergy between mixture components compensates the lack of certain substrates [21].

Apparently, the co-digestion with wastes could improve the environmental performance of biogas production [2] because only environmental burdens associated with its handling are included but none about its production [19]. It would be necessary to be aware of the quality and quantity of effects associated to biogas production [17].

Life Cycle Assessment (LCA) is a quantitative procedure to evaluate the environmental burdens associated with a product or a process and to identify opportunities to attain environmental advantages [22]. Numerous LCA studies are available in the literature concerning biogas production and use [2,23–25]. In these studies, biogas production systems from different feedstock (mono- and co-digestion) as well as their possible applications have been assessed from environmental and energy perspectives, with special attention on GHG emissions and fossil fuel depletion [23,25].

Hartmann [17] evaluated a biogas production system operated with energy crops in combination with cattle and pig manure. The results showed that the most relevant environmental impacts are related not with the biogas system itself but with the agricultural system, mainly derived from the use of fossil fuel and mineral fertilizers. Börjesson and Berglund [23] analyzed the fuel-cycle emissions from a variety of biogas systems. The results showed that the environmental impact of biogas systems largely depends on the raw material digested, the efficiency of the biogas production chain, the uncontrolled loss of methane and the development of the end-use technology. Poeschl et al. [20,25] analyzed the production and utilization of biogas in different scenarios with diverse feedstock, biogas use and digestate processing. The results obtained by these authors indicated a wide range of variations on the potential environmental impacts and energy conversion efficiency depending on the biogas production and utilization pathway selected.

The purpose of this study was to evaluate the environmental impacts and energy requirements associated with a co-digestion process as well as its further transformation into energy. This study is focused on an Italian biogas plant located in San Giorgio di Lomellina (Lombardy) which codigests pig slurry with energy crops for several reasons: 1) the annual production of pig slurry is considerably high in Italy [26,9], 2) maize and triticale silages are among the most suitable energy crops for biogas production [20,27] and, 3) there is a large number of anaerobic digestion plants throughout Italy, most of them located in Lombardy [28].

2. Materials and methods

2.1. Methodology

LCA is a methodology for the comprehensive evaluation of the impact that a product (good or service) has on the environment throughout its life cycle [22]. This method presents a holistic approach for a comprehensive environmental assessment, following a standardized method which guarantees reproducibility of results [22,29].

2.2. Goal and scope definition

The environmental impacts and energy requirements of the biogas production system from the co-digestion of pig slurry and two energy crops (maize and triticale silages) and the subsequent use for electricity and heat generation (bioenergy) were determined. An Italian biogas plant located in San Giorgio di Lomellina (Lombardy) and considered representative of the state-of-the-art was assessed in detail from a cradle-to-gate perspective. All energy and material flows as well as emissions associated were identified and quantified in detail. Moreover, the most critical stages from an environmental point of view (*hotspots*) were identified and alternatives were proposed in order to reduce the impact and improve the environmental and energy profiles.

2.3. Functional unit

The functional unit (FU) expresses the function of the system in quantitative terms and provides the reference to which all the inputs and outputs of the product system are calculated [22]. The function of this system is the production of bioenergy (electricity and heat) by means of the co-digestion of organic feedstock. Thus, the FU chosen to carry out the assessment was 100 kWh of electricity produced (kWh_{el}) in a combined heat and power unit (CHP) with pig slurry, maize silage and triticale silage as feedstock of the co-digestion process.

2.4. System boundaries and definition of the system under assessment

The representative system under study was based on a state-of-the-art biogas technology plant and was divided into four subsystems: biomass production (SS1), feedstock transport and processing (SS2), bioenergy production plant (SS3) and digestate management (SS4). The system boundaries and processes considered under assessment are illustrated in Fig. 1. Pig slurry is the main waste of pig breeding activity and its use in AD plants is a valuable solution for its management. Accordingly, the management of pig