Bioresource Technology 121 (2012) 396–403

Contents lists available at SciVerse ScienceDirect

Bioresource Technology

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

Case Study

The environmental sustainability of anaerobic digestion as a biomass valorization technology

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HIGHLIGHTS

- Anaerobic digestion is one of the most efficient biomass-to-energy routes.
- A saving of over 90% resources is achieved in most resource categories.
- Maximizing organic waste valorization is an environmentally sustainable strategy.
- Controlling emissions in digestion and agriculture induces an improvement up to 50%.

ARTICLE INFO

Article history:
Received 17 April 2012
Received in revised form 29 June 2012
Accepted 29 June 2012
Available online 7 July 2012

Keywords:
Anaerobic digestion
Sustainability
Efficiency
LCA
Biomass valorization

ABSTRACT

This paper studies the environmental sustainability of anaerobic digestion from three perspectives. First, reference electricity is compared to electricity production from domestic organic waste and energy crop digestion. Second, different digester feed possibilities in an agricultural context are studied. Third, the influence of applying digestate as fertilizer is investigated. Results highlight that biomass is converted at a rational exergy (energy) efficiency ranging from 15.3% (22.6) to 33.3% (36.0). From a life cycle perspective, a saving of over 90% resources is achieved in most categories when comparing biobased electricity to conventional electricity. However, operation without heat valorization results in 32% loss of this performance while using organic waste (domestic and agricultural residues) as feedstock avoids land resources. The use of digestate as a fertilizer is beneficial from a resource perspective, but causes increased nitrogen and methane emissions, which can be reduced by 50%, making anaerobic digestion an environmentally competitive bioenergy technology.

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1. Introduction

Mankind currently depends heavily on depleting fossil resources. While it is clear that they will keep on taking an important place in our resource supply for the next decades, it is also clear that a transition to more sustainable sources of material and energy is necessary. Biomass is such an alternative resource, which has a large potential in application range and in the mitigation of climate change. On the other hand it depends on the efficiency of photosynthesis and the process of agriculture resulting in competition with the food and feed chain. Up to now, biomass contributes by 3–13% of the energy supply of industrialized countries. Incineration and biodiesel–bioethanol production cover most of this supply, whilst biogas from anaerobic digestion is producing a small but steadily growing share (Braun et al., 2009). However, the role of biogas can become more substantial. For example in Germany, a leading country in biogas production, anaerobic digestion is considered as a key technology to meet the renewable energy and GHG mitigation targets (Pöschl et al., 2010). On a more international scale, it is stated that up to 18% of primary energy demand can be fulfilled by cultivating energy crops on 30% of the arable land (Braun et al., 2009), excluding the potential of organic waste streams and possible new bioresources such as biodegradable polymers (Guo et al., 2011).

From a technological perspective, anaerobic digestion is indeed a promising valorization technology as it is able to convert almost all sources of biomass, including different types of organic wastes, slurry and manure to a highly energetic biogas (Holm-Nielsen et al., 2009). Only strongly lignified organic substances such as wood are not suitable for digestion (Weiland, 2010). When using digestable biomass, the different molecules such as carbohydrates, proteins and lipids can be hydrolyzed to soluble sugars, amino acids and long chain fatty acids in order to start the further microbial conversions. Afterwards, during acidogenesis these components are degraded to acetate, hydrogen, carbon dioxide and a

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0960-8524/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.biortech.2012.06.109

number of organic acids, the latter converted further by acetogenesis. Methanogens then convert this mixture to biogas (Gujer and Zehnder, 1983) consisting of approximately 50–70% methane, 30–50% carbon dioxide and smaller amounts of N_2, H_2O, NH_3 and H_2S (Petersson and Wellinger, 2009). The remaining fraction in the digester, the digestate, can be further treated and processed, or can be used directly as a fertilizer. These complex microbiological reaction pathways are a major advantage in comparison to other forms of bioenergy such as bioethanol, where currently *Saccharomyces cerevisiae* converts only the glucose fraction to ethanol and such as biodiesel, where currently only the oil and fat fractions undergo transesterification. This results in better conversion efficiencies of biomass to biogas compared to other biofuel production alternatives (Börjesson and Tufvesson, 2011) which is an essential parameter in the environmental sustainability of bioenergy, as the cultivation of biomass is generally responsible for the largest impact over the life cycle of bioenergy (Zah et al., 2007). As a result, a better overall energy balance of biogas compared to for example ethanol can be achieved, where extra pre- and post treatment steps might enhance higher yields but do not have a beneficial effect on the energy balance (Schumacher et al., 2010).

The broad applicability and relatively simple setup of anaerobic digestion, is a major opportunity for the worldwide implementation of this technology as a way to treat waste, i.e. a stabilization of the waste can be achieved and to produce energy simultaneously (Weiland, 2006). It is also implemented more frequently for the digestion of energy crops, by using a large diversity of possible plant materials (Braun et al., 2009), whilst furthermore, digestion is a potential option for (organic) farmers to become energy self-sufficient where digestate application can maintain soil fertility (Oleskowickz-Popiel et al., 2012).

In this light, this paper aims to be a detailed analysis of the environmental sustainability of using anaerobic digestion for the production of electricity and heat to contribute to renewable energy targets in Northwestern Europe. As input materials municipal organic waste, farm residues and energy crops are studied by using energy and exergy efficiency assessment and by performing a resource and emission fingerprint based on ISO 14040/44 LCA, with an additional focus on the benefits of the valorization of the produced heat and digestate, the latter as a fertilizer. The limitation that many studies base themselves on small-scale test data or literature was avoided by studying full scale and operational dry digesters. The conclusions of this study are thus based on a high quality dataset with realistic data of for example the input composition, internal material and energy use, industrial conversion efficiencies, transport distances, digestate application in agriculture, etc.

The assessment is thus performed at two levels:

- First, the conversion efficiency of this technology is assessed by using an energy and exergy balance, as an efficient use of the feedstock is a critical factor in the sustainability of biomass valorization chains. Exergy assessment was used to identify process inefficiencies based on the second law of thermodynamics (Dewulf et al., 2008).
- Second, Life Cycle Assessment was used to obtain a more holistic view on the environmental profile of anaerobic digestion. For this purpose, a combination of a resource based and emissions based LCA approach was chosen.

2. Methods

In the following, the two studied full scale case studies are elaborated with a process diagram, followed by a system description and a clarification of the data sources (year average of 2010) used to construct the inventory. Afterwards, the assessment techniques are explained more in detail. The inventory of the studied cases is confidential, but can be obtained upon request.

2.1. System description

2.1.1. Case study 1

The first case study focuses on a typical setup of digestion in an agricultural context situated in Germany and having a capacity of approximately 20,000 tons biomass inputs per year (Fig. 1). The digester is currently mainly fed by silage maize, supplemented with smaller amounts of rye silage and poultry manure. After storage, biomass is fermented with a residence time of approximately 21 days. The produced biogas is collected in a gas bag, where water is condensed. Afterwards, the biogas is converted into electricity and heat in generators of 250 kW. The digestate is stored and used as a fertilizer on the surrounding fields. Because of the importance of agriculture in environmental LCA studies, the farming of silage maize was studied more in depth, with a specific focus on the impact of using digestate instead of traditional (organic and mineral) fertilizers. Data of these processes were collected together with the involved farmers and experts. Methane emissions from the digestate storage tank are taken from Liebetrau et al. (2010). Emissions from agriculture are calculated by applying the models used by Nemecek and Kägi (2007), with more detailed data of metal emissions and of nitrogen leakage taken from Freiermuth (2006) and Svoboda et al. (2011) respectively. Data of diesel consumption was obtained from the involved farmers and the resulting air emissions are taken from EMEP/CORINAIR (2000). Two alternative digester feeds were elaborated for this system in collaboration with involved experts, where all parameters of the inventory can remain constant, except for the agricultural inputs and the energy and digestate output; in the first alternative sugar beet, grass silage and poultry manure, whilst in the second alternative corn stover, cow manure and poultry manure are digested.

2.1.2. Case study 2

In the second case study a Belgian production plant was studied where domestic organic waste (±45,000 tons per year) is converted into electricity, heat and compost (Fig. 2). Biomass is collected by selective municipal organic waste collection. The collection in one part of the region is organized by using a temporary waste terminal, whilst the municipal waste collectors in the second part of the region supply the organic waste directly to the facility. The transport distances were collected in collaboration with the involved stakeholders. Because of the diversity of organic waste and contamination due to sometimes careless waste sorting, a specific pretreatment is necessary by means of drum sieves and magnets. Afterwards a piston pump feeds the digester, where the organic fraction is converted to biogas with a residence time of approximately 20–25 days. After a water condensation step, the biogas is burned in engines of 625 kW to produce electricity and heat. The resulting digestate is post treated by means of a press, centrifuge and sieve, where the separated heavy fractions are landfilled and the wastewater is treated in a treatment plant. The lighter fraction is further composted in an aerobic composting hall where air is extracted and filtered in a biofilter. All data of resource use and emissions of this plant, including the composting process and the wastewater treatment is collected based on measurements and judgement of involved stakeholders and experts.

2.2. Technological assessment based on energy and exergy efficiency

The efficiency of electricity production per digested biomass is calculated based on energy (lower heating value) and exergy. This is a sound strategy, as the efficiency of the conversion of biomass to energy is a bottleneck in the environmental sustainability of this

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