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Environmental systems analysis of biogas systems—Part II: The environmental impact of replacing various reference systems

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Abstract

This paper analyses the overall environmental impact when biogas systems are introduced and replace various reference systems for energy generation, waste management and agricultural production. The analyses are based on Swedish conditions using a life-cycle perspective. The biogas systems included are based on different combinations of raw materials and final use of the biogas produced (heat, power and transportation fuel). A general conclusion is that biogas systems normally lead to environmental improvements, which in some cases are considerable. This is often due to indirect environmental benefits of changed land use and handling of organic waste products (e.g. reduced nitrogen leaching, emissions of ammonia and methane), which often exceed the direct environmental benefits achieved when fossil fuels are replaced by biogas (e.g. reduced emissions of carbon dioxide and air pollutants). Such indirect benefits are seldom considered when biogas is evaluated from an environmental point of view. The environmental impact from different biogas systems can, however, vary significantly due to factors such as the raw materials utilised, energy service provided and reference system replaced.

Keywords: Anaerobic digestion; Energy crops; Organic waste; Fossil fuel systems; Life cycle perspective

1. Introduction

Anaerobic digestion and biogas production are promising means of achieving both global and local environmental benefits. Biogas is a renewable energy carrier, and the introduction of anaerobic digestion of farm residues and municipal organic waste may reduce potentially negative environmental impact of current agricultural practices and waste handling procedures. The development and implementation of biogas systems in Sweden is being stimulated by both existing and coming governmental incentives. Today, biogas is exempted from energy and environmental taxes, which improves the competitiveness of biogas compared with fossil fuels. Several on-going and planned biogas projects in Sweden have obtained governmental investment grants that aim at speeding up the transition of Sweden to an ecologically sustainable society. In addition, the new national waste handling policy includes a ban on landfilling with organic waste from the year 2005 and an obligation to use biological treatment methods (e.g. anaerobic digestion or composting) of wet organic waste.

Previously almost all biogas produced in Sweden was used for heat production in small-scale boilers or in large-scale district heating plants. However, there is an increasing interest in the use of biogas as a transportation fuel. One reason is the increasing price of petrol and diesel due to increased raw oil prices and national taxes, e.g. the tax on carbon dioxide, whereas the cost of alternative fuels for heat production, mainly wood fuels used in district heating systems, has not increased to the same extent. The EU directive on alternative transportation fuels is likely to increase the interest in biogas as a transportation fuel further. Today, the total biogas production in Sweden amounts to approximately 5 PJ/year, of which 3 PJ comes from digestion of sewage sludge at waste water treatment plants. Of this total, some 0.5 PJ is up graded and used for transportation services (e.g. in busses, trucks, taxies and private cars) [1].

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Biogas can also be used for electricity production, preferably in combined heat and power plants with high total conversion efficiency. Combined heat and power production provides higher profitability than stand-alone power production [2]. During 2003, an electricity certificate system was introduced in Sweden that aims at increasing the production of renewable electricity, e.g. wind power and biomass-based electricity. The additional revenue from the trade of these certificates increases the profitability of, and thus the interest in the production of biogas-based electricity.

The biogas potential in Sweden is estimated to be some 50 PJ/year, which is ten times higher than the current production and corresponds to 3–4% of the current energy consumption in Sweden. Of this total, slightly less than 40 PJ originates from agricultural biomass resources, such as manure, crop residues and dedicated ley crops [1,3]. Digestion of municipal organic waste and organic waste from the food industry could contribute to some 8 PJ, and sewage sludge to 4 PJ/year.

The big differences among biogas systems make them complex to study from an environmental point of view. The environmental impact of each system is more or less unique because of the great variety of potential raw materials, digestion technologies, and fields of application for the biogas and digestates produced [4–6]. Furthermore, the total environmental impact of the introduction of a biogas system depends largely on the reference system replaced, concerning energy supply, waste handling and farming practice. Today, there is a lack of broad environmental systems analyses of biogas production systems that include the variation between different biogas fuel chains and the indirect environmental impact of replacing different reference systems. Our research project Energy and Environmental Systems Analyses of Biogas Systems was initiated to fill this gap. The results of the project are presented in two reports (in Swedish) [4,7] and three papers, of which this is the third, analysing the total environmental impact of replacing various reference systems by biogas production systems. The first paper assesses the energy performance of various biogas systems [8], and the second the fuel-cycle emissions from these systems [5].

The aim of this paper is to assess the total environmental impact of the introduction of various biogas systems and the replacement of different reference systems. The analysis includes both the direct environmental effects of replacing various energy carriers and energy systems, and indirect effects of changed handling of raw materials, e.g. waste management and farming practice. The purpose is also to identify factors of major importance for an accurate comparison between a biogas and a reference system, and to identify the most promising application of a biogas system from an environmental point of view. The calculations are aimed to be as transparent as possible in order to make the results useful in future analyses and to enable the reader to make her/his own calculations based on specific local conditions.

2. Methods and assumptions

The analysis includes six different end-use technologies, namely large- and small-scale boilers for heat production, large- and small-scale gas turbines for co-generation of heat and power, and heavy- and light-duty vehicles. The biogas production includes six raw materials that are digested in large-scale biogas plants, or in farm-scale biogas plants in the case of agricultural raw materials (see [5,8] and Section 3). The reference systems chosen are assumed to be realistic alternatives to the biogas systems studied, based on current Swedish conditions. The emissions are expressed per energy service unit, that is, heat, heat and power, and kinetic energy for transportation, in order to allow for variations in the conversion efficiency among the final energy services. The functional unit used is 1 MJ of heat, 1 MJ of heat and power and 1 MJ of kinetic energy. This functional unit is chosen in order to account for variations in conversion efficiencies between the biogas system and the reference system compared.

The analysis is based on literature reviews and refers mainly to Swedish conditions and state-of-the-art technologies. An extensive description of our calculations on fuel-cycle emissions from various biogas systems and the system boundaries applied is given in [4,5,7,8]. Data on fuel-cycle emissions from the reference systems are based on previously published studies; a summary of the emissions assumed is given in the Appendix.

The analysis includes both fuel-cycle emissions and indirect environmental effects. Fuel-cycle emissions are defined as emissions from the production and final use of energy carriers. The indirect environmental effects are here defined to be caused by emissions that are not directly related to the energy conversion in the systems, for example, changed emissions of ammonia and nitrous oxide from arable land and leakage of nitrate due to changed farming practice, or emissions of methane, ammonia and nitrous oxide from the storage of manure (see Section 4).

The electricity used in the systems studied is assumed to be produced in condensing plants using natural gas, reflecting the estimated, long-term, marginal production of electricity in the Scandinavian countries [9]. Thus, the fuel-cycle emissions from the reference systems have been recalculated when other sources of electricity have been assumed in the studies quoted. The heat used in the biogas plants is assumed to be produced from biogas, based on present conditions at Swedish biogas plants.

Uncontrolled losses of methane from the production of biogas is here assumed to correspond to 1% of the biogas produced when the biogas is used for heat or combined heat and power production, and 2% when the biogas is upgraded and used as a transportation fuel [10]. Uncontrolled losses of methane will also increase the emission of other pollutants due to the corresponding reduction in energy efficiency in the biogas systems.

Energy crops are assumed to be cultivated on set-aside arable land, and hence replacement of food or fodder