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Research article

Consequential environmental life cycle assessment of a farm-scale biogas plant

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ABSTRACT

Producing biogas via anaerobic digestion is a promising technology for meeting European and regional goals on energy production from renewable sources. It offers interesting opportunities for the agricultural sector, allowing waste and by-products to be converted into bioenergy and bio-based materials. A consequential life cycle assessment (cLCA) was conducted to examine the consequences of the installation of a farm-scale biogas plant, taking account of assumptions about processes displaced by biogas plant co-products (power, heat and digestate) and the uses of the biogas plant feedstock prior to plant installation.

Inventory data were collected on an existing farm-scale biogas plant. The plant inputs are maize cultivated for energy, solid cattle manure and various by-products from surrounding agro-food industries. Based on hypotheses about displaced electricity production (oil or gas) and the initial uses of the plant feedstock (animal feed, compost or incineration), six scenarios were analyzed and compared. Digested feedstock previously used in animal feed was replaced with other feed ingredients in equivalent feed diets, designed to take account of various nutritional parameters for bovine feeding. The displaced production of mineral fertilizers and field emissions due to the use of digestate as organic fertilizer was balanced against the avoided use of manure and compost.

For all of the envisaged scenarios, the installation of the biogas plant led to reduced impacts on water depletion and aquatic ecotoxicity (thanks mainly to the displaced mineral fertilizer production). However, with the additional animal feed ingredients required to replace digested feedstock in the bovine diets, extra agricultural land was needed in all scenarios. Field emissions from the digestate used as organic fertilizer also had a significant impact on acidification and eutrophication.

The choice of displaced marginal technologies has a huge influence on the results, as have the assumptions about the previous uses of the biogas plant inputs. The main finding emerging from this study was that the biogas plant should not use feedstock that is intended for animal feed because their replacement in animal diets involves additional impacts mostly in terms of extra agricultural land. cLCA appears to be a useful instrument for giving decision-makers information on the consequences of introducing new multifunctional systems such as farm-scale biogas plants, provided that the study uses specific local data and identifies displaced reference systems on a case-by-case basis.

1. Introduction

The massive development of the biofuel industry has been accompanied by several controversial issues, including the food *versus* fuel debate. The use of raw food materials for bioenergy production has diverted some resources (including agricultural products and land) from their initial use. For example, in Wallonia (the southern part of Belgium) in 2012, more than 25% of the wheat produced was transformed into bioethanol (Delcour et al., 2014).

The issue of the optimum management of any product, co-

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product, by-product or waste has become very important. Regarding waste management in particular, the European Commission issued Directive 2008/98/EC (European Commission, 2008), which proposed the following hierarchy for dealing with waste: (a) prevention, (b) preparation for re-use, (c) recycling, (d) other recovery, *e.g.*, energy recovery, and (e) disposal. As one of the three Belgian Regions, Wallonia translated this Directive into a Walloon Decree (Walloon Government, 2012), but this decree does not go as far as its Flemish counterpart in northern Belgium, which set up a more detailed hierarchy for food waste management: (a) prevention, (b) use for human nutrition, (c) conversion for human nutrition, (d) use for animal feed, (e) use as raw materials in industry (in a bio-based economy), (f) processing into fertilizer by anaerobic digestion or composting, (g) use as renewable energy, (h) incineration and (i) landfill (Roels and Van Gijseghem, 2011).

The European Renewable Energy Directive 2009/28/EC (European Commission, 2009) set a restrictive goal whereby Belgium, overall, should obtain 13% of its energy from renewable sources by 2020. With regard to electricity, the goal in Wallonia is to produce a little more than 25% of its estimated final electricity consumption from renewable sources by 2020 (CWaPE, 2012). Among the available sources, biogas production via anaerobic digestion is a promising technology that could contribute significantly to these goals. Biogas plants can be fed with numerous raw materials, including agricultural, industrial and domestic by-products and waste, and can deliver various types of energy, such as electricity, heat, steam, combined heat and power (CHP), and gas that can be supplied to the natural gas grid or used as transportation fuel (Holm-Nielsen et al., 2009).

Supported by the Green Certificates mechanism (CWaPE, 2012; Van Stappen et al., 2007) and other investment aid schemes, an increasing amount of electricity in Wallonia has been generated from biogas-fueled CHP plants in recent years; between 2002 and 2012, this amount increased by 20%, and in 2012, it represented approximately 3% of total electricity consumption in the region (Simus, 2014). There are 37 biogas plants in Wallonia, 10 of which are fed with agricultural raw materials; between them, these 10 plants have an installed power capacity of 9.2 MW_{el} (EBA, 2012).

The environmental impacts of biogas production from farm-scale plants vary considerably, depending on regional parameters such as raw material availability for digestion, the energy service provided, soil, climate and the reference systems affected by the use of the co-products (Dressler et al., 2012). The influence of farming practices has also been highlighted (Alig, 2012; Börjesson and Berglund, 2007; Jury et al., 2010; Stucki et al., 2011). Optimizing the potential benefits of biogas plants calls for systems designed and located wisely (Börjesson and Berglund, 2007), as well as for environmental assessment studies such as life cycle assessments (LCA) that take account of local conditions (Dressler et al., 2012).

Using LCA fed with local data collected on-site, this study aimed at evaluating the environmental consequences of the installation of a farm-scale biogas plant producing electricity, heat and organic fertilizer. Plant feedstock was silage maize and farmyard manure, as well as by-products from surrounding agro-food industries (sugar beet tails, downgraded potatoes, cereal middlings, mown lawn grass and starch from potato fry cleaning). This study sought to explore the sensitivity of the results to assumptions on (i) the reference systems displaced by the use of the co-products and (ii) the uses of the feedstock prior to the biogas plant being installed.

2. Methods

The study followed ISO standards for LCA guidelines and requirements (ISO, 2006a, b).

2.1. Consequential LCA

There are two types of LCA, depending on the goal of the study: attributional LCA (aLCA) and consequential LCA (cLCA). aLCA describes the relevant physical input and output flows entering and exiting from a product system, whereas cLCA defines how these flows might be modified in response to a decision or a change (Finnveden et al., 2009). aLCA is useful for identifying systems with important impacts, whereas cLCA is useful for evaluating the consequences of individual decisions. The complementary goals of aLCA and cLCA make them both valid for decision-making (Ekvall et al., 2005): cLCA is more complete but less certain while aLCA is more certain but implies blind spots related to deficient consideration of secondary effects, such as affected processes and technologies outside aLCA system boundary (Schmidt, 2008). cLCA, however, seems more appropriate in regard to informing decision-makers about the environmental impact of installing a new multifunctional technology that increases the amount of products on the market (Jury et al., 2010; Rehl et al., 2012). Approaches for conducting a cLCA can utilize economic data to measure physical flows of indirectly affected processes (Earles and Halog, 2011) or include economic concepts such as marginal production costs, elasticity of supply and demand (Finnveden et al., 2009). An alternative to economic models is based on the qualitative identification of the most likely processes marginally affected by a change in the main production system (Vázquez-Rowe et al., 2013). This approach uses market information and identifies the scale and time horizon of the potential change studied (Schmidt, 2008; Weidema et al., 2009). Processes affected by diverted inputs required by the system and products provided by the system are called *displaced technologies*. They are *short-term marginal technologies* (*i.e.*, existing technologies whose output changes due to small changes in demand in the market). They need to be *unconstrained* so that they can adjust their capacity in response to changes in demand. *Short-term* implies that the changes take place within the existing production capacity and are not expected to affect capital investment (Weidema et al., 1999).

2.2. Goal and scope of the cLCA

The biogas plant under study produces three co-products: power, heat and digestate (the sludge-like material remaining after anaerobic digestion). All three co-products are used, replacing processes that delivered the same service pre-installation. The electricity produced is used for the plant and the farm, with the excess being sold to the grid. Heat is used partly for digester heating and partly sold to neighborhood houses *via* a 440 m district heating network. Excess heat (*i.e.*, surplus after the needs of the biogas plant and the houses are met) is dissipated (although in the future, the plan is for this excess heat to be used for drying wood chips). The digestate is stored in an open tank before being used as organic fertilizer.

In the joint production of power, heat and digestate by the biogas plant, power is identified as the *determining* product, *i.e.* the co-product for which a change in demand will affect the production volume of the co-producing unit process (Weidema et al., 2009). Indeed the economic viability of a biogas plant in Wallonia is closely linked to electricity sales and subsidies for green electricity production *via* the Green Certificates mechanism (Heneffe, 2014). In order to evaluate the consequences of the installation of the biogas plant, the following functional unit was used: 1 additional MJ of electricity supplied to the grid by the biogas plant.

The analysis was based on the framework proposed by Weidema et al. (2009); Schmidt (2008) and included the impacts of (1) the biogas plant operation (*i.e.*, energy crop [silage maize] production,