The role of biogas production in sustainable biofuels based biorefinery concepts

A. Bauer, C. Leonhartsberger, D. Lyson, K. Hopfner-Sixt, V. Bodiroza, V. Simic, B. Amon, T. Amon
University of Natural Resources and Applied Life Sciences, Department of Sustainable Agricultural Systems, Peter Jordan Straße 82, A-1190 Vienna, Austria
Email: thomas.amon@boku.ac.at

Abstract

Biogas is a biogenous and renewable source of energy that contributes to a sustainable material and energy use. Biomass from arable– and grass land in Austria and other European countries is already more or less successfully used for biogas production. Within biogas production energy crops are currently at the centre of interest. The largest expense for biomass fermentation is the preparation of biomass. In order to obtain an optimum yield from the biomass, their organic compounds must be as easy degradable as possible. At present the cultivation of energy crops takes place in competition with food production. Therefore, ways must be found to produce food on arable land and to use the surplus and residual substances in biogas plants. Thereof, this in most instances cellulose biomass must be pre-treated.

The crop rotation presented in this paper produced 126.84 GJ ha^{-1} a^{-1}. 12.90 GJ ha^{-1} a^{-1} are provided in the form of ethanol, and 113.64 GJ ha^{-1} a^{-1} in the form of biogas. Integrated crop rotations use the total arable area for an integrated production of food, feed and energy crops. At the same time, it is assumed that the crop rotation covers food and feed demands. It is essential that the intensity level of production is adapted to the pre-requisites of the location where energy crops, food and feed are grown.

Introduction

A biorefinery is an integrative and holistic concept for a biochemical and thermochemical conversion of renewable raw materials in a highly productive system in individual parts, which can be transformed into marketable products, such as fuels, energy, and raw materials for industry.

Through the combination of several different techniques a reduction of production costs, a minimisation of the utilisation of fossil energy sources, and the reuse of excess materials and by-products from each technique can be achieved. Thus, the ecological footprint is minimised. Biorefinery concepts are systems in which food, raw materials for industry, and energy can be produced. The aim of a sustainable biorefinery concept is the development of integrated crop rotation systems that cover the demand of food and feed, as well as the production of raw materials (e.g oil, fat, organic acids) and energy (e.g. biogas, biodiesel, bioethanol). Currently, biogas production is mainly based on the anaerobic digestion of single energy crops. In the future, biogas production from energy crops will increase and requires to be based on a wide range of energy crops that are grown in versatile and sustainable crop rotations. In addition, by-products from the agricultural, food and energy industry need to be integrated. It is essential to develop sustainable energy supply systems that aim to cover the energy demand from renewable sources. The potential of biogas production will be higher than previously assumed when sustainable systems are the base of calculations.

This aim can be achieved by the following strategies:

- Food non-food switch: alternation of crops for the production of food, feed, raw material and energy

- Cascade utilisation: different parts of the same crop for different options, e.g. starch from maize corns and biogas from the remaining maize plant
- Choice of the optimum genotype and harvesting time: e.g. energy crops must produce high biomass yields and contain optimum nutrient patterns

In this paper an example of a biorefinery system is presented. Energy (bioethanol and methane) and food are produced in a locally adapted sustainable crop rotation system. The by-products from distillery as well as crop residues from wheat, maize, barley, sunflower and sugar-beet are used for the production of renewable energy. The potential for energy production in sustainable biorefinery concepts is calculated. Possible hindrances by the realisation of this potential, and means for a better utilisation are discussed.

Material and methods

The examination focused on a biofuels (bioethanol and methane) based biorefinery system. By-products are digested in biogas plants. The wheat stillage used in the investigation was obtained from the distillery "Starrein" (Lower Austria) and the maize stillage from the distillery in "Silberegg" (Carinthia). The stillage was stored at 8 °C until digestion. Wheat straw and maize straw were harvested in Gross-Enzersdorf (Lower Austria). The straw was chopped to a length of < 1 mm. Wheat straw was steam-exploded for 20 min at 180°C prior to digestion to dissolve the lignocellulose complex. Biomass yields for the contrasting crop rotations were estimated with mean yields that were measured on locations that are typical of a major part of Austrian agriculture: "Mostviertel", "Weinviertel" and a region with Pannonian climate, all located in "Lower Austria" (BMLFUW, 2002a), (BMLFUW, 2002).

Anaerobic digestion experiments to measure the Biochemical Methane Potential (BMP) were carried out in accordance with VDI 4630 (VDI 4630, 2006). In detail, eudiometer batch digesters of 0.5 litre capacity were used and the temperature was set at 37.5 °C. In the lab experiments methane yields from each harvest and cut were measured with in 3 replicates. The investigations covered a wide range of parameters: specific biogas and methane yield, biogas quality, transformation of biomass carbon and energy into biogas carbon and energy. Biogas production is given in norm litre per kg of volatile solids (l_N kg^{-1} VS). Methane concentrations in the biogas were analysed by a Gas Data LMS NDIR analyser (accuracy: ± 1-3% of the measurement reading).

Results

The multifarious possibilities for the utilisation of renewable raw materials led to the development of the most various techniques for transforming biomass. So far, the potentials of these techniques cannot be utilised, because not all substances produced can be used, and energy must be partially provided on the basis of fossil sources.

An example of a biorefinery concept can be portrayed using the integrated crop rotation system (Table I), where food, feed, ethanol and biogas are produced. The goal is to recycle all the raw materials occurring in the system (e.g. maize straw, wheat straw, barley straw and stillage). Lignocellulosic biomass, however, can only be made limited use of without prior treatment.

Straw is currently being used mainly in straw combustion facilities, or is left on the field. With combustion, a higher energy yield is achieved in contrast to the fermentation in a biogas plant. Due to the loss of organic and humus forming substances, the loss of nitrogen and the problem of ash disposal, it is ecologically not desirable as a long-term solution. The methane potential (only available in laboratory experiments) of wheat straw without pre-treatments lies at 189 l_N kg^{-1} VS. With a pre-treatment of lignocellulosic biomass with steam explosion, a specific methane yield of 396 l_N kg^{-1} VS can be assumed. After 12 days no additional gas yields from steam exploded straw was observed. Untreated Straw is difficult for methanogenic bacteria to break down, so that in the digester a floating crust forms, whereby additional agitation must be cared for. Therefore, only pre-treated straw can be used. Through a pre-treatment of lignocellulosic biomass for example, with the “steam explosion” procedure, the biomass is broken down more quickly, and the development of a floating crust can be successfully avoided.

An additional use of stillage from ethanol production is possible in biogas plants; the biomass occurring in whole crop rotation can also be used. The specific methane yield from maize stillage gained a specific methane yield of 418 l_N kg^{-1} VS. The crop rotation outlined in table I produced 126.84 GJ ha^{-1} a^{-1}. Around 10 percent (12.90 GJ ha^{-1} a^{-1}) thereof are obtained in the form of ethanol, and 90 percent (113.64 GJ ha^{-1} a^{-1}) in the form of biogas. At the same time, it is assumed that the crop rotation covers food and feed demands. It is essential that the intensity level of production is adapted to the pre-requisites of the location where energy crops, food and feed are grown.

Table 1: Example of biomass, methane and energy yields from a sustainable crop rotation in Lower Austria that integrates food, feed and energy crop production

Year	Crop	Biomass[a]	Specific CH_4 yieldb	Specific energy yield	energy yield
		t VS ha^{-1}	l_N kg^{-1} VS	MJ kg^{-1} VS	GJ ha^{-1} a^{-1}
1	Grain maize (ethanol)	7.68	-	8.4[d]	64.30
	Maize stillage	2.85	418	16.63[c]	47.40
	Grain maize (steam exploded straw)	7.16	396	15.76	112.82
2	Winter wheat (food)	-	-	-	-
	Winter wheat (steam exploded straw)	3.43	396	15.76[c]	54.05
	Intercrop (clover grass)	2.71	335	13.33[c]	36.12
3	Summer barley (straw)	2.90	396	15.76[c]	45.69
4	Sugar beet (sugar)	-	-	-	-
	Sugar beet (leaves)	7.20	210	8.35[c]	60.16
	Pressed beet pulp silage	2.68	348	17.11[c]	36.98
5	Sunflower seeds (food)	-	-	-	-
	Sunflower (straw)	8.05	396	15.76[c]	126.84
	Intercrop (lucerne)	3.61	335	13.33[c]	48.12
Ethanol yield of the whole crop rotation					12.90
Methane yield of the whole crop rotation					113.64
Total energy yield of the whole crop rotation					128.31

[a] Biomass yields are longtime mean values (BMLFUW, 2002a), (BMLFUW, 2002). They are similar to mean EU-25 biomass yields (EUROSTAT, 2005).

[b] Specific CH_4 yields: Anaerobic digestion experiments in accordance with VDI 4630 (VDI 4630, 2006)

[b] 1 m^3_N CH_4 = 39.79 MJ (Dubbel, 1987)

[c] 1 kg ethanol = 26.8 MJ (KTBL, 2005)

Conclusions and outlook

Energy crops are very suitable substrates for anaerobic digestion. To be able to run biogas plants economically efficient the methane yields of energy crops need to be known. The methane yield of energy crops depends on their nutrient composition. Currently, biogas production from energy crops is mainly based on the anaerobic digestion of maize. In the near future, biogas production from energy crops will increase (Ress et al., 1998) and it has to be considered that energy crops are grown in versatile and sustainable crop rotations. Sustainable biogas production from energy crops must not be based on maximum yields from single crops, but on maximum methane yield from the sustainable and environmentally friendly crop rotation systems. The challenge for future biorefinery systems is to use all side- and by-products from industry processes as well as crop residues.

Ways must be found to enable the production of food in agricultural areas and the fermentation of the occurring excess materials in biogas plants. Therefore this biomass, which contains excessive amounts of lignin, must be specially pre-treated. Thermo-physical procedures can be employed as one possible option. The pre-treatment procedure ("steam explosion") should dissolve lignin from the biomass matrix of the fermentable raw materials. Thereby the availability of nutrients contained in the biomass is improved for anaerobic metabolism of methane fermentation. Simultaneously, this improves the technological properties of fermentable raw materials.

Research and development to increase the production of competitive and environmentally sound biofuels are of paramount importance. Further research and development actions should enable an improvement of existing feedstock and technologies in the short-term, a commercial production of second generation biofuels (mainly from lignocellulosic biomass) in the mid-term, and the implementation of full-scale integrated biorefineries using new energy crops and waste in the long-term. Anaerobic digestion is the key technology within biofuels based biorefinery systems for energy production in agricultural systems. It is the base for reaching high land productivity by combining the production of food, feed and energy.

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