Modelling of small-scale bioethanol plants with renewable energy supply

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The main objective of this work is to evaluate different scenarios of small-scale bioethanol production (1000, 5000 and 10000 tons bioethanol/year) from wheat and maize with innovative energy supplying facilities. All of them provide energy exclusively by exploitation of biogenic residual substances of the bioethanol process in order to substitute fossil fuels. Further residuals result from sustainable crop rotation concepts as well as by-products from grain production. The most valuable process options for renewable energy supply are identified as: (1) biogas production from stillage and co-substrates utilised in a combined heat and power (CHP) plant, (2) biogas production from stillage only utilised in a gas-fired boiler, and (3) process steam production by straw incineration. Process simulation results show that 16 out of 18 analysed plant scenarios achieve at least 100 % thermal energy supply by renewables.

1. Introduction

Within the current political framework the production of bioethanol is steadily gaining importance. However, the sustainable development of bioethanol as a renewable source of energy has to allow for ecological considerations in the production process itself, too. The level of sustainability is challenged by the fact that common large-scale bioethanol industry is still powered by fossil fuels. To meet the requirements of feedstock, also considerable transportation emissions are involved. Such large-scale concepts were already investigated in previous works (Wukovits et al., 2006a/b), evaluating both fossil and renewable energy supply.

In the following, bioethanol production in small-scale plants is scrutinised. Since the demands of small plants are much lower, they can be supplied with feedstock at local level. Transportation efforts are abated, while the position of farmers as energy producers is strengthened. Several other environmental aspects are considered, such as sustainable crop rotation concepts for regional feedstock production in accordance with local food production, and – most importantly – the thermal utilisation of biogenous residual materials in order to substitute fossil fuels.

As first option the residues of bioethanol distillation and feedstock harvest are fermented to methane rich biogas, which is intended for combined heat and power production in a CHP plant. In option 2, only thermal energy is generated by burning biogas in a combustion chamber that is coupled with a steam vessel. The third option is to supply thermal energy by incineration of straw, the by-product of cultivation of grain for bioethanol production. In total, 18 different scenarios of small-scale bioethanol production (1000, 5000 and 10000 tons bioethanol/year) from wheat and maize with innovative energy supplying facilities are evaluated. The elaboration of the most valuable process design options is based on simulation data of energy and mass balances, both computed by the industrial software package IPSEpro.

2. Methods

2.1 Simulation Models

In the equation-oriented software package IPSEpro the bioethanol, biogas and straw incineration processes are modelled. Although IPSEpro was initially designed for power plant engineering, a broader application range is made possible by creating user-defined modules in the “model development kit” (MDK) that can be integrated in the subsequent “process simulation environment” (PSE).

All units of specific interest for bioethanol and biogas production as well as biogas utilisation are developed in IPSEpro MDK, and are available for setting up different combinations of bioethanol plants with energy supplying facilities. For a detailed description on the simulation models refer to Pfeffer (2006). Simulation results for large-scale bioethanol production (15000 to 200000 tons bioethanol per year) have been published by Pfeffer et al. (2005).

2.2 Bioethanol Plant

The model of the bioethanol production process is based on data from literature according to the state of art (Jacques et al., 2003; Roehr, 2001; Gerhardtz et al., 1987). After the enzymatic conversion of starch to fermentable sugars, alcohol synthesis by yeast (*Saccharomyces cerevisiae*) is started until the ethanol concentration in the alcoholic mash reaches 8 % by weight. In the distillation/rectification system ethanol is separated, afterwards dewatered by adsorption on a molecular sieve to 99.8 % (mass based). Concentration and dewatering of ethanol refer to the concept described by NREL (Aden et al., 2002).

In conventional plants the residual by-product of bioethanol distillation, the so-called stillage, is dried to high in protein DDGS (Distillers’ dried grains with solubles). Apart from the additional proceeds of DDGS sale as animal feed ingredient, its production implies the main drawback of almost doubling the energy demand of the bioethanol plant. The alternative utilisation of stillage in biogas fermenters doesn’t only save the energy of DDGS production, but also allows covering the heat (and power) demand of the bioethanol process by biogas instead of fossil fuels. Therefore, the possibility of DDGS production is neglected in the analysed bioethanol plants in favour of generating feedstock for biogas digestion. In the straw incineration scenarios the stillage is intended as liquid animal feed or fertiliser, and leaves the bioethanol plant without further treatment.

2.3 Biogas Production and Utilisation

By anaerobic decomposition of the distillation residue biogas will be produced. Due to the fact that the plant-specific usage of biogas – CHP or biogas boiler – influences the quantity of heat produced, adequate heat supply is ensured by adapting the biogas feedstock for each option. For this purpose, stillage co-fermentation with residual substances of the bioethanol process is examined in batch and continuous experiments. Straw and clover are determined as the most interesting co-substrates: Straw is available as residue of grain cultivation, while clover remains of a specified crop rotation concept, which contributes to sustainable agriculture (Rosenberger, 2001). The experimental data on methane yield of wheat and maize stillage in mono- as well as co-fermentation (table 1) is implemented in the simulation environment of biogas production. Note: As a matter of principle the total amount of stillage is fed into the biogas plant, augmented with additional biomass. Therefore, the total dry mass of biogas feedstock of e. g. wheat stillage with co-substrates is 10 times higher than without co-substrate, which compensates for the comparatively low specific methane yield. The two different compositions of biogas feed mixtures reflect the crop rotation concepts for wheat and maize, respectively, and are in proportion to the yields of grain, straw and intergrain (i. e. clover).

Table 1: Experimental data on methane yield of different biogas feedstock

biogas feedstock	**ratio of dry matter**	**methane yield (Nm^3 / kg oDM*)**
wheat stillage	stillage only	0.380
maize stillage	stillage only	0.347
wheat stillage with co-substrates	stillage : straw : clover = 1:4:5	0.306
maize stillage with co-substrates	stillage : straw : clover = 1:3:2	0.291

* oDM: organic dry matter

The IPSEpro simulation flowsheet of bioethanol production connected to biogas production is presented in figure 1. Stillage and co-substrate are mixed and diluted to 10 % (by weight) dry substance, and anaerobically digested to biogas in a two-stage fermentation process. After passing the H_2S-scrubber the gas can be used in a CHP plant to produce electric power and process steam. Alternatively, process steam only is generated by a steam cycle linked to a biogas combustion chamber.

2.4 Straw incineration

Another promising option for renewable thermal energy supply is the incineration of straw. After minor changes of the combustion chamber IPSEpro's standard-library modules can be applied, whereas the steam cycle is taken from literature (Miltner et al., 2005). Straw production is based on crop-straw-ratios of maize and wheat (Aufhammer, 1998; Freyer, 2003). In order to guarantee long-term soil fertility, 25 % of the produced straw is left on the fields; the remaining 75 % are considered available for incineration.

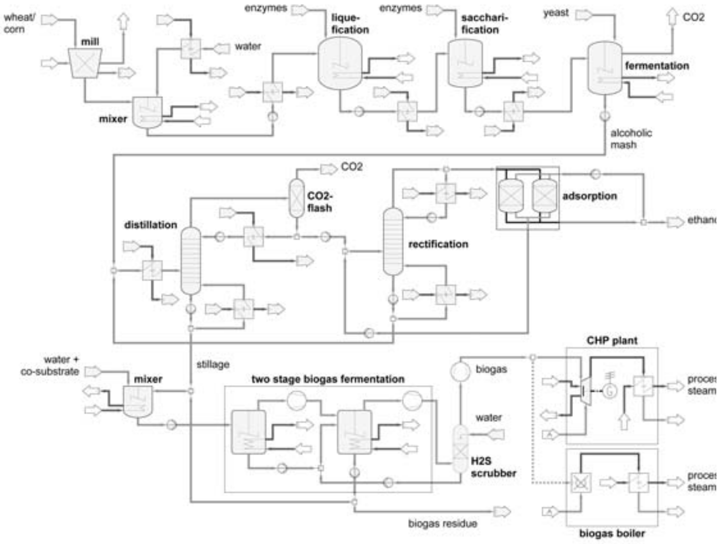

Figure 1: IPSEpro simulation model of coupled bioethanol and biogas production; biogas utilisation in CHP and biogas boiler, respectively

3. Results and Discussion

The coupled bioethanol and biogas simulations show that the amount of biogas resulting from stillage alone does not suffice in terms of process steam supply for bioethanol production when utilised in CHP plants. Nonetheless, its usage in gas-fired boilers, which have a higher thermal efficiency, allows to power bioethanol plants entirely by renewable process steam. The 1000 tons/year bioethanol production from maize is an exception, only 75 % of its heat demand is covered by the gas-boiler system (see figure 2, option 2). Therefore, adaptations of the biogas feedstock are suggested.

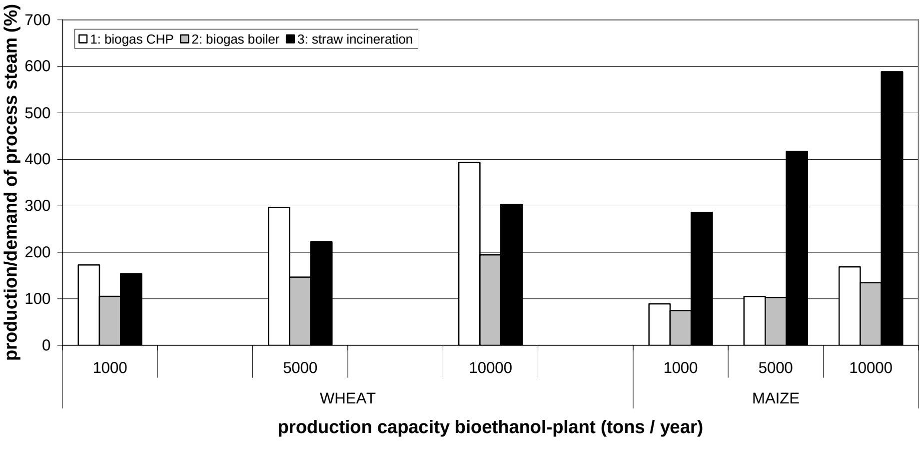

Figure 2: Coverage of energy demand of the bioethanol production from wheat and maize for 3 different production capacities

Due to the lower thermal output of CHP plants, co-fermentation of stillage with straw and clover is necessary to meet the process steam requirements of the bioethanol process (option 1, see table 2). Two tendencies are evident: First, the lower the bioethanol production capacity, the higher is the specific energy demand. Second, excess thermal energy is produced, particularly in case of wheat-to-ethanol (figure 2). The latter effect can be ascribed to a difference in biogas feedstock quantity, as the mass of wheat mixture is ten times the mass of wheat stillage, whereas the maize mixture is only 6 times the mass of maize stillage (based on dry matter, table 1). As a consequence, only 89 % of the steam requirements are met by the CHP plant combined with the 1000 t/y bioethanol from maize production. Thus, further optimisation of the biogas feedstock, e. g by co-fermentation of stillage with additional biomass, is suggested.

Table 2: Usage of biogenous residual substances of the bioethanol process for three options of renewable energy supply

energy production option	**input**
option 1: biogas CHP	wheat-/maize-stillage + wheat-/maize-straw + clover
option 2: biogas boiler	only wheat-/maize-stillage
option 3: straw incineration	75 % of total wheat-/maize-straw

By incinerating 75 % of the straw produced as bioethanol crop residue in the fields, process steam is generated in option 3. As shown in figure 2, the actual heat demand is exceeded by far. Unlike results of biogas option 1 and 2, the straw incineration scenarios for maize yield more process steam than equivalent wheat scenarios. These differences can be explained by a higher straw-crop-ratio of maize (Aufhammer, 1998; Freyer, 2003) as well as its higher calorific value (Reisinger et al., 2006). In table 3 the total amount of straw produced in the fields is illustrated. To actualise adequate, that is 100 % energy supply of bioethanol without DDGS production, the quantity of incineration feedstock can be reduced to 24-49 % of wheat straw and 13-26 % of maize straw, respectively – depending on plant capacity. In the given situation of abundant energy availability, however, the implementation of DDGS production is to reconsider, in particular for maize scenarios.

Table 3: Required percentage of straw for 100 % coverage of bioethanol plants' energy demand by straw incineration, based on total amount of wheat/maize straw available from grain cultivation

bioethanol feedstock		**wheat**			**maize**	
bioethanol plant capacity (t/y)	1000	5000	10000	1000	5000	10000
total straw available (t/y)	3240	15739	30604	5828	28310	55047
straw to cover energy demand (%)	49	34	24	26	18	13

4. Outlook

In summary, 16 out of 18 investigated scenarios of bioethanol production achieve 100 % or even more supply with renewable energy. Further works will primarily be concerned with the calculation of profitability for all presented scenarios along with the quantification of their ecological impact by the so-called “Sustainable Process Index” (Narodoslawsky et al., 1995). It is to clarify whether sustainability in general is compatible with economic efficiency, or under which conditions particularly small-capacity bioethanol production powered by renewable energy is actually more sustainable than conventional large-scale production of bioethanol as well as other biofuels.

5. Acknowledgement

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