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Evaluation of technology structure based on energy yield from wheat straw for combined bioethanol and biomethane facility

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ABSTRACT

The objective of this paper is to evaluate a combined bioethanol and biomethane production from wheat straw applying process network synthesis for maximised energy yield per ton lignocellulosic biomass input. Experimental results in combination with literature data were implemented in process synthesis software for energy optimisation. Wheat straw was steam exploded at different pretreatment conditions on laboratory scale. Glucose and ethanol yields as well as specific biogas yields of different solid and liquid fractions were determined via batch-experiments. Preferable pretreatment conditions differ between biogas and bioethanol production. The optimal process configuration was found to consist of direct biogas production from steam explosion pretreated straw at 170 °C for 20 min combined with bioethanol production from straw pretreated at 200 °C for 20 min. This process results in a purified methane yield of 7892 MJ and a purified ethanol yield of 964 MJ per ton untreated straw input.

1. Introduction

The promotion of renewable energy production has multiple drivers: reduction of greenhouse gas emissions, rising energy demands while "peak-oil" might have already been reached, or desired independency from oil imports. Utilization of biomass is a possibility to provide renewable energy without dramatic changes in infrastructure and consumption technologies as it results in material energy carriers. For every fossil energy source, a bio-based alternative already exists.

Bioethanol and biogas are the sustainable alternatives to gasoline or natural gas. Both energy carriers have different fields of application. Especially an application as sustainable fuel alternative seems to be a suitable possibility due to the necessity of only minor changes in infrastructure and drive technology. Biogas (containing bio-methane as value defining component) can be produced from diverse input materials like animal manure, different energy crops and any type of organic waste and by-product. Biomethane yields are predominantly depending on the input material [1] and the costs of transportation and storage are especially influenced by the energy content of the selected raw-material. A large number of biogas plants use energy crops like maize as their main input material [2] because of its high yield per hectare. However the proportion of arable land is limited and the rising demand on agricultural land for food and feed production caused by a rising world population and an exploding meat demand intensifies the competition for agricultural land [3]. One possibility to realise biogas production without energy crop cultivation is to develop concepts for the utilization of agricultural waste and by-products. For the production of bioethanol the situation is quite similar. Today bioethanol is primarily produced from sugar cane, maize or any type of grain. As a consequence this bio-based product is often criticised for the competition with the food market. Concepts for bioethanol production from agricultural by-products already exist in various demonstration activities [4,5]. Large scale market penetration is inhibited by the low economic competitiveness of the technology [6]. To guarantee the maximum economic output from the biomass used, biorefinery systems seem to be an attractive solution. The biorefinery concept is analogous to today's petroleum refinery, which produces multiple fuels and products from petroleum. Biomass energy and material recovery is maximized when a biorefinery approach is considered, in which many technological processes are jointly applied [7]. According to René and Bert [8], the current biorefinery classification system is in a developing stage, where categories have until now been differentiated based mainly on: raw material inputs, type of technology (e.g. biochemical or

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thermo-chemical biorefinery), status of technology (conventional and advanced biorefinery, 1st and 2nd generation biorefinery) and main (intermediate) product produced [9]. Biorefinery is being holistically defined as "an integrated pattern of farming and conversion activities capable to provide bioenergy and biomaterials as alternative to fossil-based refineries, increasing job and income in rural areas" [10]. This approach of extracting diverse resources and energy services from biomass should be preferred over simply incinerating organic materials for thermal energy production. Prioritization of fuelled conversion technologies is thus imperative. Bioethanol producing biorefineries are one possible option especially for lignocellulosic residuals like straw. The proportion of cellulose, hemicellulose and lignin determine the conversion pathway and products to be delivered. The higher the cellulose to lignin ratio, the higher the biodegradability of the biomass. Biogas plants are commonly integrated in those biorefinery concepts as end of pipe treatment facilities for solid and liquid waste (ethanol stillage and wastewater streams) [11–16], and are not recognized as energy producing facilities in their own right.

Different strategies to increase the efficiency of lignocellulosic biorefinery plants are currently persued. The pretreatment technology is one of the key steps in the lignocellulosic biorefinery [17]. In general, pretreatment technologies are divided into four major groups i.e. physical, chemical, physic-chemical and biological [18]. The intention of the pretreatment is a maximised recovery of fermentable sugars with low energy input and inhibitory co-products. Although each method has some advantages, one method could not be the choice for all types of biomass. With reference to the investigated process of combined bioethanol and biogas production from straw steam explosion pretreatment was applied for partial hemicellulose hydrolysis and improved enzyme accessibility as steam explosion is reported among the limited number of cost-effective pretreatment technologies for pilot scale demonstration and commercial application [19]. Compared to chemical pretreatment with acid, alkaline, ionic liquids or organic solvents the cellulose decrystallization and lignin removal for steam explosion pretreatment is low [20]. Besides the pretreatment simultaneous saccharification and fermentation, improved enzymes for hydrolysis, different yeast strains or yeast and bacteria mixtures, cascading fermentation of different sugars and genetic modification of yeast and bacteria strains are some of the current research topics [21–26], to improve the efficiency of biomass conversion. Especially the additional conversion of pentoses to ethanol seems to be necessary in order to become economically competitive. Compared to single glucose conversion, an increase in ethanol yield of 38% is theoretically possible using pentoses.

The approach of a combined bioethanol and biogas refinery highlights another possible way to convert pentoses to energy without sophisticated process adaptions of ethanol fermentation (often realised with genetically modified yeast). The conversion of pentoses into biomethane in conventional biogas plants can easily be done without any changes of the design and operation method. Beside the advantage of converting pentoses to methane, a biorefinery with integrated biogas production also helps to minimize wastewater output.

The current paper evaluates a combined biogas and bioethanol plant to maximise energy output based on one ton untreated wheat straw as input material and investigates synergistic effects between both separated processes. Bioethanol production from steam exploded wheat straw was performed on laboratory scale, encompassing the processing steps pretreatment, enzymatic hydrolysis and ethanol fermentation. Beside ethanol production different process streams were analysed for their biological methane potential. All data for the energetic process evaluation study was collected via own laboratory experiments to enable complete mass balances and comparable basic conditions for bioethanol and biogas production. The mass balance data from experiments was extended with process energy demand data from literature. The collected data was input for multiway optimisation via process network synthesis described below to optain maximised energetic product output (from biomethane as well as bioethanol) from 1 ton straw input.

1.1. Energetic process optimisation via process network synthesis (PNS)

Process network synthesis (PNS) is a possibility for structural optimisation. The system is based on the p-graph framework and the use of combinatorial methods to find all feasible structures linking given inputs with required products using a certain set of technological options [27–29]. It is usually used for economic optimisation of networks but in this study PNS is used for energy output optimisation. PNS is an economic simulation tool and needs detailed input data for generating reliable simulation results. In this study data was generated by laboratory experiments and literature review and the results are of theoretical character.

With the help of PNS the optimal process pathways of a combined bioethanol and biogas plant was determined. The optimal solution was defined by maximum energy output (bioethanol and/or biogas) from one ton wheat straw. PNS calculations are based on energy and mass balances in combination with economic parameters (costs and prices) allocated to each process stream and technology step. The selected approach of excluding prices and profit for every process stream and technology and assigning heating values as "prices" to the product flows allows energy output optimisation. At the start of process optimisation a so-called maximum structure has to be generated. This network includes all feasible processes and sub-processes as well as their mass and energy balances. By using PNS, scenario definition is no longer necessary. As a solution of the p-graph framework an optimal structure is created representing the process chain or network with the highest economic benefit or in the case of this work with the highest energy output. Processes with smaller economic benefit are not integrated in the optimal structure.

1.2. Basic process description

The basic flow sheet of the process is presented in Fig. 1. Data on specific flows are provided in Table 1. The ethanol process is defined as 2nd generation ethanol production with wheat straw as input material. Wheat straw is pretreated with steam-explosion and then enzymatically hydrolysed to sugar monomers. Onsite enzyme production on a partial flow of pretreated straw is performed as part of the biorefinery concept. Enzymatic hydrolysis is followed by a solid/liquid separation where "waste" fibres are separated from the sugar solution. The glucose present in the liquid fraction is fermented to ethanol by genetically unmodified yeast. Finally the ethanol solution is purified to 960 mL L^{-1} ethanol by distillation. Further purification to anhydrous ethanol is not included in the study. The process network is completed with a biogas plant and a methane purification unit for biomethane upgrade. For process network synthesis all process flows are defined as possible input substrate for biogas production. Necessary process energy is provided by optional biomass (residual lignin fraction and untreated input straw) or biogas incineration with combined heat and power generation.