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Evaluation of Ethanol from Lignocellulosic Biomass – Process Scenarios for Austria

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In bio-ethanol production lignocellulosic materials such as wood or straw constitute an attractive alternative to starchy feedstock for several reasons. The goal of this paper is to present an approach to determine the most interesting process scenarios for production of lignocellulosic ethanol in Austria. A brief review of the conversion technologies available is given. A selection of relevant conversion processes for Austria is presented. Process modeling as a tool for process analysis is introduced.

1. Introduction

In the EU the target for renewable energy in transport has been defined to be 10% at 2020 (European Union, 2009). For several reasons bio-ethanol produced from lignocellulosic materials is an adequate strategy that can contribute to reach this target. First, these materials are available abundantly and consequently affect production economics positively. Second, using parts of the raw material to cover the processes' internal energy demand renders the process ecologically friendly. As a result the greenhouse gas mitigation potential is promising (Eisentraut, 2010; Wang et al., 2007). Moreover, usage of additional acreage can be avoided if residual materials from food production or forest industry are employed.

The technological challenges for ethanol from lignocellulosic biomass are inherent to the feedstock. Structural carbohydrates like cellulose and hemicelluloses are much more recalcitrant to degradation than carbohydrates used for energy storage of the plant. To overcome this recalcitrance of the feedstock sophisticated equipment is necessary which results in a high capital cost of the conversion plant. This high capital cost can outweigh the economical benefits of the cheap feedstock.

2. Technology Options

2.1 Feedstock

There is a wide range of lignocellulosic feedstock that can be converted to ethanol. In Austria however, the most abundant lignocellulosic raw materials are wood and straw. The major components of any lignocellulosic biomass are the polysaccharides cellulose and hemicellulose and the phenolic polymer lignin. In a biological process polysaccharides which account for up to two thirds of the biomass can be fermented to

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ethanol whereas lignin cannot be used to produce ethanol but serves as a solid fuel for the process.

2.2 Enzymatic Conversion Process

To obtain fermentable sugars from lignocellulosic biomass hemicellulose and cellulose have to be hydrolyzed, which can be achieved via two strategies: acid hydrolysis and enzymatic hydrolysis (Hamelinck et al., 2005). Nowadays there is an agreement, that the enzymatic approach is the most promising technology (Hahn-Hägerdal et al., 2006; Wooley et al., 1999), mainly due to expectable improvements in enzyme technology and the high cost of stainless steel equipment and recovery or neutralization systems necessary in acid processes.

2.2.1 Pretreatment of biomass to improve enzymatic digestibility

For an efficient use of enzymes the cellulose fibers have to be rendered accessible for enzymatic attack which is achieved by a pretreatment step. There is broad range of pretreatment technologies available, each of which differing in process characteristics and mode of action. The most important technologies are physico-chemical methods like steam pretreatment with addition of acid, like SO_2, H_2SO_4 or organic acids, dilute acid pretreatment, which is very similar to steam pretreatment, organosolv pretreatments using organic solvents like ethanol or and alkali treatments using lime or ammonia (Galbe and Zacchi, 2007, Mosier et al., 2005). Depending on the pretreatment method and the microorganisms used for ethanol production detoxification can be necessary. In steam pretreatment and dilute acid hydrolysis which are the technologies applied most often hemicellulose is solubilized whereas lignin and cellulose are essentially left intact.

2.2.2 Enzyme production and enzymatic hydrolysis

After pretreatment the cellulose can be degraded to yield glucose monomers. This is achieved by an cellulase enzyme mixture. Cellulases are extracellular enzymes produced in submerged fermentation under aerobic conditions by specialized microorganisms like *T.reesei* or *A. Niger* (Lynd et al., 2002). At present enzymes are produced in dedicated enzyme production plants, however, economic considerations make on-site production of cellulose enzymes a viable option. In this case part of the pretreated material can serve as a substrate (Szengyel et al., 2000). Enzymes are partly bound to the mycelium and consequently it can be advantageous not to separate the extracellular enzymes from the broth but to add the whole slurry to the hydrolysis step (Kovács et al., 2009; Merino and Cherry, 2007).

In enzymatic hydrolysis a high cellulose conversion at low enzyme loadings, short residence times and a high content of water insoluble solids (WIS) is desired. The high WIS-content is essential since it results in a high concentration of sugars and ethanol which is crucial to reduce the energy demand of distillation.

2.2.3 Ethanol fermentation and biocatalyst propagation

In the fermentation step the sugars liberated by enzymatic hydrolysis and pretreatment are converted to ethanol by microorganisms. In well established ethanol processes converting starch- or sugar based raw materials *S.cerevisiae* has been the industrial standard. However, its lacking capability to ferment C5-sugars is a major drawback when dealing with lignocellulosic hydrolysates. A possible remedy is the use of recombinant or native C5-sugar-fermenting organisms like *rS. Cerevisiae* or *E.coli, P.stipis and Z.mobilis* (Hahn-Hägerdal et al., 2006; Aden et al., 2002).

Prior to its use in the fermentation step the microorganism has to be cultivated in an aerobic propagation step. To adapt the microorganism to inhibitors present in the hydrolysate, propagation on part of the pretreated material is beneficial (Rudolf et al., 2005; Aden et al., 2002).

Ethanol fermentation can be performed either as a separate step after enzymatic hydrolysis (Separate Hydrolysis and Fermentation, SHF) or simultaneously with hydrolysis (Simultaneous Saccharification and Fermentation, SSF). If SSF is employed end product inhibition in the hydrolysis step can be avoided and capital cost can be reduced. However, with SSF recycling of the microorganisms is not an option and neither of the two steps can be performed at its optimal conditions (Olofsson et al., 2008). An even higher degree of process integration is achieved with Consolidated Bioprocessing (CBP), where enzyme production, cellulose breakdown and alcohol fermentation are performed in one reactor by the same microorganism (Lynd et al., 2002; Lynd et al., 2005).

2.2.4 Ethanol recovery, stillage treatment and energy production

In conventional ethanol processes multicolumn distillation and pressure swing adsorption (PSA) are standard technologies to obtain fuel grade ethanol. Also with lignocellulosic feedstock these technologies are the first choice for ethanol recovery (Aden et al., 2002; Sassner et al., 2008) even though there exists a whole range of attractive alternative separation technologies like membrane-, stripping- and extraction-technologies that might be advantageous for the more dilute fermentation broths obtained from lignocellulosic hydrolysates (Vane, 2008).

To render the whole process energy efficient the stillage has to be used to supply process energy. For that purpose the insoluble solids are typically separated from the liquids dried and burnt. Solids exceeding the amount needed to cover the processes energy demand can be sold as a solid fuel. The liquid fraction can be evaporated; vapors are condensed and recycled to the process. The liquid effluent (syrup) after evaporation can be burnt together with the solids (Aden et al., 2002; Sassner et al., 2008) or used as an animal feed (Larsen et al., 2008). An alternative to evaporation is anaerobic digestion of the liquid fraction (Wingren et al., 2008). The biogas yielded can be used for generation of heat or electricity production in an engine.

3. Process Scenarios for Austria

In Austria the most relevant raw materials for production of lignocellulosic ethanol are straw, hardwood and softwood. Raw material potentials and feedstock logistics suggest the annual ethanol capacity of the plants to be in the range of 50 000 to 100 000 t/a for hardwood and straw and 50 000 to 200 000 t/a for softwood.

In order to assess the most promising process scenarios for Austria the following eligibility criteria were applied: economic aspects, technology proven in pilot-scale, energy self-sufficiency and legal situation in Austria. This led to the conclusion that the main distinctive feature for Austrian scenarios is stillage treatment. As a result the process scenarios are identical regarding the upstream process steps size reduction, steam pretreatment, enzyme production, yeast propagation and SSF as well as the

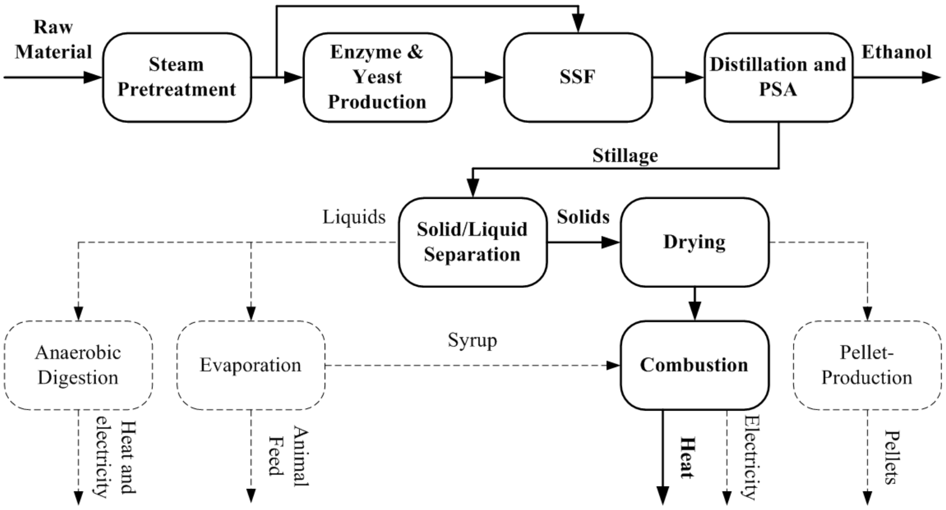

Figure 1 Summary of process scenarios differing in stillage treatment. Bold text and a solid line symbolize process steps and streams that are applied in all the scenarios. Dashed lines symbolize process steps and streams that are only applied in selected scenarios.

downstream steps distillation and pressure swing adsorption (PSA). As far as stillage treatment is concerned all the concepts introduced in section 2.2.4 are considered. Figure 1 shows a scheme of the scenarios differing in stillage treatment. Due to legal restraints in Austria fermentation of C5-sugars is not considered except for one case, which accounts for possible future changes in legislation. Table 1 summarizes the process scenarios.

Table 1 Summary of process scenarios.

Raw Material	Fermentation	Stillage Treatement
Softwood	C6 sugars	Evaporation, combustion of solids and syrup, heat and A) pellets or B) electricity production
Hardwood	C6 sugars	Evaporation, Combustion of solids and syrup, heat and A) pellets or B) electricity production
Straw	C6 sugars	Evaporation, combustion of solids and syrup, heat and A) pellets or B) electricity production
Straw	C6 sugars	Evaporation, combustion of solids, animal feed from syrup, heat production
Straw	C6 sugars	Anaerobic digestion of liquids, combustion of solids, heat and electricity production
Straw	C6 & C5 sugars	Evaporation, combustion of solids and syrup, heat and A) pellets or B) electricity production

4. Process Modelling with IPSEpro

Analysis of the process scenarios is performed via process simulation. Thereto the commercial steady state flowsheet simulation package IPSEpro is applied. The software was developed for the simulation of power plants. Consequently the standard advanced power plant library (APP_lib) contains accurate property data and basic equipment for power plant computations. Due to the flexible structure of IPSEpro's model development kit (MDK) the APP_lib can be rather easily extended by the materials and unit-operations present in biotechnological production processes of liquid and gaseous fuels from renewable materials, as shown in a prior study (Schausberger et al., 2009). Within IPSEpro's process simulation environment (PSE) graphical representations of the unit-operations are used for flowsheeting. Thanks to IPSEpro's equation oriented solving approach input and output information can be exchanged arbitrarily and complex flowsheets including recycle streams converge quickly. Consequently energy integration of the process using pinch technology can be realized easily.

For upcoming simulations of the scenarios described above, the model library was extended by materials and unit operations present in a lignocellulosic ethanol process. Future work is dedicated to flowsheet simulation of the process scenarios yielding detailed description of energy and material flows.

5. Conclusions

In this paper a brief review on the production of ethanol from lignocellulosic feedstock is given, the most relevant process scenarios for Austria are presented and an approach for modeling the conversion processes is introduced. The results obtained from process modeling can serve as a basis for techno-economic assessment, life cycle analysis, as well as energy- and exergy analysis of the process scenarios. The analysis' results should indicate the most viable process configurations of a demo-plant in Austria.

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