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Case Study

Techno-economic assessment of a wood-based biorefinery concept for the production of polymer-grade ethylene, organosolv lignin and fuel

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HIGHLIGHTS

- We simulated a biorefinery concept with Aspen Plus converting beech wood (400,000 t DM/a ≙ 250 MW) to ethylene, organosolv-lignin and fuel.
- The overall heat integration of the biorefinery was conducted by pinch analysis.
- We economically assessed the biorefinery by a discounted cash flow analysis.
- The analysis showed that the biorefinery is not yet profitable under basic assumptions.
- We carried out sensitivity analyses to determine the influence of price fluctuations.

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ABSTRACT

Lignocellulose biorefineries are distinguished by an explicitly integrative, multi-functional concept that transforms biomass into multiple products, using a variety of conversion and separation processes. This study focuses on the technical design and economic evaluation of a lignocellulose biorefinery, that converts 400,000 t DM/a (≙250 MW) of beech wood into chemicals and fuel. A model was simulated with Aspen Plus® including the process steps pre-treatment, enzymatic hydrolysis, alcoholic fermentation, dehydration and biogas generation and upgrading. Mass and energy balances showed that 61,600 t/a polymer-grade ethylene, 58,520 t DM/a organosolv lignin, 38,400 t/a biomethane and 90,800 t DM/a hydrolysis lignin can be produced with a total energy efficiency of 87.1%. A discounted cash flow analysis indicated that the heat integrated biorefinery concept is not yet profitable. However, the economic results are greatly sensitive regarding various assumptions, in particular in terms of the prices for beech wood, ethylene and organosolv lignin.

1. Introduction

The current petro-chemical industry has been built upon the by-products of crude-oil processing. The light fractions of crude oil refining are typically used to produce platform chemicals such as ethylene, propylene or butadiene. These are processed into a vast majority of products i.e. plastics, solvents and binding agents. Increasing efforts are being made to reduce the dependency of the world economy on crude oil as an exhaustible natural resource. One of the most promising approaches is to develop processes that allow the use of biomass as an alternative natural resource base. With an annual production of approximately 144×10^6 m^3 and a worldwide share of more than 3% based on energy content, biofuels already play a significant role in the transport fuel sector (OECD and FAO, 2015; Müller-Langer et al., 2014). The use of biomass for the production of platform chemicals has recently become an important research topic (Posada et al., 2013). Such a step could integrate the chemical industry into the so-called bioeconomy. The main goals are to strategically reduce the dependency on crude oil and to mitigate the greenhouse gas emissions as well as the negative impacts on the environment caused by the processing and ultimately the burning of fossil carbon sources (Taylor et al., 2015). Furthermore, a bio-based economy opens up new markets for natural resources and residues from forestry and agriculture. The implementation of non-food, lignocellulosic natural resources is of particular interest, in order to minimize the impacts on the food and fodder markets.

A general distinction can be made between the bio-chemical and the thermo-chemical routes to processing lignocellulosic biomass. Because of the possibilities for making use of the many existing molecules of this natural resource, a combination of

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raw-material fractionation and bio-chemical conversion was chosen for this study. The single processing steps to fractionate lignocellulosic material and to produce platform chemicals are currently being developed. Until now many of the approaches have been carried out in the laboratory or at the pilot scale only and have not yet been properly integrated.

Lignocellulosic biomass such as wood or straw is a recalcitrant and heterogeneous material that requires a dedicated pre-treatment and fractionation prior to further processing. Different technologies were developed to separate lignocellulosic biomass into its main components cellulose, hemicellulose and lignin. From the developed pre-treatment technologies, the organosolv pre-treatment was found to have the advantage of using mild solvents that can easily be recovered while obtaining lignin of a high quality (Alvira et al., 2010). Lignin has had limited uses in the past, i.e. as a fuel for combustion to produce heat and electricity. This is currently the typical application for the large amounts of lignin accruing from pulping operations (Kleinert and Barth, 2008). However, due to its high quality, organosolv lignin opens up opportunities for other applications such as a substitute for phenolic resins or polyurethane compounds (Pandey and Kim, 2011).

After the pre-treatment of the lignocellulosic biomass, cellulose and hemicellulose can be enzymatically hydrolyzed to C6 and C5 sugars. These sugars offer access to the sugar platform, from which a large number of biofuels and bio-based chemicals can be produced (Taylor et al., 2015). Several studies can be found on the technical design, process simulation and economic assessment of lignocellulose biorefineries. Sassner et al. (2008) introduced a techno-economic evaluation of a biorefinery producing bioethanol, solid fuel and steam out of steam pretreated Salix, corn stover or spruce. An economic assessment of a biorefinery concept, where corn stover was pretreated by dilute acid pre-hydrolysis and then converted into bioethanol, succinic acid, acetic acid and electricity, was conducted by Luo et al. (2010). Further, Laure et al. (2014) considered a biorefinery framework with organosolv pre-treatment that converts wood into glucose, lignin and xylose and analyzed it from an economic point of view. Such studies demonstrate the great variability of feedstock and products of prospective biorefineries.

The focus of this study is the technical design and economic evaluation of a lignocellulosic biorefinery concept for the integration of beech wood based products into the chemical industry. Ethylene, organosolv lignin, biomethane and hydrolysis lignin were all identified as promising products. Process simulation was chosen to virtually scale up the results from recent research projects to a commercial size. The results from process simulation were further used for an economic evaluation to assess the main cost drivers of a wood-based biorefinery producing chemicals and fuel.

2. Methods

2.1. Conceptual design

From a systematic point of view, the design of biorefineries is an open and complex problem due to the various raw materials, the potential products and the novelty of processes and technologies. Furthermore, biorefineries will always be compared to and have to compete with conventional systems. It follows that they will have to achieve maximum efficiency with a better design and process integration (Hill et al., 2006).

For the design of biorefineries, the specification of the feedstock as well as the main products and by-products was found to be a practical approach (Kokossis and Yang, 2010). In this study, beech wood was chosen as an exemplary feedstock, since it was identified as a promising raw material for the production of platform chemicals (Michels, 2009). In order to decide on a suitable product portfolio, the following five criteria were formulated (Landucci et al., 1994):

- High theoretical product yields from substrate.
- Market interest in the product as an end product or as an industrially important intermediate.
- High production volume (current or potential).
- Nonfood use of the product.
- Ability to be biologically synthesized from the common sugars derived from various forms of biomass.

Ethylene produced from the dehydration of ethanol on a large scale was selected as the primary product of the biorefinery concept. It fulfills all five product criteria: The current global market size for ethylene accounts for 127 Mt/a with a share of 0.2% (0.25 Mt/a) coming from biomass resources (Taylor et al., 2015). Moreover, the conversion pathway to produce ethylene from lignocellulosic biomass is relatively simple and well known. The second main product is organosolv lignin. Compared to other types of lignin (e.g. kraft lignin, ligninsulfonate), it has a significantly higher quality and purity. Organosolv lignin has a great market potential in the field of bio-based binding agents as well as thermosetting and thermoplastic compounds. However, one precondition for introducing organosolv lignin as an alternative commodity is its stable availability and consistent quality (Michels, 2014). Biomethane is produced from the residual streams of downstream processes in large volumes and can be fed into the gas pipeline network or used for the supply of biofuels (Ryckebosch et al., 2011). The solid by-product hydrolysis lignin (accumulates during the conversion of cellulose to sugars) is assumed to be sold as a solid fuel or as an additive for wood pellets.

Based on the defined frame conditions and the objective of minimal costs, the optimal reaction routes and appropriate flowsheet configuration, consisting of various unit operations and the corresponding operating levels are engineered. For that purpose and for mass and energy balances, the process simulation software Aspen Plus® was used. The super structure of the designed biorefinery is shown in Fig. 1.

It was assumed that the biorefinery is located in Germany on an existing chemical site, at which all required utilities and waste water treatment can be provided. A capacity to process 400,000 dry tonnes of beech wood annually was found to be reasonable (Michels, 2009). The plant operates 8000 h per year. The remaining 760 h are for maintenance, repair and restarting the operations.

2.2. Process simulation

The beech wood based biorefinery concept for the production of polymer-grade ethylene is derived from newly developed technologies and established conversion and refining processes. Process simulation was chosen as the appropriate method for the design of these processes and for the technical assessment in the form of mass and energy balances as well as the sizing of the plant equipment.

For the process simulation with Aspen Plus® NRTL (Non-Random Two Liquids) property method with Henry components was used. These routes include the NRTL equation for the liquids activity coefficients calculation and Henry's law for vapor–liquid binary interactions. Where appropriate, further property methods were used for specific processes. This is discussed in detail in the relevant sections. All unit operations were simulated with a common simplification as continuous processes (Aden et al., 2002; Sassner et al., 2008; Luo et al., 2010). Unit operations that would likely be operated in batch mode (e.g. per-treatment and