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Integration potential, resource efficiency and cost of forest-fuel-based biorefineries

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ABSTRACT

A multidisciplinary study of the implementation potential of a biorefinery, using forestry residues as feedstock, is performed by assessing techno-economic factors, system integration and feedstock supply. The process is based on biochemical conversion of logging residues to produce ethanol, biogas, pellets, heat and electricity. Nine models were designed in Aspen Plus based on the available feedstock and the required co-products. Focus was on the product ratio of pellets and heat. The net present value of the plants was calculated and thermal integration with district-heating systems in areas with regional feedstock availability was investigated. Also co-location with pulp and paper mills in Sweden was investigated to replace fossil fuels with pellets. Seven of the nine models showed a positive net present value assuming an 11% discount rate and 30% corporate tax. Five counties in Sweden were identified as potential feedstock suppliers to a biorefinery processing 200 kt dry feedstock/y.

1. Introduction

The issue of sustainable biofuel production systems has been in focus during the last years, due to the potential conflict between food and fuel production, and the increased emission of greenhouse gases from changes in the land use. Today, there is an emergent need of knowledge regarding how to produce food, fuel and bio products in a sustainable way and how to minimize the risk of land-use changes and deforestation (Berndes et al., 2011; Bogdanski et al., 2010; Karp and Richter, 2011). Researchers around the world are now studying these issues and how to develop and design so called "low indirect-impact biofuel systems".

One important strategy in the development of low indirect-impact biofuel systems is to use biomass residues as feedstock, for example, logging residues from forestry (Berndes et al., 2013). Such biomass feedstock normally fulfills the sustainability criteria included in various international standards, e.g. the EU Renewable Energy Directive (The European Parliament and the Council of the European Union, 2009). Currently, there are several global sustainability certification systems regarding biofuels, covering different perspectives (Scarlat and Dallemand, 2011). However, as a general conclusion, the utilization of residues from agriculture and forestry as biofuel feedstock has limited effects on the production of food and forest products, and thus would not lead to conflicts or indirect changes in land use. The use of lignocellulosic biomass for biofuel production is, therefore, often promoted in biofuel policies around the world (Sorda et al., 2010), although the number of commercial plants is still limited despite recent development (Menon and Rao, 2012).

An additional strategy to minimize the potential negative effects of increased utilization of biomass resources is to use them in the most efficient way, for example, in so-called biorefineries. These integrated plants generate value from the entire biomass feedstock by producing multiple products, leading to improvements in both productivity and sustainability (Cherubini, 2010). The high utilization efficiency of feedstock in a biorefinery, and the conversion of low-value lignocellulosic residues into high-value products provide biofuel production systems with good economic and environmental performance (Börjesson et al., 2013; Cherubini and Ulgiati, 2010; Ekman et al., 2013; Uihlein and Schebek, 2009).

A number of studies concerning techno and/or economic simulations have been conducted handling the biorefinery concept including bioethanol production from lignocellulosic material. Many of the studies have been focusing on hardwood (Huang et al., 2009; Piccolo and Bezzo, 2009), agricultural residues (Kumar

Abbreviations: DHS, district heating system; DM, dry matter; APEA, Aspen Process Economic Analyzer; WWT, waste-water treatment; SSF, simultaneous saccharification and fermentation; WIS, water-insoluble solids; FPU, filter paper units; CHP, combined heat and power; LHVs, lower heating values; NPV, net present value; CF, cash flow; MESP, minimum ethanol selling price; HMF, hydroxymethylfurfural.

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and Murthy, 2011; Modarresi et al., 2012) and dedicated crops (Martín and Grossmann, 2012) as well as bagasse (Dias et al., 2011a; Macrelli et al., 2012), which differ in composition and recalcitrance from softwood. A major work has also been performed at the National Renewable Energy Laboratory, which early performed modeling on different lignocellulosic material (Aden et al., 2002; Tao et al., 2011; Wooley et al., 1999) with one of their most recent reports focusing on corn stover (Humbird et al., 2011).

Some early modeling studies focusing on softwood have been performed by the Forest Products biotechnology Group at the University of British Columbia including development of techno economic evaluations models on SO_2 steam pretreated wood such as Douglas Fir (Gregg et al., 1998; Gregg and Saddler, 1995; Mabee et al., 2006). Hamelinck et al. (2005) also performed techno-economic evaluations comparing different pretreatment methods and short, middle and long term scenarios to predict future ethanol production cost for among other things softwood. Spread-sheet calculations were then used for the mass balances and Aspen Plus for the energy balances. The thermal conversion of solid residuals to steam and electricity were then modeled in Aspen Plus to investigate the potential to use internal energy for the process as well as surplus energy produced. In the study, Hamelinck et al. (2005) compared dilute acid pretreatment with sulfuric acid and steam explosion, however at the current state, steam pretreatment combined with sulfur dioxide as catalyst is considered to be one of the most suitable methods yielding high recovery of both glucose and xylose after enzymatic hydrolysis (Chandra et al., 2007; Wyman et al., 2009).

Lately techno-economic spreadsheet evaluations to determine the economic competiveness of second generation ethanol production from softwood compared with corn ethanol have been performed by Stephen et al. (2012). Stephen et al. (2012) concluded that it is likely that additional subsidies or policy support is needed to make second generation ethanol production from softwood competitive with corn ethanol in 2020. A study have also been conducted by Stephen et al. (2013) to investigate the feasibility of different lignocellulosic materials, including softwood (Douglas Fir), and the impact of facility sitting in Canada. Since softwood consists of a larger amount of lignin and a less amount of hemicelluloses, compared to hardwood and agricultural residues, it demands a harsher pretreatment to separate the hemicellulose from the lignin and cellulose. Enzymatic hydrolysis of softwood has also been shown to be more difficult resulting in a higher viscosity and longer time before the material is liquefied compared to less recalcitrant material such as straw. The harsher pretreatment may also lead to more inhibitory compounds being produced (Chandra et al., 2007; Kumar et al., 2011). More inhibitory compounds together with the higher viscosity will subsequently affect the performance in the simultaneous saccharification and fermentation (SSF) and following process steps (Hoyer et al., 2009). Since spruce is available in an abundant amount in Sweden and largely used in the forest industry its residual material has a high potential to be utilized as raw material in a biorefinery. In a Swedish perspective it would therefore be of importance to investigate this option further.

Techno-economic modeling for softwood spruce considering both material and energy balances have been by performed earlier at the Department of Chemical Engineering, Lund University by Wingren et al. (2004, 2008) and Sassner et al. (2008). The models that are based on data from experimental trials performed for pretreatment and SSF on spruce at the department were modeled in the flow sheeting program Aspen Plus and cost estimations using Icarus Process Evaluator (now Aspen Process Economic Analyzer) and vendor quotation. One of the strengths of combining data from experimental result with the simulations in Aspen Plus, which considers both energy and material balances, is that the overall energy demand for the plants can be calculated. The overall energy demand will greatly affect the co-products produced and thereby also the feasibility of the plant. The results from Aspen Plus are also an invaluable tool when performing the economic evaluation to provide sizing data of the equipment.

The models used in this study are new and updated versions of earlier models and are focusing on improving the energy utilization in the process and potential to distribute the by-products to the market considering location and supply chain. This is of great importance since the local feedstock and the potential distribution of the by-products to the market is crucial to practically implement a biorefinery.

Therefore this multidisciplinary systems study investigates the potential and prerequisites of sustainable concepts of logging-residue based biorefinery that could be implemented in Sweden. The study is divided into two parts. The first part presents an assessment of the energy and economic performance of different process designs of a biorefinery producing ethanol, biogas, carbon dioxide, electricity, pellets and heat, while the second part presents a case study of suitable locations of biorefineries in Sweden, based on feedstock supply and infrastructure for integration with district heating system (DHS) or pulp and paper mills.

2. Materials and methods

The following section presents an overview of the methods used and assumptions made in this study. The technical and economic performance of the various plant designs was evaluated in form of energy efficiency and profitability depending on product mix and plant size.

2.1. The process design

Plants were modeled on three different scales, defined by raw material loadings of 150 000, 200 000 and 250 000 t dry matter (DM)/y, corresponding to annual ethanol productions of approximately 45 700 m^3, 60 200 m^3 and 74 600 m^3. It was assumed that the plant was in operation 8000 h/y, and was run by 28 people. Nine different scenarios were developed and assessed, depending on the scale and co-products produced.

The various scenarios were modeled in the flow sheeting program Aspen Plus (version 8.2, from Aspen Technology Inc., Massachusetts, USA), based on data from lab-scale work performed by Sassner et al. (2008) and results from the process development unit at the Department of Chemical Engineering, Lund University. The property method used for calculations in Aspen Plus was the NRTL method combined with Hayden–O'Connel equation of state in all operations except for the steam cycle where STEAMNBS was used. The main process units and reactions used in Aspen Plus are presented in Appendix. Physical property data for biomass components such as lignin and cellulose were taken from the NREL database for biofuel components (Wooley and Putsche, 1996). The simulations were performed using modified versions of Aspen Plus models previously developed by Wingren et al. (2004, 2008), Sassner and Zacchi (2008) and Joelsson et al. (2014). Heat integration was implemented in the scenarios using Aspen Energy Analyzer (version 8.2) to design heat exchanger networks, as described by Joelsson et al. (2014). The capital and operational costs were evaluated using vendors' quotations and Aspen Process Economic Analyzer (APEA).

2.2. Case descriptions and process flow sheet

Three process configurations were designed based on the outgoing products, and investigated for three different plant scales, resulting in nine different cases. In all cases, ethanol, biogas, carbon