Energy Conversion and Management 62 (2012) 141–153

Contents lists available at SciVerse ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Co-production of electricity and ethanol, process economics of value prior combustion

T. Treasure [a], R. Gonzalez [a,*], R. Venditti [a], Y. Pu [a], H. Jameel [a], S. Kelley [a], Jeffrey Prestemon [b]

[a] Department of Forest Biomaterials, North Carolina State University, Raleigh, NC 27695, United States
[b] USDA Forest Service, United States

ARTICLE INFO

Article history:
Received 10 January 2012
Received in revised form 4 April 2012
Accepted 5 April 2012
Available online 26 June 2012

Keywords:
Value prior to combustion
Power
Ethanol
Hemicellulose
Autohydrolysis
Softwood
Hardwood
Minimum ethanol selling price

ABSTRACT

A process economic analysis of co-producing bioethanol and electricity (value prior to combustion) from mixed southern hardwood and southern yellow pine is presented. Bioethanol is produced by extracting carbohydrates from wood via autohydrolysis, membrane separation of byproducts, enzymatic hydrolysis of extracted oligomers and fermentation to ethanol. The residual solids after autohydrolysis are pressed and burned in a power boiler to generate steam and electricity. A base case scenario of biomass combustion to produce electricity is presented as a reference to understand the basics of bio-power generation economics. For the base case, minimum electricity revenue of $70–$96/MWh must be realized to achieve a 6–12% internal rate of return. In the alternative co-production cases, the ethanol facility is treated as a separate business entity that purchases power and steam from the biomass power plant. Minimum ethanol revenue required to achieve a 12% internal rate of return was estimated to be $0.84–$1.05/l for hardwood and $0.74–$0.85/l for softwood. Based on current market conditions and an assumed future ethanol selling price of $0.65/l, the co-production of cellulosic bioethanol and power does not produce financeable returns. A risk analysis indicates that there is a probability of 26.6% to achieve an internal rate of return equal or higher than 12%. It is suggested that focus be placed on improving yield and reducing CAPEX before this technology can be applied commercially. This modeling approach is a robust method to evaluate economic feasibility of integrated production of bio-power and other products based on extracted hemicellulose.

1. Introduction

The effective conversion of cellulosic biomass into different forms of energy has been the target for many researchers in the last decades [1–7]. Although several pathways have been developed (biomass to power, lignocellulosic biomass to ethanol, etc.) [1,2,5,8–10], very few technologies meet the key requirements to become commercial: being both profitable under current market conditions and environmentally friendly. The success of corn ethanol in the US and sugar cane ethanol in Brazil has been widely discussed [1,11–14]. Nevertheless, it is important to note that the economics of both processes benefit from the commercialization of byproducts, as well as a continued improvement in the efficiency of the conversion process (efficient conversion of the feedstock into ethanol and different byproducts) [1,10,15]. Production of goods in addition to ethanol from lignocellulosic biomass may increase profitability and reduce investment risks which will attract investors. This paper presents a process economic analysis of co-producing cellulosic ethanol and electrical power. This production process evaluated is accomplished via autohydrolysis and extraction of hemicelluloses (carbohydrate extraction for alcohol production) and burning the residues for power generation; a process termed value prior to combustion (VPC).

The hot-water extraction process, also known as autohydrolysis, can extract hemicellulose oligomers and monomers (mainly xylooligmers with different degrees of polymerization) from wood while leaving other components intact [16–20]. Temperature and reactor residence time are critical parameters to minimize sugar degradation and extraction yield. During hot-water extraction, acids are produced by the hydrolysis of hemicelluloses [18]. These acids, coupled with the dissolution of extractives in the biomass, cause the liquor pH to drop and effectively self-catalyze the hydrolysis process [21]. The sugar degradation products (furfural and hydroxymethylfurfural) are easily volatilized and may result in a loss of yield. The extracted xylose and other hemicellulose sugars can undergo fermentation to ethanol and can be considered a potential renewable resource for bio-based fuels [22,23]. Although we have focused on fermentation of extracted sugars to produce ethanol, hemicellulosic sugars can also be used to produce biodegradable plastics and chemicals that are currently derived from petroleum [18,19,24]. The residues after hot water extraction can be burned to produce steam and electricity or alternatively can be used as a raw material for wood and paper products.

* Corresponding author. Tel.: +1 9198025219.
E-mail address: ronalds.gonzalez@gmail.com (R. Gonzalez).

0196-8904/$ - see front matter
http://dx.doi.org/10.1016/j.enconman.2012.04.002

The concept of liquid fuel and power production from the same feedstock has several advantages in comparison to traditional second generation ethanol production technologies that are only focused on producing cellulosic ethanol or traditional bio-power platforms for electricity generation. Previous studies have indicated that liquid biofuel and bio-power production could profitably co-exist in an integrated process as technology improvement occurs [25–27]. From an efficiency point of view, hot water extraction removes components of the feedstock (hemicelluloses) that have low heating value but can potentially be converted to valuable by-products such as ethanol [28]. By removing the low heating value components from the raw material, the heating value of the residual solids is actually higher per unit mass and therefore a smaller boiler can be used to produce the same amount of power. From a revenue point of view, VPC diversifies the portfolio of products and reduces risk of the biorefinery in regards to fluctuations in main product selling prices. Previous research efforts in co-production of power and ethanol concluded that high capital investment and high enzyme costs limit the potential of this combined production process [28]. However, in comparison to traditional second generation cellulosic ethanol technologies, the cost of enzyme hydrolysis may be substantially lower since enzymes are only being used on soluble oligosaccharides which hydrolyze in less time with less enzyme than hydrolysis of insoluble pretreated lignocellulosics used in traditional second generation technologies. The co-production of high value bio-based products from the extracted hemicelluloses would also increase the profitability of combined production processes and may lead to greater diversity in product portfolio as the technology for bio-based product production becomes more mature [29].

The aim of this paper is to present the economics of co-producing power and lignocellulosic ethanol in an integrated process using southern mixed hardwood and southern yellow pine as feedstocks. The economics of standalone power generation from biomass in a greenfield plant is explored first and represents a base case analysis. The following economic indicators were determined to gauge the economic performance of the base case and proposed cases: internal rate of return (IRR), net present value (NPV), payback period, and minimum power selling price (to achieve a specific internal rate of return). After developing the base case, the proposed scenario involving biomass autohydrolysis and sugar extraction to produce ethanol while burning the residual solids was developed and analyzed. The discussion provides novel information needed to understand the tradeoff between producing power and ethanol in an integrated conversion process.

2. Materials and methods

In order to offer a guide for the information provided in this paper a brief description of each section is presented here. The "Feedstock" section provides the chemical composition, moisture content and delivered cost of the raw materials. The "Basis for Evaluation" section establishes the framework for comparison across the paper; defining the base case (power generation only) and alternative case (power and ethanol production). The "Proposed Pathway" section describes the integrated process for power and ethanol production in more detail by identifying the major unit operations as well as process conditions. The "Conversion Factors" section deals with wood component yields through autohydrolysis and defines the composition of both extraction liquor and solid residues. The process modeling framework, including software used, inputs, and constraints, is presented in the "Process Simulation" section. Within the "Economics Analysis" section, the variables used for the estimation of the economic indicators and the methods to estimate cost drivers are presented.

2.1. Feedstock

Feedstocks used in this analysis are softwood (southern yellow pine) and hardwood (natural southern mixed hardwood) in the form of forest residues (also called hog fuel). The moisture content estimated for hog fuel was about 40% [30–32].

The chemical composition of the feedstock (softwood and hardwood) used for this study is a normalized version of compositional analysis data collected in the lab (Table 1). The original compositional analysis was determined at the Department of Forest Biomaterials at North Carolina State University and is explored in greater detail by Pu et al. [21]. Proportional normalization of the feedstock composition was performed to satisfy mass balance constraints within the process model.

2.2. Basis for evaluation

As previously mentioned, this paper presents the economics of an integrated process producing power and ethanol. The economics of standalone power generation from biomass is explored first. In an alternative case, power and ethanol are produced in the same facility. For the economic analysis, a greenfield concept was used. Further explanation for each case is presented next.

2.2.1. Base case

Power generation from biomass is evaluated in the base case for softwood and hardwood, separately. The conversion process of a greenfield plant was simulated in WinGEMS [33] and the economics in an Excel spreadsheet. An annual input of 500,000 dry short tons (abbreviated as BDT) (or 453,592 dry metric tons), is fed into the system to achieve a power generation rate of ~72 MW. The facility was assumed to operate for 350 days per year which results in ~605 GWh of power produced annually.

2.2.2. Alternative case

In the alternative case, power and ethanol are co-produced in an integrated plant. The model was built in order to recalculate the amount of feedstock required to produce ~72 MW. The amount of biomass fed to the facility is higher than the Base Case because some of the material that was previously burned to produce electricity is now being converted to ethanol. A total of six alternative cases were evaluated as outlined in Table 2. For all the cases, the model estimates the amount of feedstock required to produce 95% of the power capacity (~72 MW), an additional production capacity of 5% has been assumed for capital investment (CAPEX) estimation. The same excess capacity and additional CAPEX requirement are also assumed in the base case.

2.3. Proposed pathway

The proposed pathway for integrated power and cellulosic ethanol production is illustrated in Fig. 1. Lignocellulosic biomass is fed into the autohydrolysis reactor for 1 h residence time at the specified temperature (Table 2). For all alternative cases, ~13% of the incoming feedstock is assumed to contain a share of under-/

Table 1
Chemical composition of softwood and hardwood feedstocks.

Component	Hardwood (%)	Softwood (%)
Lignin	27	29
Glucan	46	46
Hexan	4	14
Xylan	19	7
Extractives	3	3
Ash	1	1