Biochemical Conversion of Lignocellulosic Biomass to Ethanol

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Acronyms

AFEX	ammonia fiber explosion
BFW	boiler feed water
BLS	Bureau of Labor Statistics
C5/C6	refers to mixtures of xylose (a C5 sugar) and glucose (a C6 sugar)
CBP	consolidated bioprocessing
CIP	clean-in-place
COD	chemical oxygen demand
CSL	corn steep liquor
DAP	diammonium phosphate
DCFROR	discounted cash flow rate of return
DOE	U.S. Department of Energy
FCI	fixed capital investment
FGD	flue gas desulfurization
HHV	higher heating value
HMF	5-hydroxymethyl furfural
INL	Idaho National Laboratory
IRR	internal rate of return
ISBL	inside battery limits (of the plant)
LHV	lower heating value
MESP	minimum ethanol selling price
MM	million (e.g., MMBtu or $_MM)
MSSP	minimum sugar selling price
MYPP	OBP's Multi-Year Program Plan
NPV	net present value
NREL	National Renewable Energy Laboratory
OBP	Office of the Biomass Program
OTR	oxygen transfer rate
OUR	oxygen uptake rate
PCS	pretreated corn stover
PFD	process flow diagram
SCFM	standard cubic feet per minute
SHF	separate (or sequential) hydrolysis and fermentation
SOT	annual State of Technology case
SSCF	simultaneous saccharification and co-fermentation
TCI	total capital investment
TDC	total direct cost
TE	technoeconomic
VOC	volatile organic compound
VVM	volume (of gas) per volume (of liquid) per minute
WWT	wastewater treatment

1 Introduction

1.1 Background and Motivation

The U.S. Department of Energy (DOE) Office of the Biomass Program (OBP) promotes the production of ethanol and other liquid fuels from lignocellulosic feedstocks by sponsoring programs in fundamental and applied research that aim to advance the state of biomass conversion technology. These programs include laboratory campaigns to develop better cellulose hydrolysis enzymes and fermenting microorganisms, detailed engineering studies of potential processes, and construction of pilot-scale demonstration and production facilities. This research is conducted by national laboratories, universities, and private industry in conjunction with engineering and construction companies.

As part of its involvement in the program, the National Renewable Energy Laboratory (NREL) investigates the complete process design and economics of cellulosic ethanol manufacturing in order to develop an absolute plant-gate price for ethanol based on process and plant design assumptions consistent with applicable best practices in engineering, construction, and operation. This plant-gate price is referred to as the minimum ethanol selling price or MESP. The MESP can be used by policymakers and DOE to assess the cost-competitiveness and market penetration potential of cellulosic ethanol in comparison with petroleum-derived fuels and starch- or sugar-based ethanol.

The technoeconomic analysis effort at NREL also helps to direct our biomass conversion research by examining the sensitivity of the MESP to process alternatives and research advances. Proposed research and its anticipated results can be translated into a new MESP that can be compared to the benchmark case documented in this report. Such comparison helps to quantify the economic impact of core research targets at NREL and elsewhere and to track progress toward meeting competitive cost targets. It also allows DOE to make more informed decisions about research proposals that claim to reduce MESP.

This report builds upon previous issues written by NREL engineers with Delta-T, Merrick Engineering, Reaction Engineering, Inc., and Harris Group. For the present report, NREL again contracted Harris Group to provide engineering support for estimating and reviewing the equipment and raw material costs used in the process design. This update reflects NREL's latest envisioned biochemical ethanol process and includes recent research progress in the conversion areas (pretreatment, conditioning, enzymatic hydrolysis, and fermentation), optimizations in product recovery, and our latest understanding of the ethanol plant's back end (separation, wastewater, and utilities). NREL worked with Harris Group to identify realistic configurations and costs for critical equipment, the pretreatment reactor system in particular. An on-site cellulase enzyme section was included in this update to permit better transparency of enzyme economics than the fixed cost contribution assumed in the last design report did.

The biomass conversion efficiencies used in the design (e.g., cellulose to glucose or xylose to ethanol) are based on a slate of research targets that NREL and DOE have committed to demonstrate by the end of 2012 in a campaign of integrated pilot-scale runs. These 2012 performance targets are discussed in detail in this report. The economics of this conceptual process use the best available equipment and raw material costs and an "n^{th}-plant" project cost structure and financing. The projected 2012 n^{th}-plant MESP computed in this report is \$2.15/gal in 2007\$.

Modifications to the conceptual process design presented here will be reflected annually through NREL's State of Technology (SOT) reports. These ensure that the process design and its cost benchmark incorporate the most current data from NREL and other DOE-funded research and that equipment costs stay up-to-date.

We stress that this design report serves to describe a *single, feasible* cellulosic ethanol conversion process and to transparently document the assumptions and details that went into its design. This report is not meant to provide an exhaustive survey of process alternatives or cost-sensitivity analyses. These will be investigated in separate papers that extend and reference the present report. Furthermore, the process models and economic tools developed for this report are available to the public, and the authors and members of NREL's Biochemical Platform Analysis task will provide support to researchers who wish to use them for their own studies.

1.2 Process Overview

The process described here uses co-current dilute-acid pretreatment of lignocellulosic biomass (corn stover), followed by enzymatic hydrolysis (saccharification) of the remaining cellulose, followed by fermentation of the resulting glucose and xylose to ethanol. The process design also includes feedstock handling and storage, product purification, wastewater treatment, lignin combustion, product storage, and required utilities. The process is divided into nine areas (see Figure 1).

- *Area 100: Feed handling.* The feedstock, in this case milled corn stover, is delivered to the feed handling area from a uniform-format feedstock supply system. Only minimum storage and feed handling are required. From there, the biomass is conveyed to the pretreatment reactor (Area 200).
- *Area 200: Pretreatment and conditioning.* In this area, the biomass is treated with dilute sulfuric acid catalyst at a high temperature for a short time to liberate the hemicellulose sugars and break down the biomass for enzymatic hydrolysis. Ammonia is then added to the whole pretreated slurry to raise its pH from ~1 to ~5 for enzymatic hydrolysis.
- *Area 300: Enzymatic hydrolysis and fermentation.* Enzymatic hydrolysis is initiated in a high-solids continuous reactor using a cellulase enzyme prepared on-site. The partially hydrolyzed slurry is next batched to one of several parallel bioreactors. Hydrolysis is completed in the batch reactor, and then the slurry is cooled and inoculated with the co-fermenting microorganism *Zymomonas mobilis*. After a total of five days of sequential enzymatic hydrolysis and fermentation, most of the cellulose and xylose have been converted to ethanol. The resulting beer is sent to the product recovery train (Area 500).
- *Area 400: Cellulase enzyme production.* An on-site enzyme production section was included in this design. Purchased glucose (corn syrup) is the primary carbon source for enzyme production. Media preparation involves a step in which a portion of the glucose is converted to sophorose to induce cellulase production. The enzyme-producing fungus (modeled after *Trichoderma reesei*) is grown aerobically in fed-batch bioreactors. The

entire fermentation broth, containing the secreted enzyme, is fed to Area 300 to carry out enzymatic hydrolysis.

- *Area 500: Product recovery.* The beer is separated into ethanol, water, and residual solids by distillation and solid-liquid separation. Ethanol is distilled to a nearly azeotropic mixture with water and then purified to 99.5% using vapor-phase molecular sieve adsorption. Solids recovered from the distillation bottoms are sent to the combustor (Area 800) while the liquid is sent to wastewater treatment (Area 600).
- *Area 600: Wastewater treatment.* Plant wastewater streams are treated by anaerobic and aerobic digestion. The methane-rich biogas from anaerobic digestion is sent to the combustor (Area 800), where sludge from the digesters is also burned. The treated water is suitable for recycling and is returned to the process.
- *Area 700: Storage.* This area provides bulk storage for chemicals used and produced in the process, including corn steep liquor (CSL), ammonia, sulfuric acid, nutrients, water, and ethanol.
- *Area 800: Combustor, boiler, and turbogenerator.* The solids from distillation and wastewater treatment and the biogas from anaerobic digestion are combusted to produce high-pressure steam for electricity production and process heat. The majority of the process steam demand is in the pretreatment reactor and distillation columns. The boiler produces excess steam that is converted to electricity for use in the plant and for sale to the grid.
- *Area 900: Utilities.* This area includes a cooling water system, chilled water system, process water manifold, and power systems.