Process design and economic analysis
for production of electricity, fuels, and chemicals from biomass

Mark F. Ruth* and Andy Aden
Biotechnology Division for Fuels and Chemicals, National Bioenergy Center,
National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, Colorado, USA 80401
Fax: 303-384-6827; mark_ruth@nrel.gov

For roughly 20 years, the U.S. Department of Energy (DOE) has contracted the National Renewable Energy Laboratory (NREL) to perform research in the conversion of biomass to fuel ethanol as well as other biomass products. To assist in directing that research we have created process designs, developed material and energy balances for those designs, and performed economic analyses on them. Those designs include ethanol as the primary product with electricity as the solitary byproduct and have been reported[1] and published[2]. Recently, the analysis has been expanded from production of ethanol with byproduct electricity to production of sugar that can then be converted to other chemical products and conversion of residual lignin to fuels and chemicals.

Methodology

The first steps in conceptual process design and economic analysis are to choose a process technology, feedstock, plant size, and plant generation. Several process technologies have been analyzed at NREL and the model technology that will be described in this presentation involves dilute acid prehydrolysis followed by simultaneous enzymatic hydrolysis and co-fermentation of both glucose and xylose. The model feedstock is corn stover and a 2000 dry metric tonne per day plant size is modeled. An "*n*th" plant generation was chosen so "first of a kind" and other early generation plant costs are not accounted for. These costs include engineering guarantees, other costs related to risk, and below capacity performance due to an operation learning curve.

Once the technology has been chosen a set of process flow diagrams (PFDs) is developed with input from both NREL researchers and engineering companies contracted by NREL. The process is then modeled using Aspentech's ASPEN Plus process simulator[3]. The simulator calculates rigorous material and energy balances as well as providing a format that minimizes calculation errors. It also allows us to simulate all the process design's important streams. A table of all process parameters (e.g., process conditions, yields, power requirements) is developed with input from the following sources: DOE/NREL sponsored research results; outside engineering studies for wastewater treatment, lignin residue combustion, ethanol recovery, and other established systems; and estimates from commercial technology.

The resulting material and energy balances are then used to calculate equipment and operating costs. Equipment costs have been estimated with input from vendors, engineering companies, and ICARUS cost estimation software[4]. Installation factors are used to determine installed costs for each equipment item and overall factors are used to estimate warehouse, site preparation, engineering, and other project-related costs. The resulting total capital investment is valid within +30%/-15%. Variable operating costs (e.g., raw material costs) are calculated directly from stream flows and fixed operating costs are scaled with the plant size.

Process technology

This presentation focuses on dilute acid prehydrolysis to hydrolyze the hemicellulose followed by simultaneous enzymatic cellulose hydrolysis and co-fermentation of both glucose and xylose to ethanol. Corn stover is fed into the process where it is milled, washed, and conveyed to the prehydrolysis system. There, the stover is mixed with water and dilute acid and heated to 190°C in a continuous reactor with a residence time of 10 minutes. Within the reactor, 75% of the hemicellulose is converted to fermentable sugars. The pretreated slurry is released into a flash tank and is pressed to separate a cake from the liquor.

The liquor is pumped through an ion-exchange system to remove sulfate and acetate ions and is overlimed followed by gypsum removal. Finally, the liquor and the cake are remixed.

The remixed slurry is pumped to the simultaneous saccharification and co-fermentation (SSCF) area. There it flows through trains of continuous bioreactors. In each train's first vessel, cellulase enzyme, corn steep liquor (CSL), and a broth containing *Zymomonas mobilis* are added. The cellulase enzyme converts 80% of the cellulose to glucose. *Z. mobilis* ferments both the glucose and xylose to ethanol and carbon dioxide. CSL is a nutrient source that helps keep the microorganism healthy.

The resulting ethanol broth is distilled in two columns until it reaches the ethanol/water azeotrope. The ethanol is then dehydrated in molecular sieves and denatured before sale as product. The distillation bottoms contain the water, lignin residue, cell mass, and involatile dissolved chemicals. The lignin residue and cell mass are recovered with a press. The dissolved chemicals are concentrated in an evaporator producing clean water that can be recycled.

The concentrate from the evaporator and the lignin residue/cell mass cake are combusted to produce steam. The steam flows through a multistage turbogenerator to produce electricity. The turbogenerator has several extraction ports where steam that is needed by the process is removed.

Utilities (e.g., cooling water, chilled water, process air) are included in the design. Effluent from the ion-exchange system is mixed with blow-down from the cooling tower and treated.

Basic Economic Results

The above process results in a 2000 dry metric tonne per day facility with a total capital investment of $230,000,000 +30%/-15% (1999$). The facility's nameplate capacity is 51,000,000 gal ethanol/yr at a yield of 66 gal/dry U.S. ton. The facility can produce enough byproduct steam and electricity for its own operation as well as 262,000,000 kW hr/yr to be sold to the grid. The variable costs for the facility include $0.15/gal for cellulase enzyme, $0.13/gal for raw materials not including enzyme or feedstock, $0.03/gal for waste disposal. The feedstock cost fraction is approximately $0.015/gal ethanol for every dollar per dry ton purchase cost (i.e., at a purchase cost of $35/dry ton the feedstock cost fraction is $0.52/gal ethanol). The variable costs include labor, overhead, maintenance, and permitting fees and are $0.16/gal ethanol.

Other Analyses

One process analysis option is determination of a sugar production cost where that sugar can than be sold or converted to other products. Glycerol, butanol, lactic acid, and other biological products have been considered. More efficient conversion of lignin to electricity is a process option that is being considered. Other options include conversion of the lignin residue to a product that has either a lower capital investment than electricity or has a greater value. One potential product with greater value is a liquid fuel produced by thermochemical conversion of the lignin.

---

[1] Wooley, R.; Ruth, M.; Sheehan, J.; Majdeski, H.; Galvez, A. *Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis Current and Futuristic Scenarios.* NREL/TP-580-2615. Golden, CO: National Renewable Energy Laboratory, July 1999. http://www.ott.doe.gov/biofuels/process_engineering.html
[2] Wooley, R.; Ruth, M.; Glassner, D.; Sheehan, J. "Process Design and Costing of Bioethanol Technology: A Tool for Determining the Status and Direction of Research and Development" *Biotechnol. Prog.* Vol. 15, 1999; pp. 794-803.
[3] ASPEN Plus, Release 10.2.1, Aspen Technology, Inc., Cambridge, MA, 2000.
[4] ICARUS Process Evaluator Version 4.0, ICARUS Corporation, Rockville, MD, 1997 and ICARUS Questimate Version 14.0A, ICARUS Corporation, Rockville, MD, 2001.