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Biochemical Conversion of Lignocellulosic Biomass to Ethanol

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Module 1: Introduction

Learning Objectives

By the end of this section, you will be able to:

- **Identify** the primary conversion areas and stages involved in the biochemical ethanol production process.
- **Evaluate** the role of Technoeconomic Analysis (TEA) and "nth-plant" assumptions in determining the Minimum Ethanol Selling Price (MESP).
- **Compare** various process alternatives and research targets to assess their impact on the commercial viability of cellulosic ethanol.

Executive Summary: This chapter establishes the 2012 benchmark for NREL's biochemical ethanol process, projecting a Minimum Ethanol Selling Price (MESP) of \$2.15/gal (in 2007\$) based on nth-plant economics. The process utilizes dilute-acid pretreatment, enzymatic hydrolysis, and co-fermentation of corn stover, supported by on-site enzyme production and integrated wastewater and utility systems.

Background and Motivation

The U.S. Department of Energy (DOE) Office of the Biomass Program (OBP) sponsors fundamental and applied research to advance biomass conversion technology. This includes developing high-efficiency enzymes, fermenting microorganisms, and engineering studies to move from laboratory scales to pilot-scale production.

Minimum Ethanol Selling Price (MESP)

The National Renewable Energy Laboratory (NREL) investigates process design to determine the **plant-gate price** of ethanol, known as the MESP. This metric is used by policymakers to:

- **Assess** cost-competitiveness against petroleum and starch-based fuels.
- **Direct** research by examining the sensitivity of the MESP to process alternatives.
- **Track** progress toward core research targets and competitive cost goals.

This 2011 update reflects the latest biochemical process configurations, including optimizations in pretreatment, conditioning, product recovery, and wastewater treatment. Notably, an **on-site cellulase enzyme** section is included to improve transparency in enzyme economics.

Process Overview

The conversion of lignocellulosic biomass (corn stover) to ethanol follows a co-current dilute-acid pretreatment path, followed by enzymatic hydrolysis and fermentation.

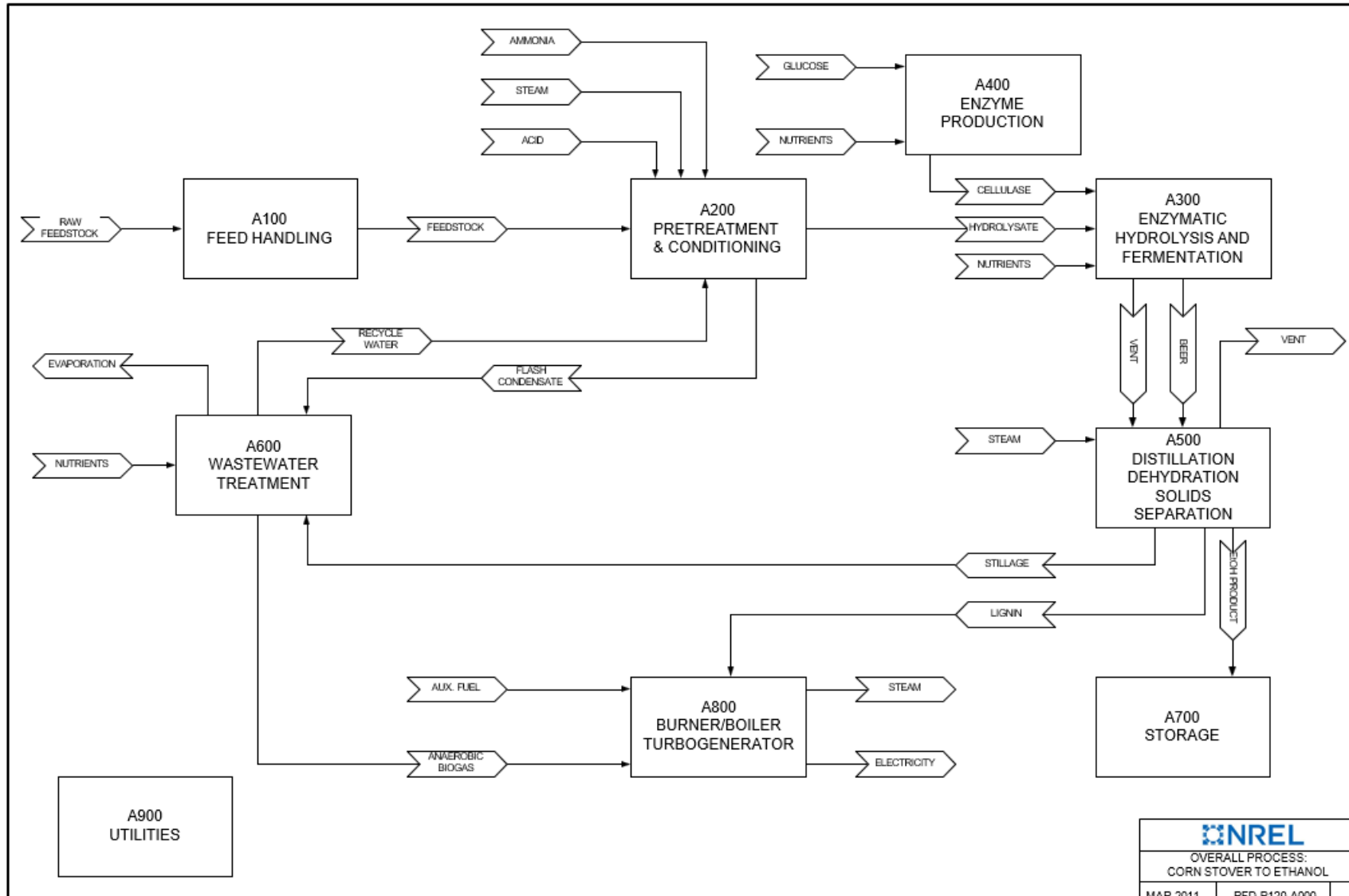


Figure 1. Simplified flow diagram of the overall process, PFD-P120-A000



The facility is organized into nine functional areas:

- **Area 100: Feed Handling:** Milled corn stover is delivered and conveyed to the pretreatment reactors.
- **Area 200: Pretreatment and Conditioning:** Biomass is treated with **dilute sulfuric acid** at high temperatures to liberate hemicellulose sugars. The slurry is then neutralized with **ammonia** (pH ~1 to ~5).
- **Area 300: Enzymatic Hydrolysis and Fermentation:** Cellulose is broken down into glucose using on-site enzymes. The mixture is inoculated with *Zymomonas mobilis* to ferment both glucose and xylose into ethanol over a five-day period.
- **Area 400: Cellulase Enzyme Production:** Enzymes are produced on-site using a *Trichoderma reesei* model fungus, utilizing purchased glucose as the carbon source.
- **Area 500: Product Recovery:** Distillation and molecular sieve adsorption purify the ethanol to 99.5%. Residual solids are sent to the combustor.
- **Area 600: Wastewater Treatment:** Anaerobic and aerobic digestion treat plant streams. Biogas is sent to the combustor, and treated water is recycled.
- **Area 700: Storage:** Bulk storage for chemicals (sulfuric acid, ammonia, CSL) and finished ethanol.
- **Area 800: Combustor, Boiler, and Turbogenerator:** Lignin, biogas, and sludge are burned to produce high-pressure steam and electricity.
- **Area 900: Utilities:** Manages cooling water, chilled water, and power systems.

Technoeconomic Analysis Approach

NREL uses a multi-step engineering approach to model the conversion process and economic outcomes.

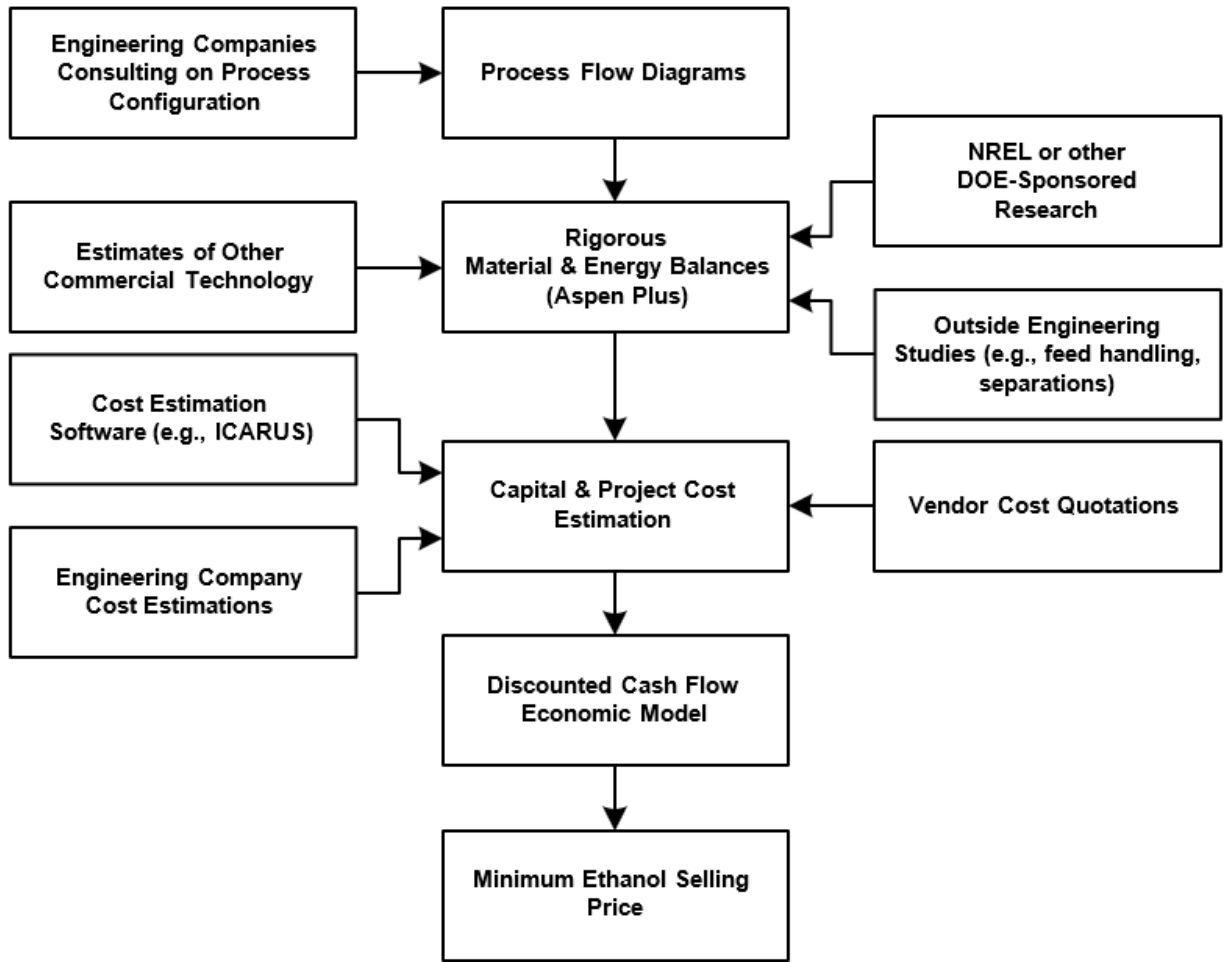



Figure 2. NREL's approach to process design and economic analysis

The TEA Workflow

1. **Process Simulation:** Aspen Plus software is used to compute mass and energy balances.
2. **Capital Cost Estimation:** Material balances assist in sizing equipment. Costs are derived from vendor quotes or proprietary databases.
3. **Total Capital Investment (TCI):** Factored overhead costs (installation, contingency) are applied to equipment costs.
4. **Discounted Cash Flow (DCFRROR):** A 10% internal rate of return (IRR) is used to determine the MESP.

 **Design Tip:** The absolute MESP has limited relevance without understanding the underlying basis; its primary value lies in comparing technological variations and performing sensitivity analyses.

About nth-Plant Assumptions

The analysis assumes "nth-plant" economics, implying a mature industry where several similar plants have already been built.

Key nth-Plant Characteristics

- **Risk Exclusion:** Ignores the inflated costs of pioneer plants (risk financing, long start-ups).
- **Standardized Performance:** Assumes a process uptime of **96%**.
- **Factored Costs:** Uses a standardized model for determining TCI from purchased equipment.

⚠ **Safety Constraint:** While 2012 performance targets (e.g., xylan to xylose conversion) were once speculative, research progress has made these benchmarks realistic targets for current engineering designs.

Review of Related Technoeconomic Studies

Technoeconomic models have historically predicted the production costs of existing biofuels (corn/sugarcane ethanol) within reasonable accuracy when compared to market studies.

Table 1. Comparison of Technoeconomic Analyses and Market Studies for Existing Biofuels

Fuel	Market Study	TE Model
Corn ethanol	\$1.53/gal ^a	\$1.54/gal ^b
Sugarcane ethanol	\$1.14/gal ^a	\$1.29/gal ^c
Soy biodiesel	\$2.15/gal ^d	\$2.55/gal ^e

^aF.O. Lichts, 2007 [5].

^bKwiatkowski et al., 2006 [6].

^cRodrigues, 2007 [7]; Seabra, 2007 [8].

^dGraboski & McCormick, 1998 [9].

^eHaas et al., 2006 [10].

Recent studies on cellulosic ethanol show a wide range of MESP values (from ~\$0.63 to >\$4.00) due to variations in:

- **Feedstock costs** and compositions.
- **Process pathways** (e.g., CBP vs. SHF).
- **Financial assumptions** and co-product values.



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