National Renewable Energy Laboratory
Innovation for Our Energy Future

The Current State of Technology for Cellulosic Ethanol

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NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy operated by Midwest Research Institute • Battelle

U.S. National Commitment to Ambitious Biofuels Goals

Near-term – Cost Goal

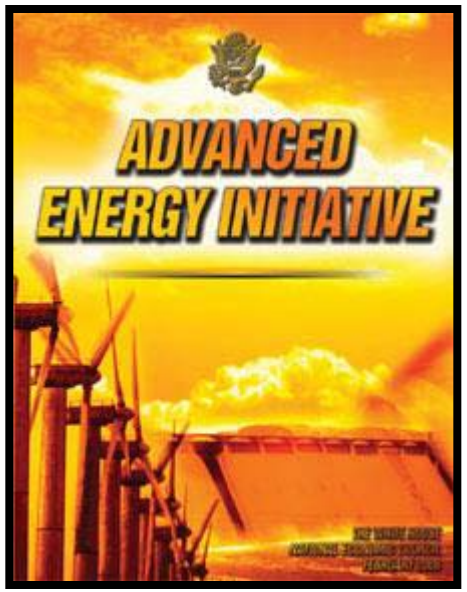
"Cost-competitive cellulosic ethanol"

- Cost-competitive in the blend market by 2012

Longer-term – Volumetric Goal

EISA (Energy Independence & Security Act)

- **36 billion** gallons renewable fuel by 2022
  - **21 billion** gallons advanced biofuels

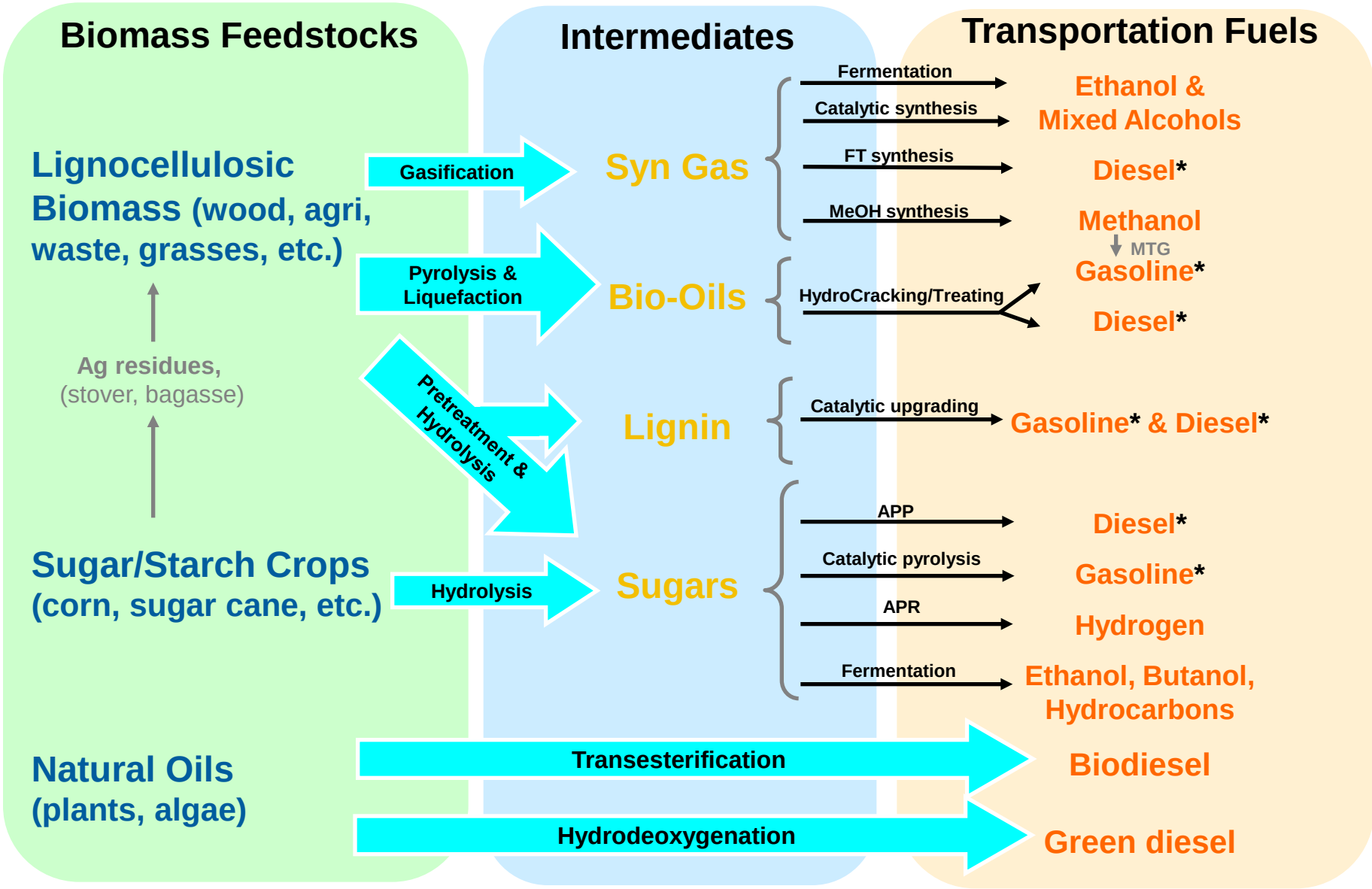


Renewable Fuel Standard (RFS) goals for biofuels penetration are based on specific GHG reductions from the fossil fuel it replaces.

- Biomass-based diesel = 50% reduction
- Advanced biofuels = 50% reduction
- Corn grain-based ethanol = 20% reduction
- Cellulosic Biofuels = 60% reduction

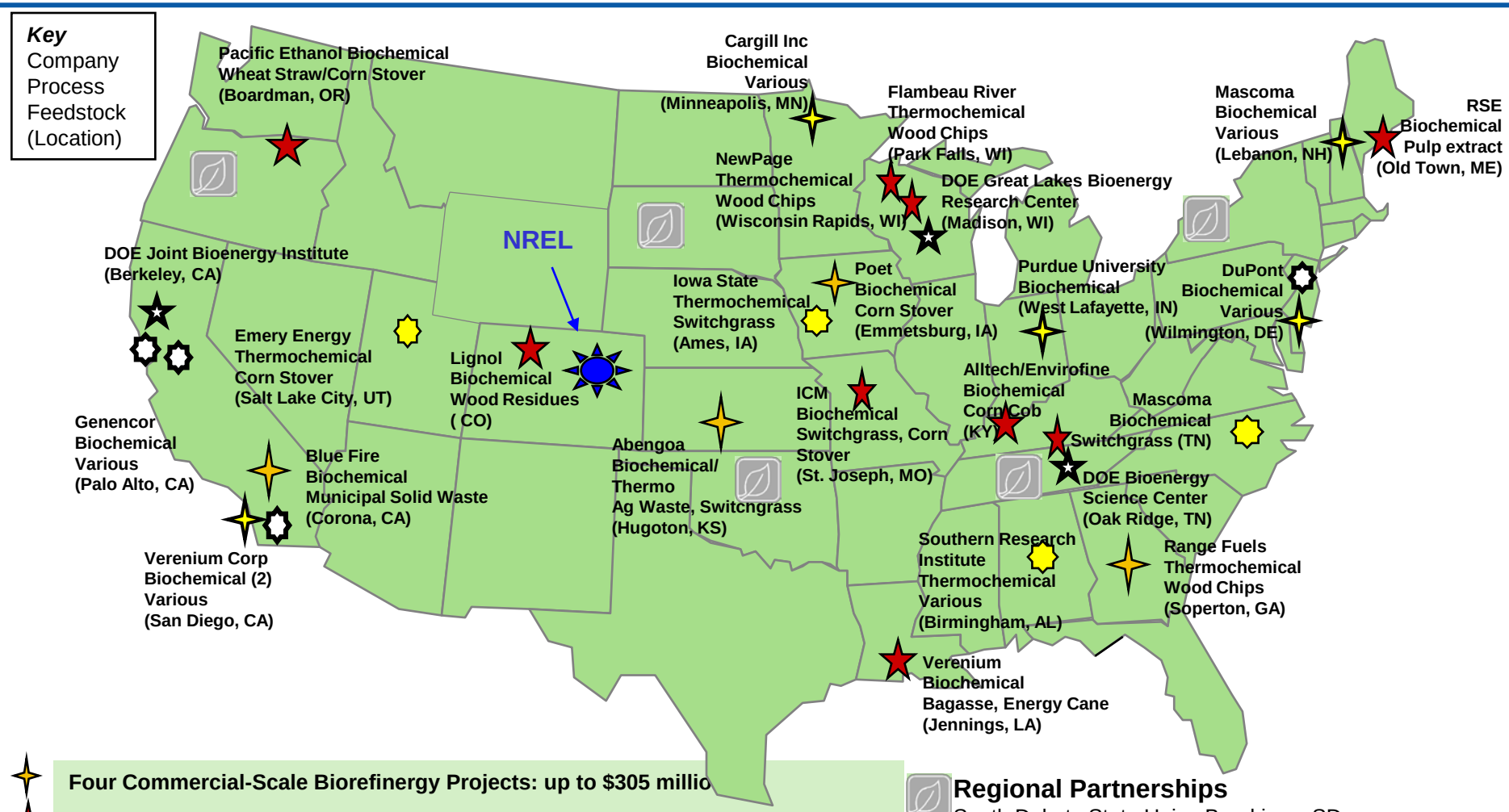
* light-duty vehicles only

Biofuels Transportation Options



* Blending Products

Major DOE Biofuels Project Locations



Four Commercial-Scale Biorefinergy Projects: up to $305 millio

Nine Small-Scale (10%) Biorefinery Projects: up to $240 million (first round)

Three Bioenergy Centers: up to $405 million

Four Thermochemical Biofuels Projects: up to $7.7 million

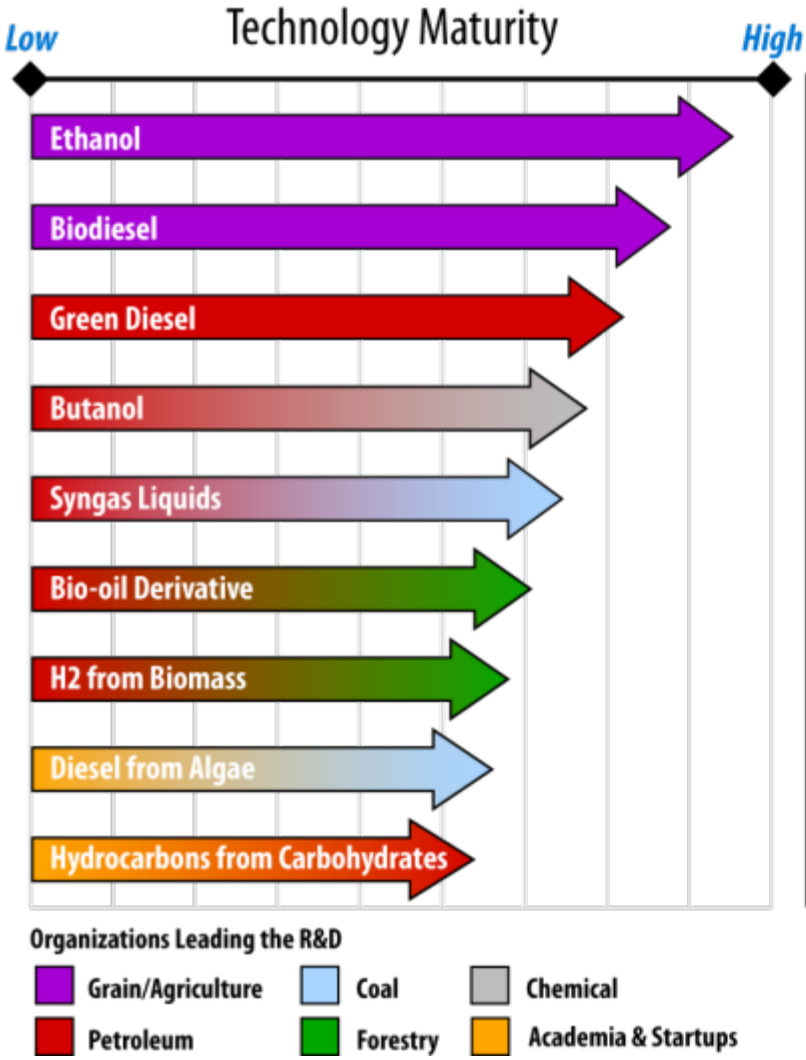
Four Improved Enzyme Projects: up to $33.8 million

Five Projects for Advanced Ethanol Conversion Organisms: up to $23 million

Regional Partnerships

South Dakota State Univ., Brookings, SD
Cornell University, Ithaca, NY
Univ. of Tennessee, Knoxville, TN
Oklahoma State Univ., Stillwater, OK
Oregon State Univ., Corvallis, OR

Ethanol is the Most Mature Biofuel Technology



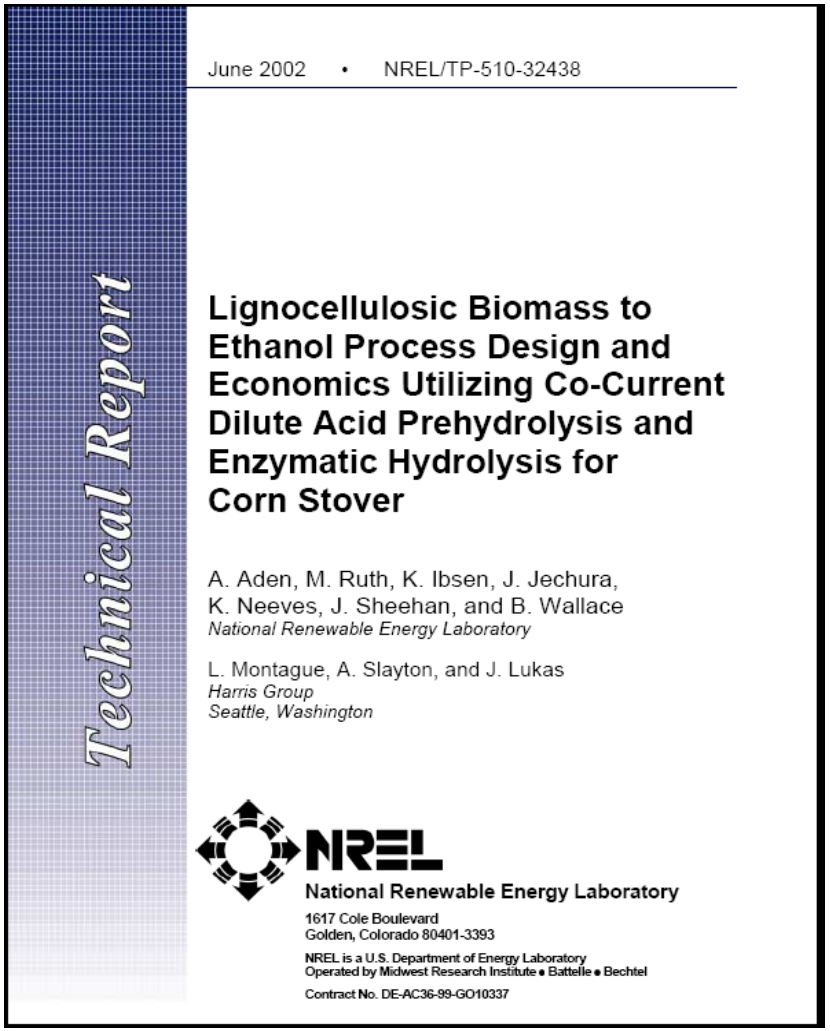
Key Drivers	Value Added
New market for grain and agriculture products. Large supply of lignocellulose.	High octane gasoline blend stock from carbohydrates.
New market for excess oils, fats, and greases.	Petroleum compatible and biodegradable.
Lower cost and higher product quality than FAME.	Utilize existing assets. High quality jet fuel or diesel.
New market for grain and agriculture products. Large supply of lignocellulose.	Better gasoline blending properties than ethanol.
Integration of biomass with Coal, Coke, Shale, or Heavy Oils.	High quality jet fuel or diesel. Reduced criteria for sequestration, and economy of scale (in combination with fossil).
Technical fit with woody biomass and liquid bio-crude.	Potential to integrate into existing large scale refinery and pipeline infrastructure.
Potential transportation fuel from any fuel/power source.	Ideal feed for fuel cells, and lowest tail pipe emissions.
Lg. source of biomass on non-arable land, and capture of CO^2.	High quality jet fuel or diesel yield per acre, with both off-shore and on-shore potential.
Better compatibility with petroleum products.	Potential for higher reaction rates than fermentation, and potential as H2 carrier.

Renewable Fuels & Low GHG Emissions

2002 NREL Design Report

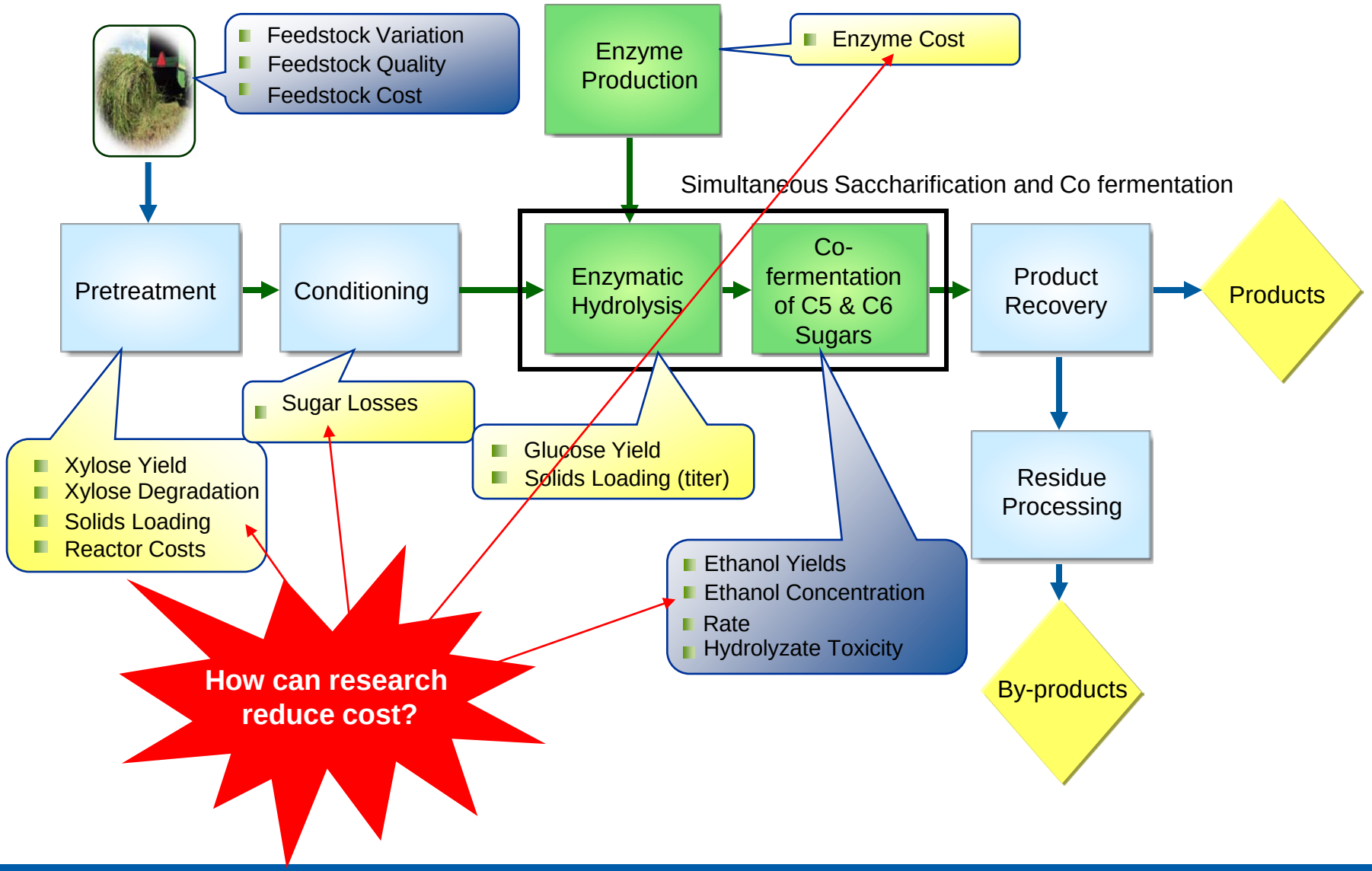
(Currently being updated)

http://www.nrel.gov/docs/fy02osti/32438.pdf



- *Documented one possible technology package for cost-effective production of ethanol from biomass via biochemical routes*
- *Established a basis for comparison of other technology options with clear and transparent data and assumptions*
- *Rigorous and detailed modeling performed to quantify the research targets necessary for achieving economic targets*
- *Enabled the quantification of research progress made towards goals*
- *Allowed for better industrial collaboration*
- *Has undergone numerous peer reviews by*
  - *Industry*
  - *Academia*
  - *Government*

Technical Barriers for the Biochemical Platform



Enzymatic Hydrolysis Research

NREL worked with *Genencor* and *Novozymes* for 4 years

- Focusing on enzyme biochemistry, cost, and specific activity
- Investigating the interaction of biomass pretreatment and enzymatic hydrolysis

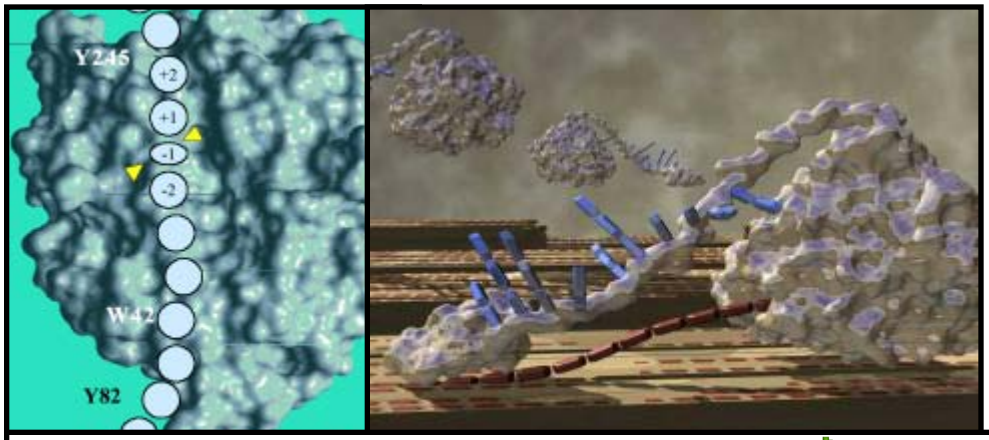
Result

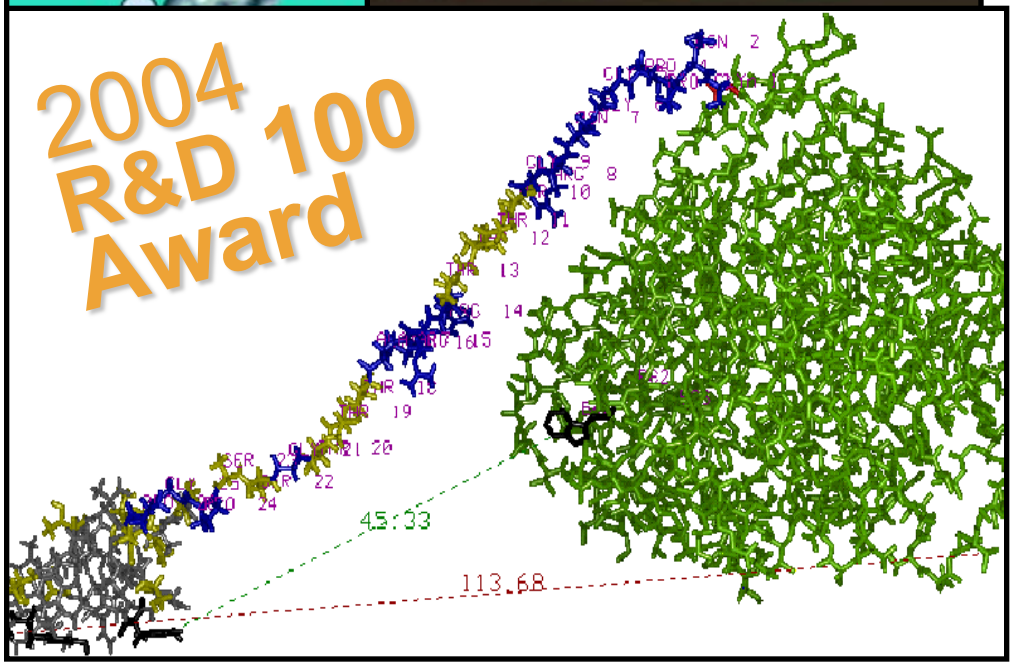
- 20-fold reduction in cost contributions of enzymes

  ($/gal ethanol)

$40 million R&D effort cost-shared by the Office of the Biomass Program and the enzyme manufacturers

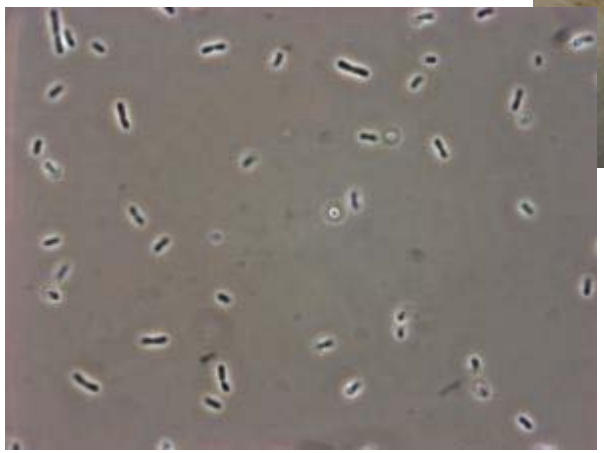
E1 from *A. cellulotiticus* CBH1 from *T. reesei*



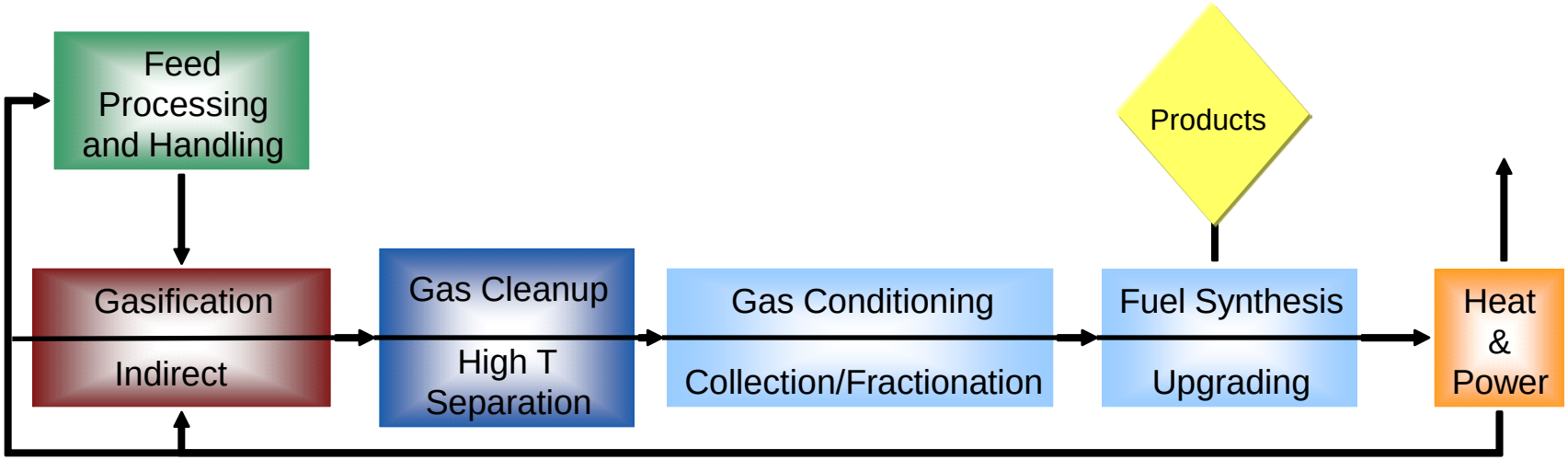


Fermentation

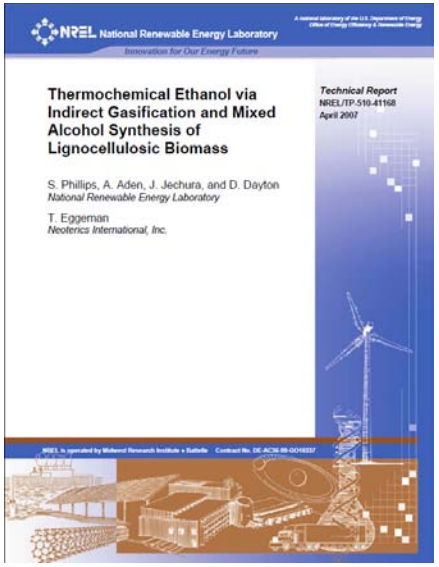
- Biologically convert simple sugars (glucose, xylose, etc) to alternative fuels (ethanol, butanol, etc)
- Recombinent technology used to engineer organisms for enhanced performance
- Many candidate organisms:
  - Yeast
  - Bacteria (*z. mobilis, e. coli, clostridia*, etc)
- DOE grants given to enhance strain robustness
  - Cargill
  - Mascoma
  - Purdue
  - DuPont
  - Verenium



Thermochem Conceptual Design Report Drives R&D Targets



Indirect Gasification and Mixed Alcohol Synthesis



- **Conceptual design of a 2000 tonnes/day commercial plant**
- **NREL pilot plant based on this process**
- **Basis for connecting R&D targets to cost targets**
- **Has undergone rigorous peer review**

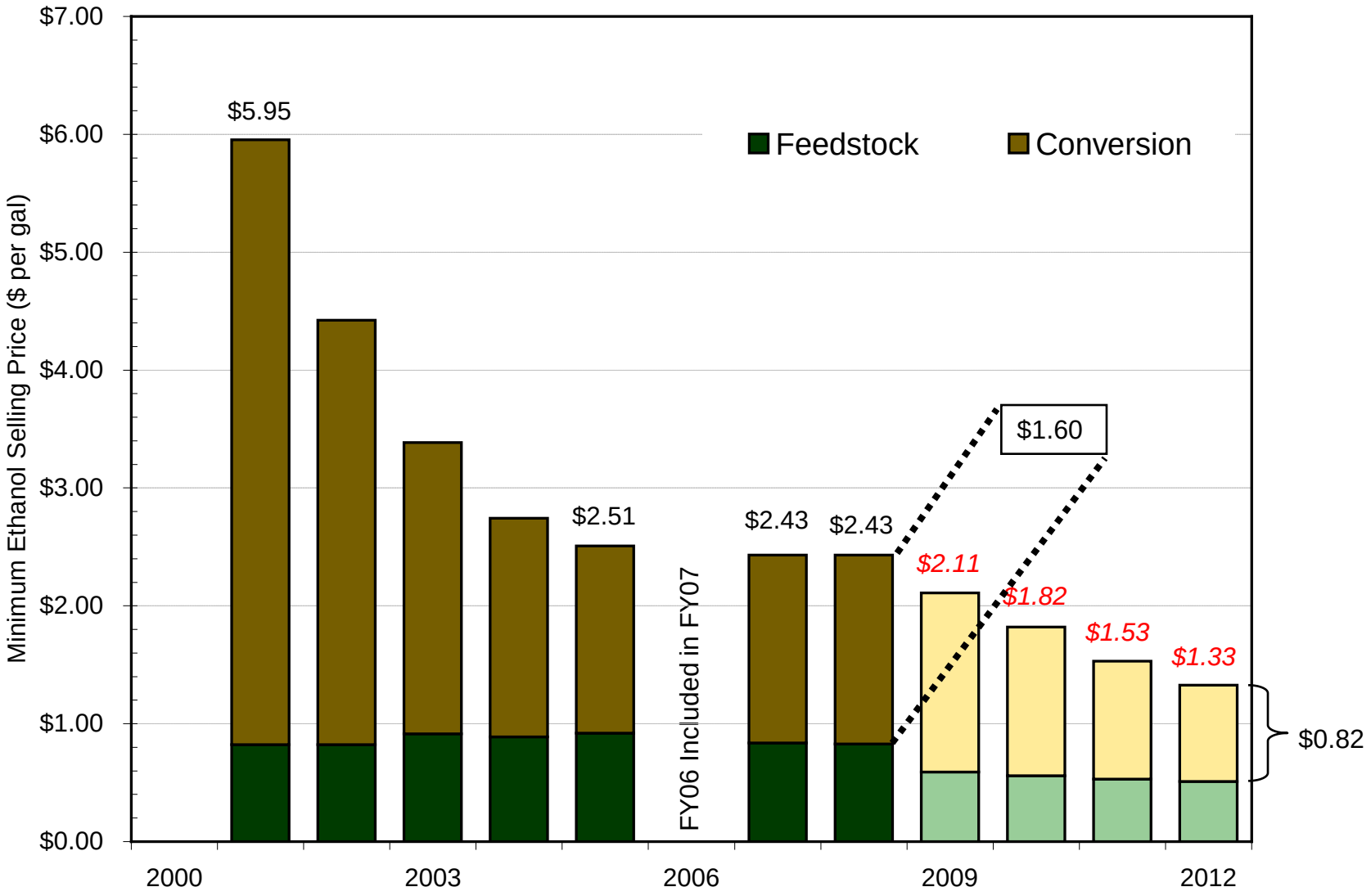
Technology Comparison

- Biochemical and thermochemical ethanol processes are similar with regard to:
  - Yield
  - Capital Investment
  - Level of development
  - Emissions profile
- Many feedstocks are appropriate for both processes
  - Feedstock is a regional choice
  - Some feedstocks do offer slight benefits in processability over others
- Choice of technology will depend more on industrial expertise and IP position
- Differences in indirect capital costs seen
  - Installation factors for example
  - Need further investigation as part of design report update

What is the State of Technology?

- Experimentally verified
- An annual update of model parameters with data from actual laboratory and/or pilot scale experiments
- Used to demonstrate technical progress and translate into easy-to-understand economic progress towards the 2012 goal
- Used to guide both biochem and thermochem platforms
- Limitations:
  - captures only single process technology options when a myriad of technologies are being researched
  - Assumes n^{th} plant assumptions, not pioneer plant costs

FY08 Biochem State of Technology (yr 2007(est.))



Sustainability Challenges

Biomass to Biofuels System

Greenhouse Gas Emissions

Economic Prosperity
- Rural and urban communities
- Industry

Social Well-being

Biofuels and Biomass
- Supply infrastructure
- *Fuel production*
- Distribution and use

Land
- Use and change
- Competition with food
- Soil

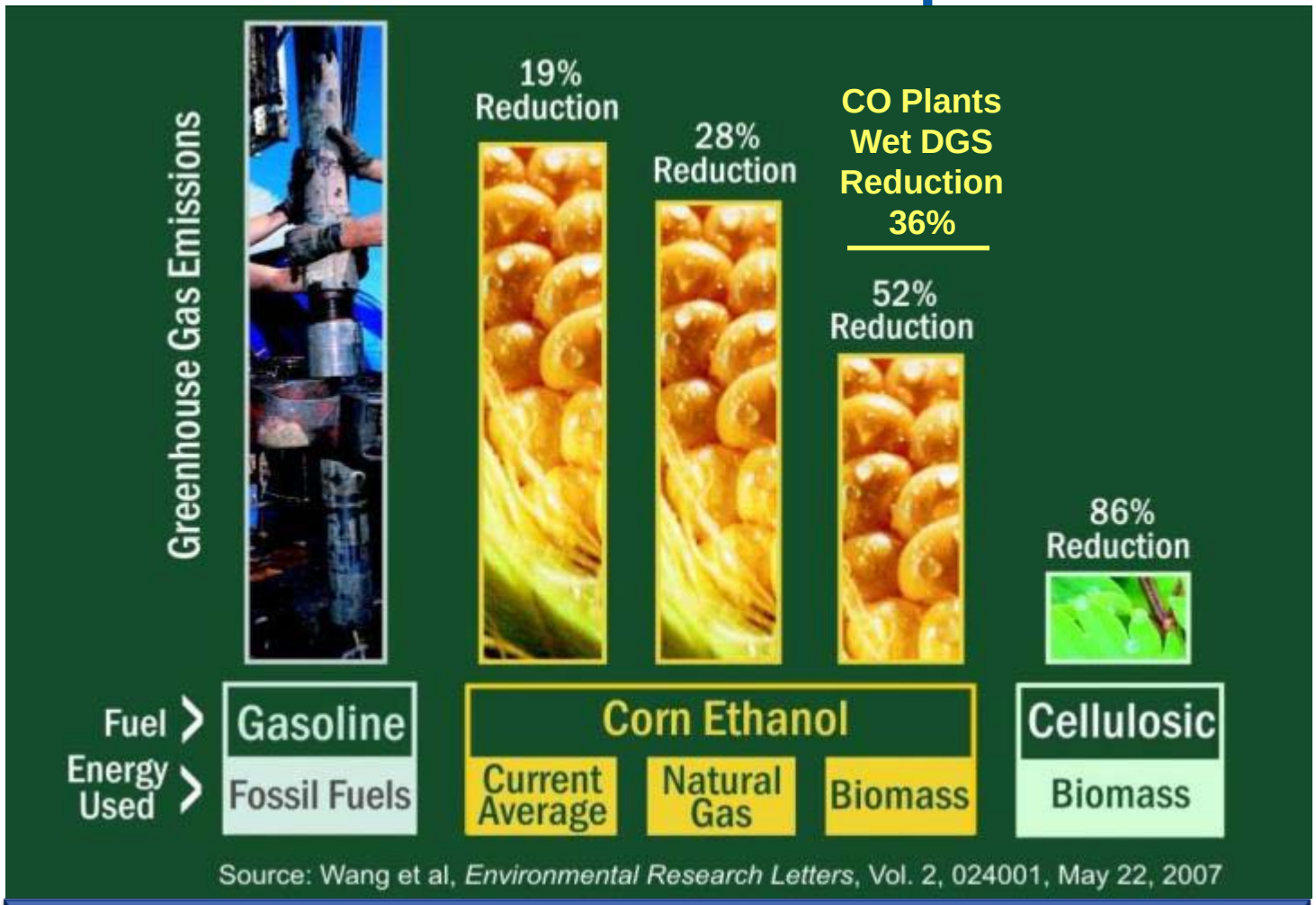
Biodiversity

Water
- *Use*
- Quality
- *Efficiency of use*

Environmental Impacts

Increase Food and Energy Security

Relative Emissions Impacts



Greenhouse gas emissions of fuels vary by feedstock and by type of energy used for processing.

Thank you for the opportunity.

Range of Biorefinery Concepts

- Trees
- Grasses
- Agricultural Crops
- Residues
- Animal Wastes
- Municipal Solid Waste
- Algae
- Food Oils

- Enzymatic Fermentation
- Gas/liquid Fermentation
- Acid Hydrolysis/ Fermentation
- Gasification
- Combustion
- Co-firing
- Trans-esterification

Products

Fuels
- Ethanol
- Biodiesel
- "Green" Gasoline & Diesel

Power
- Electricity
- Heat

Chemicals
- Plastics
- Solvents
- Chemical Intermediates
- Phenolics
- Adhesives
- Furfural
- Fatty Acids
- Acetic Acid
- Carbon Black
- Paints
- Dyes, Pigments, and Ink
- Detergents
- Etc.

Food and Feed

Current Biofuels Status

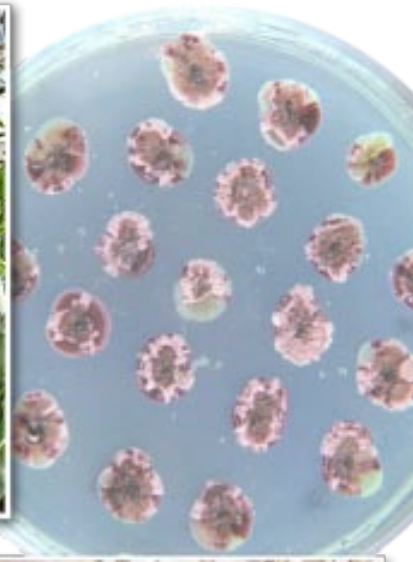
Biodiesel – 165 Companies; 1.85 billion gallons/yr capacity[1]

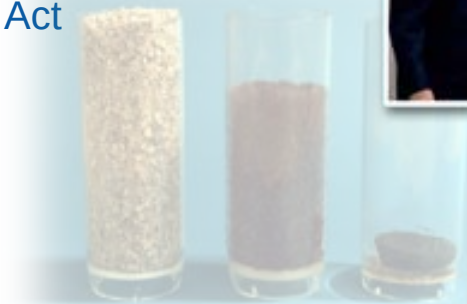
Corn ethanol

- 134 commercial plants[2]
- 7.2 billion gal/yr. capacity[2]
- Additional 6.2 billion gal/yr planned or under construction

Cellulosic ethanol (current technology)

- Projected commercial cost ~$3.50/gge





Key DOE Goals

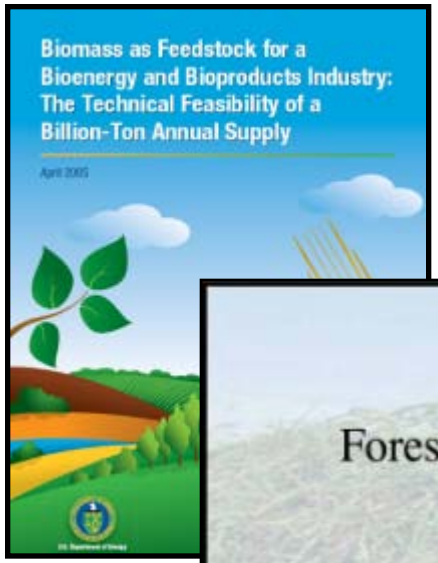
- 2012 goal: cellulosic ethanol $1.33/ETOH gallon or ~$2.00/gge
- 2022 goal: 36B gal Renewable Fuel; 21B gal "Advanced Renewable Fuel"– 2007 Energy Independence and Security Act

NREL Research Thrusts

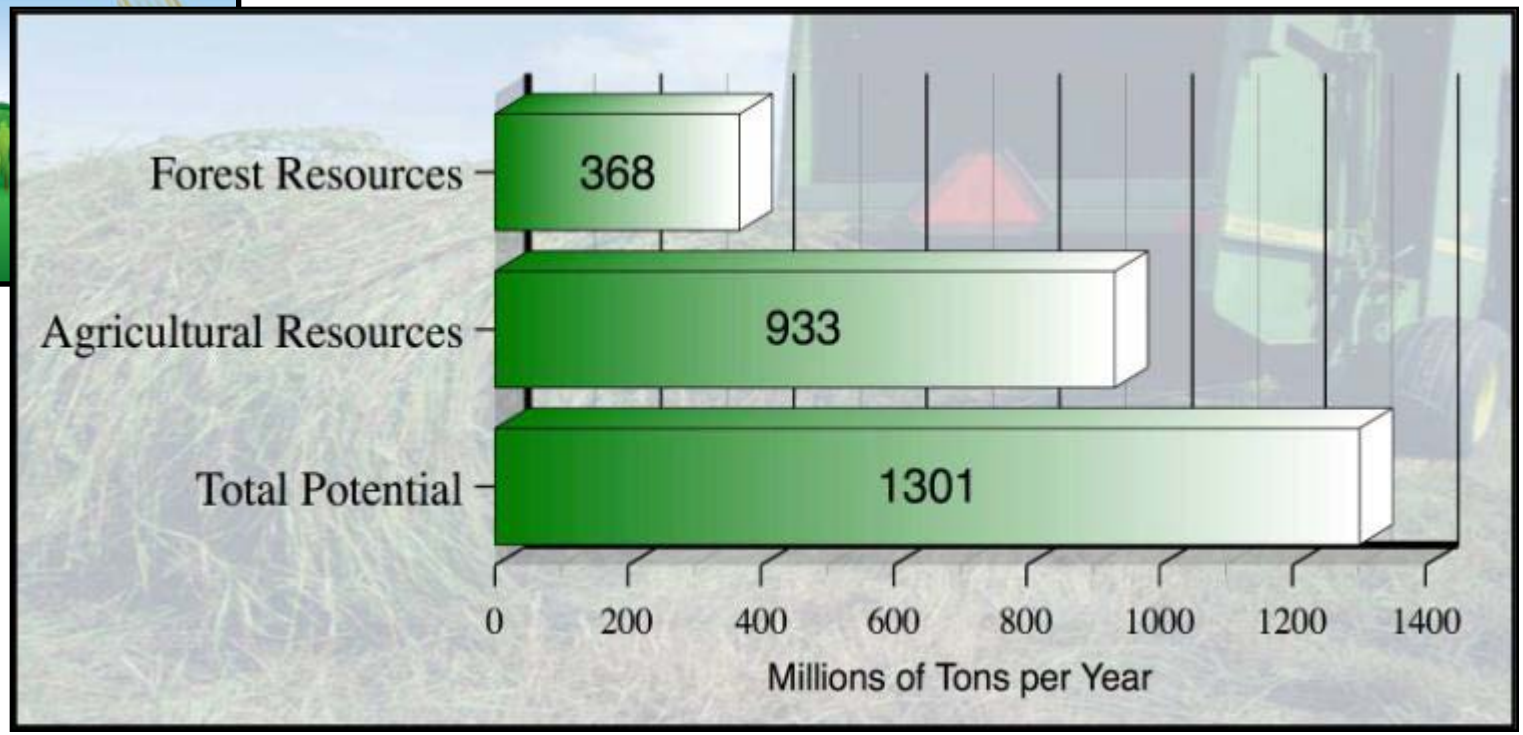
- **The biorefinery and cellulosic ethanol**
- **Solutions to under-utilized waste residues**
- **Energy crops**

Updated January 2008
Sources: 1- National Biodiesel Board, 2 - Renewable Fuels Association, all other information based on DOE and USDA sources

U.S. Biomass Resource Assessment



- Updated resource assessment - April 2005
- Jointly developed by U.S. DOE and USDA
- Referred to as the “Billion Ton Study”



Analysis Approach

Appropriate Stage Gate Level of Analysis for Project Stage of Development

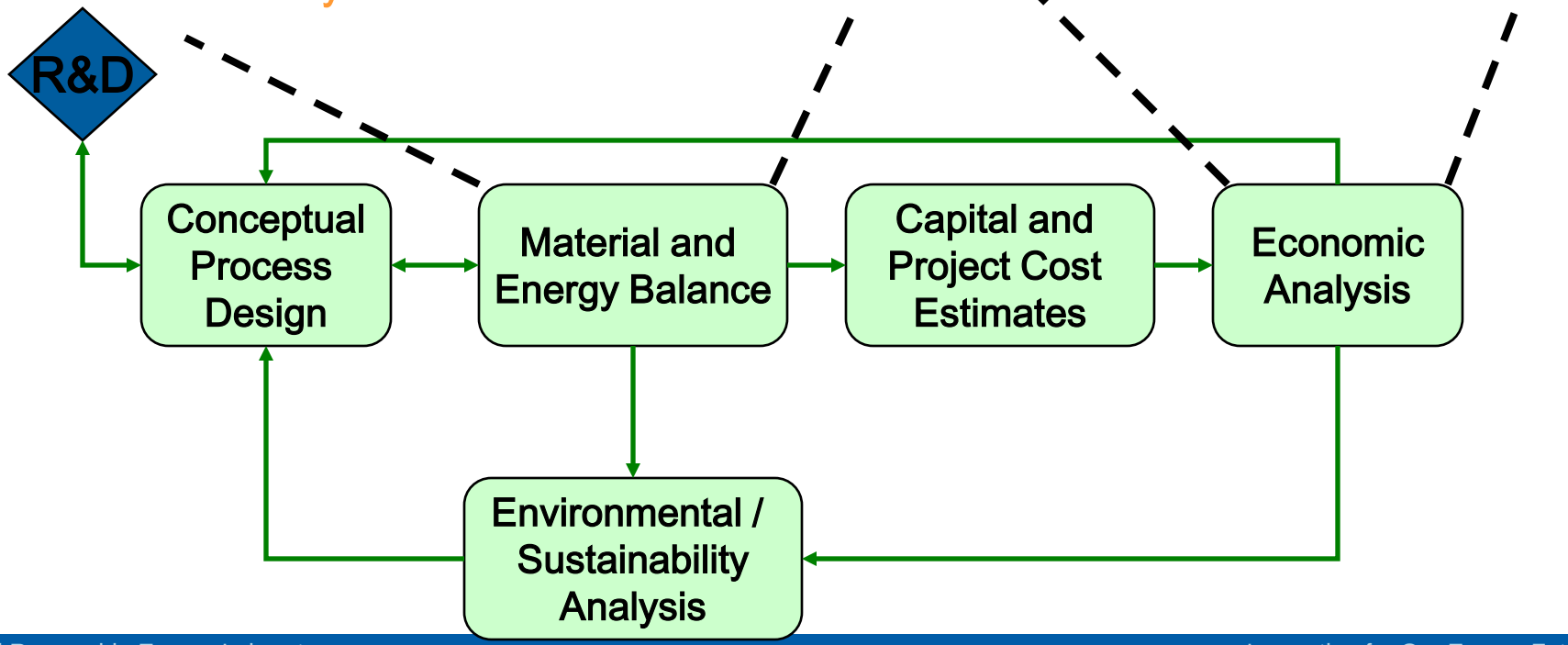
✓Early Stage: Back-of-the-envelope estimates

✓Mid Stage: Industry-relevant ASPENPlus™ process simulation

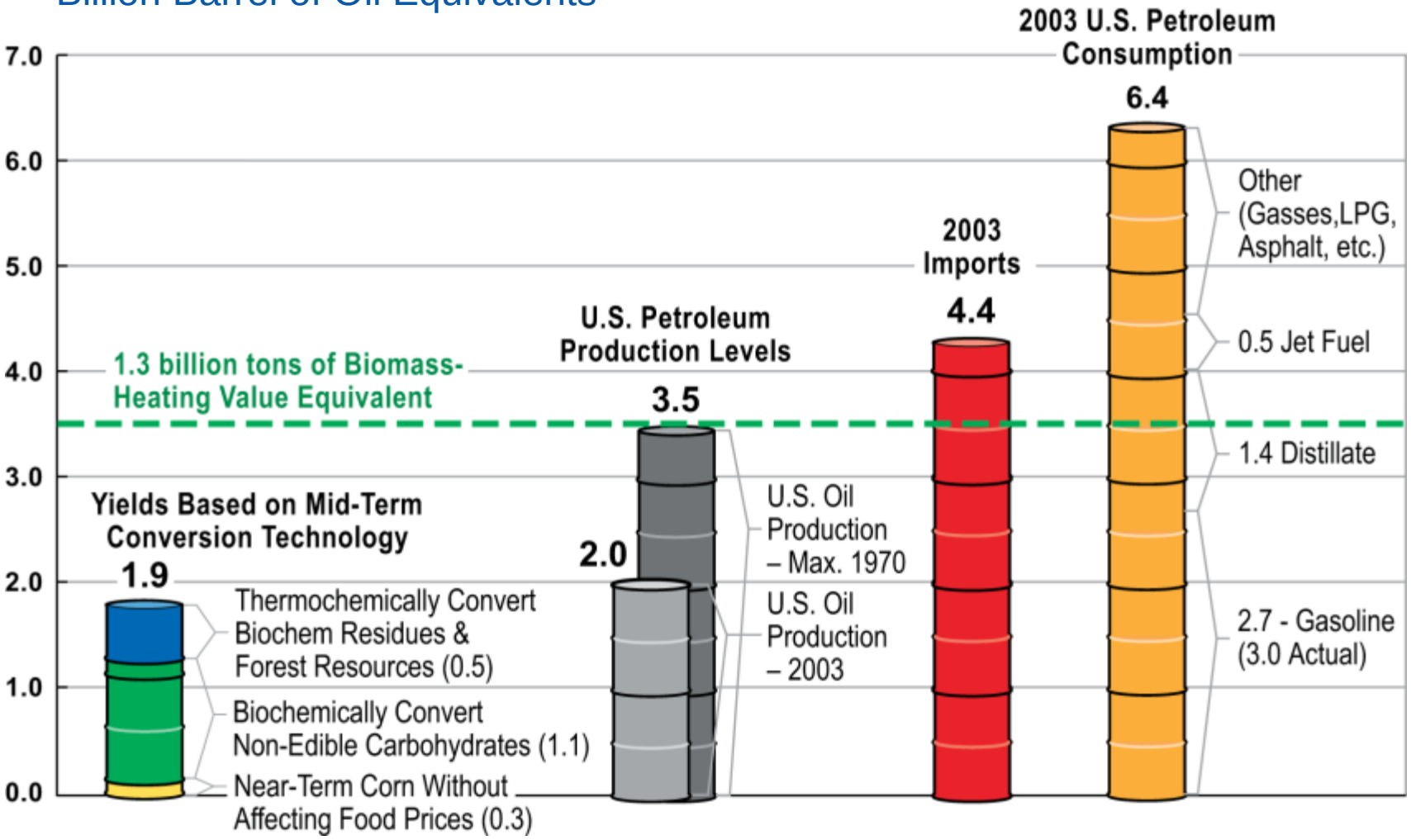
✓Kinetic modeling and regression analysis tools

✓ Early Stage: Simple cash flow analysis

✓ Mid Stage: Discounted cash flow rate of return analysis



Significance of the “Billion Ton” Scenario



$1.33/gallon ethanol is equivalent to $65-$70/bbl without a subsidy