National Renewable Energy Laboratory

Bioethanol: A Renewable Transportation Fuel from Biomass

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AIChE Spring Conference
March 12, 2002

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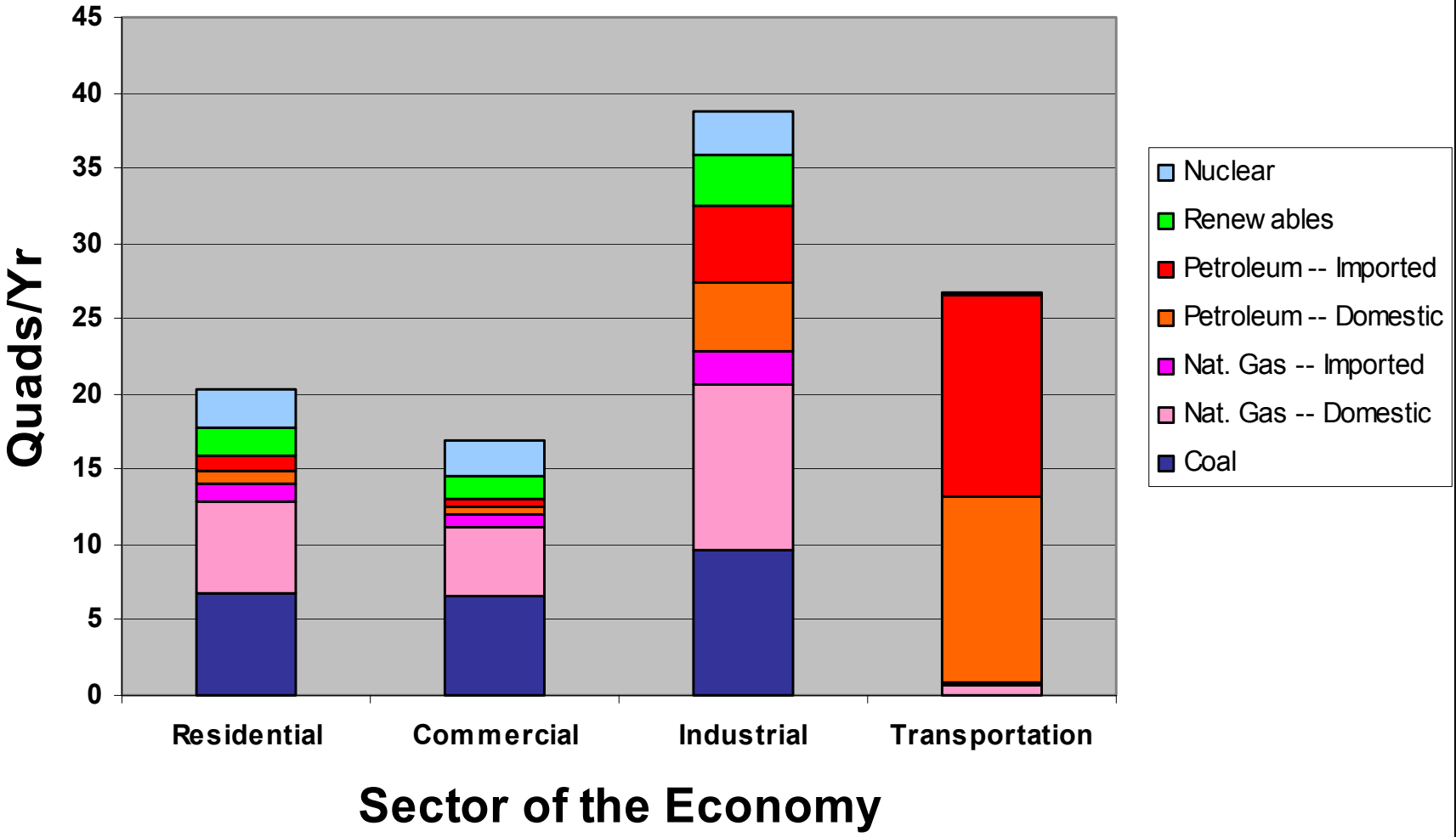
Outline

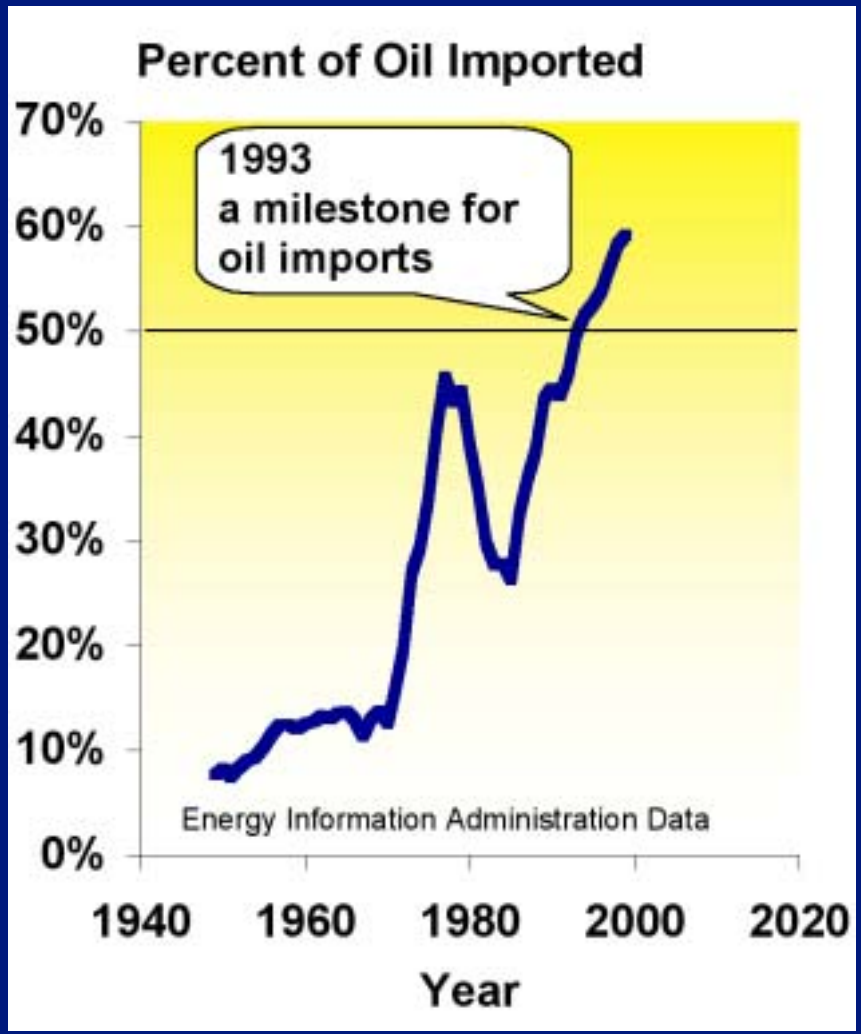
- Energy for Transportation
- Life Cycle Assessment
- Biomass Resources
- Ethanol Production Process
  - Biomass Hydrolysis
    - Chemical
    - Enzymatic
  - Fermentation
- Future – The Biorefinery

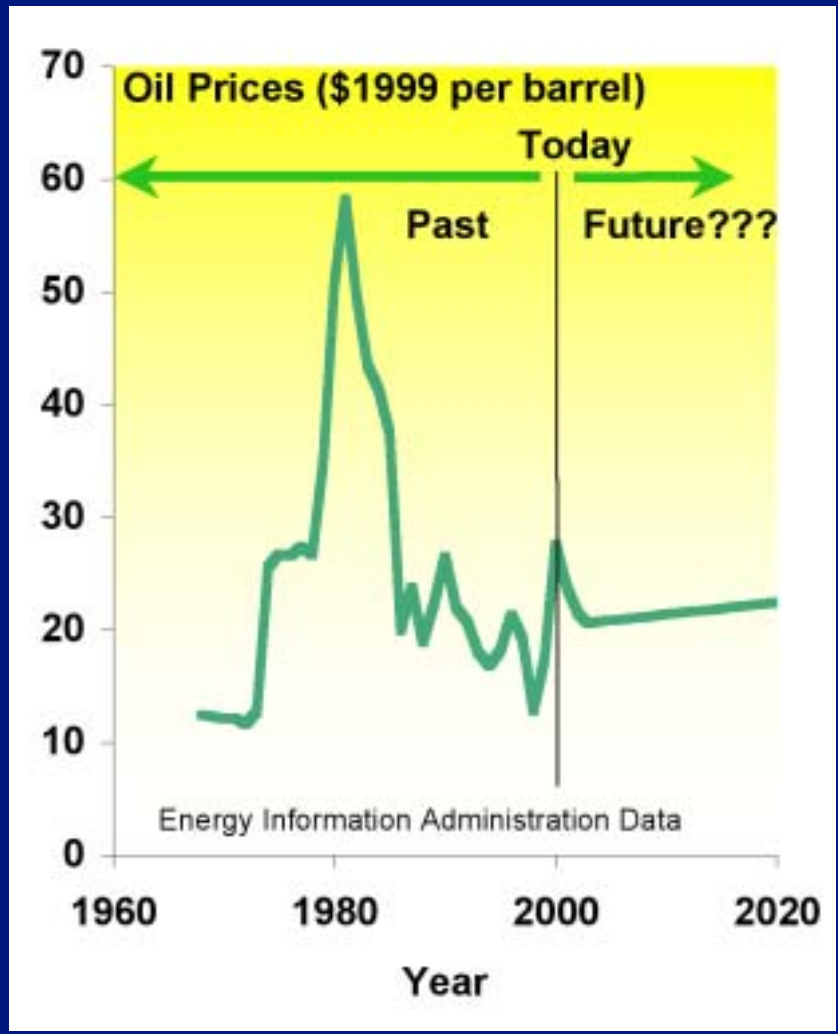
U.S. Primary Energy Consumption - 1999



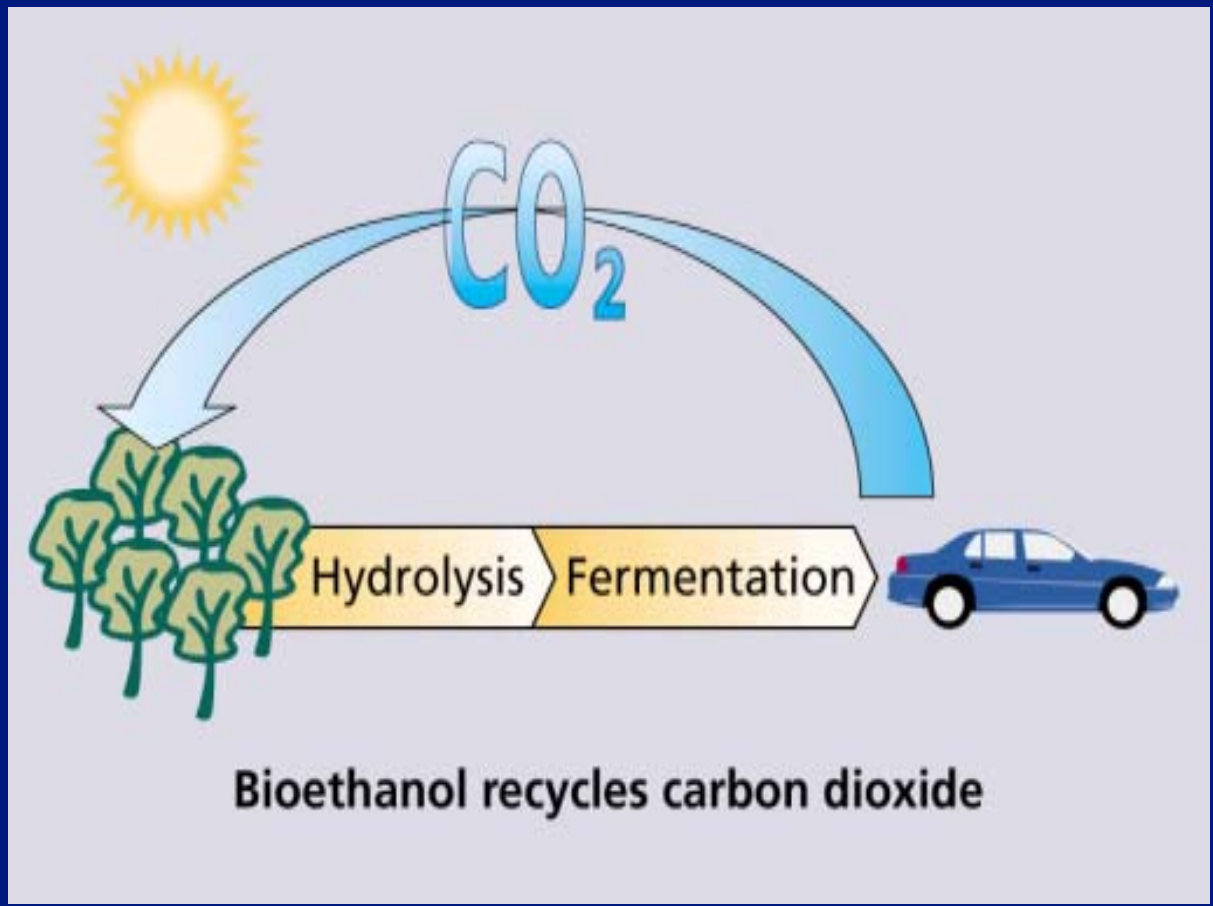
Just under 7% of all energy consumed in U.S. is for non-fuel purposes.

U.S. Oil Imports and Prices



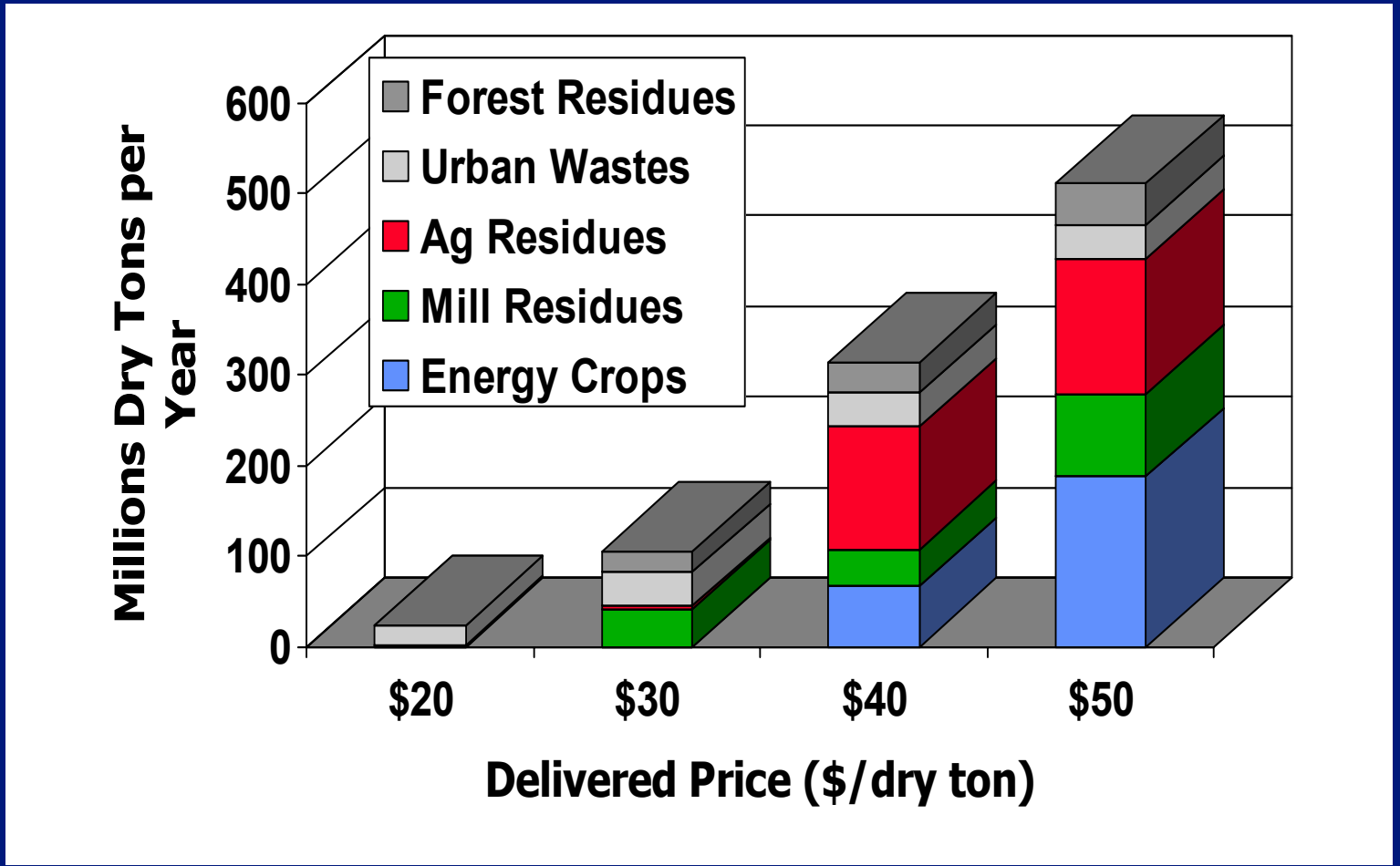


What is bioethanol?



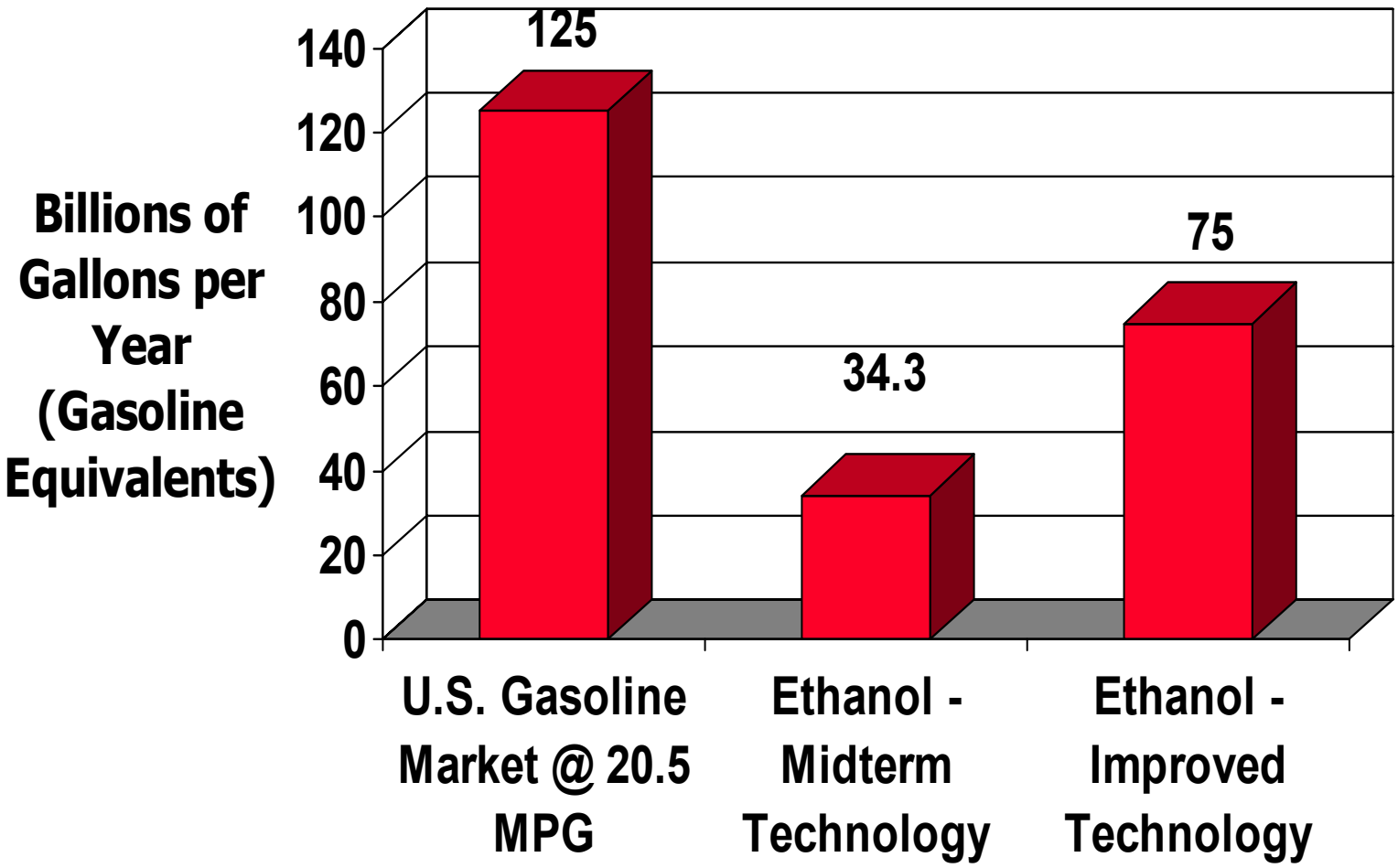
- Fuel ethanol made from non food biomass sources
- Requires "new" technology:
  - **To break down (hydrolyze) cellulose and hemicellulose to sugar**
  - **To ferment "unusual" sugars in biomass**

Potential Midterm U.S. Biomass Supply



- 42 million acres (10% of total cropland) switches to bioenergy crops, includes 13 million acres of CRP land
- 181 million dry tons of switchgrass per year at $50 per ton or less.

Impact of Bioethanol on U.S. Gasoline



Life Cycle Assessment—a framework for making choices that support a sustainable society

- "Cradle to grave"
- Accounts for all flows to and from the environment
  - Air, water and solid waste emissions
  - Energy resources
  - Other primary resources extracted from the environment
- Basis for technology and policy decisions by business and government

Sustainability: the life cycle of fuels

Energy Crop, Waste, Residue

Biomass Transport

Hydrolysis and Fermentation

Ethanol

One Mile Traveled

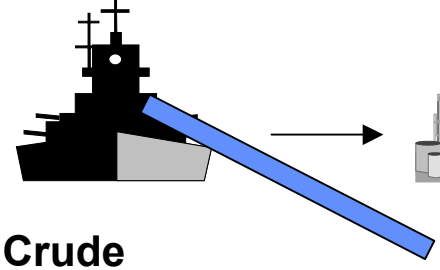
Gasoline

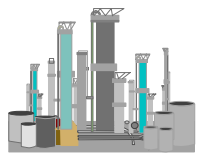
Feedstock Production

Feedstock Transport

Feedstock Conversion

Fuel Distribution



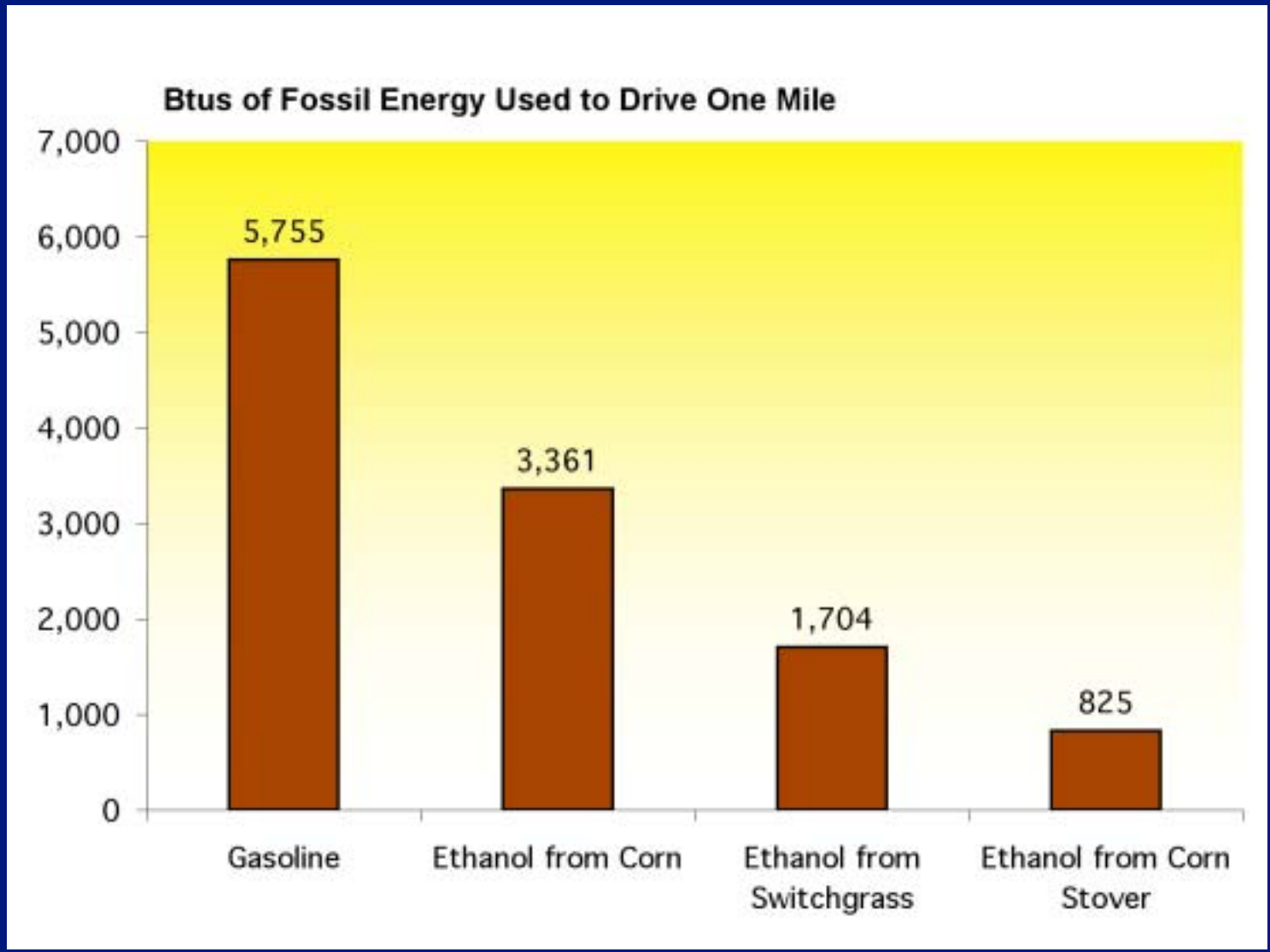


Crude Oil Production

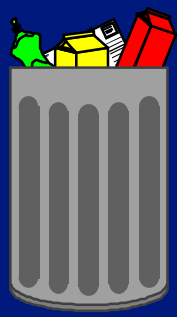
Crude Transport by barge, pipeline

Oil Refining to Gasoline

Avoiding fossil fuel use: bioethanol from corn stover



Biomass Resources and Issues



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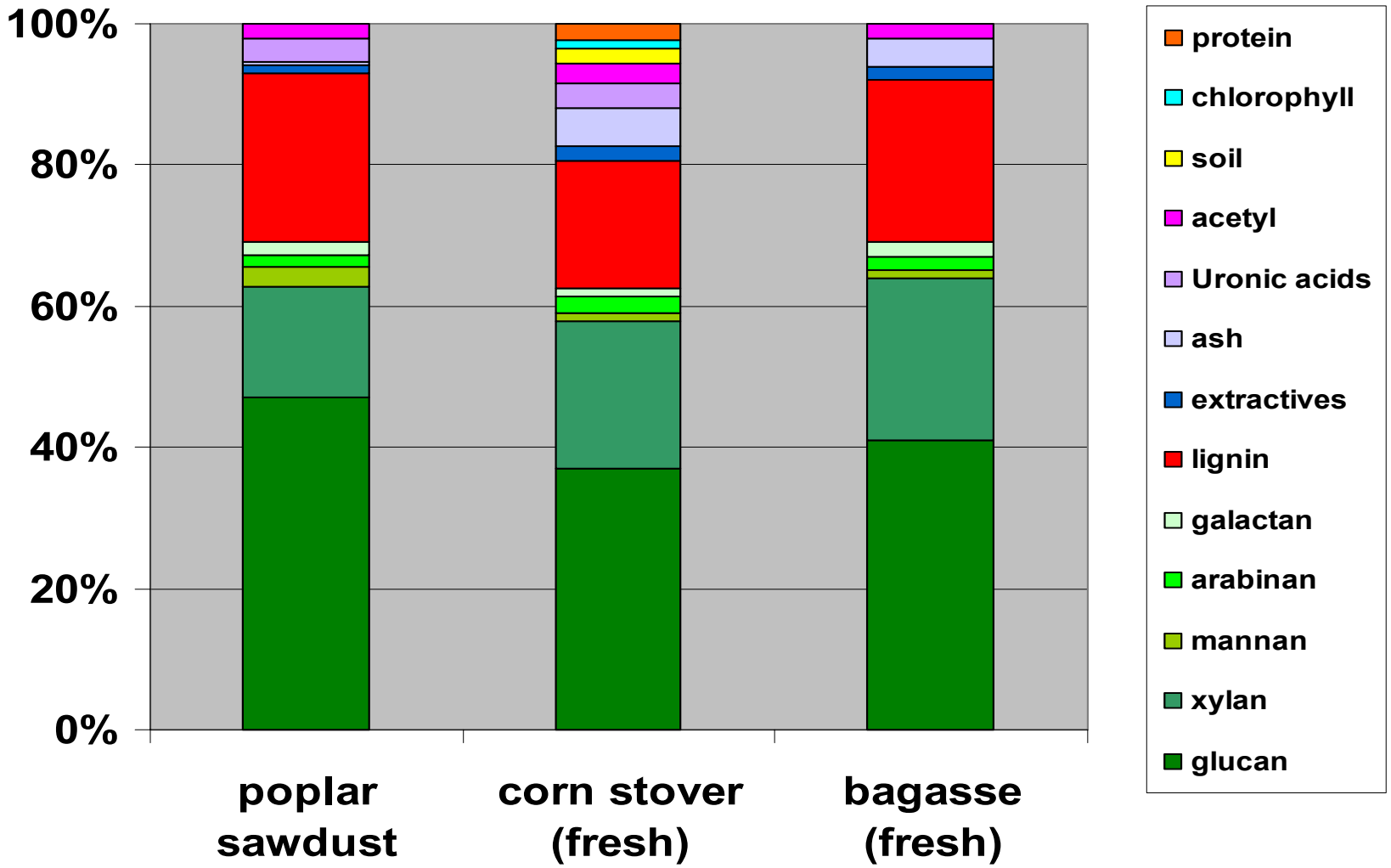
Ag. Crops and Residues

Grasses

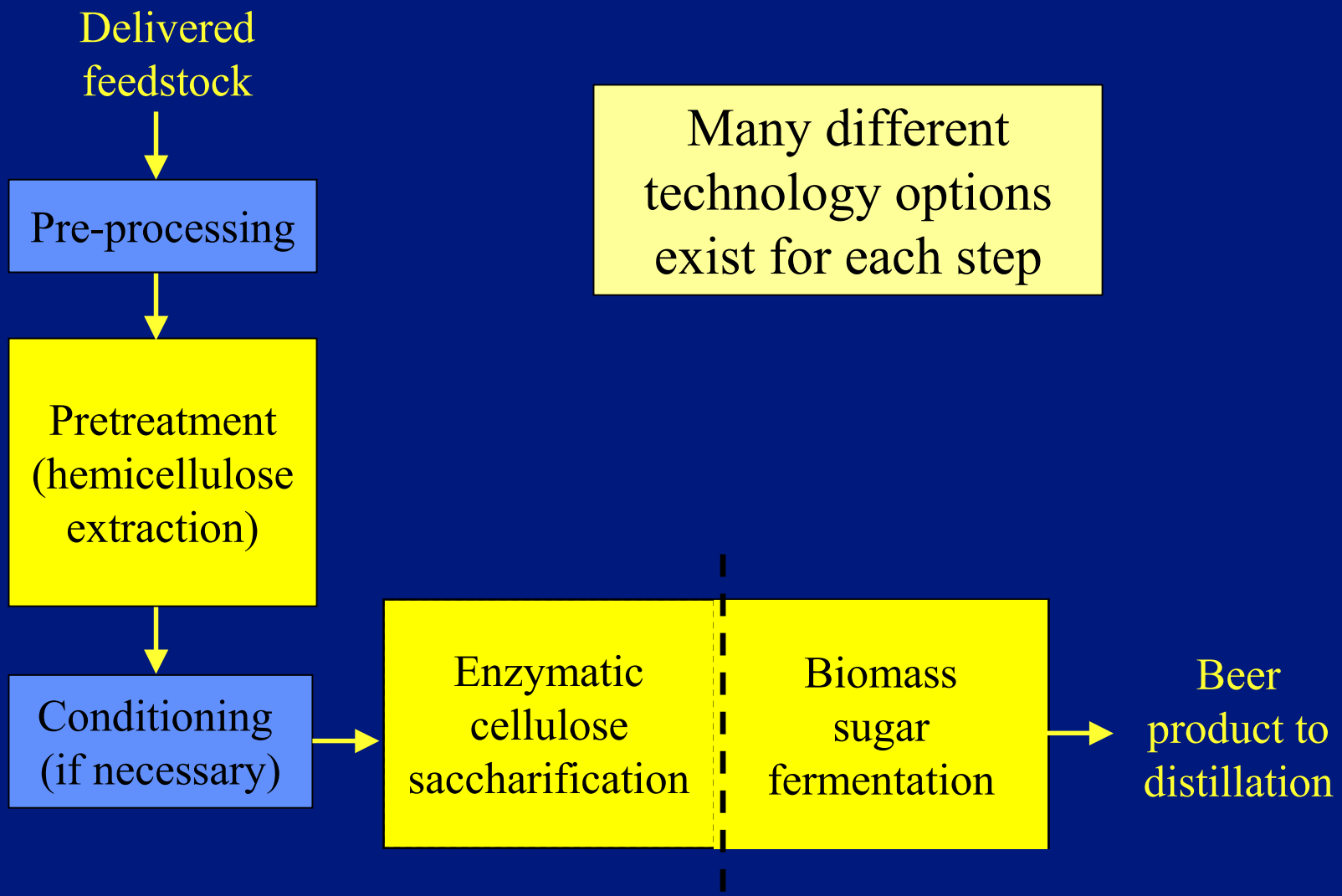
Trees

- Quantity
  - Wastes
  - Ag. Crops and Residues
  - Energy Crops
- Quality
  - Composition
  - Ease of Conversion
- Biomass Cost
  - Production
  - Collection and Transportation
- Sustainability
  - Land, Air and Water Resources

Biomass Composition Comparison

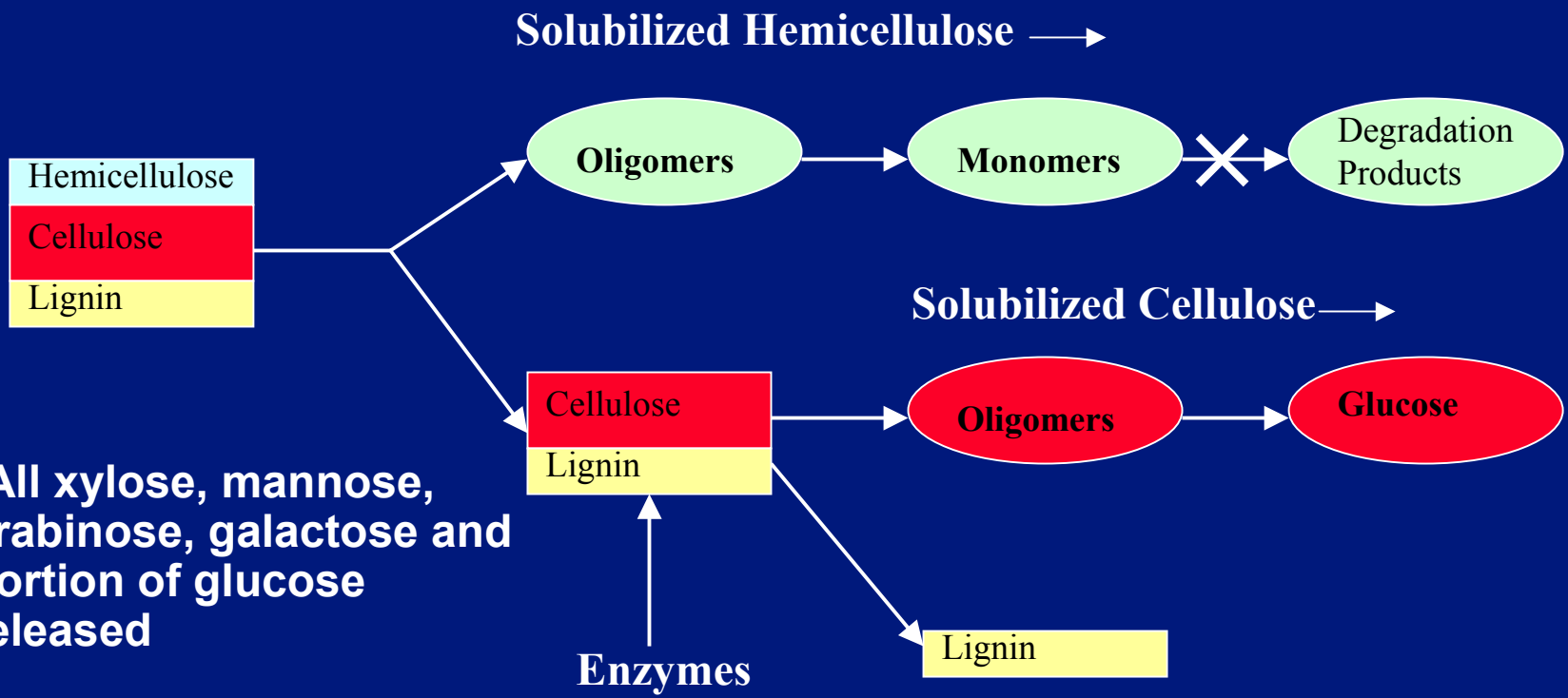


Major Steps in Enzymatic Process



Goals of Biomass Pretreatment

Acid-Catalyzed Process



- All xylose, mannose, arabinose, galactose and portion of glucose released
- Remaining cellulose is highly digestible
- Minimal sugar degradation products

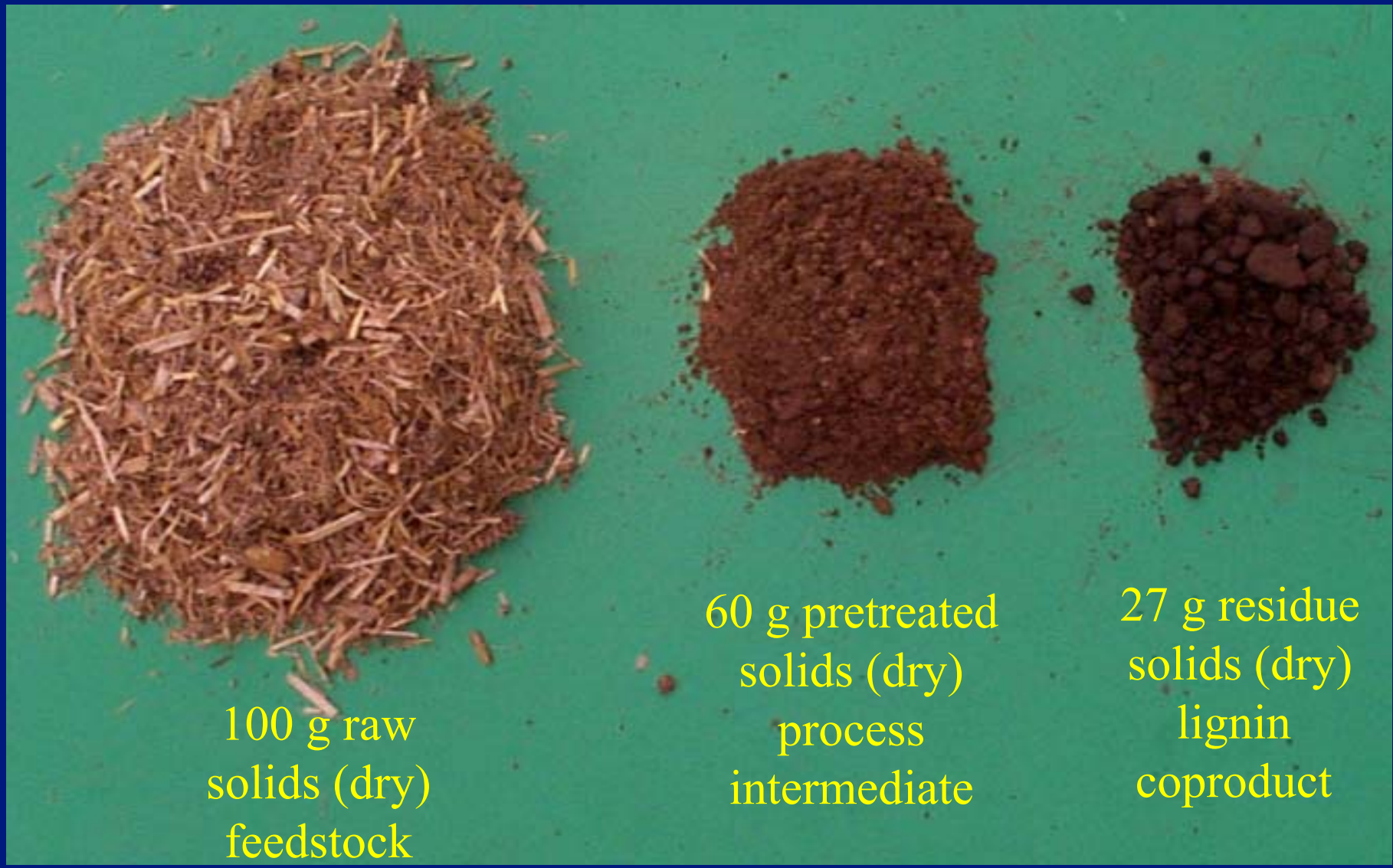
Biomass Pretreatment

Chemical partial hydrolysis prior to enzyme hydrolysis

- Reactor design is complex!
  - Continuous processing
  - High solids, erosive, corrosive
  - High temperature, pressure
  - Heterogeneous catalysis of complex substrate
  - Many simultaneous reactions

- Tools for improving pretreatment
  - Multiple reactor sizes and configurations
  - Impeccable analytical process chemistry
  - Kinetic and molecular modeling
  - Computational fluid dynamics

Conversion of Biomass



Pretreatment Equipment

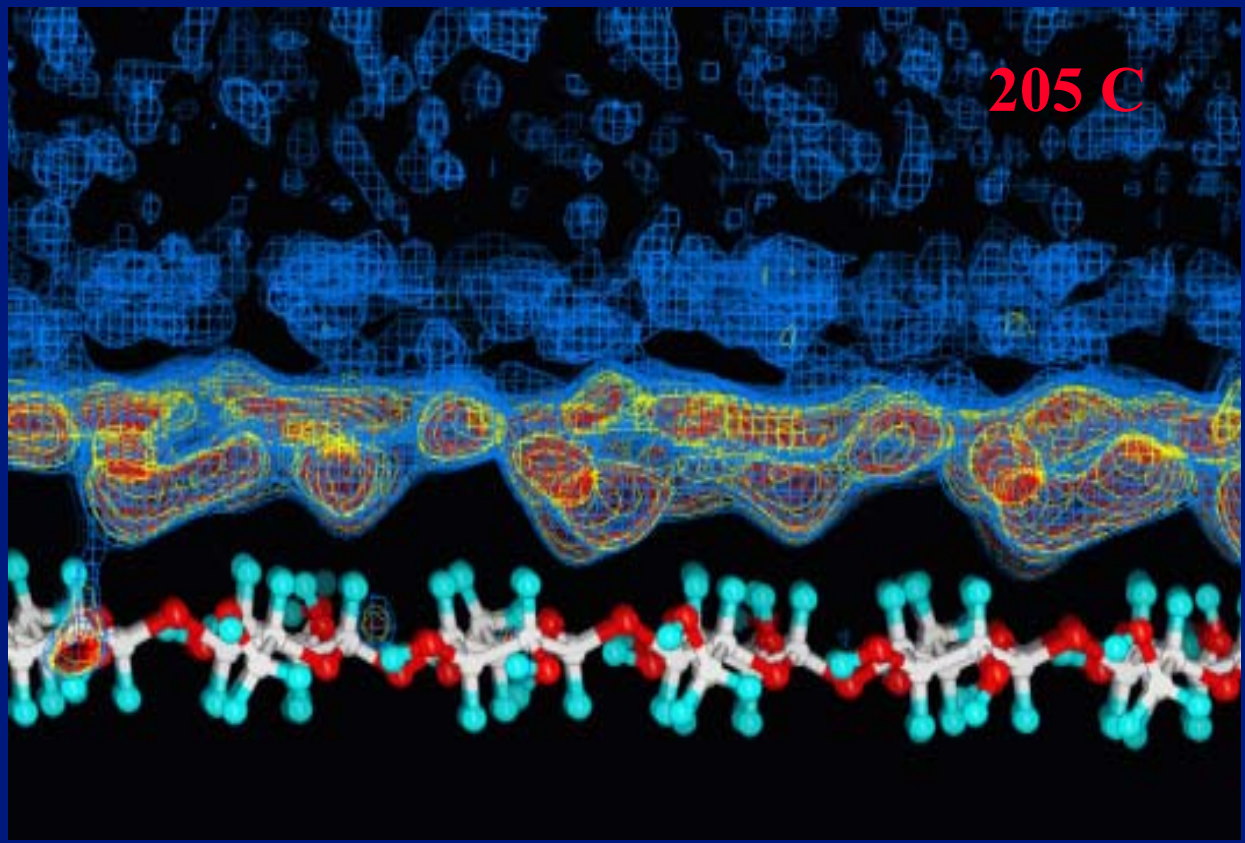
4 L Batch Steam Digester

2 ton/day Sunds Prehydrolyzer

200 kg/day Sunds Two-stage Countercurrent Reactor System

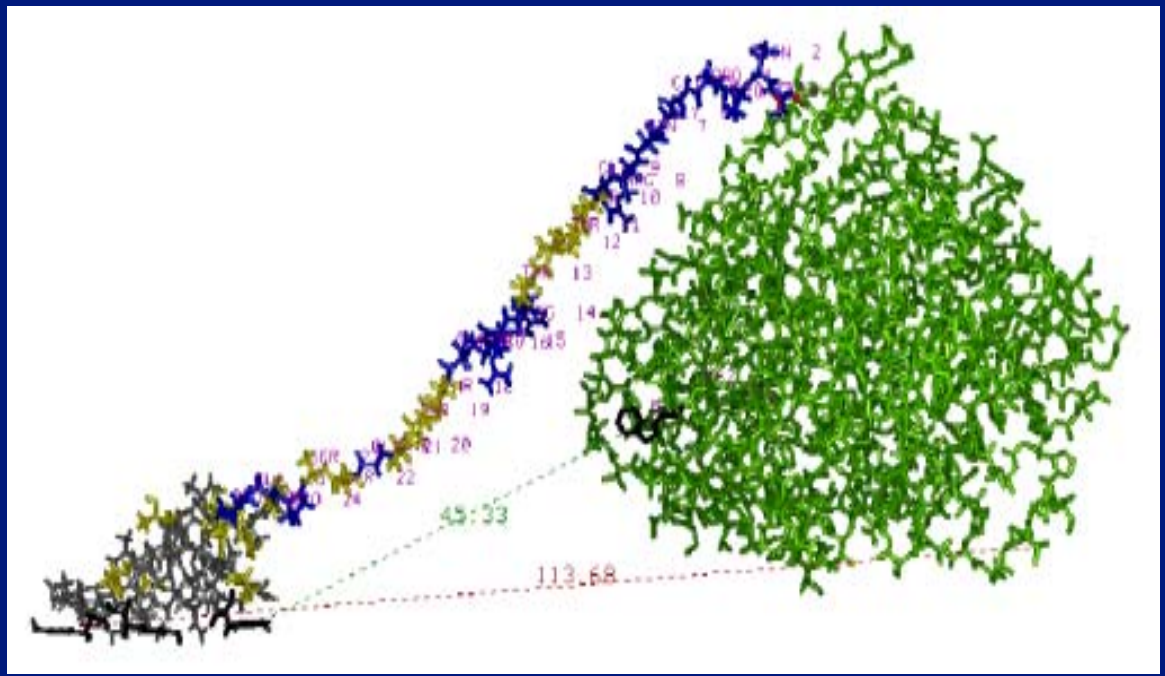
Mass Transfer Resistances – The Boundary Layer Theory

- The hydrophobic surface of crystalline cellulose imparts a structuring to adjacent water molecules.

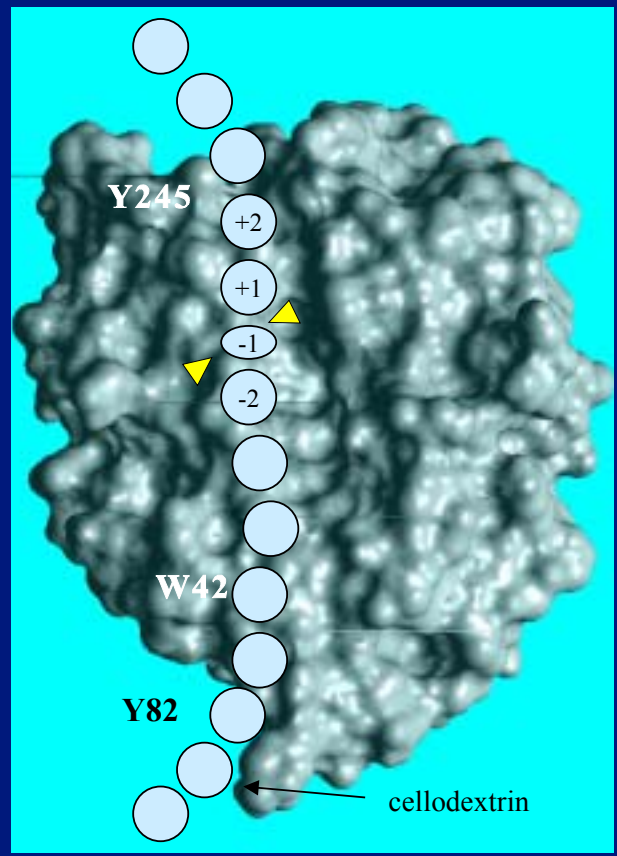


Enzymatic Hydrolysis

- Enzymes offer greater opportunities for cost reduction in the long term compared to acid hydrolysis technology
  - Enzyme Biochemistry and specific activity
  - Cellulase:Cellulose Interaction
  - Cost of Enzyme Production



CBH1 from T. reesei

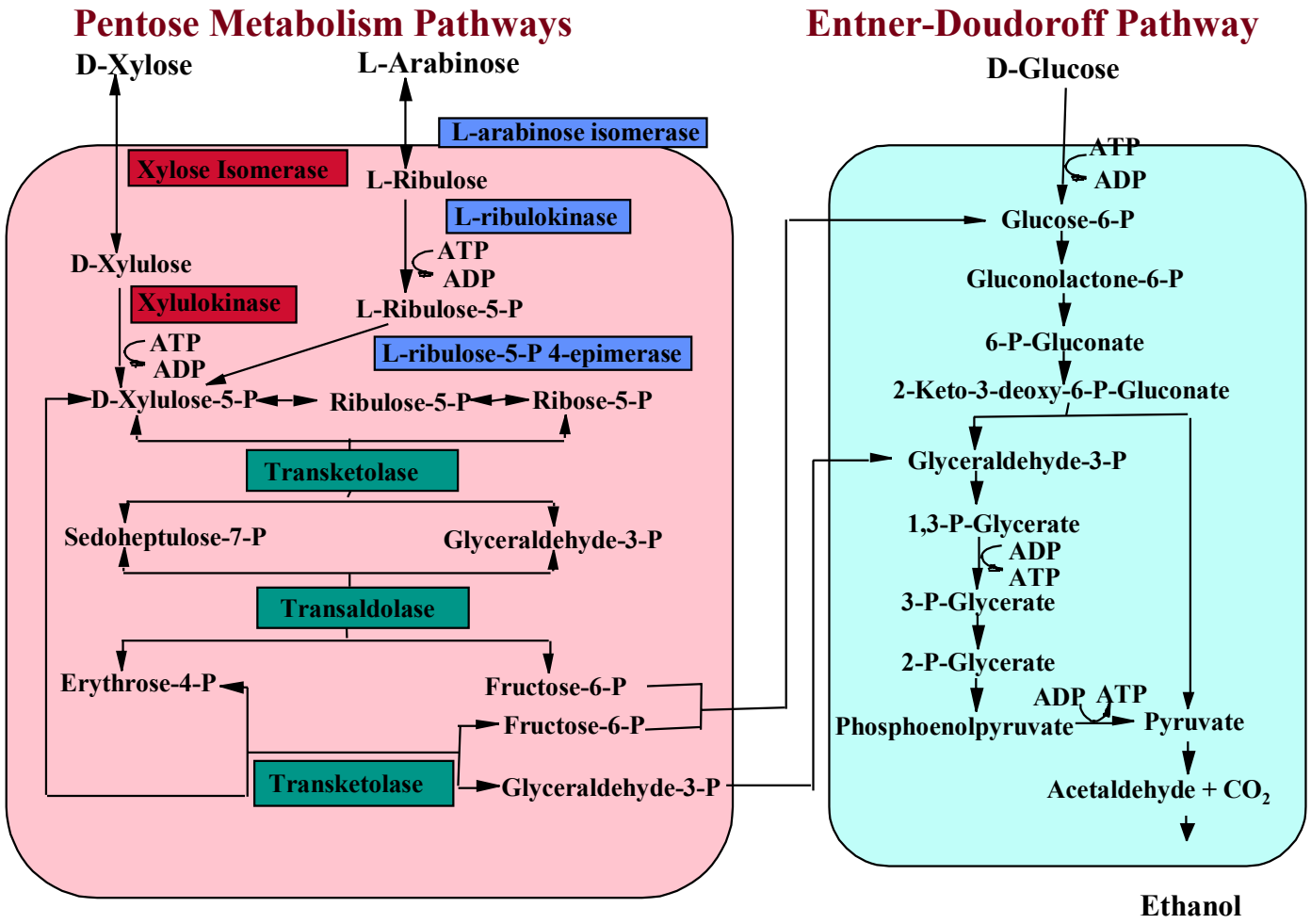


E1 from *A. cellulotiticus*

Biomass Sugar Fermentation

- Ferment all Biomass Sugars
  - Glucose, Xylose, Arabinose, Mannose, Galactose
- Resistant to toxic materials from pretreatment
  - Furfural, HMF, Acetic, Uronic and other Acids, phenols, cations, sugar oligomers, …
- Robust, able to out-compete contaminant microorganisms
  - Thermo-tolerant
  - Ethanol tolerant
  - pH tolerant
  - High fermentation rates
- Minimum metabolic byproducts

Pathways Required for Pentose Fermentation



Critical Success Factors for Pioneer Plants

- **Accurately estimate cost and performance!***

- Plant cost growth strongly correlated with:
  - Process understanding (integration issues)
  - Project definition (estimate inclusiveness)

- Plant performance strongly correlated with:
  - Number of new steps
  - % of heat and mass balance equations based on plant data
  - Waste handling difficulties
  - Solid feedstock

* "Understanding Cost Growth and Performance Shortfalls in Pioneer Process Plants", a study by the Rand Corp. for DOE (1981)

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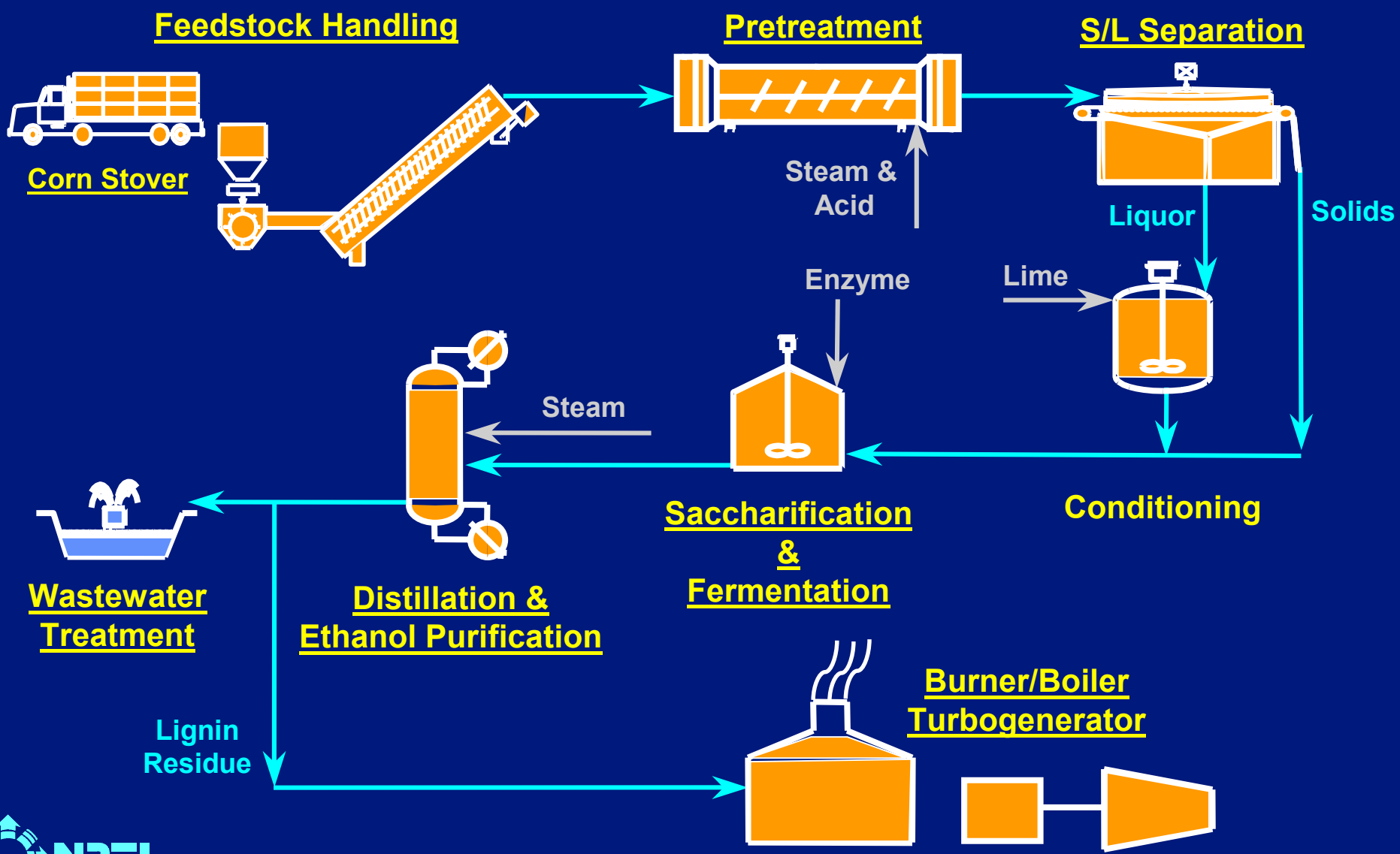
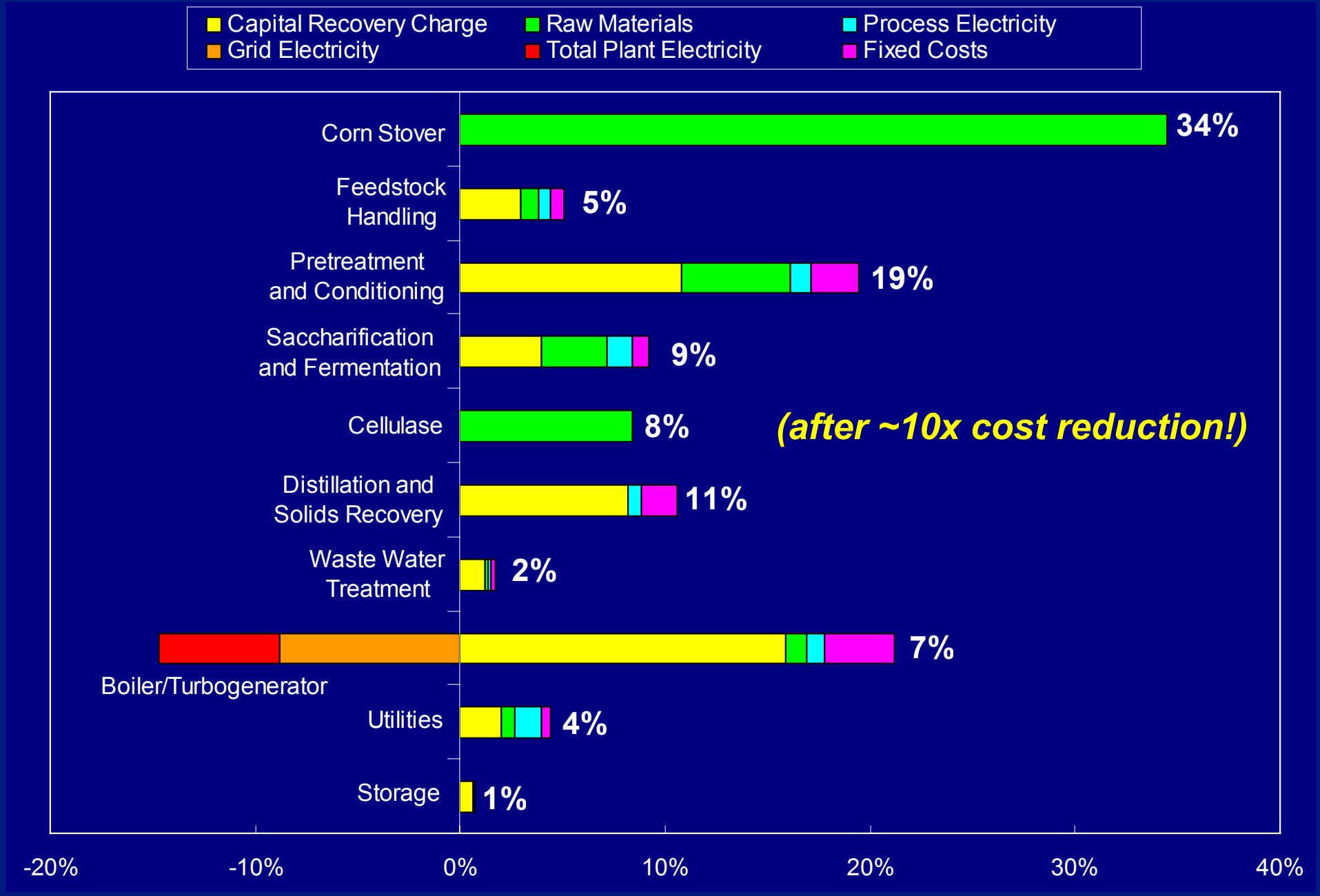
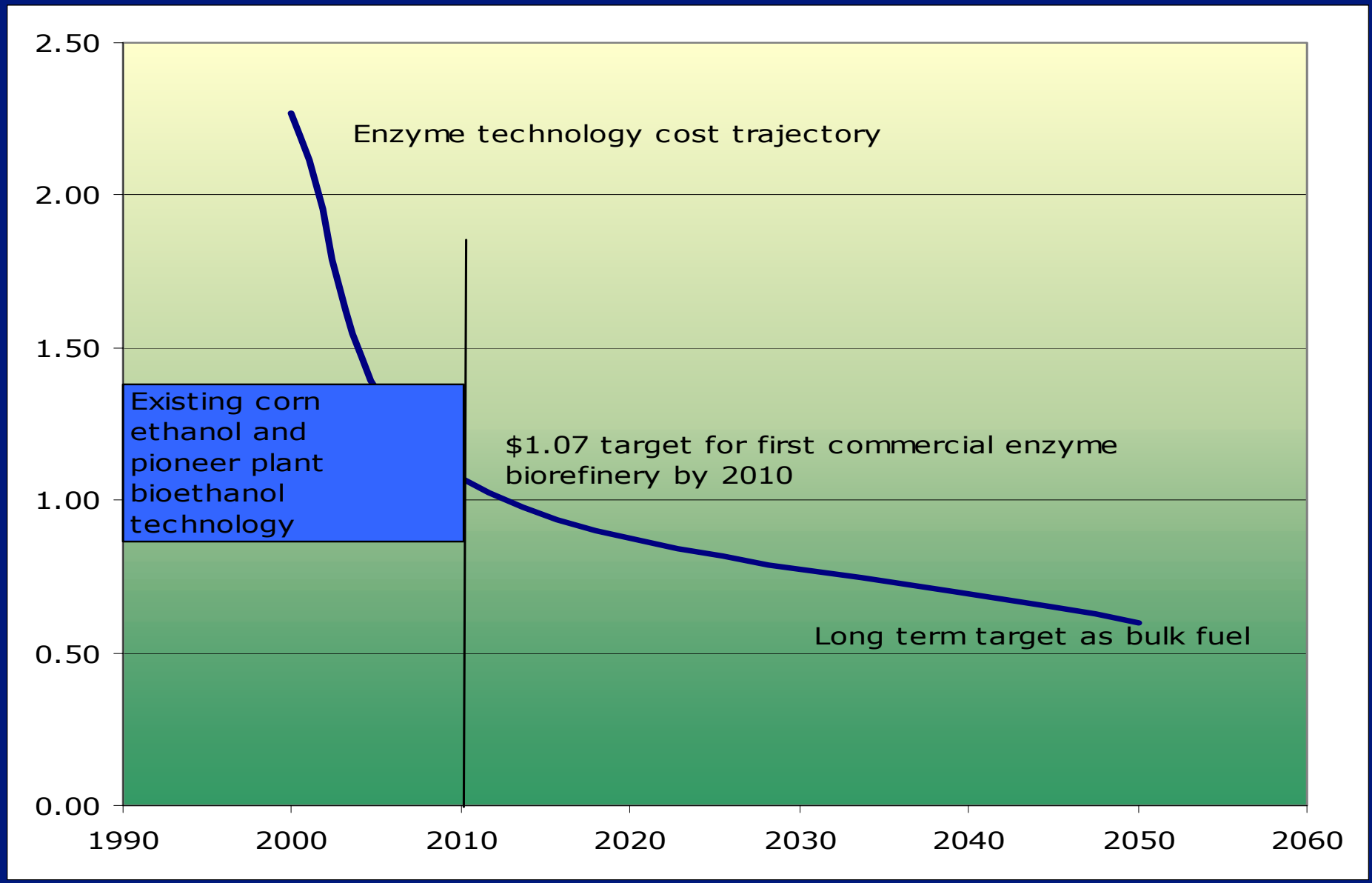
Simple Bioethanol Process Flow Diagram



Corn Stover Case Normalized Cost by Area



The costs of Cellulosic Conversion?



Biorefineries of the Future

Biomass Feedstocks

- Trees
- Grasses
- Bio-product Crops
- Agricultural Crops
- Agricultural Residues
- Animal Wastes
- Municipal Solid Waste

Conversion Processes

- Enzymatic Fermentation
- Gas/liquid Fermentation
- Acid Hydrolysis/Fermentation
- Gasification
- Product Synthesis from Syn-gas
- Combustion
- Co-firing

Products

Fuels:
- Ethanol
- Renewable Diesel
- Methanol
- Hydrogen

Electricity

Heat

Chemicals:
- Plastics
- Solvents
- Pharmaceuticals
- Chemical Intermediates
- Phenolic Compounds
- Adhesives
- Furfural
- Fatty acids
- Acetic Acid
- Carbon black
- Paints
- Dyes, Pigments, and Ink
- Detergents
- Etc.

Summary

- Environmentally acceptable scenarios exist in which bioethanol is a major energy carrier for a sustainable transportation sector.
- Significant progress has been made in developing the new technologies needed but they remain to be proven at the commercial scale.
- **But this entails big changes!**
- As do all transition paths to a sustainable world.
- If we reject potential paths because they involve large changes, we will probably have none left.

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For More Information

- Visit the 20 Bio Posters Upstairs!
  - Bioethanol
  - Biobased Products – Chemicals and Materials
  - Enzyme Development
  - Biomass Collection, Processing and Analysis
  - Biomass Development
  - Assessment Methods

And also visit the Biofuels Web site at:

www.ott.doe.gov/biofuels

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Acknowledgments

Funding Provided by U.S. Department of Energy,

Office of Transportation Technologies,

Office of Fuels Development