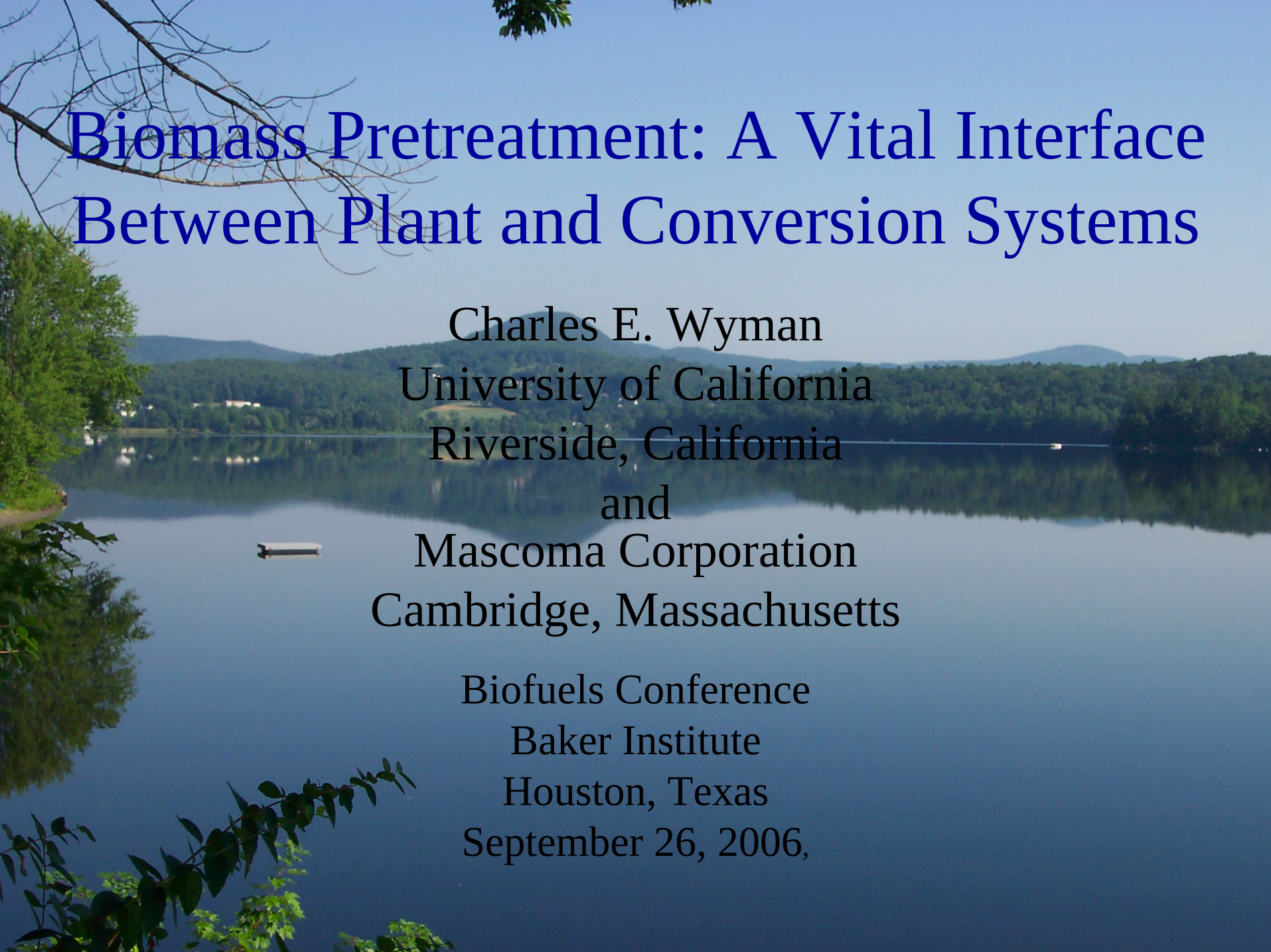


Biomass Pretreatment: A Vital Interface Between Plant and Conversion Systems

Charles E. Wyman
University of California
Riverside, California
and
Mascoma Corporation
Cambridge, Massachusetts

Biofuels Conference
Baker Institute
Houston, Texas
September 26, 2006

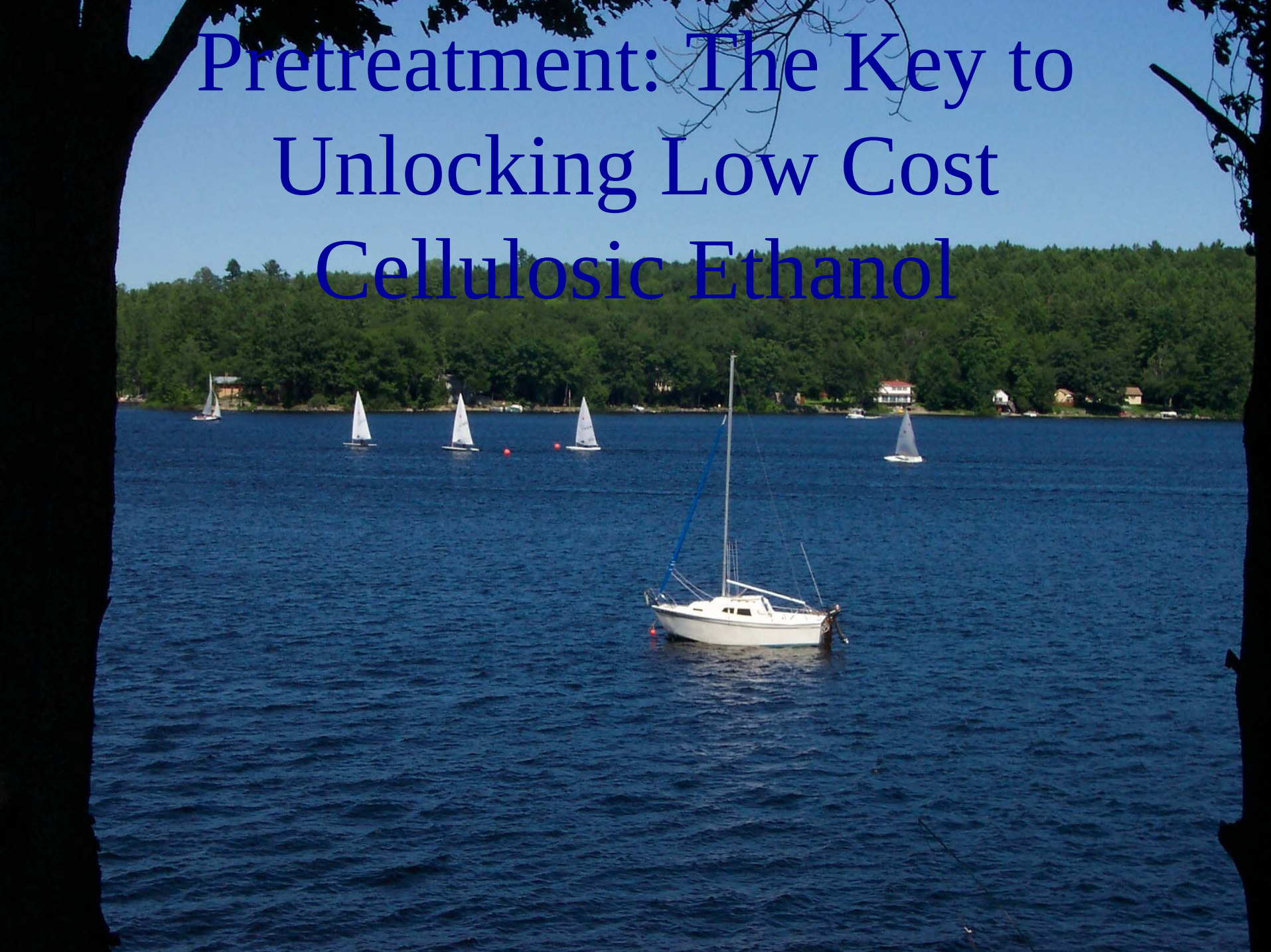
Mascoma Corporation

- Conceived in summer 2005
- Developing advanced technologies for conversion of cellulosic biomass to ethanol
  - Initially based on Dartmouth biological systems
- Forming partnerships to commercialize advanced cellulosic ethanol technologies

Mascoma Corporation

- Founders: Charles Wyman, Lee Lynd
- President: Colin South
- Chairman of Board: Vinod Khosla
- First round of capital from Khosla Ventures, Flagship Ventures
- More information: Mascoma.com

Pretreatment: The Key to Unlocking Low Cost Cellulosic Ethanol



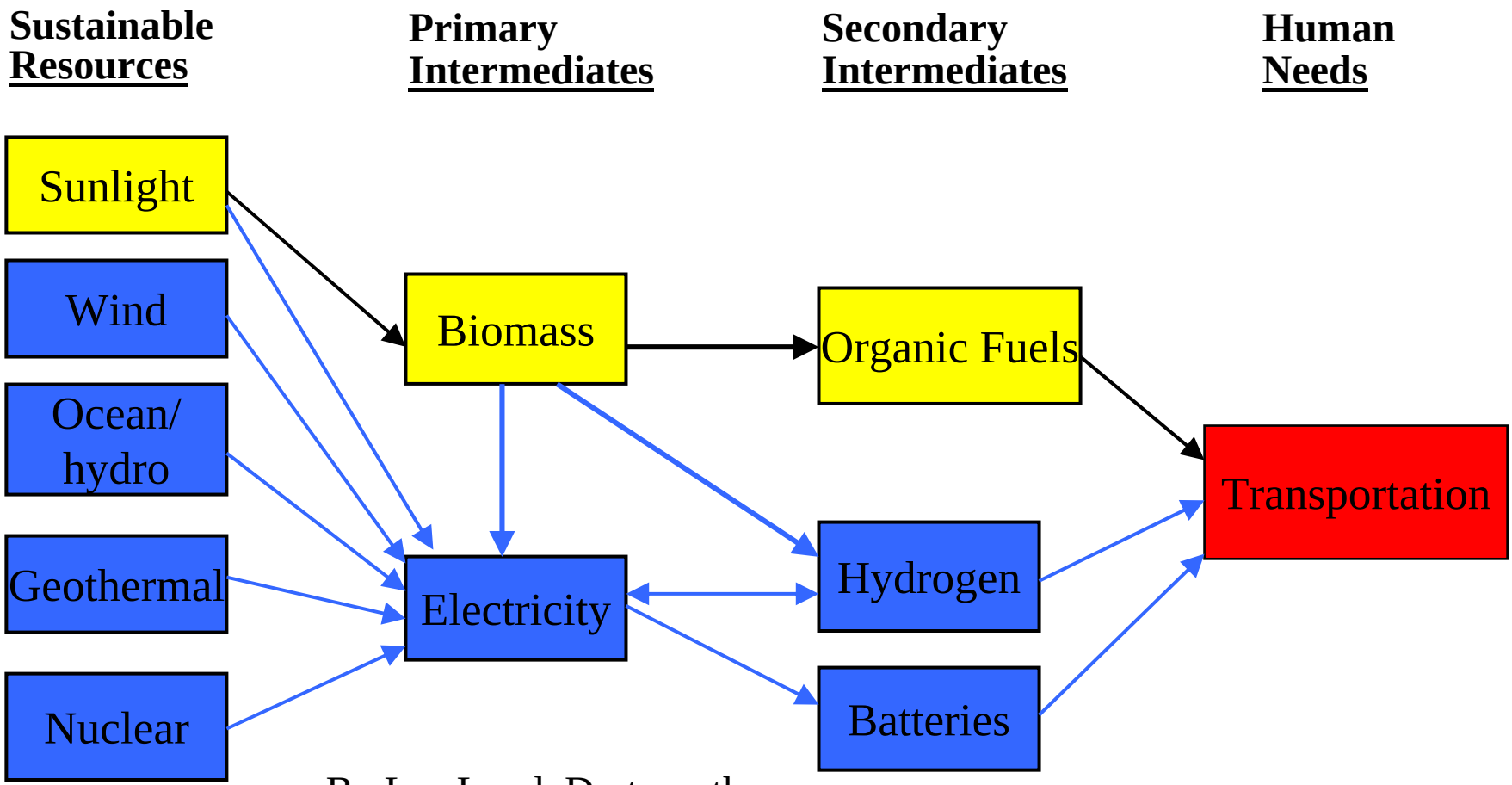
Where is a New Energy Source Needed in United States?

- U.S. energy production and demand are nearly balanced for all but one energy source: petroleum
  - We use more petroleum than we produce – >60% imported
- Petroleum is single largest energy source in U.S. supplying ~38.5% of total energy

Petroleum and Transportation

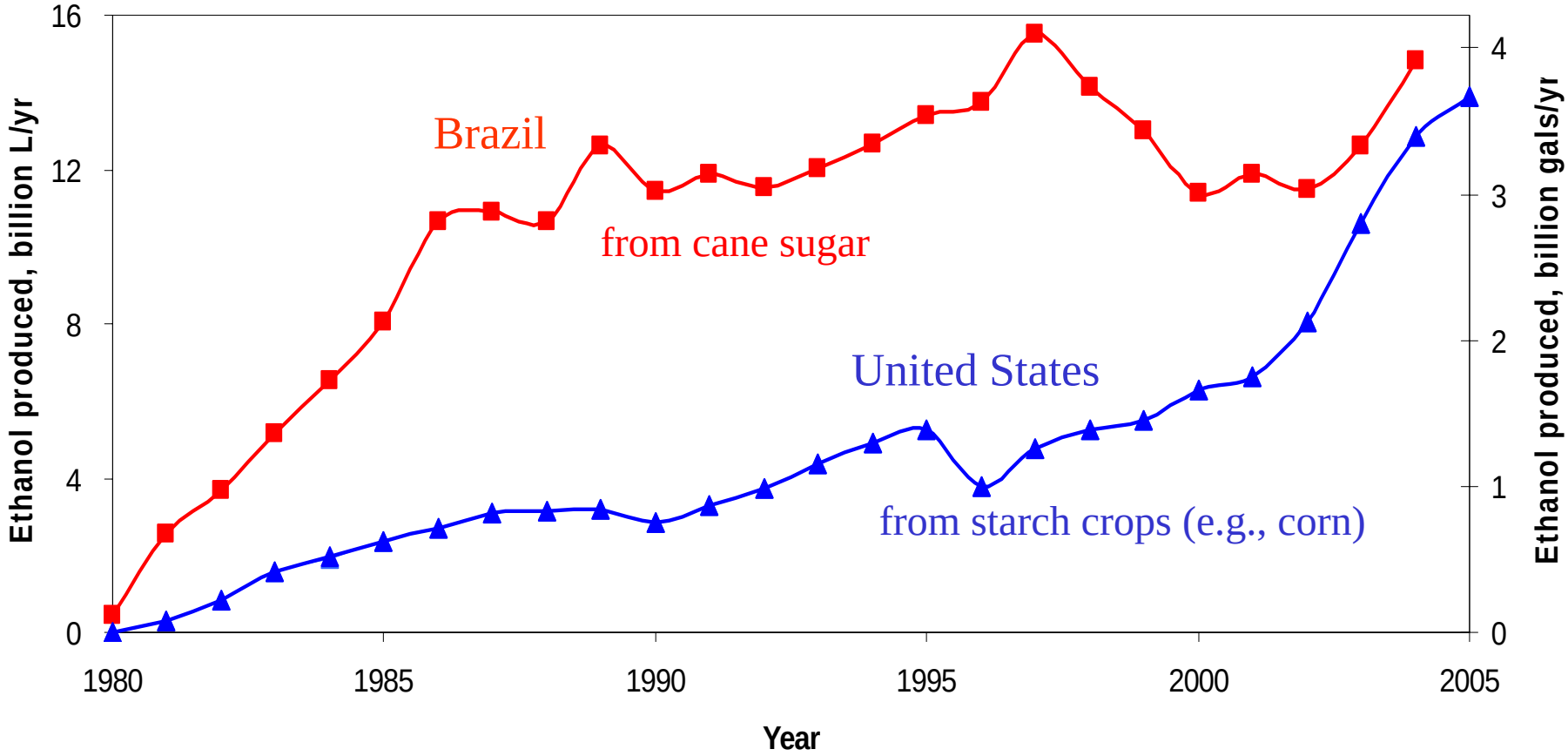
- About 2/3 of petroleum goes to transportation
- Transportation is almost totally dependent on petroleum (~96.4% in 2000)
- The largest source of greenhouse gases comes from transportation, ~32.8%
- Need to find alternatives to petroleum for transportation
- Should seek sustainable fuels to avoid future transitions and reduce greenhouse gases

Sustainable Alternatives for Transportation



By Lee Lynd, Dartmouth

Ethanol Production in Brazil and the United States



Biomass Refining CAFI

Sugar Cane in Brazil


Brazilian Ethanol Fermentors

For higher octane!

Focus: Cellulosic Biomass - Abundant, Inexpensive

- Existing resources
  - Agricultural wastes
    - Sugar cane bagasse
    - Corn stover and fiber
  - Forestry wastes
    - Sawdust
  - Municipal wastes
    - Waste paper
    - Yard waste
  - Industrial waste
    - Pulp/paper sludge
- Future resources
  - Dedicated crops
    - Herbaceous
    - Woody
- Not sugar or starch crops such as used for making ethanol in Brazil and the U.S. respectively

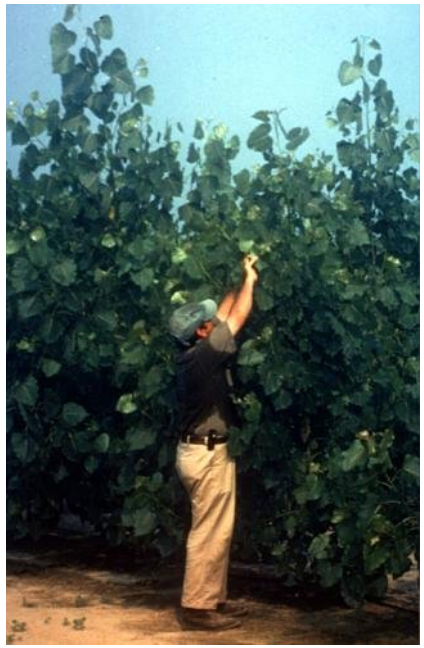
Sugarcane

Sugarcane Bagasse

Louisiana Rice Hulls Pile

Energy Crops

Switchgrass harvested annually or biannually

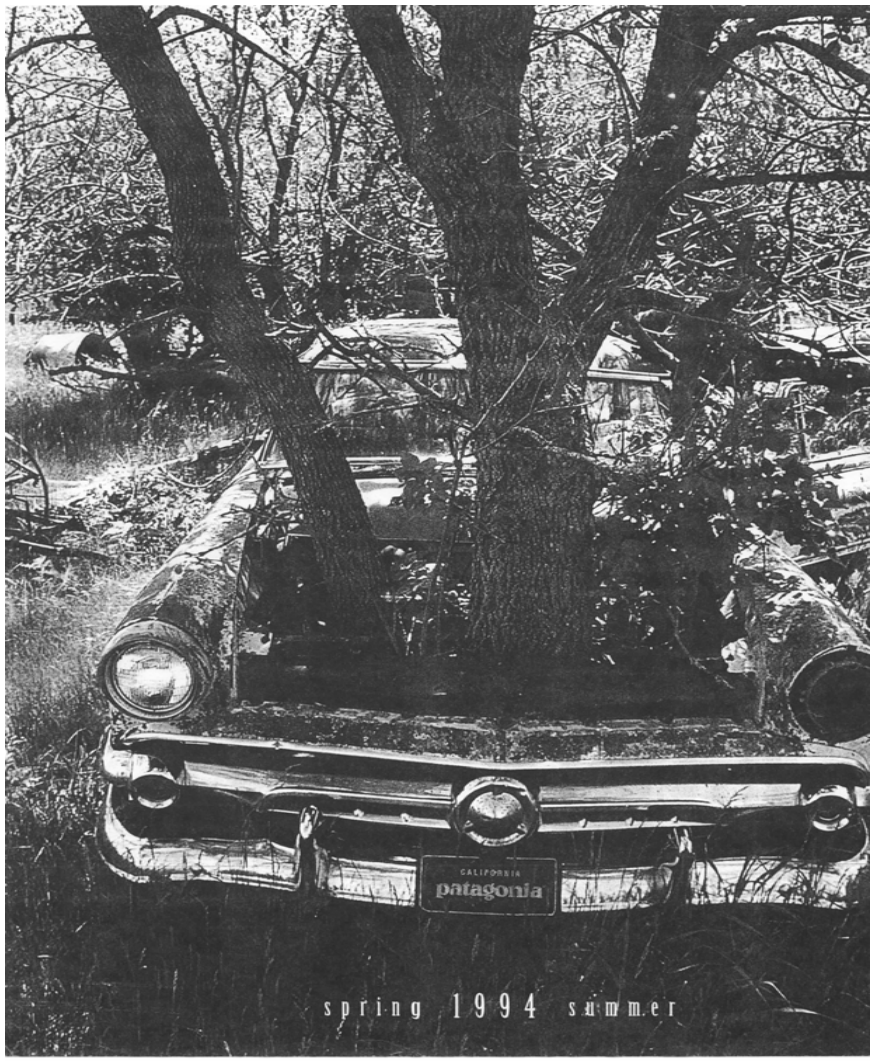


Hybrid Poplar harvested at age 5 to 10

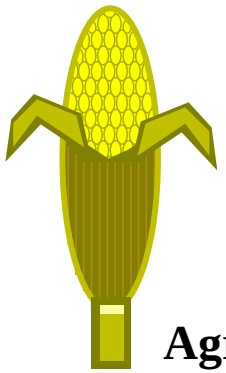
Willow coppice harvested at age 3 or 4

Courtesy of L. Wright, ORNL

Challenge: How Do You Put Low Cost Biomass in Your Car?

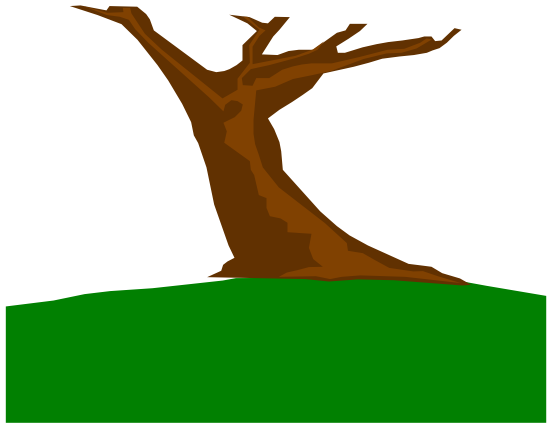


Cellulosic Biomass Composition



Cellulose 43%
Hemicellulose 27%
Lignin 17%
Other 13%

Agricultural Residues



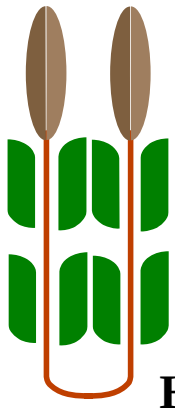
Cellulose 45%
Hemicellulose 25%
Lignin 22%
Extractives 5%
Ash 3%

Woody Crops

Cellulose 45%

Ash 15%
Lignin 10%
Hemicellulose 9%
Other carbohydrates 9%
Protein 3%
Other 9%

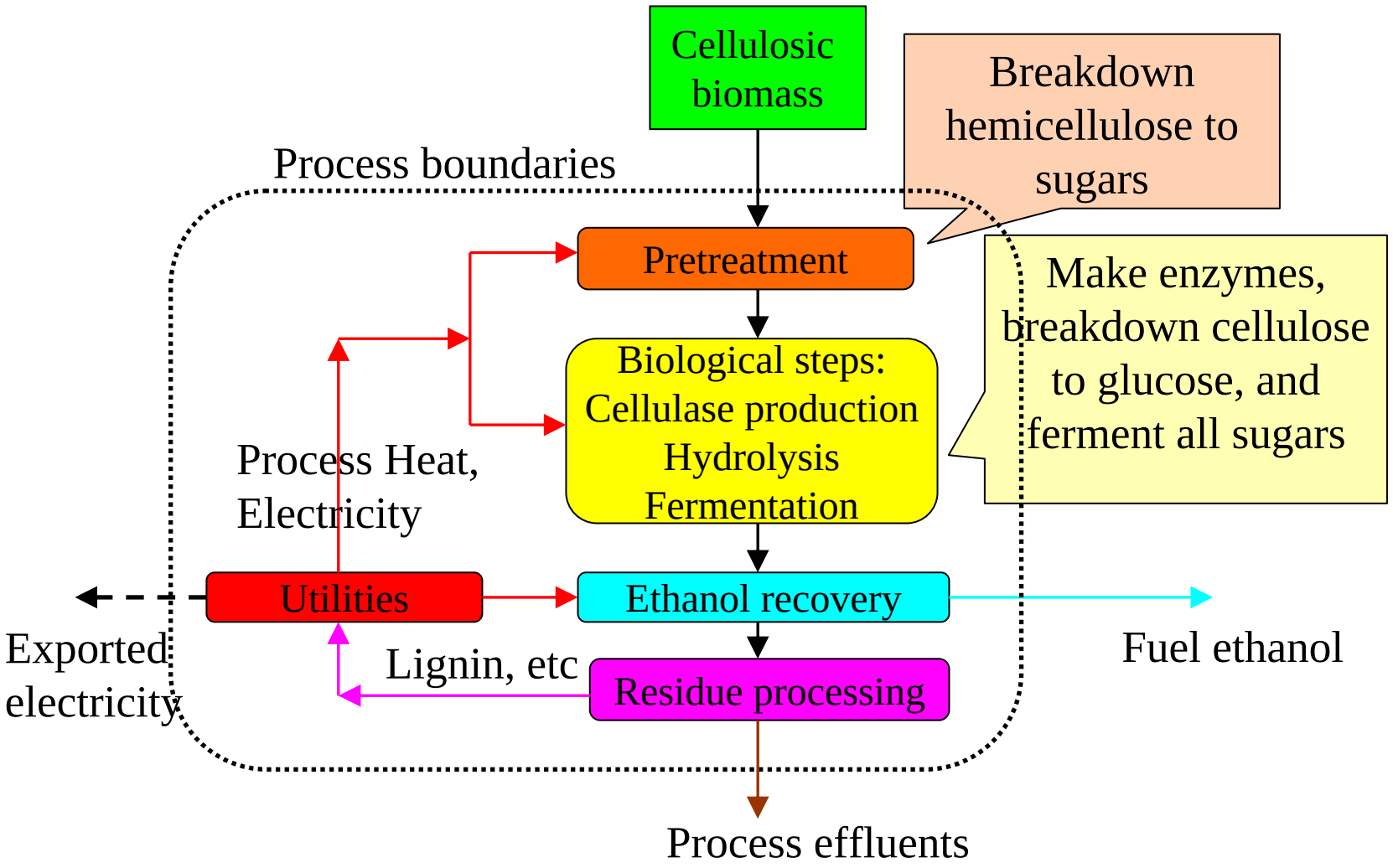
Municipal Solid Waste



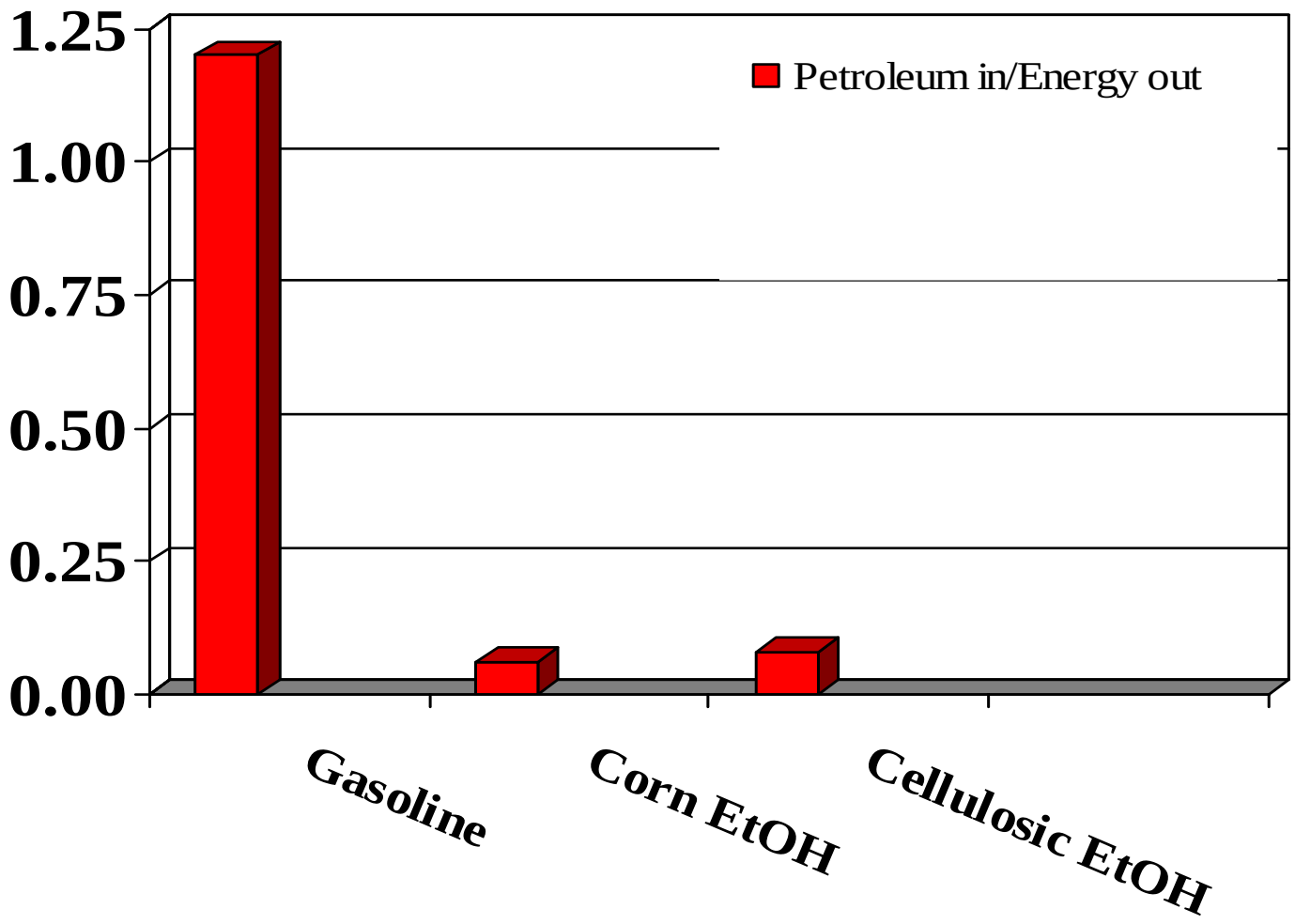
Cellulose 45%
Hemicellulose 30%
Lignin 15%
Other 10%

Herbaceous Energy Crops

Enzymatic Conversion of Cellulosic Biomass to Ethanol



Relative Metrics for Ethanol



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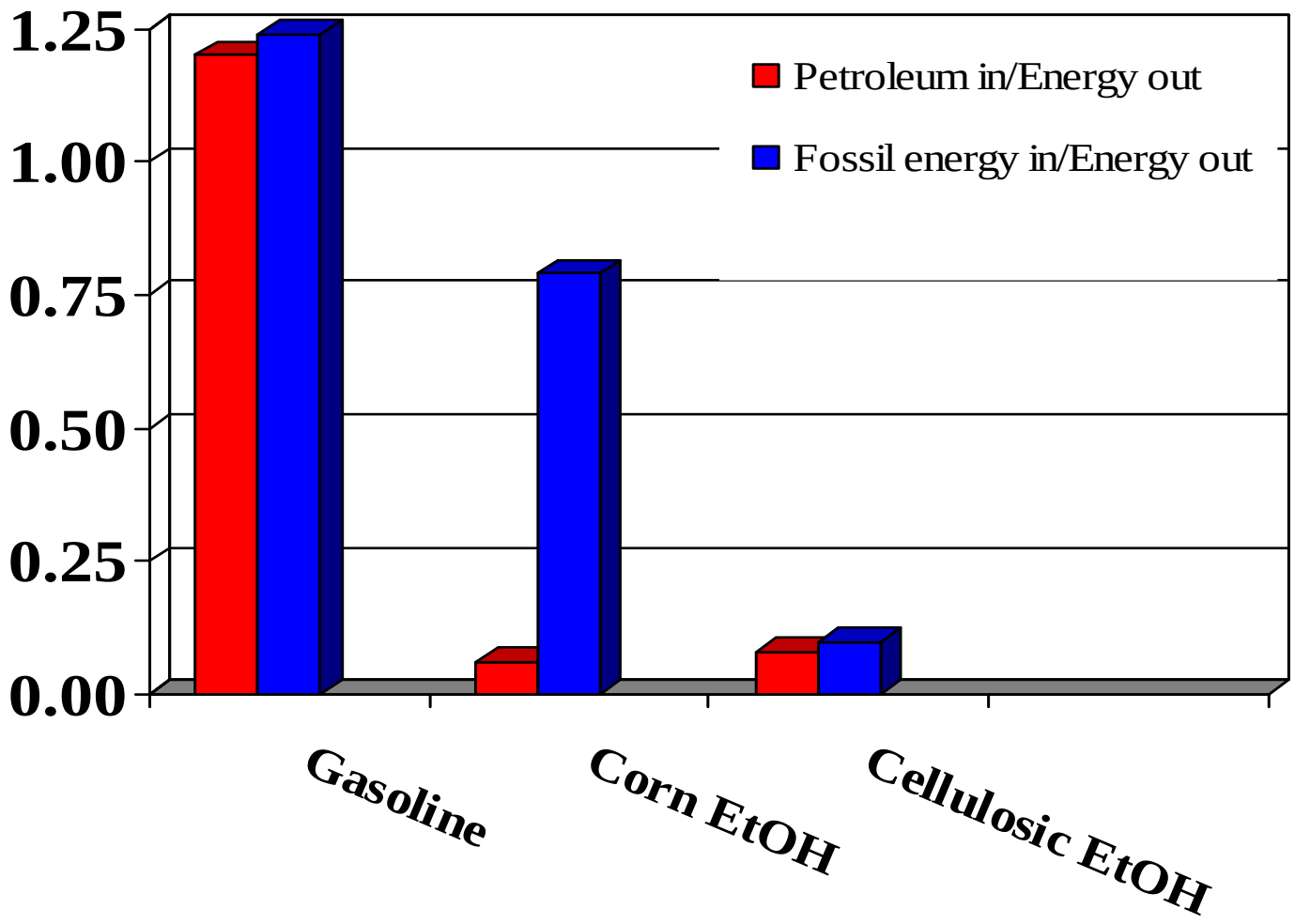

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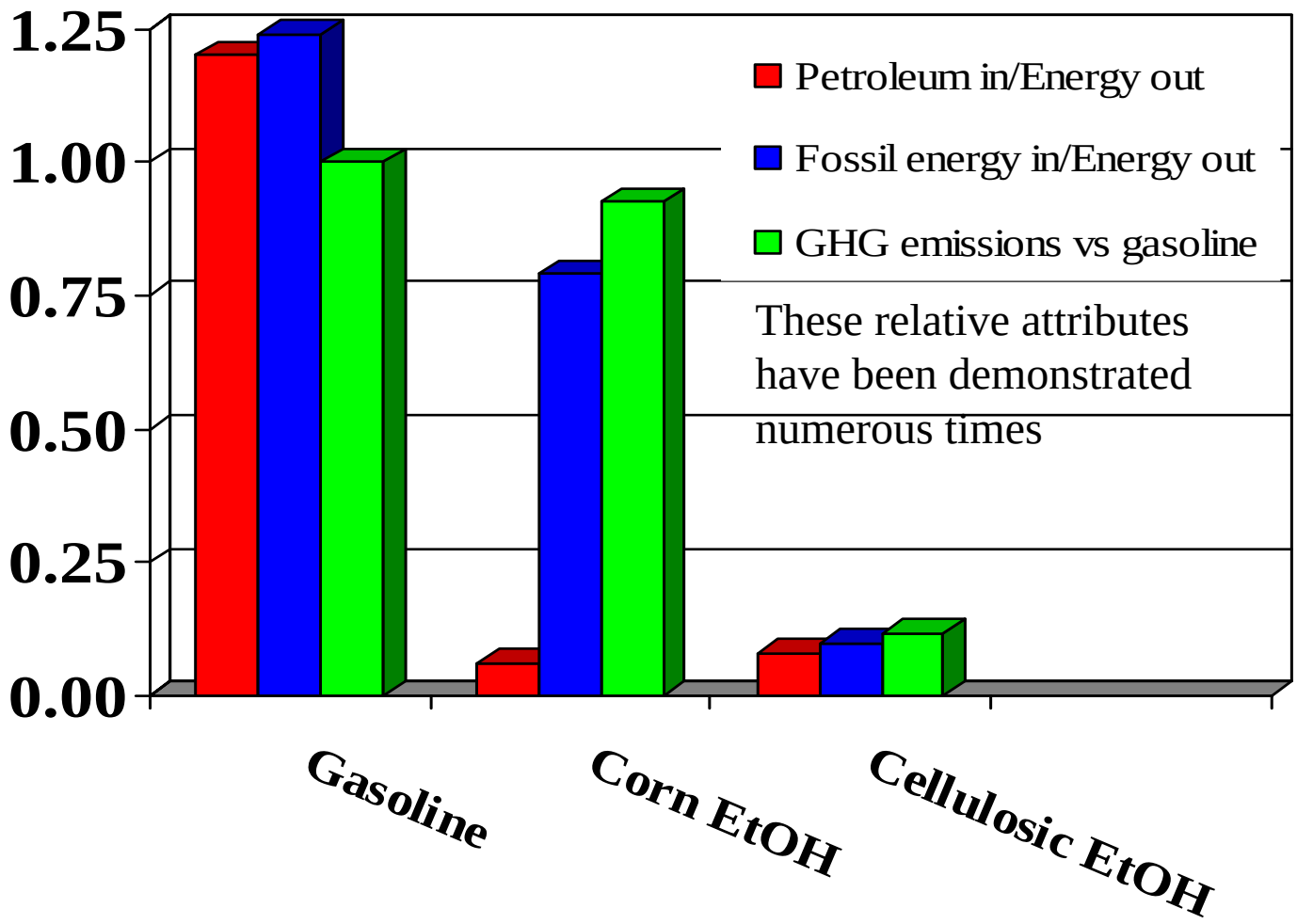
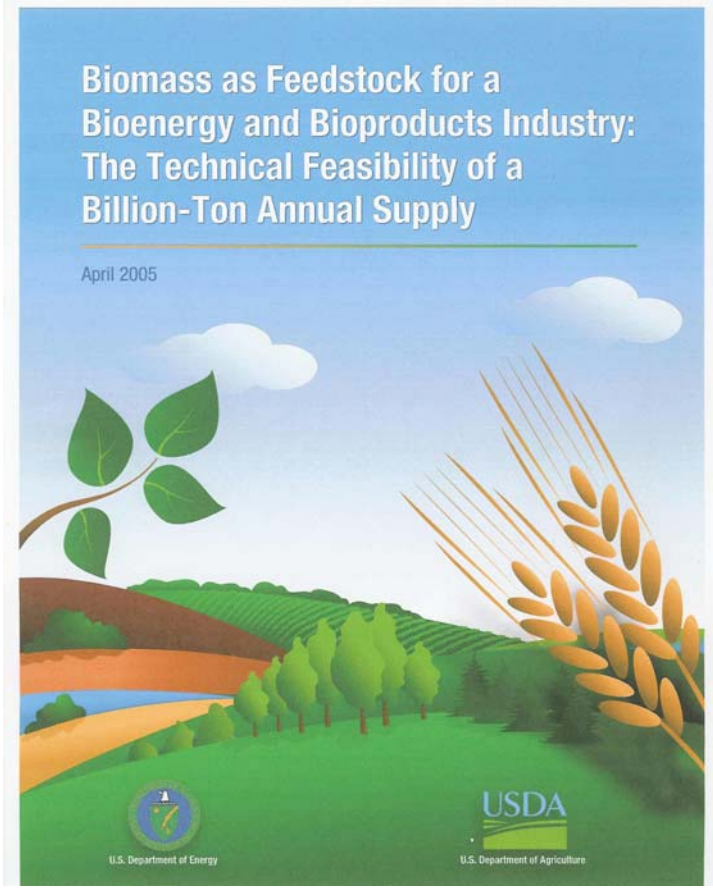


Billion Ton Supply of Cellulosic Biomass

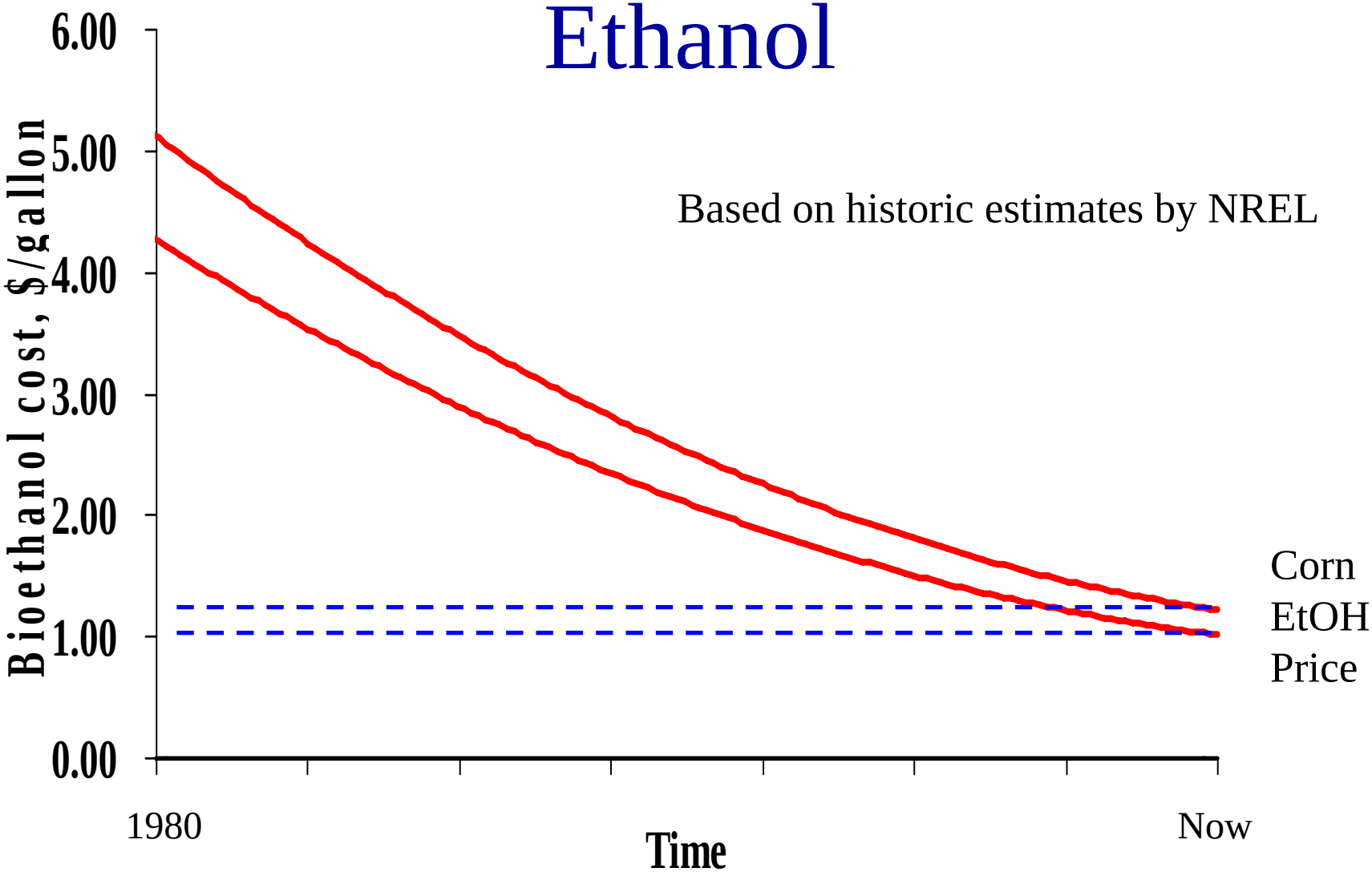
- DOE and USDA recently estimated 1.3 billion tons of cellulosic biomass could be available
- Includes 368 million dry tons from forests and 998 million dry tons from agriculture



Benefits of Cellulosic Ethanol Technology

- Environmental
  - Little if any net carbon dioxide emissions
  - Solid waste disposal
  - Low impact biomass crops
  - Can improve air quality
- Economic
  - Abundant, inexpensive, domestic feedstock
  - Low cost potential without subsidies
  - Agricultural and rural manufacturing employment
  - Provides synergies for emergence of biorefining
- Energy
  - Secure resource available for most countries

Significant Progress in Enzyme Based Technology for Cellulosic Ethanol



Key to Advances To Date in Cellulosic Ethanol Technology

- Overcoming the recalcitrance of cellulosics
  - Improved pretreatment to increase yields from hemicellulose and cellulose
  - Improved cellulase enzymes to increase rates from cellulose, reduce enzyme use
  - Integrated systems to improve rates, yields, concentrations of ethanol (SSF)
- Overcoming the diversity of sugars
  - Recombinant organisms ferment all five sugars to ethanol at high yields

Overall Status of Cellulosic Ethanol

- Operating costs are low
- Technology is ready to be commercialized
- Capital costs are high
- The cost of capital is high – particularly for new technologies
- The technology is not proven at large scale
- Ethanol is a commodity product with low returns
- Challenges are to improve ability to predict performance to support first uses and to advance technologies to reduce costs

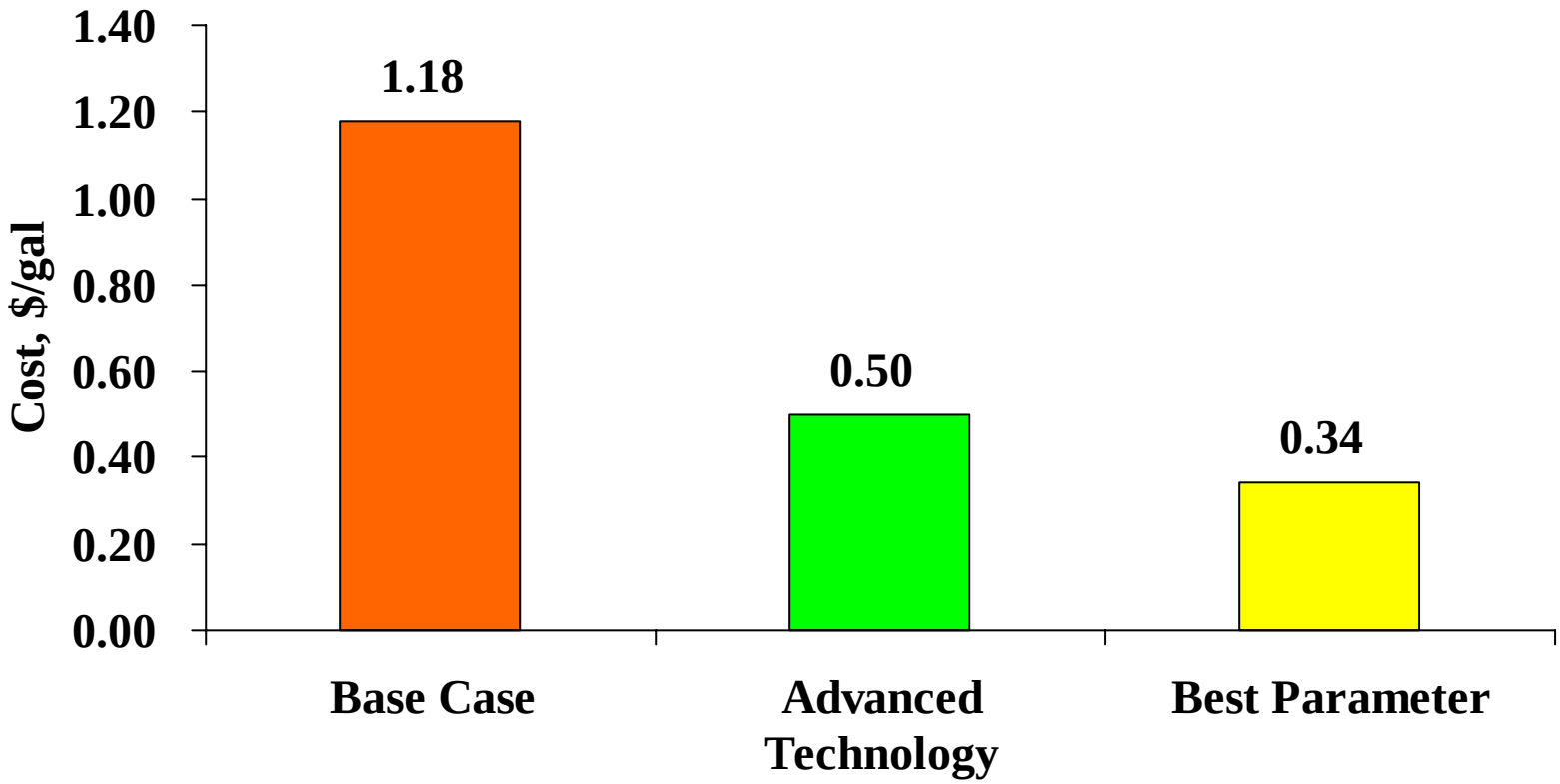
Reducing Processing Costs

- Biomass is a low cost abundant feedstock that is competitive in price with petroleum
- The challenge is to reduce the processing costs to be competitive with fossil derived products without need for subsidies
- Biotechnology offers potential for lower cost processing
- Lower costs will facilitate commercial use by improving return on investment

Advancing Cellulosic Ethanol Technology

- In paper with Lee Lynd of Dartmouth and Rick Elander of NREL Considered three scenarios
  - NREL“current” technology
  - Advanced technology - judged to have most likely features for mature technology
  - Best parameter technology - represents ultimate potential for R&D driven advances

Projected Cellulosic Ethanol Costs



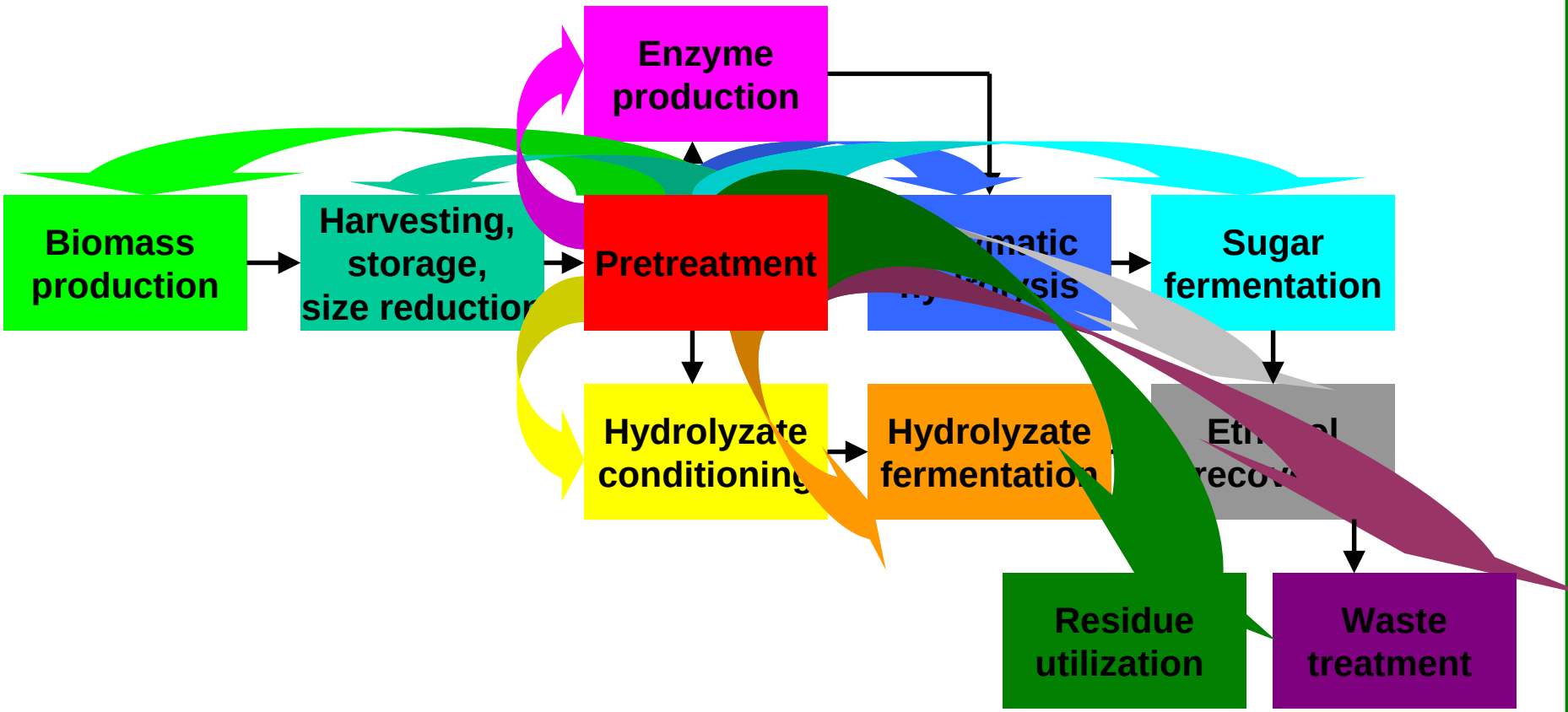
Implications for R&D: Advancing Technology

- Cost of ethanol production has potential to be competitive without tax incentives
- Achieving competitiveness requires advanced process configurations for
  - Pretreatment
  - Biological processing
- Key is to focus on advanced technology configurations to overcome the recalcitrance of biomass

Biological Processing of Biomass

- Biological processing of cellulosic biomass to ethanol and other products offers the potential of high yields vital to economic success
- Biological processing can take advantage of the continuing advances in biotechnology to dramatically improve technology and reduce costs
- In response to recent petroleum price hikes, new initiatives seek to support major research efforts to reengineer plants and biological processes for more efficient conversion of plants into fuels, e.g.
  - $500 million over 10 years for BP Energy Biosciences Institute
  - $250 million over 5 years for 2 DOE Bioenergy Research Centers

Central Role and Pervasive Impact of Pretreatment for Biological Processing



Opportunity/Impact for Advances

Operation	Enhance yield	Reduce costs
Biomass production	M	M
Harvesting/Storage	L	M
Size reduction	L	L
Pretreatment	H	H
Enzyme production	H	M
Enzymatic hydrolysis	H	H
Glucose fermentation	L	M
Hydrolyzate conditioning	H	H
Hydrolyzate fermentation	L	M
Ethanol recovery	L	M
Residue utilization	M	H
Waste treatment	L	L

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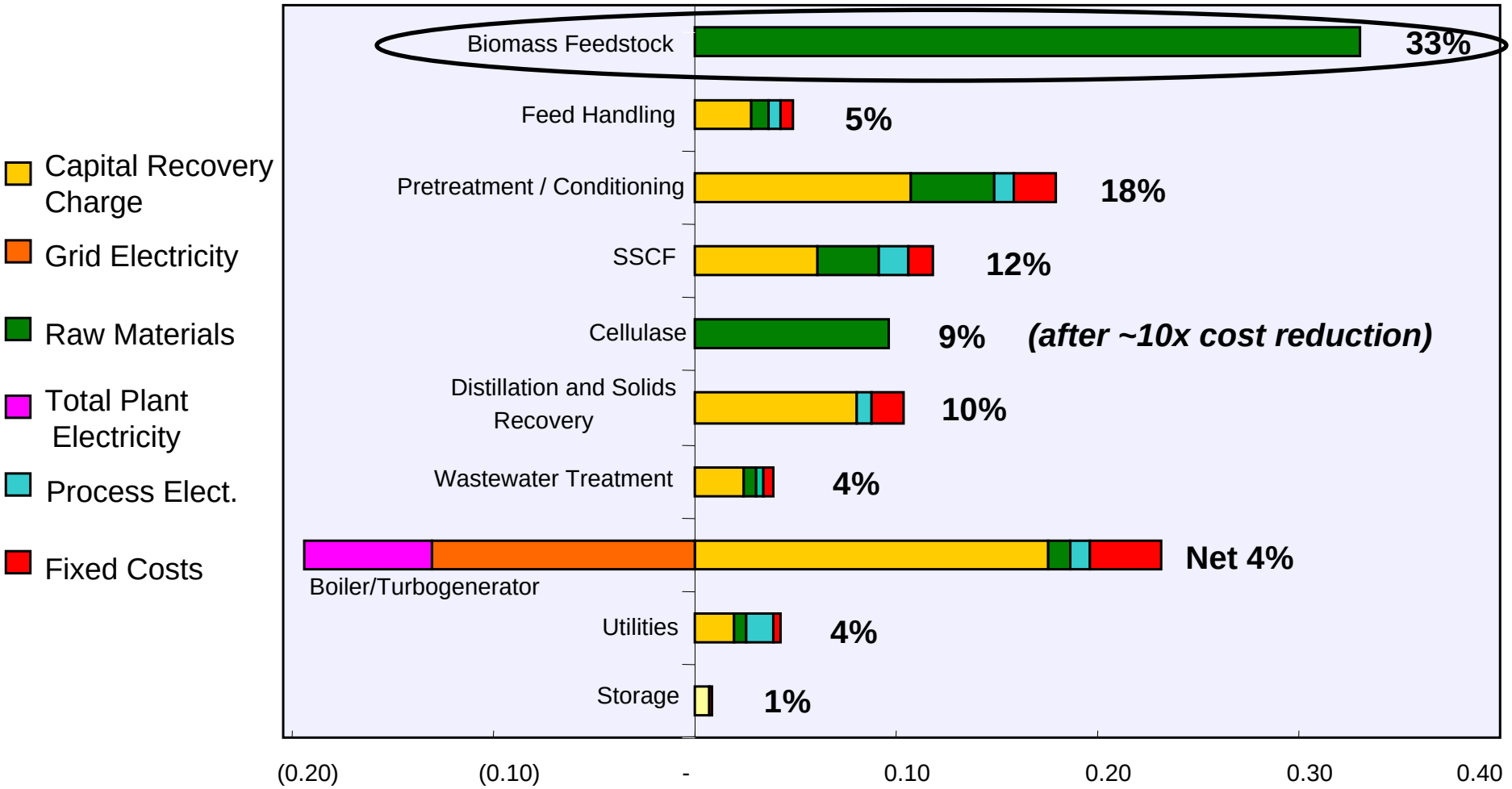
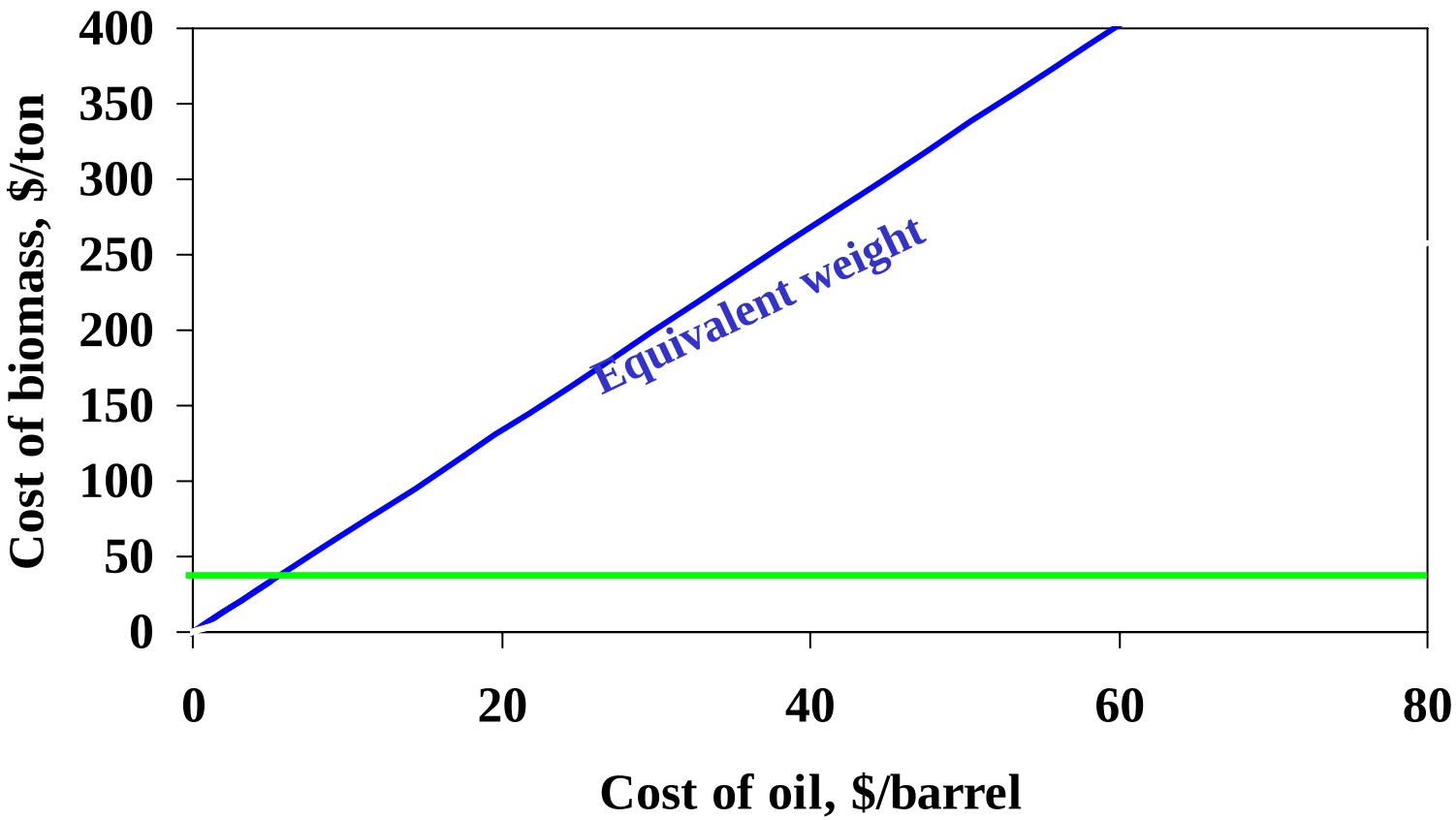
Key Processing Cost Elements



Cost of Cellulosic Biomass vs Petroleum



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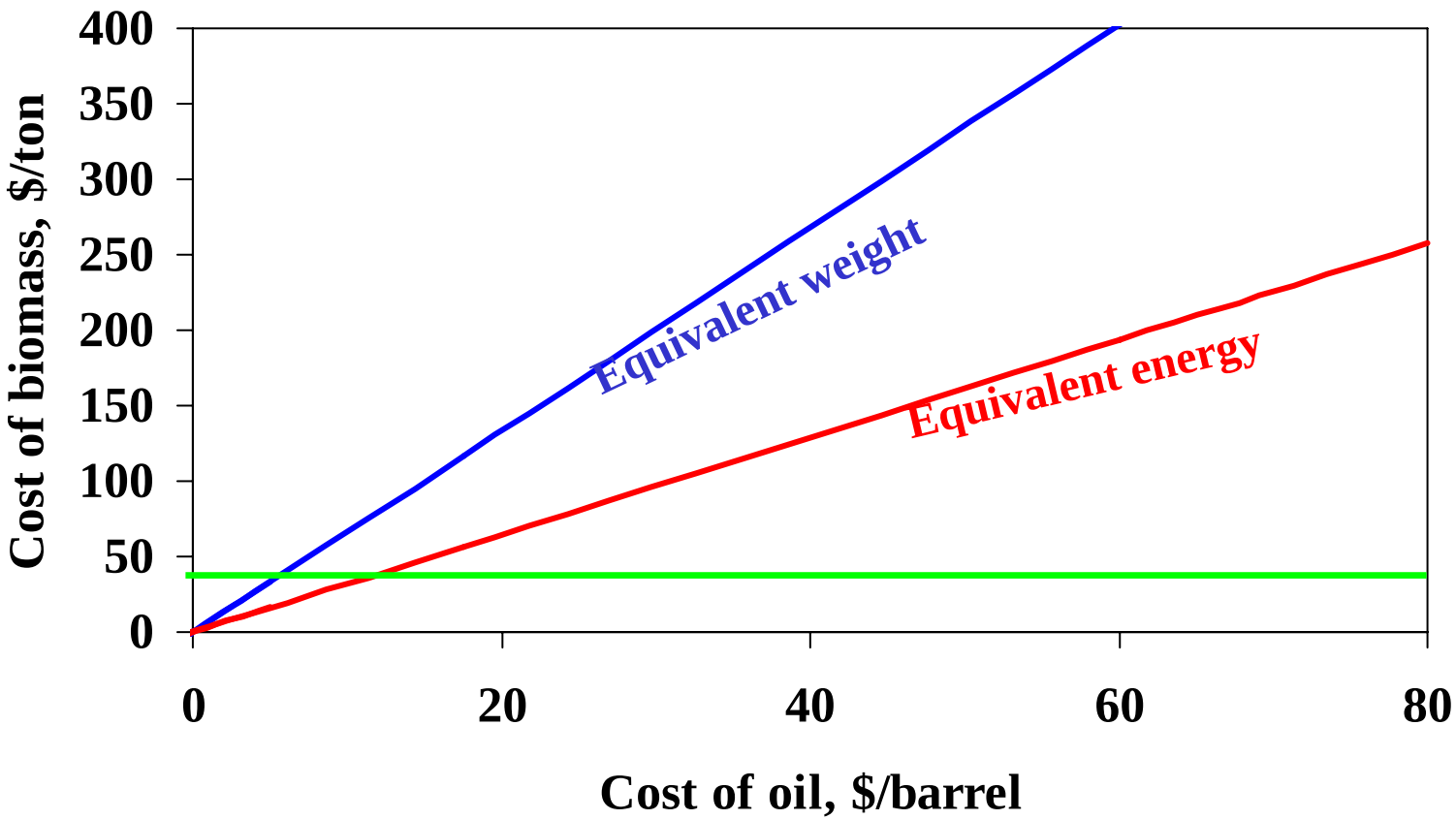

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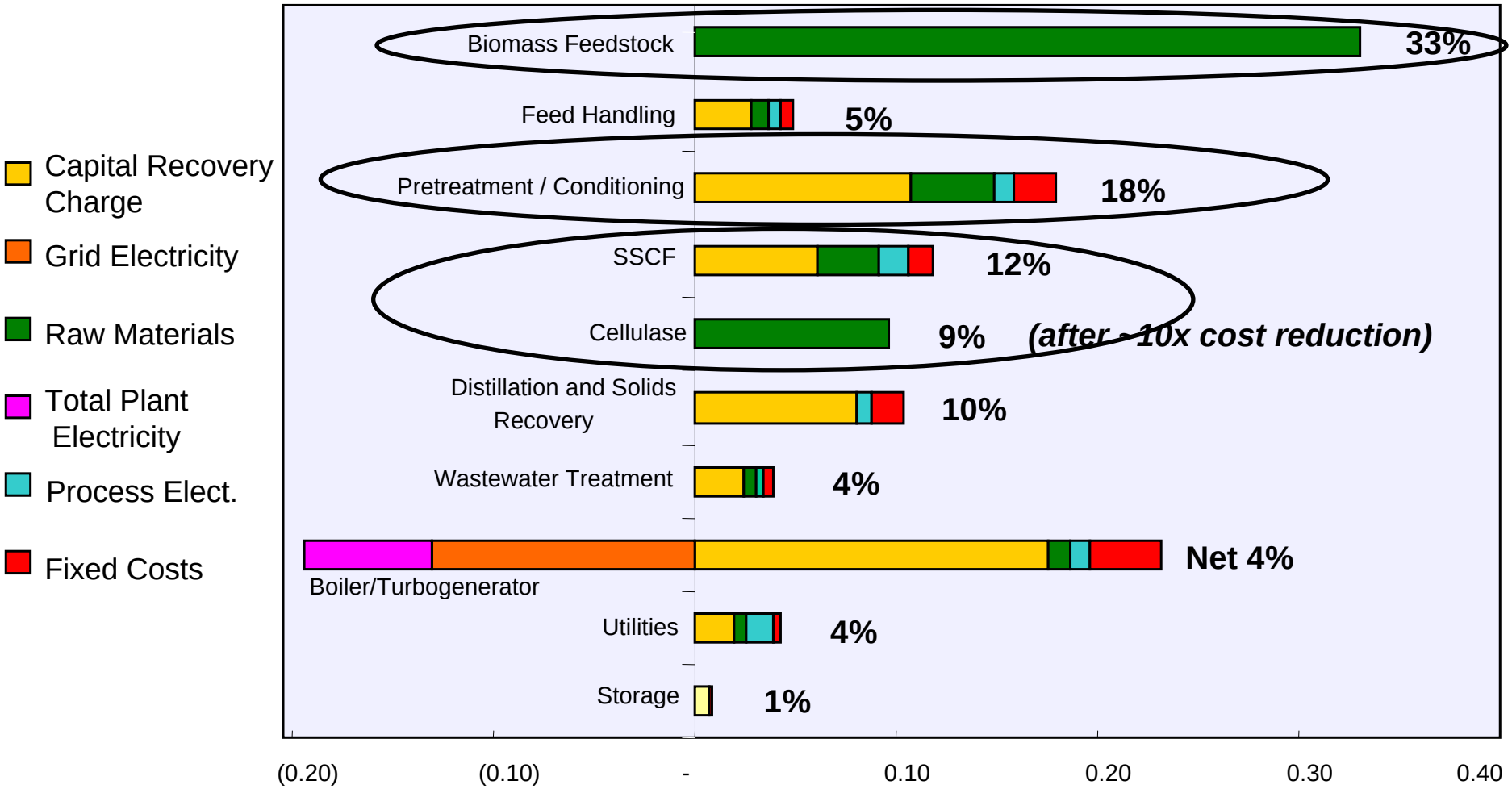

Importance of Pretreatment

- Although significant, feedstock costs are low relative to petroleum
- In addition, feedstock costs are a very low fraction of final costs compared to other commodity products
- Pretreatment is the most costly process step: the only process step more expensive than pretreatment is no pretreatment
  - Low yields without pretreatment drive up all other costs more than amount saved
  - Conversely enhancing yields via improved pretreatment would reduce all other unit costs
- Need to reduce pretreatment costs to be competitive

Current and Goal Yields

Parameter	Current	Goal
Feedstock storage	97% +	99%
Xylan to xylose	63%*	95%
Pretreatment solids loading	30%*	50%
Pretreatment materials construction	Hastelloy	CS equiv'lt
Pretreatment pressure	100 psig	<30 psig
Conditioning	87-88%*	99%
Xylose to ethanol	95%	95%
Minor sugars to ethanol	92%	95%
Cellulase loading	15 FPU/g	5 FPU/g
Product recovery	99%	99%

* from NREL

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* from NREL

Key Pretreatment Needs

- Achieve high yields for multiple crops, sites, ages, harvest times
- Achieve very high total sugar yields
- Reduce chemical use for pretreatment and post treatment
- Lower cost of materials of construction
  - Less corrosive chemicals
  - Lower pressure
- Eliminate hydrolyzate conditioning and its losses
- Reduce enzyme (cellulase and hemicellulase) use
- Minimize heat and power requirements
- Achieve high sugar concentrations

Closing Thoughts

- Biology provides a powerful platform for low cost fuels and chemicals from biomass
  - Can benefit both crop production and conversion systems
- The resistance of one biological system (cellulosic biomass) to the other (biological conversion) requires a pretreatment interface
- Advanced pretreatment systems are critical to enhancing yields and lowering costs
- Not all pretreatments are equally effective on all feedstocks
- Focus on 2 biologies - plants and biological conversion - without integrating their interface – pretreatment – will not significantly lower costs

Acknowledgments

The following sponsors are gratefully acknowledged for making our research possible:

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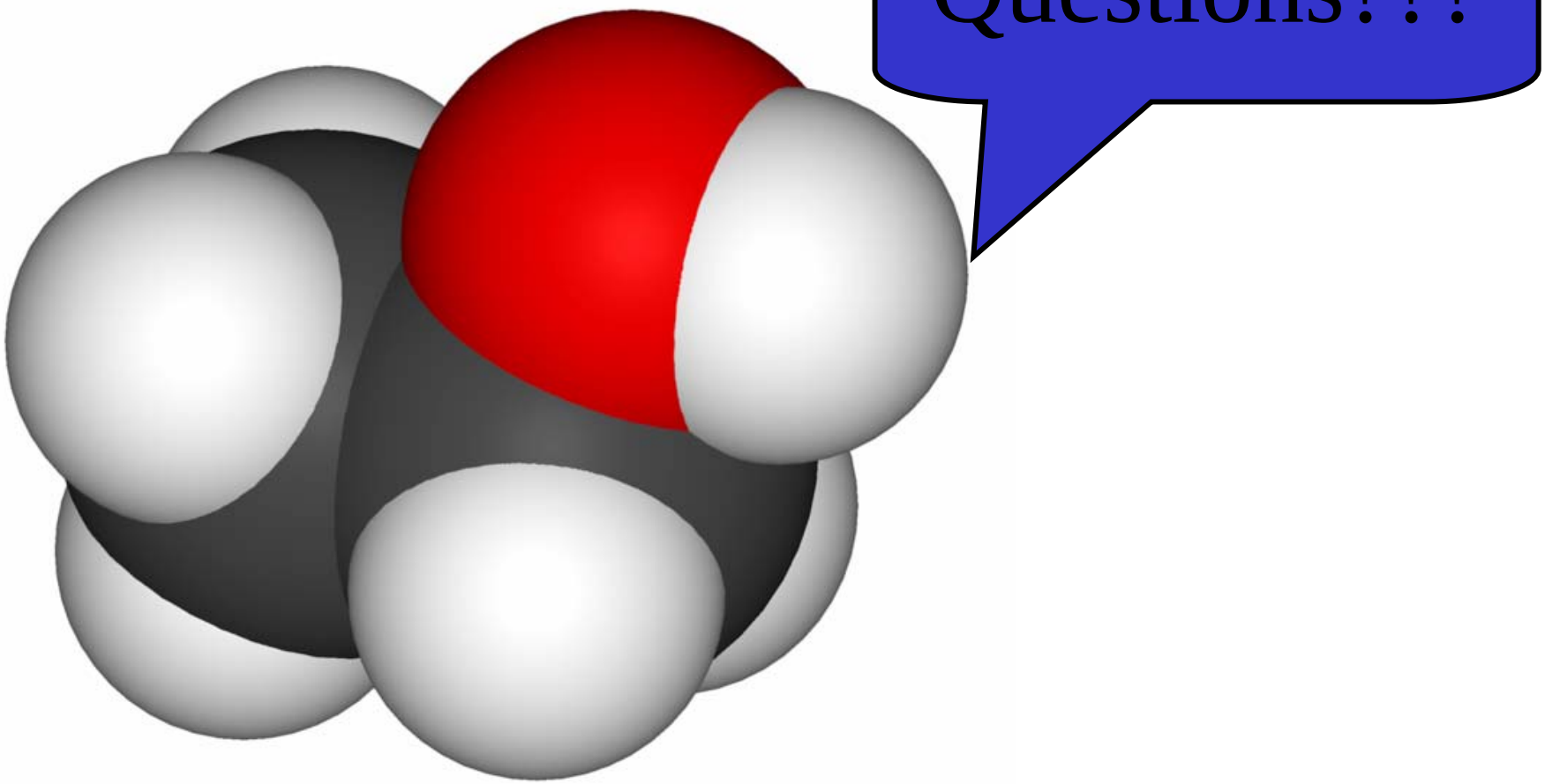
- US Department of Energy Office of Fuels Development, contract DE-FC36-01GO11075 (10/2001-9/2002)
- US Department of Energy Office of the Biomass Program, contract DE-FG36-04GO14017
- Natural Resources Canada for supporting partners
- Thayer School of Engineering at Dartmouth College

Insanity is doing what you always have always been doing and expecting different results


Questions???