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Current Status of Cellulosic Biofuels in the U.S.

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Presented at:
Biorefinery Integration Workshop
Osnabrueck, Germany
January 29, 2009

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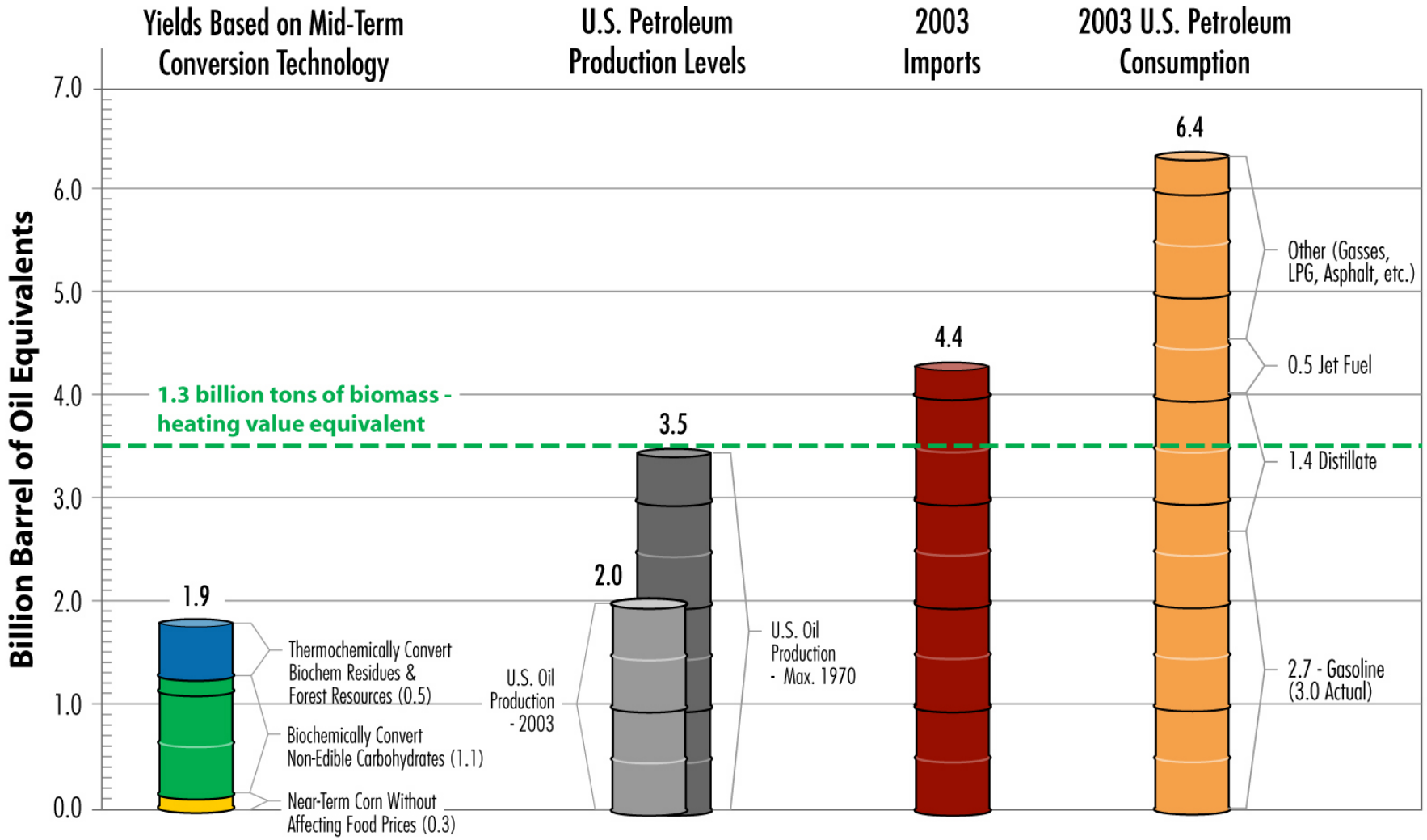
Significance of the 1.3 Billion Ton Biomass Scenario



Based on ORNL & USDA Resource Assessment Study by Perlach et.al. (April 2005)
http://www.eere.energy.gov/biomass/pdfs/final_billionton_vision_report2.pdf

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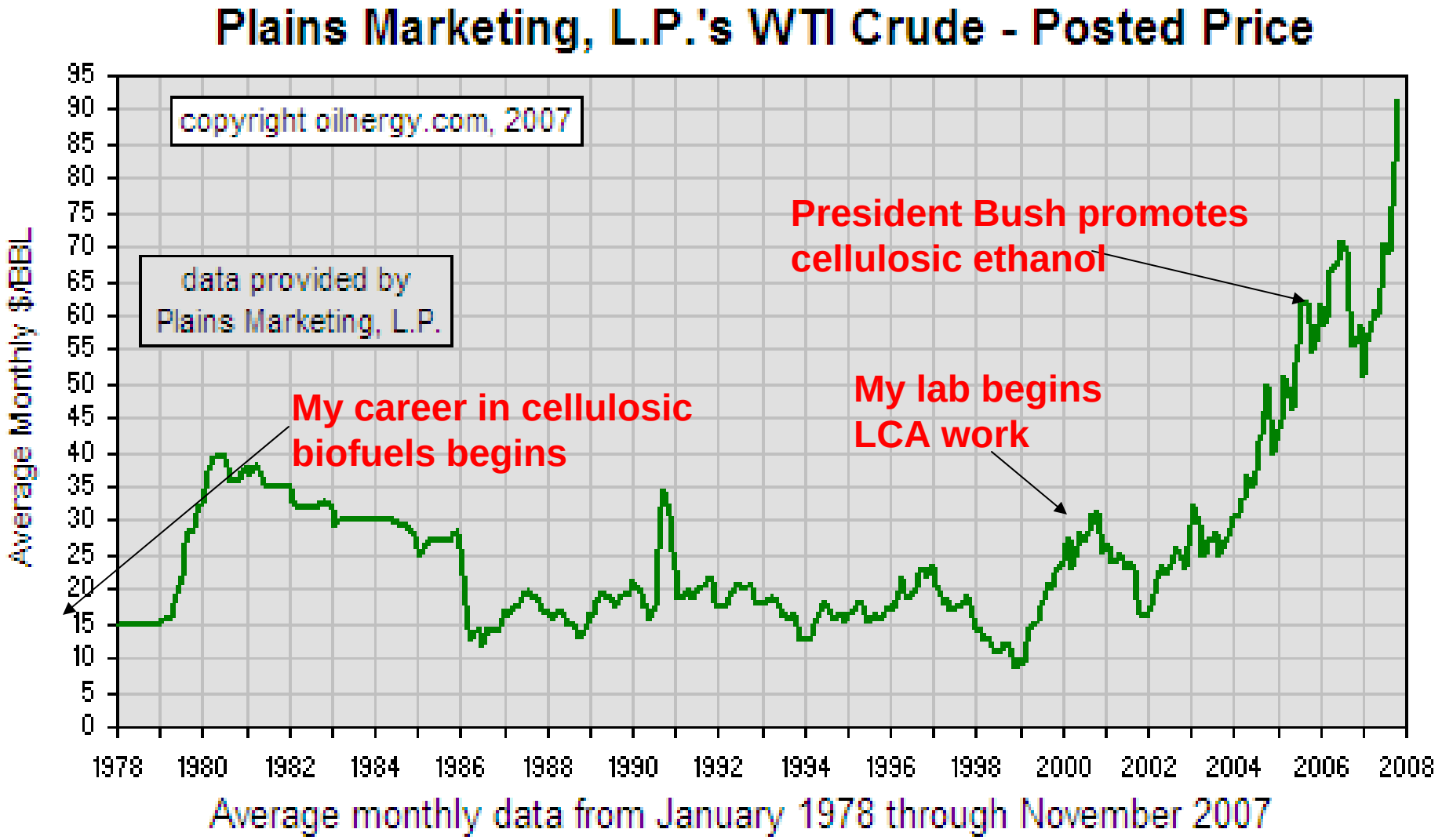
1978 – 2007 CRUDE OIL PRICES

IT PAYS TO BE PATIENT (OR STUBBORN)



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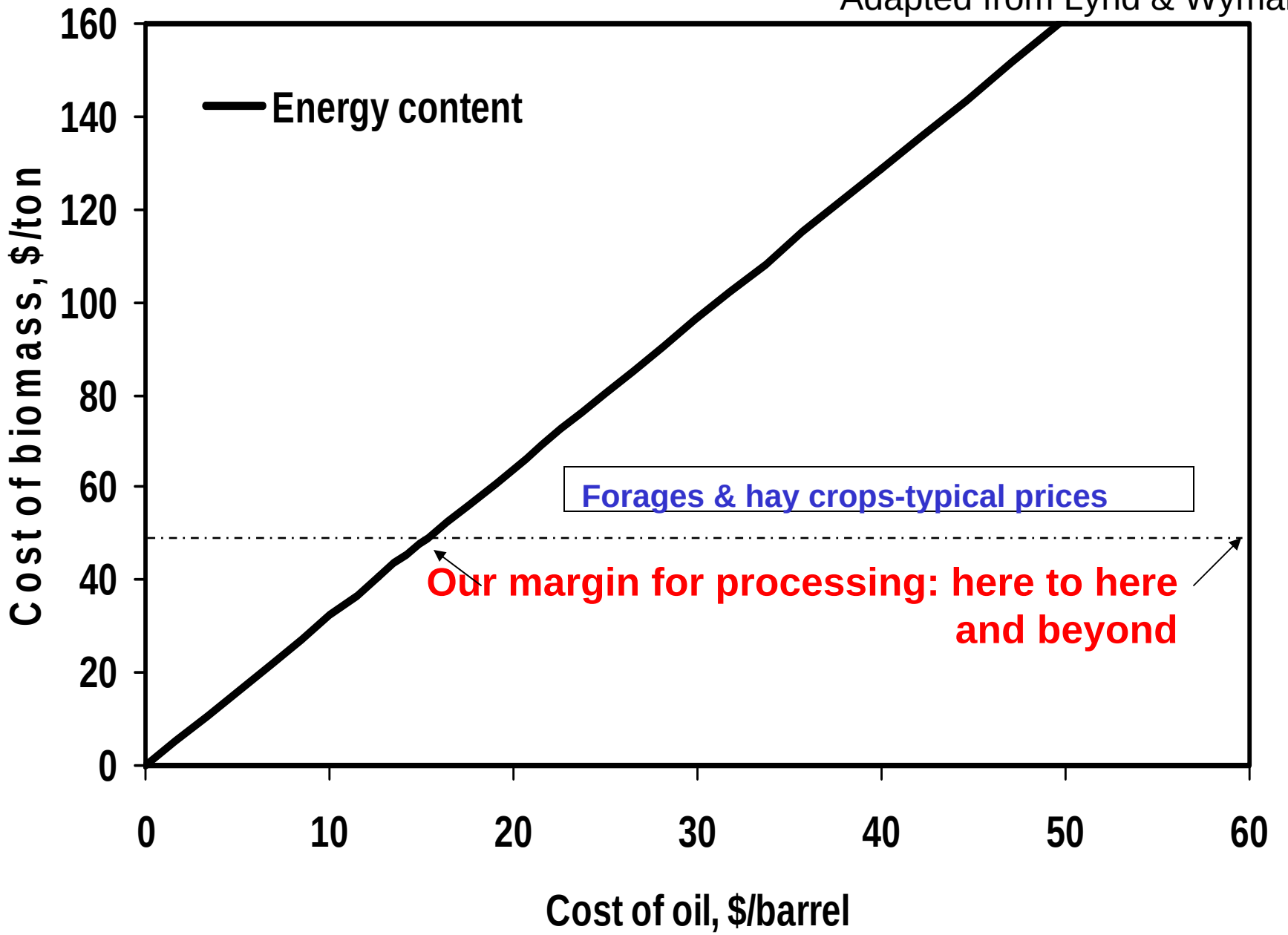
Adapted from Lynd & Wyman



Cellulosics are the cheapest carbon source in a carbon-constrained world

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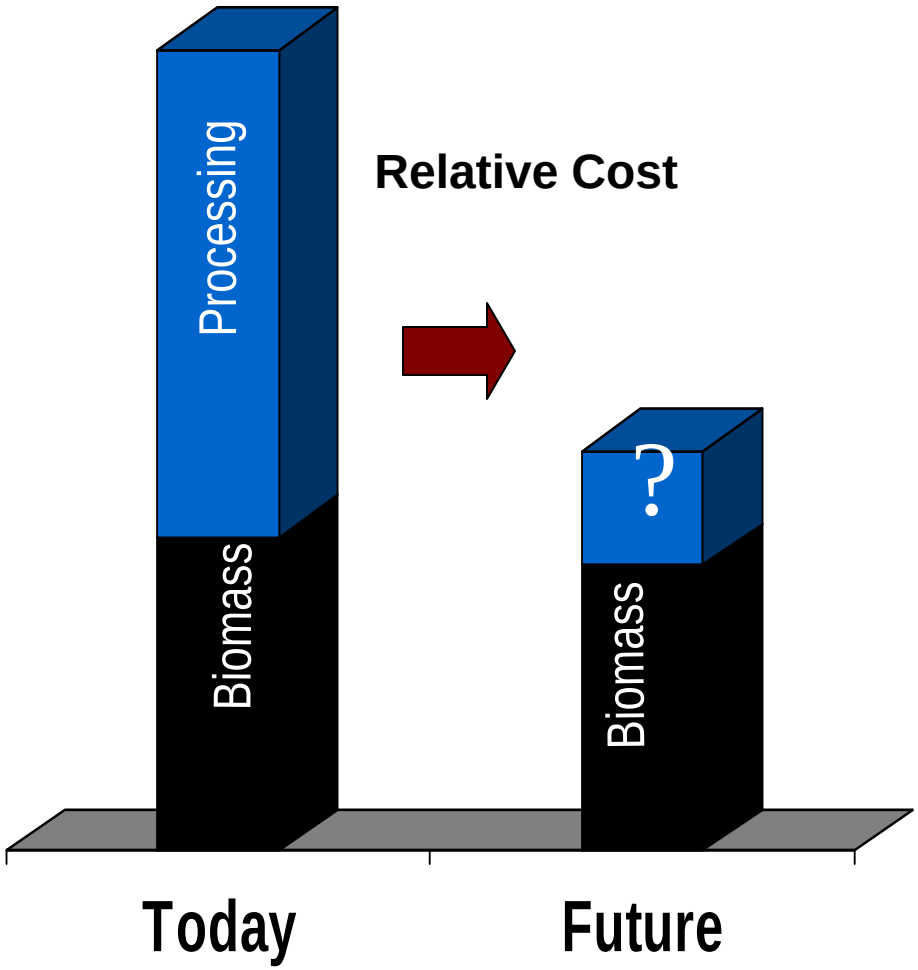
Impact of Processing Improvements: The Future of Biomass Conversion



Adapted from J. Stoppert, 2005

- Processing is dominant cost of cellulosic biofuels today
- Cellulosic raw material costs should be stable or decrease
- Processing costs dominated by pretreatment, enzymes & fermentation
- Biomass processing costs will decrease: deserves high priority to make it happen sooner rather than later
- Much more attractive future
  - Domestically produced fuels
  - Environmental improvements
  - Rural/regional economic development

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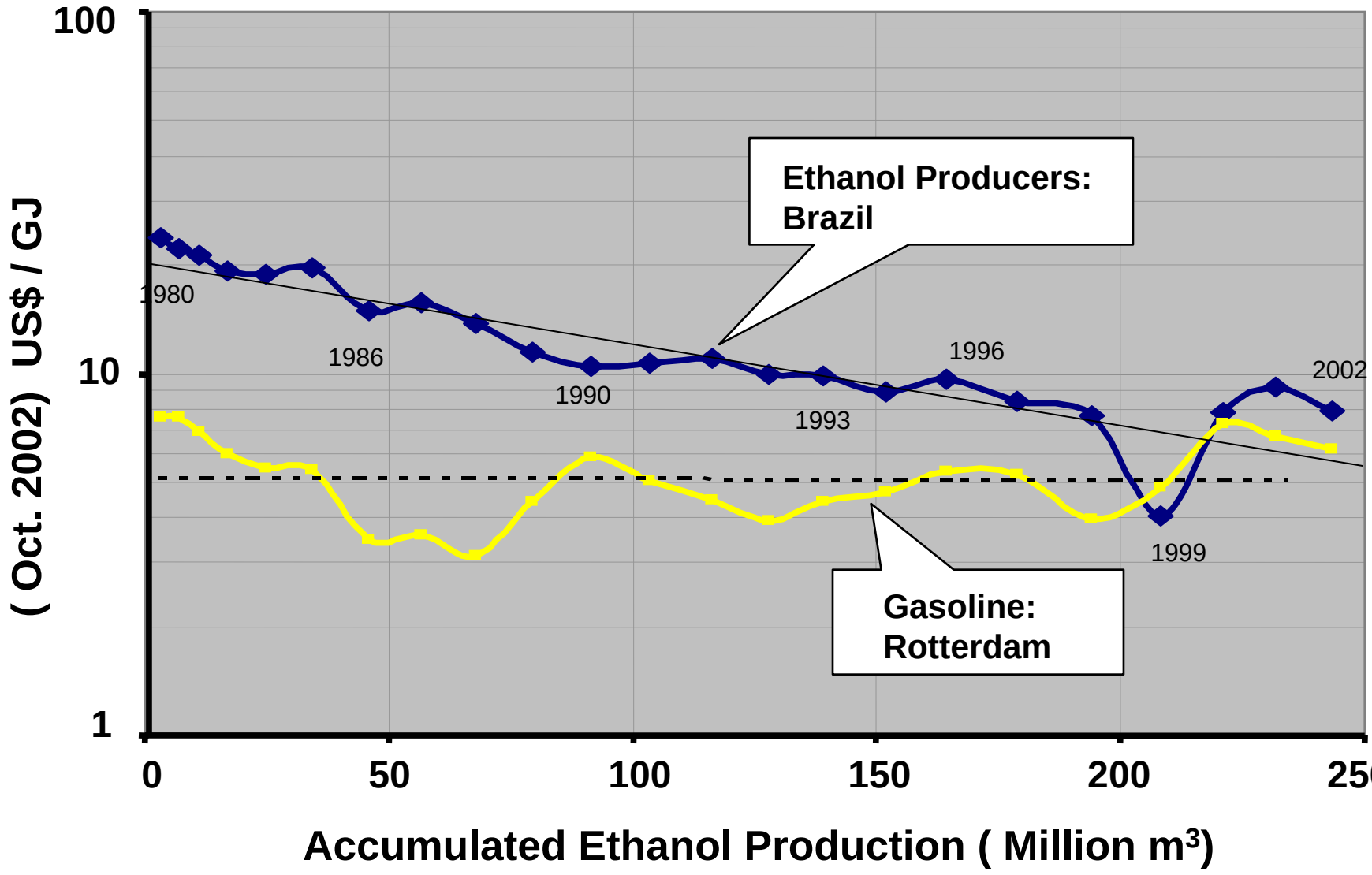
Learning Curve: Sugar Ethanol Production Cost

(J. Goldemberg, 2003)



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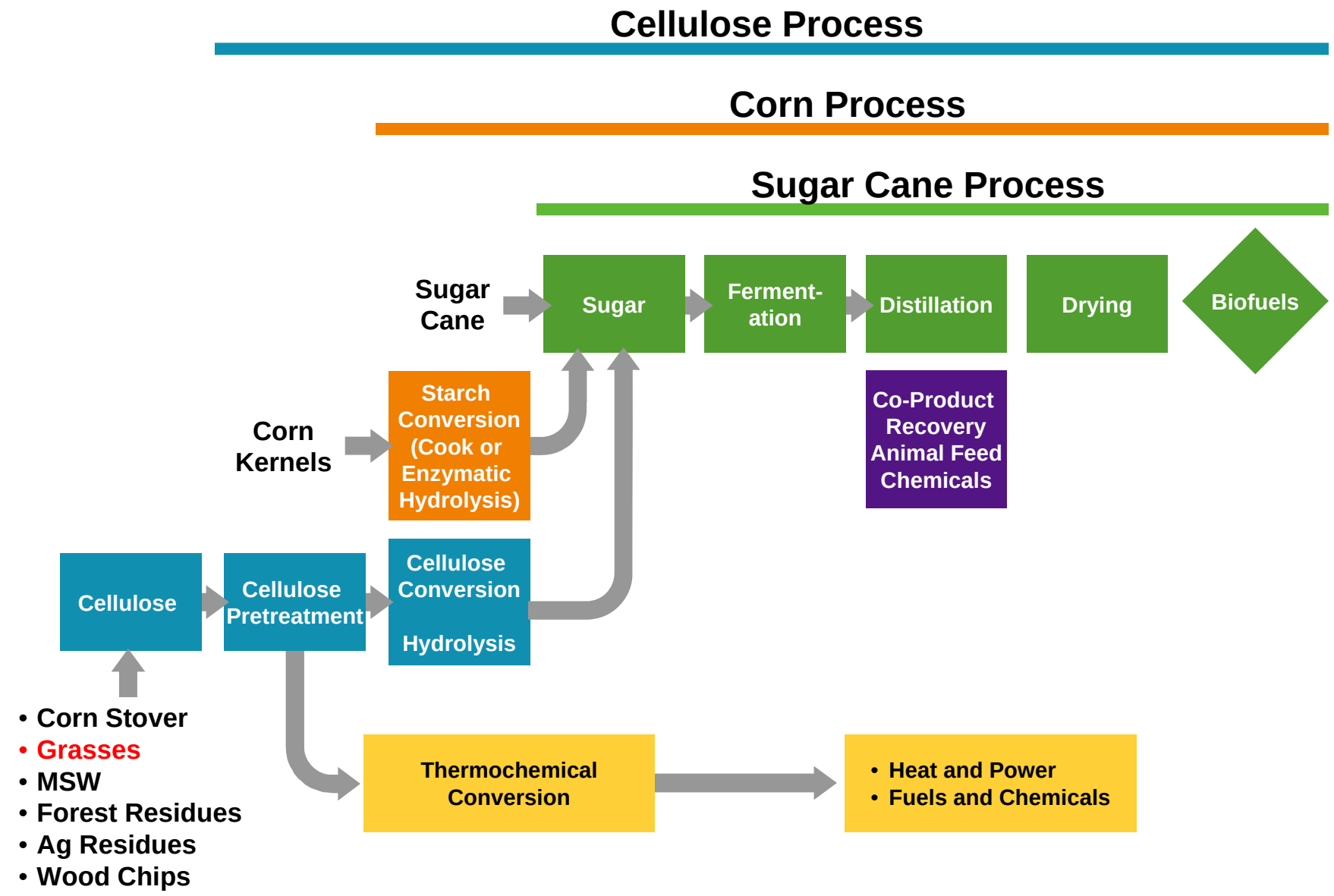
Biofuel Production Flowchart



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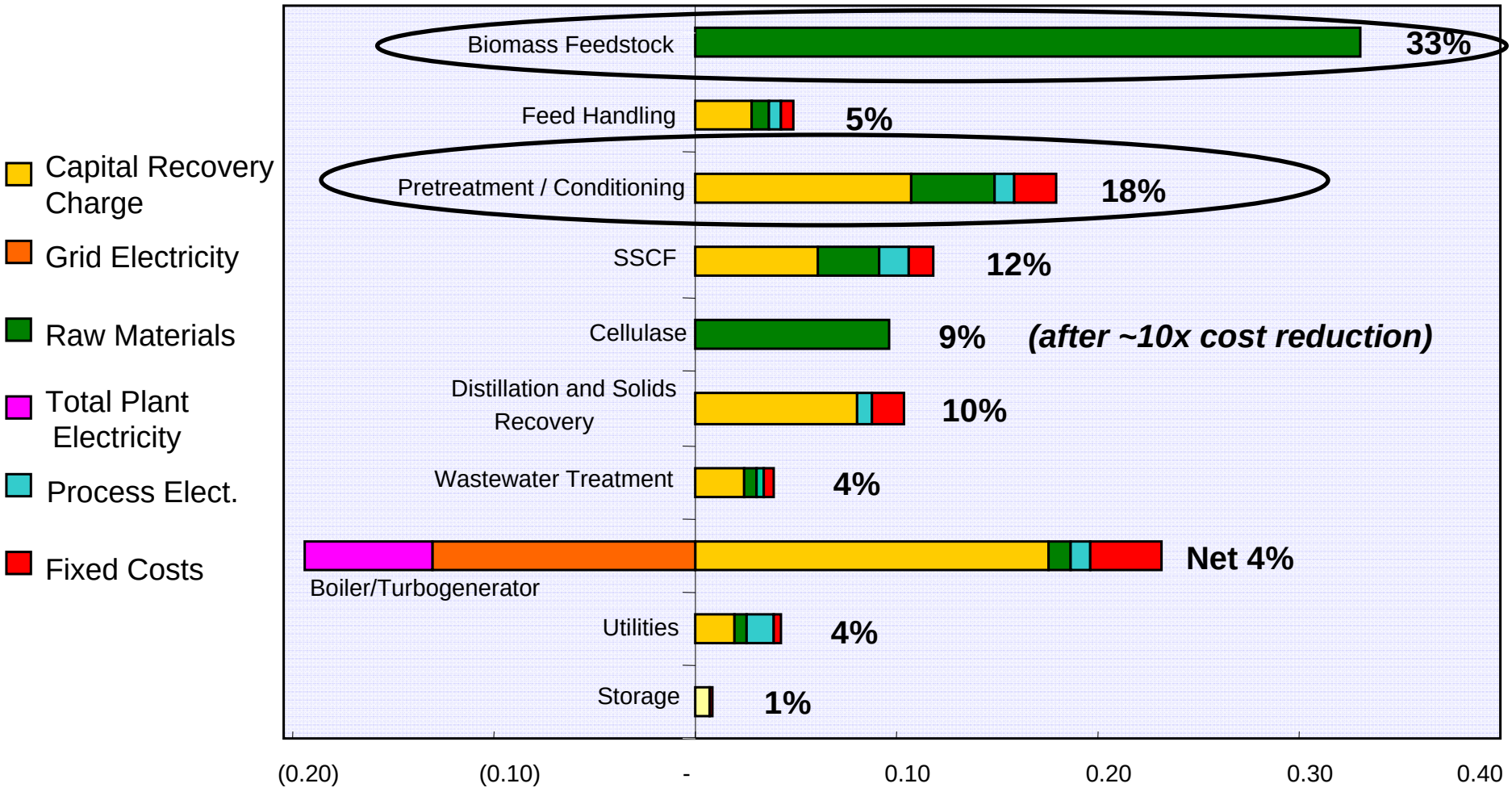
Key Processing Cost Elements



Biomass Refining CAFI

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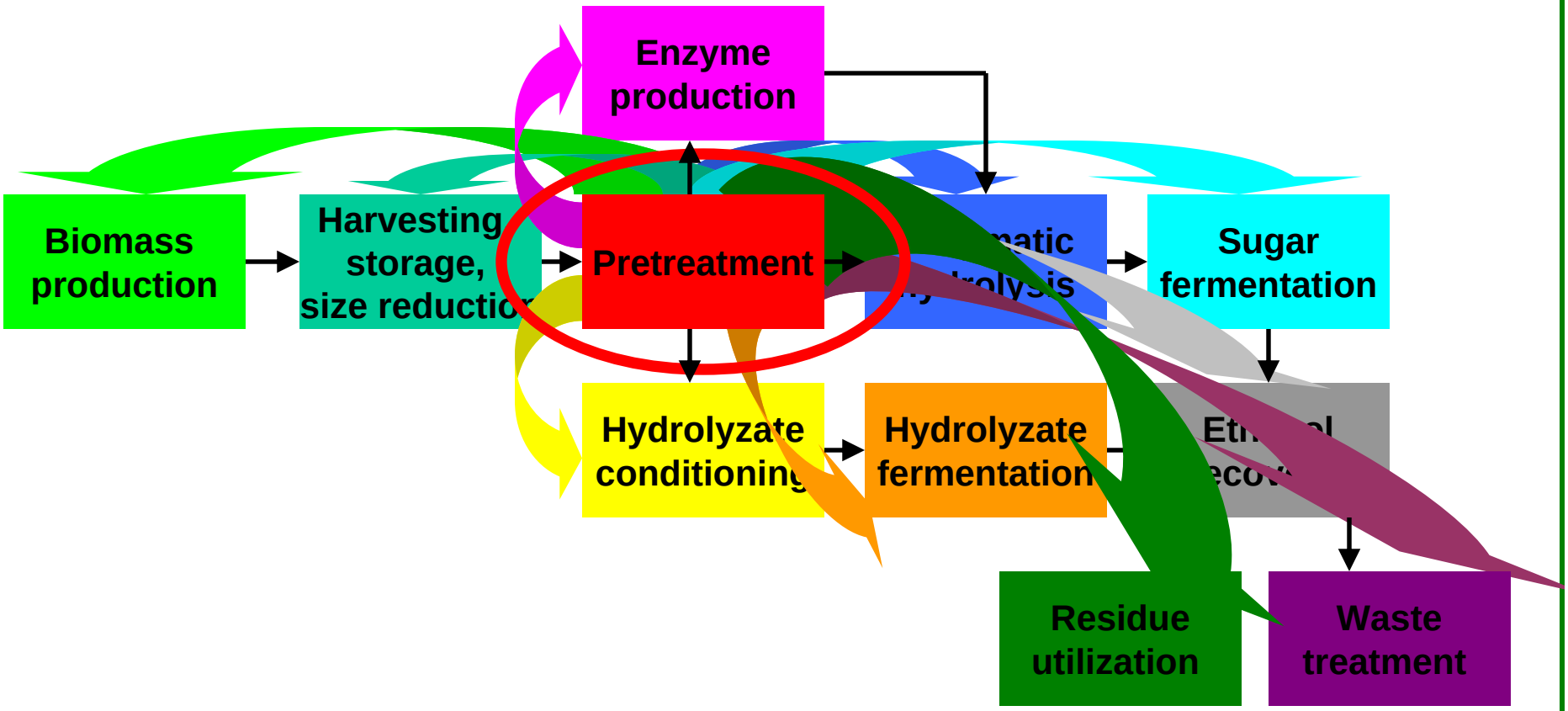
Central Role and Pervasive Impact of Pretreatment for Biological Processing



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Status of U. S. R&D Support for Cellulosic Biofuels: Overview

- Federal process development support: DOE programs (all cost shared)
  - Large demonstration plants $375 million (in place)
  - Processing demonstrations $200 million (in place)
  - Newer integrated technologies $200 million (request just issued)
- Supply chain projects: USDA
  - Much smaller, more politically directed $100 million
  - No clear summary available of projects funded
- Private support
  - Venture capital approx. $1-2 billion inc. Khosla Ventures
  - Corporate R&D support
    - Energy Biosciences Institute (BP-- $500 million)
    - Conoco Phillips ($30 million at Iowa State Univ.)
    - Chevron and a few others (~$50 million scattered around)
    - General Motors: Coskata and Mascoma (unknown investment)
- Federal research support
  - 3 Bioenergy Research Centers $400 million over 5 years, renew?
  - A host of smaller programs

The Future is Now for Cellulose Ethanol

- **Abengoa BioEnergy**
  - 11.4 million gallon plant in Kansas using stover, wheat straw, milo stubble, switchgrass, and other feedstocks.
- **Alico, Inc.**
  - A 13 million gallon plant in LaBelle, Fl using gasification technology to process yard, wood, and vegetative wastes and eventually energycane.

Withdrawn

- **Bluefire Ethanol**
  - A 19 million gallon plant located in southern California sited on a landfill to process sorted green waste and wood waste with acid.
- **Broin Companies**
  - A 125 mgy biorefinery planned in Emmetsburg, Iowa to process, corn, corn fiber and corn stover. 25% of the feedstock will be cellulose.
- **Iogen Biorefinery Partners**
  - 18 mgy ethanol facility in southeastern Idaho using enzymatic conversion technology to process wheat straw.

Withdrawn

- **Range Fuels**
  - 40 million gallon plant in Georgia using thermal conversion technology to process wood waste and wood-based energy crops.

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Status of U. S. R&D Support for Cellulosic Biofuels: Overview

- Private support
  - Venture capital approx. $1-2 billion inc. Khosla Ventures
    - Mascoma: CBP organisms with steam explosion
    - Range Fuels: thermoconversion
    - Coskata: syngas fermentation
  - Corporate R&D support
    - Energy Biosciences Institute (BP-- $500 million) basic biology mostly, has an energy crops program
    - Conoco Phillips ($30 million at Iowa State Univ.) thermoconversion
    - Chevron and a few others (~$50 million scattered around)
    - General Motors: Coskata and Mascoma (unknown investment size)
- Federal research support: 3 Bioenergy Research Centers $400 million over 5 years, renew?
  - BESC- Oak Ridge Nat. Lab overcoming recalcitrance
  - JBEI- Berkeley Lab mostly synthetic biology
  - GLBRC- only university led center- inc. sustainability, broad focus
  - A host of smaller programs
- Disappointing level of support for pretreatments
  - Mostly enzymes and new bugs

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Status of U. S. R&D Support for Cellulosic Biofuels: Overview

- Integrated processing systems
  - KL Energy (extrusion technology)
  - Mascoma (CBP organisms)
  - Novozymes/Genencor (enzyme development)
  - ICM (plant design) withdrawn
  - Coskata (syngas fermentation)
  - Ceres (energy crop development)
  - Abengoa (enzymes plus steam explosion)
  - Several others… memory fails me.
- New technology $200 million just issued
  - We are competing for one of these, stay tuned
- Waking up to need for supply chain development/integration with biorefinery

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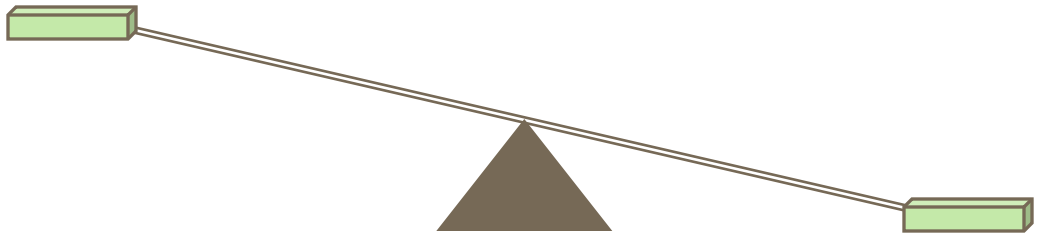
Biofuels: Changing Balance Between Processing and Feedstock

Today



Feedstock

Processing

- Pretreatment
- Enzymes
- Fermentation

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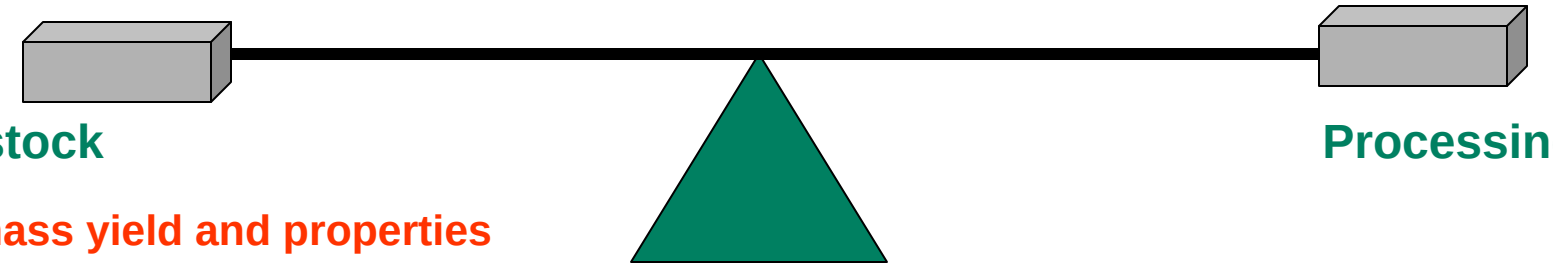
Biofuels: Changing Balance between Processing and Feedstock

Near Future



Feedstock

Processing

- **Biomass yield and properties**
- **Harvest/transport logistics**
- **Sustainability**
- **Rural economic development**
- **Co-products**
- **Many more!**

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Technical Advances Required for Cellulosic Biofuels

1. Key enabling advance: Effective, economical pretreatment to increase accessibility/digestibility of cellulose and hemicellulose (60-80% of forages)
2. Later advances: Complete utilization of all biomass components: carbohydrates, lignin, protein, lipids, minerals, pigments, pectin, organic acids, etc.
3. Taken together, these advances will significantly alter how we provide calories & protein to feed animals, particularly ruminant animals.

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We Don't "Grow Food", We Grow Feed

- Three major U.S. crops *alone* (corn, soy, wheat) produce 1300 trillion kcal & 51 trillion grams protein/yr
- Could meet U.S. human demand for protein & calories with 25 million acres of corn (~5% of our cropland)
- *Most U. S. agricultural production (inc. exports) is fed to animals-- i.e., we are meeting <u>their</u> protein/calorie needs from our land resources. Their needs are:*
  - 1040 trillion kcal/yr (6 times human demand)
  - 56.6 trillion gm protein/yr (10 times human demand)
- Thus we can address perceived "food vs. fuel" conflict by providing <u>animal feeds</u> more efficiently, on less land
- Dairy & beef cattle consume more than 70% of all calories and protein fed to livestock
- Cattle are well suited to consume grasses & cellulosic materials—particularly high digestibility grasses

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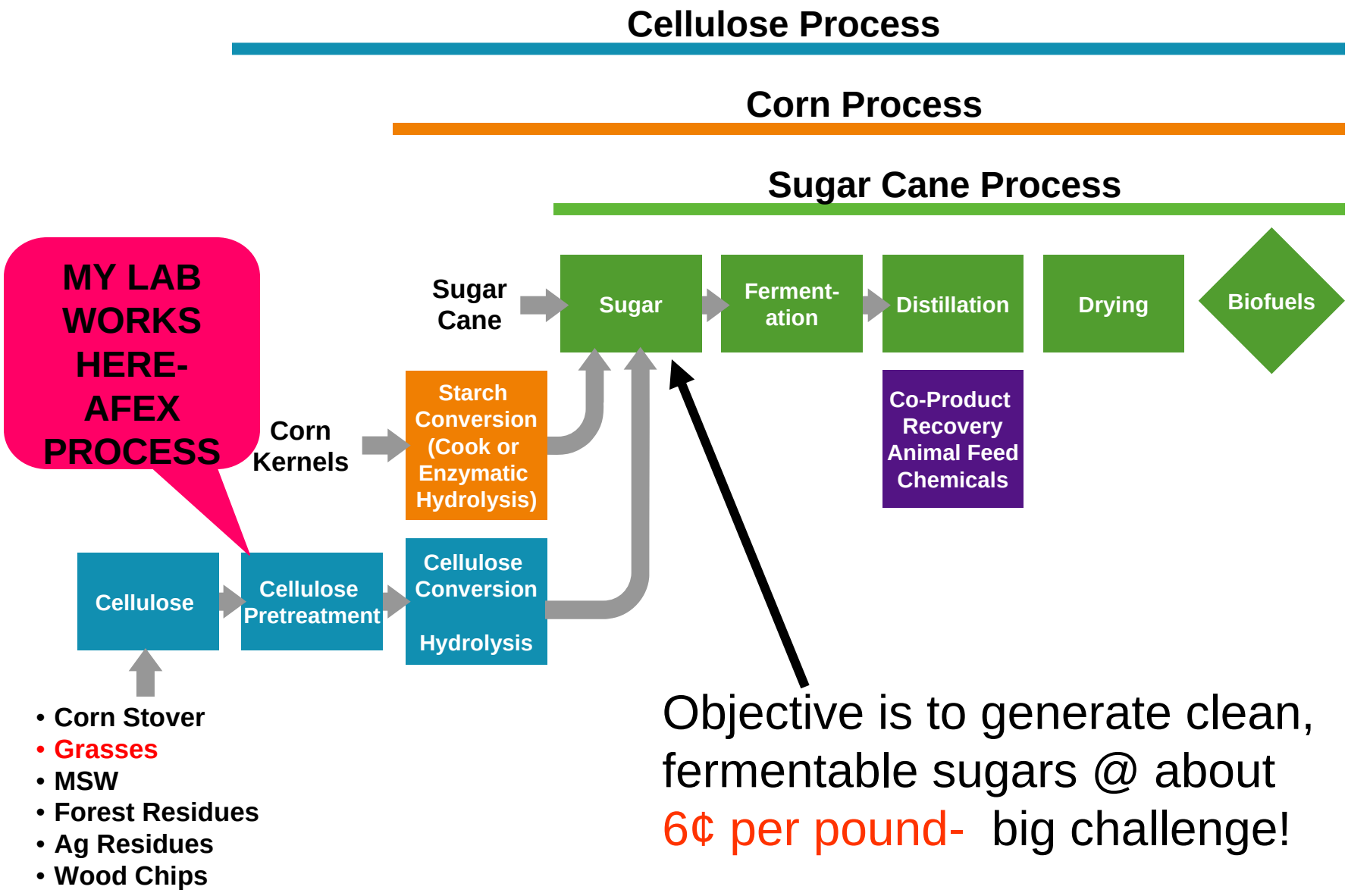
Biofuel Production Flowchart: Sugar Platform



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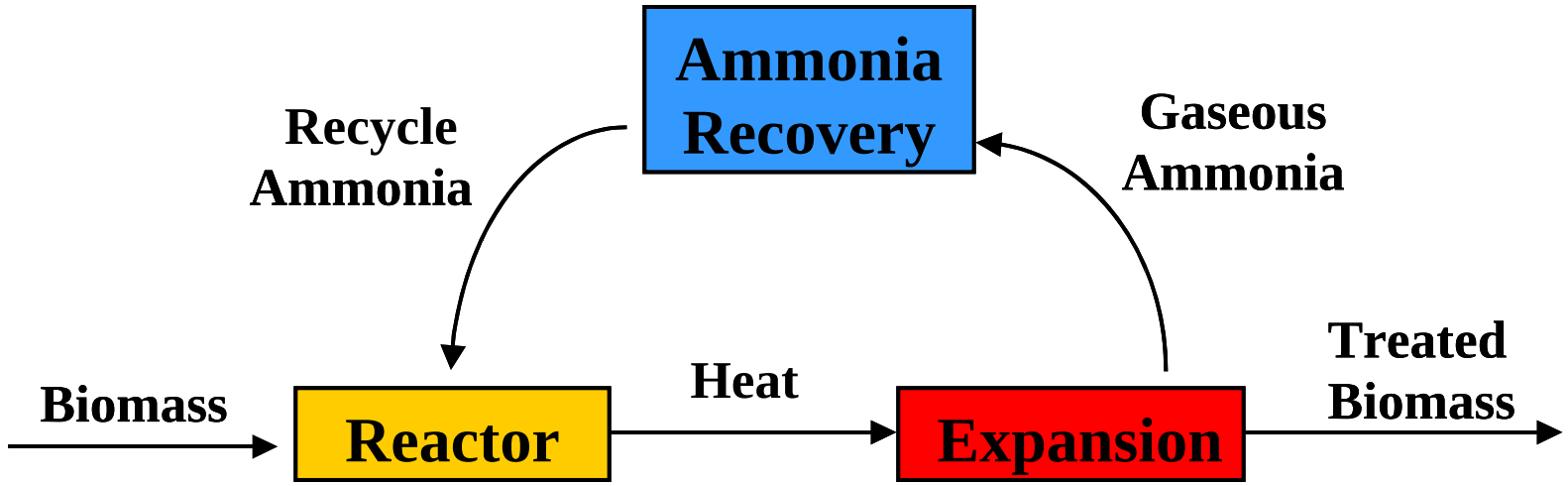
How does AFEX work?



AFEX process description and properties

- hot, concentrated (~15M) ammonia:water mix, short rxn time
- rapid pressure release ends treatment, cools system
- little biomass degradation, high yields, residual ammonia value
- "dry to dry" process—very high concentrations possible
- Typical process conditions
  - Pressure 20-30 atm
  - Temperature 70-140 C
  - Residence time 5-10 minutes
  - Ammonia: dry biomass loading (0.3 -2.0 to 1) (w/w)
  - Water: dry biomass content (0.2 – 2.5 to 1) (w/w)

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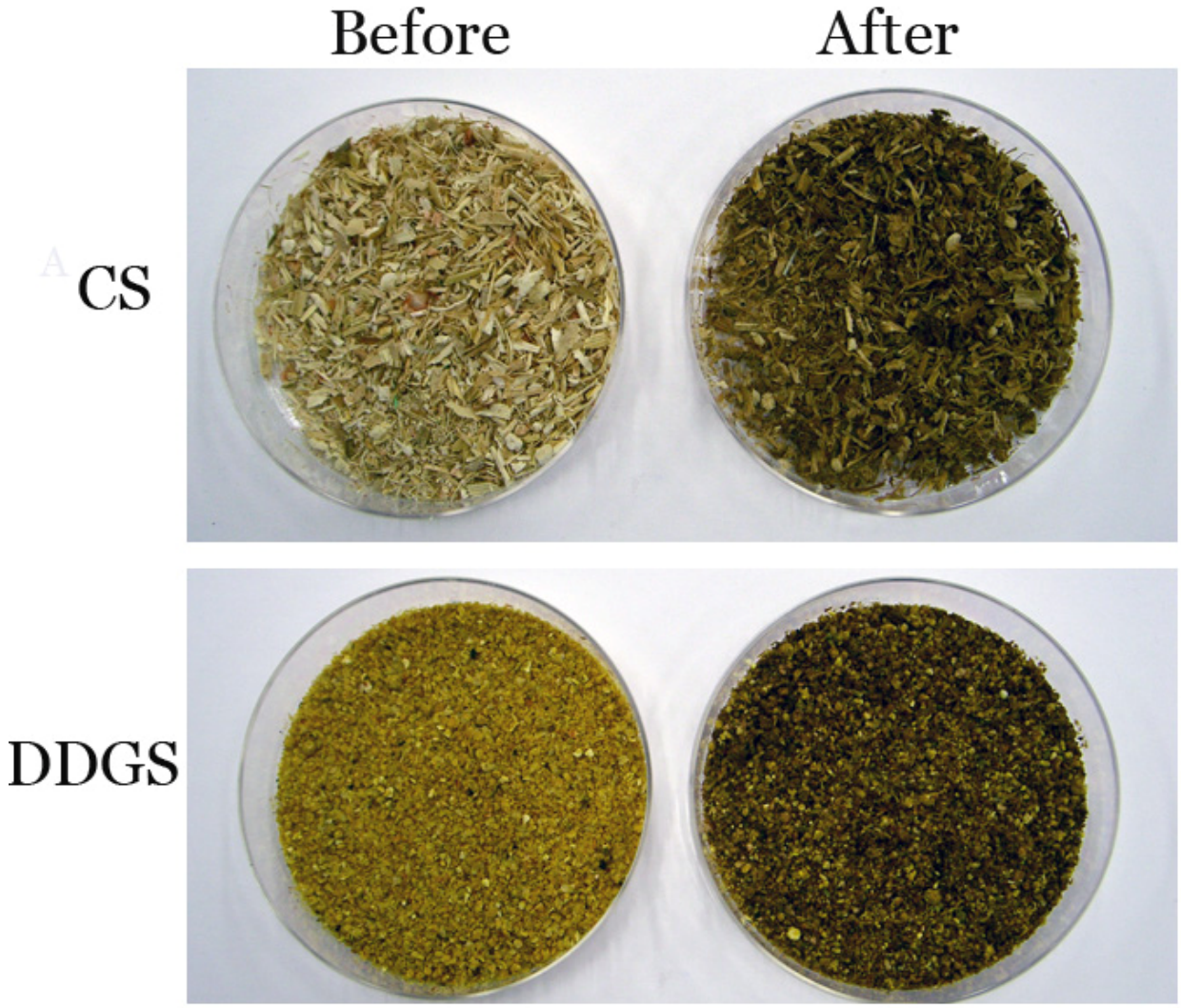
Before and After AFEX



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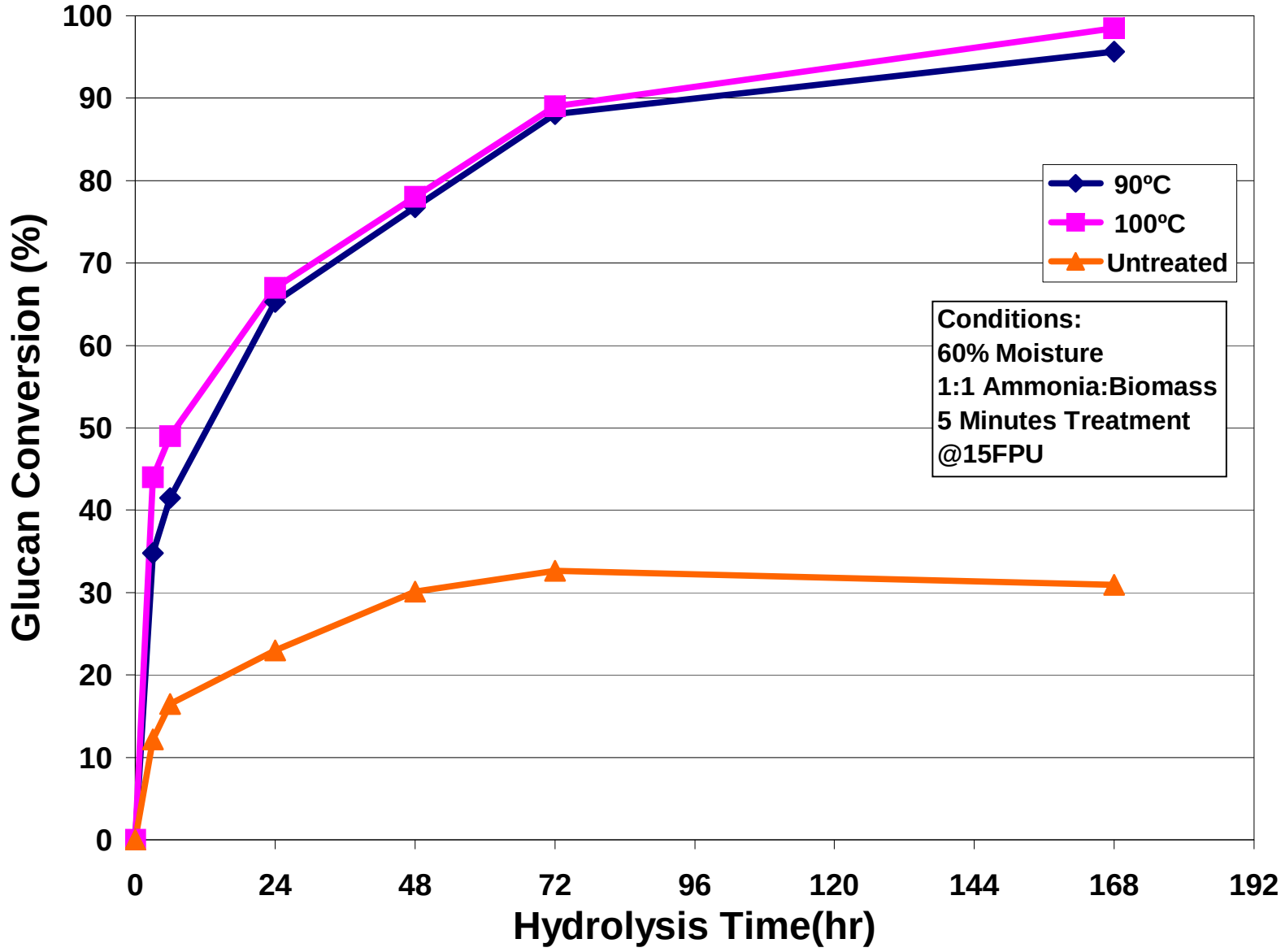
Corn Stover Response to AFEX



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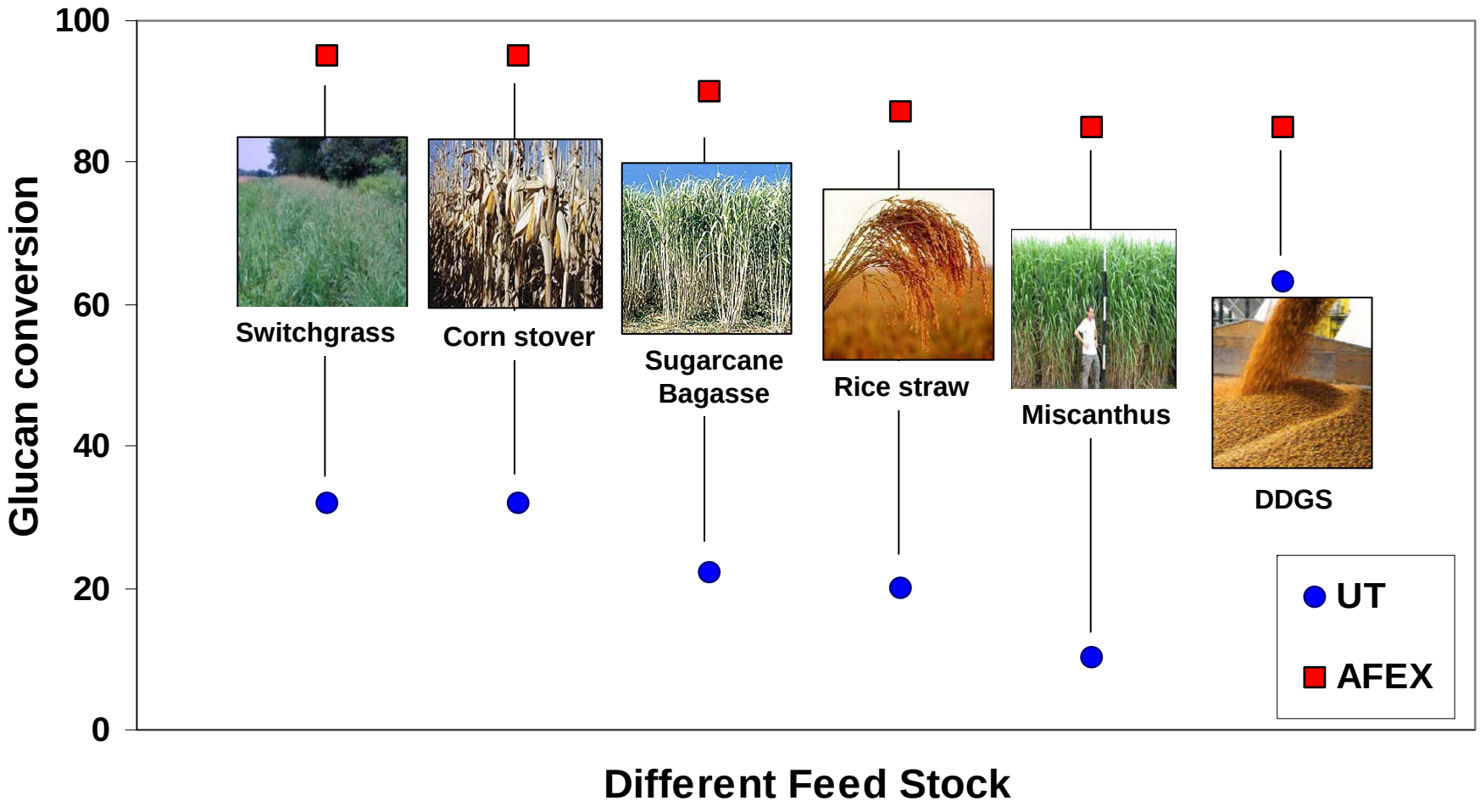
Biomass Conversion for Different Feedstocks Before and After AFEX Pretreatment



Enzymatic hydrolysis: 25 mg of Cellulase and 2.5 mg of xylanase/g of glucan, 50 ^{o}C, for 168h. About 70% xylan conversion achieved for most feedstocks.

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Fed Batch SSF of AFEX Treated and Untreated Corn Stover (15 IU/gm glucan)

AFEX treated stover in fed batch SSF at 24% solids loading

Untreated stover in SSF 24% solids loading

Flows very easily

Doesn't flow worth a dang

Dark appearance is deceptive- caused by autoclaving & media

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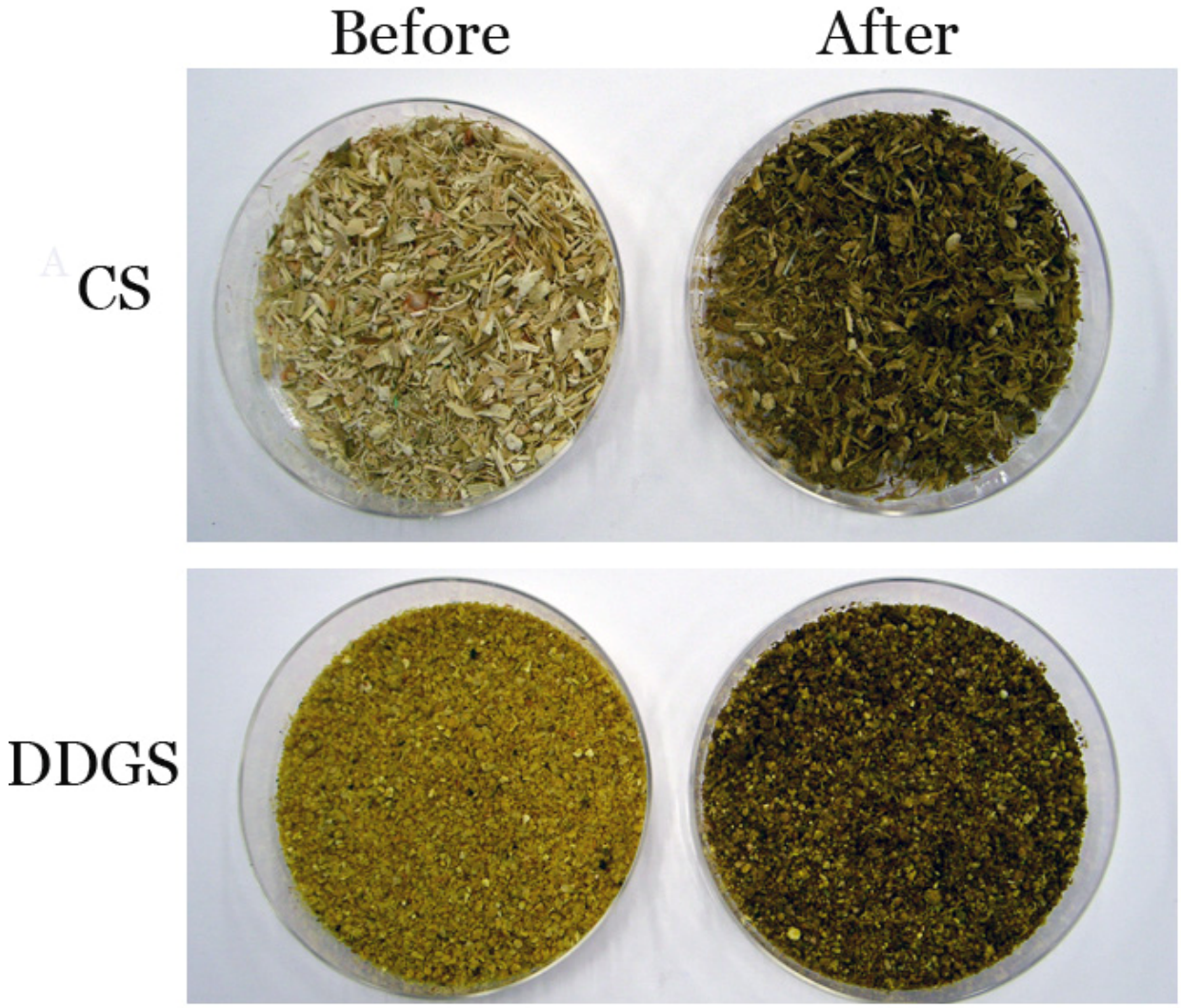
Before and After AFEX



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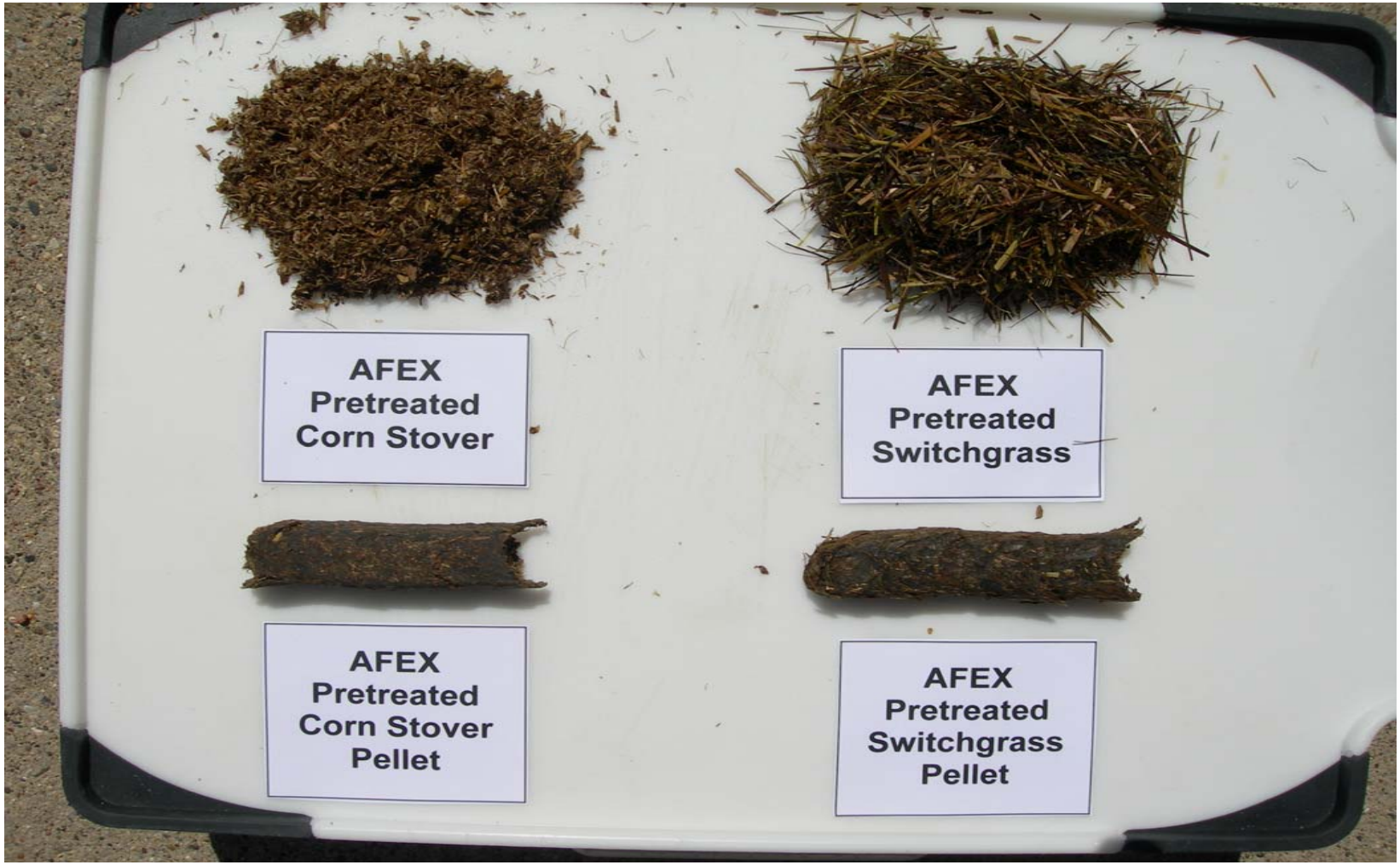
AFEX Biomass Pellets: No Binder



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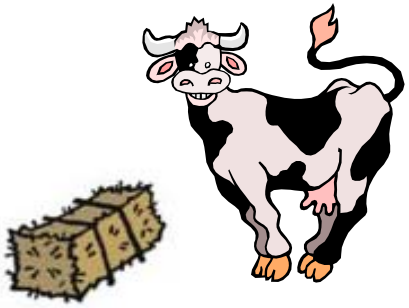
Ruminant Animals & Biorefineries:

Improve Cellulose Conversion for Biorefinery
= Improve Cellulose Digestibility for Cows

Mobile Cellulose Biorefinery
(a.k.a. Cow)



Stationary Cellulose Biorefinery

Ruminant Bioreactor:

Biomass Input ~ 26 Lb/Day*

Capacity ~ 40 Gal Fermentor

SSCF Bioreactor:

Biomass Input ~ 5,000 Dry Ton/Day
= 10 M Dry Lb/Day
Capacity ~ 45 M Gal Fermentor

Cow is 3x more efficient than industrial bioreactor

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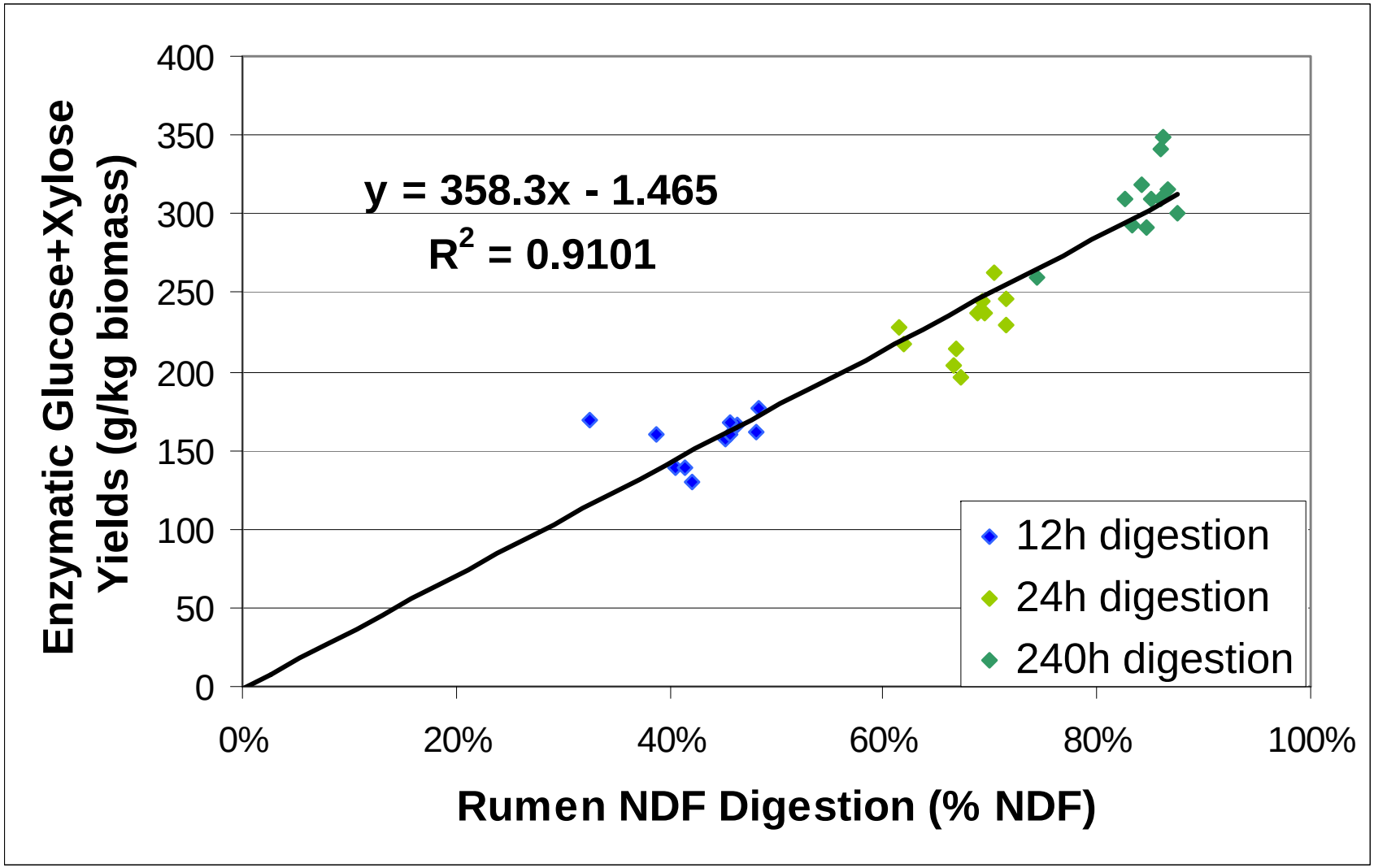
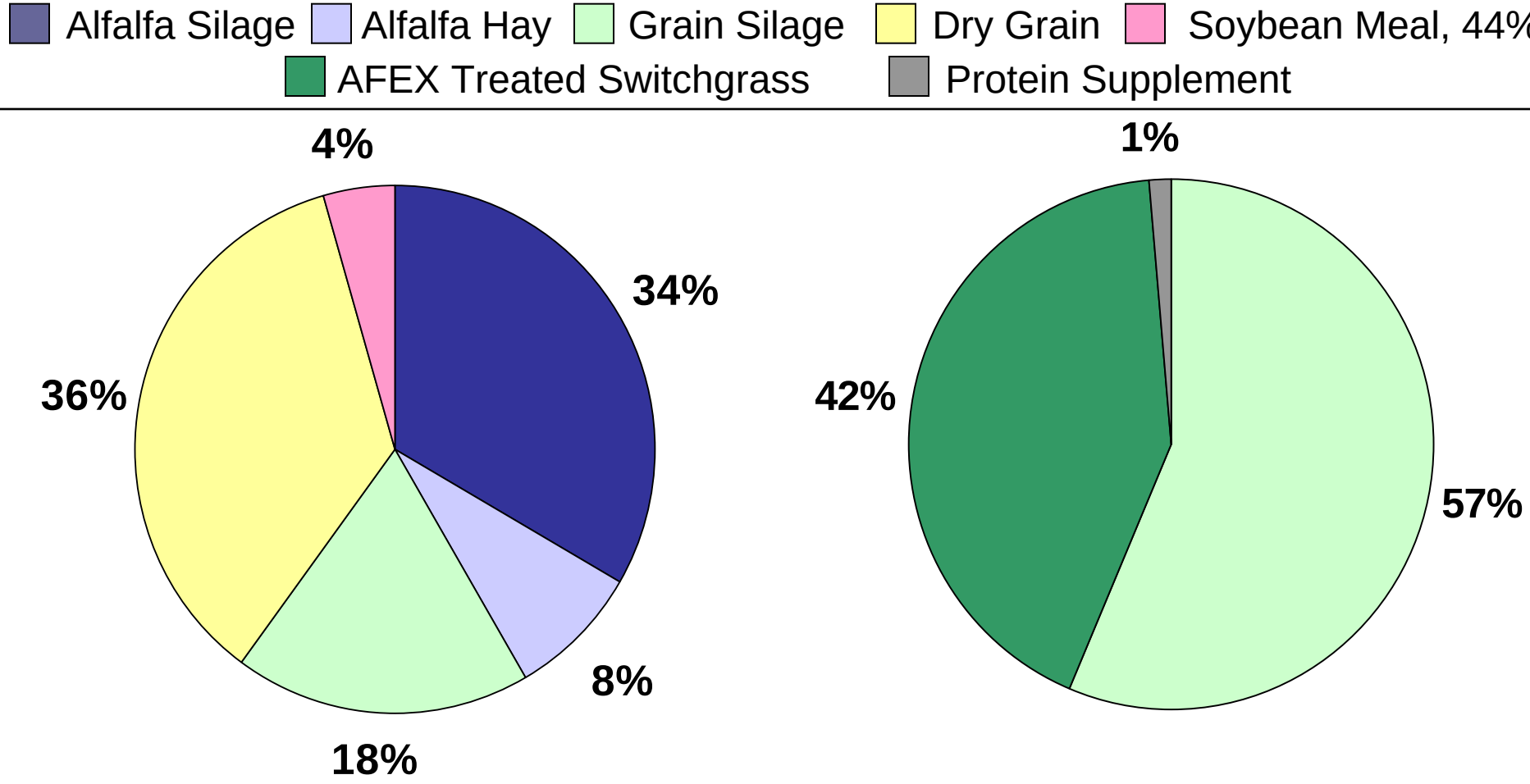
Enzymatic and Rumen Fluid Digestion of AFEX-Treated Grass



Dairy Diet- Black Hawk County Iowa Farm



$150,242/yr
265 acres/yr

$92,388/yr
167 acres/yr

Assumes 6 tons/acre/yr of switchgrass– modest goal

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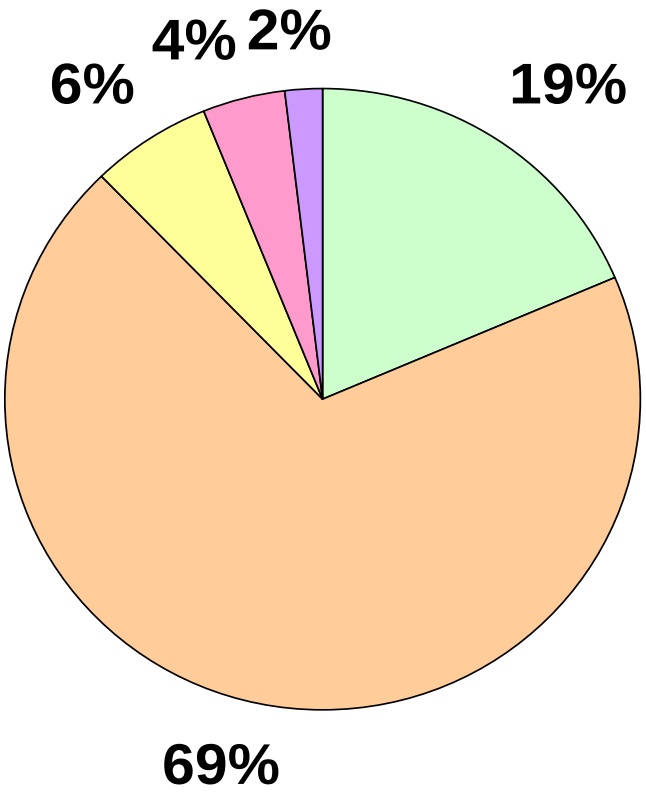
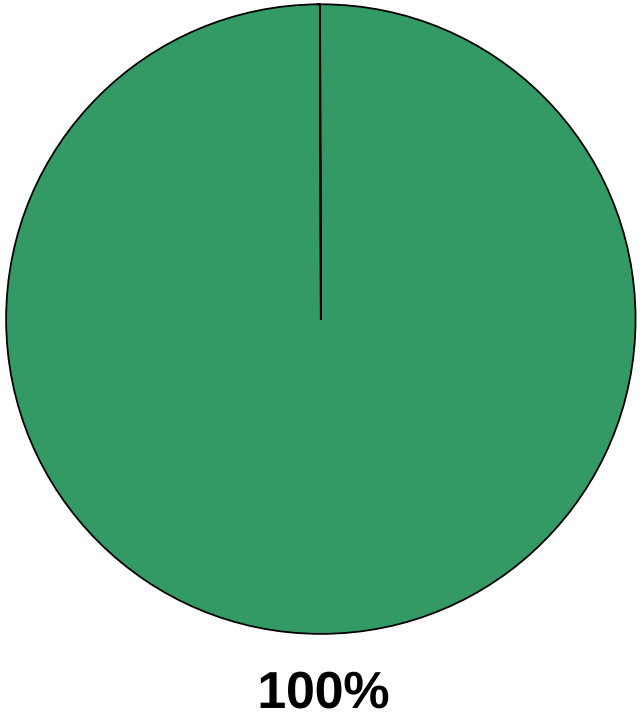
Beef Diet- Aberdeen South Dakota Ranch

Grain Silage | High Moisture Grain | Dry Grain | Soybean Meal, 44% | Meat and Bone Meal | AFEX Treated Switchgrass





$248,381/yr
436 acres/yr

$134,897/yr
227 acres/yr

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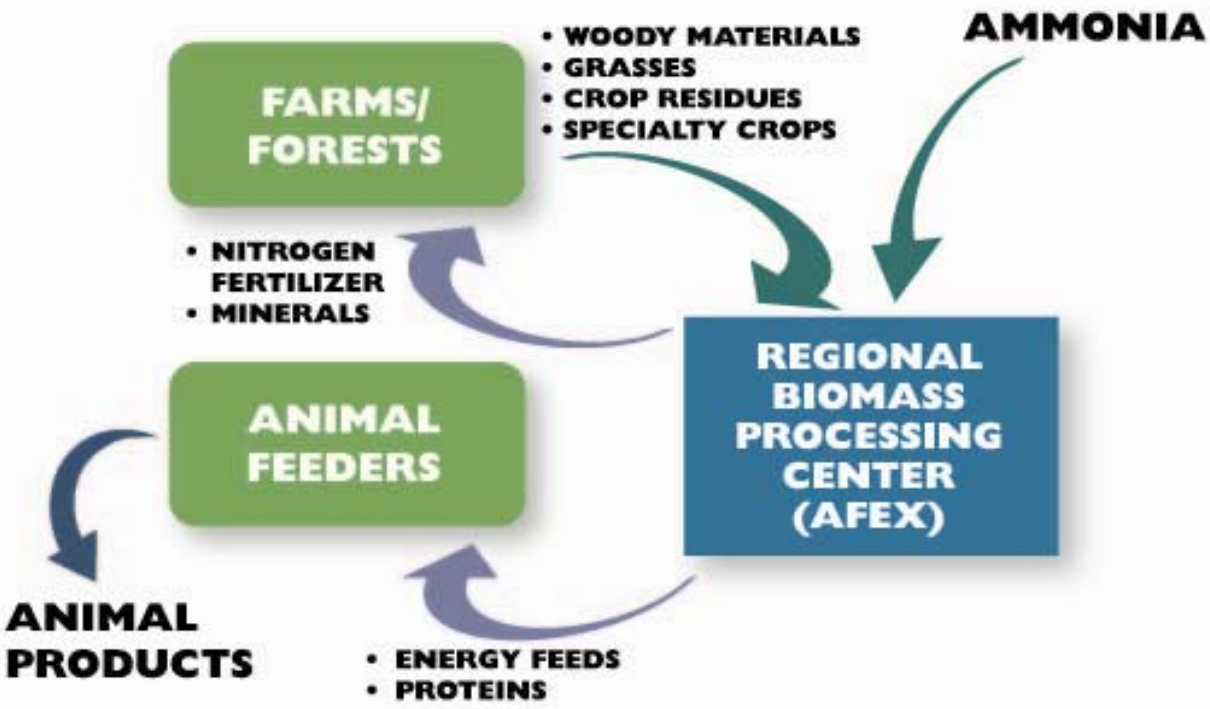
REGIONAL BIOMASS PROCESSING: SUPPLY CHAINS



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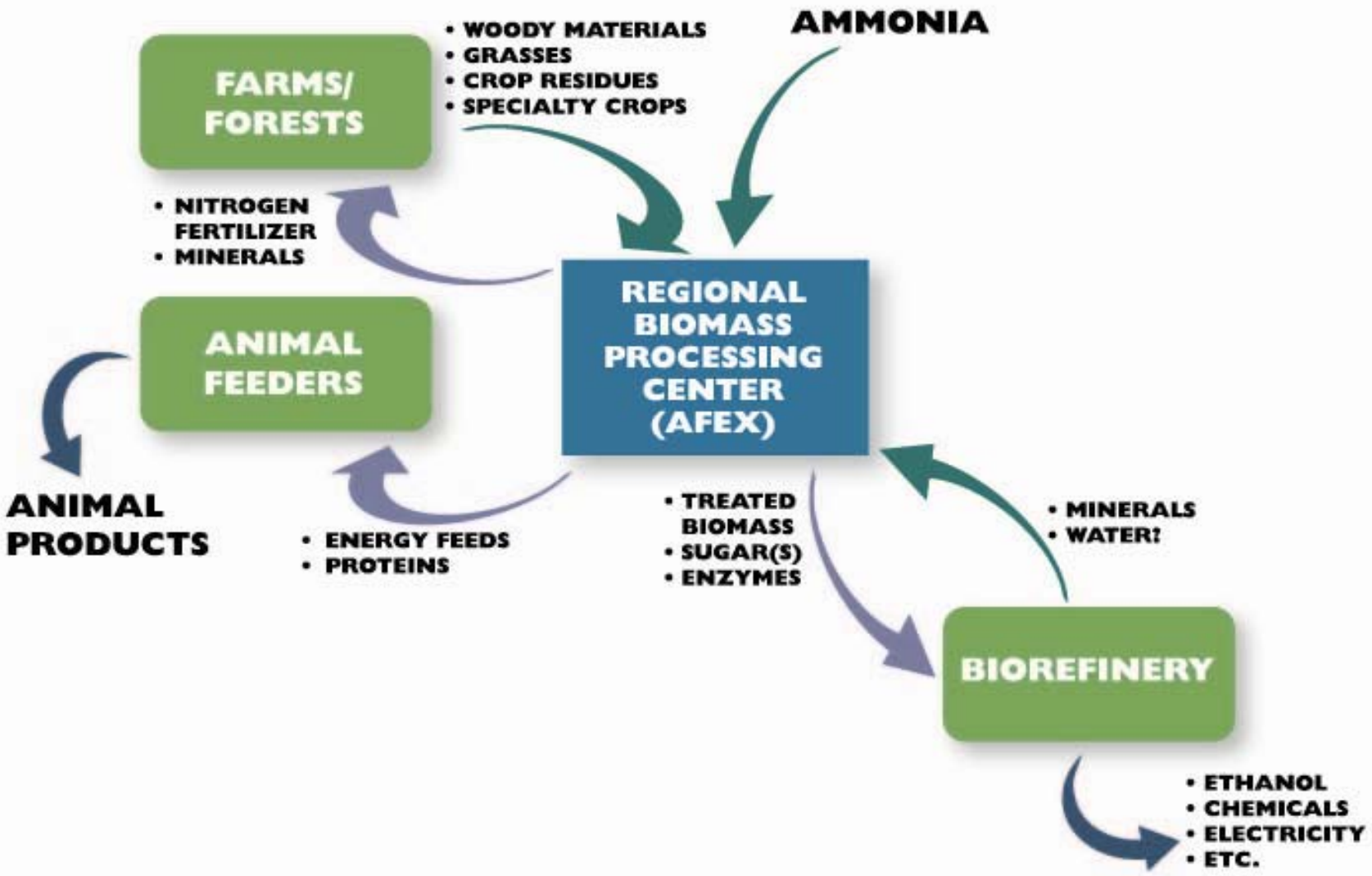
REGIONAL BIOMASS PROCESSING: SUPPLY CHAINS



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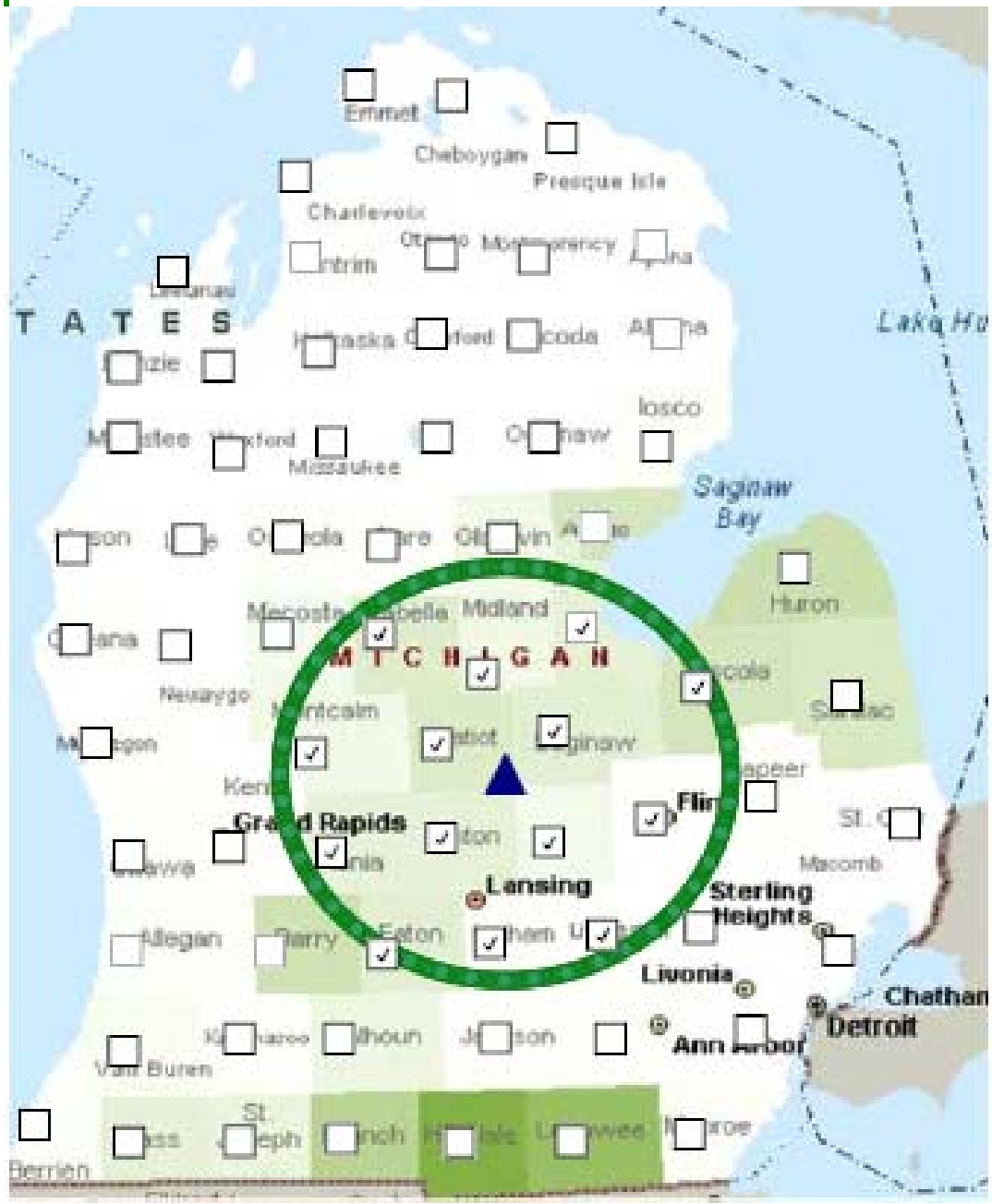
Current thinking



Nth Generation:

- Fully integrated
- Small # per state (1 in MI)
- Limits to optimal size
  - Geographic:
    - Low cost biomass availability
    - Transport costs
  - Large # contracts to manage

Potential Problems

- Market Structure
- Supply Chain Logistics
- Sustainable rural development?

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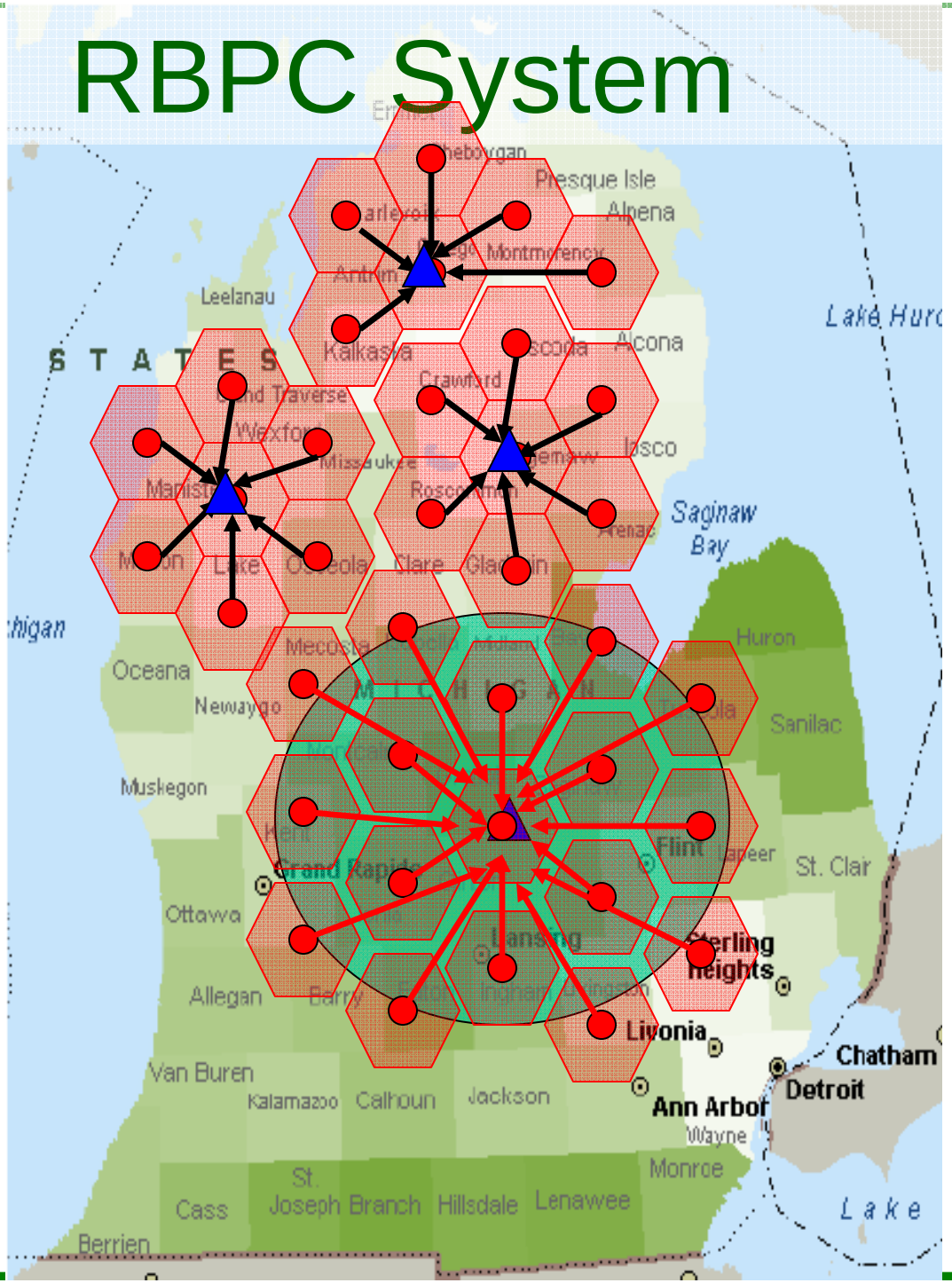
RBPC System

Effect 1 – Larger Biorefineries in high yield areas

+

Effect 2 – biorefiners in remote rural areas

Sustainable rural economies + Sustainable biofuels



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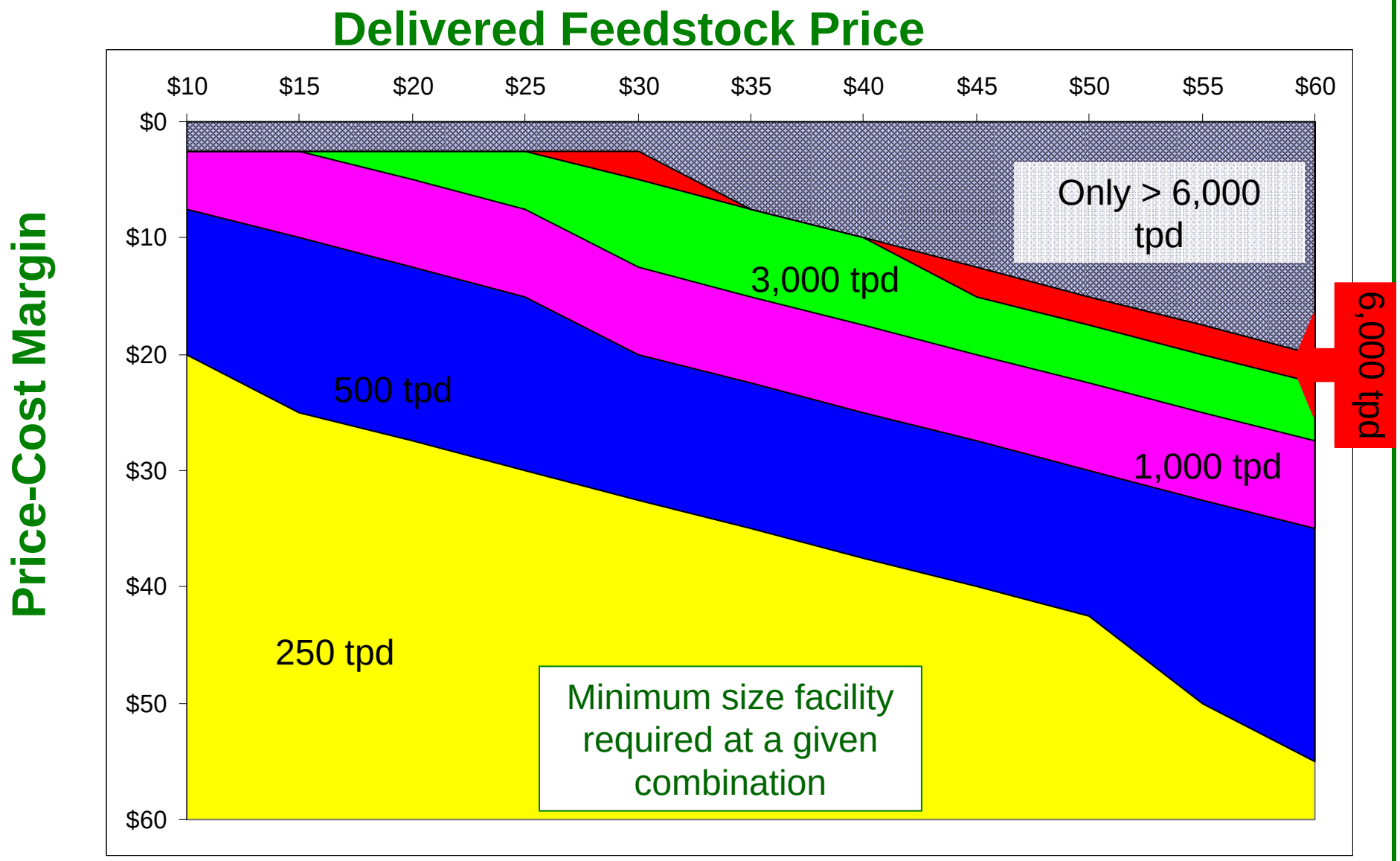
Feasible Set of Feedstock Prices and PCM



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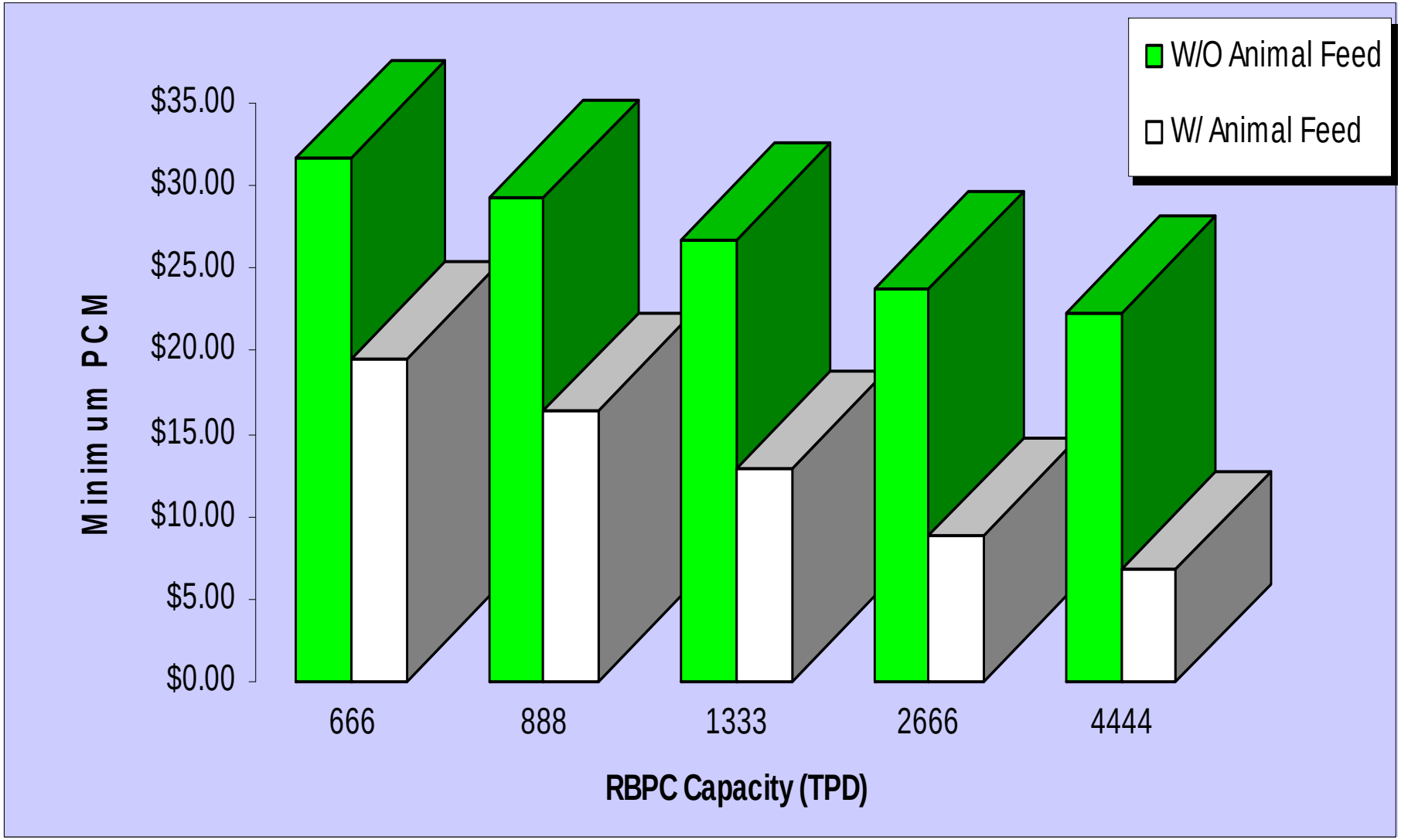
Feed Cross-Subsidization



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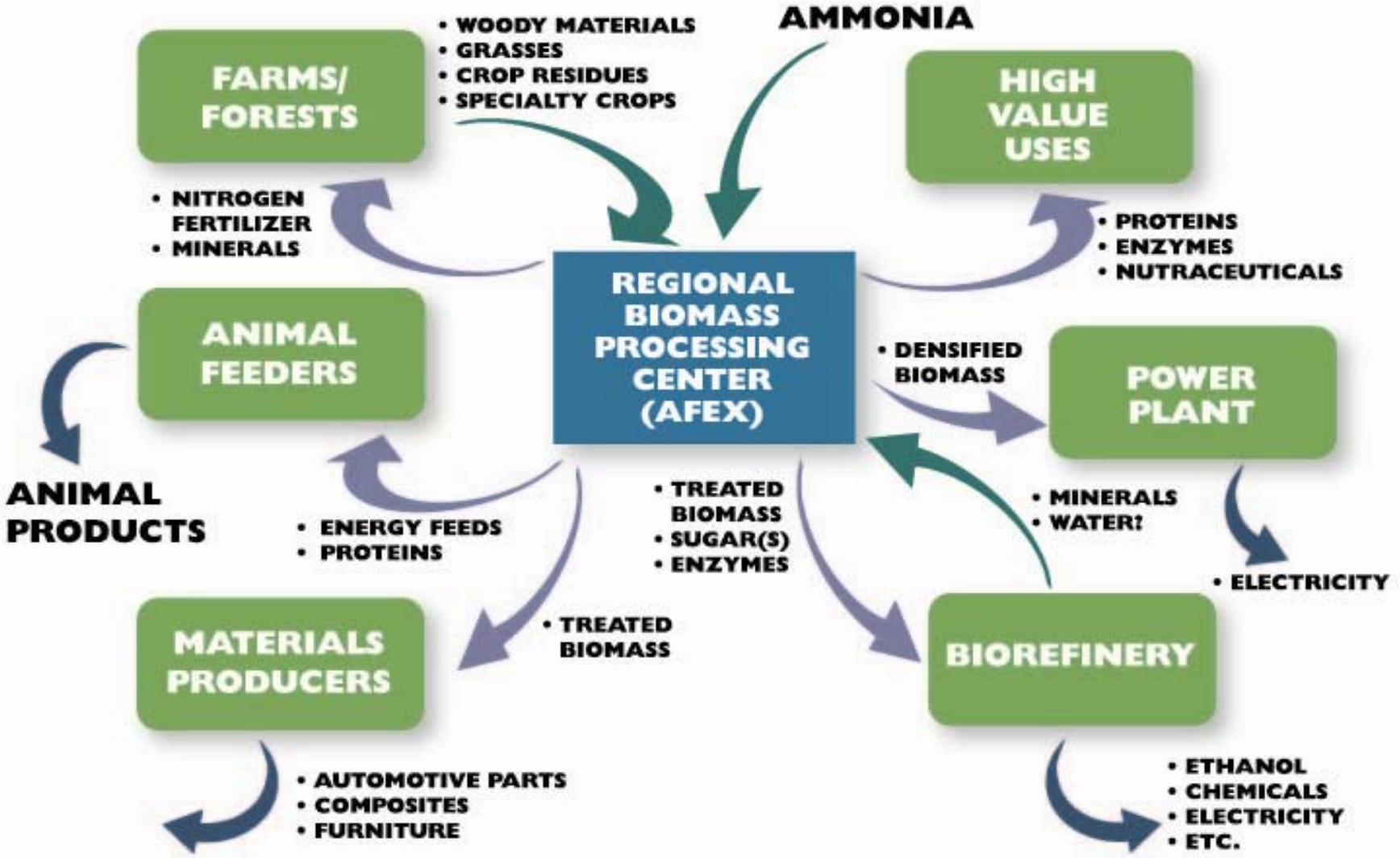

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Capturing Local Benefits from Biofuels

- Some issues for farmers/local interests
  - If farmers merely supply raw biomass, they will not benefit much from the emerging cellulosic biofuels industry
  - Environmental benefits depend largely on local factors—requires local control & optimization
  - Investment required for cellulosic ethanol biorefinery is huge ~ $500 million and up—difficult for farmers to participate
- Some issues for biofuel firms/larger society
  - Supply chain issues are enormous—need 5,000 ton/day from ~1,000 farmers: chemicals/fuels industries have zero experience with such large agricultural systems
  - Supply chains established for grains, not so much for grasses
  - Cellulosic biomass is bulky, difficult to transport
  - Need to resolve "food vs. fuel": actually "feed & fuel opportunity"
- Is there a common solution?
  - Regional Biomass Processing Center– concept worthy of further study and development
  - Pretreat biomass for biorefinery & ruminant animal feeding
  - Much lower capital requirements—accessible to rural interests
  - Perhaps some higher value uses: feed protein, materials, nutraceuticals, enzymes, etc.

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Why Regional Biomass Processing Centers?

- Concept: separate pretreatment operations from hydrolysis & fermentation ("distributed biorefining")
- Pretreatment enhances value of cellulosic biomass for animal feeding and biofuel production
- Advantages:
  - Logistics: aggregate, process, store, supply biomass
  - Densify biomass for easier transport
  - Homogenize different biomass materials by pretreatment—diversify feedstock supply
  - Increase economic scale of biorefinery
  - Simplify contract issues
  - Provide locus for economic development/wealth creation
  - Address "Food vs Fuel" concerns directly
  - Increase land use efficiency of biofuels
  - Provide expertise to certify environmental performance

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What Happens Because of Inexpensive Biofuels?

- Petroleum dominance declines
  - *Reduce petroleum's influence on prosperity & politics*
  - *Less chance for international conflict*
  - *Greater economic growth opportunities for poor nations*
- Environmental improvements possible
  - *Reduced greenhouse gases*
  - *Reduced nitrogen & phosphorus-related pollution*
  - *Improved soil fertility*
- Rural economic development possible
  - *Local cellulosic biomass processing*
  - *Greater wealth accumulation in rural areas*
  - *Less migration to cities to find economic opportunity*
- Less expensive food (animal feed) possible
  - *Improved animal feeds: protein & calories*
  - *Less expensive, more abundant human food*

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“The Stone Age did not end for lack of stone, and the Oil Age will end long before the world runs out of oil.”

Sheikh Zaki Yamani
Former Saudi
Arabia Oil Minister

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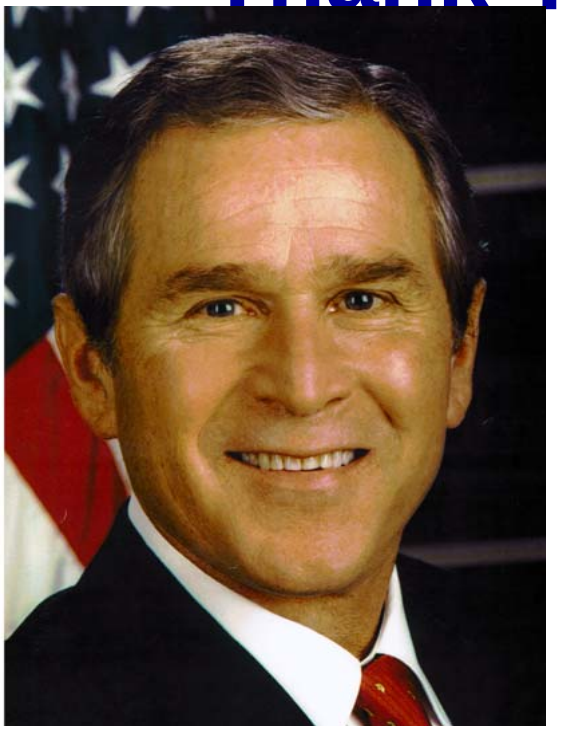
Thank You Mr. President



"…We'll also fund additional research in cutting-edge methods of **producing ethanol…from** wood chips and stalks, or **switch grass**…"

State of the Union Address, **2006**

Ethanol Production from Enzymatic Hydrolysates of AFEX-Treated Coastal Bermudagrass and Switchgrass

SULTAN RESHAMWALA,[1] BAHAA T. SHAWKY,[2] AND BRUCE E. DALE*[1]

[1]*Department of Chemical Engineering, Texas A&M University, College Station, TX 77843-3122; and* [2]*Microbial Chemistry Department, National Research Center, Cairo, Egypt*

Applied Biochemistry and Biotechnology, Vol. 51/52

1995

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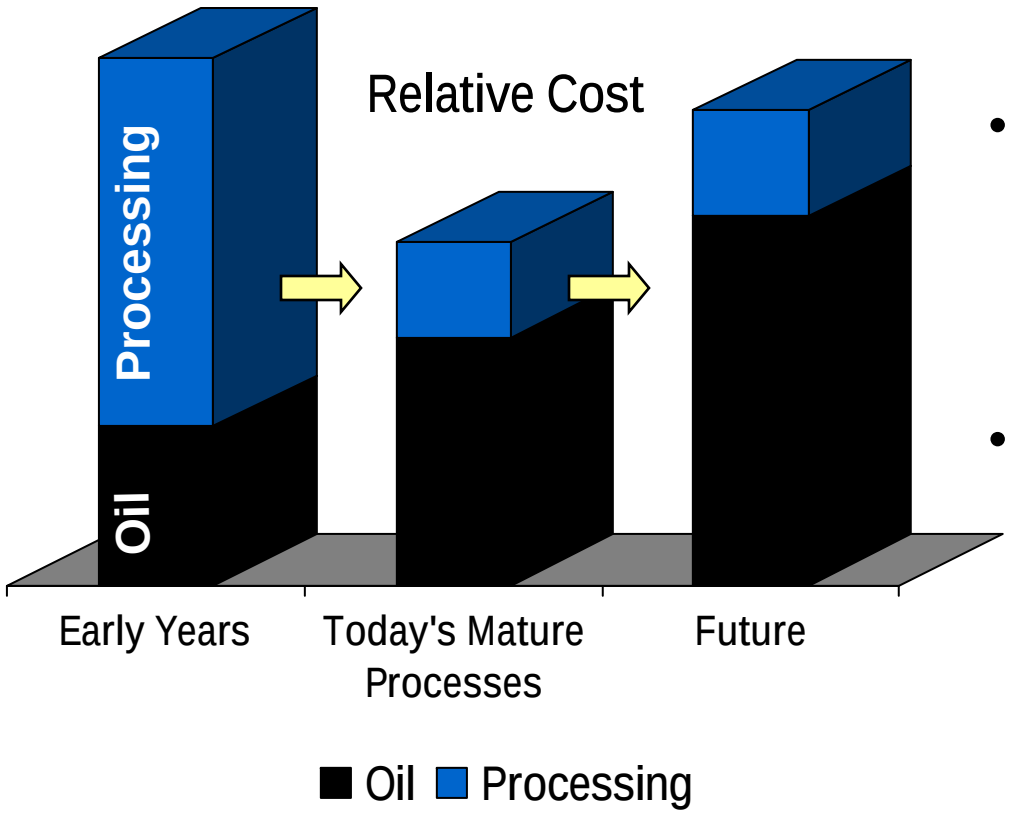
Impact of Processing Improvements: Oil's Past & Future



- Historically, petrochemical processing costs exceeded feedstock costs
- Petroleum processing efficiencies have increased and costs have decreased dramatically but reaching point of diminishing returns
- Petroleum raw materials have long-term issues
  - Costs will continue to increase as supplies tighten
  - High price variability
  - Impacts national security
  - Climate security concerns
  - Not renewable
- **Not a pretty picture for our petroleum dependent society**

From J. Stoppert, 2005

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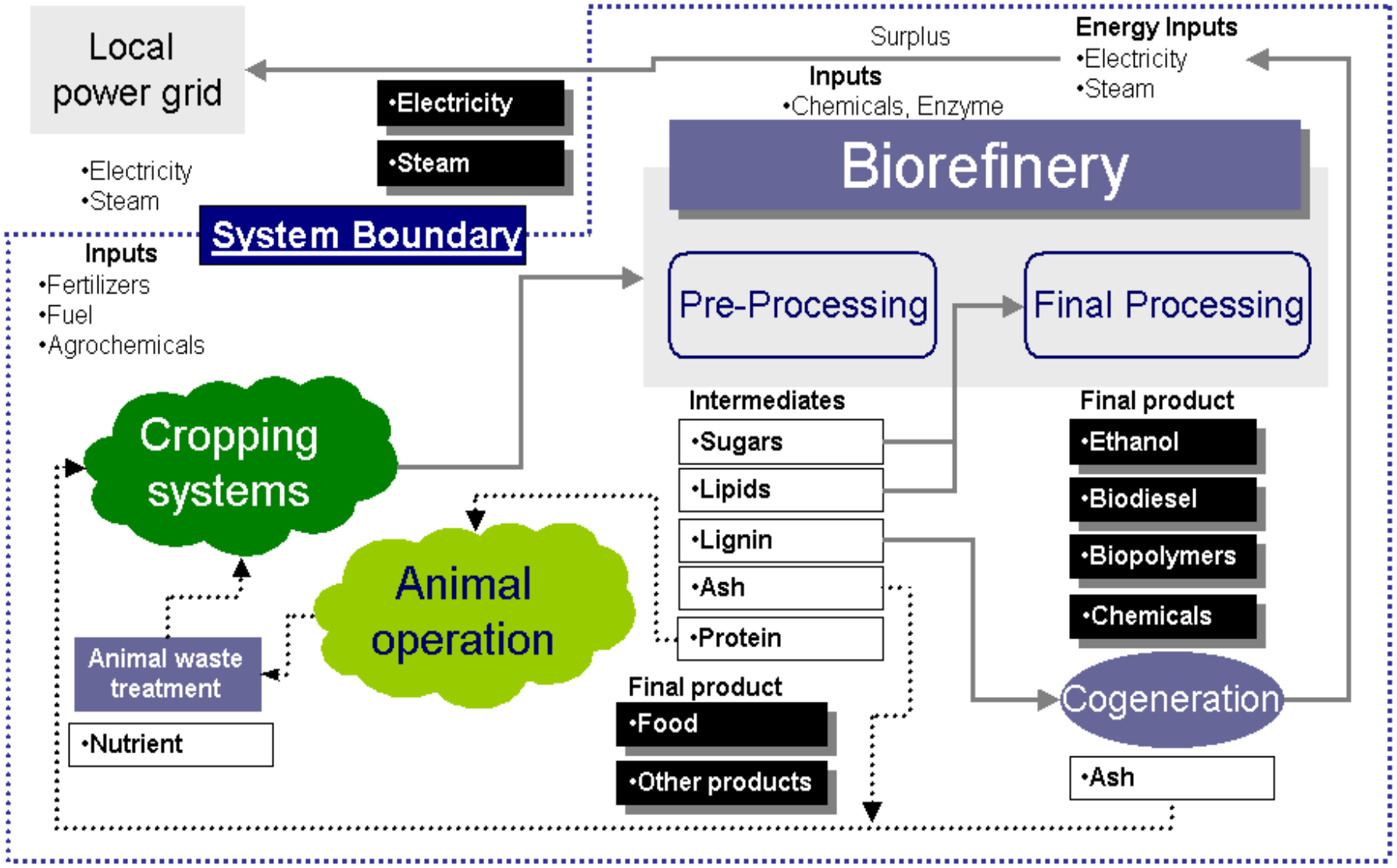
ALL BIOMASS IS LOCAL



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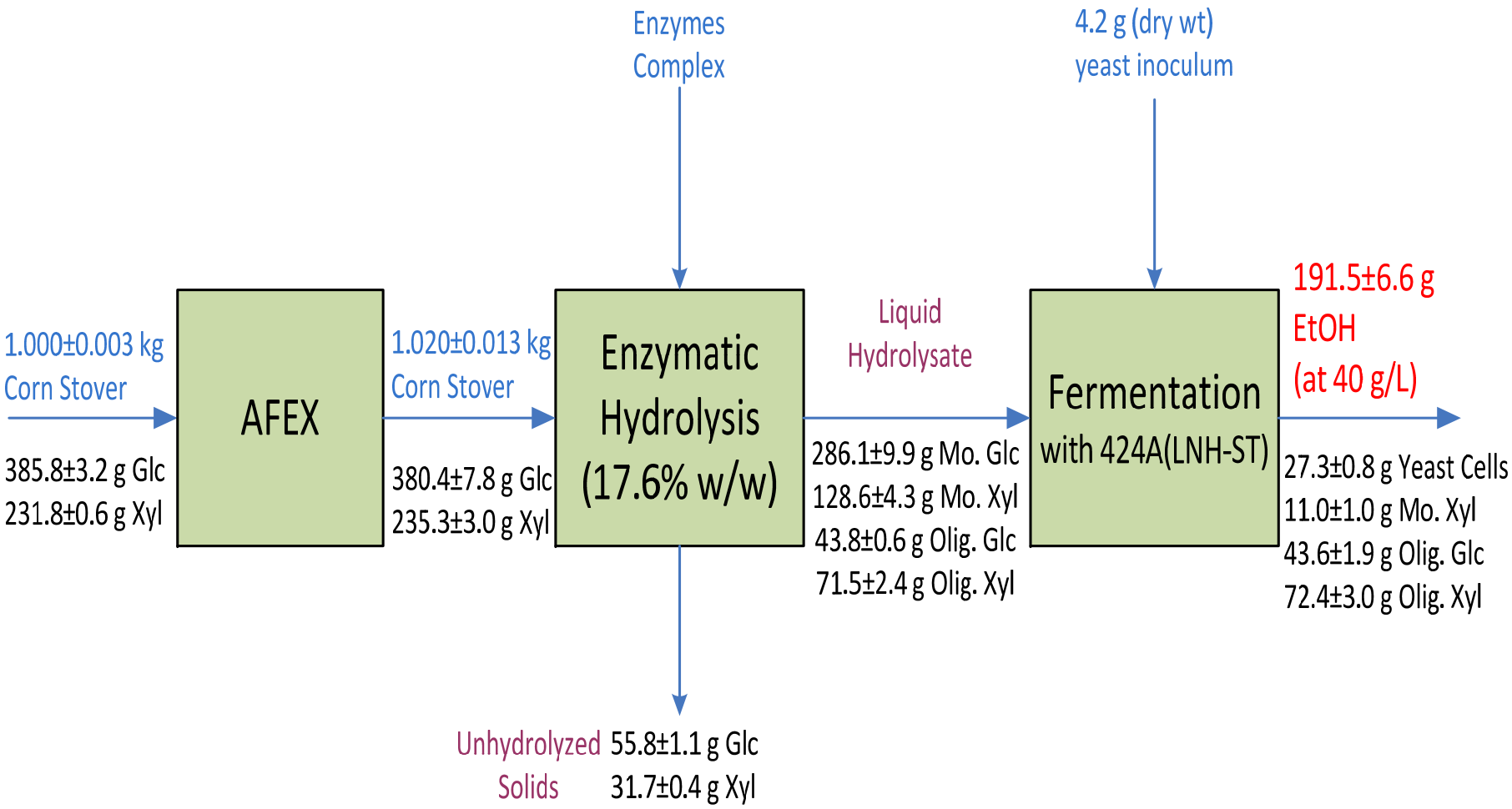
Mass Balance: Corn Stover Hydrolysis & Fermentation



Must hydrolyze & ferment pentosans at high solids loading

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Results of AFEX Economic Analysis*

- Reduce ammonia loadings
- Reduce required ammonia recycle concentrations (manage system water)
- Reduce capital cost of AFEX
- **Analysis performed by Dr. Tim Eggeman of NREL*