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Recent Improvements for the Ammonia Fiber Explosion (AFEX) Process and Resulting Reductions in Projected Ethanol Prices

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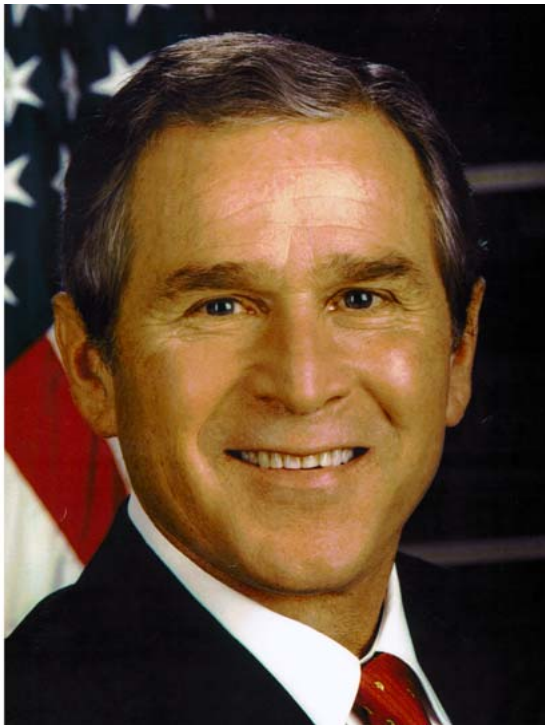
Thank You Mr. President



"…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

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How We Got Here

- Two years ago, CAFI team did techno-economic comparisons of leading pretreatments*
- Ammonia Fiber Explosion (AFEX) Minimum Ethanol Selling Price (MESP) ~ $1.40/gallon
- Key AFEX process economic parameters identified
- MSU & collaborators at Dartmouth worked on AFEX improvements during last two years
- We report here our results:
  - Improved AFEX process parameters
  - Improved ammonia recovery approach
  - These two improvements reduce MESP by ~$0.40/gallon and are “ready to build”
  - Integration of AFEX with consolidated bioprocessing (CBP) in “mature biorefinery” scenario reduces costs another ~$0.20/gal
  - CBP option is not “ready to build”

* *Our sincere thanks to NREL & Dr.Tim Eggeman*

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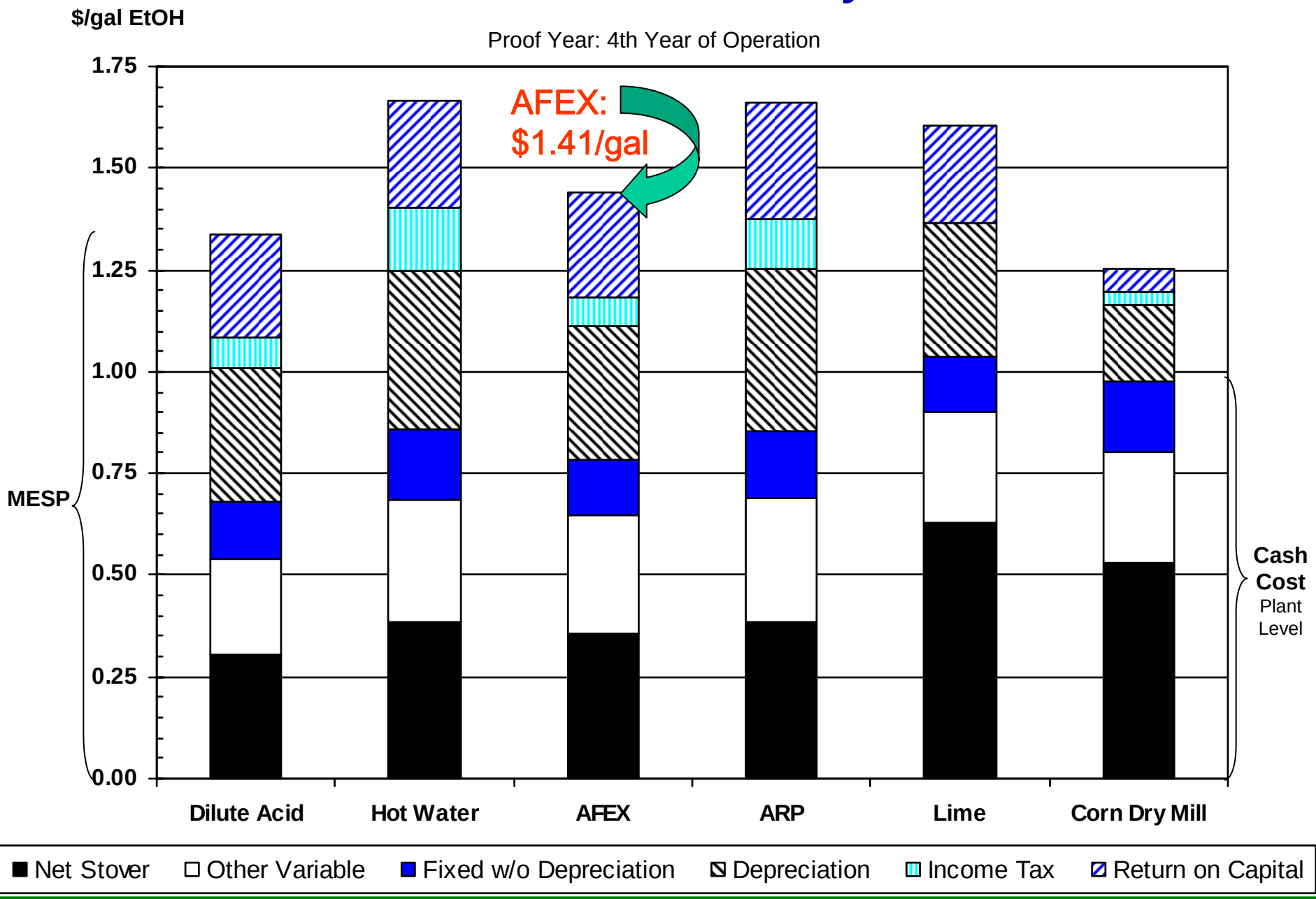
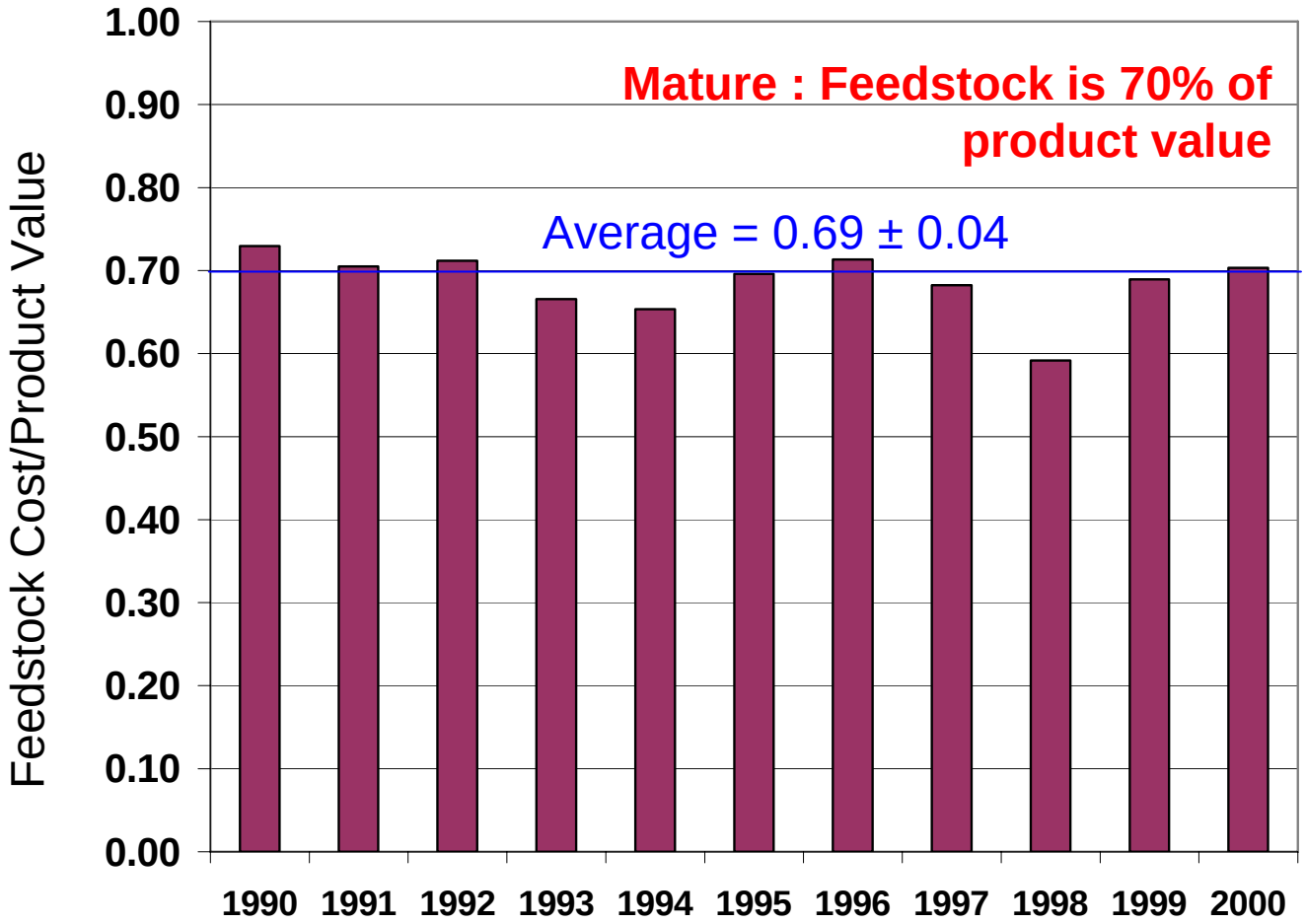
Pretreatment Economic Analysis: CAFI Team



Key Findings: AFEX Economic Analysis

- Reduce ammonia loadings (kg NH3/kg dry biomass)
- Reduce required ammonia recycle concentrations (manage system water)
- Reduce capital cost of AFEX
- Reduce enzyme loadings for >90% conversion of glucan plus xylan
- AFEX is not a “mature” process
- Neither is overall cellulosic ethanol process

U.S. Petroleum Refining Feedstock Cost/Product Value, 1990-2000



Sources: Yields: API, Basic Petroleum Databook; Prices: EIA, Petroleum Marketing Annual; *Oil & Gas Journal* database.

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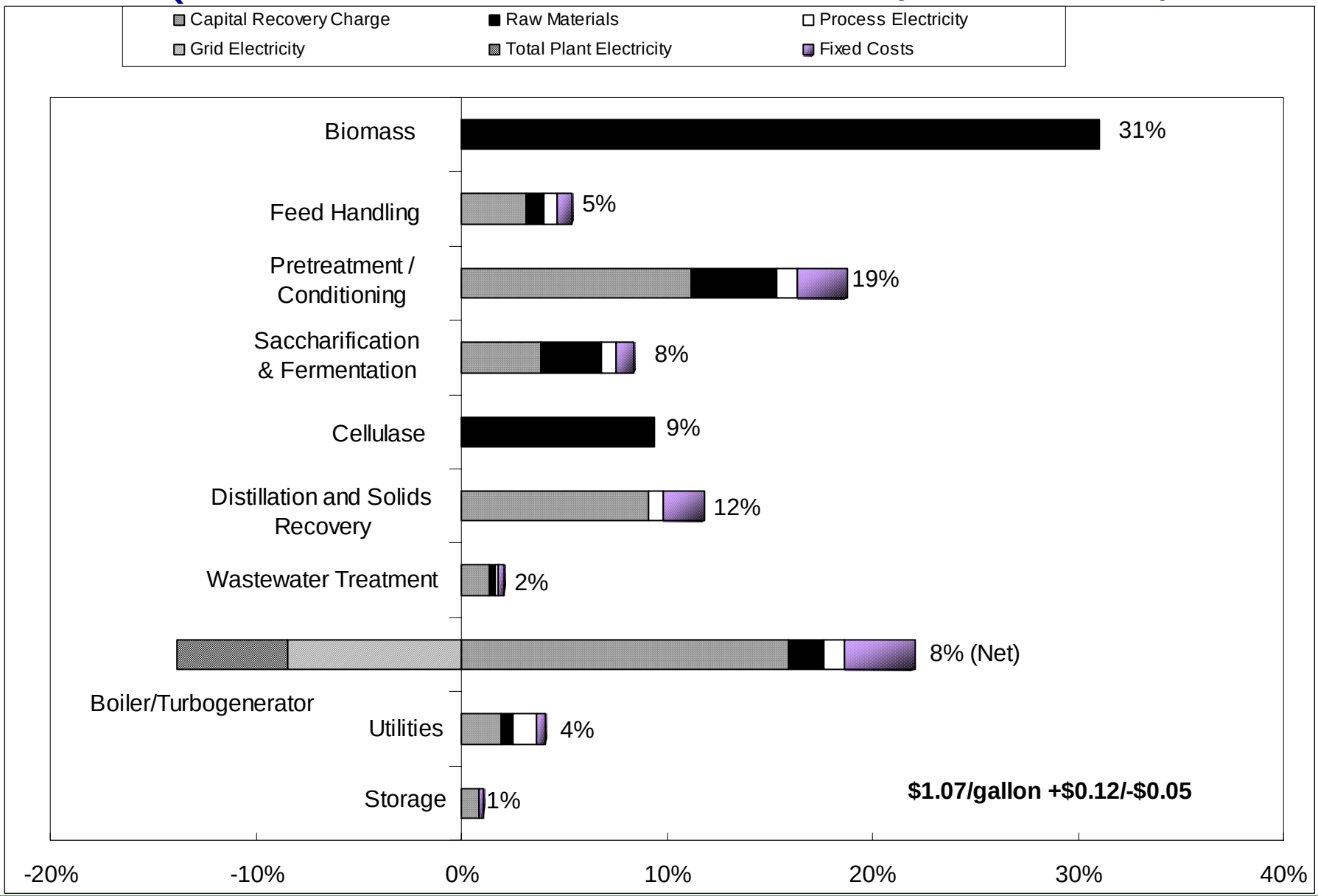
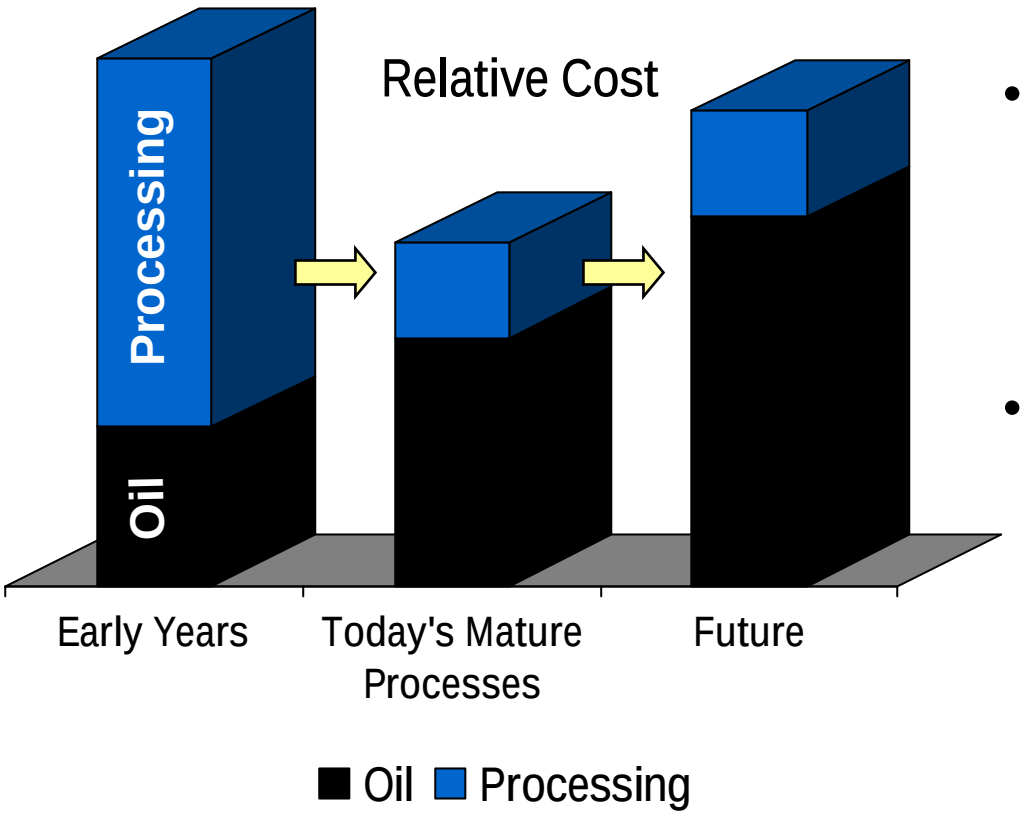
NREL Design Report ($2002)

(June 2002 NREL/TP-510-32438 by Aden, *et al*)



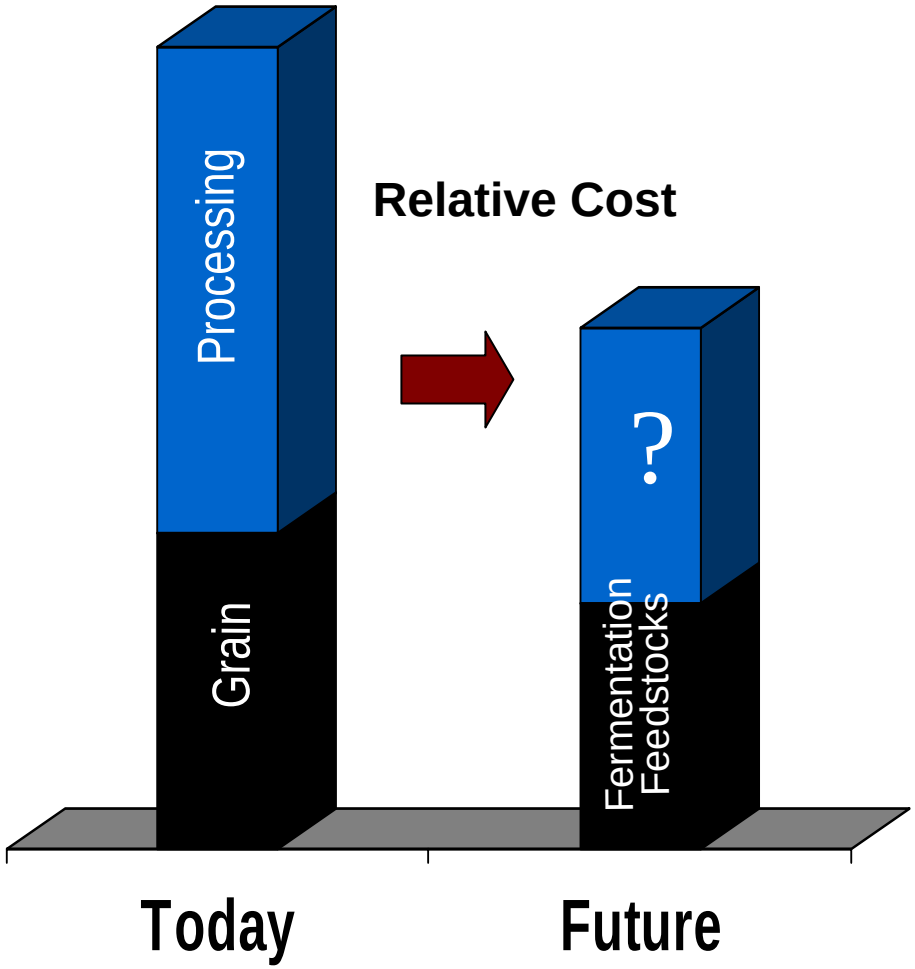
Impact of Processing Improvements: Oil's Past & Future



Adapted from J. Stoppert, 2005

- 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 problems which will NOT improve
  - Costs will continue to increase as supplies tighten
  - High price variability
  - Impacts national security
  - Climate security concerns
  - Not renewable
- **Not a pretty future for oil--or for our oil dependent society**

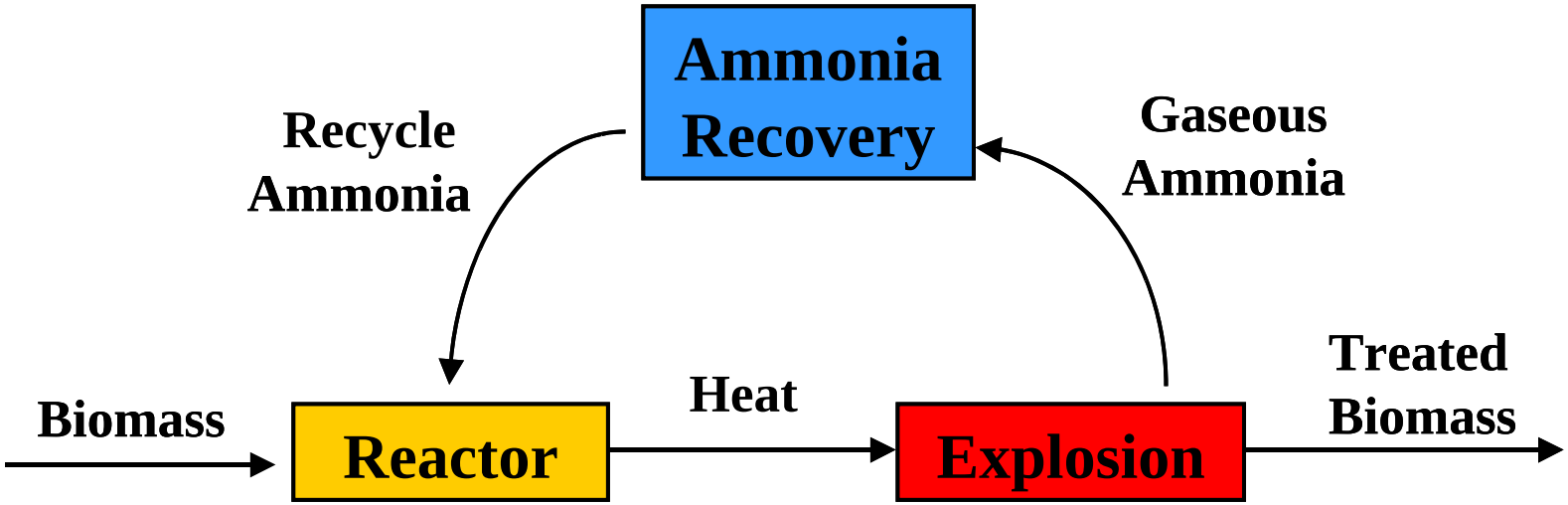
Impact of Processing Improvements: The Future of Biomass Conversion



Adapted from J. Stoppert, 2005

- Processing costs dominate cellulosic ethanol today
- Cellulosic raw material costs should be stable or decrease
  - Renewable resource
  - Potential for very large yield increases
- Biomass processing costs **will** decrease: Key question is *how far* and *how fast*
- For ethanol from cellulosics:
  - Pretreatment costs
  - Enzyme costs
  - Fermentation costs
- Pretreatment affects all other downstream operations

How does AFEX pretreatment work?



- Biomass heated (~100 C) with concentrated ammonia
- Rapid pressure release ends treatment
- 99% of ammonia is recovered & reused, remainder serves as N source downstream for fermentation
- No sugar degradation, relatively mild conditions
- No hydrolysis to sugar monomers, xylooligomers formed

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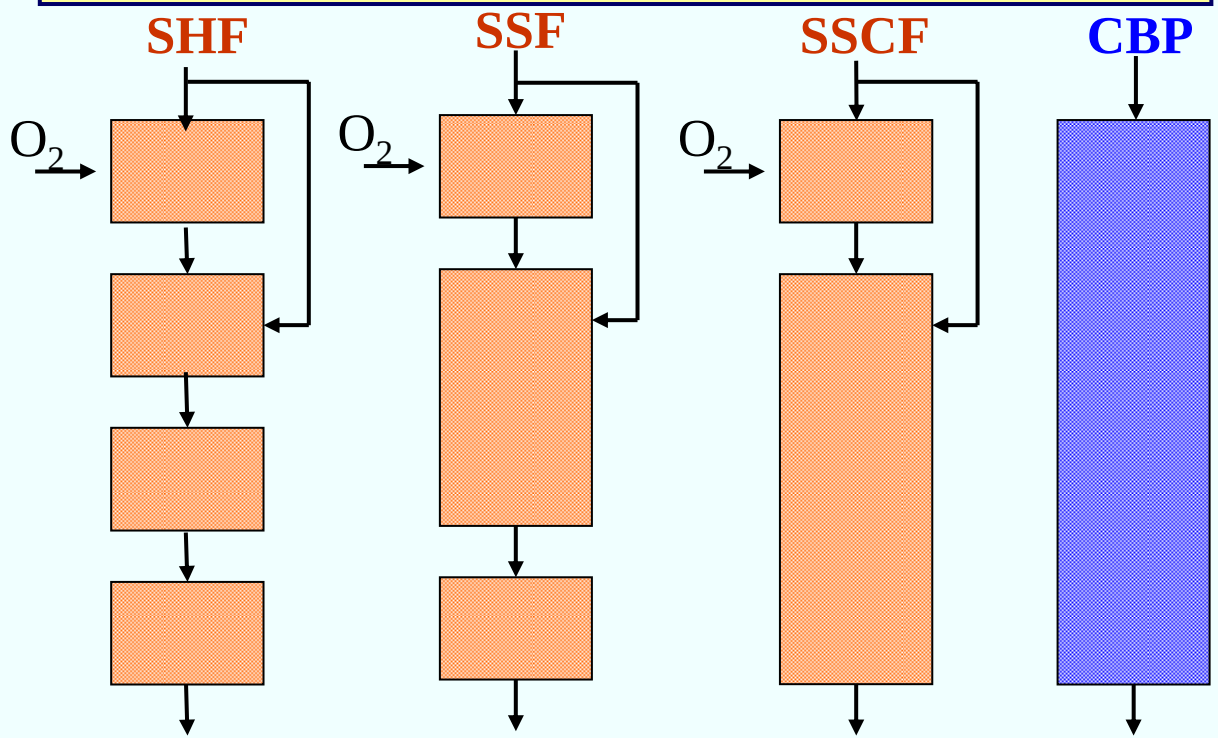
Evolution of Biomass Processing Featuring Enzymatic Hydrolysis

Biologically-Mediated Event

Processing Strategy
(each box represents a bioreactor - not to scale)



SHF: Separate hydrolysis & fermentation

SSF: Simultaneous saccharification & fermentation

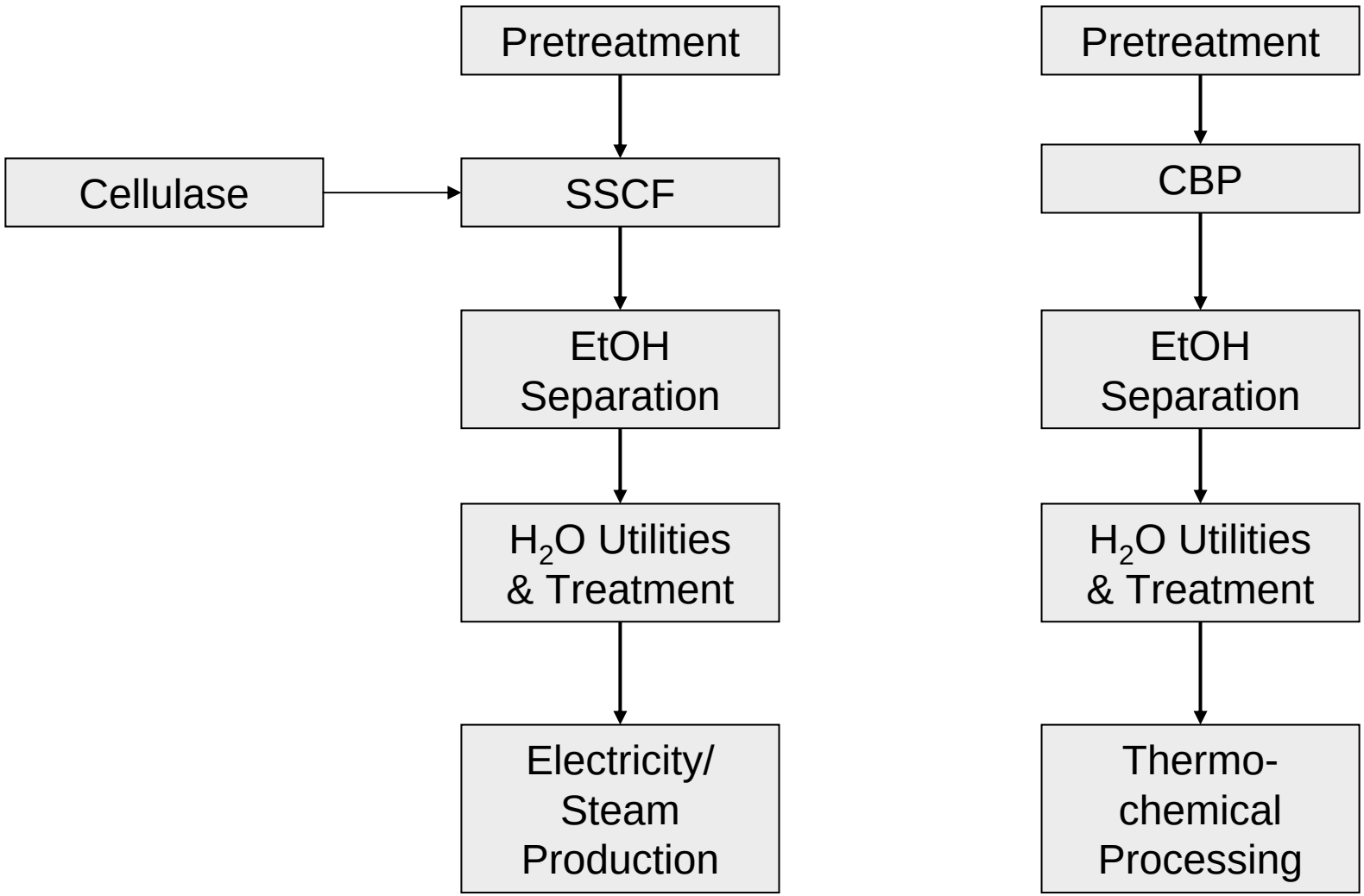
SSCF: Simultaneous saccharification & co-fermentation

CBP: Consolidated bioprocessing

Process Modeling Context

- NREL Approach (nearer term)
  - NREL/Eggeman
  - SSCF
  - 2,000 dry ton/day
  - Feedstock washing
  - AFEX pretreatment; old process parameter
  - Ammonia recompression recovery
  - Evaporation of still bottoms
- "Mature technology" RBAEF Approach
  - Dartmouth/RBAEF team
  - 5,000 dry ton/day
  - No feedstock washing
  - AFEX pretreatment
  - New ammonia recovery approach
  - Heat pumps
  - Evaporation of still bottoms eliminated
  - Other changes

Overall Process

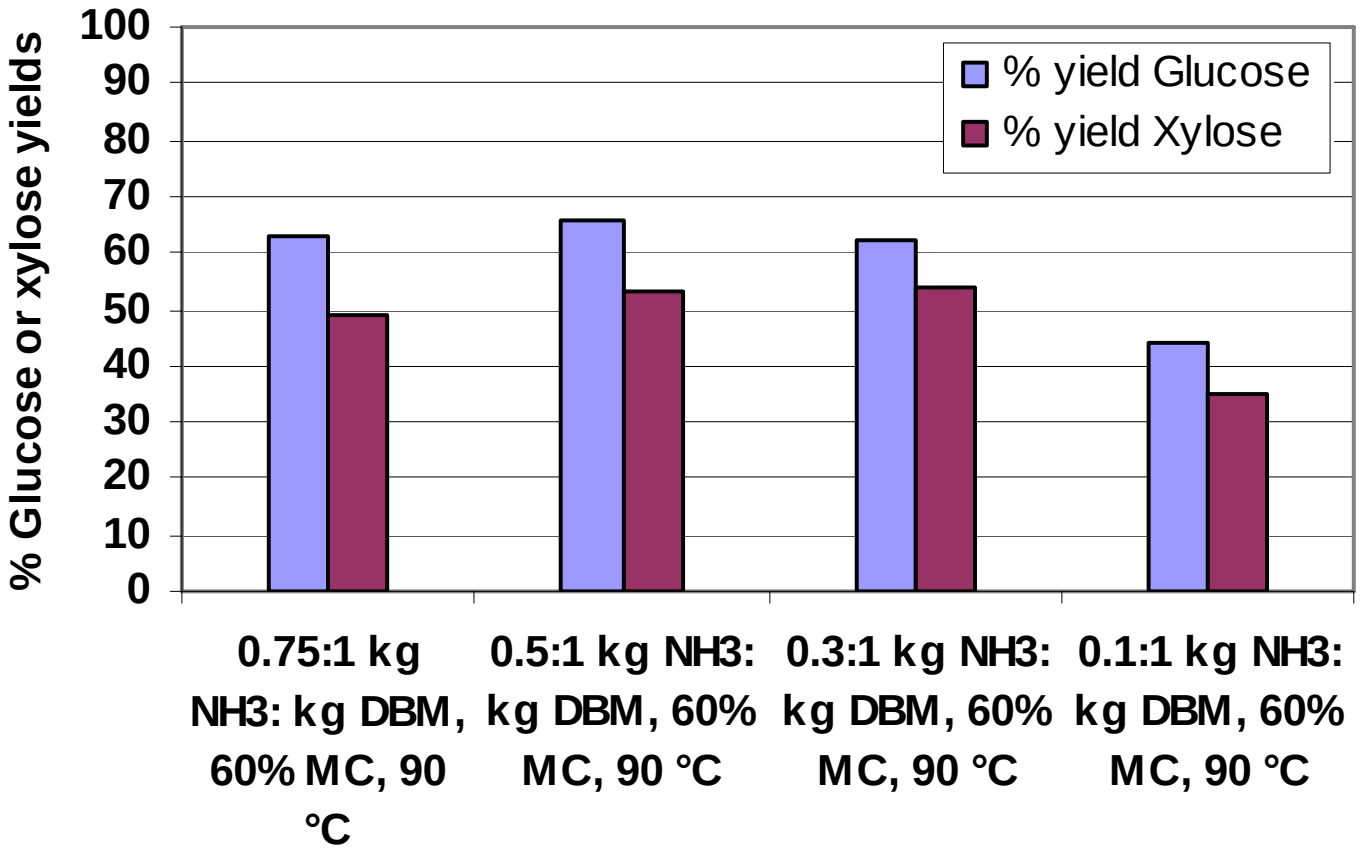


Process Improvements

- Report technoeconomic advances in
  - AFEX process parameters: reduce ammonia loading & ammonia recycle concentration
  - AFEX process design: trade recompression for quench system
  - AFEX integration with advanced bioconversion by CBP
- Some details of new lower capital cost ammonia recovery approach
- Cumulative effect of all changes cuts $0.60/gallon from MESP
- Have not yet estimated economic effects of enzyme synergies (reduce total enzyme loadings?) between cellulase and xylanase

Reducing Ammonia Loading

Key is to keep ammonia in liquid phase: minimize ammonia vaporization



16 hr yields
15 FPU cellulase/gm glucan

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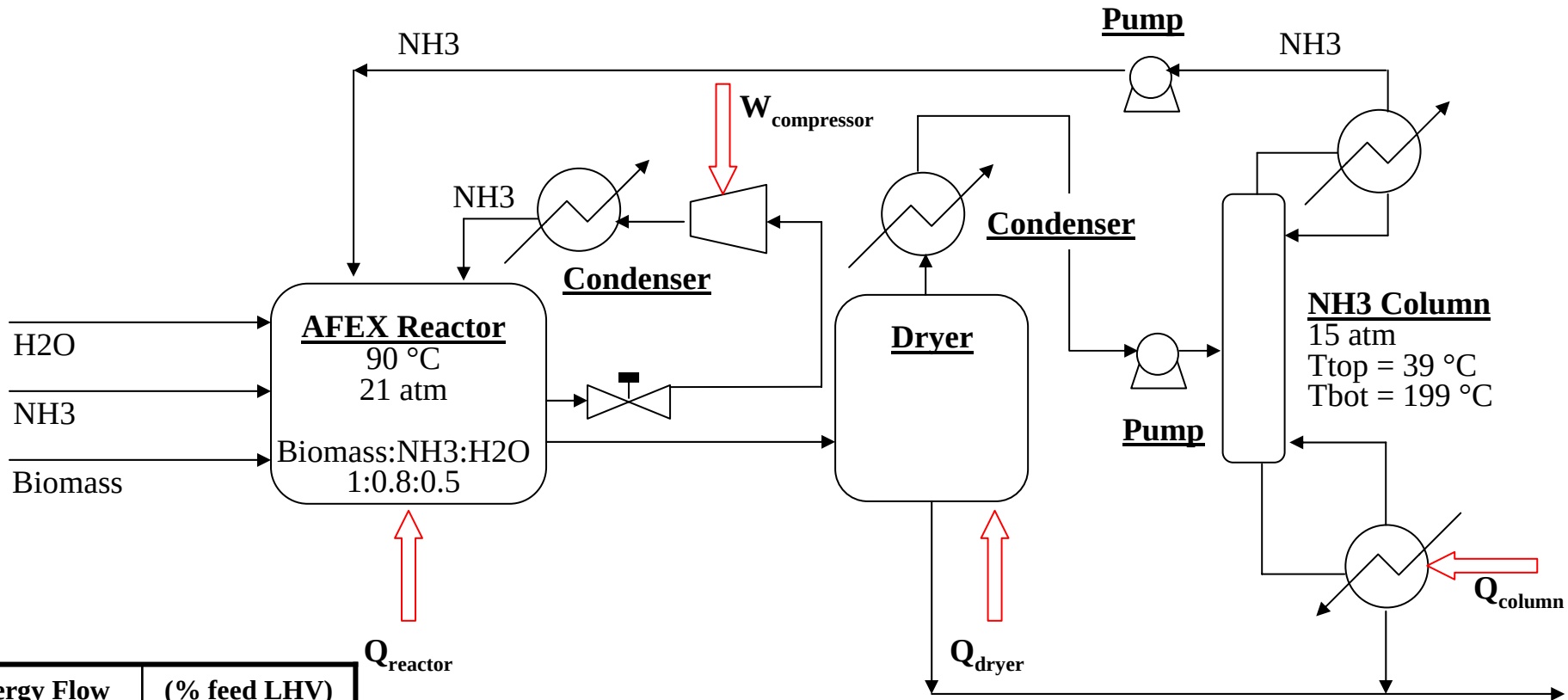
Managing Ammonia & Water in AFEX for High Sugar Yields*

Ammonia Distribution	Water Distribution	% Sugar Yields G/X
All as NH3	All in stover	93.0/74.3
¾ NH3; ¼ NH4OH	½ NH4OH; ½ stover	93.0/78.9
“” “”	All in NH4OH	79.9/64.9
½ NH3; ½ NH4OH	All in NH4OH	57.7/47.9
“” “”	½ NH4OH; ½ stover	97.8/82.0
All NH4OH	All NH4OH	71.0/57.0
“” “”	¾ NH4OH; ¼ stover	97.1/79.0

Uniform final conditions: 1:1 NH3:stover; 60% moisture DWB; 90 C

AFEX Pretreatment (Recompression)

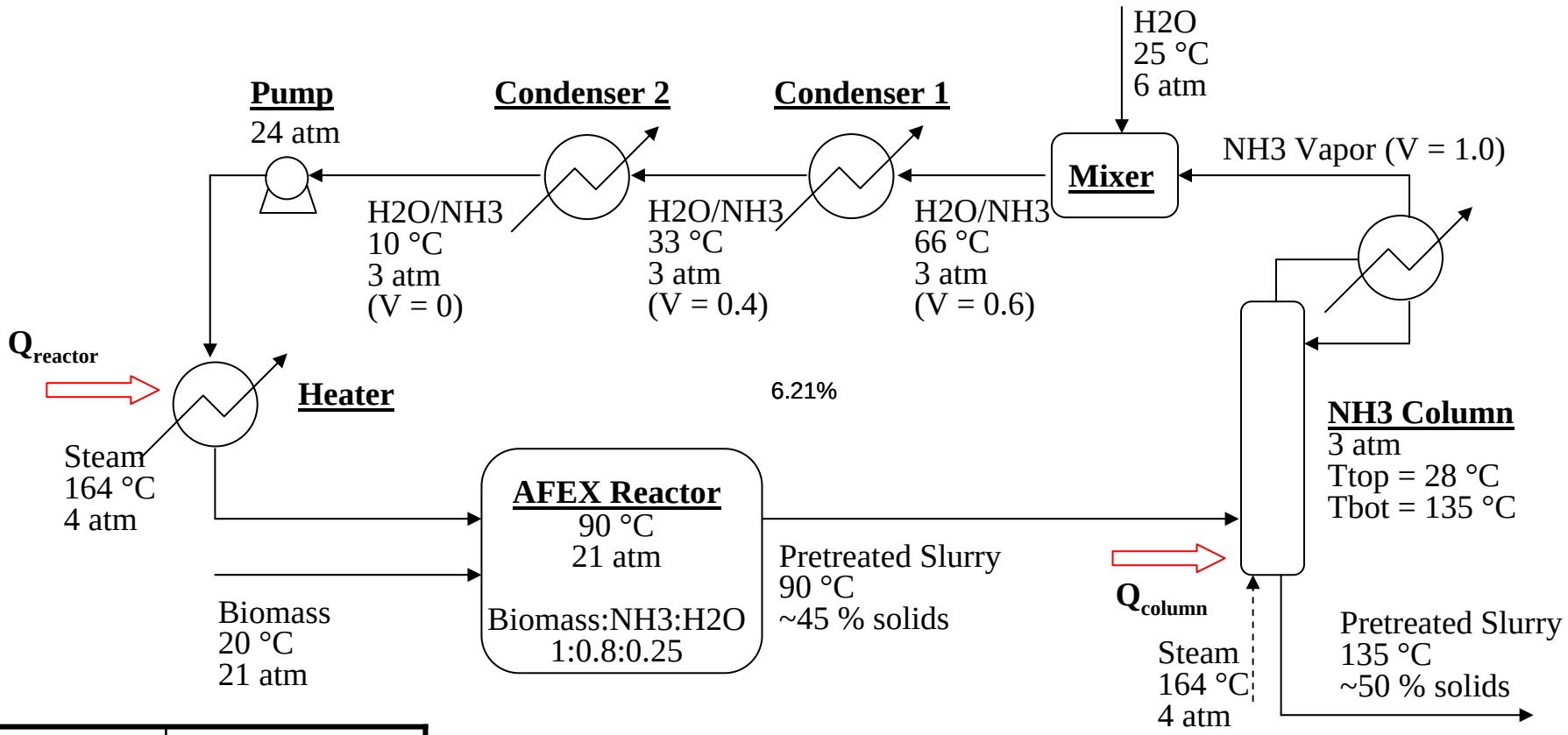
Flash + Distillation NH_3 Recovery



Energy Flow	(% feed LHV)
$Q_{reactor}$	0%
Q_{dryer}	8.4%
Q_{column}	3.7%
$W_{compressor}$	0.5%
TOTAL	12.6%

AFEX Pretreatment (New Approach)

Distillation w/Quench Condensation NH_3 Recovery



Energy Flow	(% feed LHV)
$Q_{reactor}$	0%
Q_{column}	6.21%
$W_{chilled\ water}$	0.75%
TOTAL	6.95%

Note: 3 atm (upper limit to keep T column < 140 °C at bottom)

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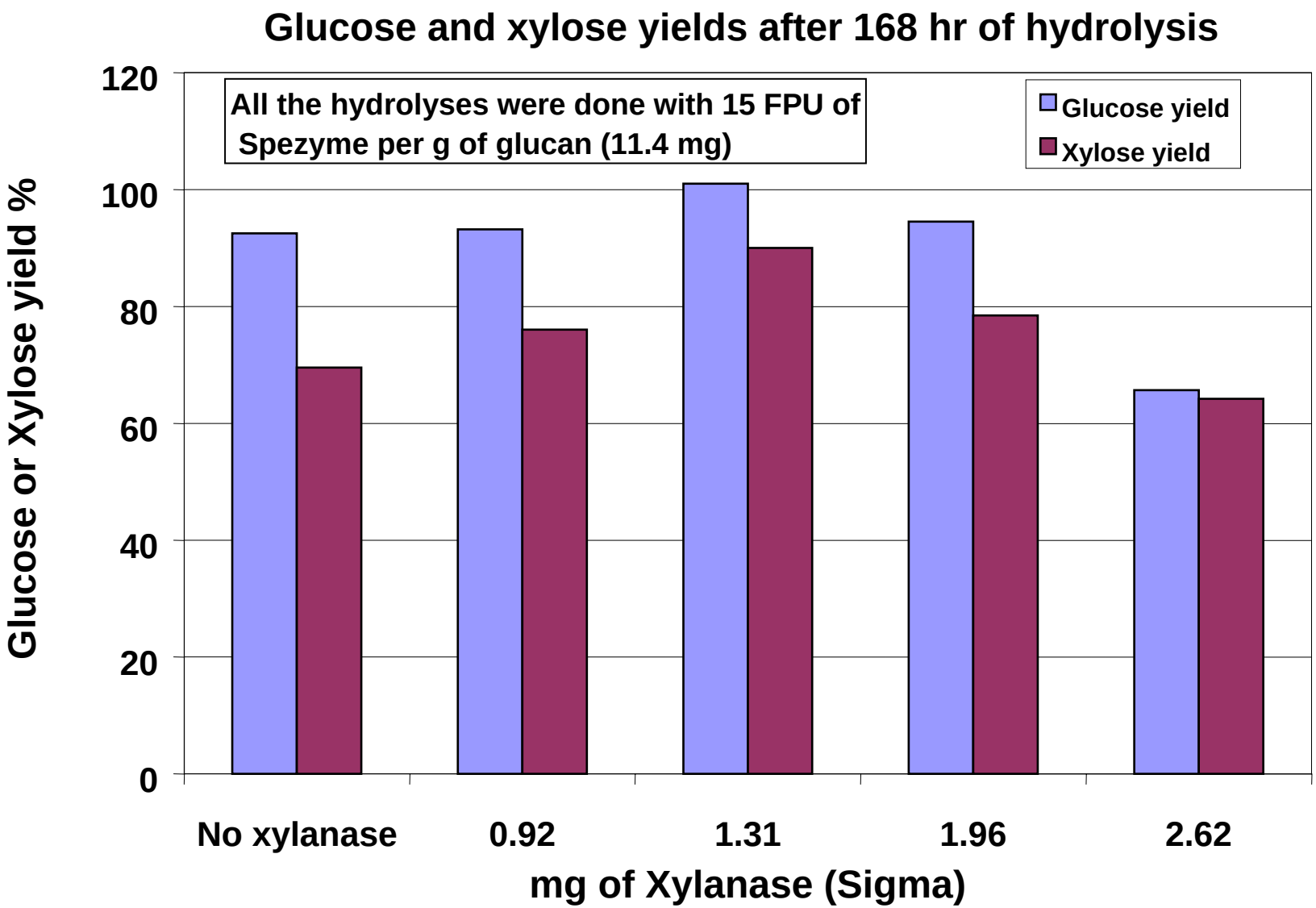
Effects of adding xylanase: AFEX treated corn stover



AFEX Pretreatment & CBP

- Have shown nearer term ("buildable today") results with AFEX and SSCF
- Have not yet exploited "enzyme cost lever"
  - Tailor enzyme mixture for AFEX treated biomass
  - Exploit cellulase/xylanase synergies for AFEX
- Longer term RBAEF approach "mature" technology would use
  - AFEX
  - CBP
  - Many other advances
- What do economics look like with these current and future advances?

Effects of AFEX Process Improvements: New Cost Estimates (w/out Reduced Enzyme)*

Abbreviation	Meaning
NREL-2004	SSCF, NH_3 Recompression, Old AFEX parameters
SSF-COMP-UPD	SSCF, NH_3 Recompression, Updated AFEX parameters
SSF-NEW-UPD	SSCF, New NH_3 Recovery approach, Updated AFEX parameters
CBP-NEW-UPD	CBP, New NH_3 Recovery approach, Updated AFEX parameters
Fully Mature	Cost 70% Feedstock, 30% Processing

*Assumes 2,200 tons per day scale

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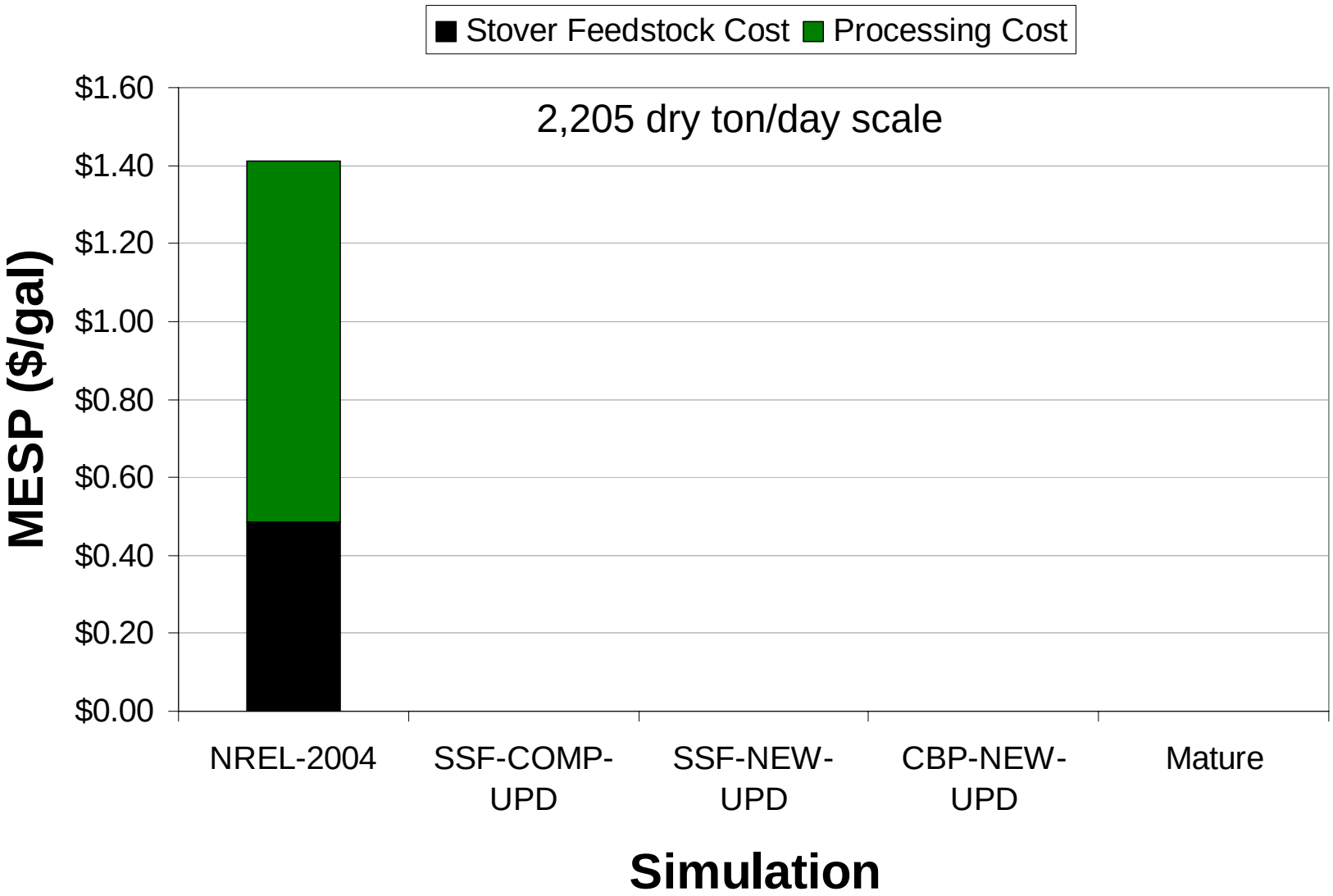
Final Results



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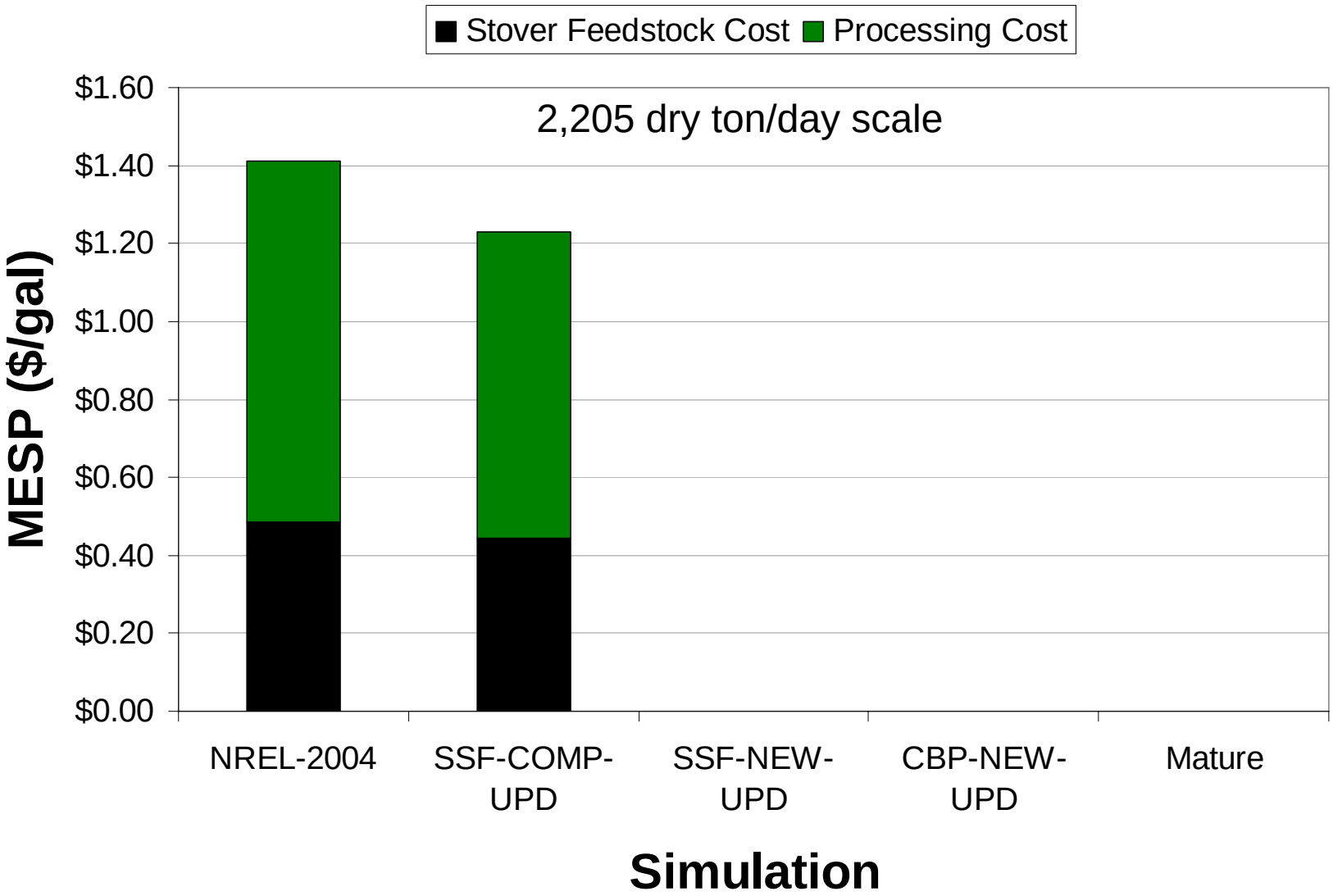

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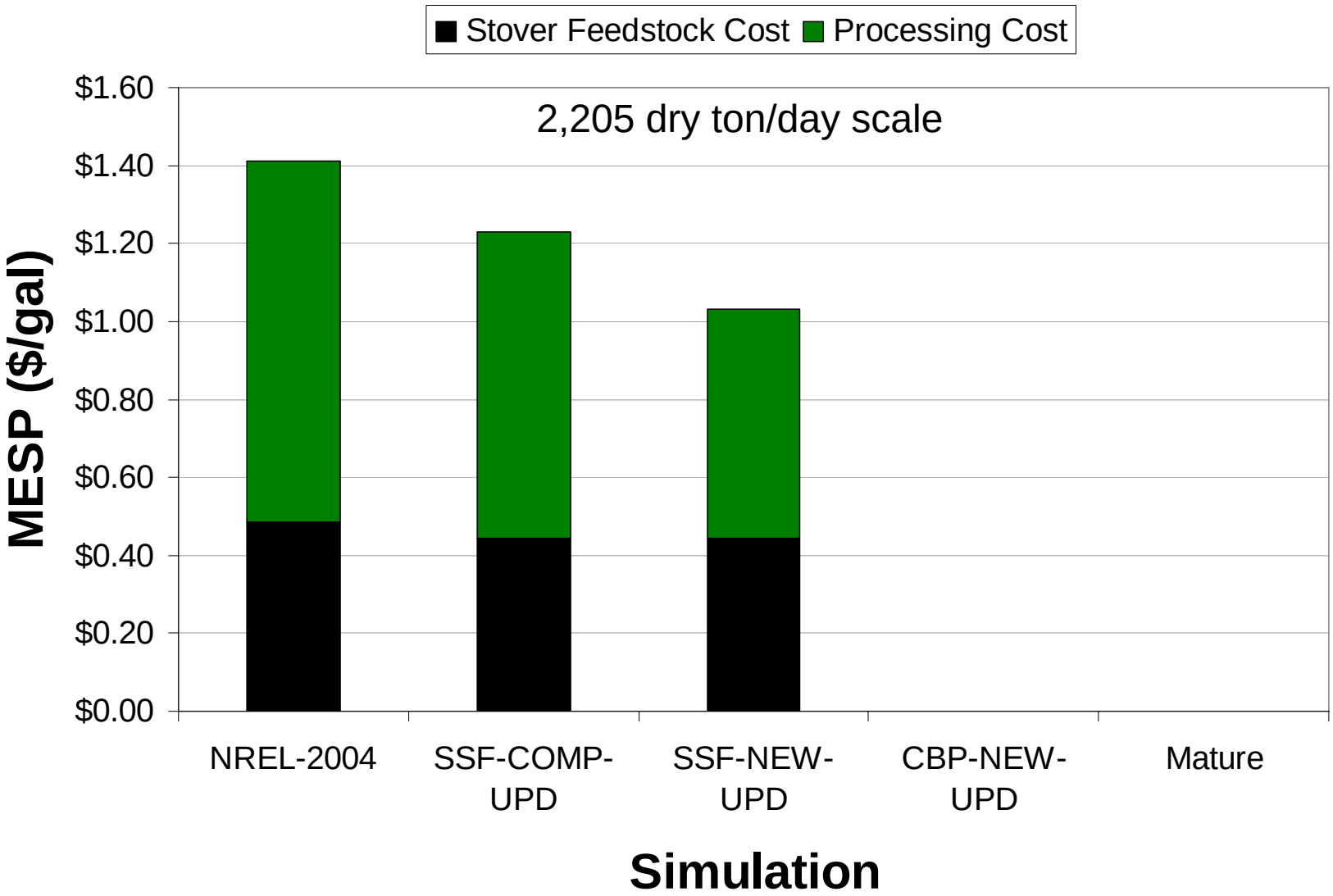

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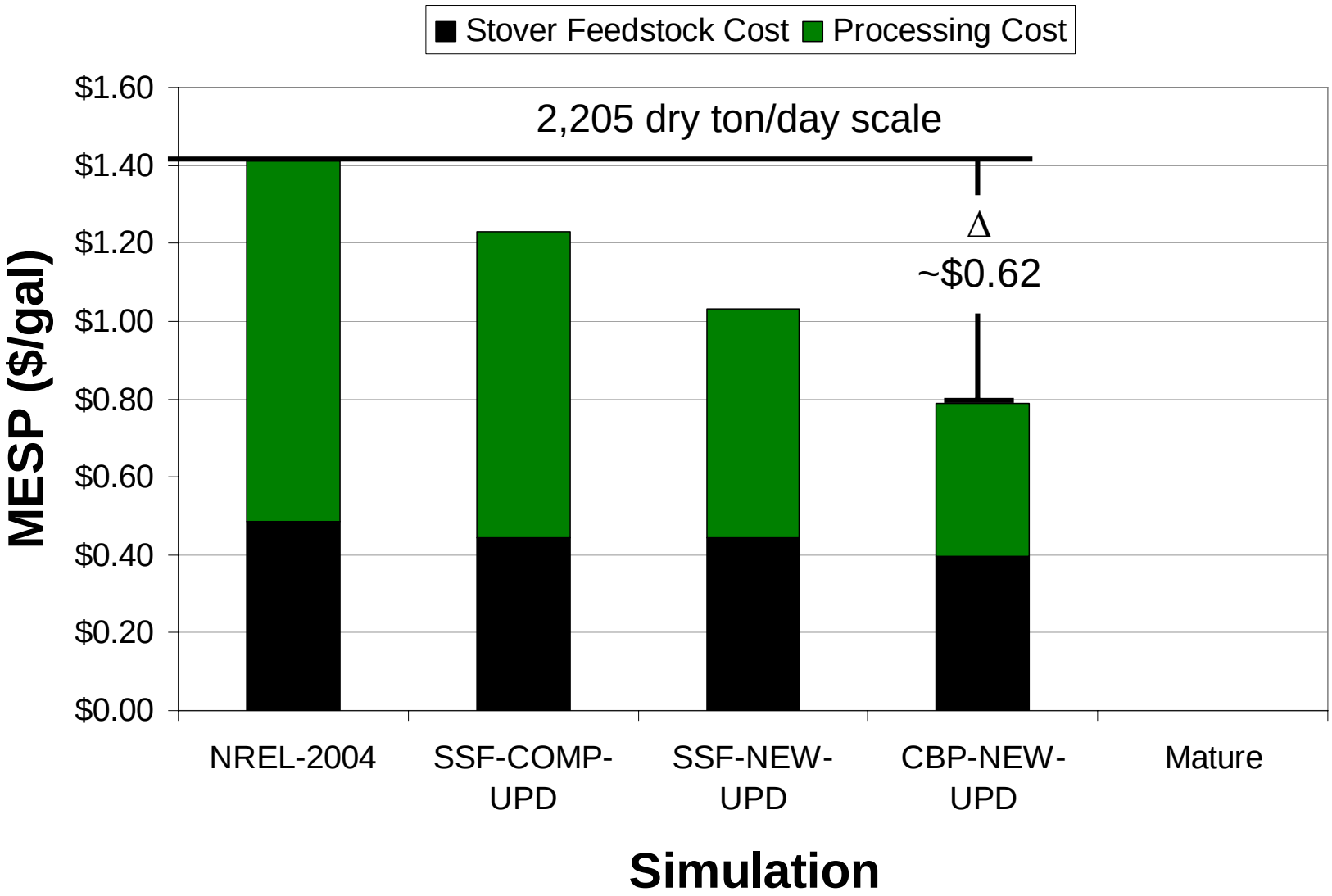

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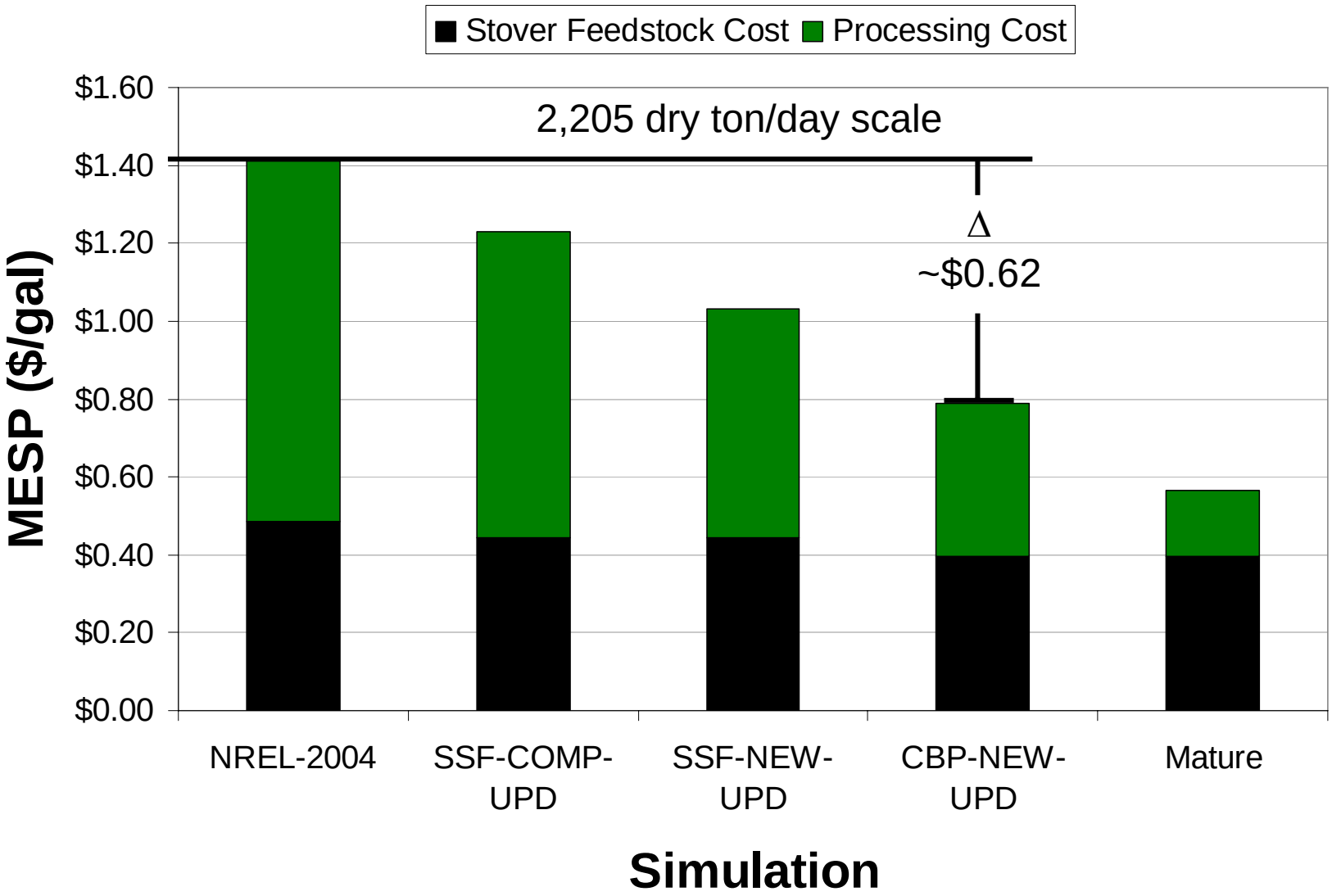

In Summary

- Large scale cellulosic ethanol is nearer than many think
  - Processes improving rapidly: pretreatment, enzymes, fermentations
  - Favorable raw material costs
- Increased awareness of oil “externalities”
- Venture capital & (we hope) increased R&D funding
- $60 per barrel (and up) oil
- High level political support

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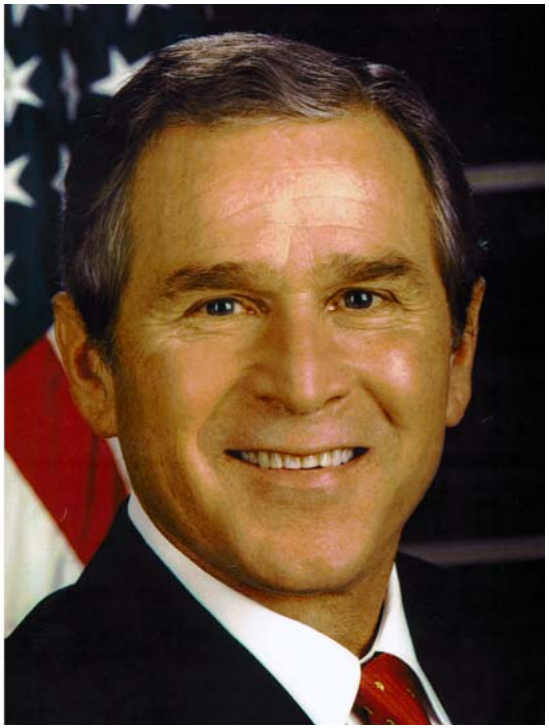

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Questions?

- Thank You for Your Attention
- Thanks to All Our Collaborators
- For Further Information Visit www.everythingbiomass.org

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Relative Cost Contribution by Area: Processing Dominates (NREL 2005)