Biomass Energy Systems of the Future

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Growing the Bioeconomy

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August 28, 2006

Changing Times for Biomass Energy (& Advocates)

Now

Energy concern widespread

Biomass energy is hot!

- **Increasingly seen as major player**
- **Corn ethanol booming**
- **VC investment**

Many looking (scrambling?) to position themselves

- **Government**
- **Industry (new value chains)**
- **Investors**
- **Academia/researchers**
- **Farmers**

We need to:

Educate ourselves/each other

Increase strategic clarity

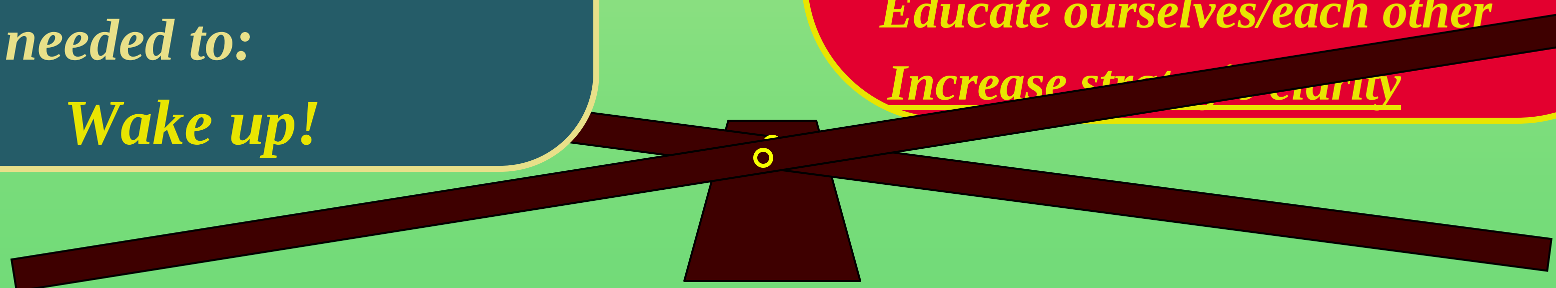
Then

Limited sense of urgency about energy

Few anticipated more than modest biofuel contribution

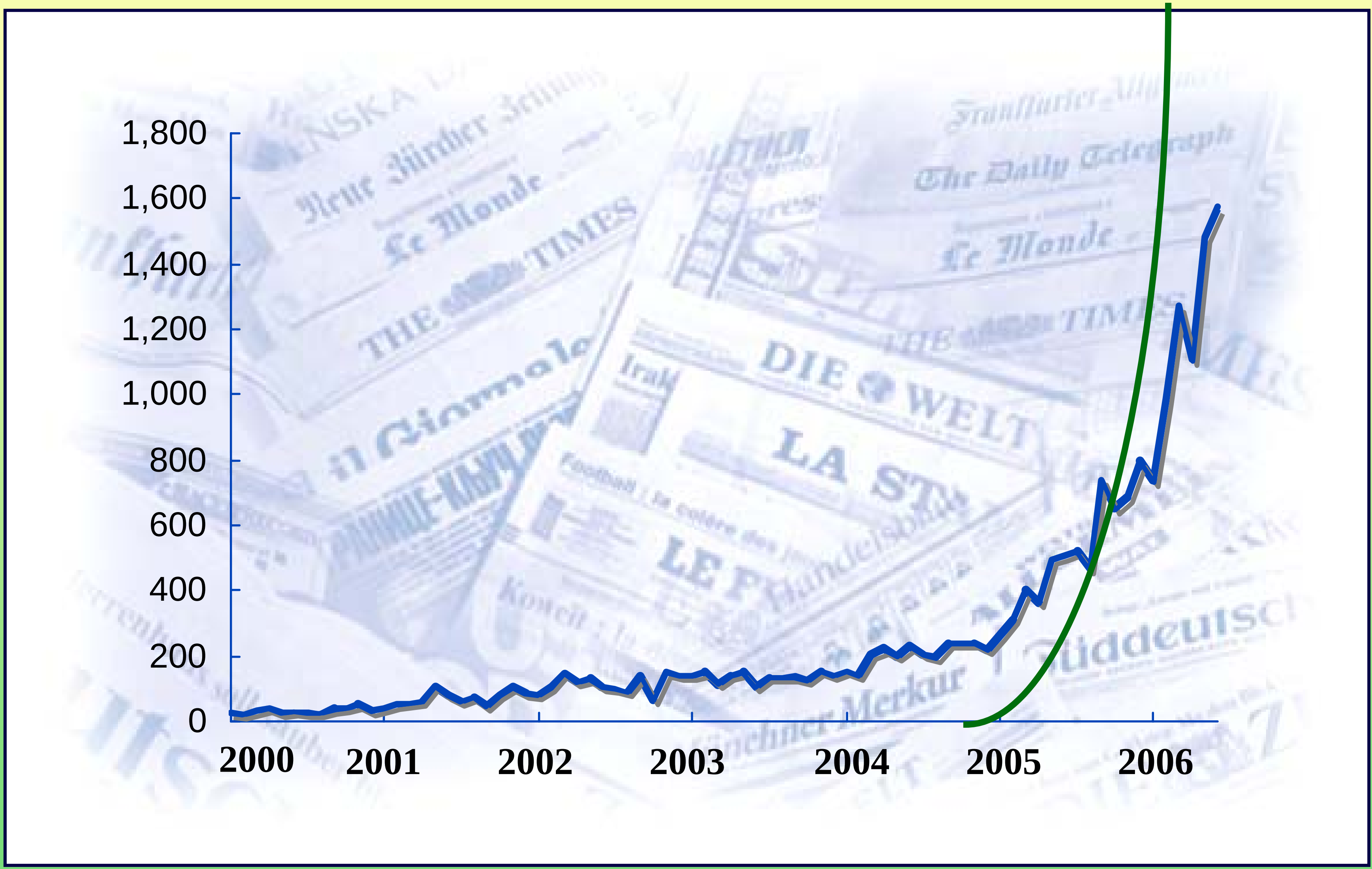
We needed to:

Wake up!



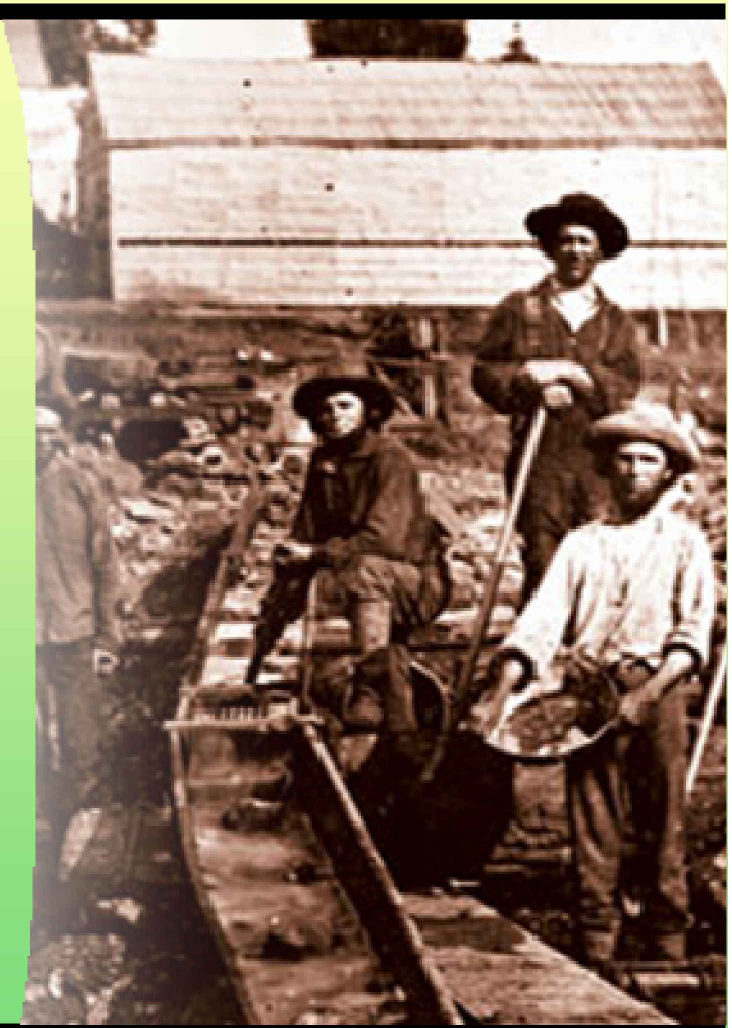
Monthly press mentions of industrial biotech ***(Jens Riese, McKinsey)***

Relative mention of cellulosic ethanol ***(My estimate)***



The gold rush is on…

ADM
Cargill
Chevron
bp
Shell
TOTAL
DUPONT
ceres
Genencor International, Inc.
ABENGOA
IOGEN TECHNOLOGIES
novozymes
syngenta
BR PETROBRAS
crop. energies
Bayer
Lurgi



Courtesy Jens Riese, McKinsey

Some Questions

What products should we be focusing on?

What feedstocks should we be focusing on?

What will mature biomass conversion systems look like?

How will mature biomass conversion systems perform?

Can bioenergy be practiced on a large enough scale to impact mega issues?/
How might agriculture be reimagined to respond to this challenge & opportunity?

Emphasis

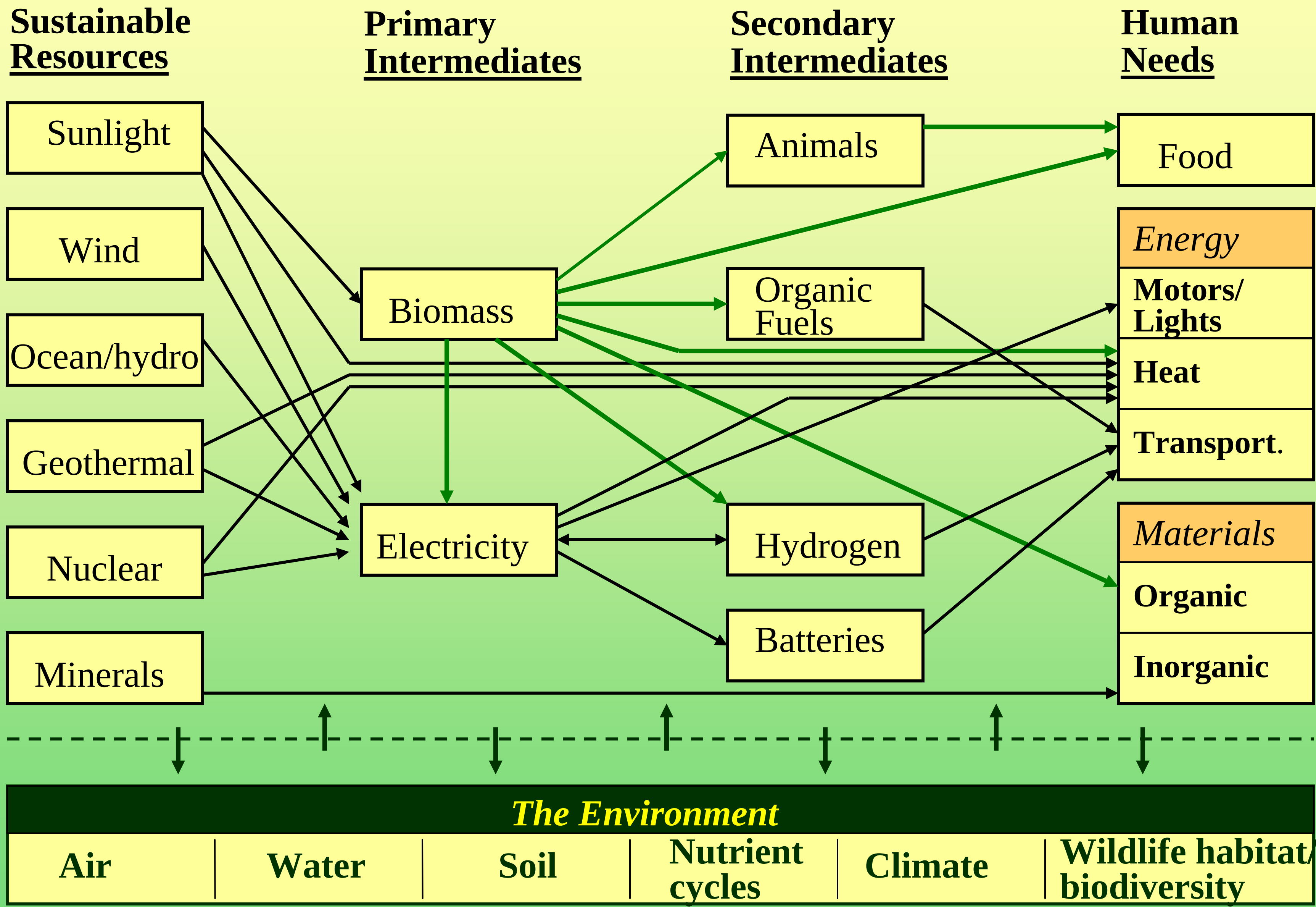
Mega issues

- **Sustainability - especially climate**
- **Energy security - which means oil**
- **Farm economy - contributions, benefits related to sustainability & security**

Long term

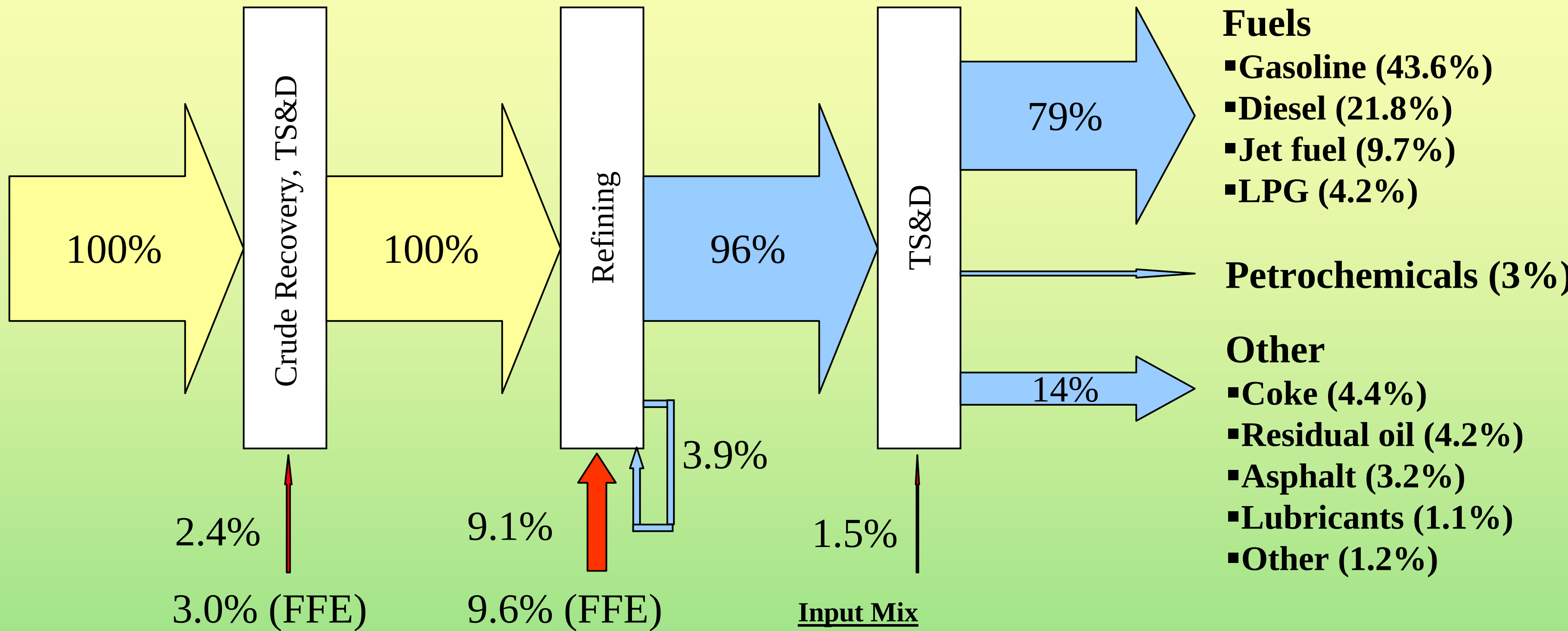
What products should we be focusing on?

Imagining a Sustainable World



Oil Refining

(Numbers Denote Energy Flows)



Input Mix

Crude	**1%**
Residual oil	**1%**
Diesel	**15%**
Gasoline	**2%**
Natural gas	**62%**
Electricity	**19%**

Input Mix

Coal	**13%**
Residual oil	**3%**
Gasoline	**2%**
Natural gas	**78%**
Electricity	**4%**

Input Mix

Diesel 100%

Energy must be impacted for biomass conversion to offer more than small energy security & climate benefits

Sources:

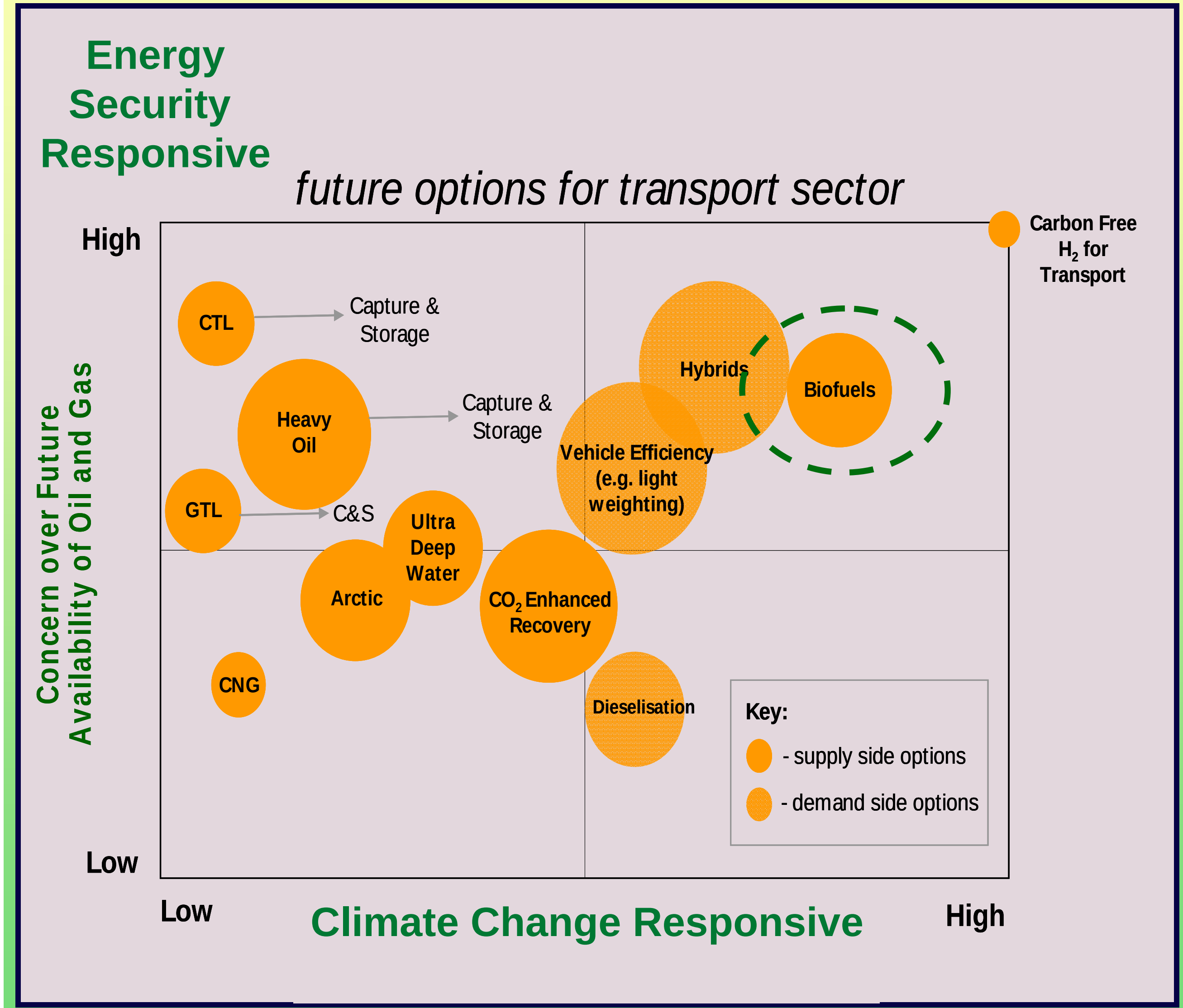
External energy inputs/efficiencies: GREET

Refinery outputs: API

Hierarchy of Biomass end-uses

End Use	Availability of Alternatives		Biomass Uniquely Suited?	Size of Demand (relative)
	Non-Sustainable	Sustainable		
Food	No	No	Yes	Large
Organic Materials	Yes	No	Yes among sustainable	Small
Transportation Energy Storage				Large
Liquid @ 1atm	Yes	No	Yes among sustainable	
Non-liquid	Yes	Yes	No	
Electricity	Yes	Yes	No	Large
Heat	Yes	Yes	No	Large

Biofuels: The Only Supply-Side Option Available to Address Both Security & Climate Concerns (BP)



Bio-Fuels Value

- Belief that hydrocarbons will remain dominant (energy density, existing infrastructure, cost)
- Multiple options to increase supply of transport fuels
- But limited options to reduce carbon impact
- On supply side only biofuels have potential
- Other demand side options (e.g. hybrids)

Courtesy Paul Bennett, BP

What feedstocks should we be focusing on?

Different Plant Feedstocks are Responsive to Different Objectives

	Large Scale Production		Rural Economic Development		Petroleum Displacement (Security)		Fossil Fuel Displacement/ GHG Reductions		Soil Fertility & Ag. Ecology	Low Cost Fuels (feedstock & conversion)	
	Per unit	Total	Now	Future	Per unit	Total	Per unit	Total		Now	Future
Cellulosic	very good	very good	fair	excellent	excellent	excellent	excellent	excellent	excellent	fair	excellent
Starch-rich	very good	fair	very good	good	excellent	good	fair	fair	fair	good	good
Sugar-rich	good	fair	very good	good	excellent	good	good	fair	very good	good	good
Oil seed	poor	poor	good	fair	good	poor	good	poor	good	poor	poor

Ratings:

- excellent
- very good
- good
- fair
- poor

Cellulosic biomass is the focus of all studies foreseeing (very) large-scale widespread energy supply from plants.

- **Environmentally benign/beneficial production; low inputs**
- **Low purchase cost**
- **New opportunities for ag. integration; Broad site range**
- **Large-scale production --> large benefits**

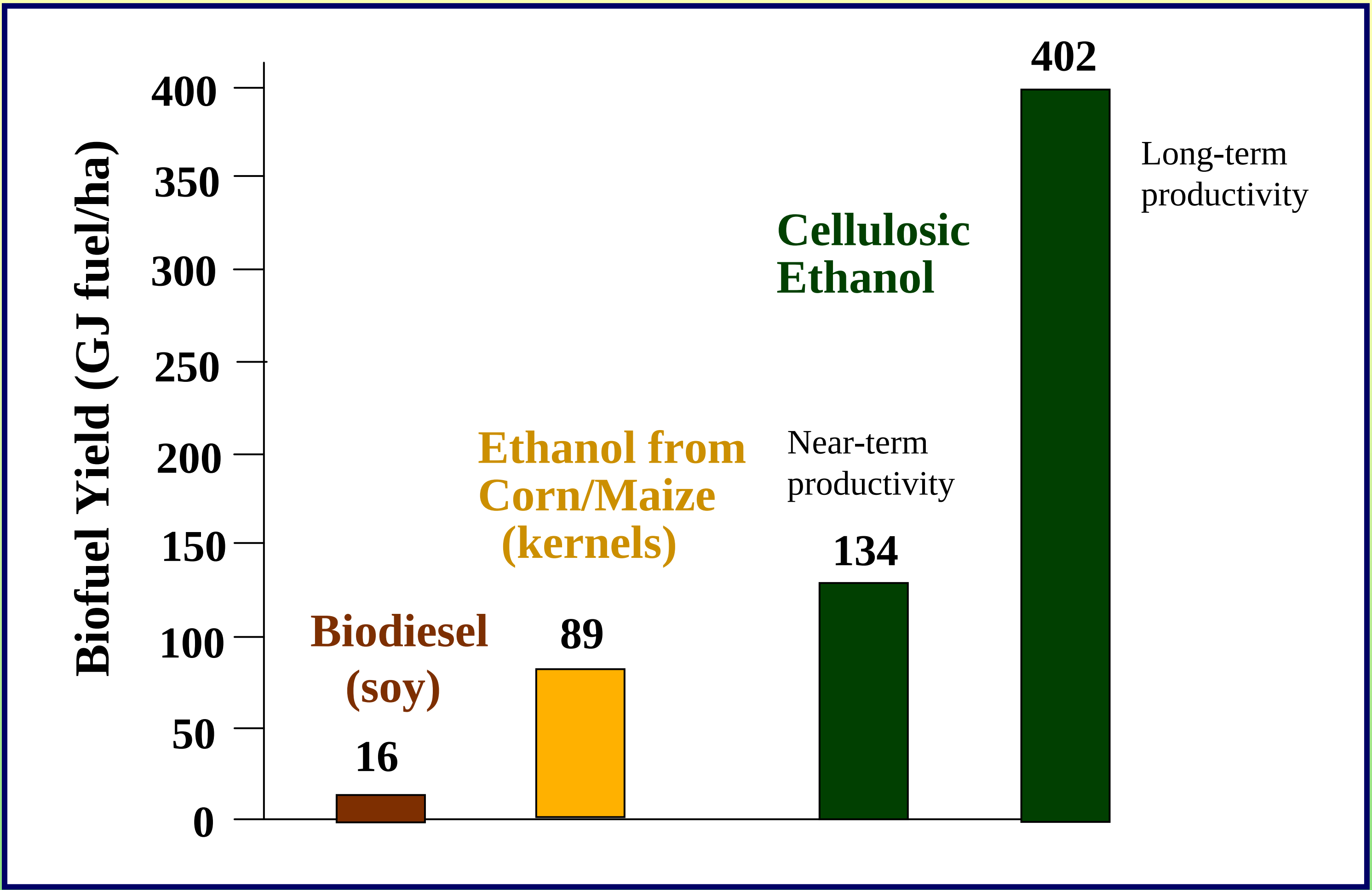
Biomass Feedstocks, Especially Cellulosic, are Cost Competitive with Oil & Gas

Energy Carrier	Price: Common	Price: $/GJ	Cost/Difficulty of Subsequent Conversion
Fossil			
Petroleum	$50/bbl	$8.8	Low
Gasoline	$1.67/gal[a]	$13.8	-
Natural gas	$7.50/scf	$7.9	Low
Coal	$20/ton	$0.94	Moderate to high; Higher w/ CO_2 capture
Electricity	$0.04/kWh	$11.1	Very low for many applications; High for storage as H_2, batteries
Biomass			
Soy oil	$0.23/lb	$13.8	Very low
Corn kernels	$2.25/bu	$6.5	Low
Cellulosic crops[b]	$50/tonne	$2.5	High now; Moderate/low in the future
Cellulosic residues	≤ crops, so[...]		High now; Moderate/low in the future

[a]Wholesale

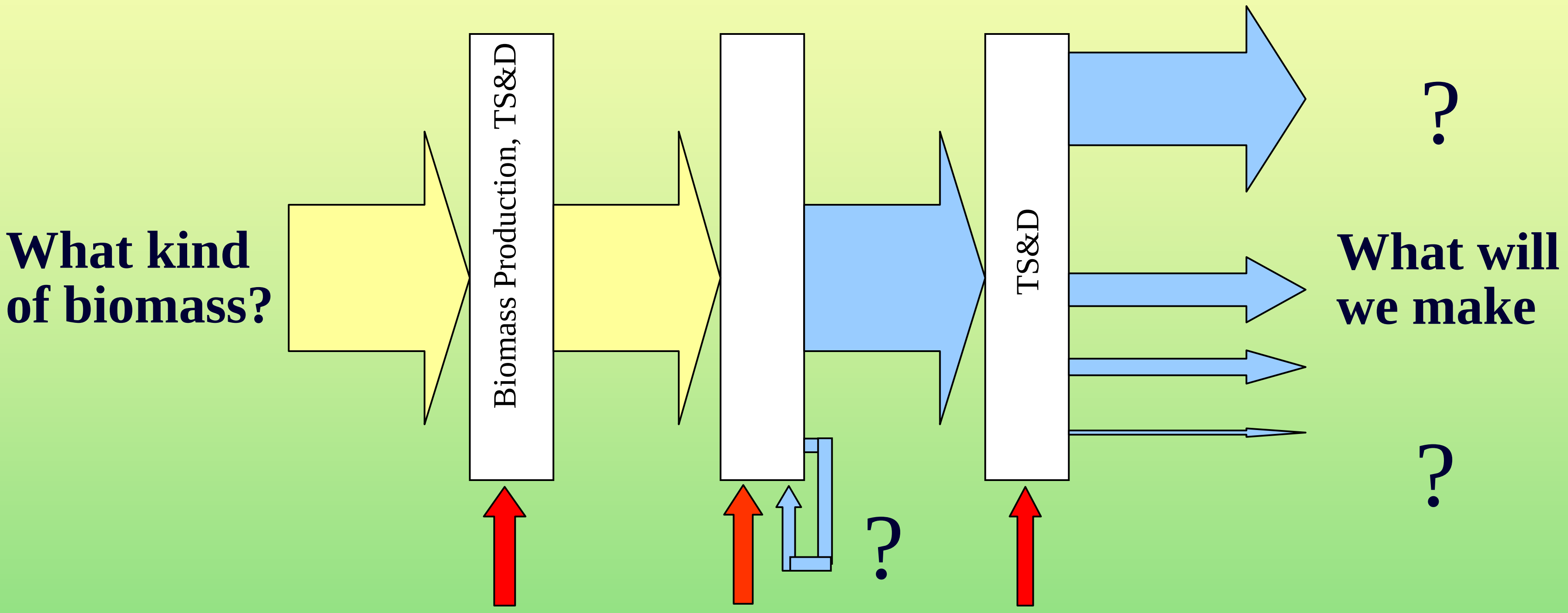
[b] e.g. switchgrass, short rotation poplar

Comparative Land Productivity of Biofuel Options



<u>Crop Yields (U.S.)</u>	<u>Fuel Yields</u>
Near-term celllulosic: 5 dry ton/acre	Cellulosic ethanol from RBAEF
Long-term cellulosic: 15 dton/acre	Corn ethanol: 2.8 gal/bushel
Corn yield: 160 bushel/acre	Soy oil: 18% of bean (dry basis)
Soy yield: 42 bushel/acre	Biodiesel yield: 0.95 kg/kg soy oil

What will mature biomass conversion systems look like?



What inputs will be required?

What will it cost?

The Role of Biomass in America's Energy Future (RBAEF) Project

Multi-institutional

- Dartmouth
- Argonne National Lab
- National Renewable Energy Lab
- Union of Concerned Scientists
- University of Tennessee
- Natural Resources Defense Council
- Michigan State University
- Princeton
- USDA Agricultural Research Service
- Oak Ridge National Lab

Multi-sponsor

- Department of Energy
- The Energy Foundation
- National Commission on Energy Policy

Objectives

Identify & evaluate paths by which biomass can make a large contribution to future demand for energy services.

Determine what can be done to accelerate biomass energy use and in what timeframe associated benefits can be realized.

Framing Biorefinery Analysis

Broad range of technologies (but not all) considered in a common framework.

Emphasis on *mature technology*

What: Asympotic state such that further research & experience yield but incremental improvement in cost/benefit realization.

Evaluation: Knowledgeable optimist's most likely estimate.

Importance: More important to know where we *can get* than where we *are* to evaluate

- **Appropriate levels of research effort, policy intensity for biomass-based options.**
- **The potential contribution of biomass to a sustainable world.**

RBAEF Process Analysis

Material & Energy Balance Models

Implemented using ASPEN

Build on extensive prior work

- **Princeton (thermochemical fuels & power)**
- **NREL & Dartmouth (ethanol)**

Basis for

Thermodynamic analysis "energy balance"

Material flows for environmental analysis

Economic analysis

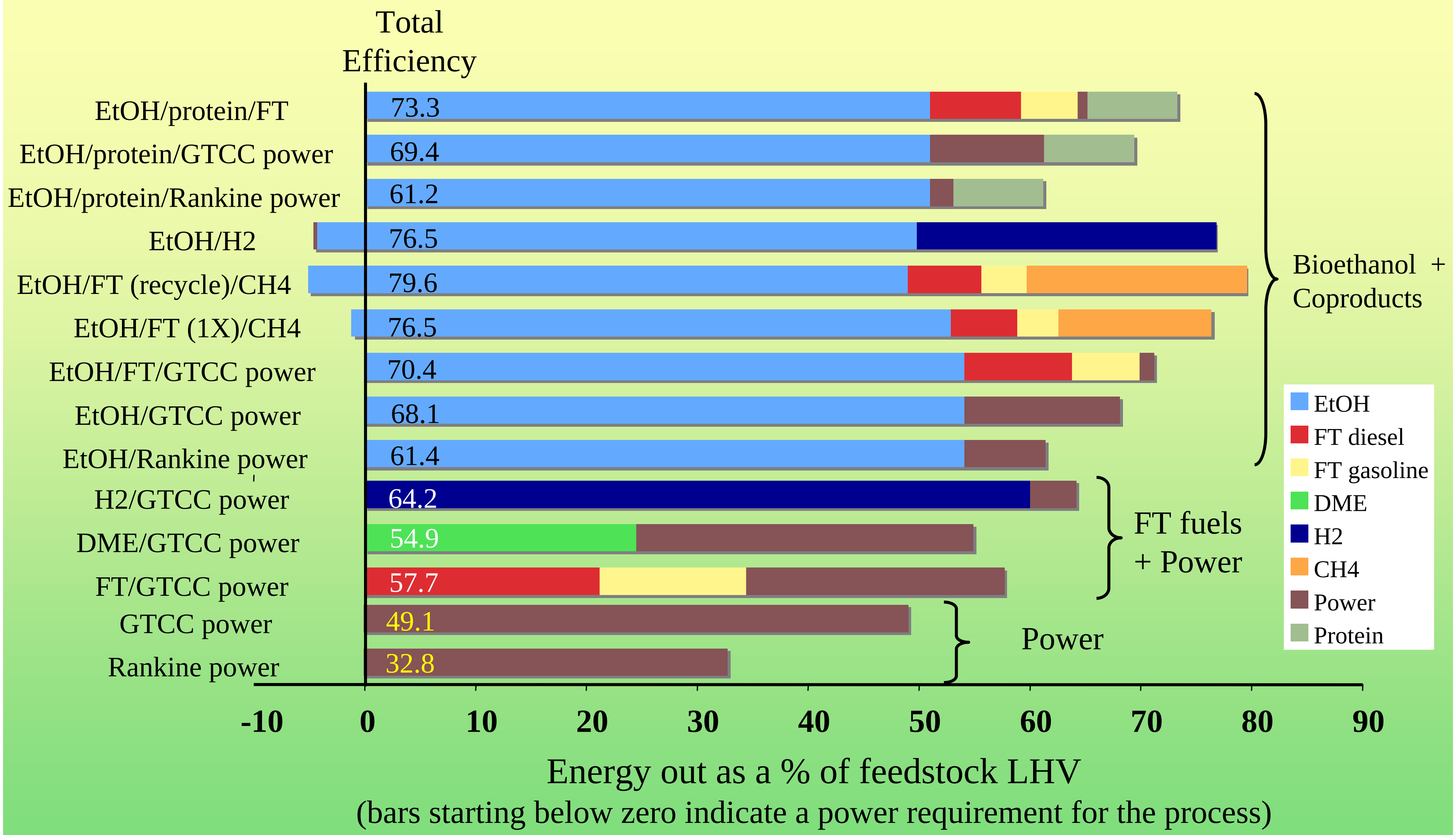
~8 person-year effort undertaken jointly by Dartmouth, Princeton

24 different scenarios including many products & combinations

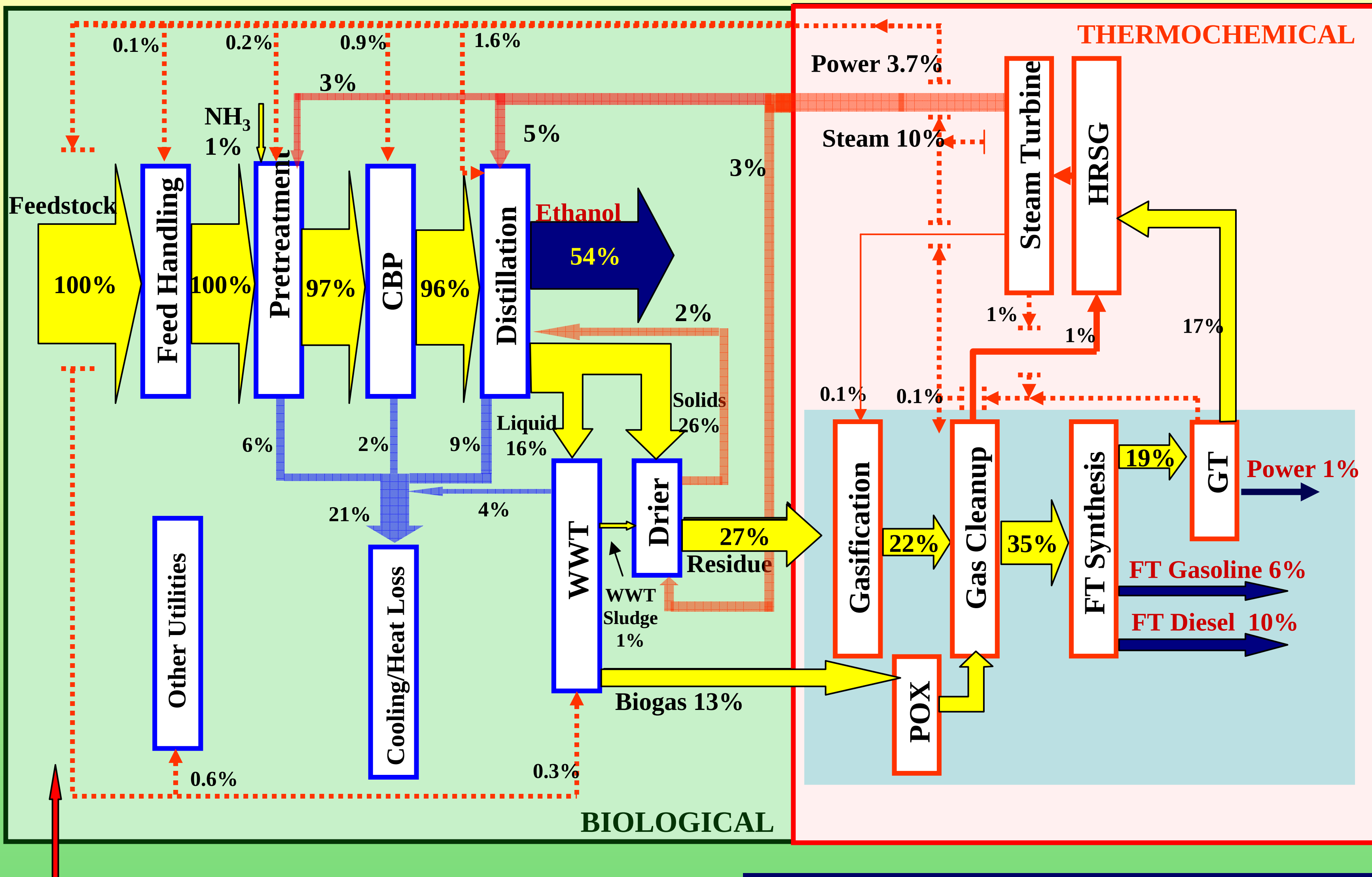
- **Electrical power**
- **Fischer Tropsch Fuels**
- **Ethanol**
- **Hydrogen**
- **Dimethyl ether**
- **Light gases**
- **Animal feed**

Unprecedented for mature biomass conversion technologies

Efficiency of Mature RBAEF Process Scenarios



Mature Biomass Refining Energy Flows (one of 24 scenarios)

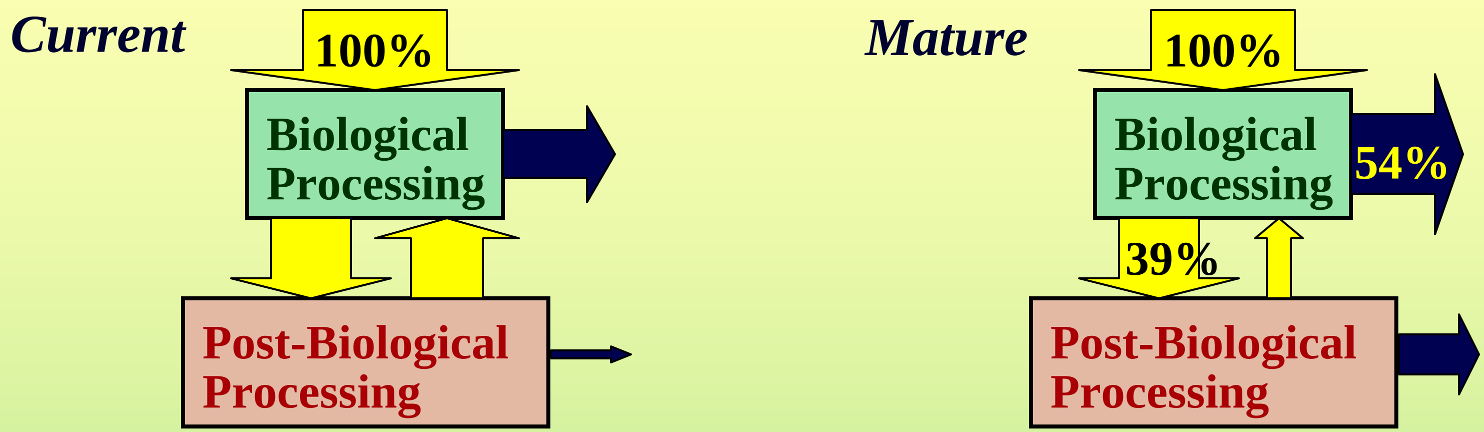


Ag Inputs (Farming, feedstock transport) ~ 5 %

Energy out/Ag inputs in = 71/5 = ~14

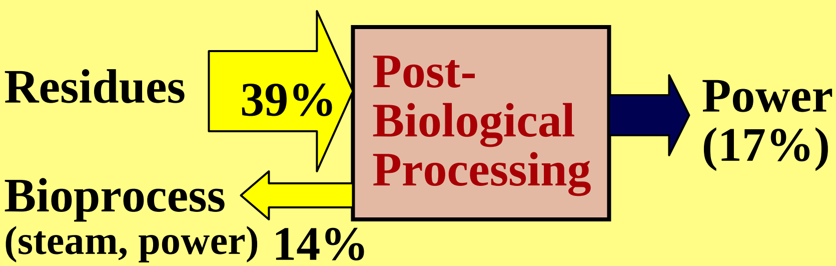
Integration of TC and Biological Processing Offers Lots of Value

Maturation of biological conversion --> much larger opportunities



Internal cogeneration - most energy for biological processing is from *waste* heat accompanying power and/or FT fuel production

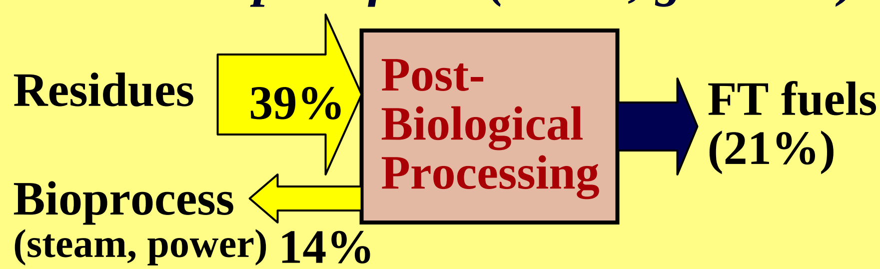
Power



$$\eta_{power} = 17/(39 - 14) = 0.68$$

<u>Large</u> baseload power contribution, compliments intermittent sources

Fischer-Tropsch fuels (diesel, gasoline)

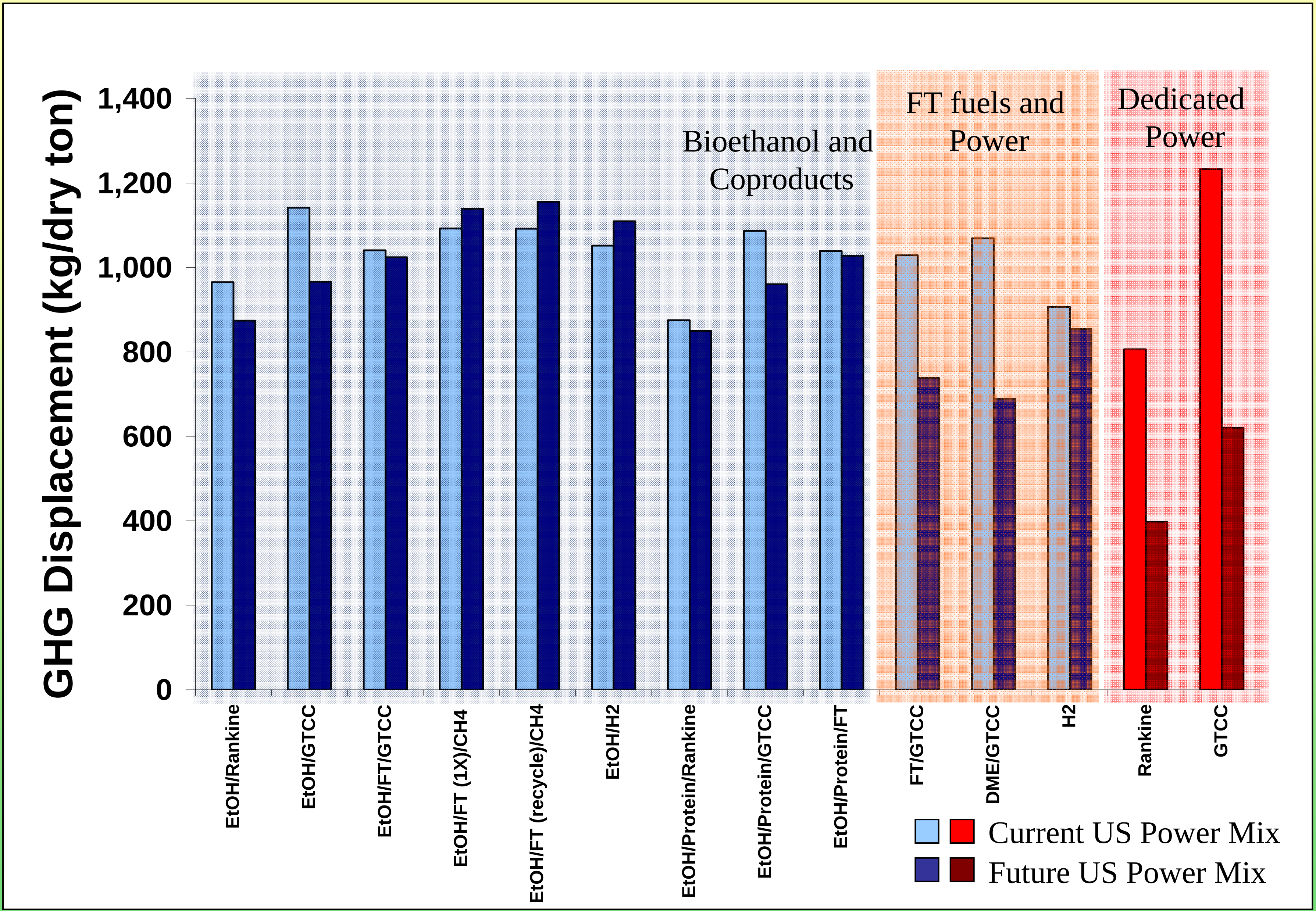


$$\eta_{FTfuels} = 21/(39 - 14) = 0.84$$

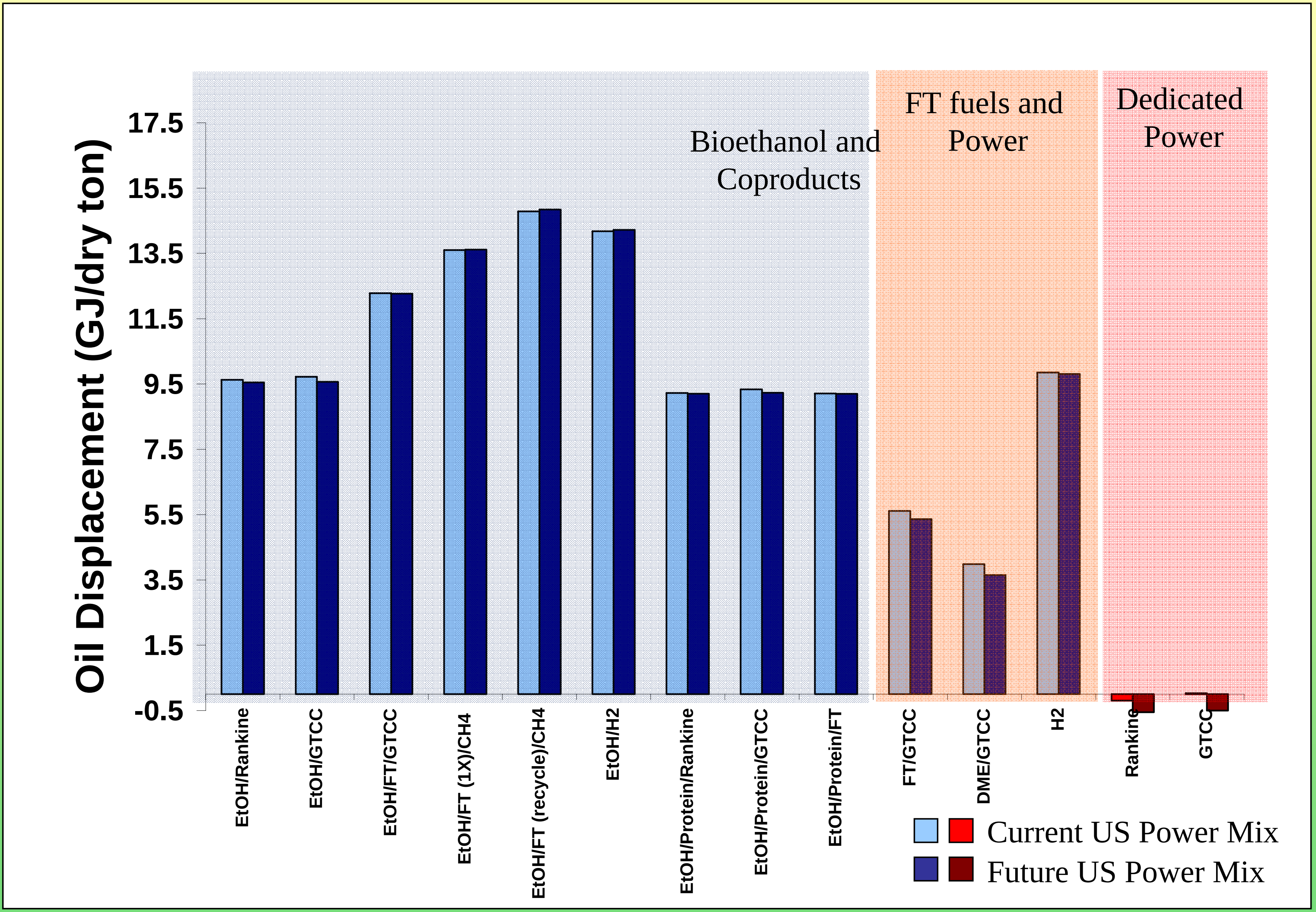
E90 entirely from renewables

How will advanced biomass conversion systems perform?

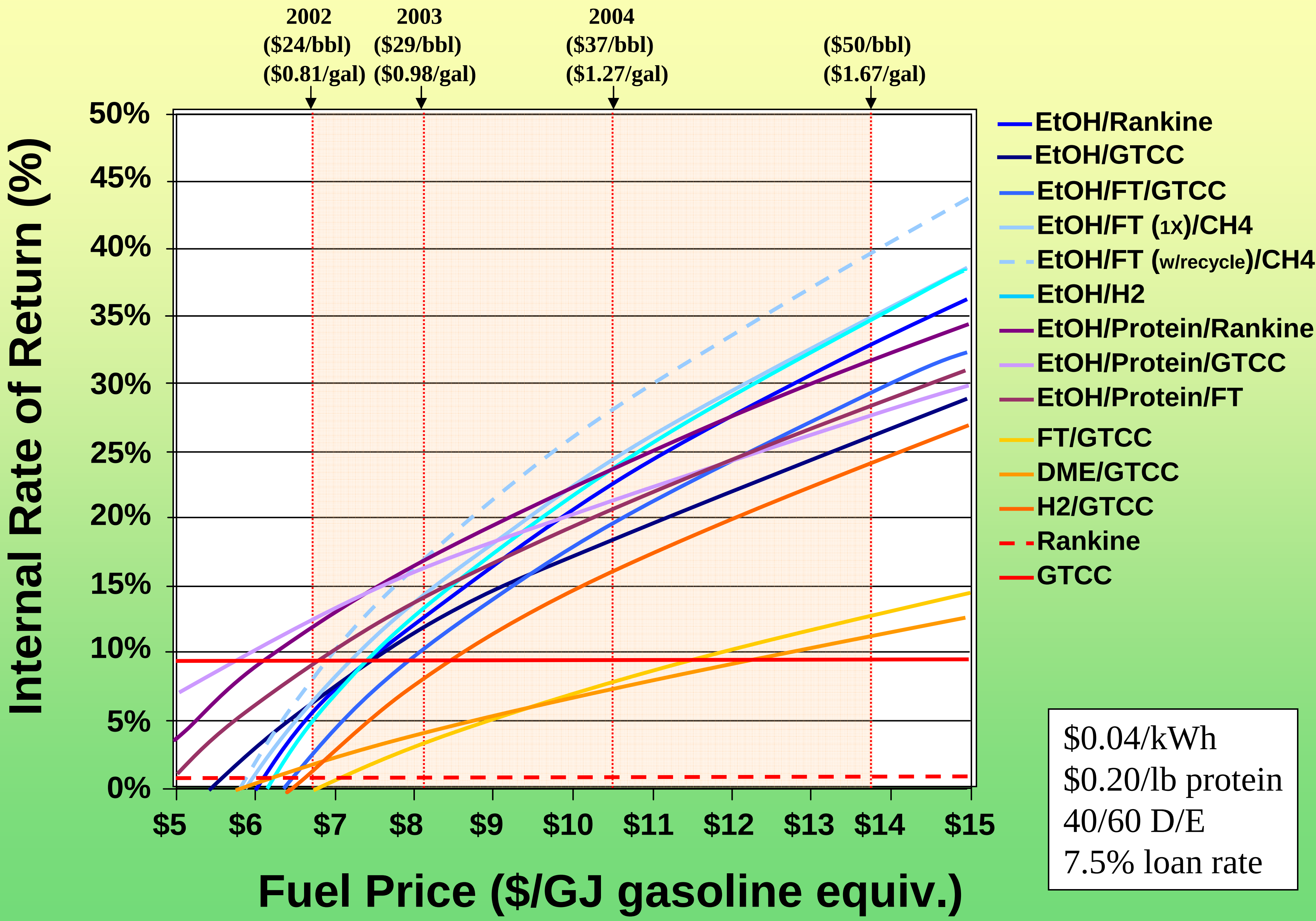
Comparative Greenhouse Gas Displacement



Comparative Petroleum Displacement

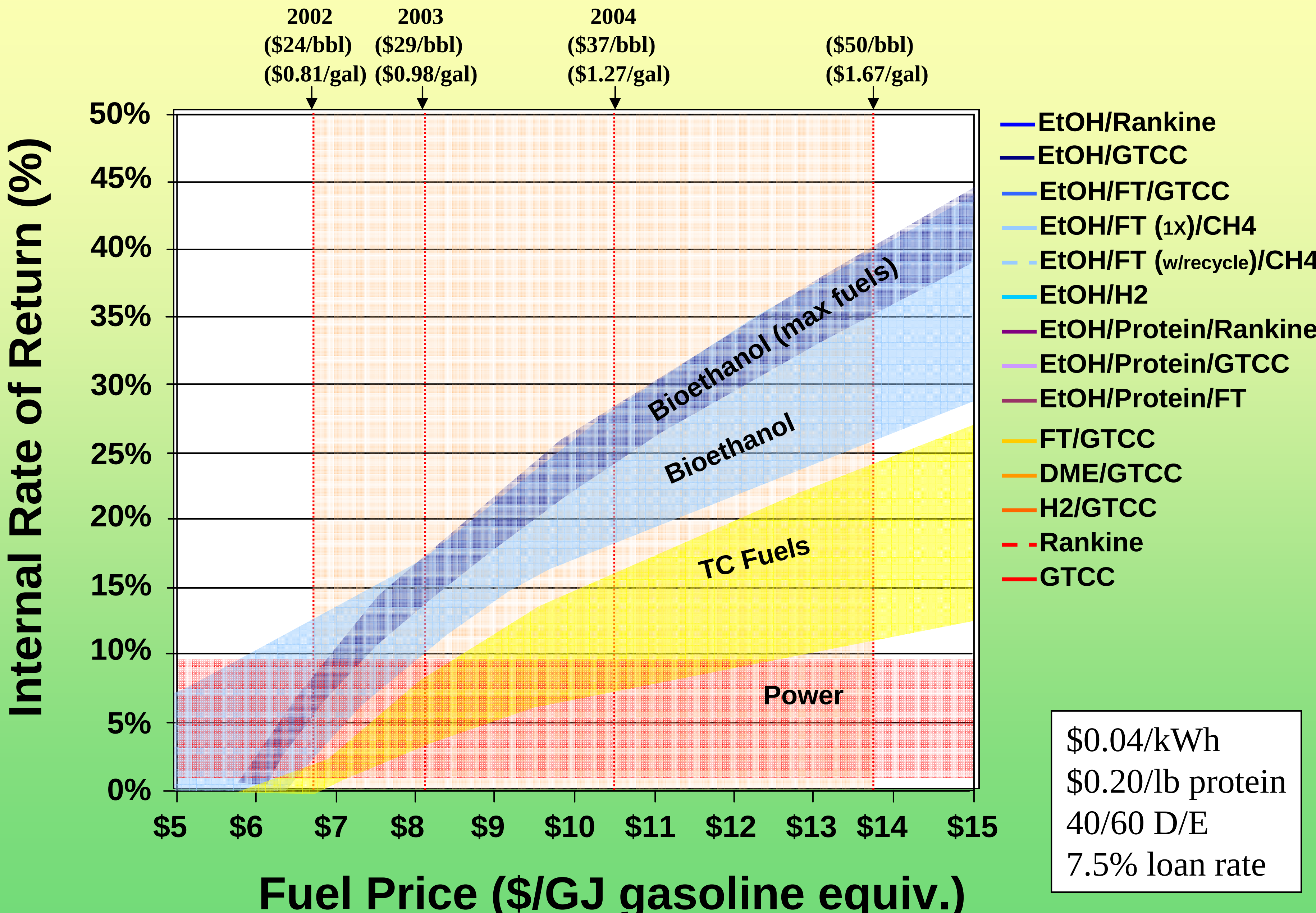


Scenario Comparison: Fuel price variable, power price constant, 5,000 tpd



$0.04/kWh
$0.20/lb protein
40/60 D/E
7.5% loan rate

Scenario Comparison: Fuel price variable, power price constant, 5,000 tpd



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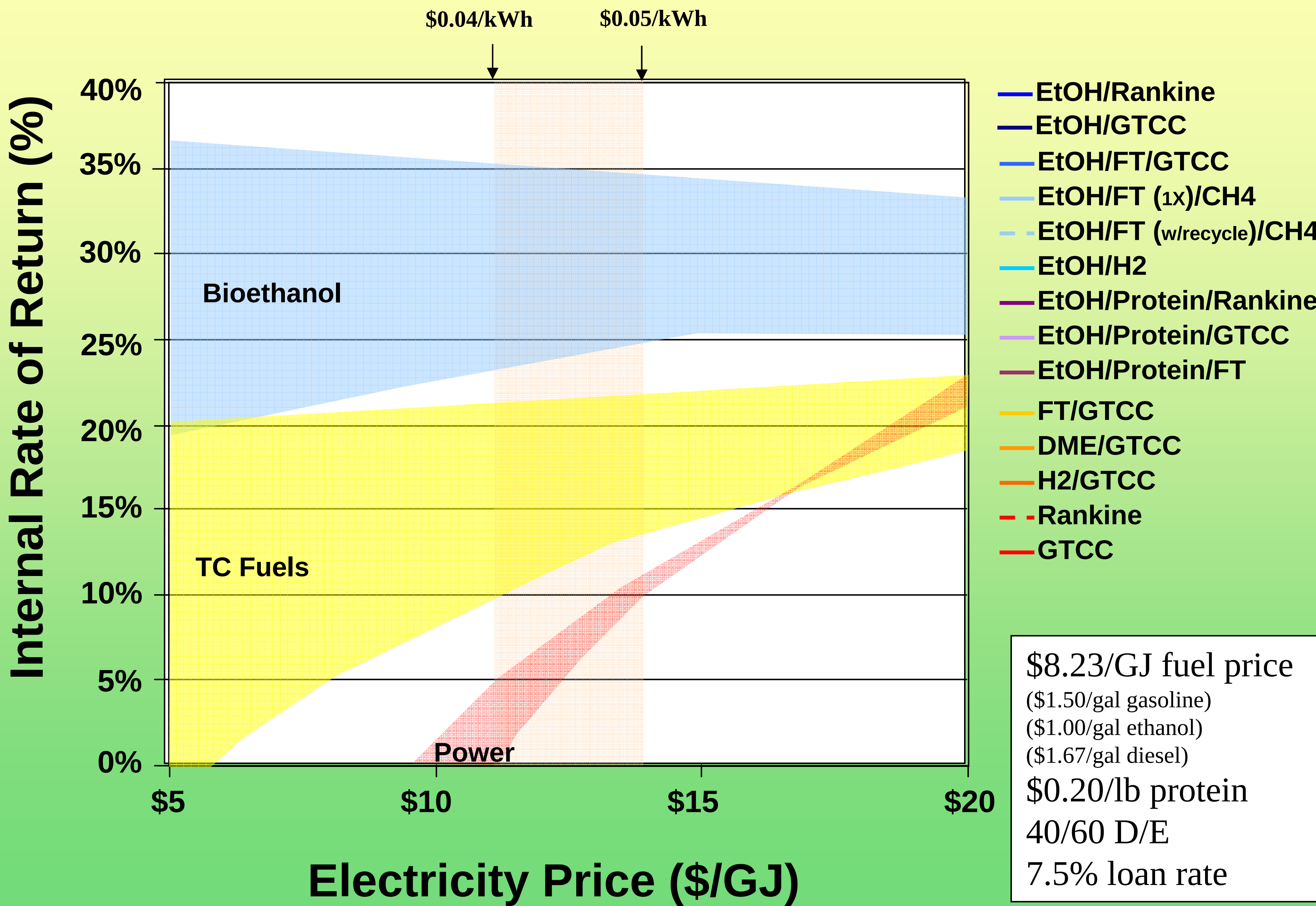


$8.23/GJ fuel price
($1.50/gal gasoline)
($1.00/gal ethanol)
($1.67/gal diesel)
$0.20/lb protein
40/60 D/E
7.5% loan rate

Can bioenergy be practiced on a large enough scale to impact mega issues?

$$\text{Benefits } (+\text{or}-) = \left(\frac{\text{Benefits}}{\text{Unit Utilized}}\right) \times \left(\text{Units Utilized}\right)$$

Normalized Metrics

e.g. per ton, per gallon, per mile, per acre

Life cycle analysis a prominent example

Many biomass-based energy options score very well

Resource Sufficiency

An acre devoted to bioenergy production is not available exclusively for

- **Food production**
- **Wildlife habitat/biodiversity**
- **Recreation**

A greater challenge

How might agriculture be reconfigured to respond to this challenge & opportunity?

Resource Sufficiency: Radically Different Conclusions

Large contribution possible & desirable

United States

Biomass will eventually provide over 90% of U.S. chemical and over 50% of U.S. fuel production (NRC, 1999*, Biobased Industrial Products,*).

20% of petroleum demand in 2025 (Lovins et al., 2004, *Winning the Oil End Game*).

1.3 billion tons of biomass could be available in the mid 21st century - 1/3 of current transport fuel demand (Perlack et al., 2005, *"Billion Tons Study"*).

50 % current transportation sector energy use, and potentially nearly all gasoline, by 2050 (Greene et al., 2004, *Growing Energy*)

Goal of 100 billion gallons of ethanol by 2025 (Ewing & Woolsey, 2006, *A High Growth Strategy for Ethanol)*

Worldwide

Biomass becomes the largest energy source supporting humankind by a factor of 2 (Johanssen et al., 1993, *Renewables-Intensive Global Energy Scenario*).

Biomass potential comparable to total worldwide energy demand (Woods & Hall, 1994; Yamamoto, 1999; Fischer & Schrattenholzer, 2001; Hoogwijk et al., 2005)

Resource Sufficiency: Radically Different Conclusions

Large contribution not possible and/or not desirable

David Pimentel's group (8 papers, 1979 to 2002)

"Use of biomass energy as a primary fuel in the United States would be impossible while maintaining a high standard of living"

"Large-scale biofuel production is not an alternative to the current use of oil and is not even an advisable option to cover a significant fraction of it."

Others

Power density of photosynthesis is too low for biofuels to have an impact on greenhouse gas reduction (Hoffert et al., 2002)

Impractically large land requirements for biomass energy production on a scale comparable to energy/petroleum use (Trainer, 1995; Kheshgi, 2000; Avery, 2006)

2030: Ethanol (corn and cellulose) 2.5% of transportation energy - 2% of this cellulosic (EIA, 2006)

Any substantial increase in biomass harvesting for the purpose of energy generation would deprive other species of their food sources and could cause collapse of ecosystems worldwide (Huesemann, 2004)

Because of large land requirements, biofuels are not a long-term practical solution to our need for transportation fuels (Jordan and Powell, July 2006, *Washington Post*)

Understanding the Disparity of Resource Sufficiency Studies

The math is simple

$$NNL_{FP} = \left\{ \frac{VMT}{MPG \cdot Y_{P/F}} - I \right\} \frac{1}{P}$$

NNL_{FP}: Net new land, ignoring changed land for food production (acres)
VMT: Vehicle miles traveled (miles/yr)
MPG: Miles/gallon gasoline equivalent
$Y_{P/F}$: Process yield (gallons gasoline equivalent/ton dry biomass)
I: Feedstock produced from currently-managed lands (ton dry biomass)
P: Productivity of biomass production (tons/acre/year)

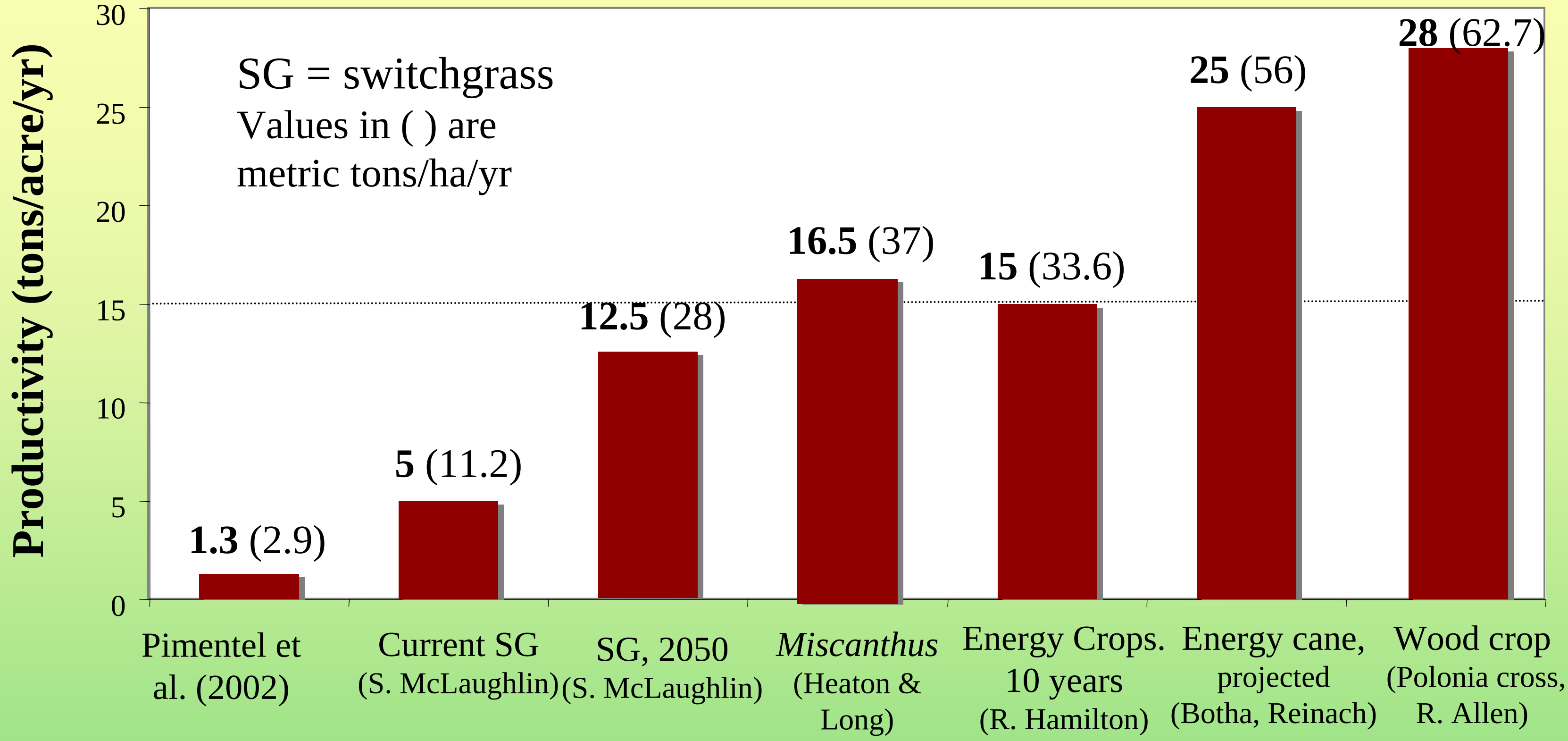
Understanding the Disparity of Resource Sufficiency Analyses… continued

The determining factor: values for input variables

Parameter	Least Efficient	Most Efficient	Ratio (Max/Min)	Source (High, Low)
VMT (billion miles, 2050)	6.1	4.5	1.4	“Car Talk” scenarios
MPG (LDV)	21	50	2.4	Current, D. Friedman
$Y_{P/F}$ (gallons/ton)	36	91	2.5	Recent NREL, RBAEF
I (tons)	0	600	Infinite	Many, “Billion tons”
P (tons/acre/year)	1.3	15	12	D. Pimentel, R. Hamilton
***NNL_{FP}** (million acres)*	**5,328**	**23**	**230**	

$$NNL_{FP} = \left\{ \frac{VMT}{MPG \bullet Y_{P/F}} - I \right\} \frac{1}{P}$$

Factors Impacting Biomass Feedstock Availability: Feedstock Productivity (*P*)



***Heaton and Long:* 3 site average in Illinois over 2 years, direct comparison with switchgrass (Cave-in-Rock), which averaged 4.6 tons/acre/yr**

Richard Hamilton (Ceres) *"[Available information]…*strongly suggest[s] that over the next decade or so the deployment of modern breeding technologies will result in average energy yields of at least 15 tons per acre, and that these averages can be sustained across a broad range of geographic and environmental conditions, including the approximately 75 million acres of crop and pasture land in the United States that could easily be converted to their cultivation without impacting domestic food production."

Feedstock Availability in Relation to Food Production, Consumption

Where have we been?

Three-fold increase in population fed, ~ constant amount of cropland

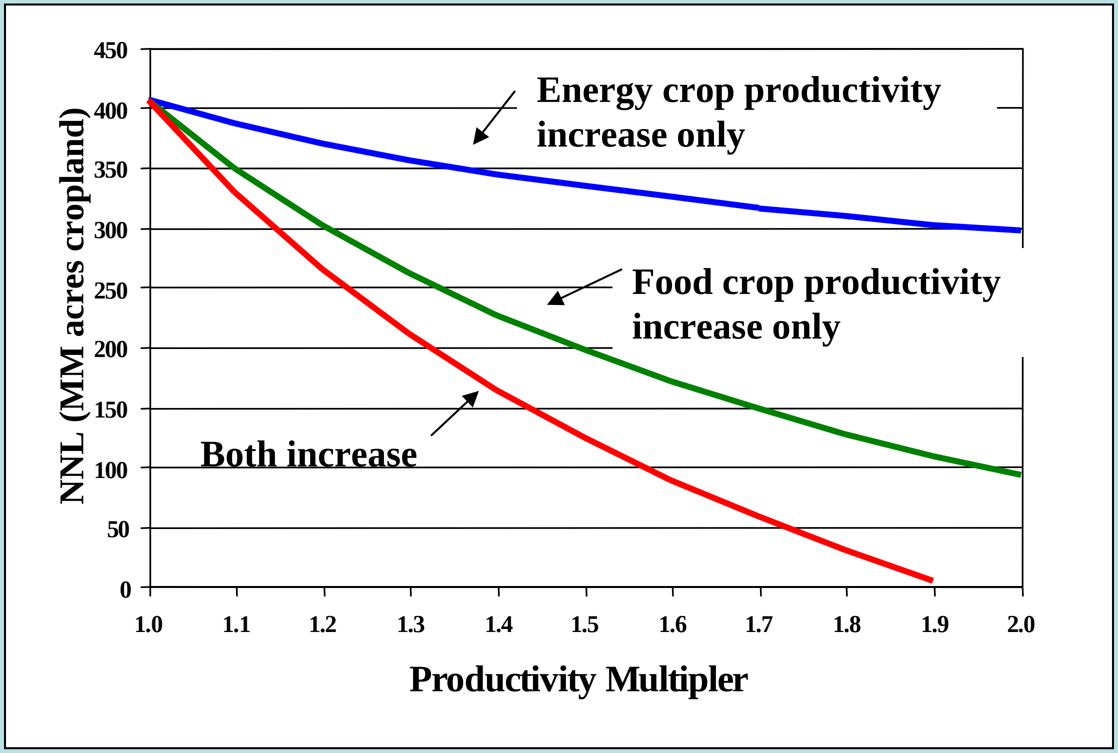
Many anticipate significant additional further increases in land use efficiency for food production

Hard to argue will increase indefinitely

Feedstock Availability in Relation to Food Production, Consumption - continued…

Future scenario:

- **U.S. in 2050**
- **419 million people**
- **100 x10^9 gal gas equiv./yr**
- **No dietary changes**
- **Increased productivity of energy, food crops**



- **Land demand for food production will increase if food productivity does not keep pace with population**
- **Increased productivity beyond that needed to keep pace with population will free land for energy production**
- **As long as more land is used for food than energy, a given increase in crop productivity will have a larger impact on land availability than the same increase in energy crop productivity**

Diet

Recent past

Changes in per capita meat consumption, 1975 to 2000

- **Beef: Down 19%**
- **Pork: Little change**
- **Poultry: Up 92%**

	Kg Feed/Kg Edible	Relative Consumption 2000	Relative Consumption Hypothetical future
Beef	25	41 %	25 %
Pork	9.4	27 %	25 %
Poultry	4.5	32 %	50 %
Kg Feed/Kg Edible (weighted ave.)		14.3	10.9
Change			24%

24% of 250 million acres used to produce animal feed: 60 million acres

Even modest dietary changes can have a substantial impact on land availability

Recent dietary trends are favorable to land availability for bioenergy

Factors Impacting Biomass Feedstock Availability: Integrating Feedstock Production Into Currently-Managed Land (*I*)

Food production is usually assumed to remain static in analyses of biomass supply.

Hasn't happened in the past.

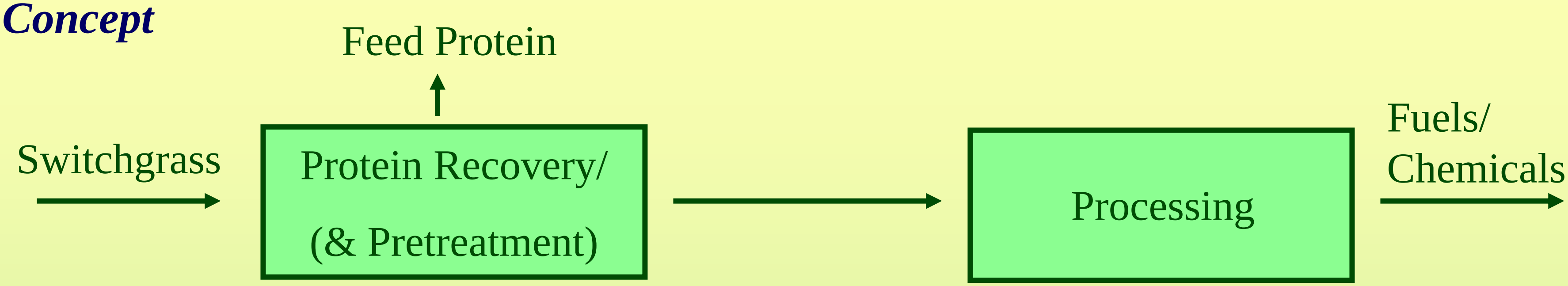
New demand for non-nutritive cellulosic biomass due to cost-competitive processing technology would very likely result in large changes.

Farmers would rethink what they grow and how they grow it.

- **Feed protein/feedstock coproduction**
- **Feedlot pretreatment to make calories more accessible**
- **Increase production on under-utilized land (e.g. hay, pasture)**
- **Winter cover crops**
- **Agricultural residue removal, enhanced by appropriate crop rotations**

Feed Protein/Feedstock Coproduction

Concept



Composition & productivity comparison

Crop	Mass Productivity (tons/acre/year)	Protein (Mass Fraction)	Protein Productivity (tons/acre/year)
Switchgrass	5.0 – 10	.08 -0.12 (early cut)	0.4 – 1.2
Soybeans	1.1 – 1.3	0.36 - 0.5 (bean only)	0.40 – 0.65

- **Production of perennial grass could potentially produce the same amount of feed protein per acre while producing a large amount of feedstock for energy production**
- **Requires readily foreseeable processing technology to recover feed protein**
- **Many positive indications of feed protein quality, but not fully established**
- **Not pursued now because of absence of demand for cellulosic residues**
- ***Cellulosic feedstocks might also be coproduced from large biomass soybeans***

Reimagining Agriculture to Accommodate Large Scale Energy Production

New demand --> new rewards & opportunities --> new agriculture

- **New uses for existing crops (e.g. corn stover)**
- **New combinations of existing crops**
- **New & improved crops & cropping systems**

This new agriculture has received only scant investigation worldwide

Different solutions will be most practical in different local situations

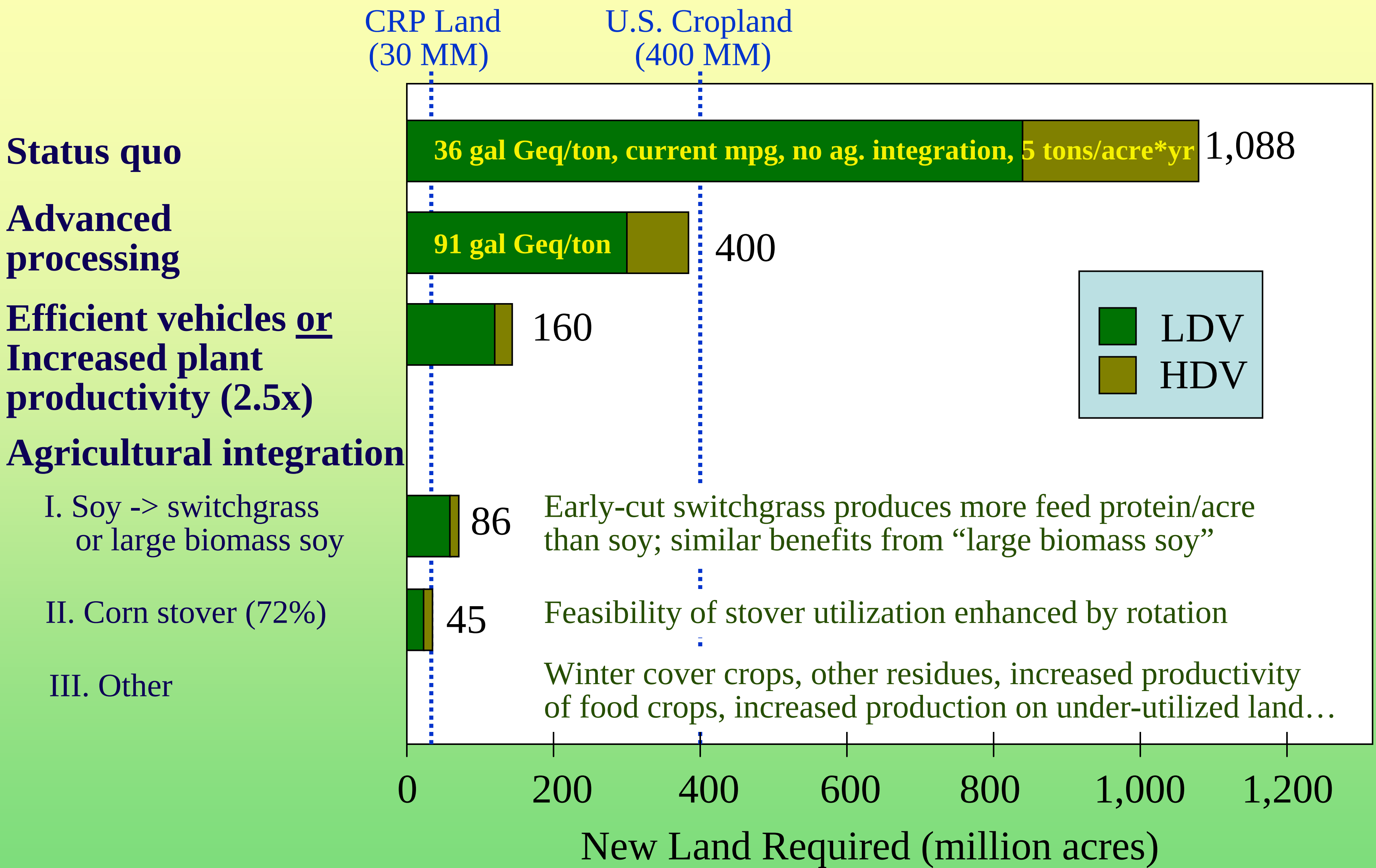
Invited paper for *Global Change Biology*

- **Lee Lynd, Kara Podkaminer (Dartmouth)**
- **Rob Anex, Andy Heggenstaller, Matt Leibman (ISU)**
- **Bruce Dale (Michigan State University)**
- **David Bransby (Auburn University)**
- **Nathanael Greene (NRDC)**
- **Housein Shapouri (USDA)**
- **John Sheehan (NREL)**

Biomass Resource Sufficiency: Summary Observations

<u>**Category of Change**</u>	<u>**Illustrative Large Impacts**</u>
Primarily technological (process yield, crop productivity)	**Anticipated improvement in process yield & energy crop productivity together would increase per acre biofuel yield by ~ 8-fold (1370 gal gasoline equivalent, GE, per acre)** **Increased productivity of food crops could substantial acreage of existing cropland available for energy crops**
Primarily behavioral (diet, exports, VMT)	**80 million acres currently devoted to producing export crops has a biofuel production potential of 110 billion gal GE** **Shifts in meat consumption could make available ~60 million acres, with a corresponding biofuel production potential of 82 billion gallons GE of fuel**
Both technological & behavioral (MPG, integration of feedstock production into managed land)	**Integration potential, on the order of 600 million tons, could produce 55 million gallons GE with no new land required** **Technically-possible mileage increases could decrease fuel demand by 2.5-fold**
Multiple complimentary changes	***Becomes realistic to consider meeting <u>all</u> U.S. mobility demand from biofuels, with some scenarios requiring little if any new land to achieve this***

New Land Required to Satisfy U.S. Mobility Demand



U.S. mobility demand, the largest per capita in the world, could be met from land now used for agriculture while maintaining food production

Parting Thoughts

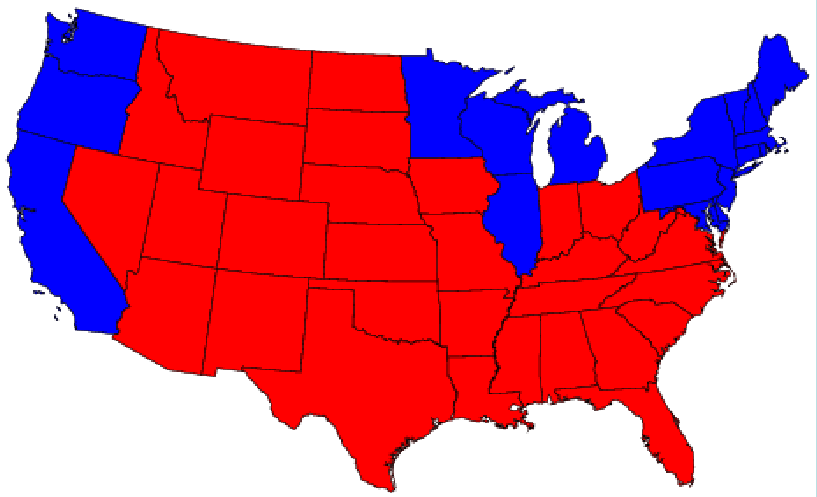
Biofuels & Agriculture

The emergence of a lignocellulose-based biofuels industry offers clear potential for permanent, transformative benefits for U.S. agriculture and rural America.

Potential value added: ~$50 billion for feedstocks, additional for processing.

Today there is a large and unprecedented opportunity for increased support for agriculturally-based responses to energy security and sustainability challenges.

In particular, these strategies have clear potential to garner broad national support as well as support of "farm states".



Initiatives must be carefully evaluated and implemented to be sure that they meet national objectives in a meaningful way, or they will likely backfire.

American agriculture must embrace change to fully realize energy-related opportunities, but can reasonably demand continuity and ever-increasing demand for farm products.

Parting Thoughts

Changes Needed for Biomass to Play a Large Energy Service Supply Role

The secure and sustainable energy future we want is not an extrapolation of the present… neither are the paths to get there.

These changes look much less improbable today than a few years ago.