

# A Global View of the Biorefinery 20 Years From Now

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**Advanced School on the Present and Future of Bioenergy**

October 15, 2014

University of Campinas, Brazil

Need for bioenergy (selected)

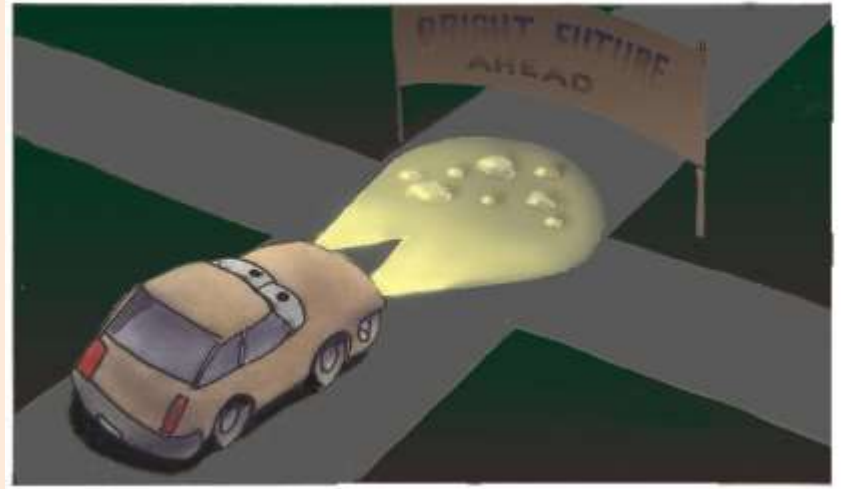
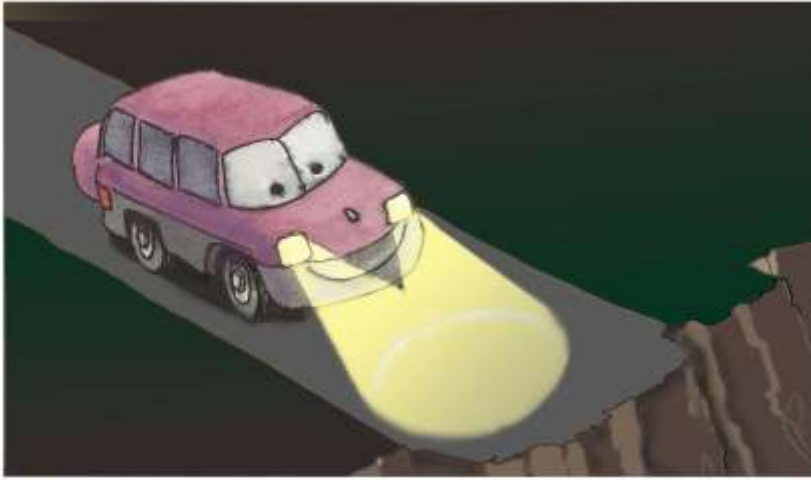
Feedstocks & land

Biorefinery products

Biorefinery technologies – A high beam perspective

From here to there

*Hazards of driving with the low beams on*



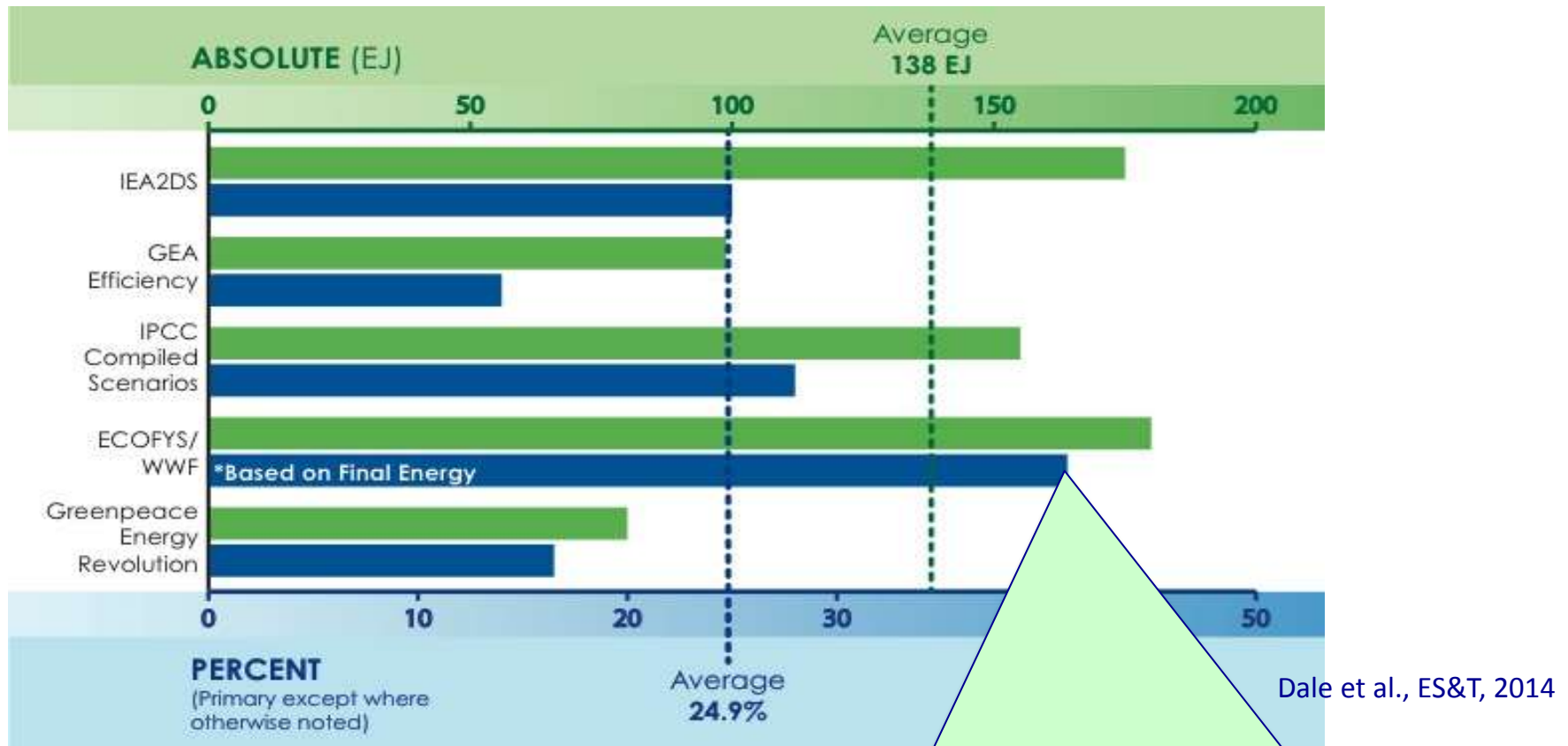
*High beams perspective*



# I. Need for Bioenergy

## Low-Carbon Energy Supply

### Bioenergy Contribution in 2050: Five Low-Carbon Energy Scenarios

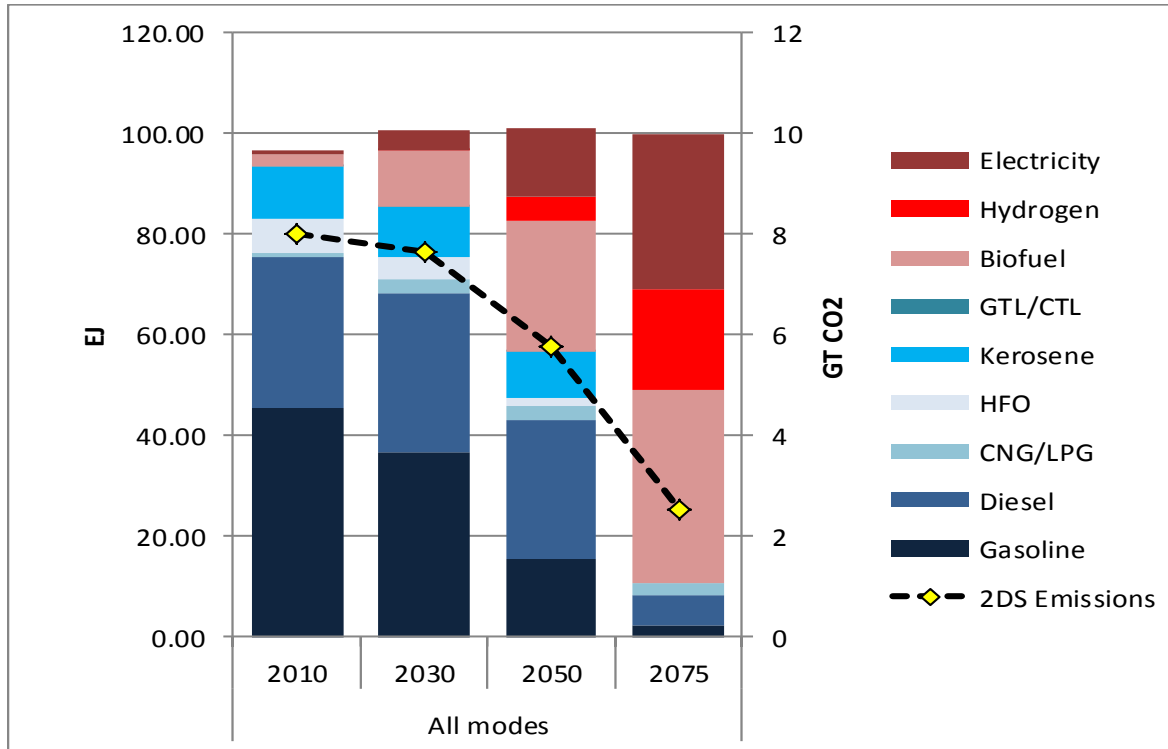


**Other renewables first:** “To achieve ... high renewable energy shares, finding a renewable fuel and heat supply is the biggest challenge. The scenario’s bioenergy is therefore ... used mainly to provide transport fuel and industrial fuel and heat – i.e. to meet energy demands that cannot be met through renewable electricity or other renewable heat applications.” ECOFYS/WWF 100% Renewable Energy by 2050 Report.

# Need for Bioenergy

## Low-Carbon Energy Supply

Aggregated transport energy use, 2DS (Fulton et al., in review)



Lots of time for non-biofuel renewables to overcome kinetic barriers by 2075. Further penetration faces steep technical hurdles.

*The greater the distance between refueling, the greater the advantages of liquid biofuels as compared to other low carbon alternatives*

# Need for Bioenergy

## Economic Development & Serving the World's Poor

None of the Millennium Development Goals can be met without major improvement in the quality and quantity of energy services in developing countries (UNDP).

Wilson Conway, Can we Feed the World? (Courtesy Jeremy Woods)

Agriculture typically accounts for over 80% of the work force and 50% of GDP in developing countries.

A 1% gain in GDP originating from agriculture generates a 6% increase in overall expenditure of the poorest 10% of the population.

A 1% gain in GDP originating from non-agricultural sectors creates zero growth in overall expenditure of the poorest 10% of the population.

The green revolution bypassed Africa primarily due to serious organizational & institutional weaknesses, not geographically-limited capacity: August Temu, ICRAF.

In Brazil – the foremost example of bioenergy deployed in a developing country context – social development, agricultural development and food security, and bioenergy development have been synergistic rather than antagonistic. Lynd et al. in review.

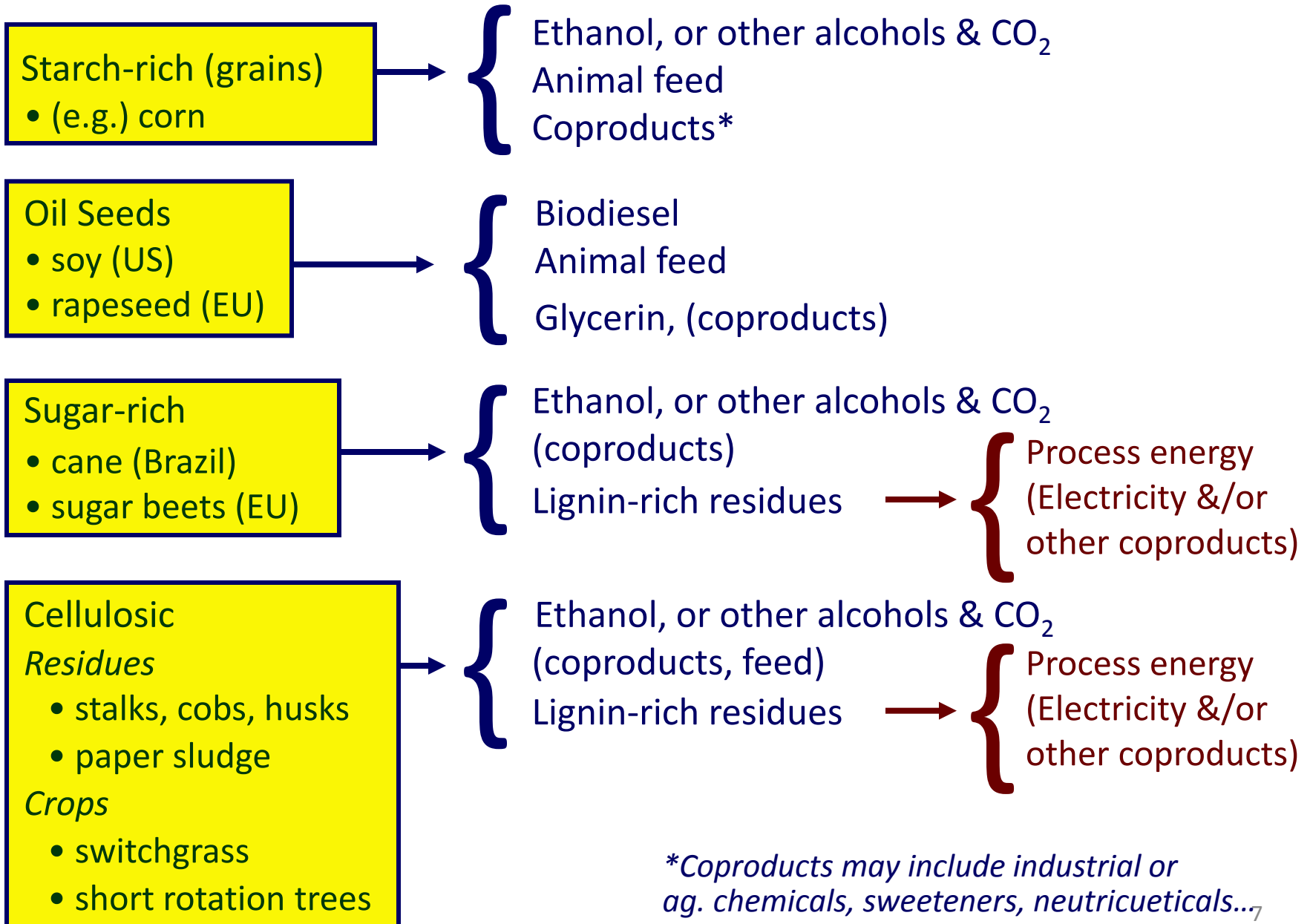
## Benefits of incorporating perennials into agricultural landscapes also key motivations

- Water quality
- Carbon capture & land reclamation
- Wildlife habitat
- Erosion prevention

## II. Feedstocks and Land



# Biofuel Feedstock & Product Options



*\*Coproducts may include industrial or ag. chemicals, sweeteners, nutraceuticals...<sup>7</sup>*

# Feedstocks: Dominant Determinants of Cost, Scale, Sustainability

|   | 1st Generation (Deployed Now) |              |                  |                 | 2nd Generation    |                |
|---|-------------------------------|--------------|------------------|-----------------|-------------------|----------------|
|   | <u>Sugar Cane</u>             | <u>Maize</u> | <u>Oil seeds</u> | <u>Palm Oil</u> | <u>Cellulosic</u> | <u>Algae</u>   |
| <b>Feedstock production</b>                                 |                               |              |                  |                 |                   |                |
| Rural economic development                                  | Very favorable                | Favorable    | Favorable        | Favorable       | Very favorable    | Favorable      |
| Low cost  | Very favorable                | Favorable    | Unfavorable      | Favorable       | Very favorable    | Unfavorable    |
| Land efficiency (fuel/ha)                                   | Favorable                     | Favorable    | Unfavorable      | Favorable       | Very favorable    | Very favorable |
| Geographical range  | Unfavorable                   | Favorable    | Favorable        | Unfavorable     | Very favorable    | Favorable      |
| <b>Sustainability &amp; Environmental</b>                   |                               |              |                  |                 |                   |                |
| Manageable process effluents                                | Very favorable                | Favorable    | Favorable        | Favorable       | Very favorable    | Very favorable |
| Water quality & soil fertility                              | Favorable                     | Unfavorable  | Unfavorable      | Favorable       | Very favorable    | Unfavorable    |
| GHG emission reduction                                      | Very favorable                | Unfavorable  | Favorable        | Favorable       | Very favorable    | Very favorable |
| Large-scale expansion feasibility<br>r.e. land use concerns | Favorable                     | Unfavorable  | Unfavorable      | Unfavorable     | Very favorable    | Very favorable |
| <b>Processing cost (current)</b>                            | Very favorable                | Favorable    | Favorable        | Favorable       | Unfavorable       | Favorable      |

Very favorable

Favorable

Unfavorable

Very unfavorable

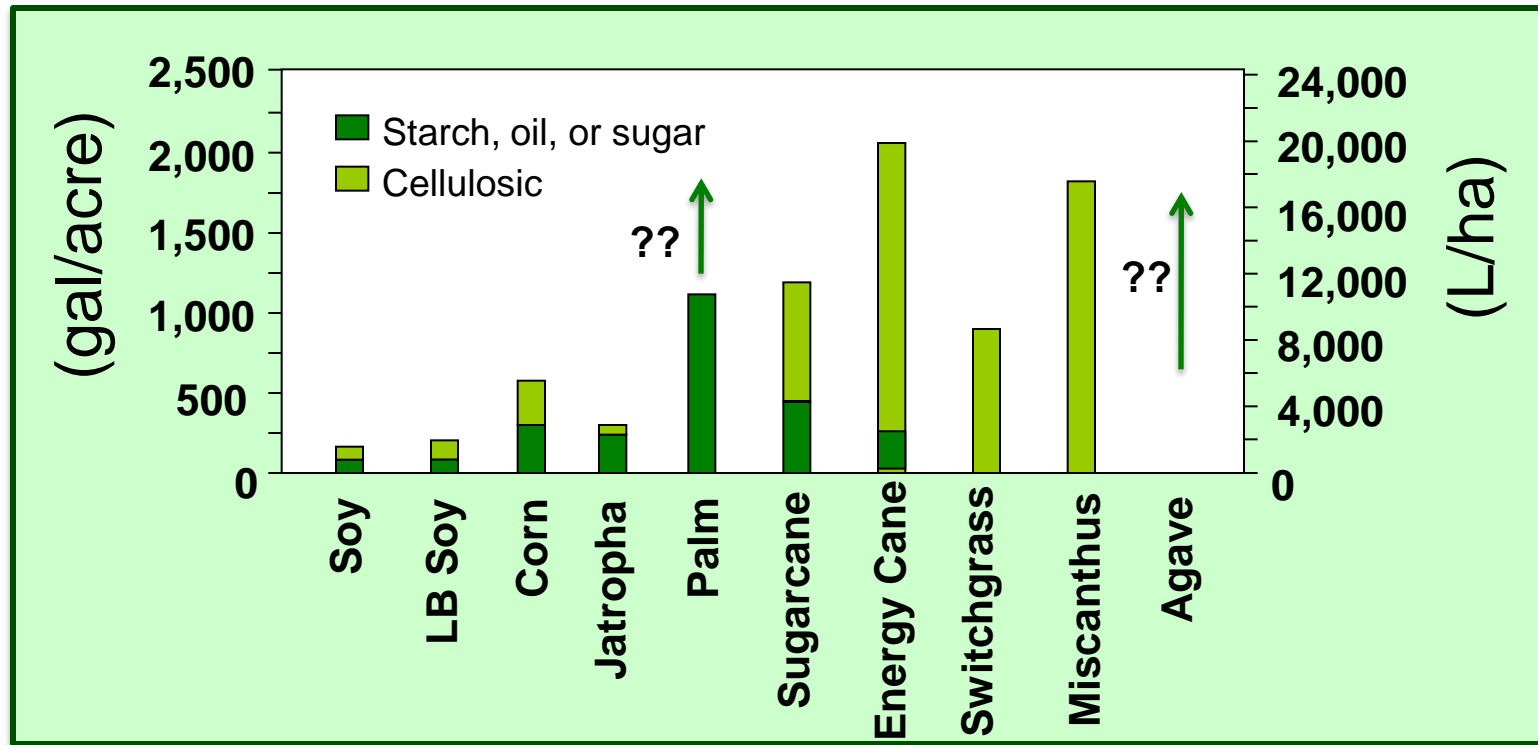
- Sugar cane: Most meritorious of 1<sup>st</sup> gen. feedstocks, range restricted. Scores more like cellulosics as more of the plant is utilized, sugar content decreases.

- Cellulosic biomass: Focus of all studies foreseeing widespread biofuel production on the scale thought necessary for climate change mitigation.  
**Main focus of this talk.**

- Algae worthy of study but potential for algae production at cost/GJ  $\leq$  foreseeable petroleum prices has yet to be established.



## Energy Productivity Per Unit Land is Critically Important



Robust, fundamental rather than incidental conclusions about land-efficient biomass production can be drawn

Harvest the whole plant

Grow plants with composition optimized for photosynthesis rather than accumulation of sugar, starch, or oil

Perennials, C<sub>4</sub> plants

|                           | Maximum Productivity<br>(Mg/ha) |
|---------------------------|---------------------------------|
| C <sub>4</sub> perennials | 70                              |
| C <sub>3</sub> perennials | 40                              |
| Most annual crops         | < 20                            |

Nobel et al., 1992

# Production of Bioenergy Feedstocks on Pasture land

**Lots of land.** At 3 to 3.5 billion ha, pasture is the largest land category managed by humans - twice as large as cropland

**Great intensification potential.** Analysis thus far suggests much greater intensification potential than cropland using a consistent methodology (Sheehan et al. in preparation).

**Large fraction does not have livestock on it.** Almost half (FAO, Sheehan et al.)

**Minor food supply contribution.** 1.3 % of global dietary calories, 2.7% of global dietary protein (Laser and Lynd)

|                | A                       | B  | C                         | D  | E                           | F = A*C                     | G = A*E                    |
|----------------|-------------------------|--|---------------------------|--|-----------------------------|-----------------------------|----------------------------|
| Animal Product | Production from Grazing | Animal Product Consumption (kcal/person/d) | Percent of Total Calories | Animal Protein Consumption (kcal/person/d) | Percent of Protein Calories | Total Calories from Pasture | Total Protein from Pasture |
| Meat           | 8.4%                    | 252  | 8.9%                      | 58   | 17.8%                       | 0.8%                        | 1.5%                       |
| Milk           | 12.0%                   | 127  | 4.5%                      | 33   | 10.1%                       | 0.5%                        | 1.2%                       |
| Eggs           | 0.8%                    | 33   | 1.2%                      | 11   | 3.4%                        | 0.0%                        | 0.0%                       |
| <b>Total</b>   |                         | <b>412</b>                                 | <b>14.6%</b>              | <b>102</b>                                 | <b>31.3%</b>                | <b>1.3%</b>                 | <b>2.7%</b>                |

Sources:

1

2

2

2

2

1,2

1,2

Note: Human calories consumption: 2,831 kcal/day; Per capita protein: 325 kcal/day

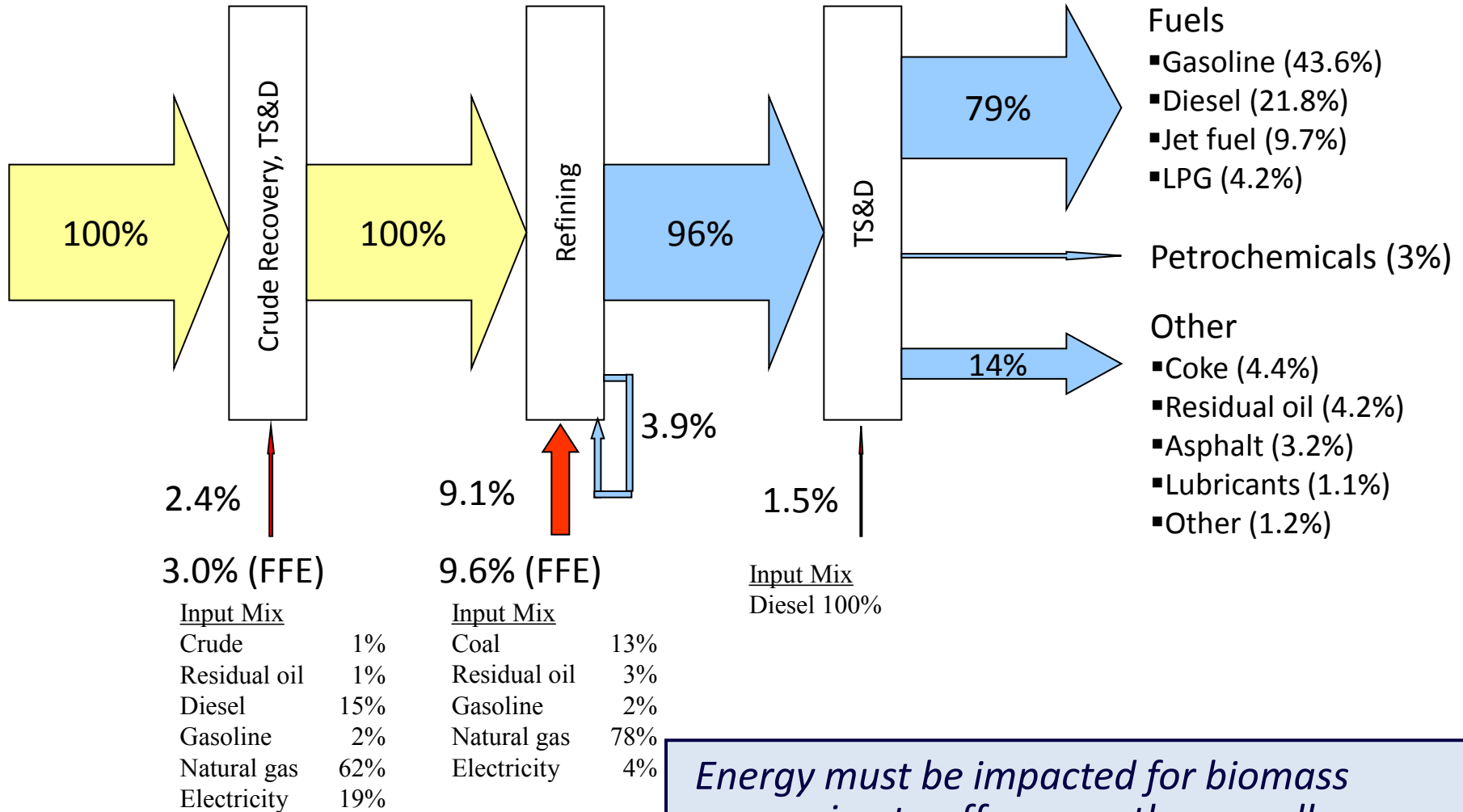
Sources:

- 1) Steinfeld et al., 2006; Livestock's Long Shadow: Environmental Issues and Options; Table 2.9; FAO. <http://www.fao.org/docrep/010/a0701e/a0701e00.HTM>
- 2) FAO/FAOSTAT; Food Balance Sheet for 2009; Balance as Domestic Supply/Utilization; <http://faostat3.fao.org/faostat-gateway/go/to/download/FB/FB/E>; accessed 12/31/13

**Two prominent criticisms of bioenergy – food competition and deforestation – are largely specific to cropland and forest land, and are much less applicable to pastureland**

# III. Products

## Petroleum Refining (Numbers Denote Energy Flows)



*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

# Bioenergy & Bioproducts

**Coproduction synergies → multi-products over time (likely in steps)**

**Bioenergy:** Large scale lowers bioproduct price

**Bioproducts:** Larger profit margins lowers bioenergy price

**Role in meeting large scale sustainability & security challenges**

## Bioenergy

**Direct role:** If biomass is to play more than a minor role in responding to sustainability & security challenges, energy must be impacted

## Bioproducts

**Indirect role:** Enable economic viability of bioenergy production

Organic chemicals 3% of U.S. refinery output, 1 to 2 years growth in fossil fuel utilization

Most organic chemicals are more practical as coproducts than dedicated products

Even lumber and paper are relatively small compared to energy

**Past emergence of refining industries**

**Fuels first:** Petroleum, coal (South Africa)

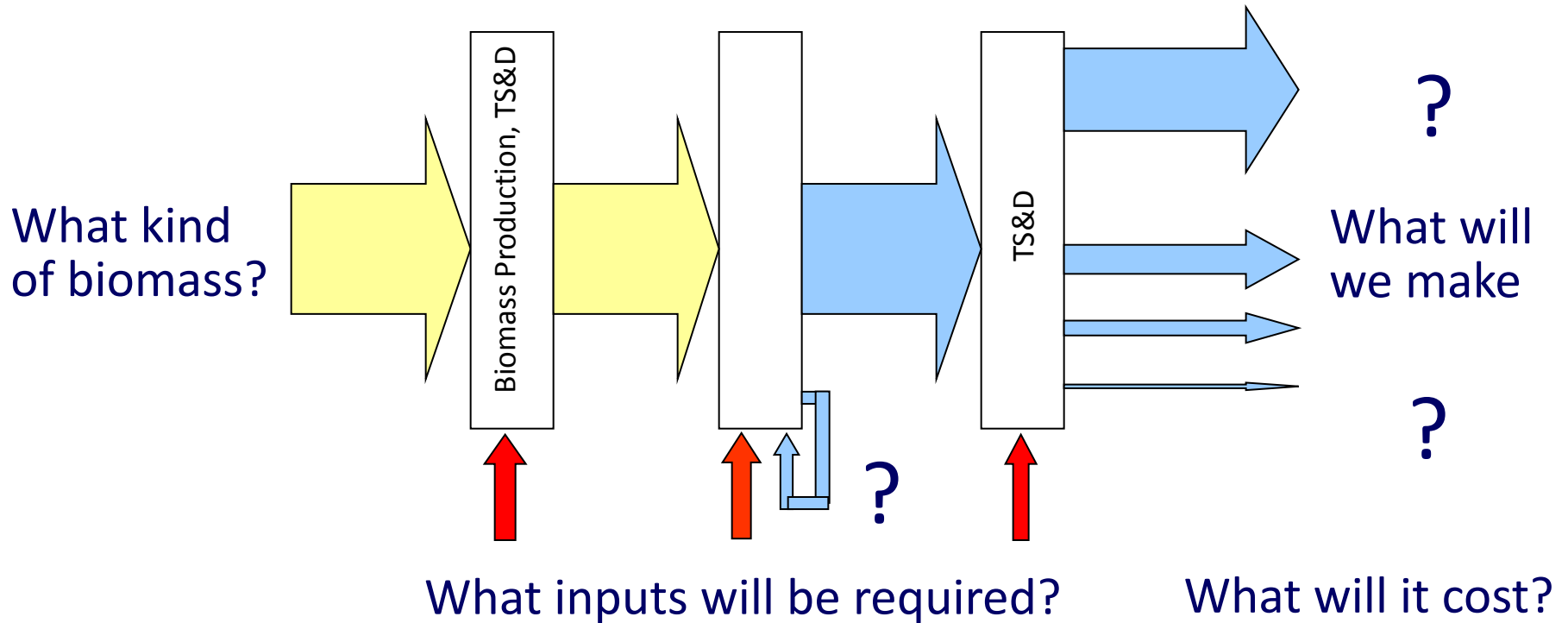
**Sugar important:** Cane ethanol (Brazil), corn wet milling (US)

**Animal feed important:** Corn ethanol (US, especially dry milling)

# Hierarchy of Biomass End-Uses

| End Use                           | Availability of Alternatives |             | Biomass Uniquely Suited? | Size of Demand (relative) |
|-----------------------------------|------------------------------|-------------|--------------------------|---------------------------|
|                                   | Non-Sustainable              | Sustainable |                          |                           |
| Food (& Feed)                     | No                           | No          | Yes                      | Large                     |
| Liquid transport fuels            | Yes                          | No          | Yes among sustainable    | Large                     |
| High temp heat (industrial)       | Yes                          | No          | Yes among sustainable    | Large                     |
| Organic Materials                 | Yes                          | No          | Yes among sustainable    | <b>Small</b>              |
| Non-liquid                        | Yes                          | Yes         | No                       | Large                     |
| Electricity                       | Yes                          | Yes         | No                       | Large                     |
| Low temp. heat (e.g. residential) | Yes                          | Yes         | No                       | Large                     |

# IV. Biorefining Technology – A High Beams Perspective



## Role of Biomass in America's Energy Future Project

Unprecedented analysis of mature biomass conversion technology

Lead institutions: Dartmouth, Natural Resources Defense Council

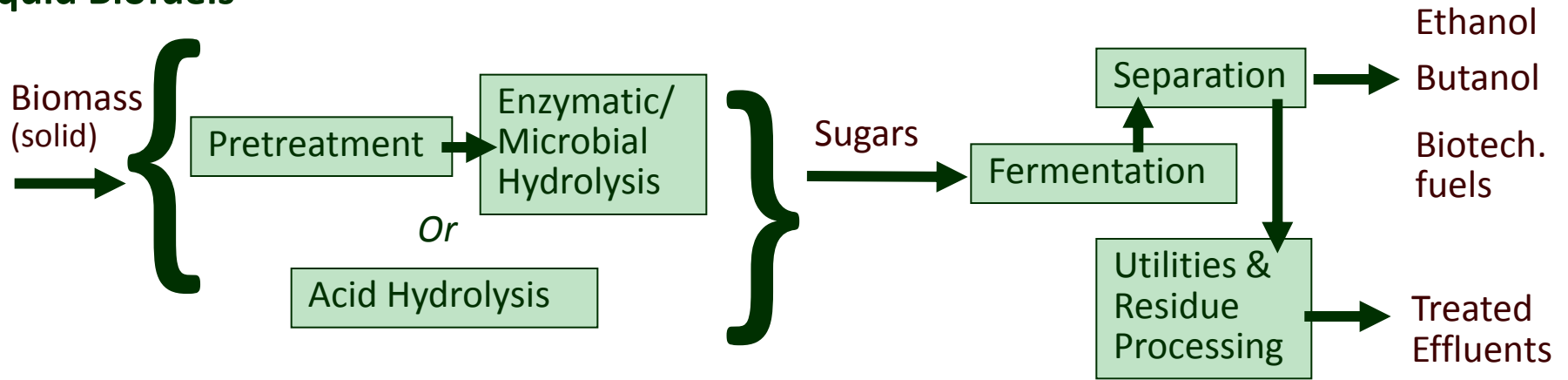
Participants: Auburn U., ANL, Iowa State U., Michigan State U., NREL, ORNL, Princeton, Union of Concerned Scientists, USDA, U. of Tennessee,

Sponsors: DOE, Energy Foundation, National Commission on Energy Policy

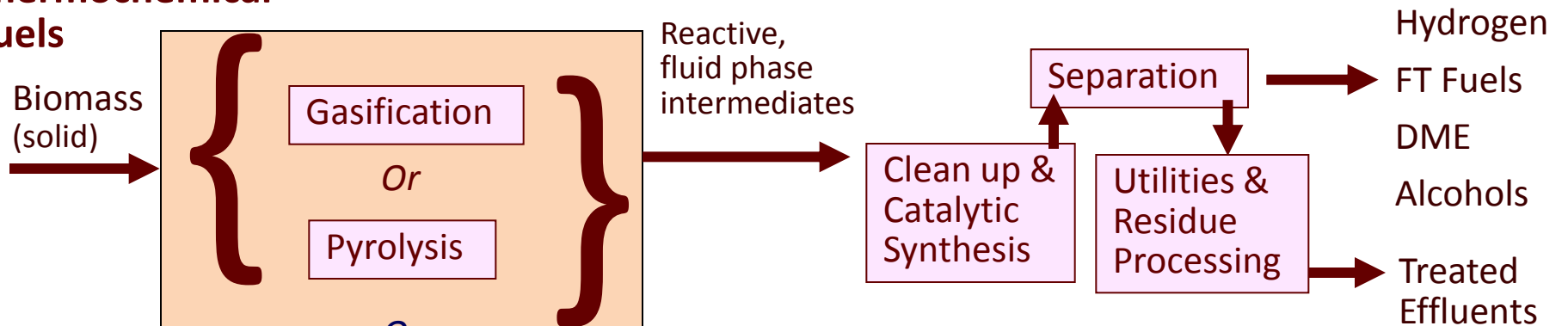
Seven papers in a special issue of Biofuels, Bioproducts, and Biorefining (2009)

# 2<sup>nd</sup> Gen Process Options

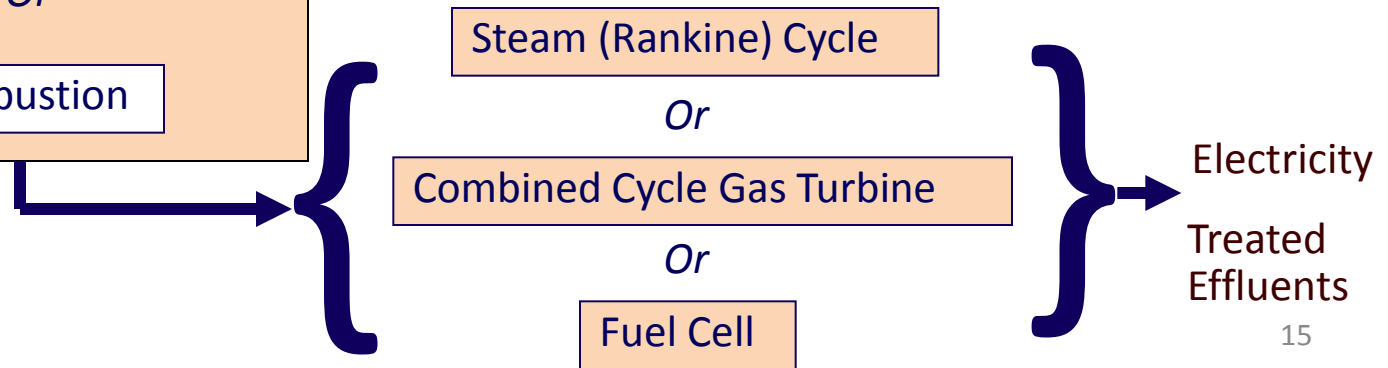
## Liquid Biofuels



## Thermochemical Fuels

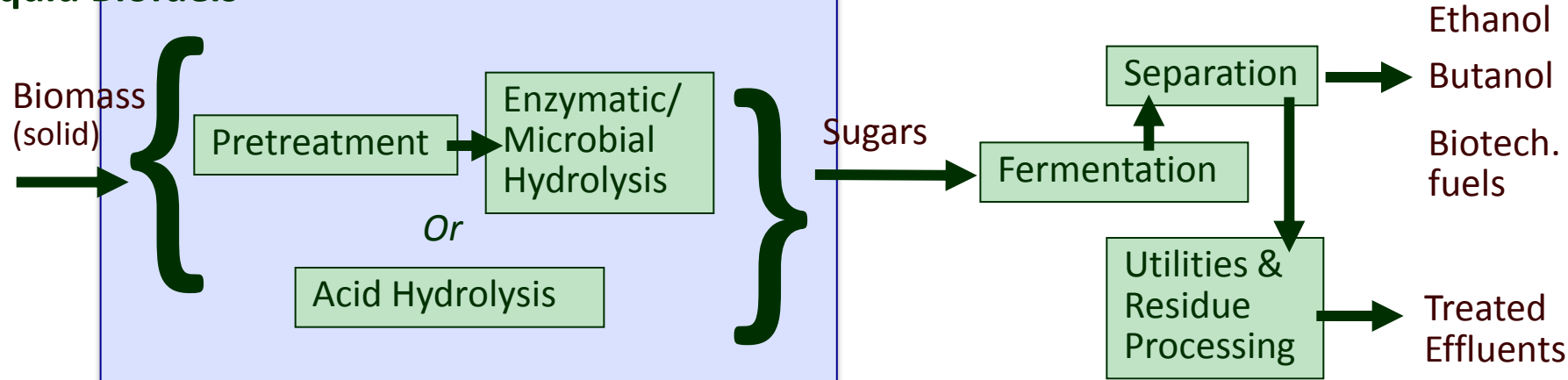


## Dedicated Electricity Generation

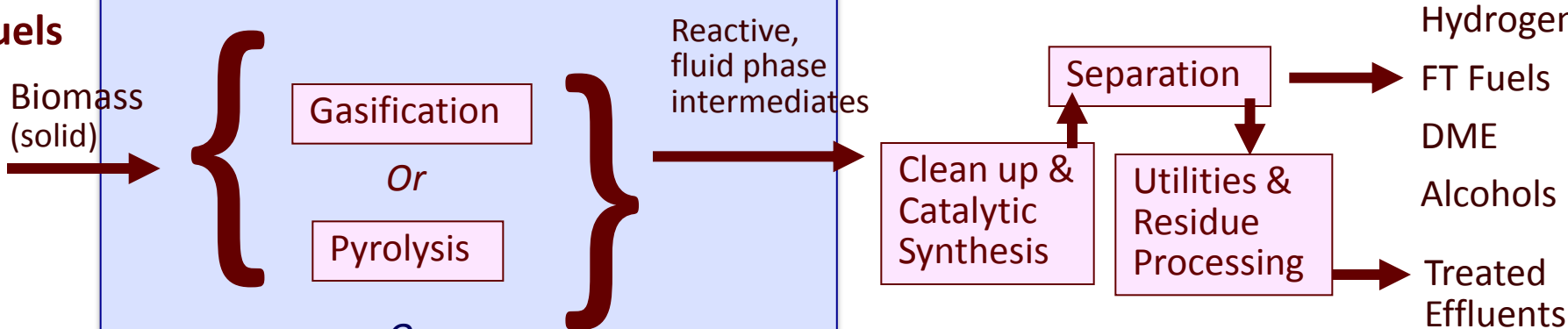


# 2<sup>nd</sup> Gen Technology Challenge

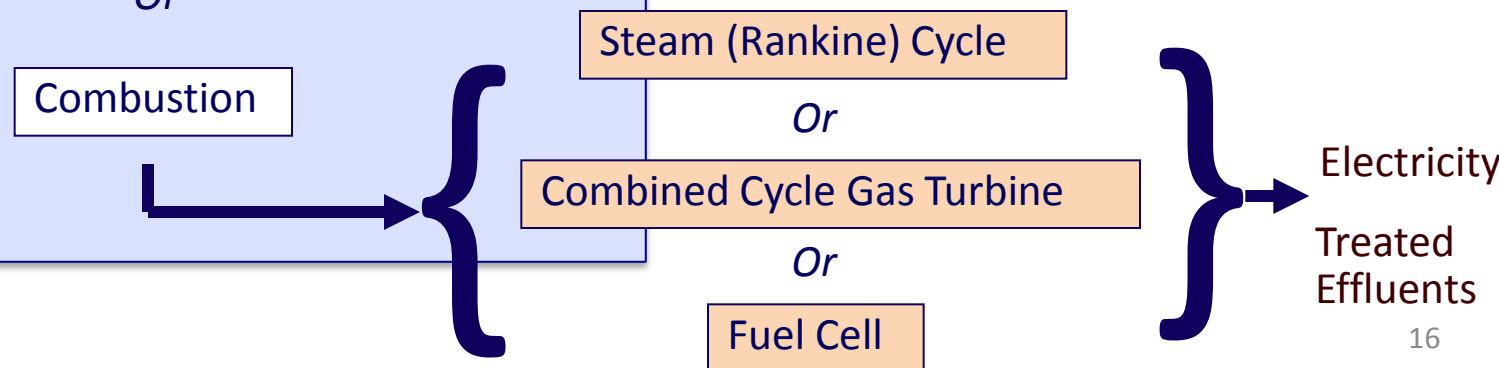
## Liquid Biofuels



## Thermochemical Fuels



## Dedicated Electricity Generation





# RBAEF Process Analysis

## Material & Energy Balance Models

Implemented using ASPEN

Built on extensive prior work

Princeton (thermochemical fuels & power)

NREL & Dartmouth (ethanol)

## Basis for

Thermodynamic analysis “energy balance”

Material flows for environmental analysis

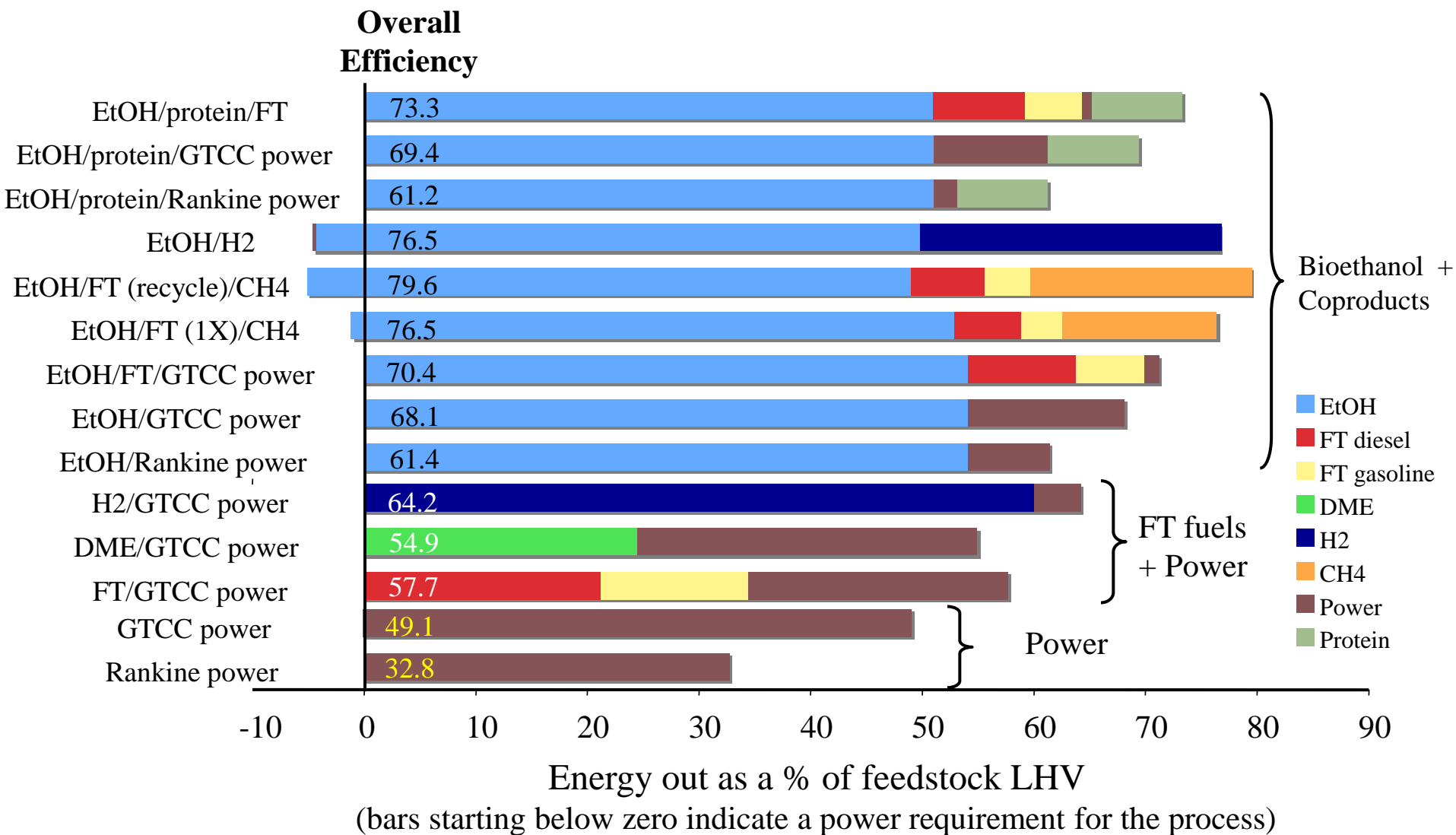
Economic analysis

*24 different scenarios including many products & combinations*

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

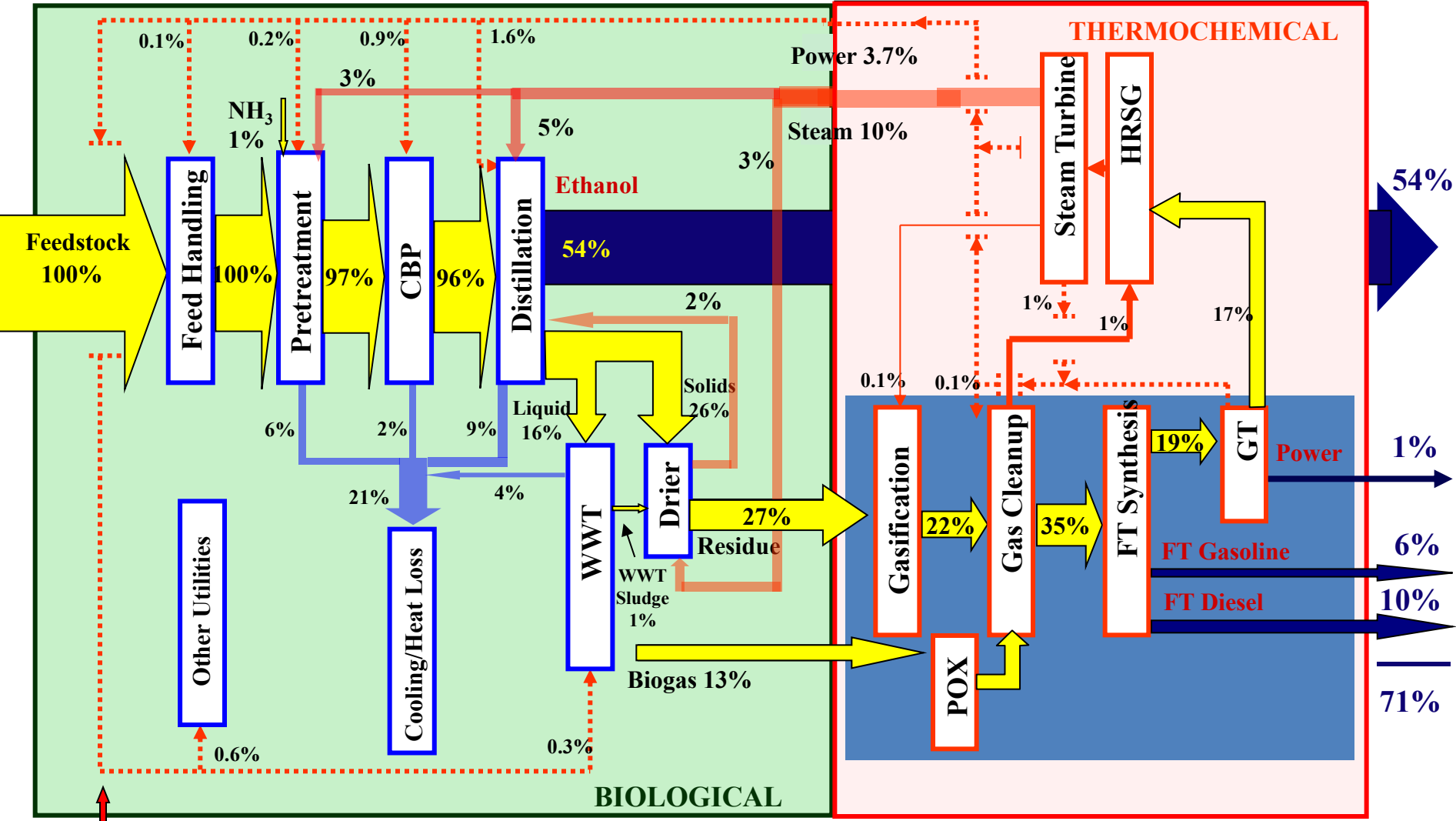
*Unprecedented for mature biomass conversion technologies*

# Efficiency of Mature RBAEF Process Scenarios



# Biorefinery Energy Flows (one of many RBAEF scenarios)

*Fermentation is very efficient - e.g. 96% for stoichiometric sugar → ethanol*



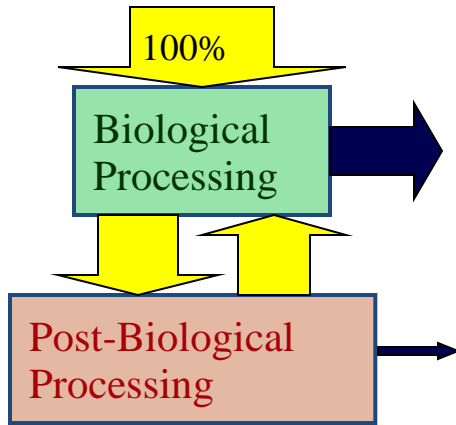
**Ag Inputs (Farming, feedstock transport) ~ 7 %**

**Energy out/Energy in = 71/7 = ~10**

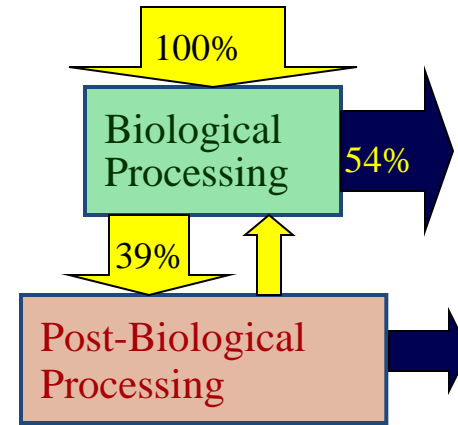
# Integration of TC and Biological Processing Offers Lots of Value

*Maturation of biological conversion → much larger opportunities*

*Current*

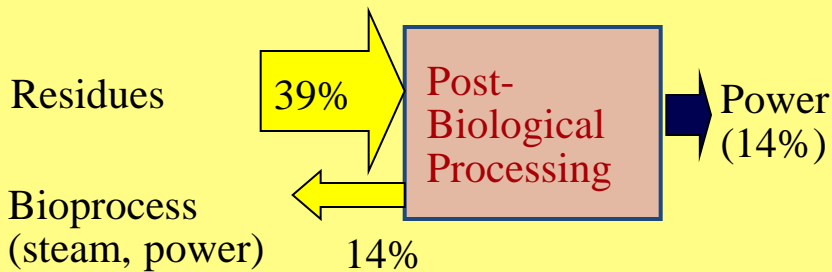


*Mature*



**Internal cogeneration - most energy for biological processing is from *waste* heat accompanying post biological processing**

*Power*

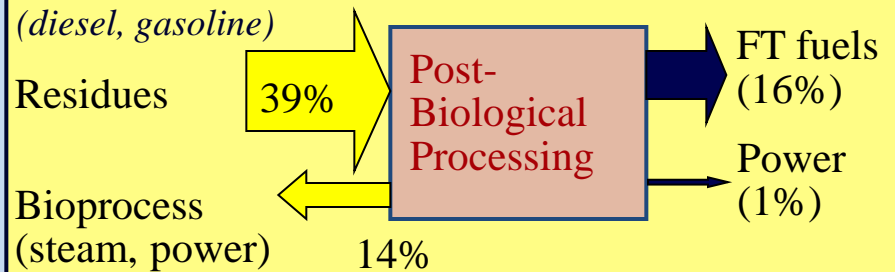


$$\eta_{power} = 14 / (39 - 14) = 0.56$$

$$(\eta_{power\ only} = 0.49)$$

*Large baseload power contribution, compliments intermittent sources*

*Fischer-Tropsch fuels*

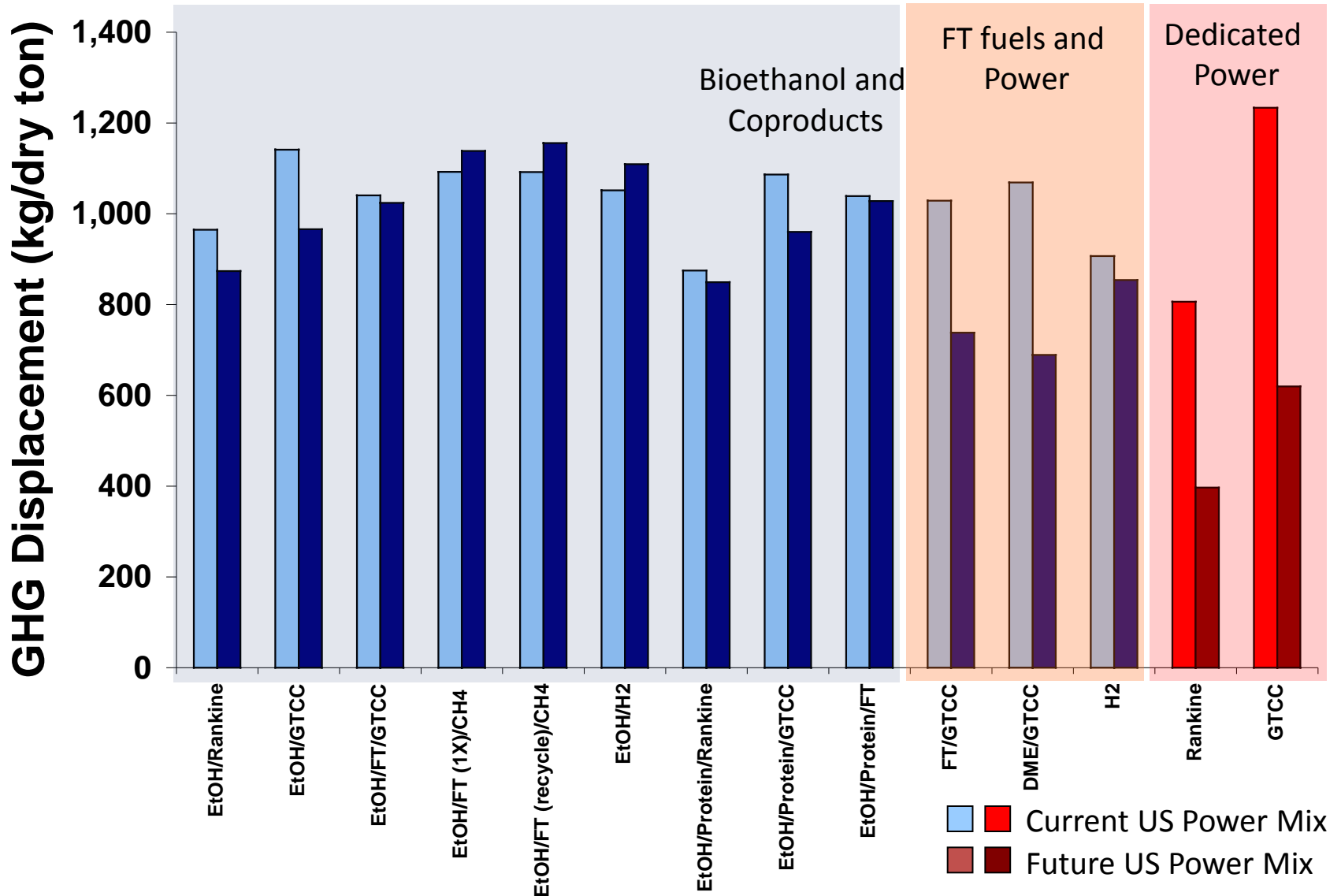


$$\eta_{FTfuels} = (17 + 1) / (39 - 14) = 0.72$$

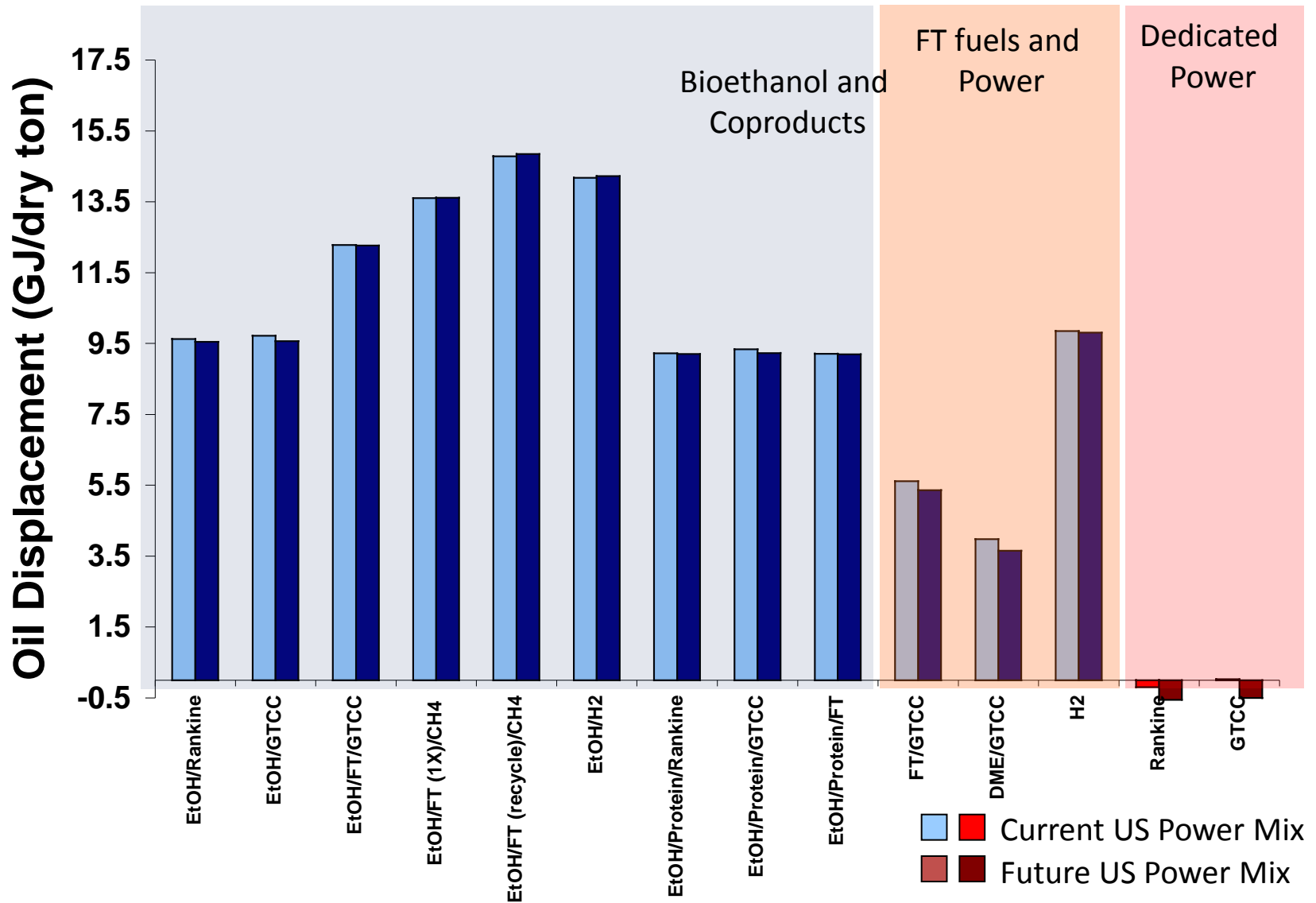
$$(\eta_{FTfuels\ only} = 0.55)$$

*E90 entirely from renewables*

# Comparative Greenhouse Gas Displacement



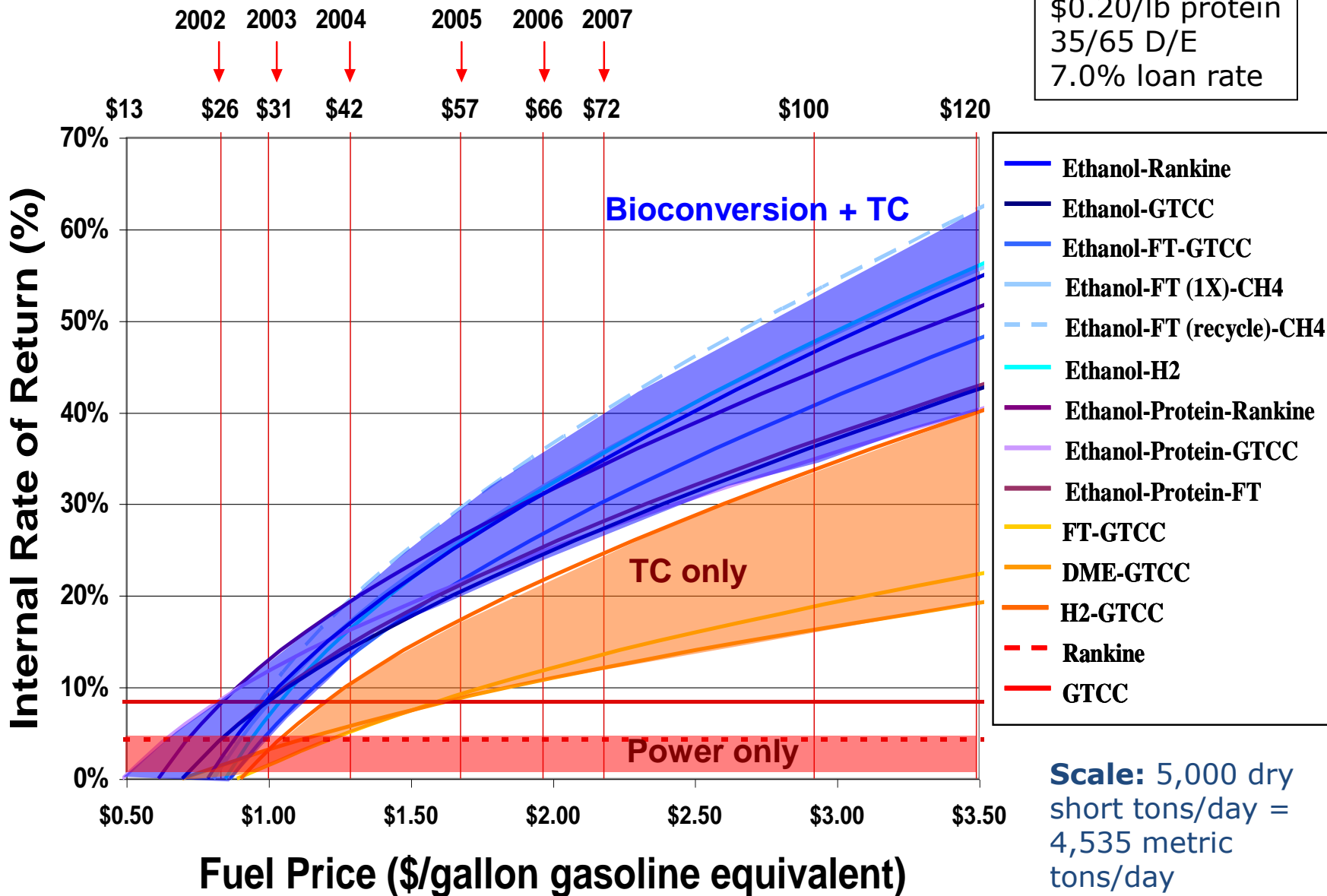
# Comparative Petroleum Displacement



# Comparative Economics

Crude Oil Price (\$/barrel oil)

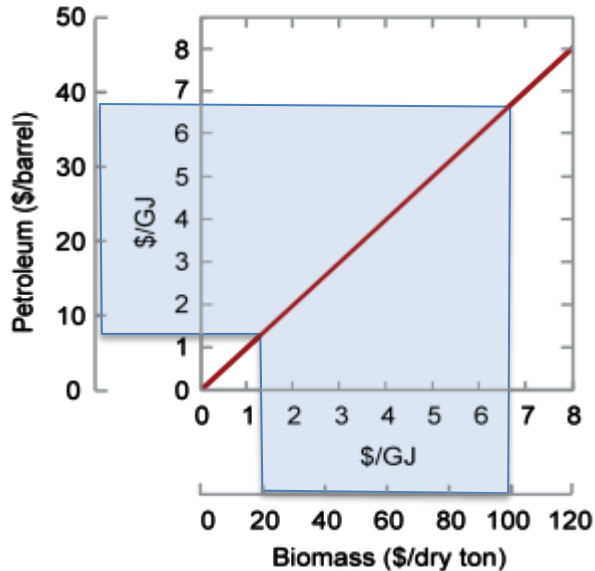
\$0.05/kWh  
 \$0.20/lb protein  
 35/65 D/E  
 7.0% loan rate



# Cost Competitive 2<sup>nd</sup> Gen Biofuels “Sniff Test”

## Cost-Competitive Feedstocks (Now)

|                                      | <u>(\$/Dry ton)</u> | <u>\$/GJ</u> | <u>Equivalent Oil Price (\$/bbl)</u> |
|--------------------------------------|---------------------|--------------|--------------------------------------|
| Cellulosic energy crops (e.g. grass) | 60 to 80            | 4 to 5.3     | 23 to 31                             |
| Bagasse (existing cogen plant)       | 50 to 60            | 3.3 to 4     | 19 to 23                             |
| Bagasse (new, optimized cogen plant) | ~25 to 30           | 1.7 to 2     | 10 to 12                             |



## Cost-Competitive Processing (Future)

### Pretroleum

#### Cost (\$/GJ)

Feedstock (@ \$100/bbl): **18**  
 Processing: **6**  
**24**

#### Processing advantages

Fluid (more physically accessible)

### Cellulosic Biomass

Feedstock (@ \$60/ton): **4**  
 Allowable processing: **20**

More reactive chemical groups (more chemically accessible)

Amenability to biotechnology

Due to the raw material price advantage, the cost of processing cellulosic biomass could be about 3 times that of processing petroleum and still be competitive.



# RBAEF ~ two dozen biomass processing scenarios developed based on performance & configurations anticipated for mature technology

## The following working hypotheses are supported by our results

All the most cost-effective scenarios feature biological processing - *one cannot afford not to biologically process the carbohydrate fraction of biomass*

However, post biological thermochemical processing is very important

- Responsible for processing ~ 40% of the energy in the original feedstock
- Adds substantially to efficiency, revenues, greenhouse gas displacement
- Strong thermodynamic synergies with biological processing

Production of ethanol in combination with several coproduct combinations is cost-competitive with gasoline over a range of oil & power prices

| <u>Metric</u>               | <u>Biological &amp; coproducts*</u> | <u>TF fuels &amp; power</u> | <u>Power</u> |
|-----------------------------|-------------------------------------|-----------------------------|--------------|
| GHG emission reductions**   | +++                                 | +++                         | +++          |
| Relative cost effectiveness | +++                                 | ++                          | +            |
| Petroleum displacement      | +++                                 | ++                          | -            |

\*Thermochemical fuels (TF) and/or power and in some cases protein

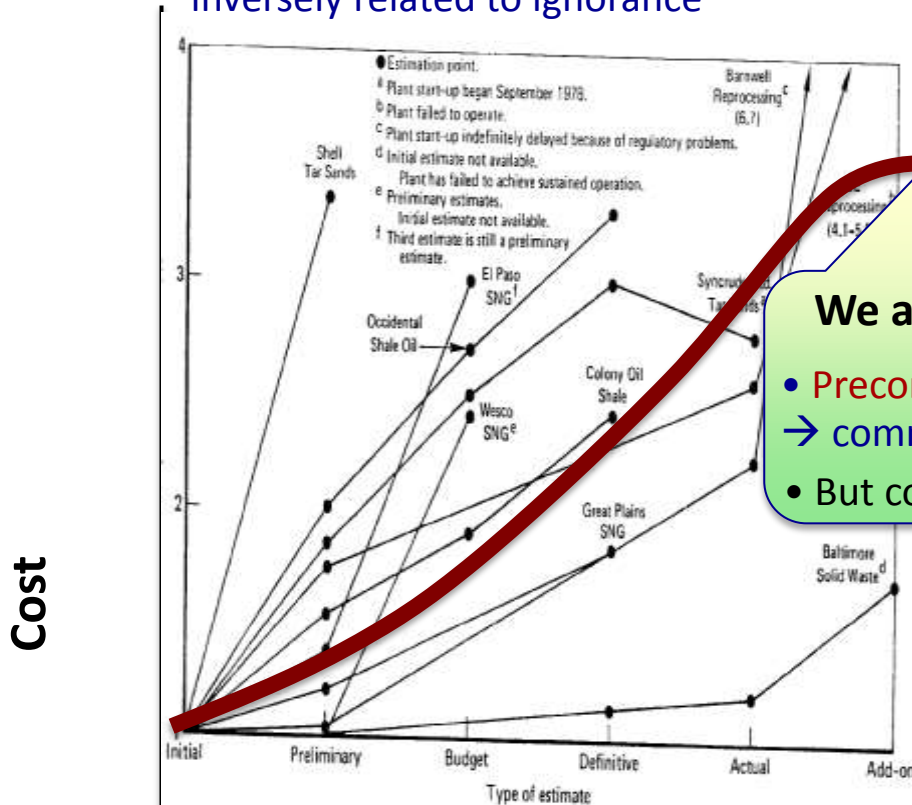
\*\*Greenhouse gas emission reductions, per ton (or per acre) basis

# V. From Here to There

## New technology activation energy

### Rand Curve

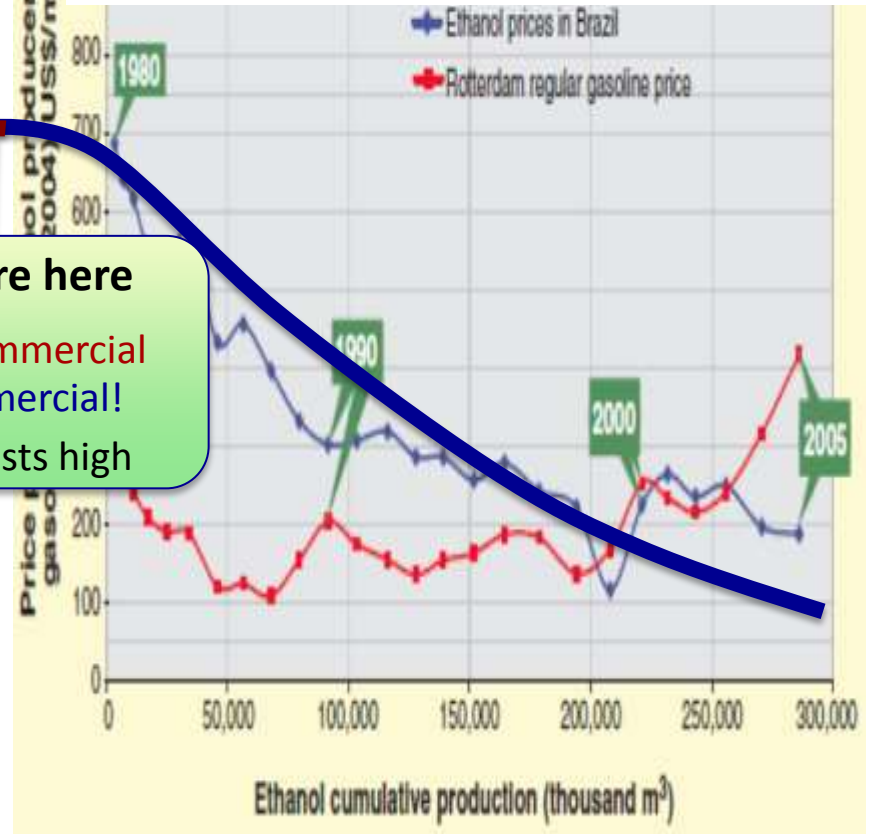
Estimated cost increases with experience, inversely related to ignorance



Rand Study, 1979

### Brazil 1<sup>st</sup> Gen Ethanol Curve

Actual cost decreases with experience & innovation



Goldemberg *et al.*, 2004

**We are here**

- Precommercial
- commercial!
- But costs high

Progress/Experience

# Taking Stock: Commercial-Scale Cellulosic Biofuel Projects (US)

*Brown & Brown. A review of cellulosic biofuel commercial-scale projects in the United States. Biofuels Bioprod Bioref 7:235-245. 2013.*

| Table 1. Details of commercial-scale cellulosic biofuel projects expected to be in operation by 2014. |   |                    |                |                                     |                        |
|---|---|--------------------|----------------|-------------------------------------|------------------------|
| Company   | Pathway   | Location           | Capacity (MGY) | Feedstock                           | Capital cost (million) |
| KIOR  | Catalytic pyrolysis & hydrotreating to hydrocarbons       | Natchez, MS        | 41             | Yellow pine                         | \$350                  |
| ClearFuels  | Gasification & F-T synthesis to hydrocarbons              | Collinwood, TN     | 20             | Woody biomass                       | \$200                  |
| Sundrop Fuels   | Gasification & MTG synthesis                              | Alexandria, LA     | 50             | Mixed biomass, natural gas          | \$500                  |
| ZeaChem   | Dilute acid hydrolysis & acetic acid synthesis to ethanol | Boardman, OR       | 25             | Agricultural residue, hybrid poplar | \$391                  |
| Abengoa   | Enzymatic hydrolysis to ethanol                           | Hugoton, KS        | 25             | Corn stover                         | \$350                  |
| Beta Renewables   | Enzymatic hydrolysis to ethanol                           | Sampson County, NC | 20             | Arundo, switchgrass                 | \$170                  |
| DuPont Biofuel Solutions  | Enzymatic hydrolysis to ethanol                           | Nevada, IA         | 25             | Corn stover                         | \$276                  |
| POET  | Enzymatic hydrolysis to ethanol                           | Emmetsburg, IA     | 20             | Corn stover, corn cobs              | \$250                  |
| Mascoma   | CBP to ethanol  | Kinross, MI        | 40             | Hardwood pulpwood                   | \$232                  |

## Back-of-the-Envelope Economics (\$/gallon gasoline equivalent)

Capital<sup>1</sup>

OpEx

2.05

Feedstock: ~ 0.9<sup>2</sup>

2.40

Other: ≥ 0.50<sup>3</sup>

2.40

5.63

5.04

3.06

4.00

3.97

4.00 (revised)

**Wholesale gasoline price**

**2.40**

<sup>1</sup> Based on 16% ROI (CRF = 0.2) + 0.04xtotal capital for capital-related OpEx (e.g. insurance, maintenance).

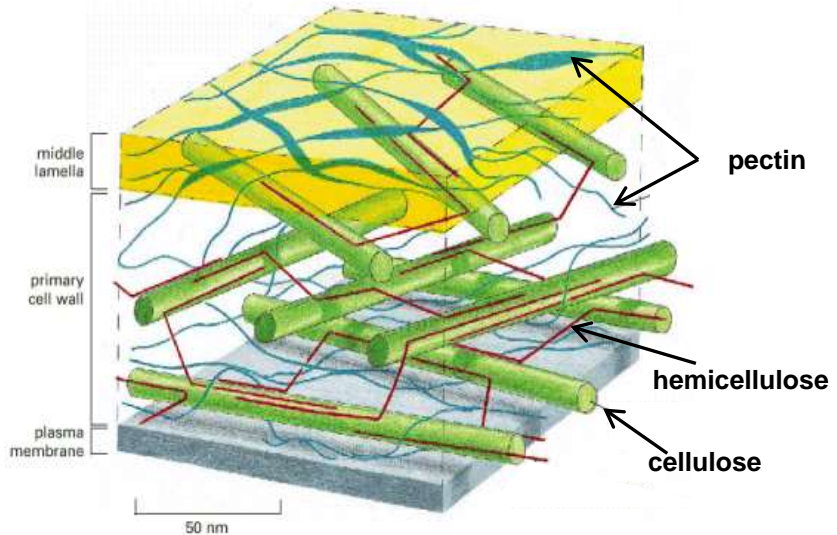
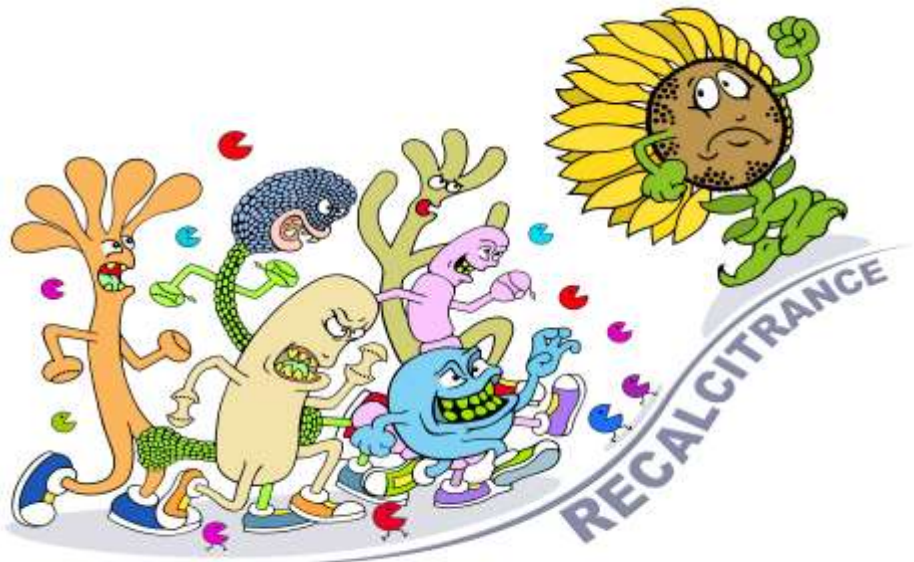
<sup>2</sup> Based on \$65/ton, 75 gal fuel produced/ton.

<sup>3</sup> Includes chemicals, labor, waste disposal). Excludes capital-related. Representative of current technology.

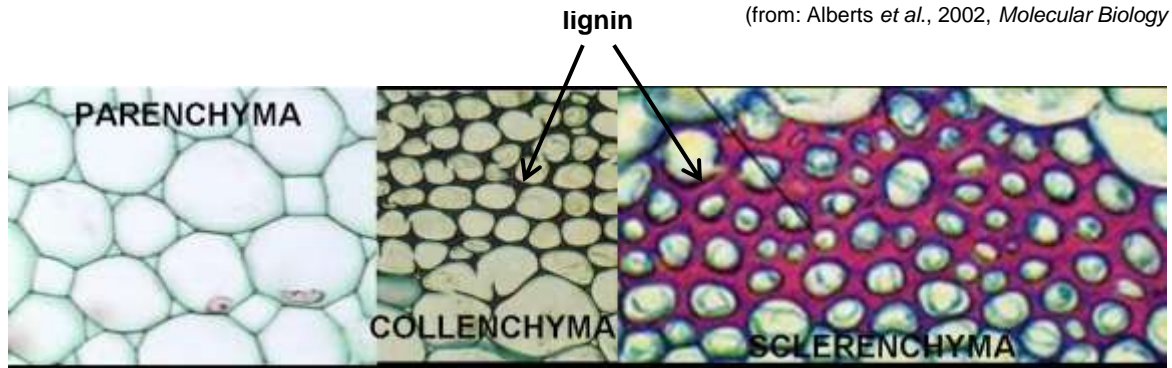
# Technological Challenge: Recalcitrance of Cellulosic Biomass

**What:** Difficulty of converting cellulosic biomass into reactive intermediates (Lynd *et al.*, *Biotechnol Prog*, '99). For intracellular bioprocessing, reactive intermediates must be soluble.

In response to environmental & microbial assault plants have evolved recalcitrant cell walls



(from: Alberts *et al.*, 2002, *Molecular Biology of the Cell 4<sup>th</sup> ed.*)



[http://biologyintro2life.blogspot.com/2010/08/multicellular-organization-plants\\_18.html](http://biologyintro2life.blogspot.com/2010/08/multicellular-organization-plants_18.html)

# Commercialization Challenges

## Internal

**A lot to do at once:** Tough to be a technology deployment company (no cellulosic biofuel industry to sell to) and a technology development company (to be cost-competitive), in a multi-step process (involving feedstock logistics as well as processing technology) competing against mature technology. Fortunately this is becoming less necessary as the field matures.

**Not a classic venture investment.** Bigger payout but bigger cost, longer timelines.

## External

**Unfulfilled expectations**

**Performance of advanced biofuel IPOs**

**“Blend wall” (US)**

**Wide swings in perceived merit/need, investor confidence**

# Commercialization Challenges

## US Experience – Wide Pendulum Swings

### Expectations

### Funding availability

### Commercial Focus

### Innovation

'06 to '08:

High, mostly not met

High

Aggressive, high cap projects → limited success

- Not much emphasis
- Technology judged adequate
- Demand judged strong enough that cost secondary

'10 – now:

Low

Low

Near-term revenue

Hard to justify with limited funds, little investor confidence

*“It just has to work”: Appropriate strategy when investor confidence was high, became an inappropriate strategy as investor confidence declined*

*When funds for innovation were available, the need was not appreciated. When the need for innovation was appreciated, funds were not available.*

# Commercialization Challenges

## Some Lessons Gleaned Over the Last 5 Years (US Experience)

1. It is important to set realistic expectations and meet them. Future ventures will unfortunately inherit a burden from the past. At this point it is critical that the field start showing success.

2. Recognize when innovation is needed and there is an opportunity to pursue it.

3. Start-up companies need to identify and serve customers.

4. It is not possible to do too many new things at once.

Unlikely to happen in my view:

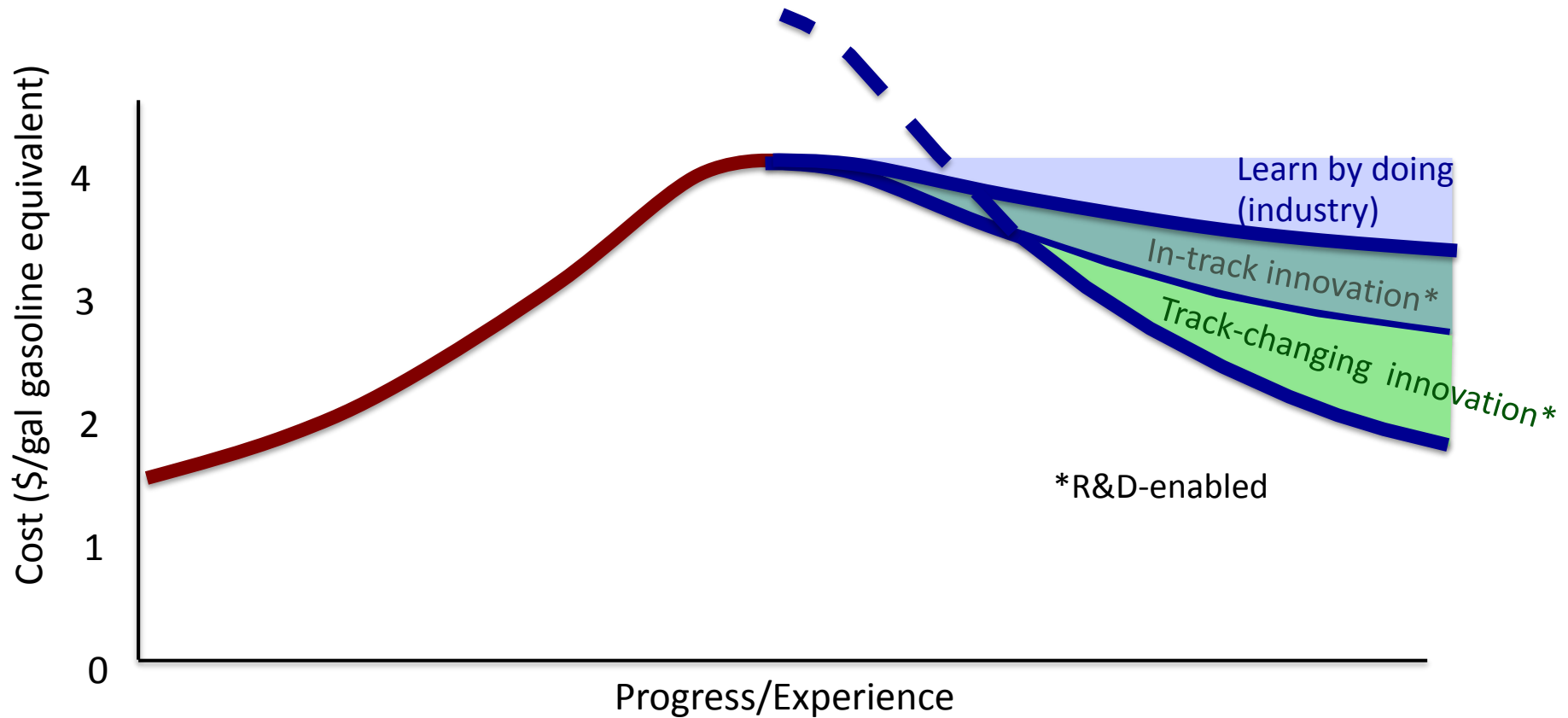
a) Proceed in one step to a multi-product biorefinery with each product involving technical and market risk;

b) Commercialize new technology to produce new fuel molecules at the same time the challenges associated with lignocellulose conversion are overcome.

5. Having a profitable sideline with a short path to revenue has proven near essential and is correlated with health of advanced biofuel companies.

6. The key to success is to devise a stair-case consisting of a set of achievable activities, each of which enables the next both technically and economically.

# Winning With Wedges: Layers of Innovation



## Good news

- Appearance of pioneer 2<sup>nd</sup> gen plants – vital to initiate learning by doing.
- Advanced bioenergy refineries have clear potential to be cost-effective, sustainable, and provide multiple important human benefits.

## Challenge/Opportunity

- Realizing potential in the timeframe needed for climate change mitigation will likely require R&D-enabled innovation beyond learning by doing.
- Current levels of innovation investment likely not sufficient, in many countries declining.



# Winning With “Wedges”: The Big Picture

