A Global View of the Biorefinery 20 Years From Now

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October 15, 2014
University of Campinas, Brazil

Need for bioenergy (selected)

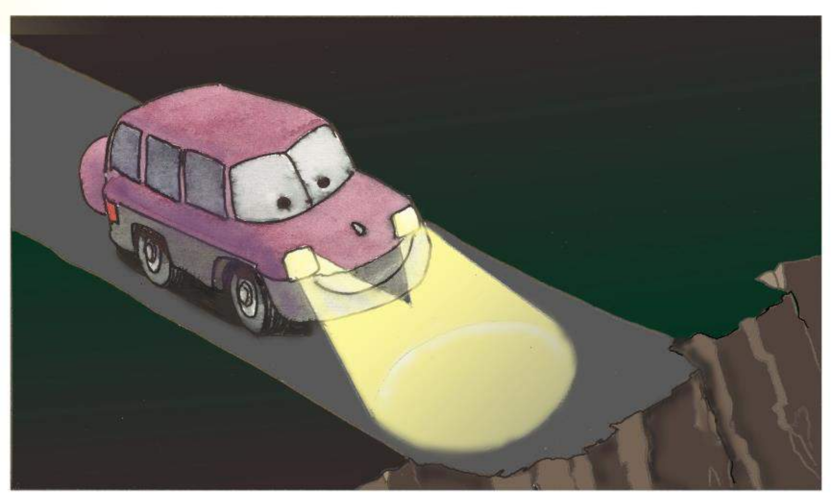
Feedstocks & land

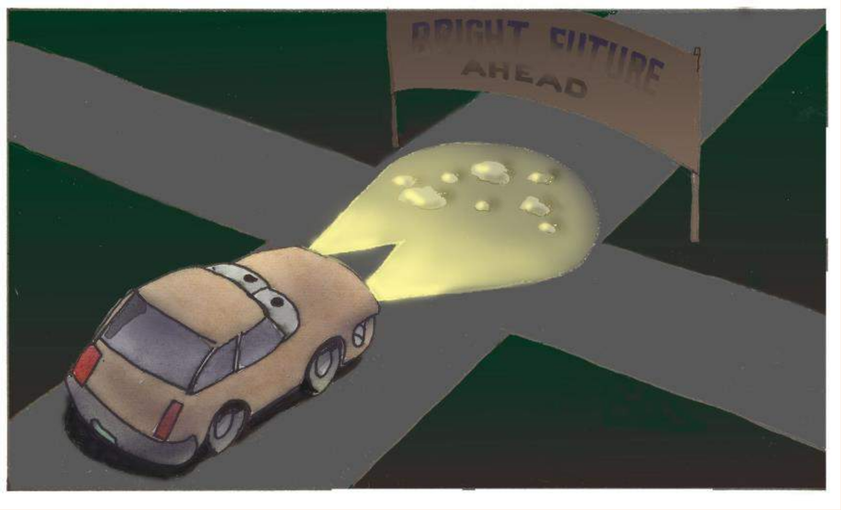
Biorefinery products

<u>Biorefinery technologies – A high beam perspective</u>

From here to there

Hazards of driving with the low beams on



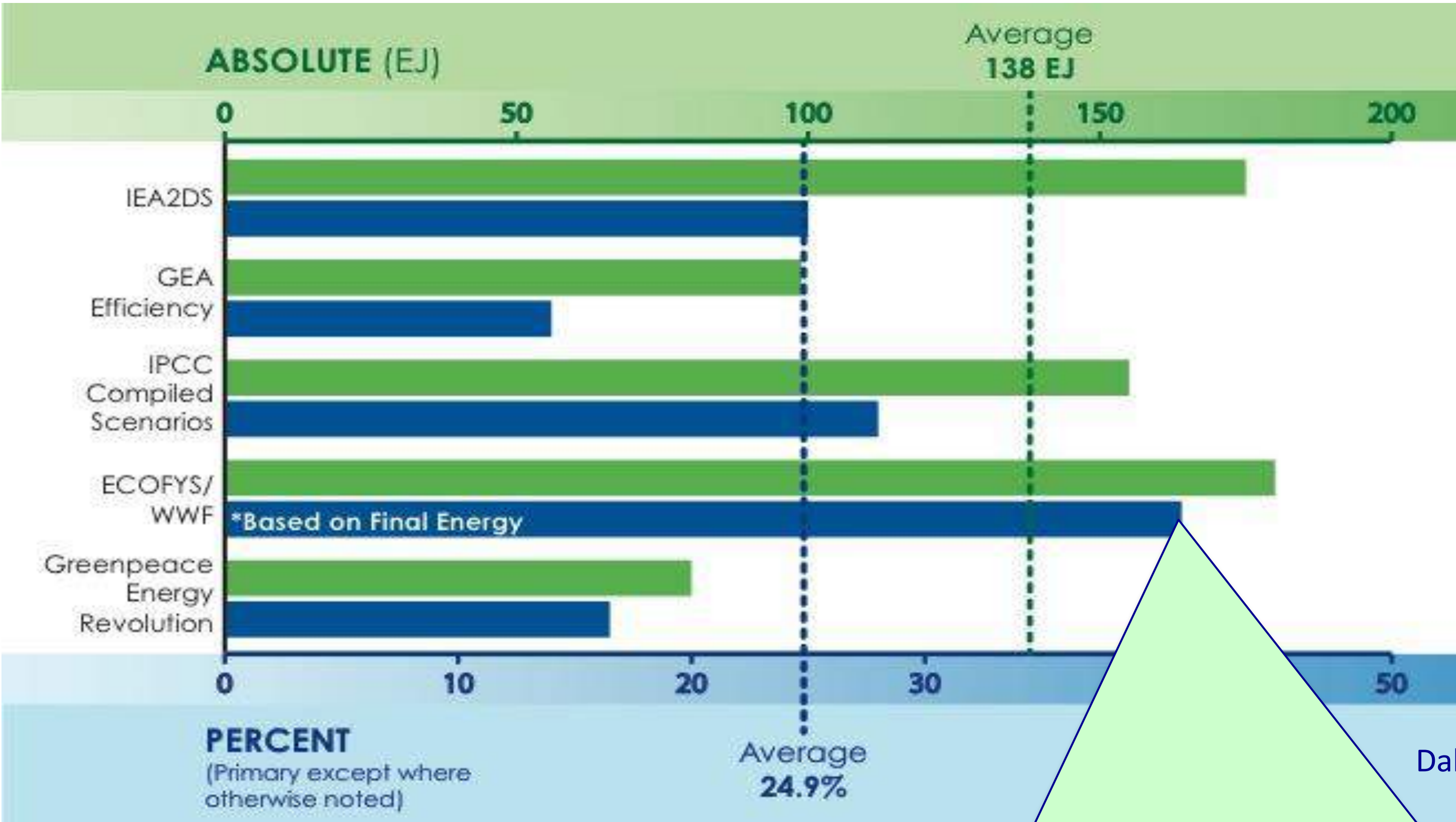


High beams perspective

I. Need for Bioenergy

Low-Carbon Energy Supply

Bioenergy Contribution in 2050: Five Low-Carbon Energy Scenarios



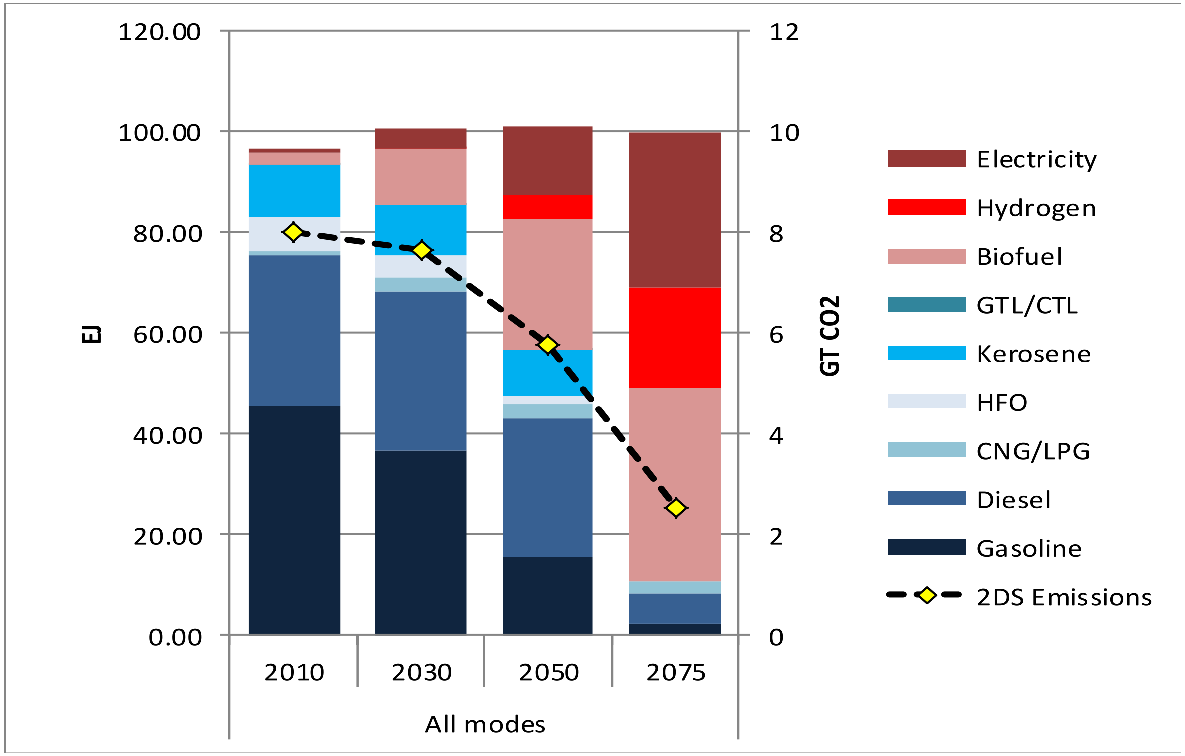
Dale et al., ES&T, 2014

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.

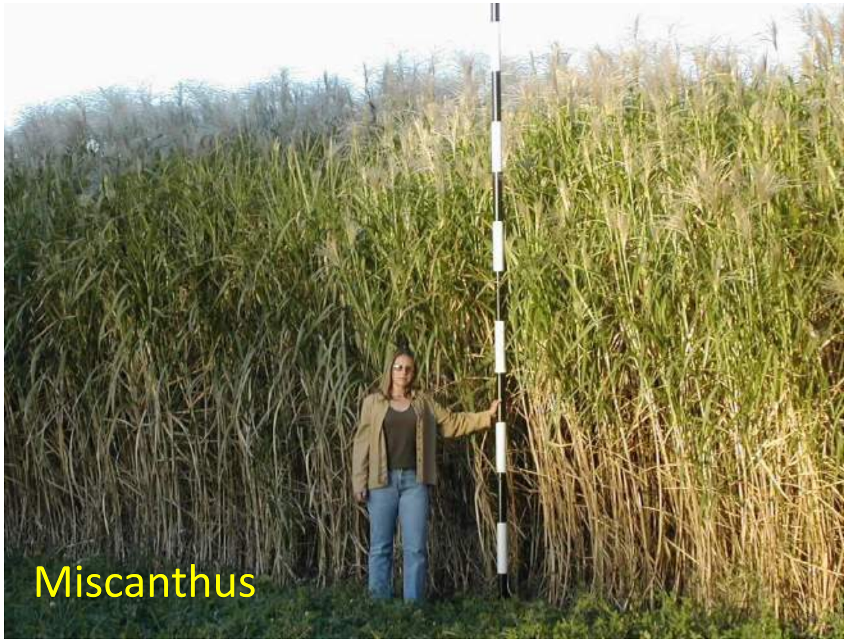
The green revolution bypassed Africa primarily due to serious organizational & institutional weaknesses, not geographically-limited capacity. August Temu, ICRAF.

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

Starch-rich (grains)
- (e.g.) corn

→ Ethanol, or other alcohols & CO_2; Animal feed; Coproducts*

Oil Seeds
- soy (US)
- rapeseed (EU)

→ Biodiesel; Animal feed; Glycerin, (coproducts)

Sugar-rich
- cane (Brazil)
- sugar beets (EU)

→ Ethanol, or other alcohols & CO_2; (coproducts); Lignin-rich residues → Process energy (Electricity &/or other coproducts)

Cellulosic

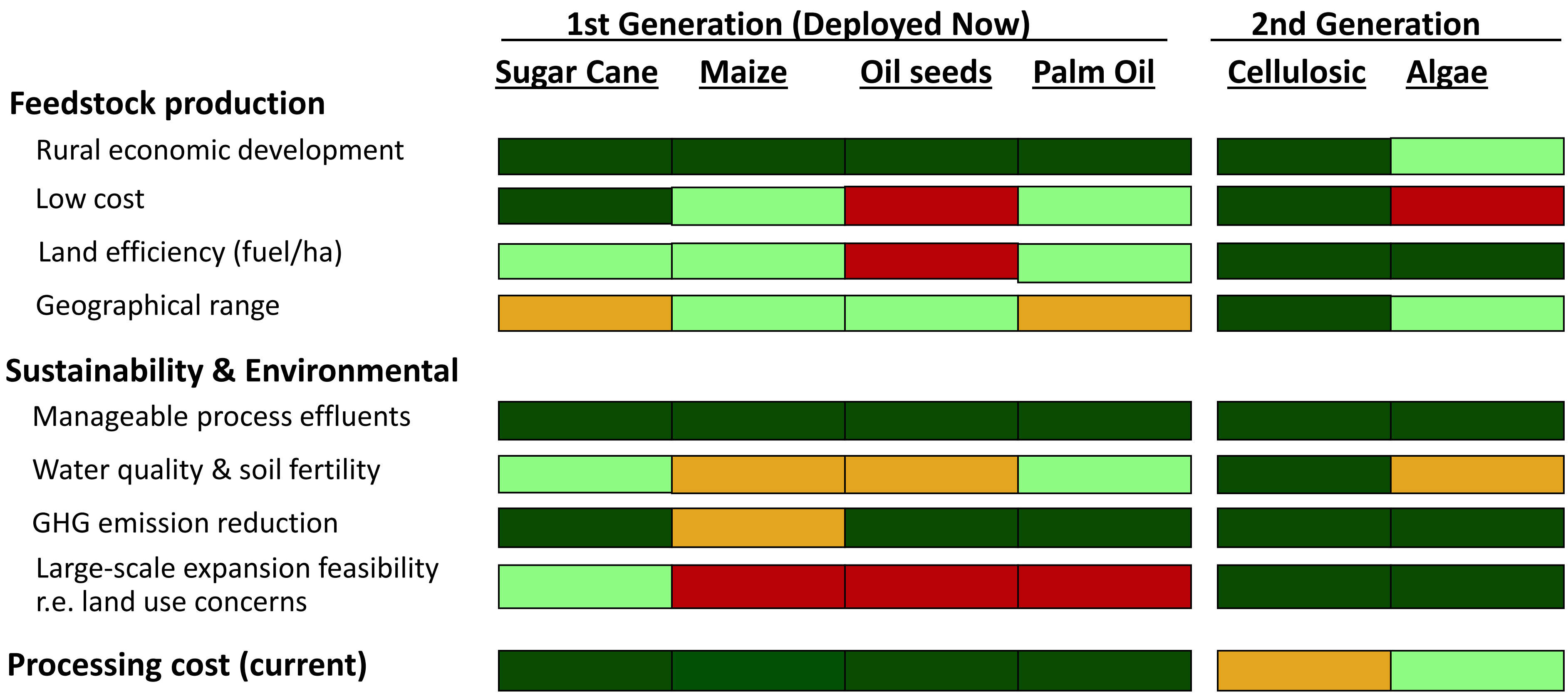
Residues
- stalks, cobs, husks
- paper sludge

Crops
- switchgrass
- short rotation trees

→ Ethanol, or other alcohols & CO_2; (coproducts, feed); Lignin-rich residues → Process energy (Electricity &/or other coproducts)

**Coproducts may include industrial or ag. chemicals, sweeteners, neutricueticals…*

Feedstocks: Dominant Determinants of Cost, Scale, Sustainability



Very favorable

Favorable

Unfavorable

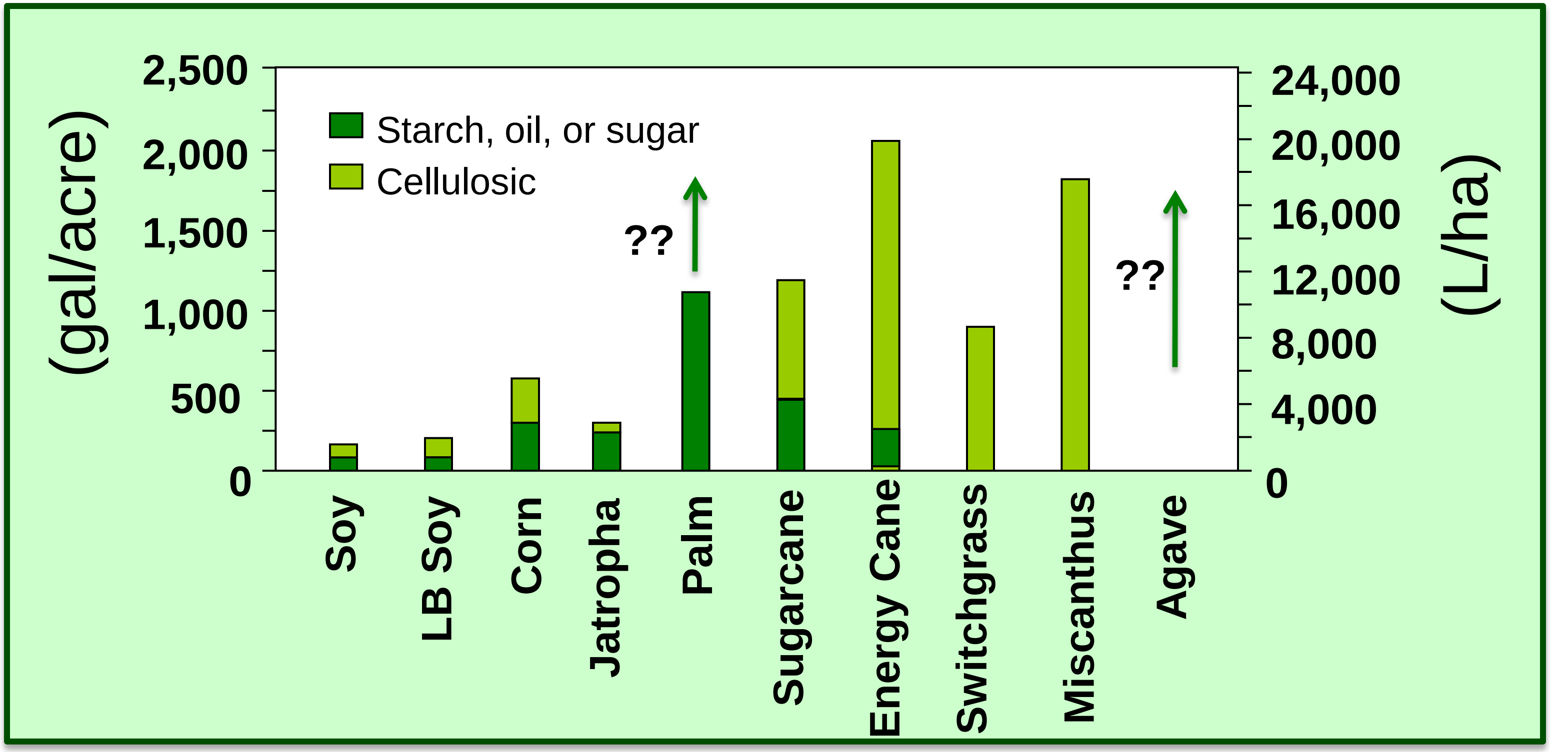
Very unfavorable

- Sugar cane: Most meritorious of 1st 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 ≤ 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_4 plants

	Maximum Productivity (Mg/ha)
C_4 perennials	70
C_3 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%
Total		412	14.6%	102	31.3%	1.3%	2.7%
Sources:	1	2	2	2	2	1,2	1,2

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

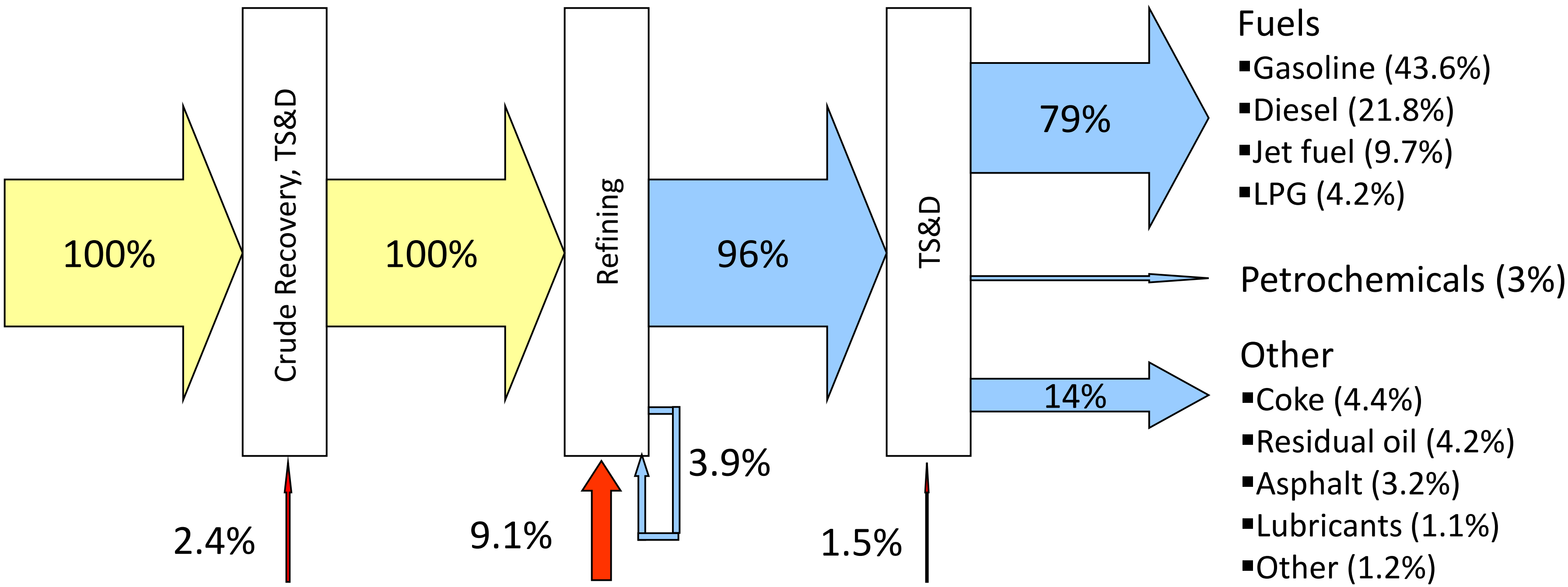
Sources:

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)



3.0% (FFE)

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

9.6% (FFE)

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

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 Affrica)

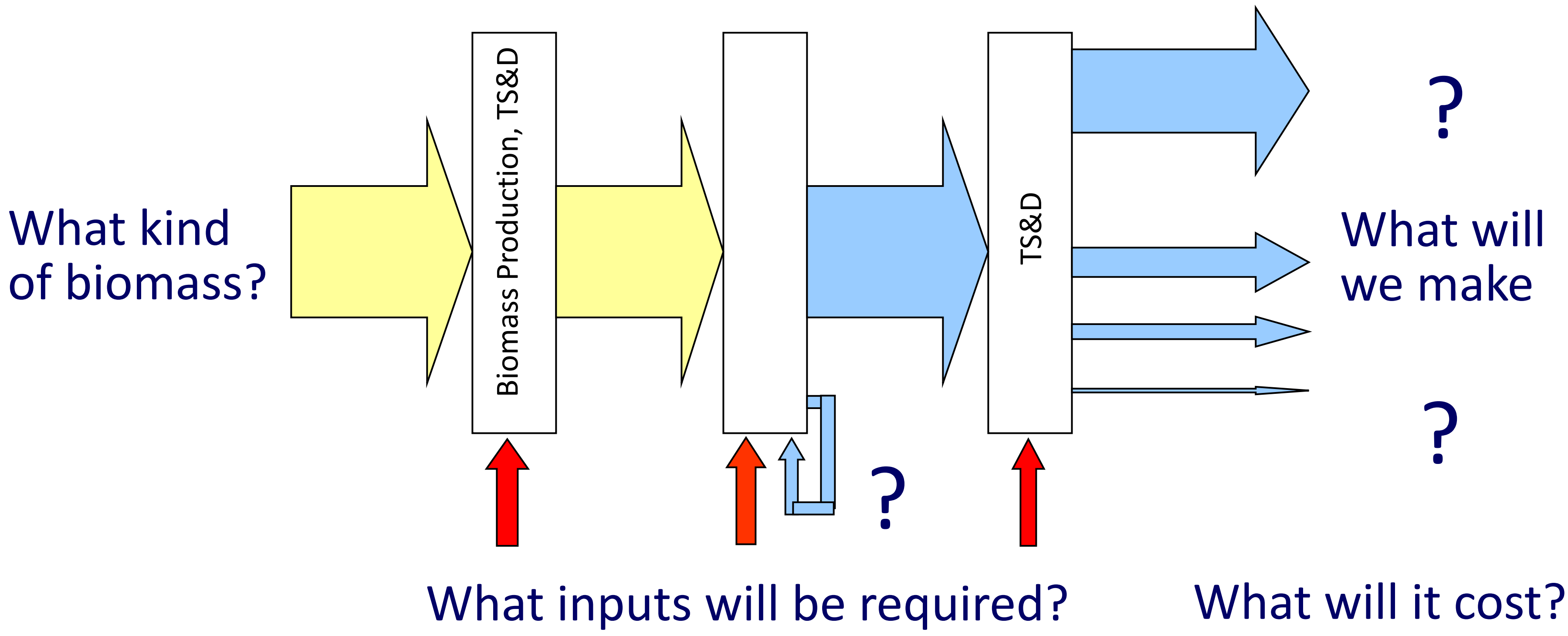
Sugar important: Cane ethanol (Brazil), corn wet milling (US)

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	**Small**
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 <u>mature</u> biomass conversion technology

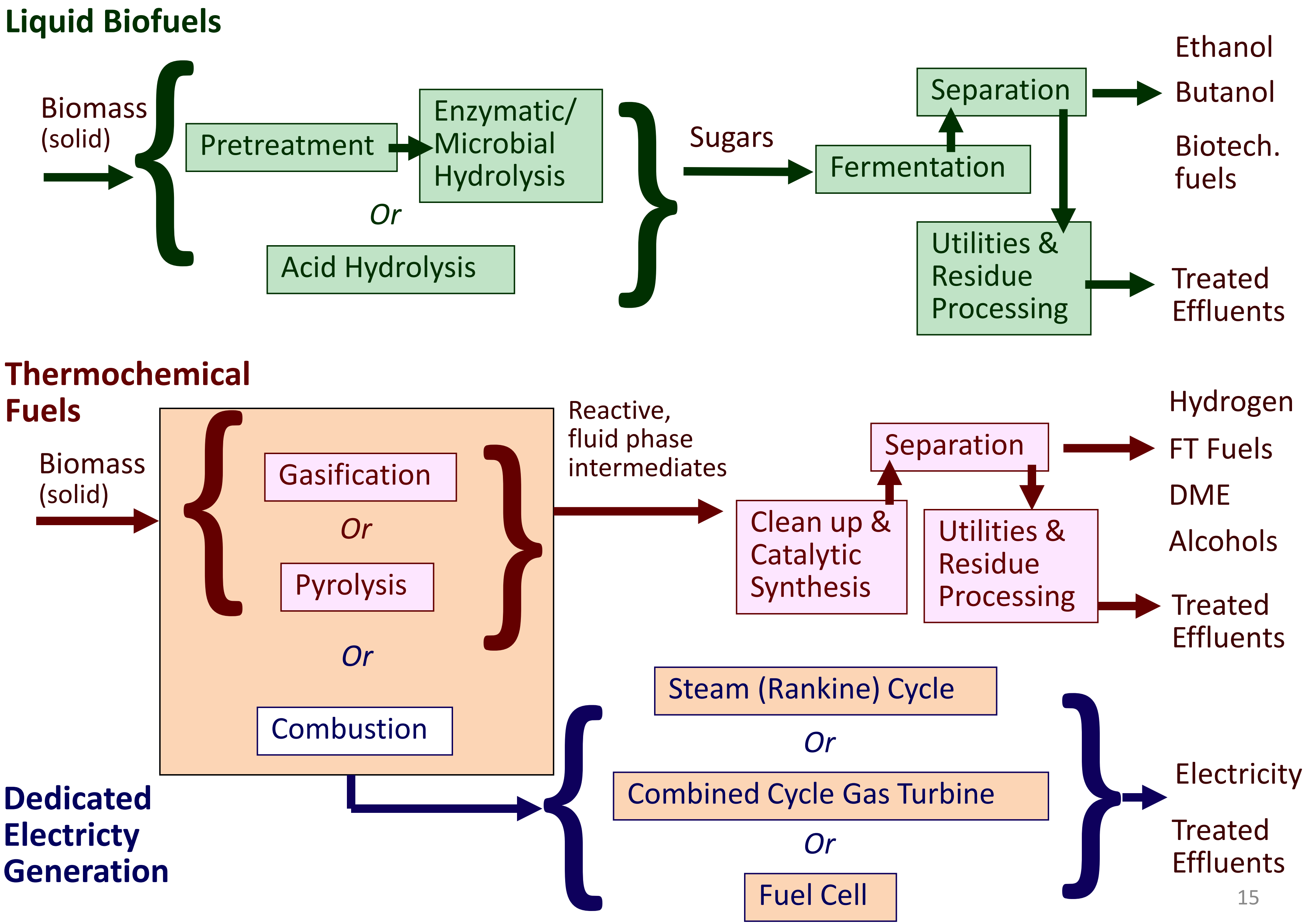
Lead institutions: Dartmouth, Natural Resources Defense Council

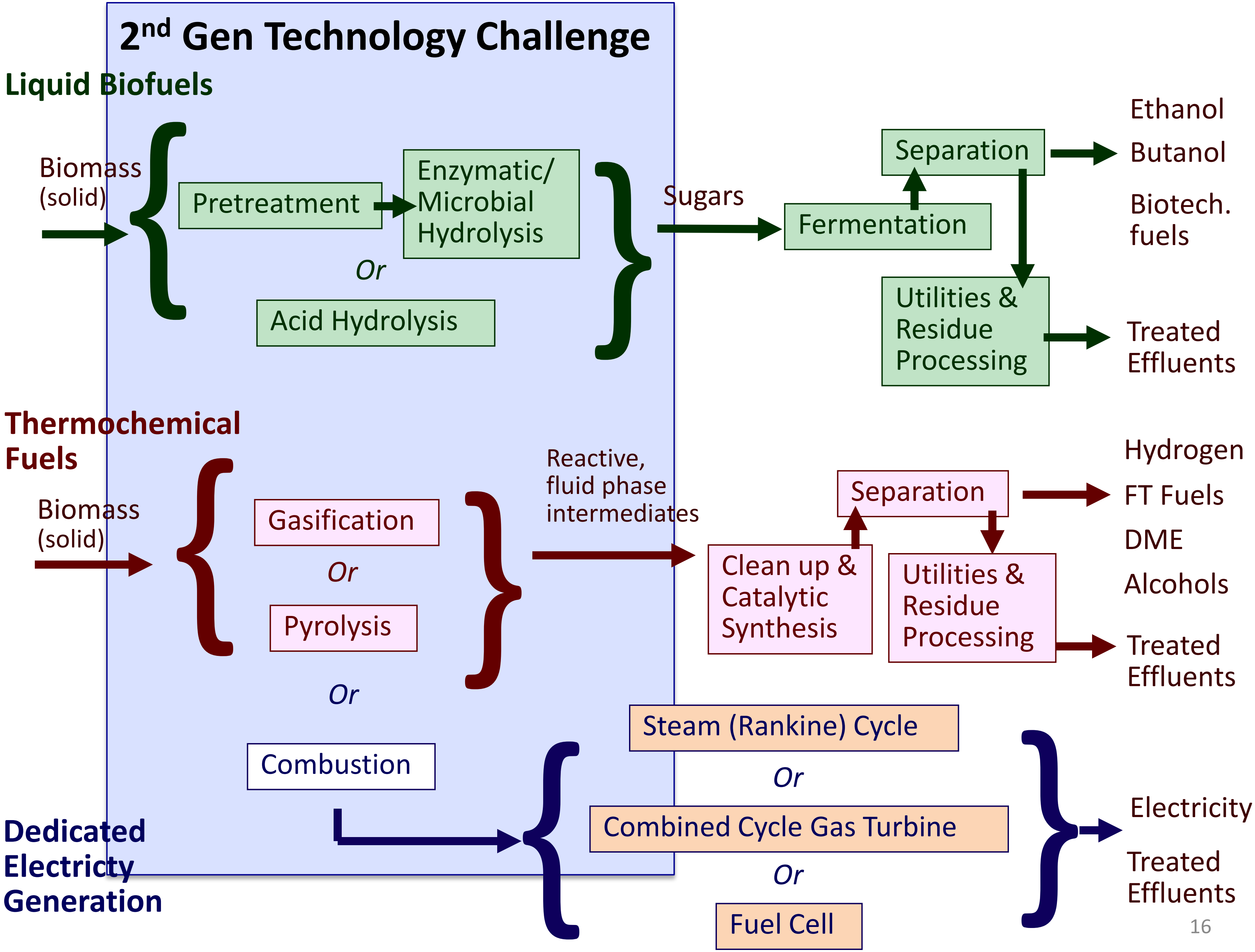
Participants: Auburn U., ANL, Iowa State U., Michigan State U., NREL, ORNL, Princeton, Union of Concerned Scientists, USDA, U. of Tennessee,

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

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

2nd Gen Process Options





2nd Gen Technology Challenge
Liquid Biofuels
Biomass (solid)
Pretreatment
Enzymatic/ Microbial Hydrolysis
Or
Acid Hydrolysis
Sugars
Fermentation
Separation
Utilities & Residue Processing
Ethanol
Butanol
Biotech. fuels
Treated Effluents
Thermochemical Fuels
Biomass (solid)
Gasification
Or
Pyrolysis
Reactive, fluid phase intermediates
Clean up & Catalytic Synthesis
Separation
Utilities & Residue Processing
Hydrogen
FT Fuels
DME
Alcohols
Treated Effluents
Or
Combustion
Dedicated Electricty Generation
Steam (Rankine) Cycle
Or
Combined Cycle Gas Turbine
Or
Fuel Cell
Electricity
Treated Effluents

RBAEF Process Analysis

Material & Energy Balance Models

- Implemented using ASPEN
- Built on extensive prior work
  - Princeton (thermochemical fuels & power)
  - NREL & Dartmouth (ethanol)

Basis for

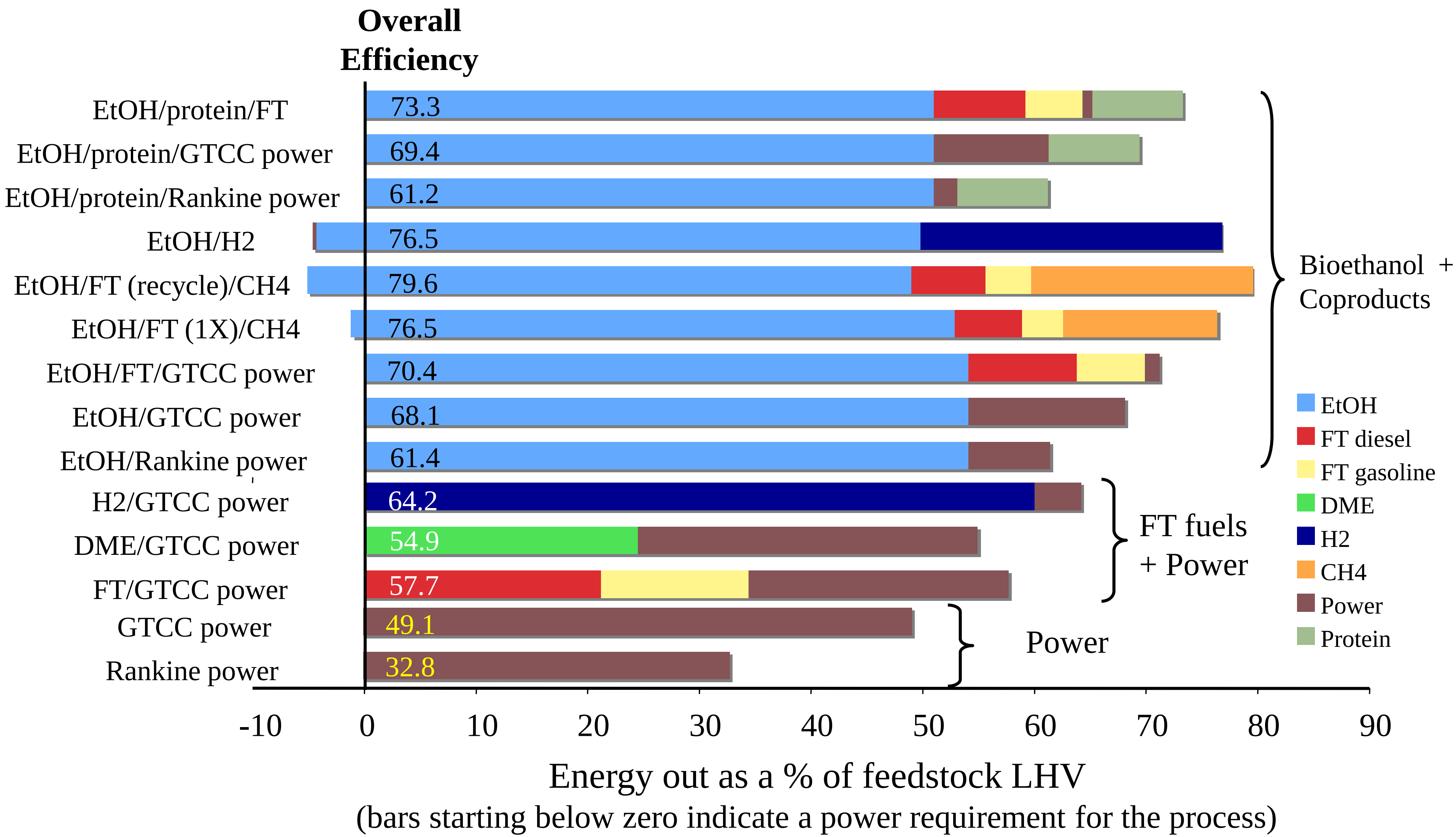
- Thermodynamic analysis "energy balance"
- Material flows for environmental analysis
- Economic analysis

24 different scenarios including many products & combinations

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

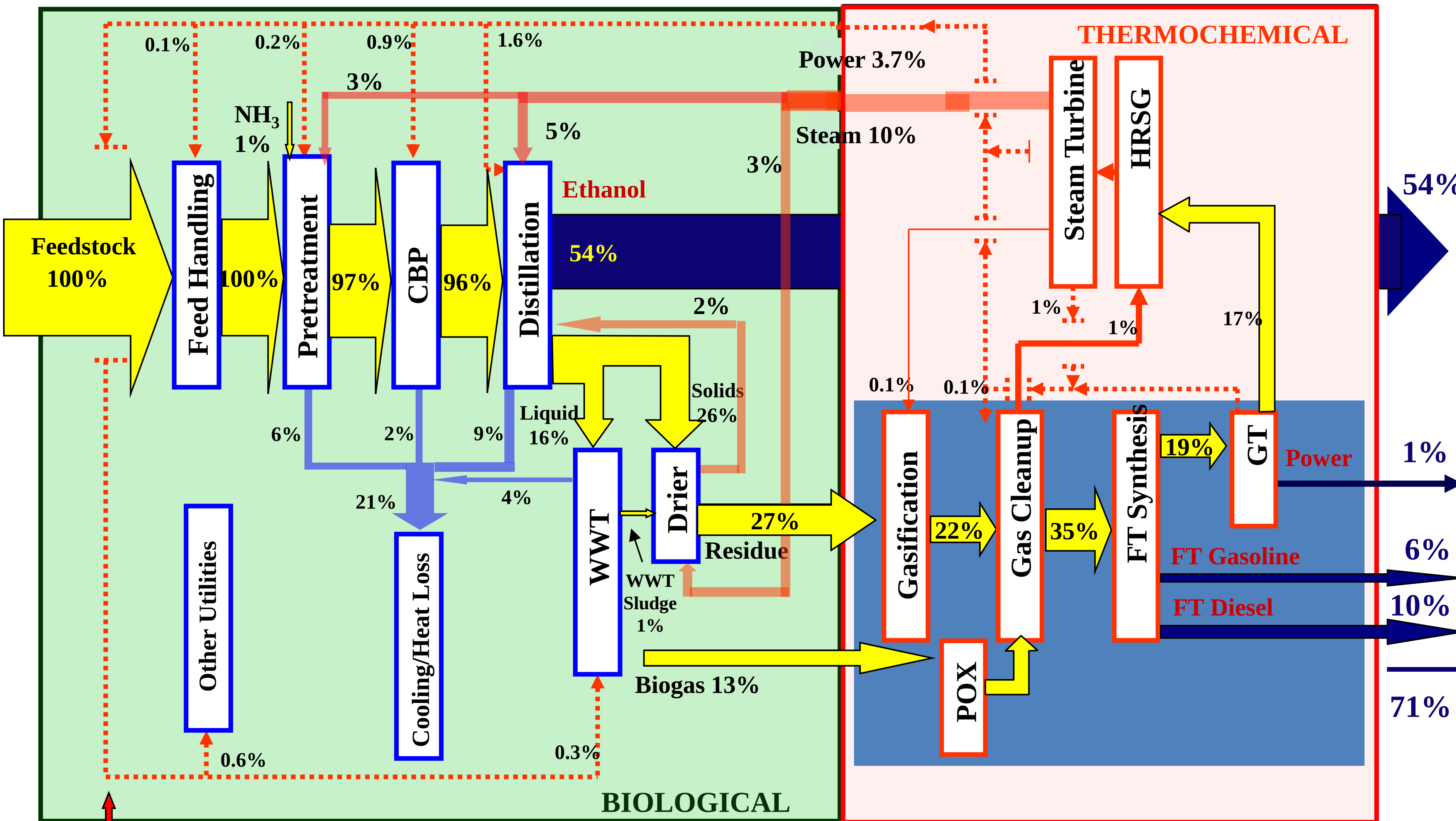
Unprecedented for mature biomass conversion technologies

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 %

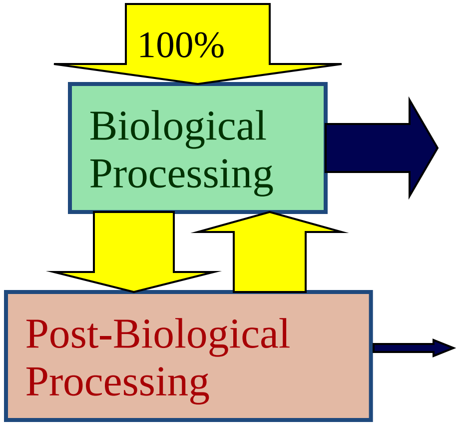
Energy out/Energy in = 71/7 = ~10

Laser et al., BioFPr, 2009

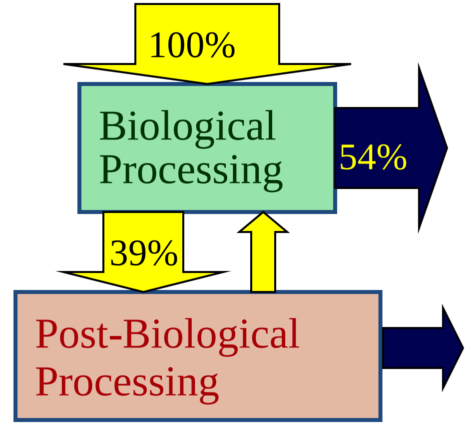
Integration of TC and Biological Processing Offers Lots of Value

Maturation of biological conversion → much larger opportunities

Current

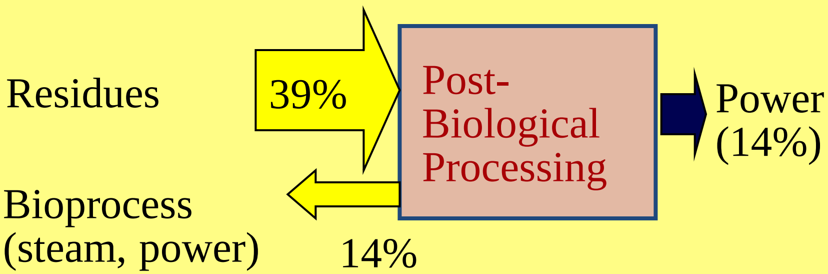


Mature



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

Power



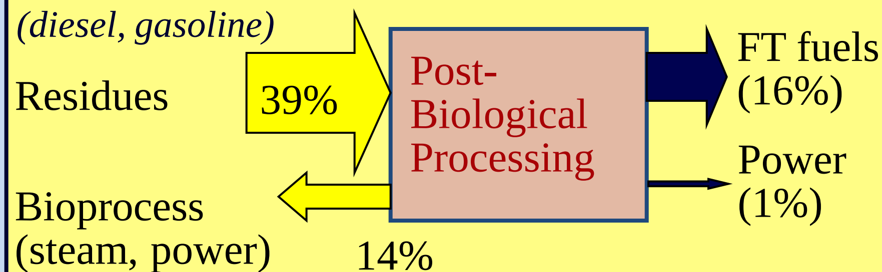
η_{power} = 14/(39 - 14) = 0.56

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

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

Fischer-Tropsch fuels

(diesel, gasoline)

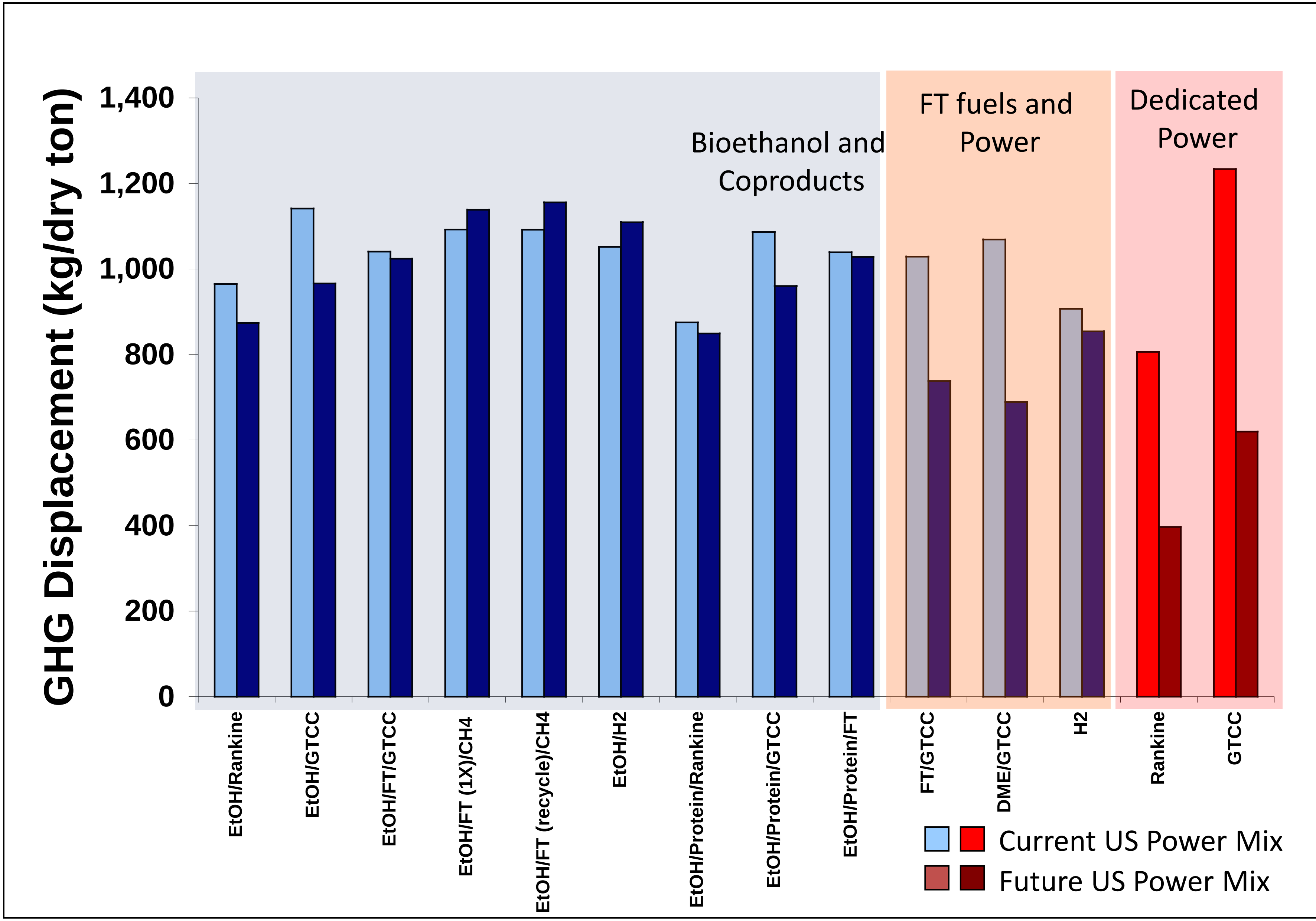


$\eta_{FTfuels}$ = (17 + 1)/(39 - 14) = 0.72

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

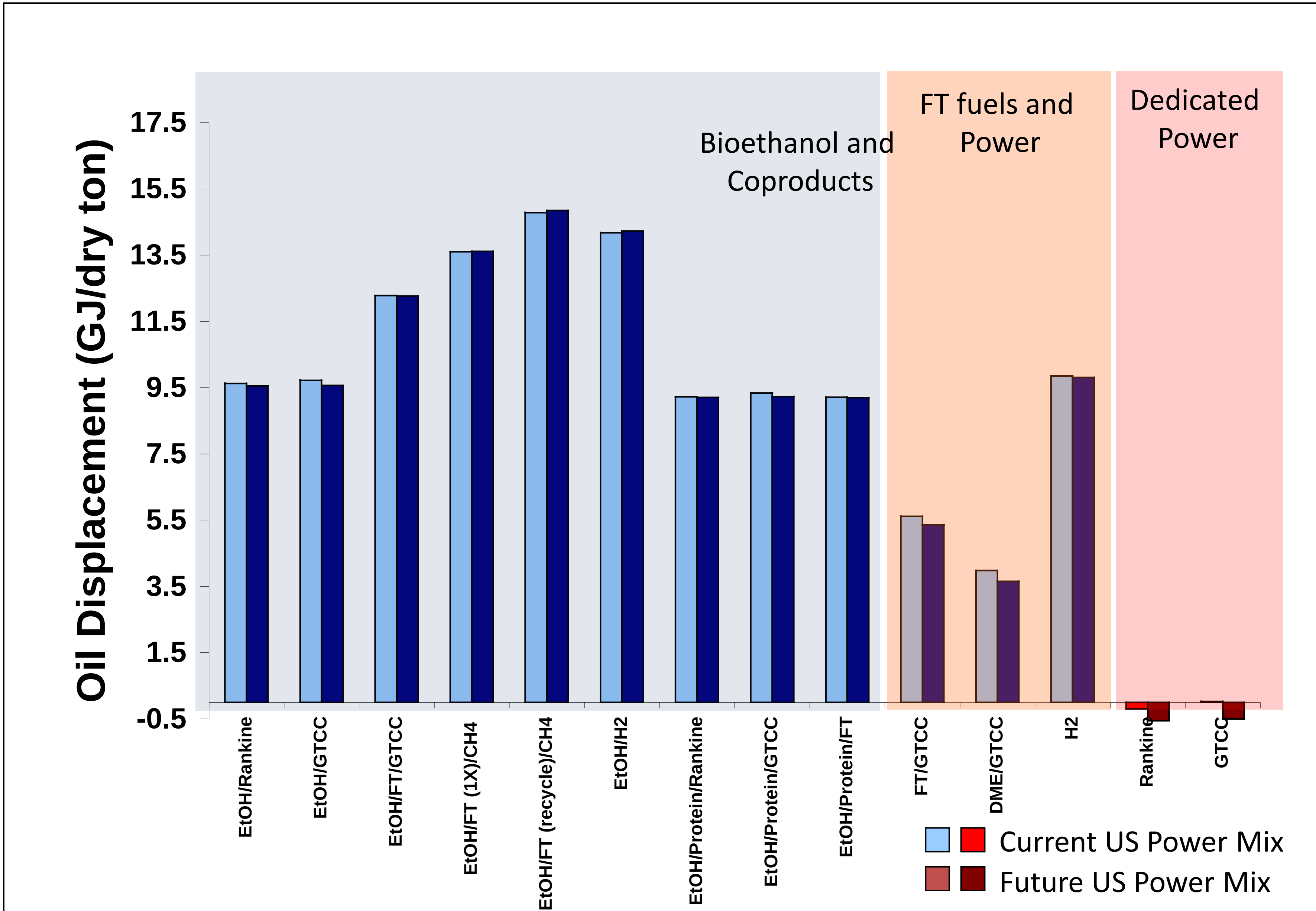
E90 entirely from renewables

Comparative Greenhouse Gas Displacement



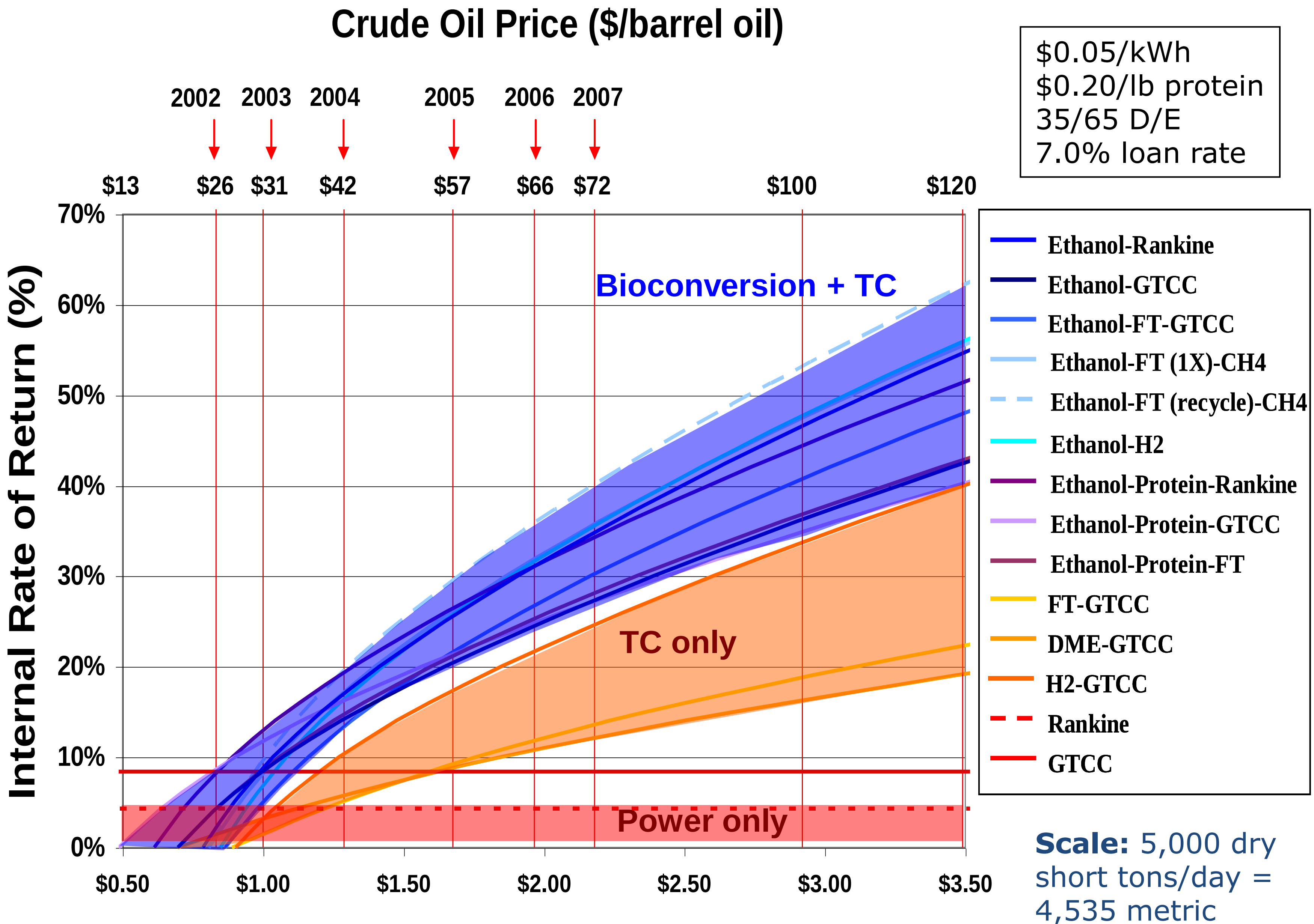
Laser et al., Role of Biomass in America's Energy Future (RBAEF) Project, BioFPr, 2009

Comparative Petroleum Displacement



Laser et al., Role of Biomass in America's Energy Future (RBAEF) Project, BioFPr, 2009

Comparative Economics

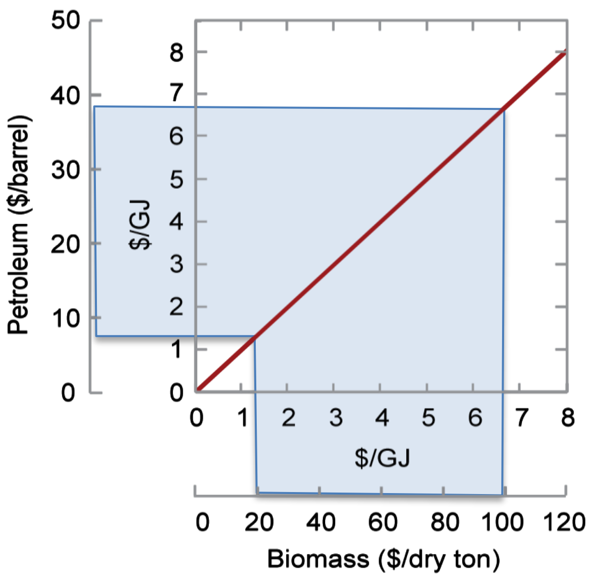


Scale: 5,000 dry short tons/day = 4,535 metric tons/day

Cost Competitive 2nd Gen Biofuels "Sniff Test"

Cost-Competitive Feedstocks (Now)

	($/Dry ton)	$/GJ	Equivalent Oil Price ($/bbl)
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	Cellulosic Biomass
Cost ($/GJ)		
	Feedstock (@ $100/bbl): **18**	Feedstock (@ $60/ton): **4**
	Processing: **<u>6</u>**	Allowable processing: **<u>20</u>**
	24	
Processing advantages		
	Fluid (more physically accessible)	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

Metric	Biological & coproducts*	TF fuels & power	Power
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

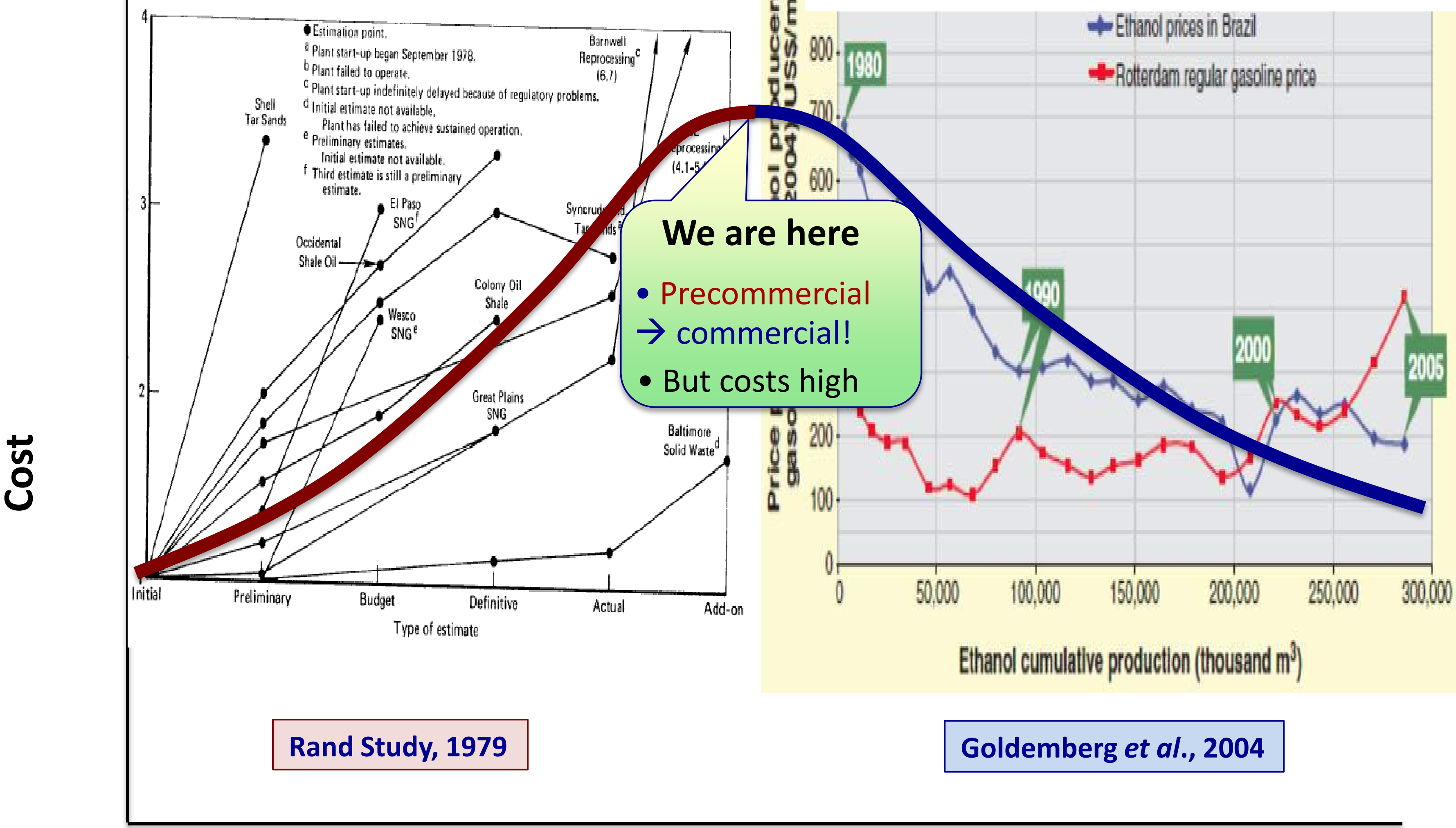
New technology activation energy

Rand Curve

Estimated cost increases with experience, inversely related to ignorance

Brazil 1st Gen Ethanol Curve

Actual cost decreases with experience & innovation



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-Envelop Economics ($/gallon gasoline equivalent)

Capital[1]	OpEx
2.05	Feedstock: ~ 0.9[2]
2.40	Other: ≥ 0.50[3]
2.40	
5.63	
5.04	
3.06	
4.00	
3.97	
4.00 (revised)	

Wholesale gasoline price 2.40

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

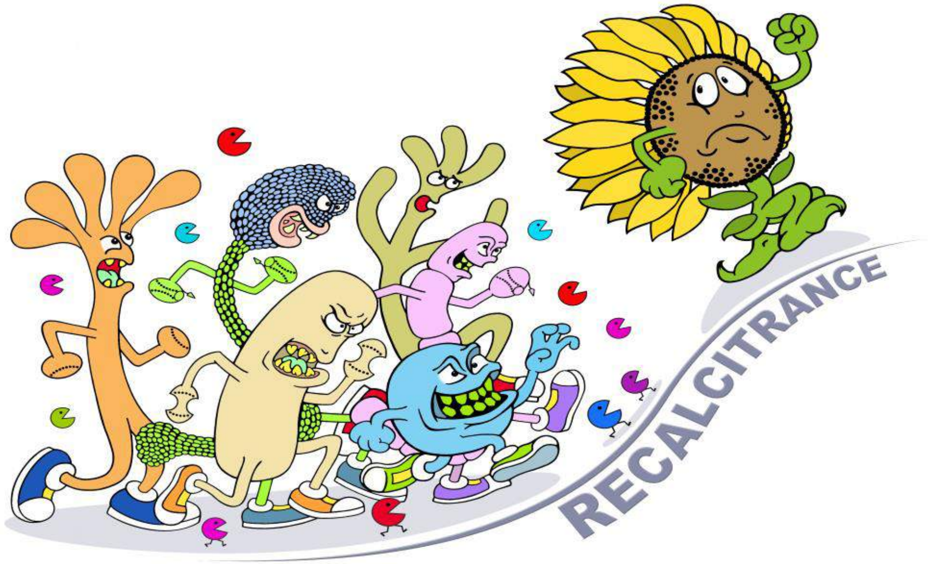
[2] Based on $65/ton, 75 gal fuel produced/ton.

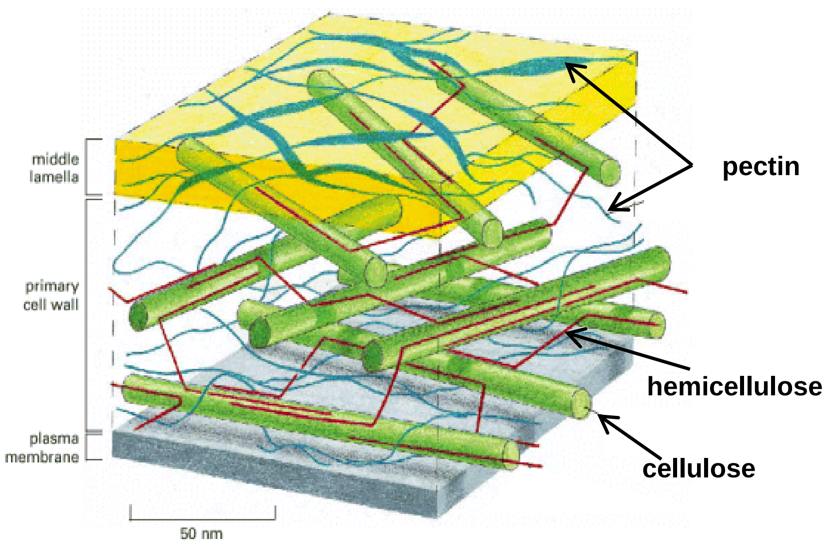
[3] Includes chemicals, labor, waste disposal). Excludes capital-related. Representative of current technology.

Technological Challenge: Recalcitrance of Cellulosic Biomass

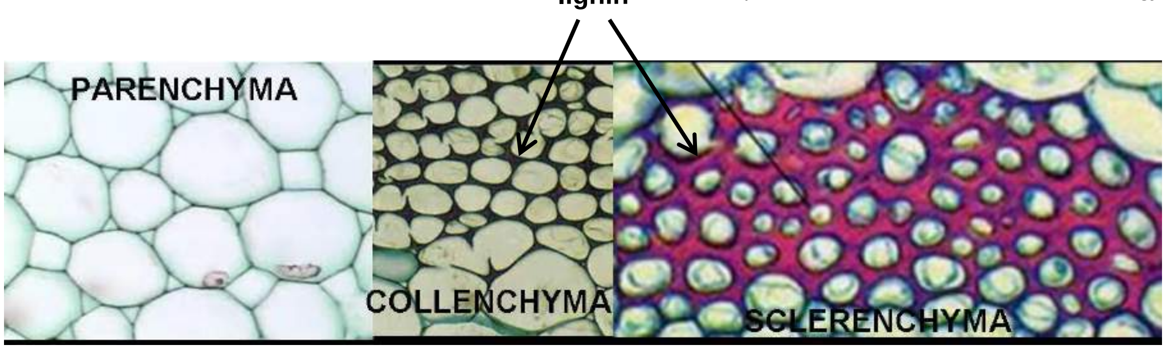
What: Difficulty of converting cellulosic biomass into reactive intermediates (Lynd *et al.*, *Biotechnol Prog*, '99). For intracellular bioprocessing, reactive intermediates must be soluble.

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





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



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:

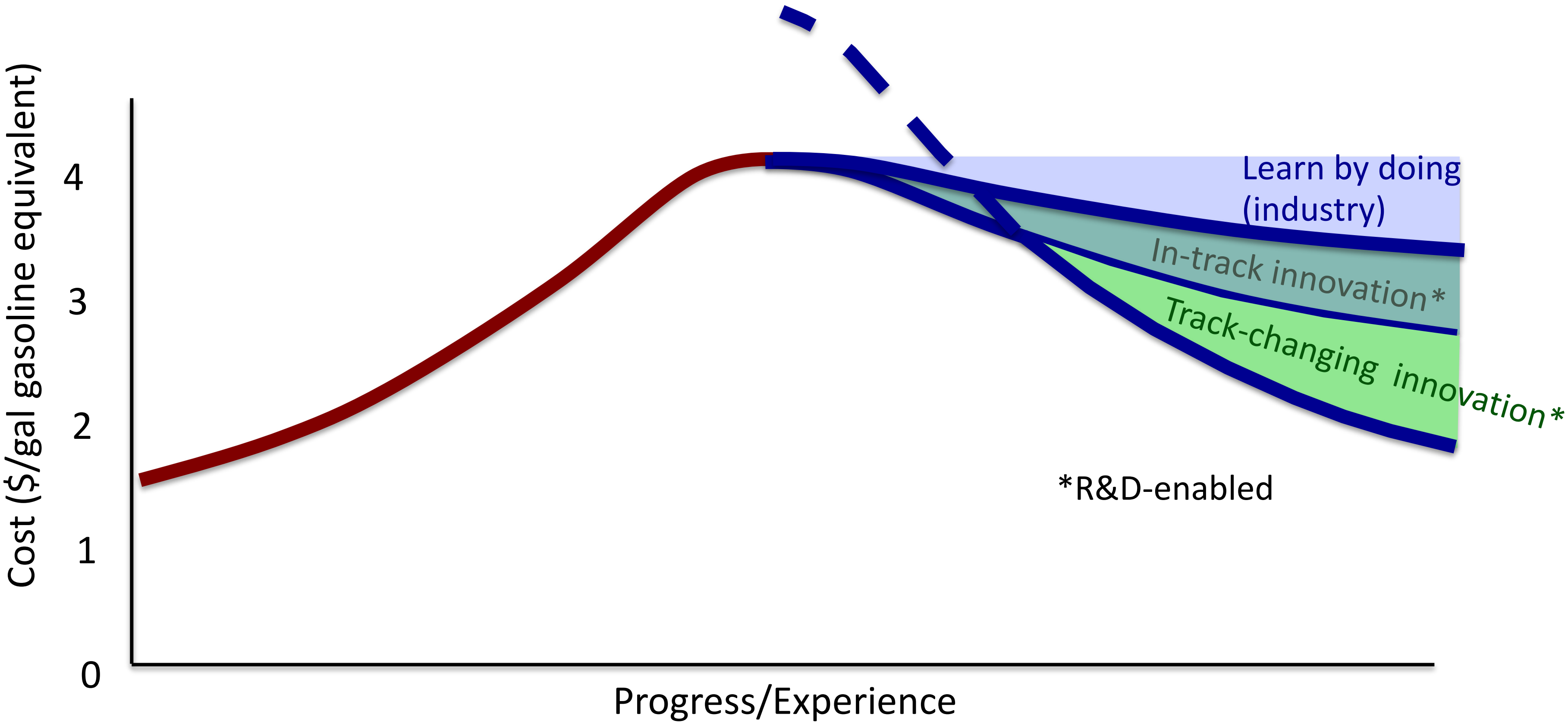
a) Proceed in one step to a multi-product biorefinery with each product involving technical and market risk;

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



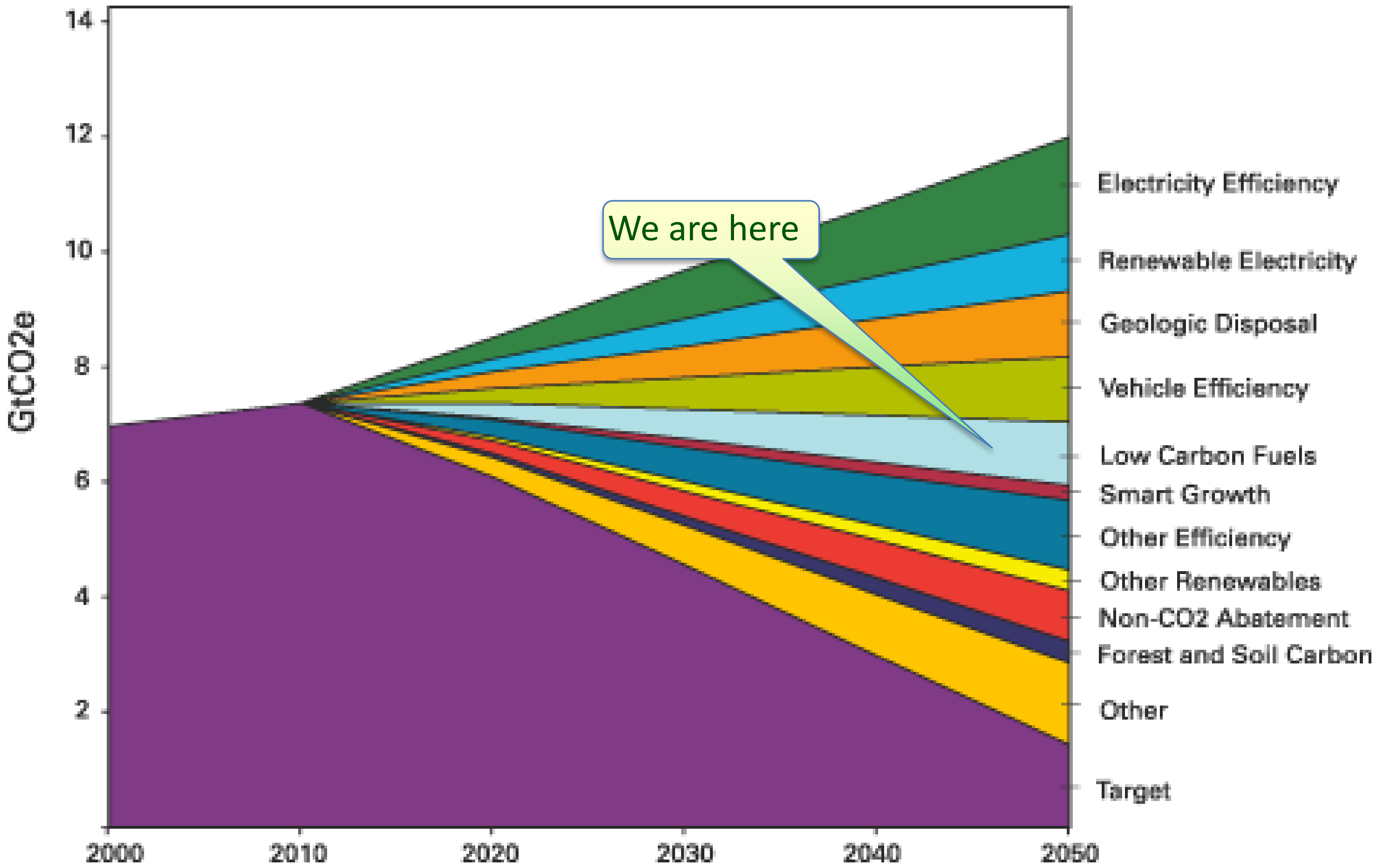
Good news

- Appearance of pioneer 2nd 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



http://www.nrdc.org/globalwarming/blueprint/methodology.asp.
Modified from Pacala and Socolow, Science, 2004.