



Biochemical Refining of Lignocellulose to Biofuels: Status and Prospects



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Sustainable Biorefineries
Plenary, Paper 431b

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Outline

Current Situation

- Biofuels progress and drivers
- New initiatives
- RDD&D situation

NREL R&D Progress

- Biochemical cellulosic ethanol
- Improved piloting facilities
- R&D beyond cellulosic ethanol
 - National Advanced Biofuels Consortium (NABC)

Outlook and Final Thoughts

- On-going challenges and unresolved issues

Recent History of Advanced Biofuels

- 1995-2000: Demonstrate technical feasibility
Focus on cellulosic ethanol
- 2000-2005: Show economic feasibility & scale potential
Focus remains largely on cellulosic ethanol
- 2005-2010: Increase funding to accelerate biofuels RDD&D
Expand product portfolio to encompass higher alcohols and hydrocarbons, begin funding new concepts including hybrid BC/TC and algal pathways

Current Situation

Advanced biofuels R&D booming

- Many potential routes being rigorously studied (BC, TC, hybrid, algae, etc.)
- Major bioenergy research centers formed, actively engaged (BESC, JBEI, GLBRC, EBI, etc.)
- R&D community 100x bigger (more than 50 sessions at this meeting!)

Commercialization starting

- Many dozens of companies pursuing technology development
- Cellulosic and algal biofuels production occurring, albeit at a pace much slower than planned or initially forecasted



Danish fueling station pump dispensing E5 gasoline-ethanol blend containing wheat straw-derived cellulosic ethanol

photo courtesy of Claus Felby (U. Copenhagen)

Drivers for Advanced Biofuels Remain Strong

“Developing the next generation of biofuels is key to our effort to end our dependence on foreign oil and address the climate crisis – while creating millions of new jobs that can't be outsourced. With American investment and ingenuity – and resources grown right here at home – we can lead the way toward a new green energy economy.”

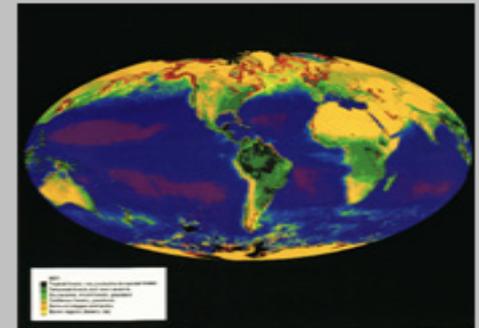
– Secretary of Energy Steven Chu

Science and Discovery



Economic Prosperity

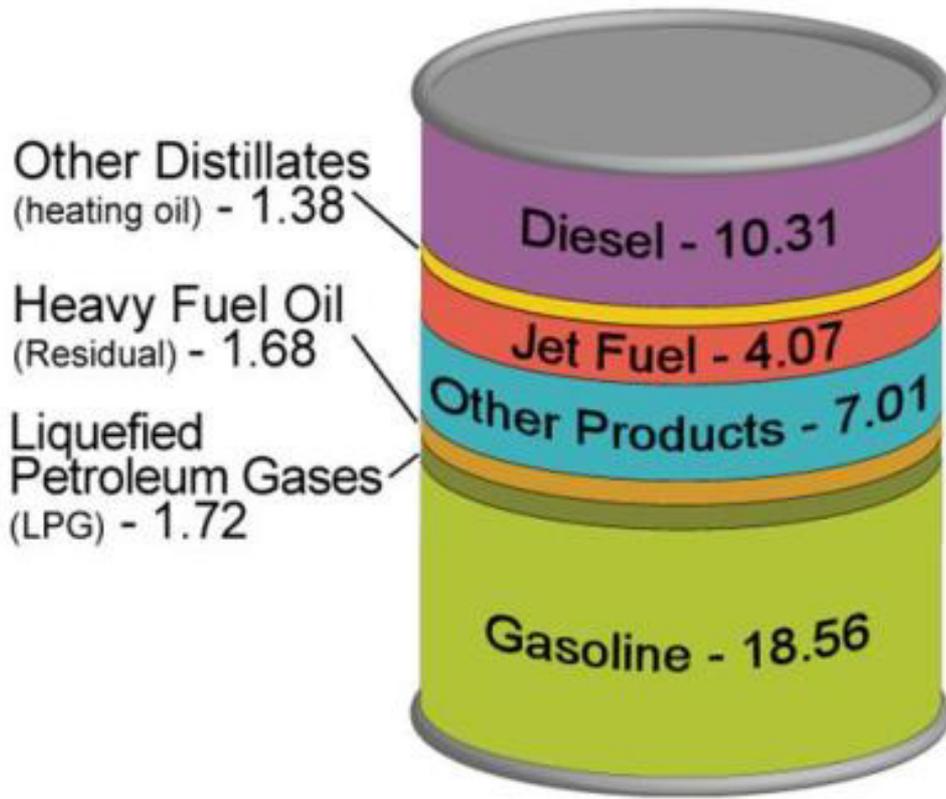
Clean, Secure Energy



Climate Change

More Fuels Needed to Displace Fossil Oil

Products Made from a Barrel of Crude Oil (Gallons)



- Advanced biofuels and products are needed to displace the entire barrel (14.7 mbd = 225 bgy = 70% of U.S. petroleum use)
- < Heavy duty/diesel and jet fuel substitutes required to displace several components (43 bgy diesel + 25 bgy aviation fuel + 10 bgy fuel oil for shipping = 78 bgy = 36% of transportation fuel)
- < Cellulosic ethanol displaces light duty gasoline fraction (140 bgy = 64% of transportation fuel)

Source: Energy Information Administration, "Petroleum Explained" and AEO2009, Updated (post-ARRA), Reference Case.

DOE Stimulating Progress Across Supply Chain

The USDOE Biomass Program is working to advance biomass technologies in support of its mission to strengthen America's energy security, environmental quality, and economic vitality through:



Feedstocks

Developing lower cost feedstock logistics systems



Conversion technologies

Improving conversion efficiencies and costs



Integrated biorefineries

Systematically validating and deploying technology at first-of-a-kind facilities



Infrastructure

Evaluating vehicle emissions, performance, and deployment options



Biopower

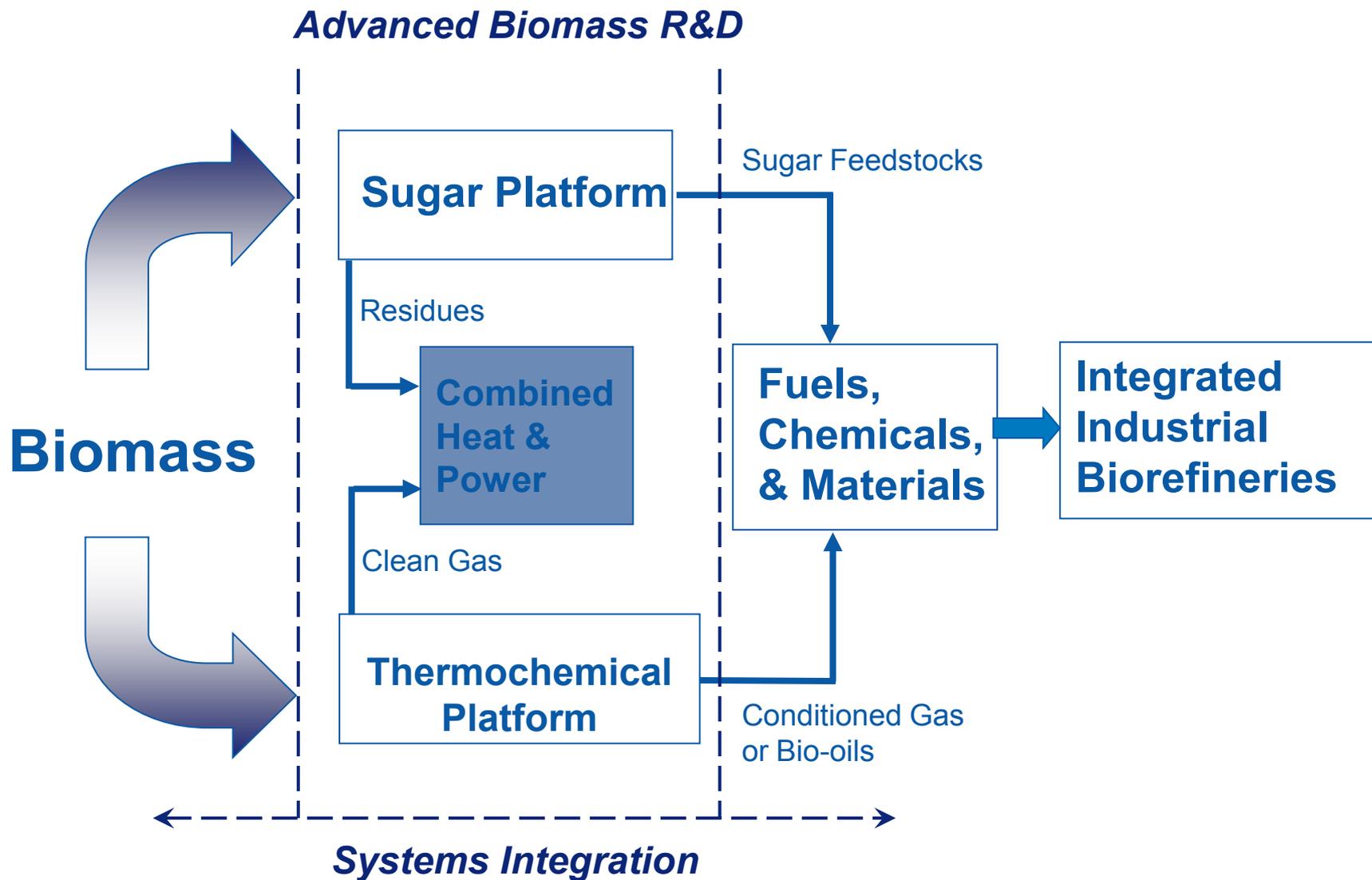
Providing a clean, domestic, dispatchable renewable source of power



Advanced biofuels

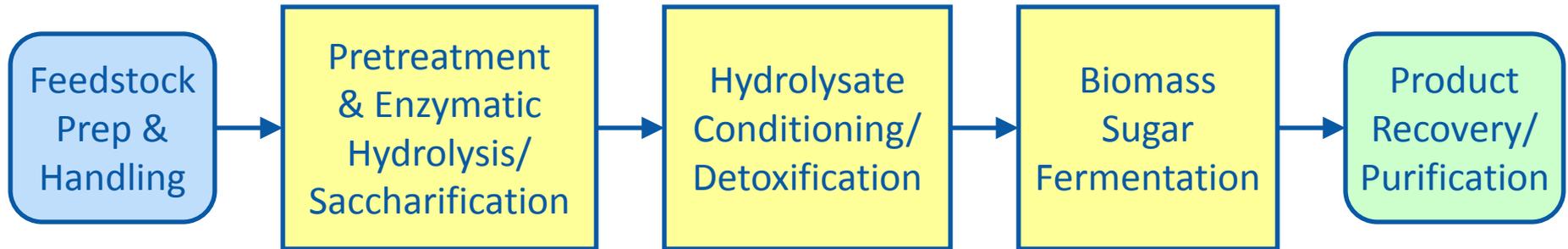
Expanding portfolio beyond cellulosic ethanol to hydrocarbon fuels

Integrated Biorefinery Conversion Platforms



Biomass Conversion to Fuels

Major *Biochemical* Conversion Steps

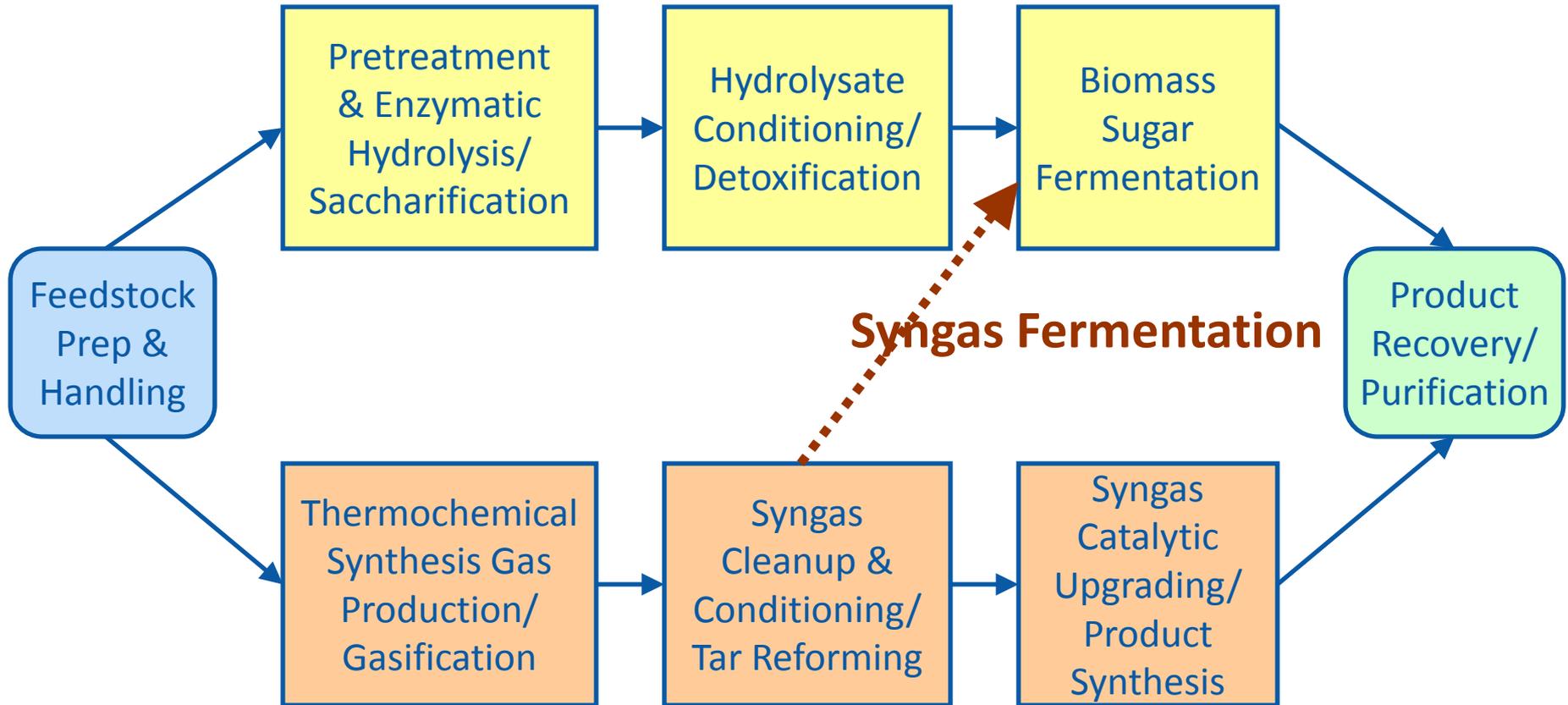


Major *Thermochemical* Conversion Steps



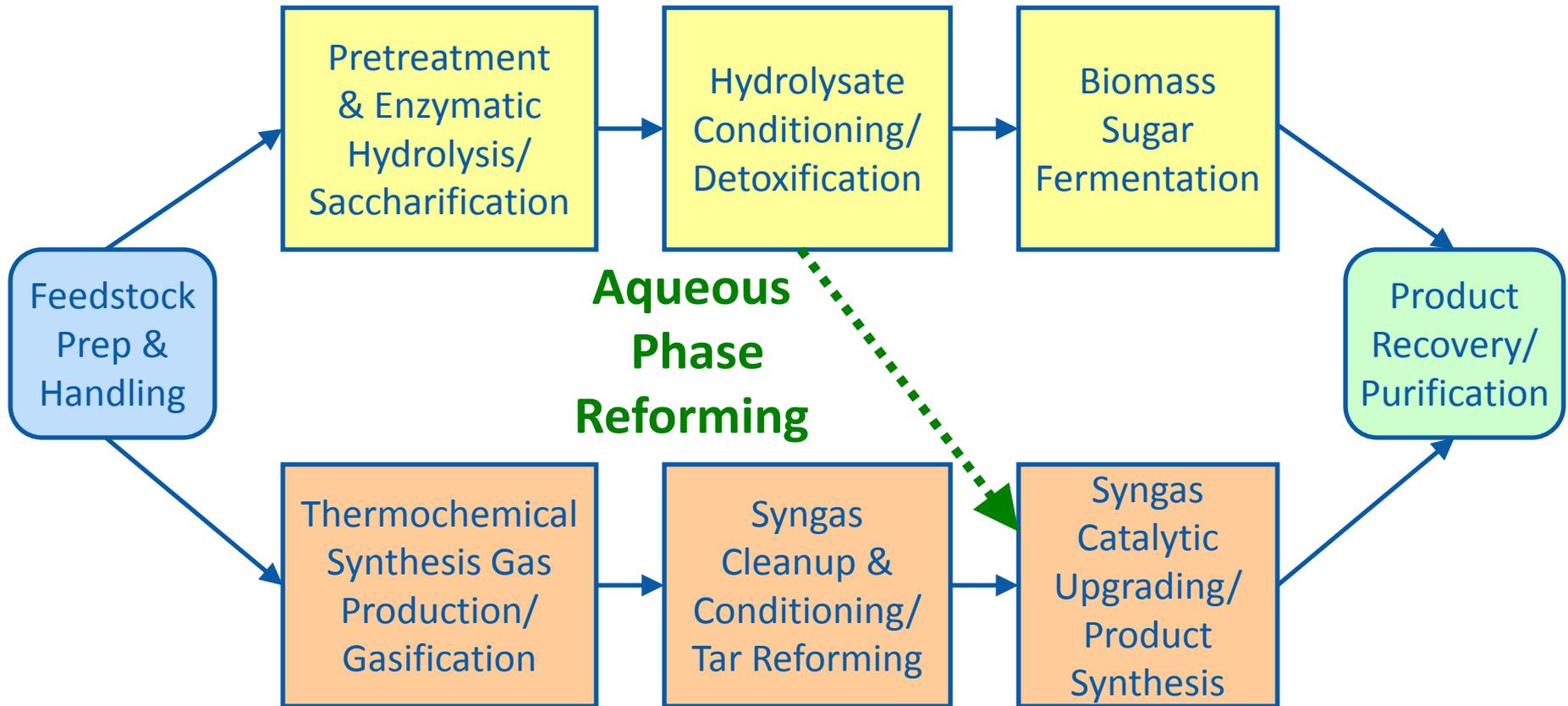
Biomass Conversion to Fuels

Hybrid Approaches



Biomass Conversion to Fuels

Hybrid Approaches



Integrated Biorefinery Projects

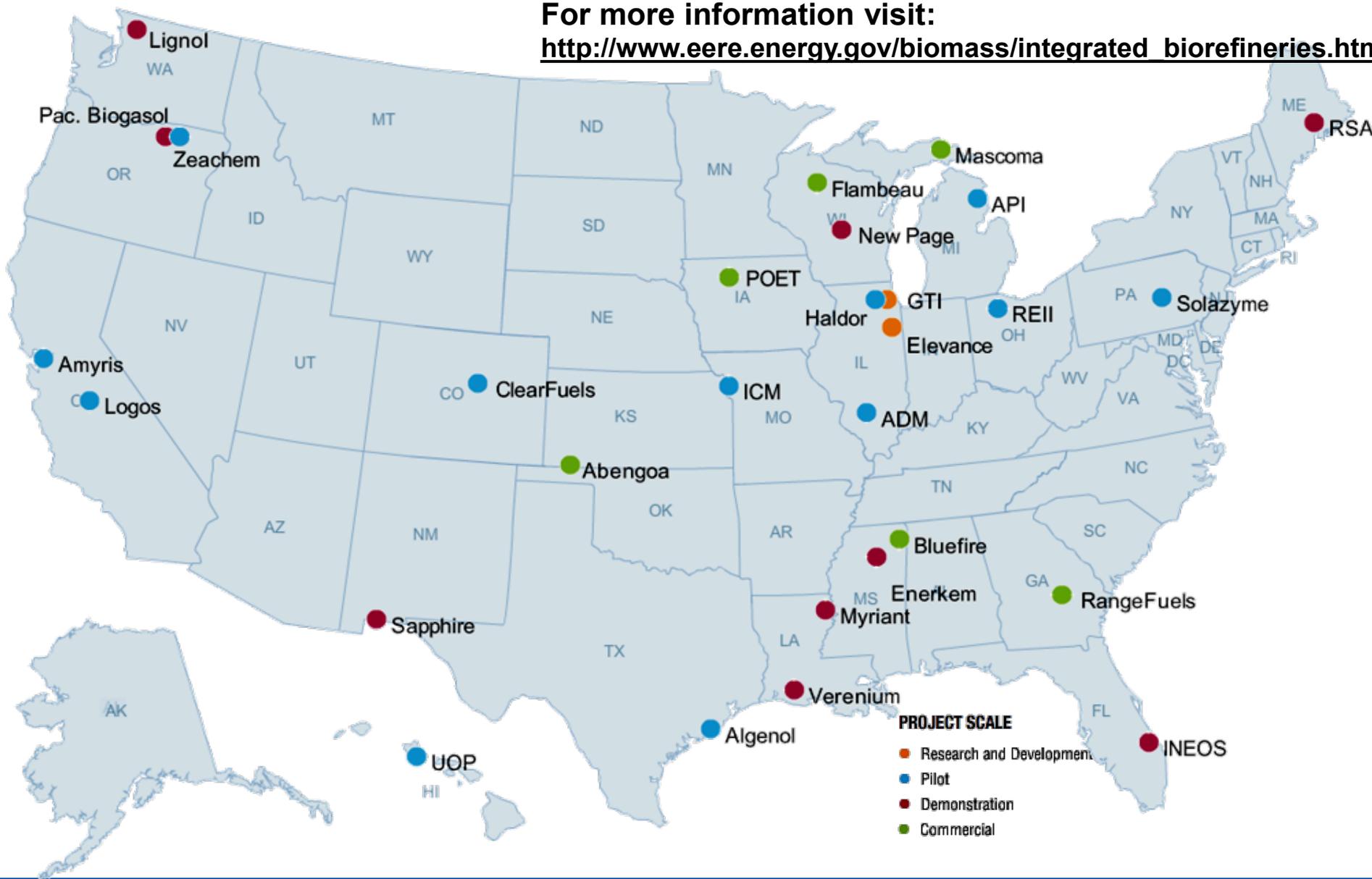
Scale	Description	Feedstocks	Fuel/Product
R&D 2 projects	Includes R&D and a preliminary engineering design	Poultry Fat, Woody Biomass, Ag Residue, Algal Oil	Renewable Fuels, Renewable Gasoline, Renewable Diesel
Pilot Scale 12 projects	Process a minimum of 1 dry ton per day biomass and verify integrated performance of the given suite of technologies from both a technical and an economic perspective for the first time	Algae, CO ₂ , Woody Biomass, Sweet Sorghum, Corn Stover, Switchgrass, Energy Sorghum, Ag and Forestry Residue, Hybrid Poplar	Ethanol, Cellulosic Ethanol, Renewable Diesel, Jet Fuel, Renewable Diesel
Demonstration Scale 9 projects	Validate process technology performance from both technical and an economic perspectives at a scale predictive of a commercial facility	Wheat Straw, Corn Stover, Poplar Residues, Woody Biomass, Algae, Mill Residues, MSW, Ag and Forestry Residue	Cellulosic Ethanol, Renewable Sulfur-free Diesel Fuel, Renewable Hydrocarbon-based Fuel, Renewable Gasoline, Renewable Diesel, Jet Fuel, Succinic Acid
Commercial Scale 6 projects	Process a minimum of 700 dry tons per day biomass in a a first-of-a-kind or “beta” commercial facility	Lignocellulosic Biomass, Corn Cobs, Woody Biomass, Mill Waste, Sorted MSW	Cellulosic Ethanol, Ethanol, Methanol



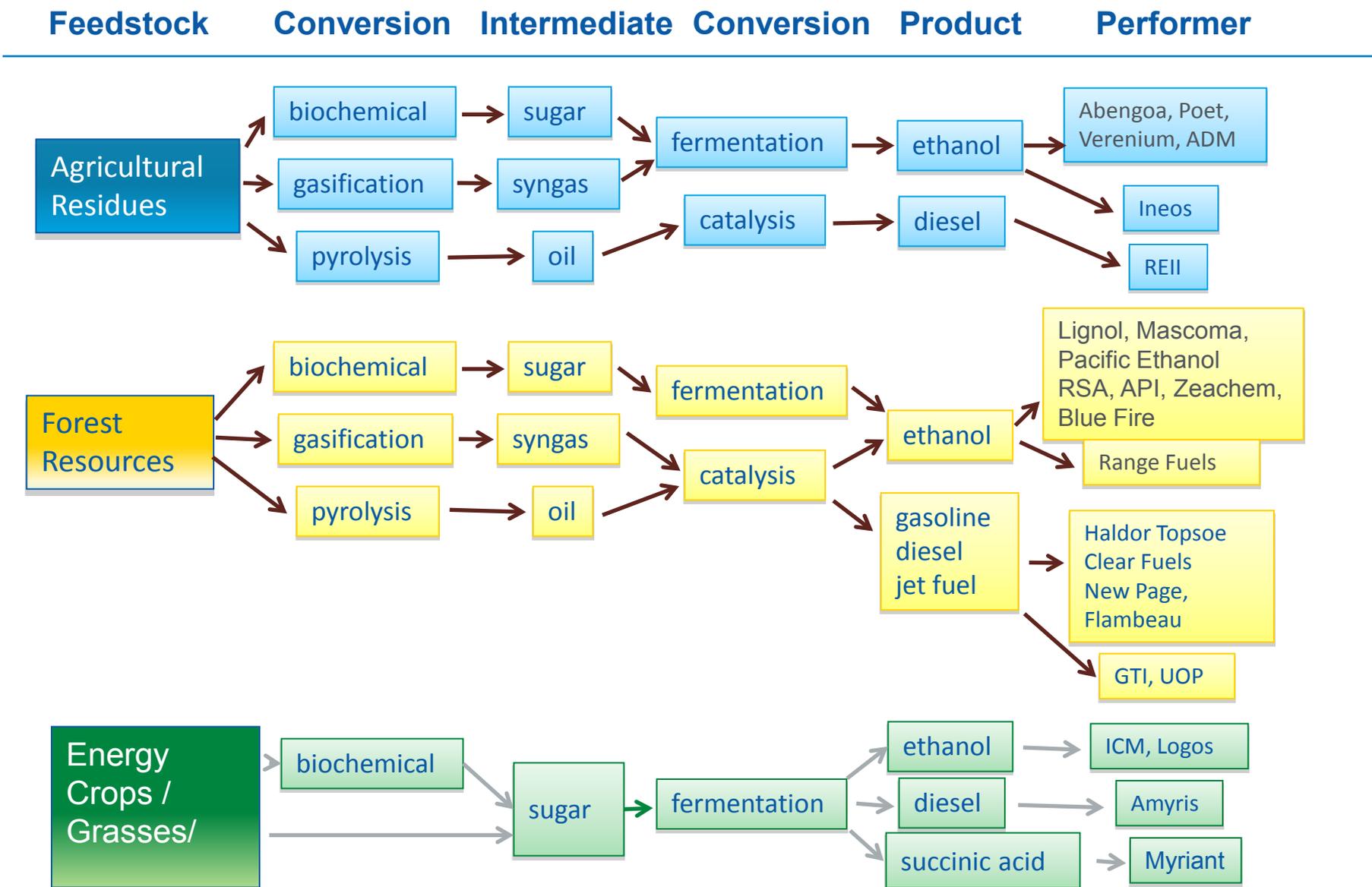
DOE's Integrated Biorefinery Project Map

For more information visit:

http://www.eere.energy.gov/biomass/integrated_biorefineries.htm



Integrated Biorefinery Projects, cont'd.



NREL R&D Highlights

Biochemical Cellulosic Ethanol Progressing

New Facilities Coming On-line (TCPDU and **IBRF**)

New Initiatives Underway (BESC and **NABC**)

Achieving Economic Feasibility

Process cost drivers

→ Yield > Conc > Rate

– Feedstock

– Capital equipment

- Pretreatment

- Enzyme Production

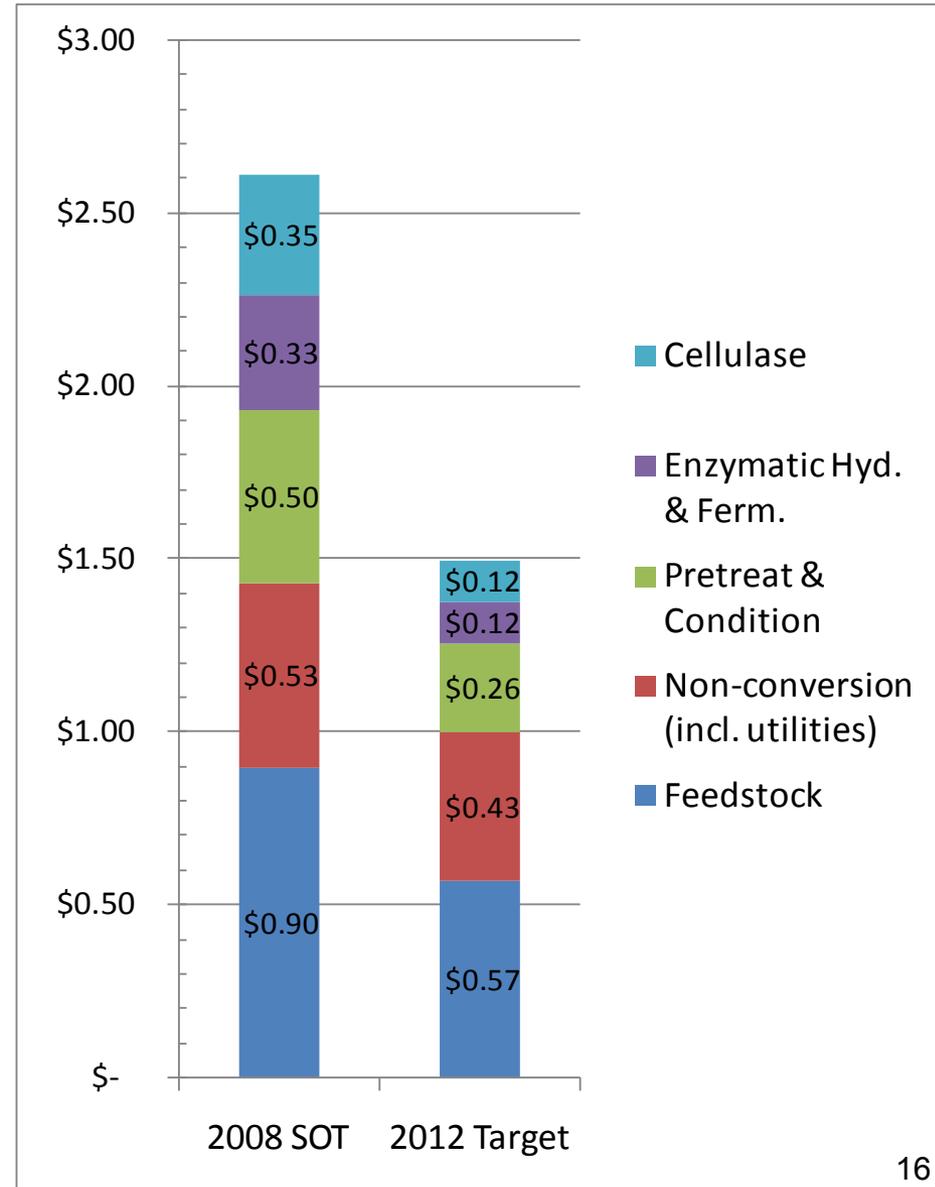
- Distillation

- Boiler/CHP

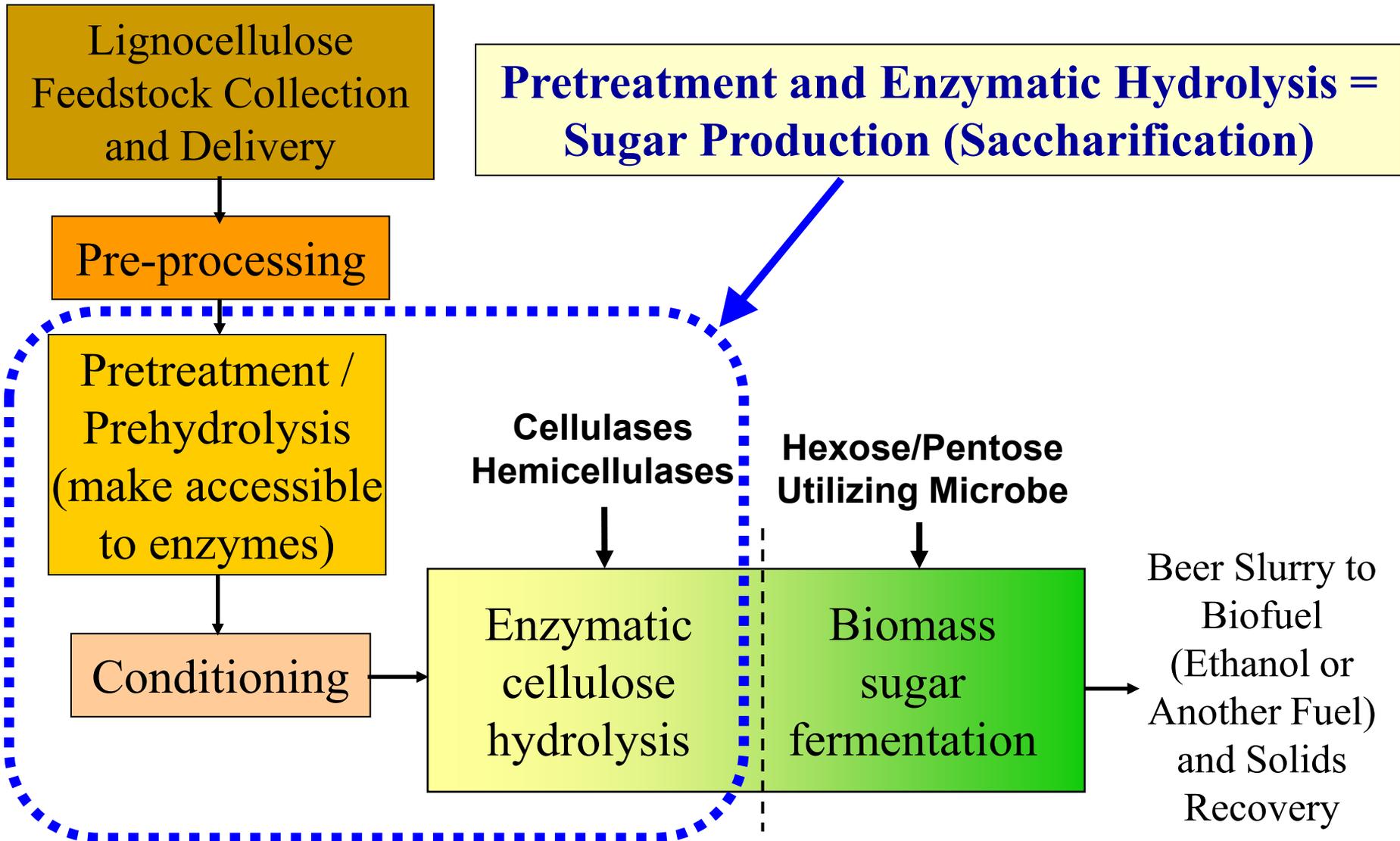
– Operating cost

– Coproduct value

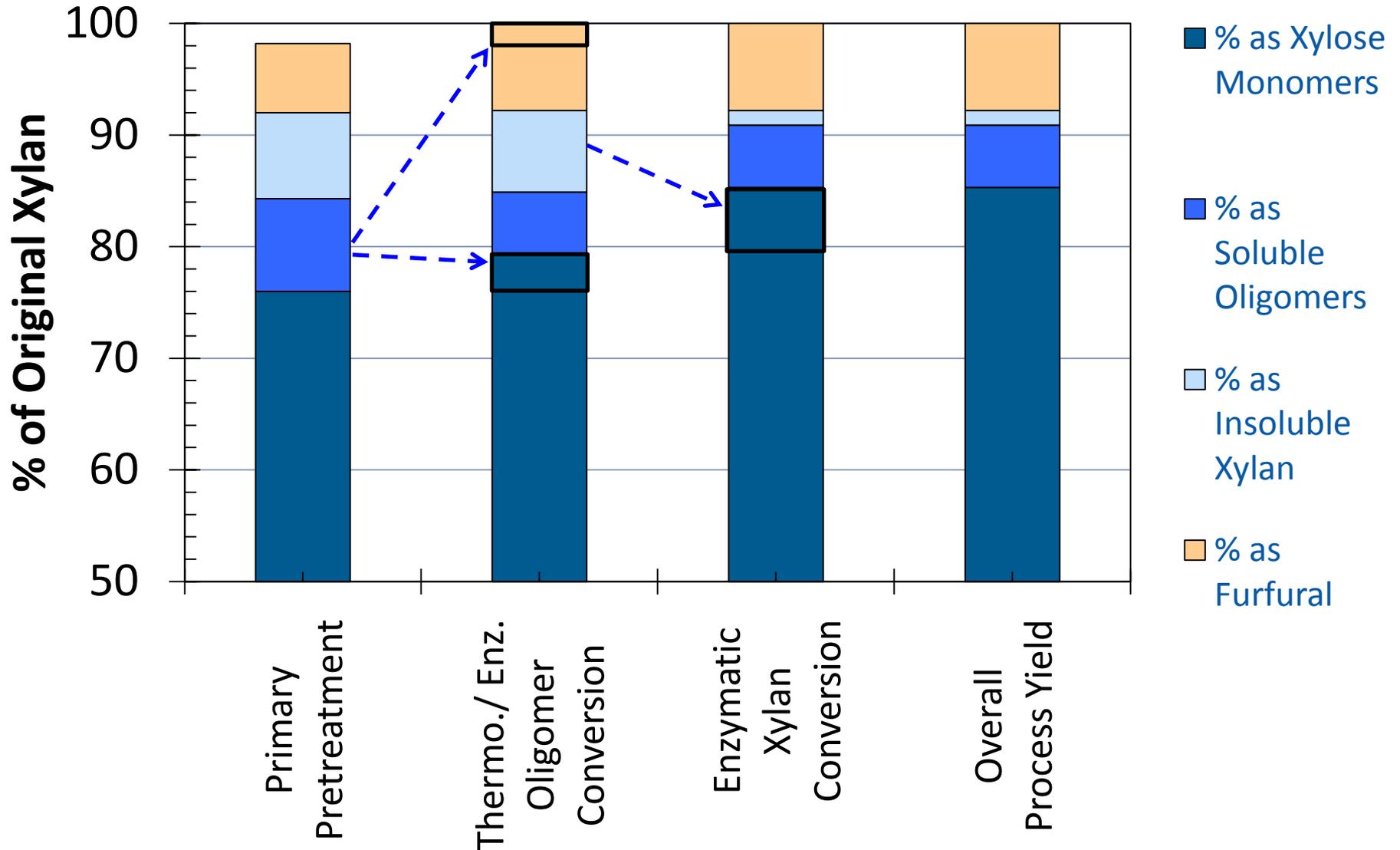
→ Reduce CAPEX through co-location and process intensification



Economic Sugar Production Remains Biggest Challenge

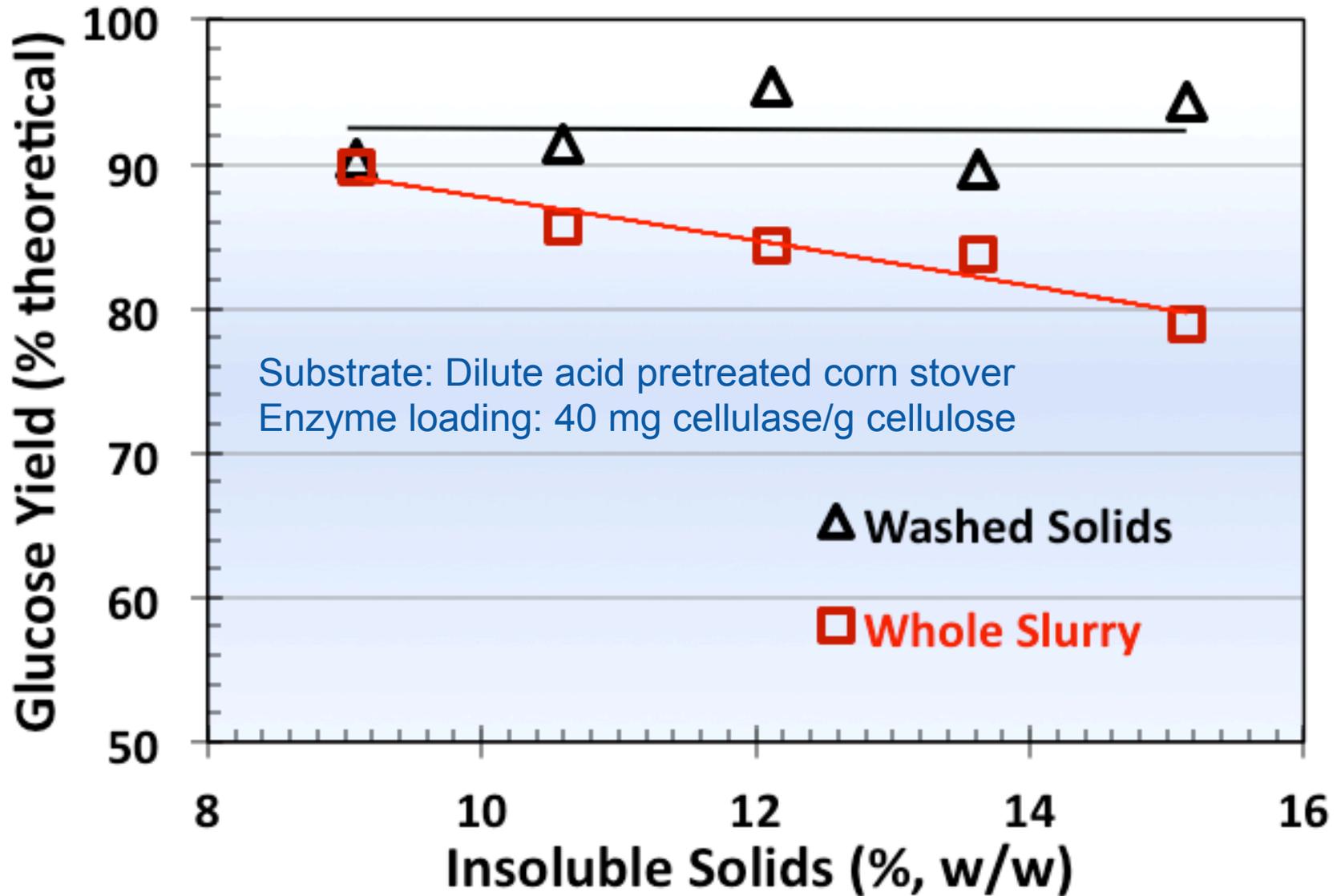


Increasing Monomeric Xylose Yields



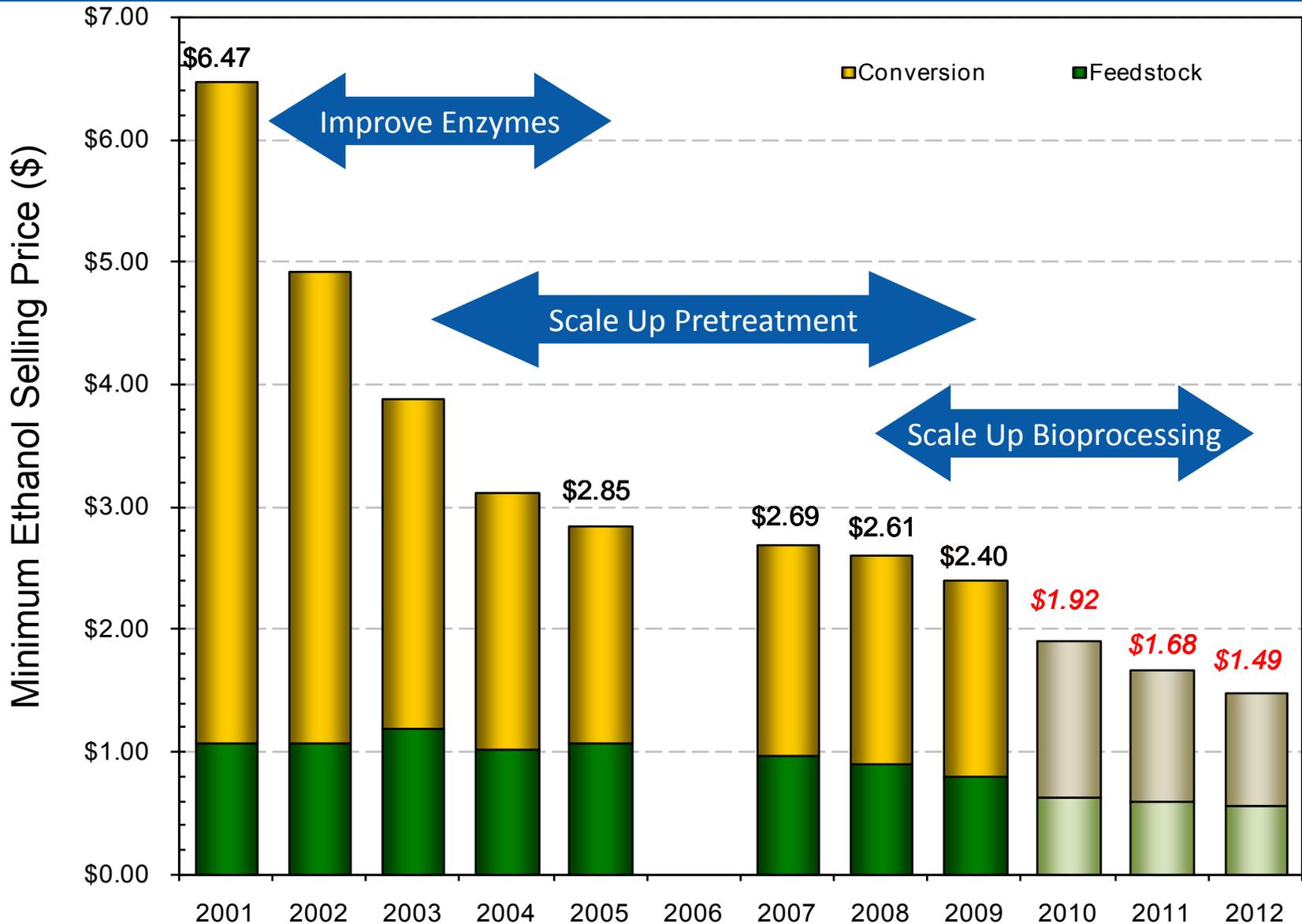
Source: Rick Elander (NREL)

Intensifying Enzymatic Hydrolysis



Source: Dan Schell (NREL)

Biochemical Technology Progress (2007\$)

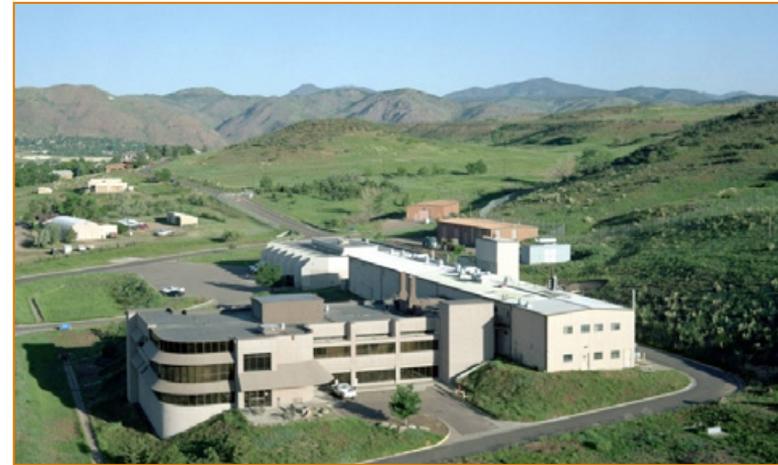


Source: Humbird and Aden. 2009. NREL/TP-510-46214.

Integrated Biorefinery Research Facility (IBRF)

NREL's (DOE's) Expanded Pilot Plant (IBRF)

- State of the art cellulosic biofuels piloting facility
- Two (2) parallel processing trains for pretreatment and primary enzymatic liquefaction
- Accelerate cost reduction focused R&D for 2012 and beyond
- Provide multiple biomass pretreatment/feedstock options for RD&D support (unparalleled flexibility)
- Greatly improve industry partnering capabilities to speed scale up and commercial deployment
- DOE'S prime facility for future pilot scale pretreatment and enzymatic saccharification R&D



Early March 2010



Integrated Biorefinery Research Facility



June 2010

Inside View of IBRF Operations Level



National Advanced Biofuels Consortium (NABC)

Project Objective – Develop cost-effective technologies to supplement petroleum-derived fuels with sustainable advanced “drop-in” biofuels compatible with today’s transportation infrastructure.

ARRA Funded:

- 3 year effort
- DOE Funding \$35.0M
- Cost Share \$15.1M

Total **\$50.1M**

Consortium Leads

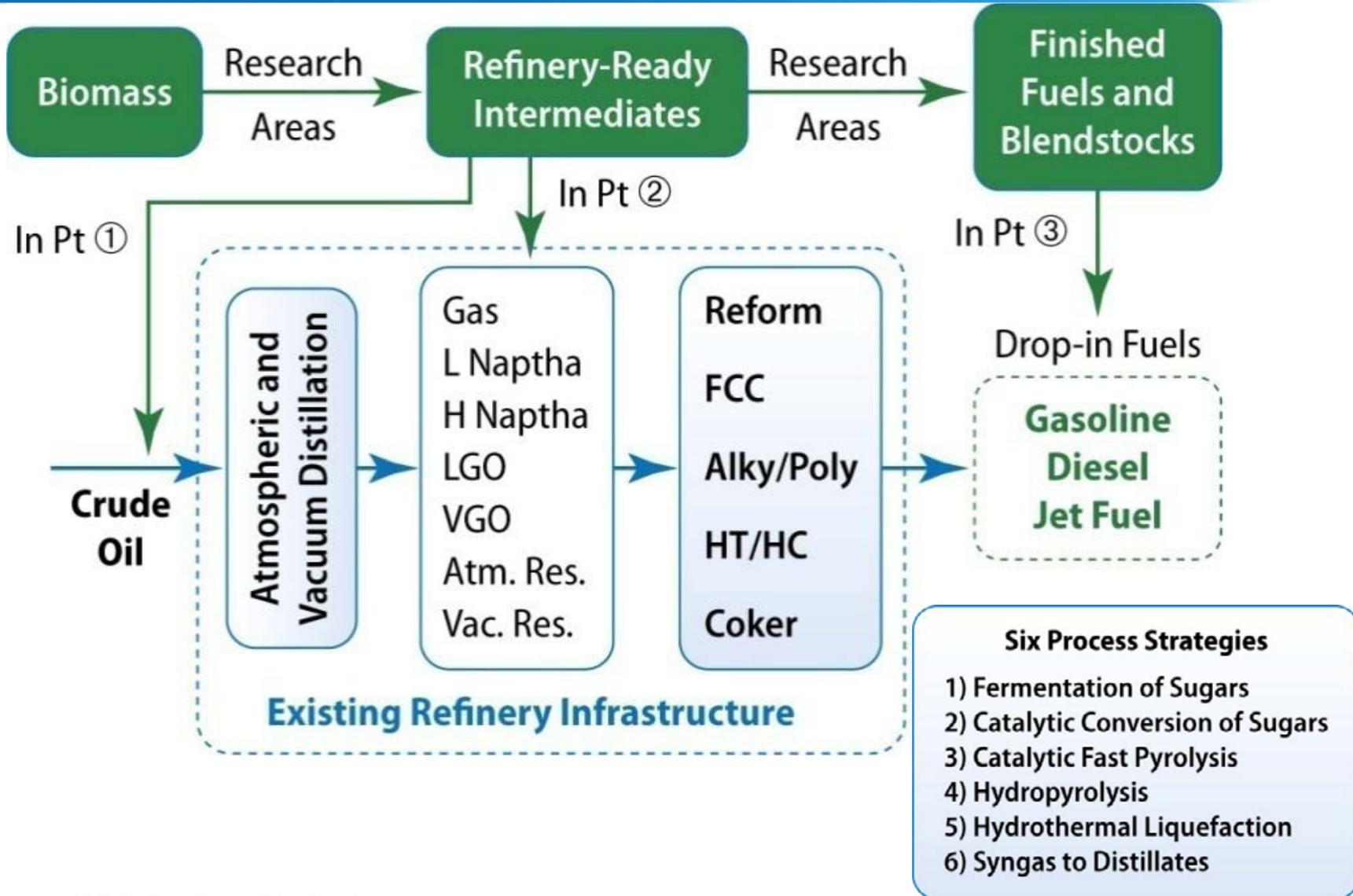
National Renewable Energy Laboratory
Pacific Northwest National Laboratory

Consortium Partners

Albemarle Corporation
Amyris Biotechnologies
Argonne National Laboratory
BP Products North America Inc.
Catchlight Energy, LLC
Colorado School of Mines
Iowa State University
Los Alamos National Laboratory

Pall Corporation
RTI International
Tesoro Companies Inc.
University of California, Davis
UOP, LLC
Virent Energy Systems
Washington State University





Outlook and Final Thoughts

Outlook for 2011-2015

- 1990-2000: Demonstrate technical feasibility
Focus on cellulosic ethanol
- 2001-2005: Show economic feasibility & scale potential
Focus remains largely on cellulosic ethanol
- 2006-2010: Increase funding to accelerate biofuels RDD&D
Expand RDD&D portfolio to higher alcohols and hydrocarbons, begin funding new concepts including hybrid BC/TC and algal pathways
- 2011-2015: Prove out & winnow advanced biofuels options
Bring first large scale demonstrations on line

Leverage Past Learnings to Succeed in Commercialization Efforts

➔ **Key to success at scale is accurately estimating cost and performance at smaller scales!**

Plant cost growth strongly correlated with:

- Process understanding (*integration issues*)
- Project definition (*estimate inclusiveness*)

Plant performance strongly correlated with:

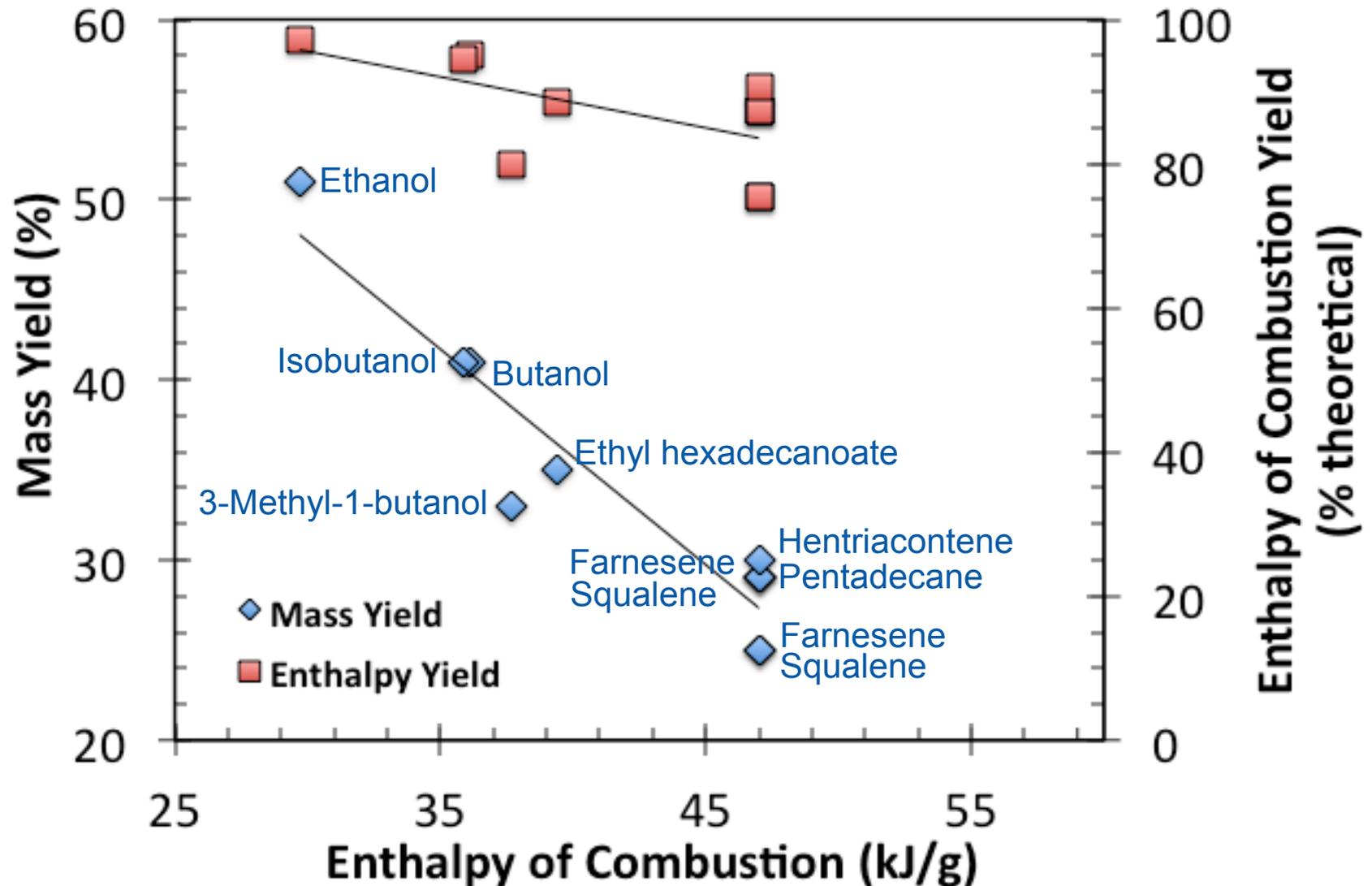
- Number of new steps
- % of heat and mass balances based on data
- Waste handling difficulties
- Plant processes primarily solid feedstock

➔ **These issues all apply to lignocellulose processing using new technologies. We must directly tackle them!**



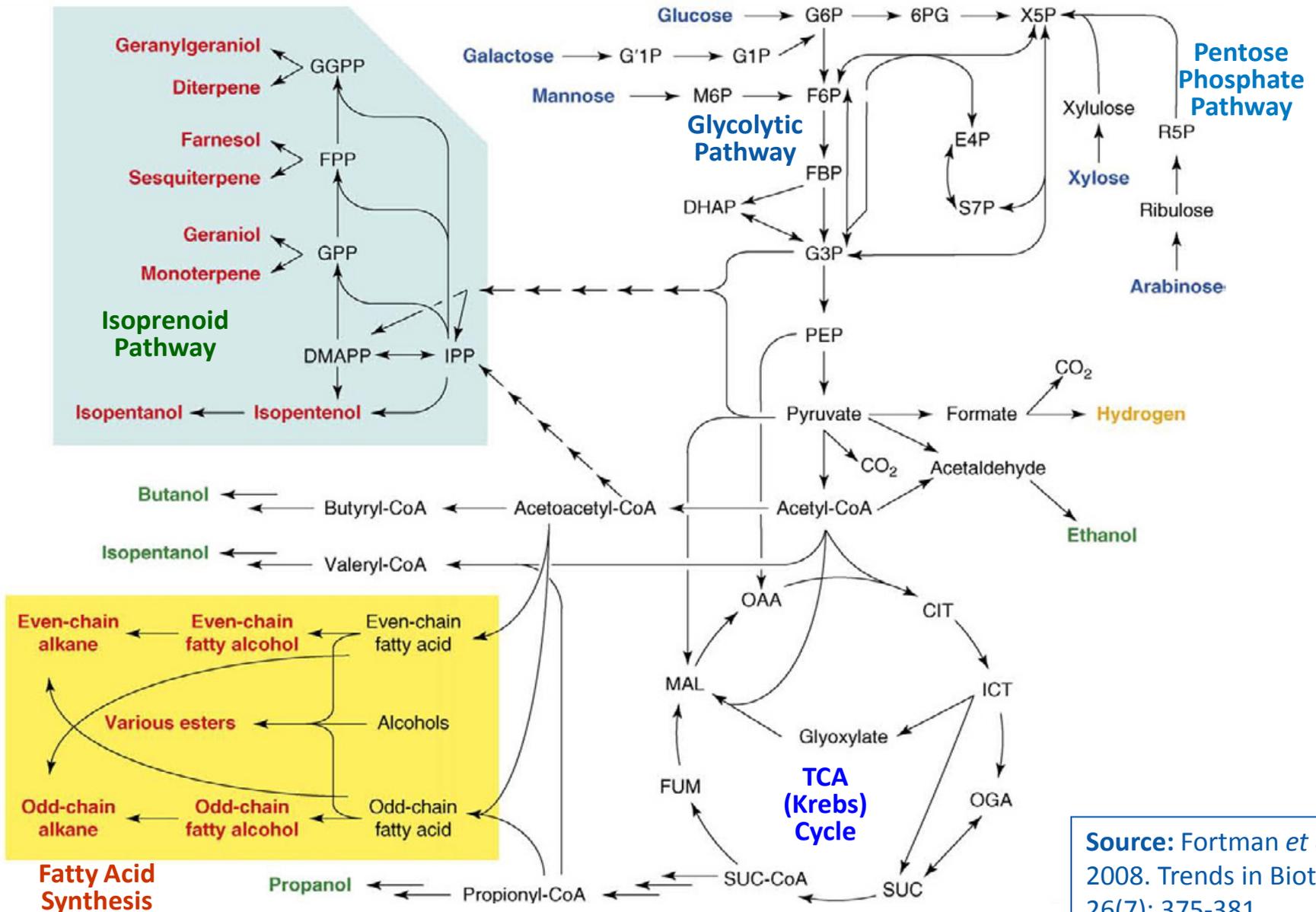
Rand. 1981. Understanding Cost Growth and Performance Shortfalls in Pioneer Process Plants.

Energy Density vs. Mass and Enthalpy Yield



Theoretical yield calculations from: Rude and Schirmer. 2009. Current Opinions in Microbiology, **12**:274-281.

Anabolic vs. Catabolic Product Pathways



Source: Fortman *et al.* 2008. Trends in Biotech. 26(7): 375-381

Final Thoughts

Lots of progress happening. Many process and product options being advanced and scaled up to pilot and demonstration scales. Commercialization beginning.

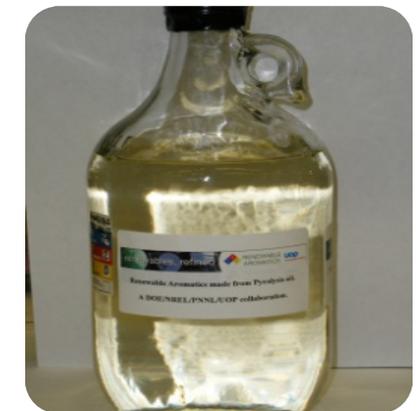
Solids handling issues and compositional analysis throughput are still challenging technical issues that hinder the pace of biomass to biofuels RDD&D

Factors in play for cellulosic biofuels include:

- What pretreatment and enzymatic hydrolysis (saccharification) schemes will prove out?
- How much and how quickly will hydrolytic enzymes and biofuels production strains be improved?
- How quickly will higher alcohols and hydrocarbons be proven at scale?

Potential game changers include:

- Price on (net) carbon, GHG emissions mitigation
- Competition for feedstocks (biopower, bioproducts)
- Production of higher value coproducts
- Price of petroleum & ethanol blend limit for non-FFVs



Acknowledgments



- USDOE's EERE's Office of the Biomass Program – Funding and selected slides on USDOE's strategy and investments
- NREL's Rick Elander, Steve Decker, Erik Kuhn, Nick Nagle and Joe Shekiro – Data on xylan to xylose yield improvement
- NREL's Dan Schell, Alex Chapeaux, Nancy Dowe Farmer and Andrew Lowell – Data on enzymatic hydrolysis glucose yields = $f[\text{insoluble solids}]$

Thanks for Your Attention! Questions?



More Information

National Renewable Energy Laboratory

www.nrel.gov

DOE's Biomass Program

www.eere.energy.gov/biomass/

DOE-USDA Biomass R&D Initiative

www.brdisolutions.com

Alternative Fuels

www.afdc.doe.gov