Outlook for 2nd and 3rd Generation Biofuels: Where we are and where are we going?

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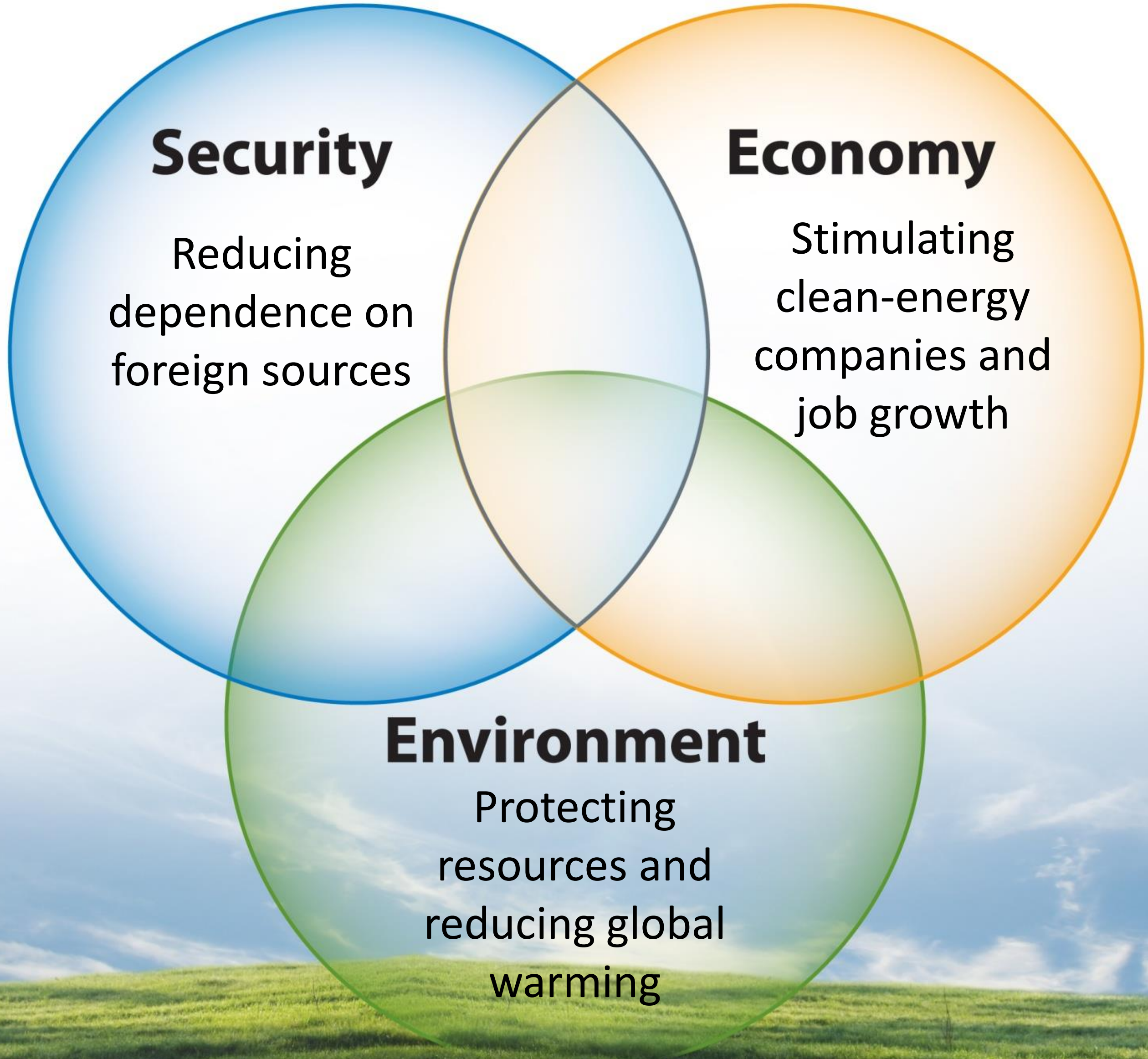
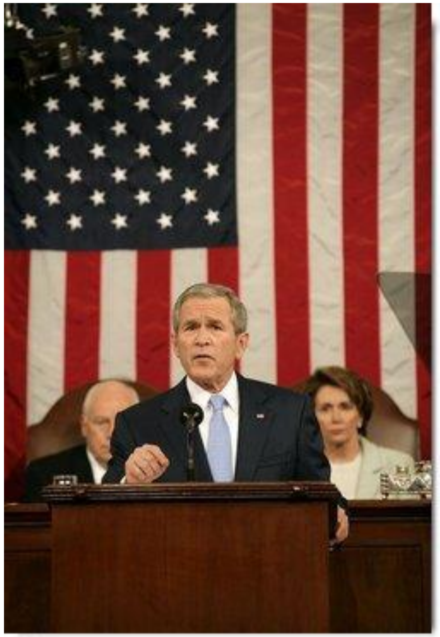
Why Renewable Energy?



US Administration Priorities – Recent History



2006 State of the Union

"America is addicted to oil…the best way to break this addiction is through technology."

"Our goal is to make cellulosic ethanol practical and cost competitive within 6 years."

2007 State of the Union

"Reduce U.S. gasoline usage by 20% in 10 years – 75% from new fuels and 25% from vehicle efficiency"

"Mandatory fuel standard to require 35B gallons of renewable and alternative fuels by 2022."

US Administration Priorities – Current Status

Utilizing biomass for fuels, products, and power is critical to the nation's plan to reduce dependence on imported oil.

President Obama's March 2011 speech and *Blueprint for a Secure Energy Future* outlined a portfolio of actions that would support reducing U.S. oil imports by one-third by 2025.

Steps to further innovation in bioenergy include:

- Accelerating advanced biofuels research and development (R&D)
- Breaking ground on several first-of-a-kind biorefineries to support the commercialization of advanced biofuels
- Encouraging closer partnerships among the Departments of Defense, Energy, and Agriculture
- Facilitating more dialogue on international bioenergy sustainability.

Photo courtesy of DOE/NREL

Sustainable Design

2030 Subsystem Target

- **25%** of US electricity generation comes from renewable resources
- Building fleet is **50%** more efficient
- Sustainable communities are the **standard** for new development
- **50%** of LDVs are EV/PHEV/FCEV
- **60 million gallons** of biofuels in system (cellulosic ETOH and advanced fuels)

2050 Energy System Target

By 2050, we will have a clean and sustainable energy system that contributes to economic prosperity, enhances national security, and maintains environmental quality.

Oil use will be reduced to **15%** of current levels, CO_2 will be reduced by **80%**

Highly Efficient Integrated Renewables

Distributed and Utility-Scale Renewable Power

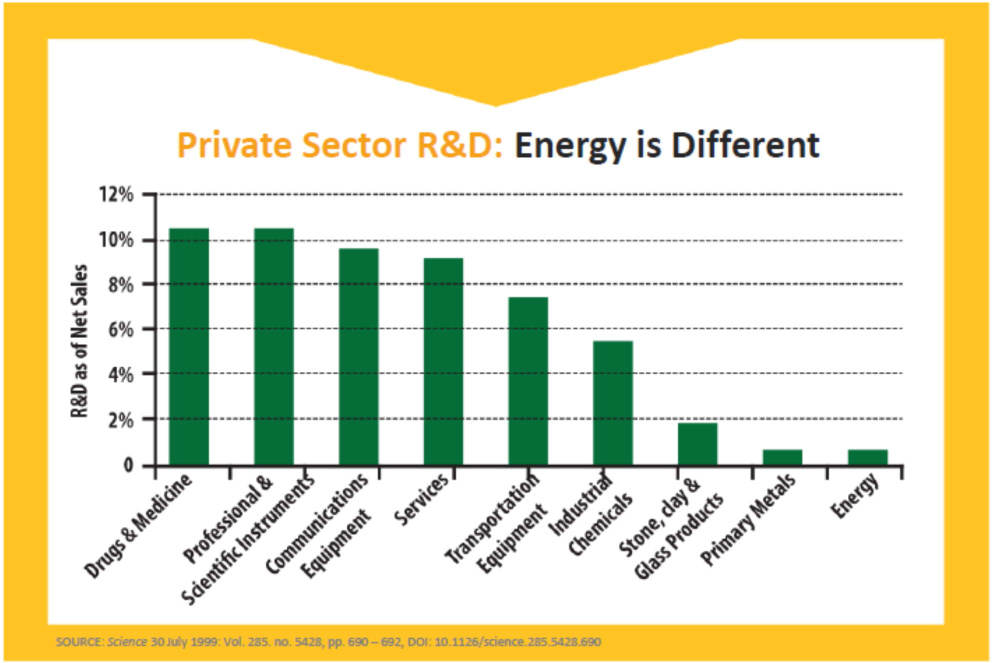
Highly Efficient Fuel Flexible

Renewable Fuels

Challenges to Success

Energy Market Barriers

- Inconsistent policies
- Aging infrastructure
- Undifferentiated commodity
- Lack of knowledge
- Limited private investment



To Achieve a Clean Energy Vision…

- ✓ Innovation
- ✓ Integration
- ✓ Collaboration

The shift toward renewable energy will be evolutionary, not revolutionary, over decades

Historically, renewable energy development was seen as a competitive endeavor. Now there is a growing focus on **international collaboration**!

NREL - Laboratory Snapshot

Only US National Laboratory Dedicated Solely to Energy Efficiency and Renewable Energy

- Leading clean-energy innovation for 37 years
  - SERI 1977, NREL 1991
- 1740 employees with world-class facilities
- Campus is a living model of sustainable energy
- Owned by the Department of Energy
- Located in Golden, CO
- Operated by the Alliance for Sustainable Energy

Alliance for Sustainable Energy, LLC

MRI

Battelle
The Business of Innovation

Stanford University

Colorado
University of Colorado at Boulder

Colorado School of Mines 1874

Colorado State University

MIT
Massachusetts Institute of Technology

Scope of Mission

Energy Efficiency

- Residential Buildings
- Commercial Buildings
- Personal and Commercial Vehicles

Renewable Energy

- Solar
- Wind and Water
- Biomass
- Hydrogen
- Geothermal

Systems Integration

- Grid Infrastructure
- Distributed Energy Interconnection
- Battery and Thermal Storage
- Transportation

Market Focus

- Private Industry
- Federal Agencies
- Defense Dept.
- State/Local Govt.
- International

Biomass Program Priorities

The Biomass Program supports the following national priorities:

Dramatically reduce dependence on foreign oil

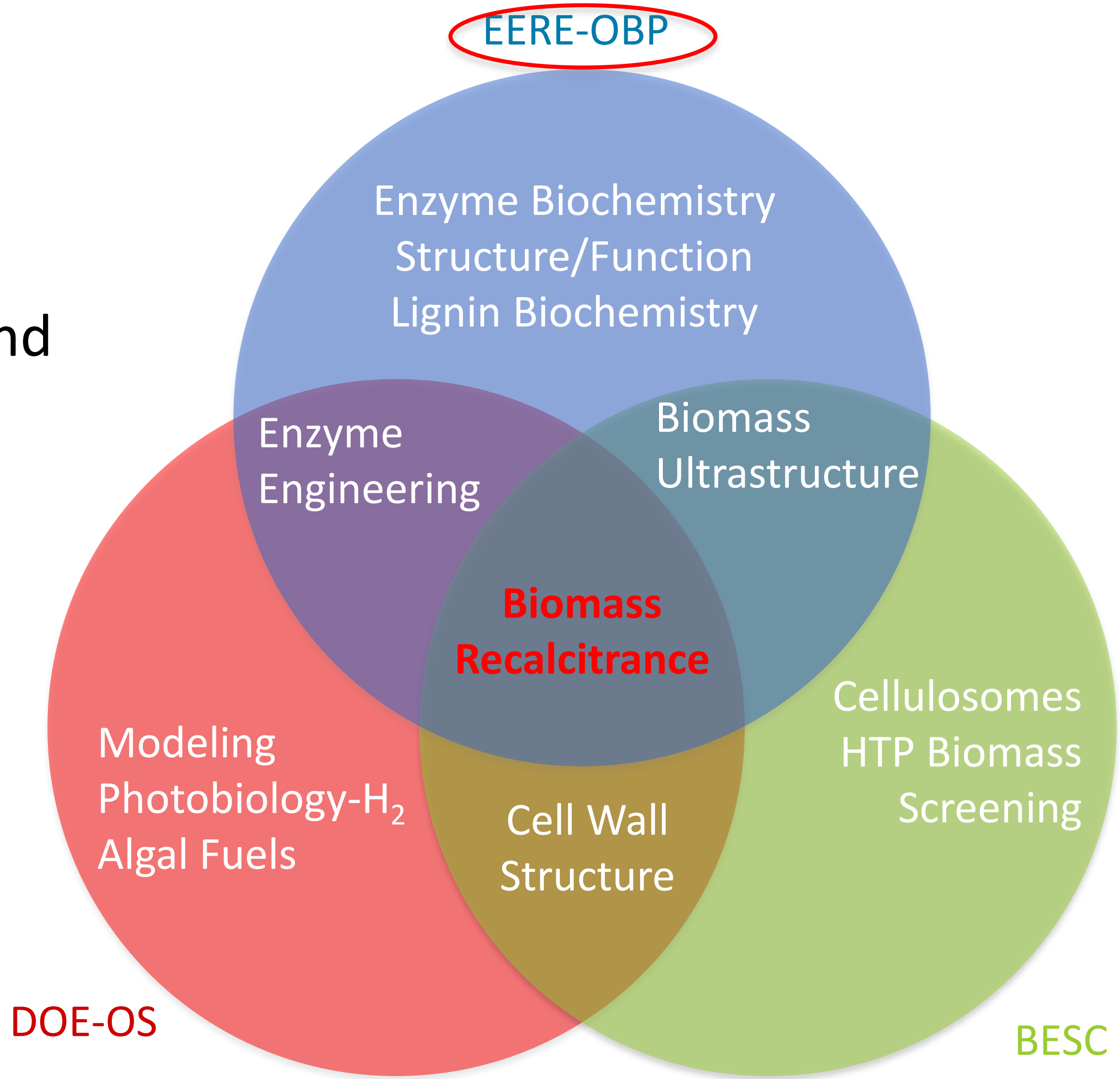
Promote the use of diverse, domestic, and sustainable energy resources

Establish an advanced bioindustry and create jobs

Reduce carbon emissions from energy production and consumption

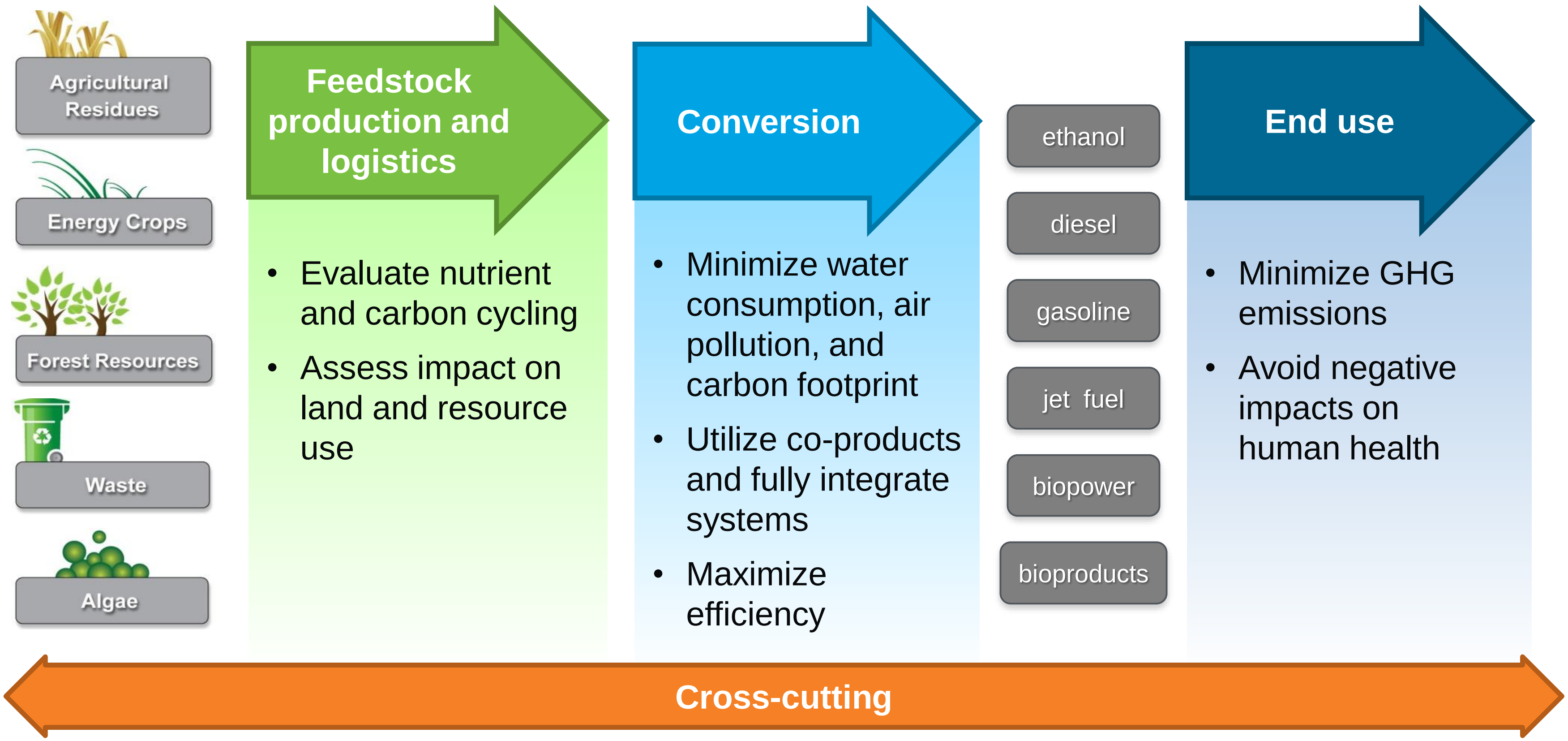
Biomass Program Research Focus

Understanding the lessons from biology to conceive and develop novel energy capture and conversion systems, whether they are enzymes, microbes, plants, biohybrid, or biomimetic systems



Sustainability

Current efforts are developing and integrating the resources, technologies, and systems across the supply chain needed to grow a biofuels industry in a way that protects the environment.



- Life-cycle analysis of water consumption and GHG emissions
- Land-use change modeling
- Water quality analysis
- Environmental, economic, and social factors

Diversification of Biofuels

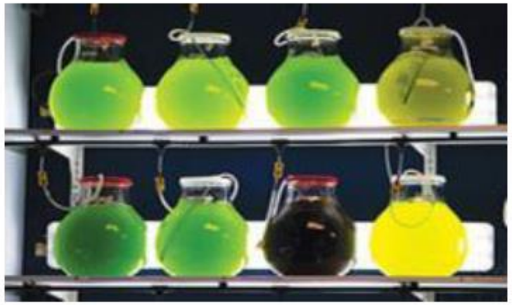
As biofuel technologies are developed and demonstrated, RD&D priorities adjust to bring more diverse biofuel pathways closer to commercialization.

Starch-based ethanol (and Sugar)!

- Well-established commodity fuel
- Wide market acceptance through low-level blends in conventional vehicles and at higher blends in flex-fuel vehicles

Cellulosic ethanol (Corn stover, Bagasse, energy crops)

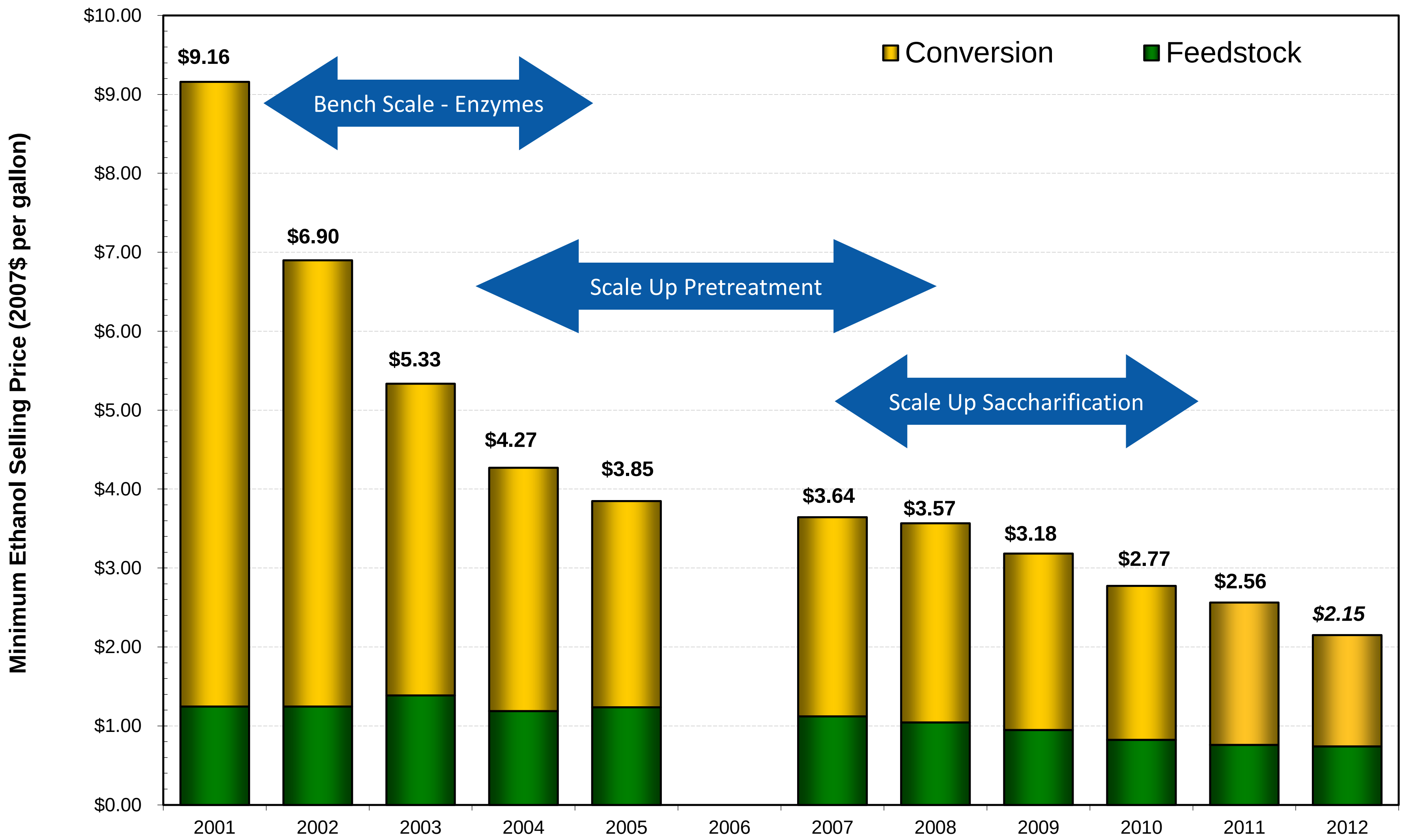
- Over the last two decades, R&D has significantly lowered the cost of converting cellulosic biomass to fuel ethanol
- Cellulosic ethanol technology is now in the demonstration phase



Cellulosic and algal hydrocarbon fuels

- Including renewable diesel, gasoline, and jet fuel
- DOE and the bioenergy community are leveraging cellulosic ethanol RD&D successes to accelerate algal and other "drop-in" biofuels technologies

Sustained R&D Efforts Result in Cost Reduction



Biofuels – Existing & Emerging

NREL Roles

Gen 1 — Fuel Testing

- 

Corn Ethanol
- 
Biodiesel

Gen 2

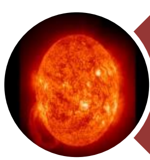
- 
Cellulosic Ethanol

Gen3 /Advanced

- 
Hydrocarbon Biofuels
- 
Algal Biofuels

Gen 2 and Gen3 /Advanced — Fuel Production; Technoeconomic Analysis; Sustainability Analysis

Future — Emerging Involvement

- 
Fuels from Sunlight

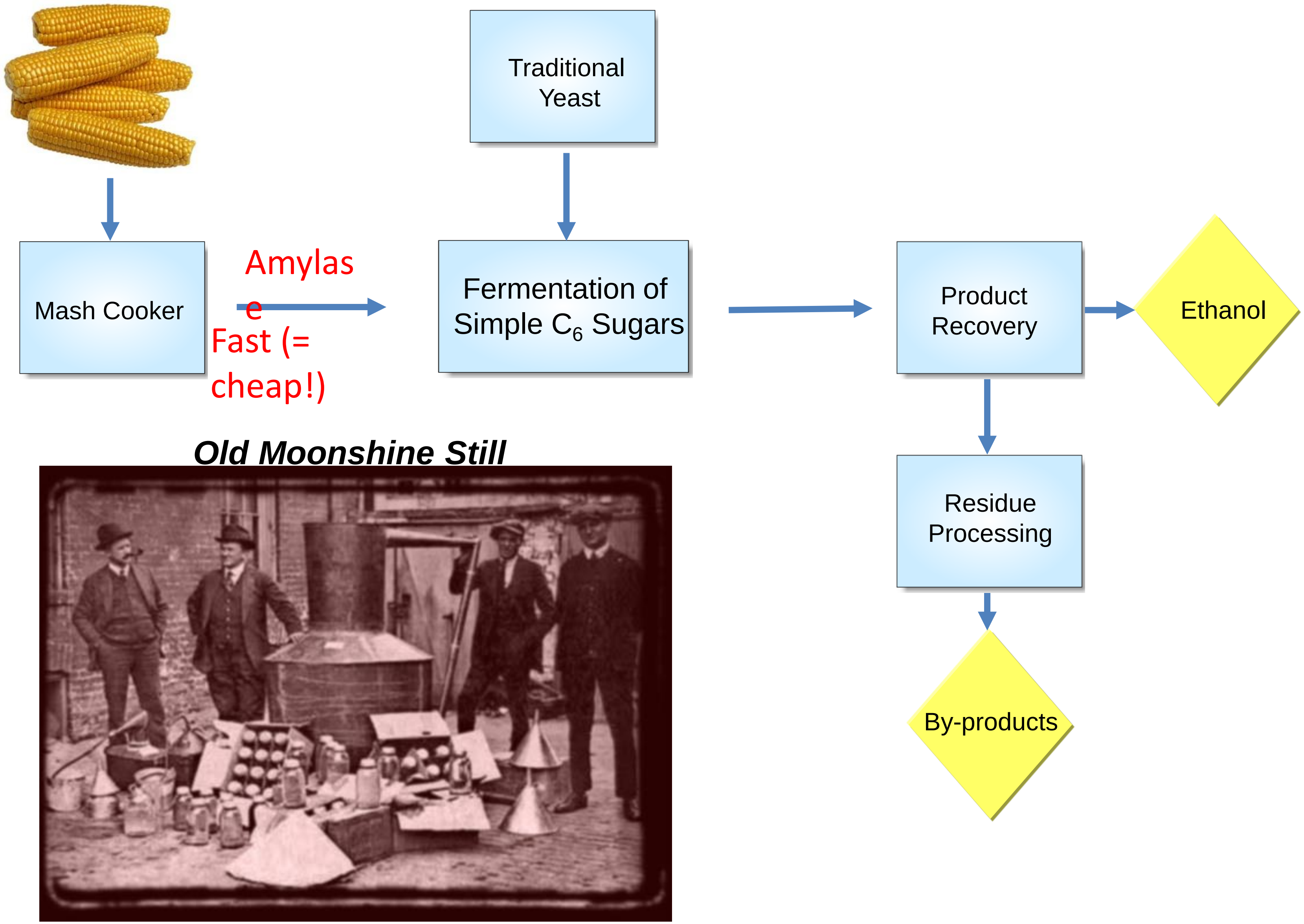
Corn Ethanol

Biodiesel

Current Biofuels Status in U.S.

- **Corn ethanol**
  - 200 commercial plants
  - 14+ billion gal/yr capacity
  - 13+ billion gal produced in 2011
- **Biodiesel**
  - 175 companies; 2+ billion gallons/yr capacity
  - 0.8 billion gallons produced in 2011

Corn Based Ethanol Process Flow Diagram



Old Moonshine Still

Existing Biodiesel Biorefinery Process

The new Gray's Harbor facility is the largest biodiesel production plant in the United States.
Credit: Imperium Renewables 2007

Seed Oils
Fats &
Greases

Feedstock Preparation

Methanol

Transesterification Process

Product Recovery

- Biodiesel
- (Glycerol)

Second Generation

Cellulosic Ethanol

Lignocellulosic Biomass

Biochemical Process

(to Sugars, then Fermentation into Ethanol)

Thermochemical Process

(to Syngas, then Synthesis or Refining into Ethanol)

NREL’s Process Development Units

Biochemical
Process Development Unit

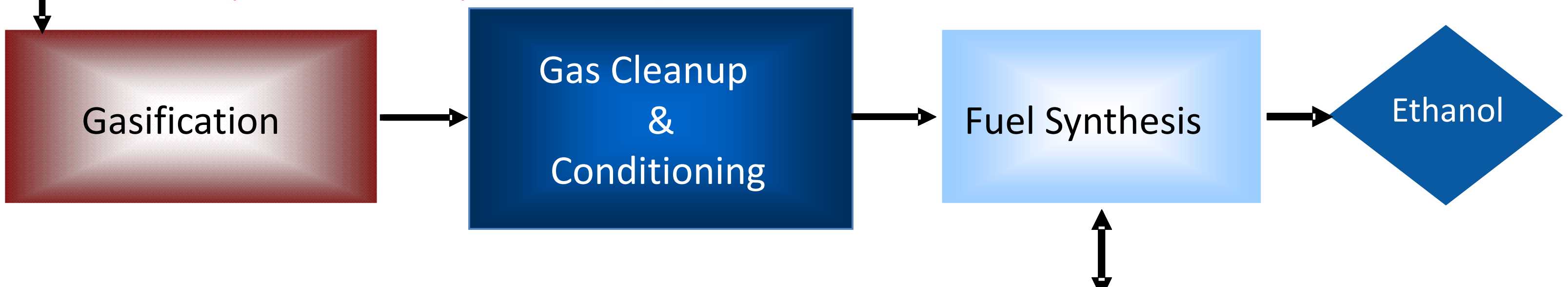
Thermochemical
Process Development Unit

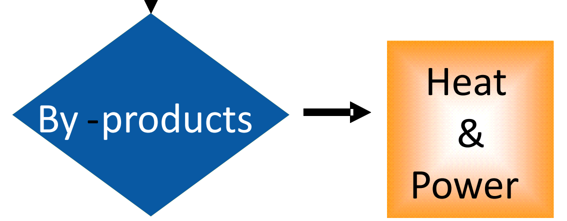
Thermochemical Gasification of Biomass to Ethanol

Feedstock Processing

Synthesis Gas ("syngas')

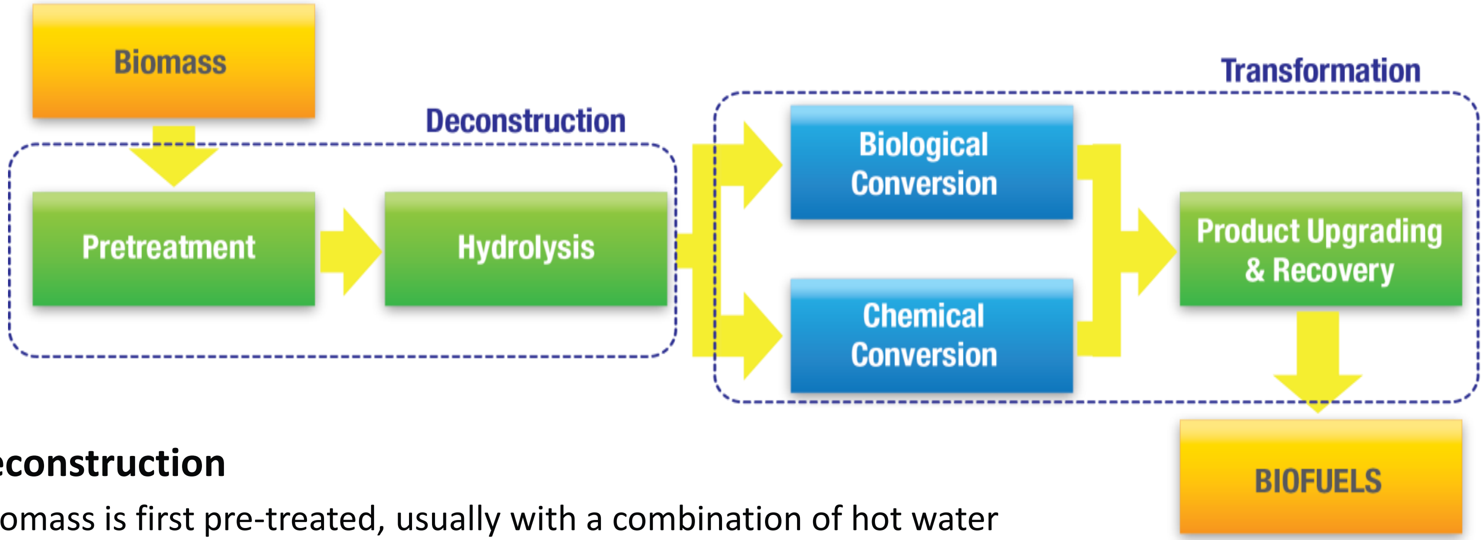
- Carbon Monoxide (CO)
- Hydrogen (H_2)
- (plus, unfortunately, contaminants)





Biochemical Conversion

Current RD&D projects are improving the biochemical conversion of cellulosic biomass to biofuels and chemicals.



Deconstruction

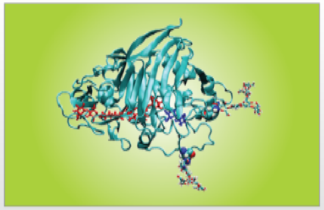
•Biomass is first pre-treated, usually with a combination of hot water and chemicals to make it amenable to hydrolysis

•The pre-treated biomass slurry is then exposed to enzymes, which unlock and release (hydrolyze) the biomass sugars

Transformation

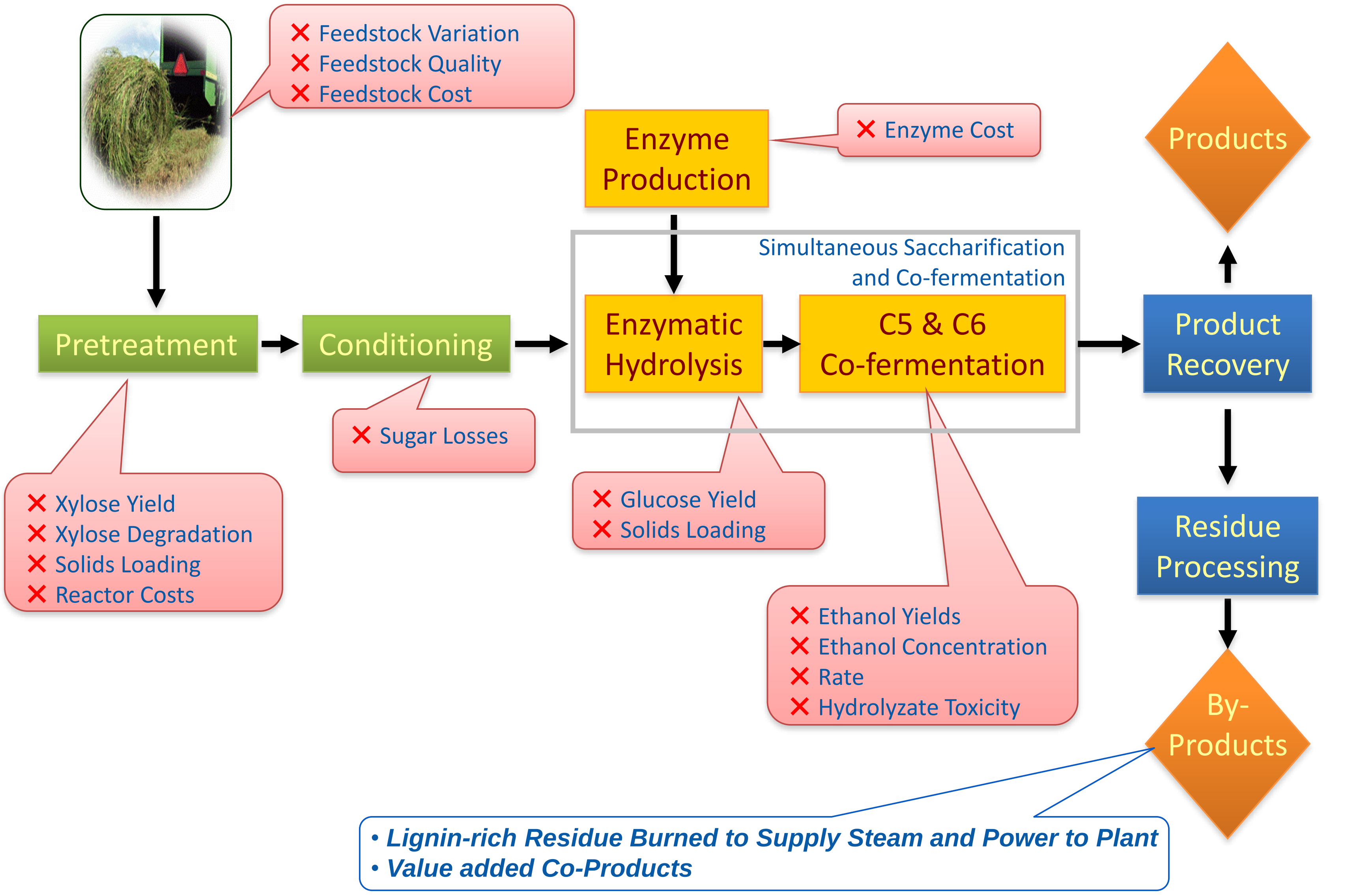
•The sugar-rich media is then fed to organisms, like yeast and *E. coli*, which transform the sugars into biofuels and chemicals

•Chemical catalysis can also be employed to transform the sugars into biofuels and chemicals



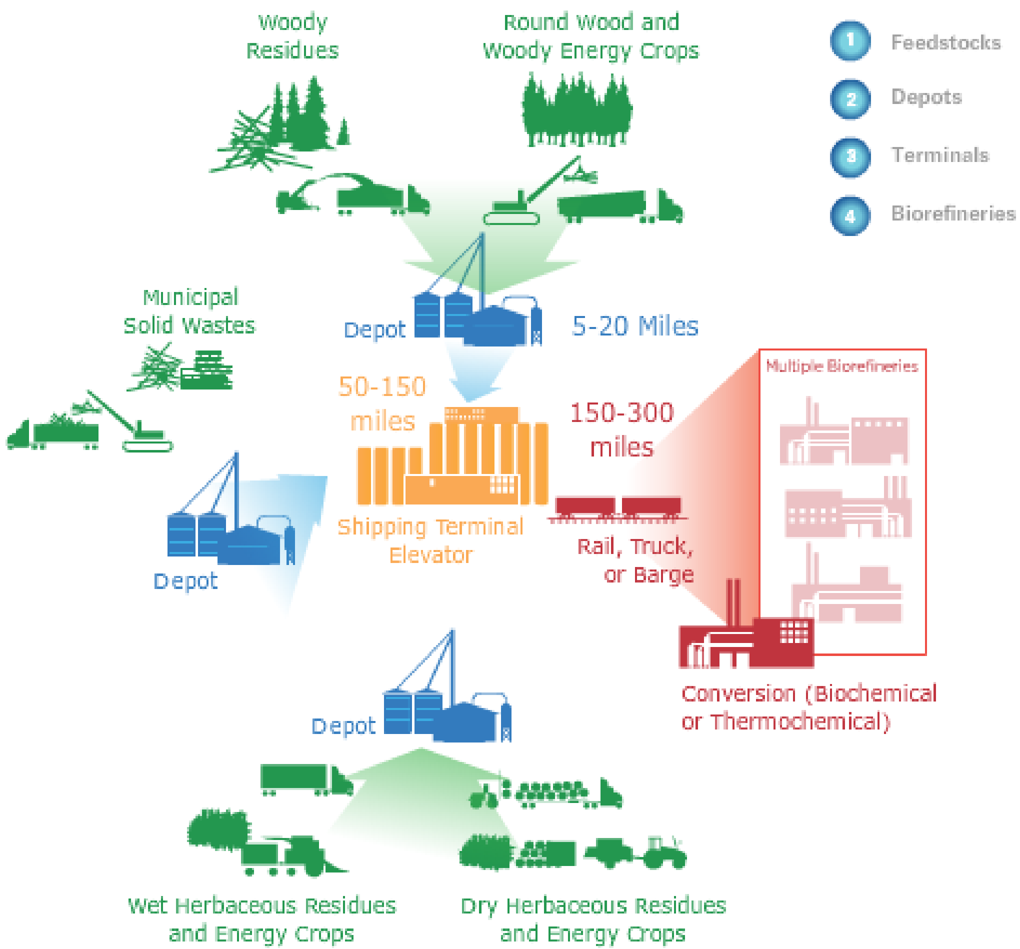
An enzyme that turns cellulose into sugar (image courtesy of NREL)

Biochemical Conversion of Biomass to Ethanol



Feedstock Logistics

Current activities deal with major RD&D challenges associated with developing a logistics system that is capable of supplying biorefineries with high density, aerobically stable, and high-quality biomass material.



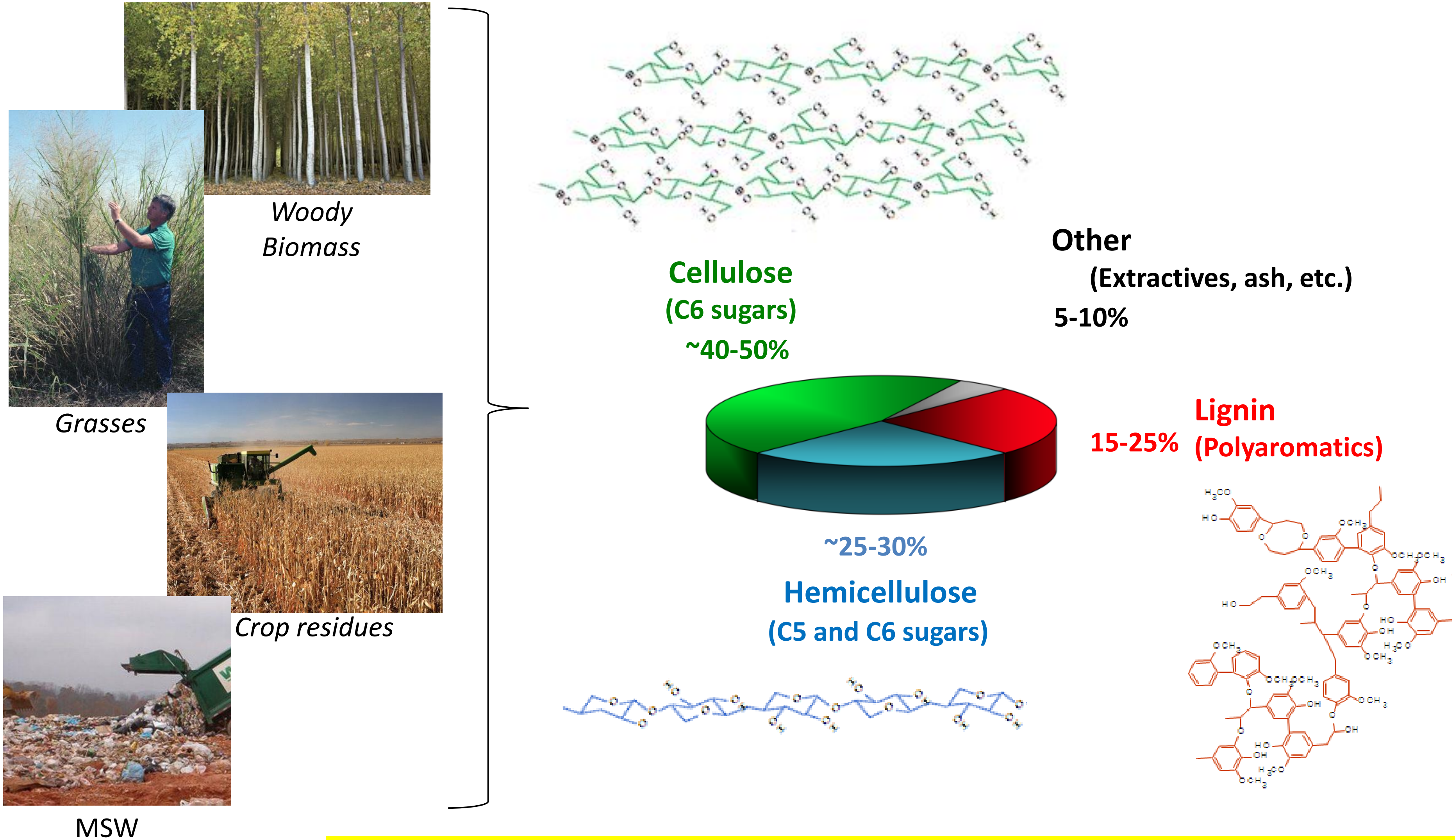
Existing Supply Systems	Depot Supply Systems
Nearer-term Platform Focus (through 2012)	Longer-term Platform Focus (2013+)
Access to a niche or limited feedstock resource	Access to a broader resource
Based on a dry supply system design (field-dried feedstocks)	Allows higher-moisture feedstocks into supply system
Designed for a specific feedstock type (dry corn stover)	Design addresses multiple feedstock types

NREL Roles:

1) Compositional Analysis

2) Convertibility Impacts

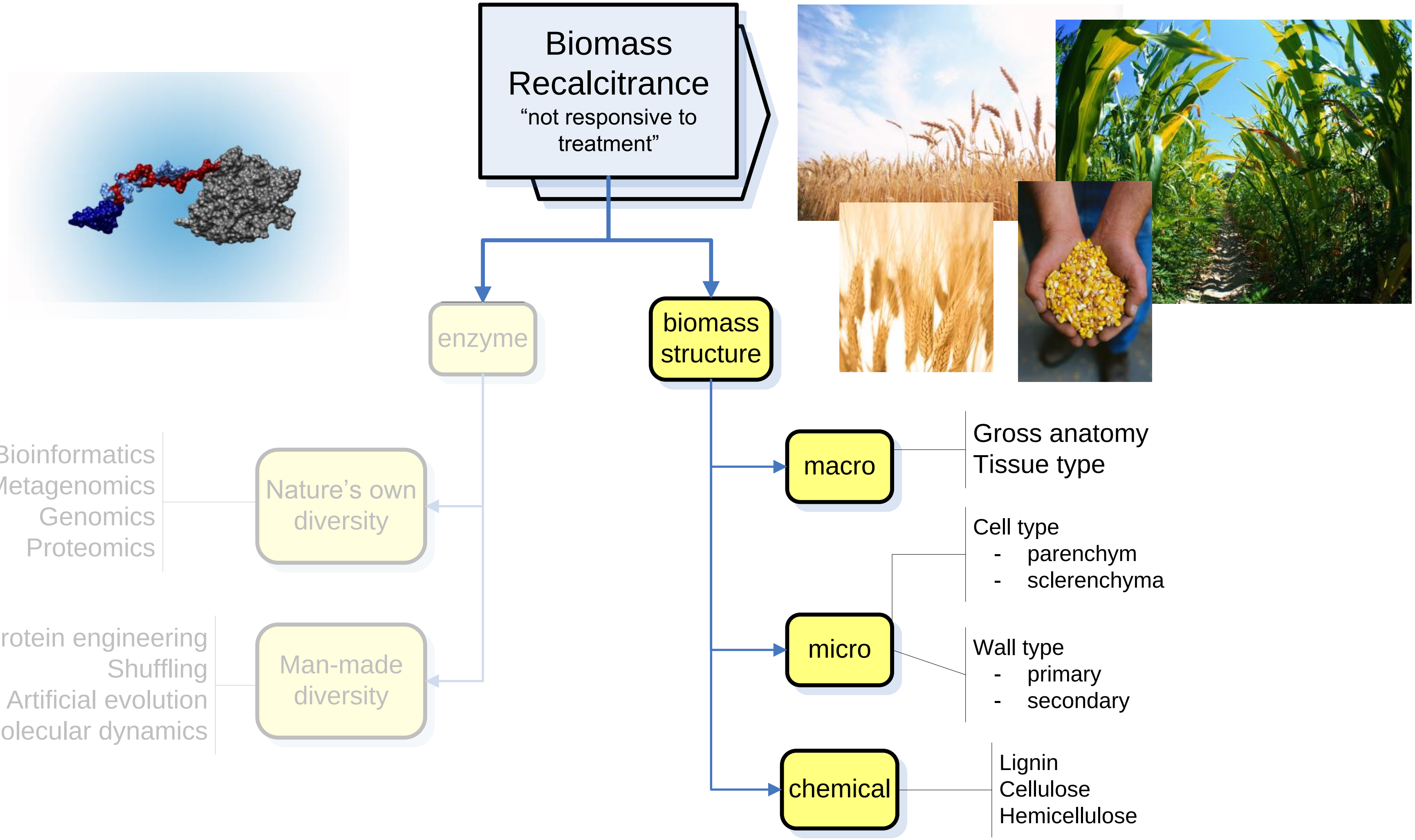
So… What is Lignocellulosic Biomass? And Why is it Recalcitrant?



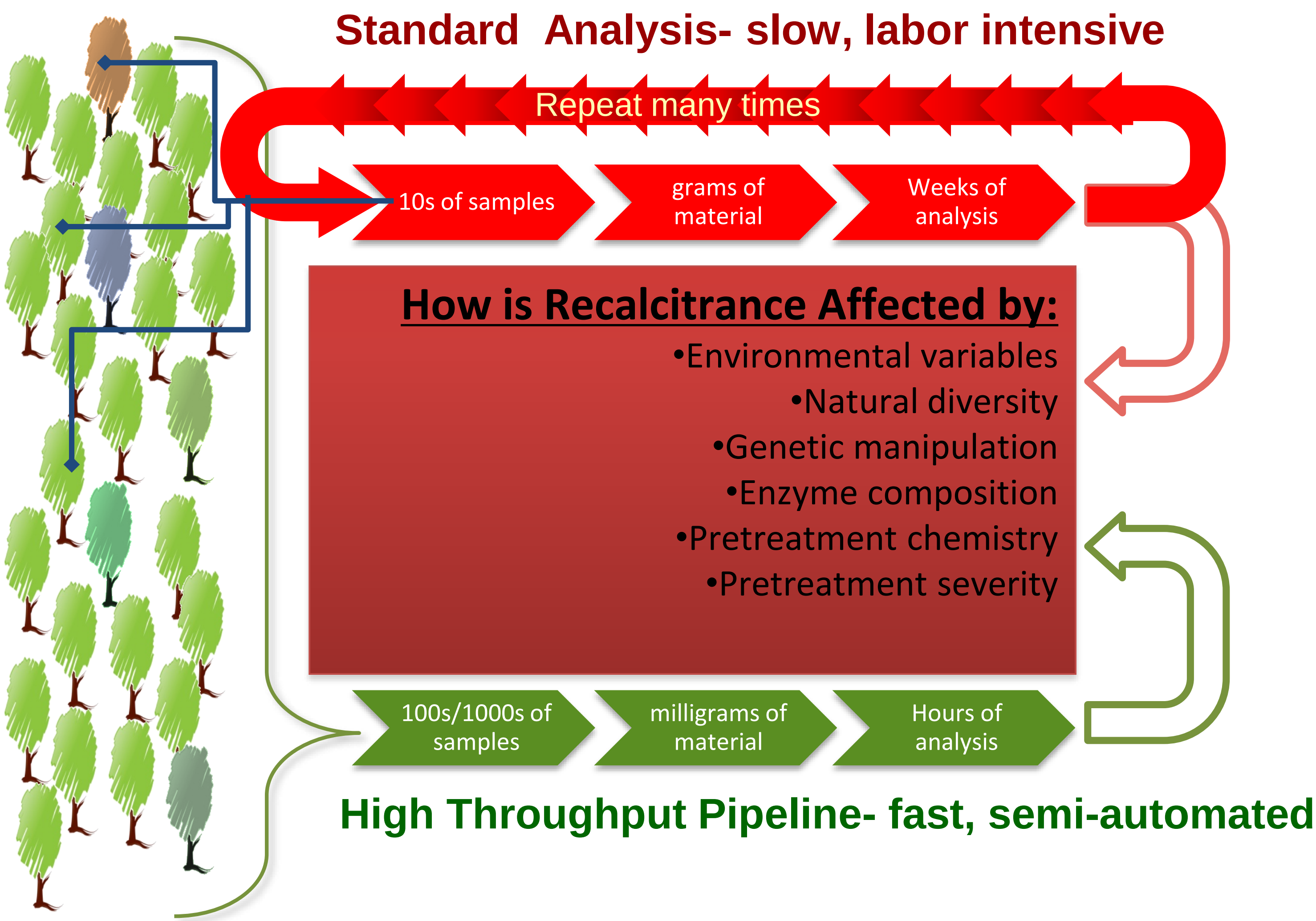
Over 1 billion tons/year of non-food lignocellulosic biomass could be available in the U.S.

- Potential to displace >>30% of gasoline

Approaches to Overcoming Biomass Recalcitrance

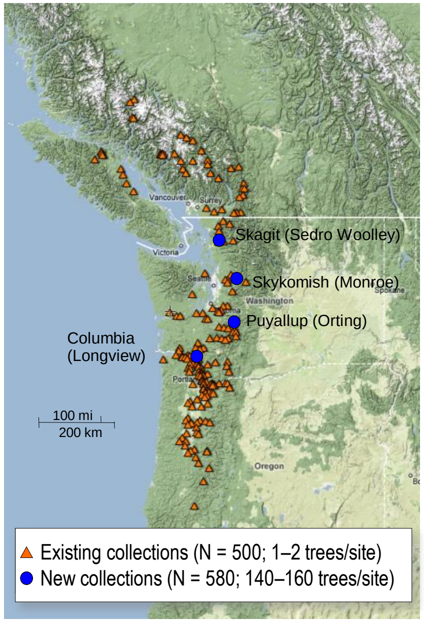


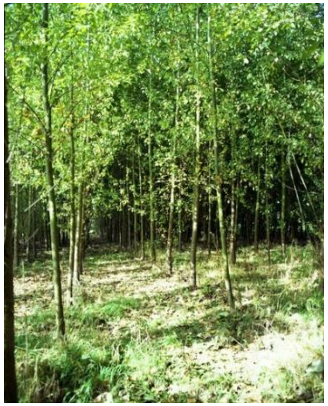
Screening Large Populations for Recalcitrance Variants



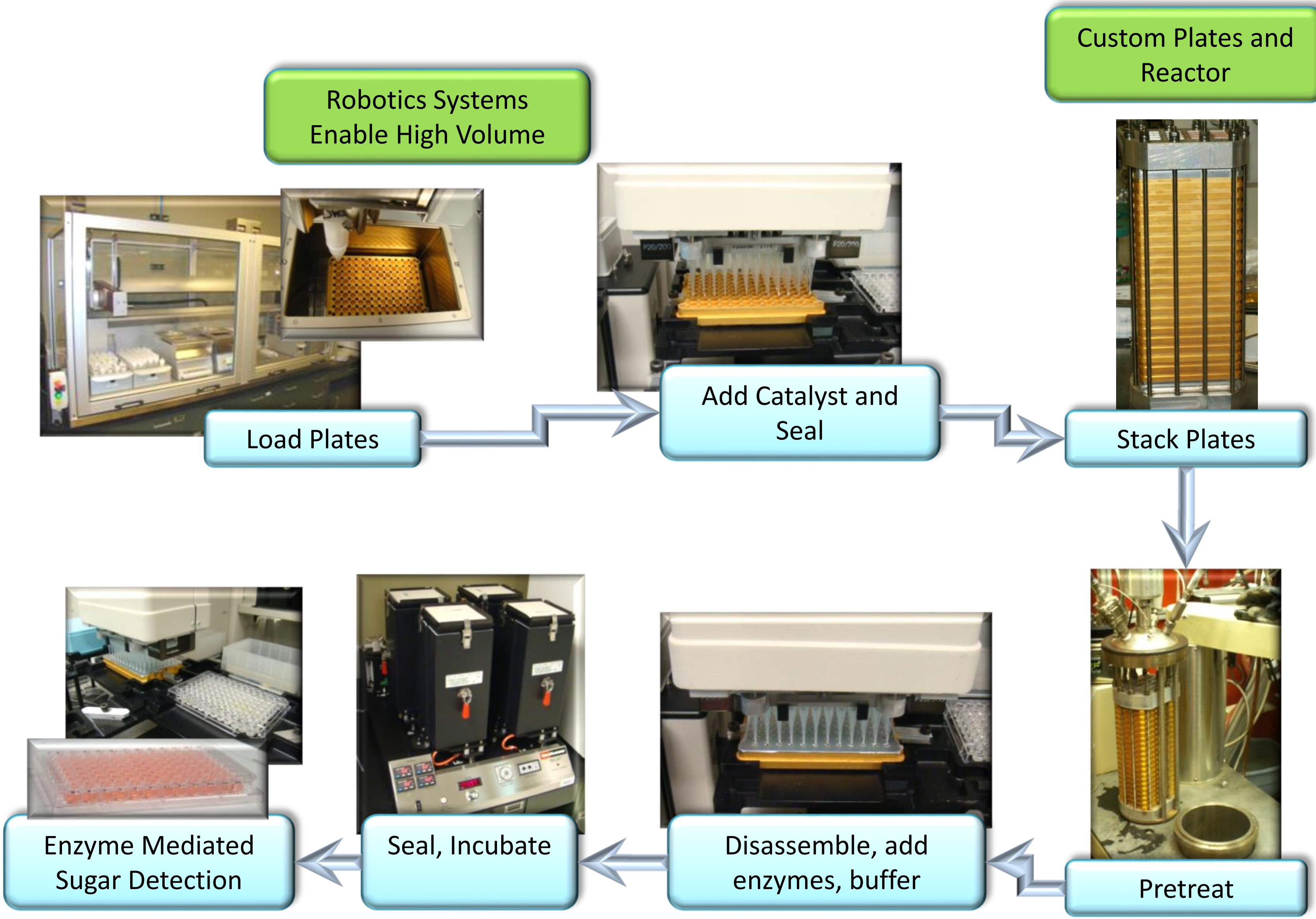
High Throughput Screening for Biomass Conversion

- Defined by large sample sets
  - Manual labor in collecting, milling, extracting, starch removal
  - Demands small-scale, automated processing
- Biomass is insoluble, heterogeneous
  - Accurate dispensing, distribution is difficult
  - Static is major problem
- Severe pretreatment conditions
  - High temperatures (150-200^{o}C), pressures, low pH
- Solids/Liquids separation
  - Small scale losses→ large impact on analysis
- Enzyme systems are complex, slow
  - Long conversion times (days, not minutes)
- Sugar product detection
  - HPLC is slow (one plate = 2 days of HPLC time)
- Chemical analysis/composition
  - Standard techniques too slow
- Systematically addressed/constrained the barriers





Parallel Plate System Overview



HTP Biomass Recalcitrance Screening at NREL

Capabilities

•96 samples/plate, 20 plates/run = 1920 samples/run

•400 mL reaction well volume

•Analysis for total lignin, S-to-G lignin ratio by Molecular Beam Mass Spectrometry

•Hastelloy HTP reactors for dilute acid, liquid hot water pretreatment temps to 200^{o}C

•Enzymatic glucose and xylose release, any enzyme mix, multi-day digestion

•Hardwoods, softwoods, grasses- with or without extraction and/or destarching

•*Coming soon- structural carbohydrate analysis*

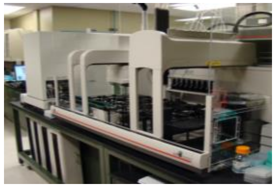
Liquids Handling – Beckman-Coulter Biomek FX

- Integrated w/ Cytomat plate hotel for high volume analysis
- 8 and 96 channel pipetting heads; 2-200 µl range
- < 1.0% std dev of volume

Solids Handling – Symyx Powdernium MTM (x2)

- Dispense and record to nearest 0.01 mg
- Quantities as small as 50 mg
- Loading rate 45-90 min/plate
- 15 plates per run
- 160 or 200 samples per run

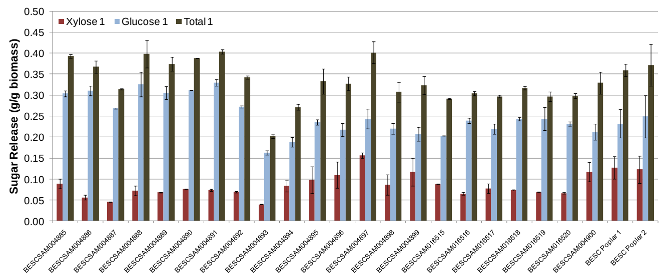


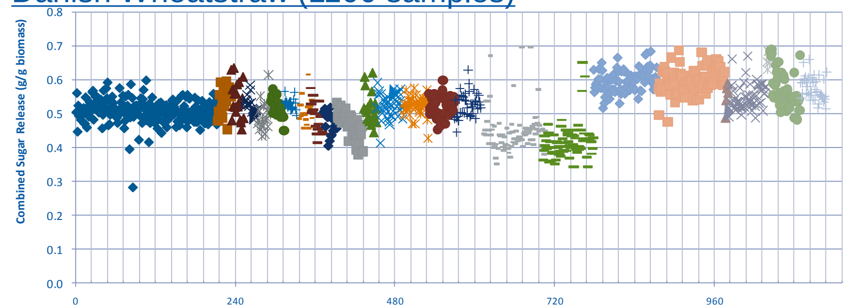

High Throughput Recalcitrance Assay

Species/Study	Last year
Poplar Association Study	648
Poplar 4CL	100
Alfalfa	24
Arabidopsis	150
VIGS-Noble	435
Tension wood	50
Lemongrass (UTK)	12
ORNL	2,656
Switchgrass (UTK)	4,000
Switchgrass COMT	58
Switchgrass (Saha)	1,442
Pinus radiata (Scion-BESC)	13
	9,588
Collaborations	
Danish wheat straw	**1,100**

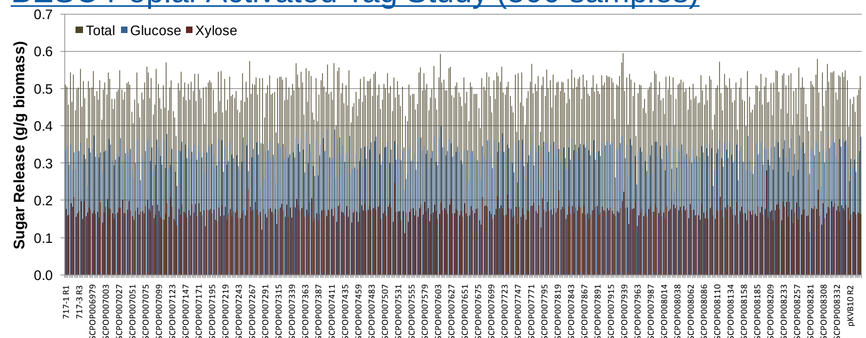
BESC Arabidopsis Mutant Strains (22 samples)



Danish Wheatstraw (1100 samples)

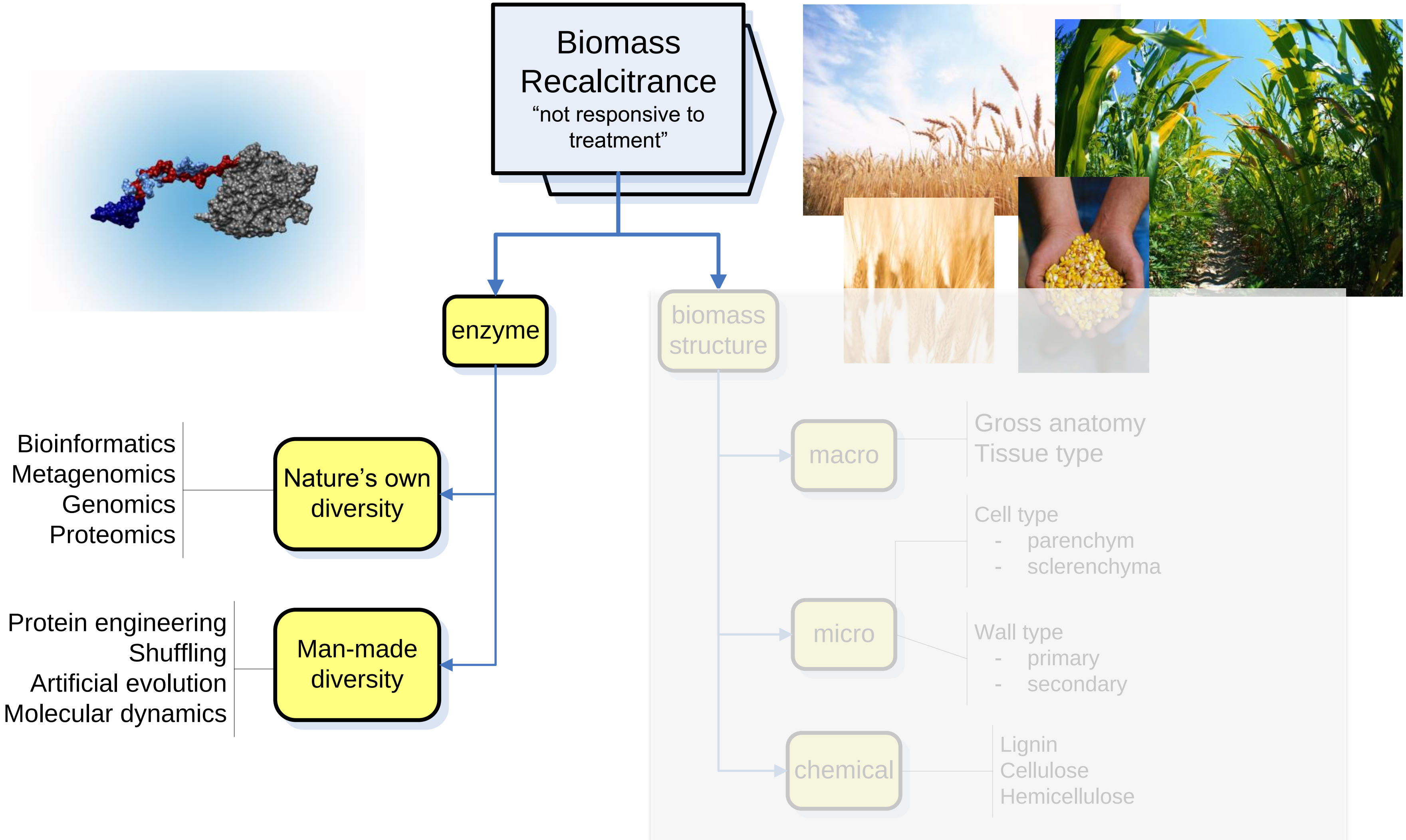


BESC Poplar Activated Tag Study (500 samples)

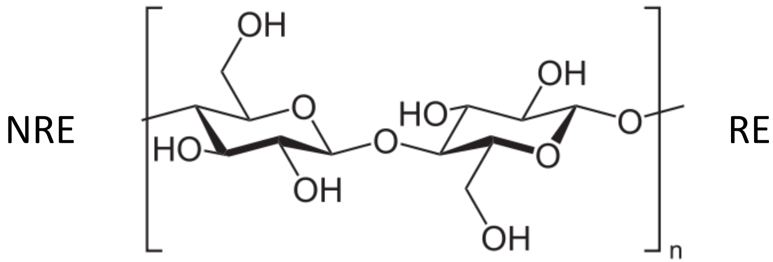


- The NREL High-Throughput Pretreatment and Hydrolysis (HTPH) System has analyzed 11,000 in the last 6 months

Approaches to Overcoming Biomass Recalcitrance



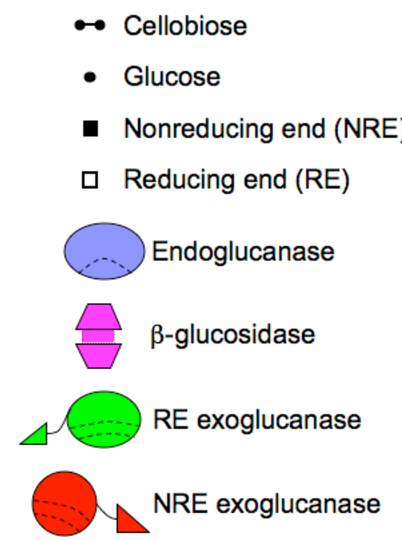
Nature Uses Cellulase Cocktails

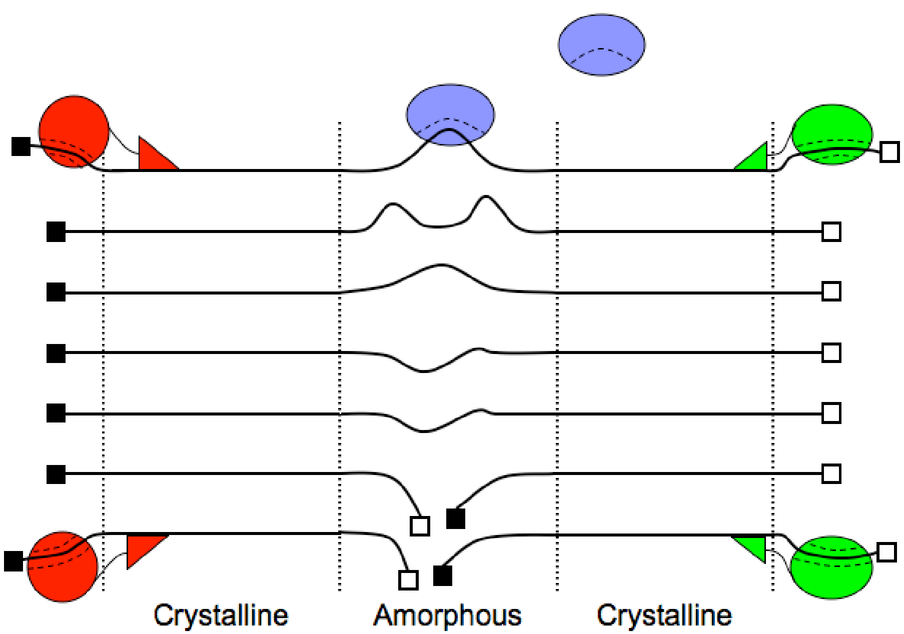


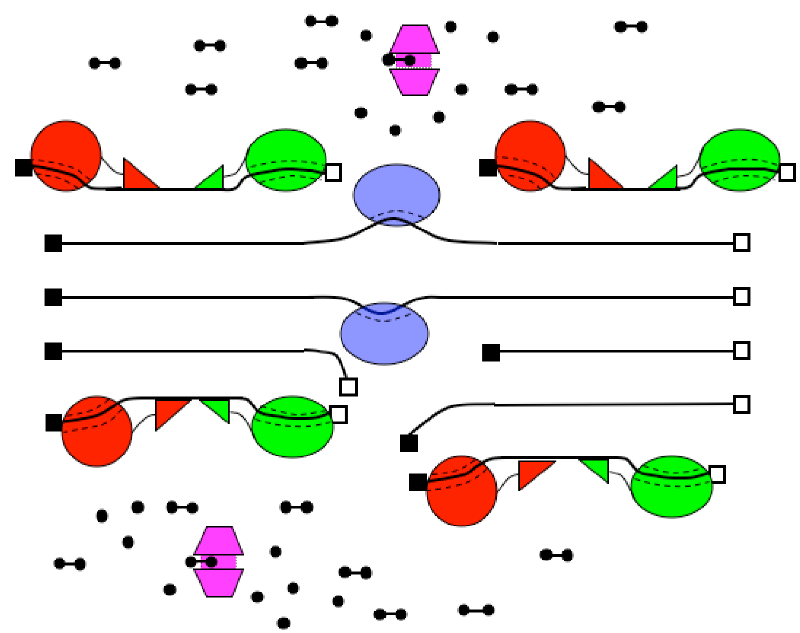
Processive and non-processive enzymes are synergistic

β-glucosidases reduce product inhibition by converting glucose dimers to monomers

Exocellulases are heavy lifters in fungal systems

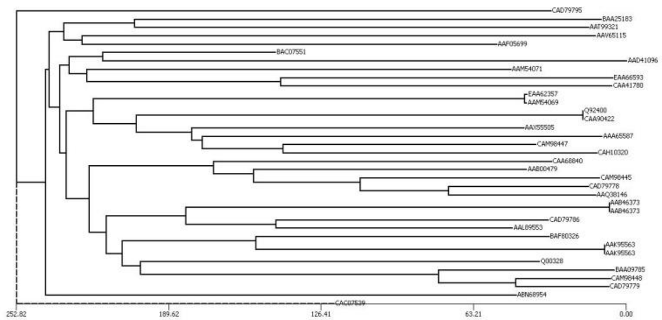


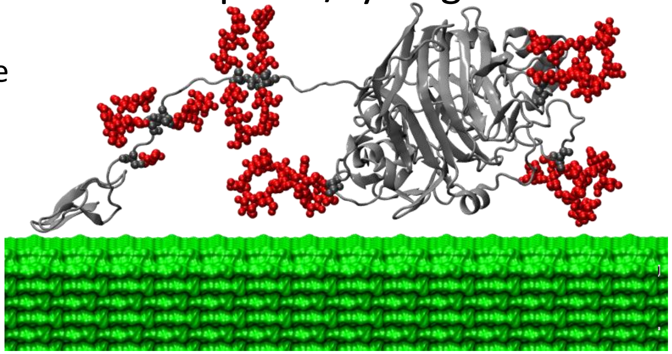


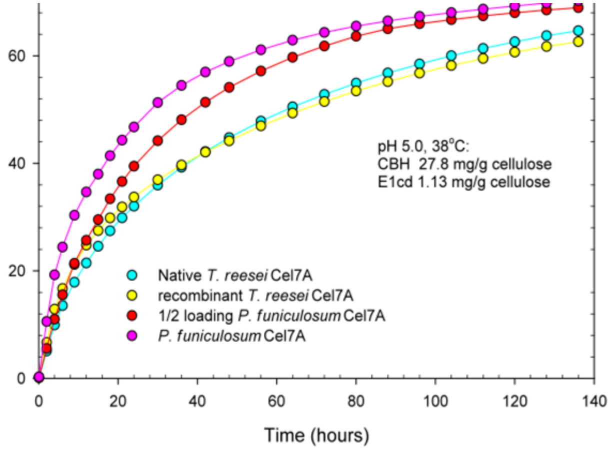


Improving Cellulases

- Combining modeling with experimental validation
- Learning from natural enzyme diversity
  - Fungal, bacterial, other
  - GH7 family diversity
    - Fungi, protists, arthropods
- Cel7A is most critical cellulase enzyme; mechanism is not known.
  - What is the biochemical relationship between structure and function?
  - What are the experimental strategies for improving Cel7A?
- Genetic engineering of Cel7A
  - Domain swapping (chimeras)
  - Site-directed
  - Loop engineering
- What enzyme components are required/synergistic?
  - Cellulase-Cellulase
  - Cellulase-Hemicellulase
  - Cellulase-PMOs
  - Cellulase-Cellulosomes







US Cellulosic Ethanol Status and Outlook

- Cellulosic ethanol (2012)
  - ~30 pilot/demo plants DOE-funded
  - ~500 mgy capacity projected

- Not meeting the RFS
  - EPA has "reduced" the goal last 2 years

- Issue – the demand side
  - "Blend wall" reached at 14 bgy
  - Easily met by corn ethanol

  - Where is the "pull" for additional ethanol ??

  - E85?
    - Hygroscopic, no back-compatibility with older vehicles

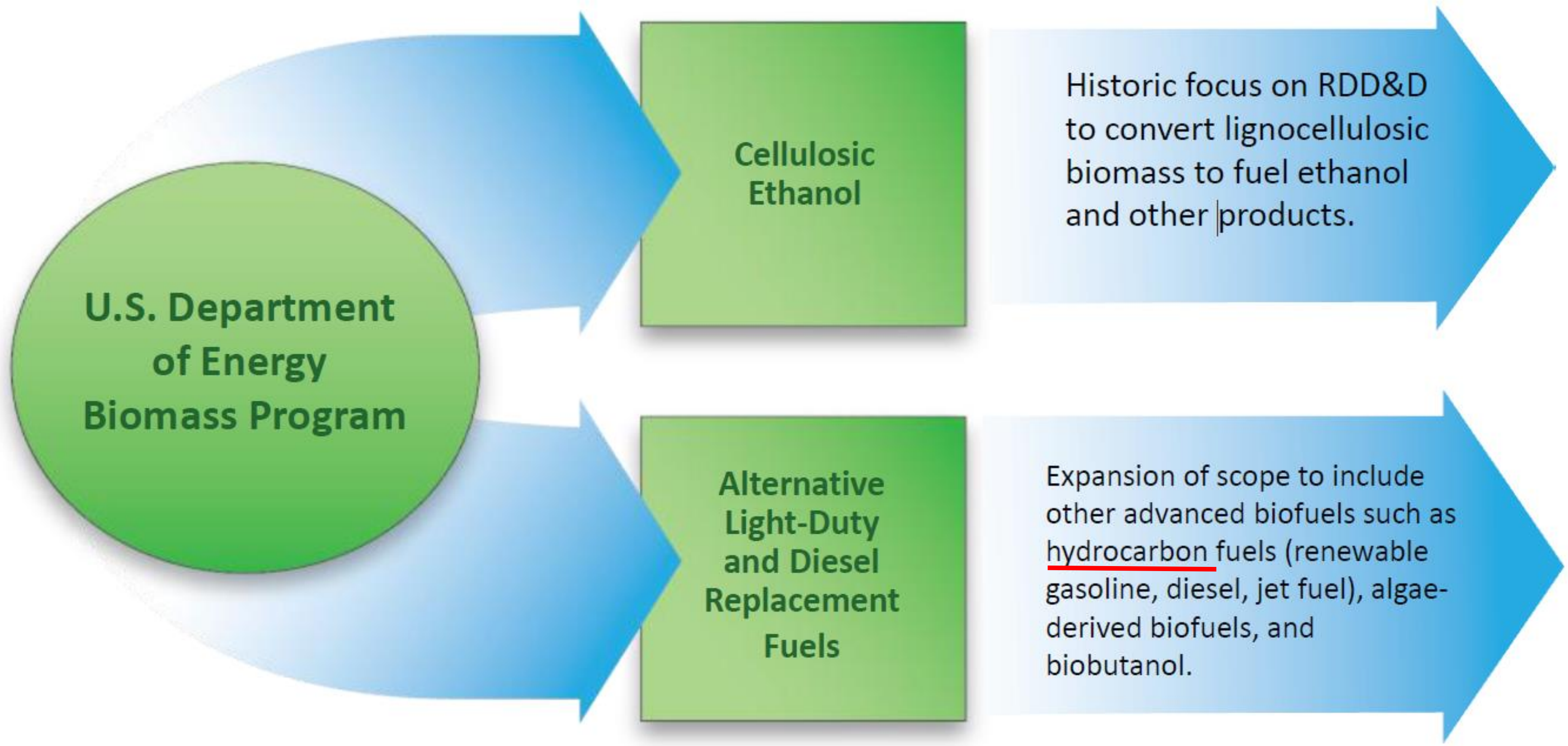
- Seen as a near to medium term solution to reduce food/fuel dilemma. Other solutions needed long term

Advanced (3rd Generation) Biofuels

Hydrocarbon Biofuels

Algal Biofuels

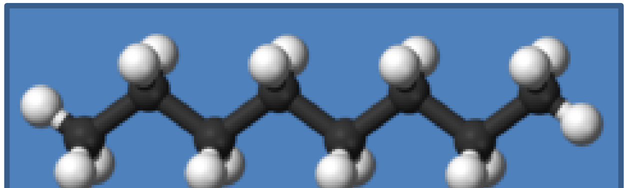
Expanding Scope



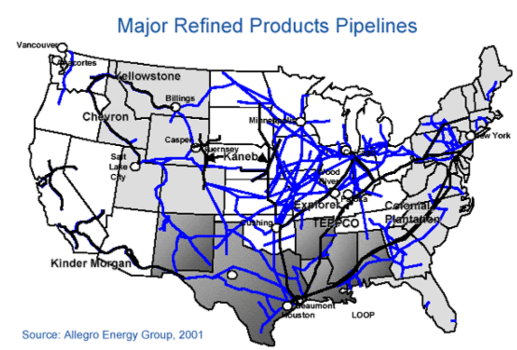
The Biomass Program forms cost-share partnerships with key stakeholders to develop, demonstrate, and deploy technologies for advanced biofuels, bioproducts, and biopower from lignocellulosic and algal biomass.

What is this "hydrocarbon" stuff ???

- Hydrocarbons are molecules made up of just hydrogen (H_2) and carbon (C) atoms
  - Our petroleum-based gasoline, diesel, and jet fuel are mixtures of many different hydrocarbons
  - These molecules contain from 5 carbons (C5's) to around eighteen (C18's)
  - Nature has put the energy into the carbon-carbon bonds – that is the energy we get back out when we burn the fuel
- If we make hydrocarbons from biomass, they will be more compatible with fuel systems and engines
  - "drop-in" fuels
  - "infrastructure compatible" fuels



Octane

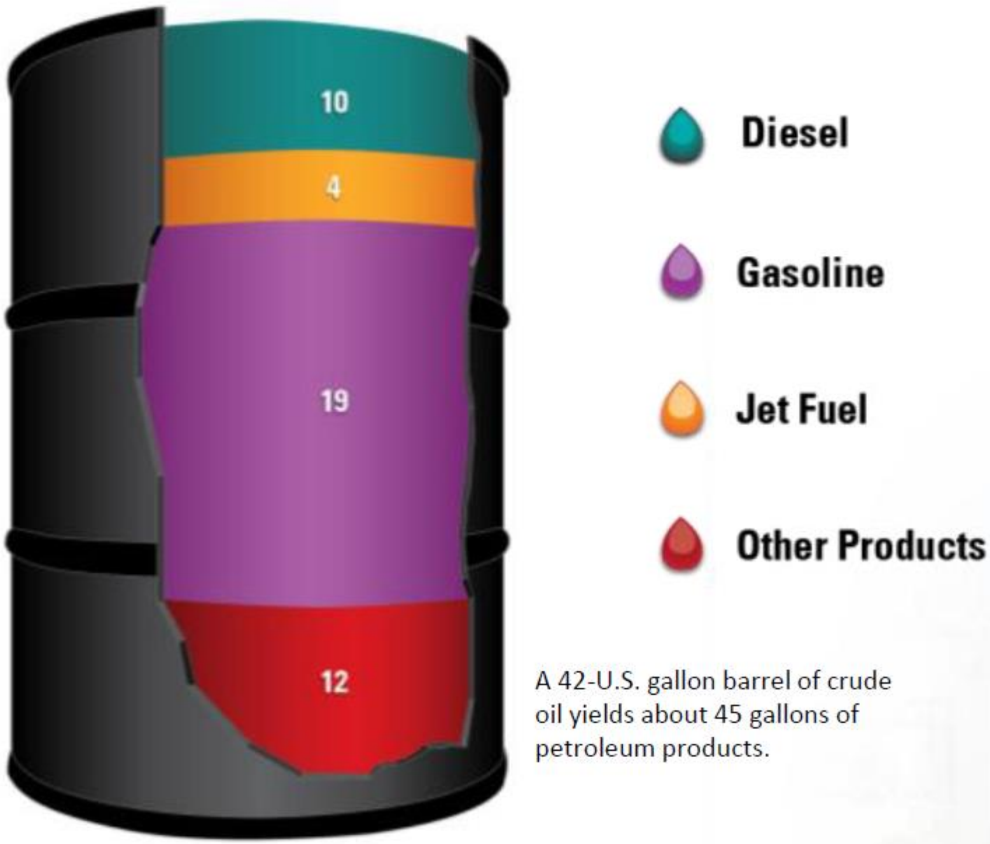


Replacing the Whole Barrel

The U.S. spends about $300 billion/year on imported oil; that's nearly $**1 billion/day.**

- The U.S. transportation sector accounts for more than 70% of U.S. oil consumption.
- Only about 40% of a barrel of crude oil goes toward light-duty petroleum gasoline.
- Reducing dependence on oil requires developing technologies to replace gasoline, diesel, jet fuel, heavy distillates, and a range of biobased chemicals and products.

Products Made from a Barrel of Crude Oil (Gallons)

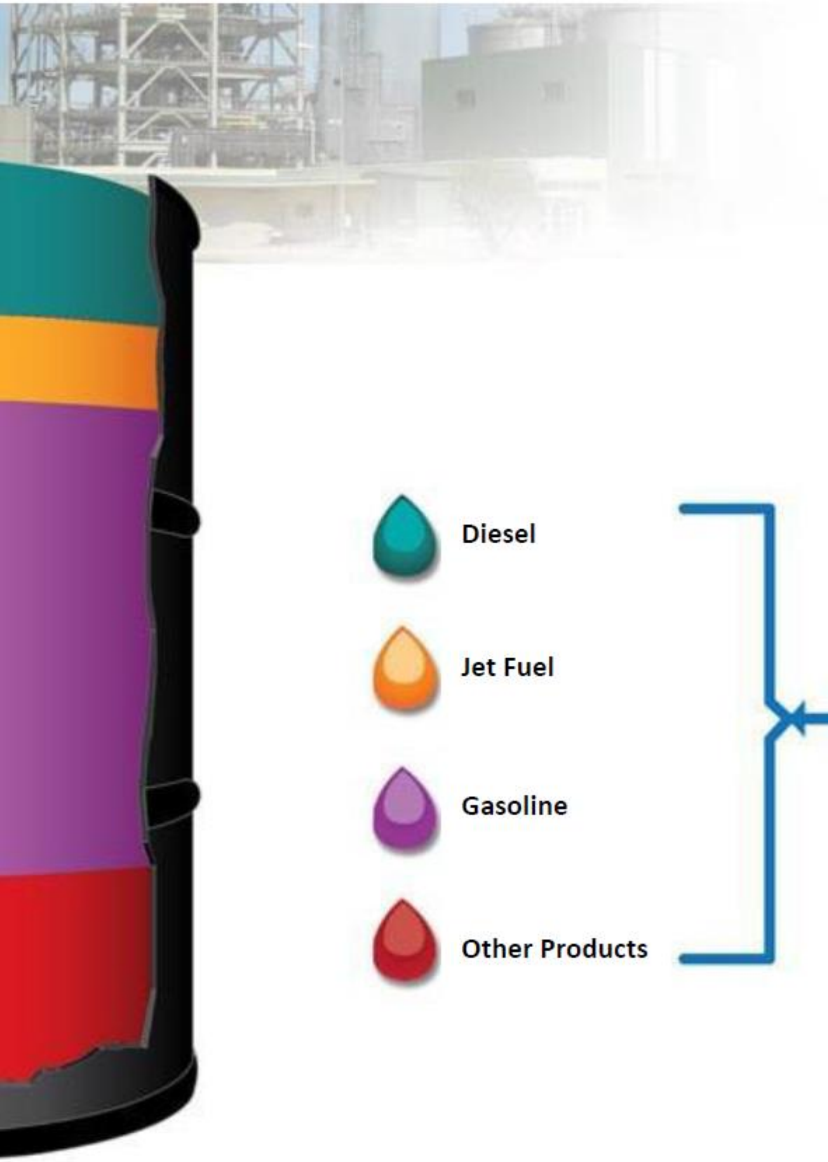


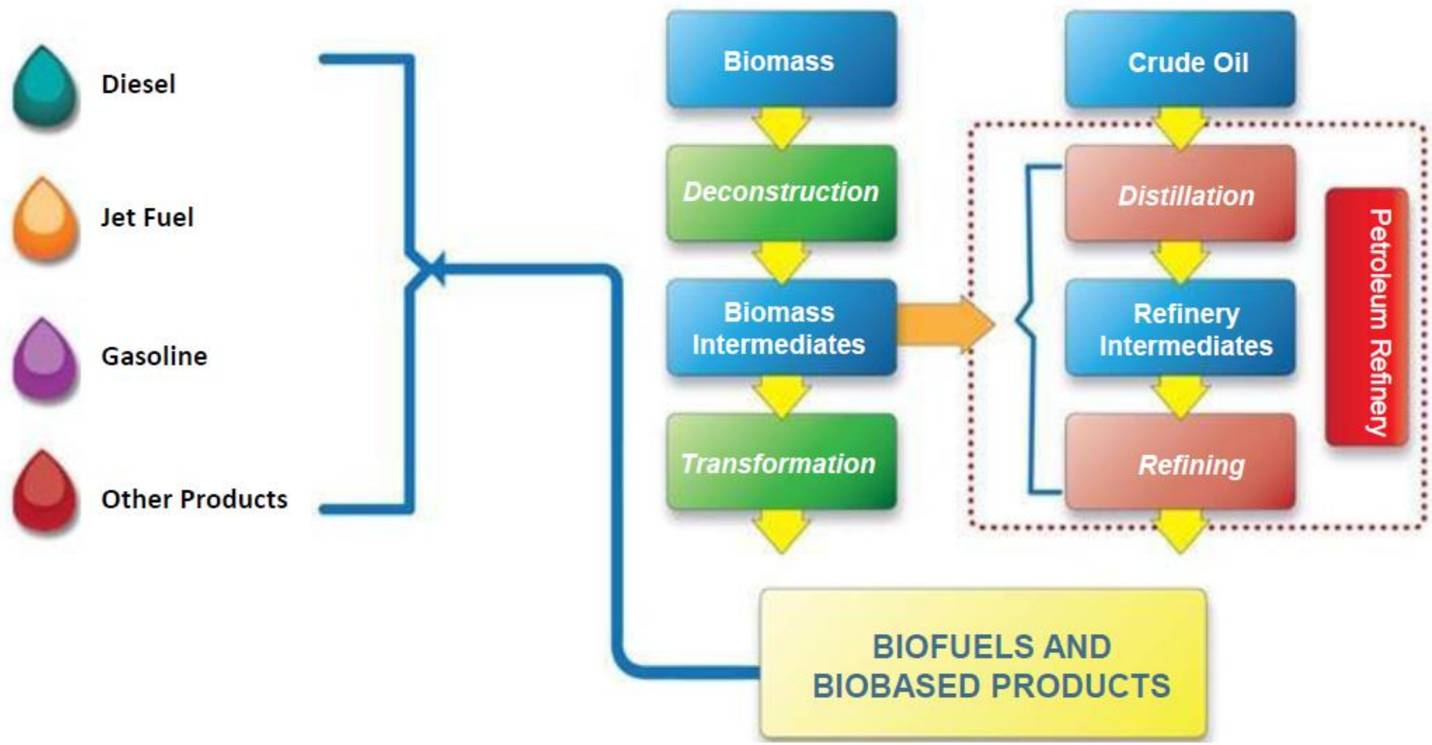
A 42-U.S. gallon barrel of crude oil yields about 45 gallons of petroleum products.

Source: Energy Information Administration

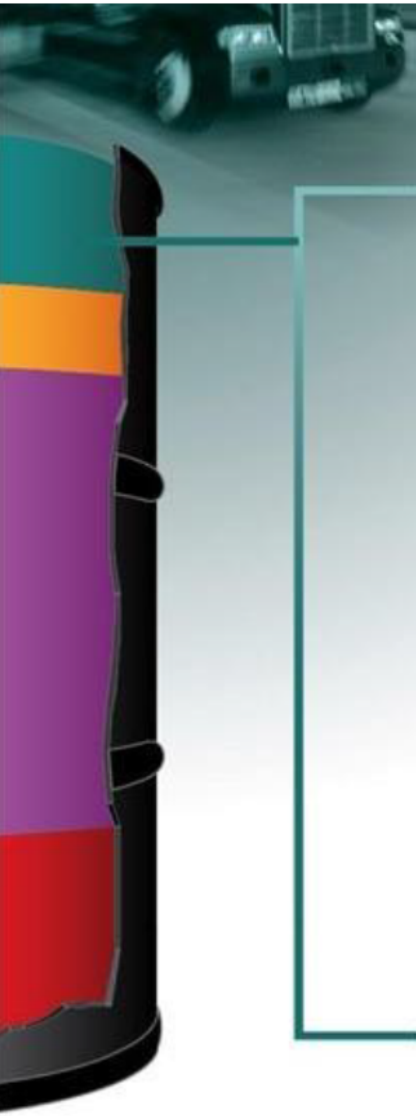
Replacing the Whole Barrel

Biomass can be converted into a range of biofuels and biobased products that displace crude oil. Biomass intermediates can be transformed into end products or integrated into the pre-existing petroleum refinery infrastructure:





Diesel



Biomass-based diesel blendstocks

- **Potential Markets**
  - Light- to heavy-duty vehicles; military; rail
- **Technologies in Biomass Program Portfolio**
  - Biochemical
  - Thermochemical
  - Algal
- **Biomass Program Project Partners**
  - Targeted R&D
  - Integrated biorefinery demonstrations

Diesel Gasoline Jet Fuel Other Products

Jet Fuel

Biomass-based jet blendstocks

- **Potential Markets**
  - Commercial and military aviation
- **Technologies in Biomass Program Portfolio**
  - Biochemical
  - Thermochemical
  - Algal
- **Biomass Program Project Partners**
  - Targeted R&D
  - Integrated biorefinery demonstrations

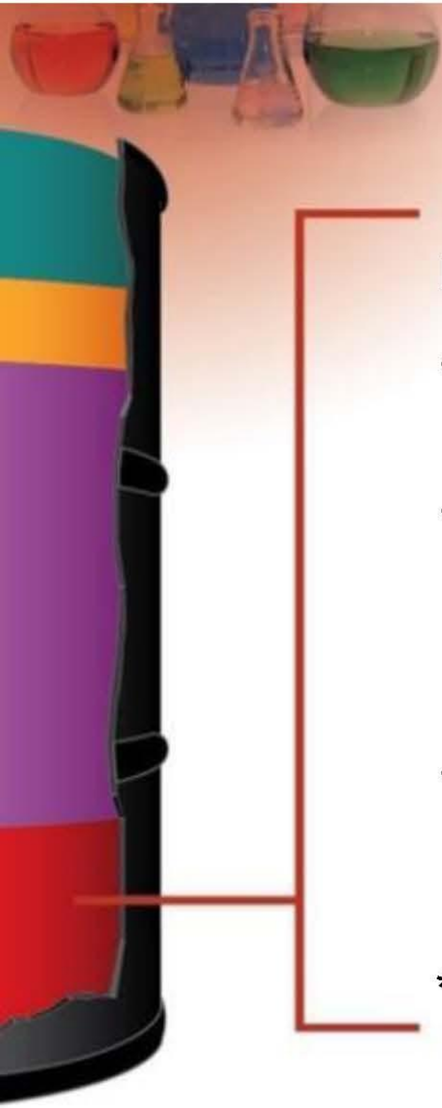
Gasoline

Biomass-based gasoline blendstocks
(ethanol and renewable gasoline)

- **Potential Markets**
  - Light-duty vehicles
- **Technologies in Biomass Program Portfolio**
  - Biochemical
  - Thermochemical
  - Algal
- **Biomass Program Project Partners**
  - Targeted R&D
  - Integrated biorefinery demonstrations

Diesel   Gasoline   Jet Fuel   Other Products

Other Products*



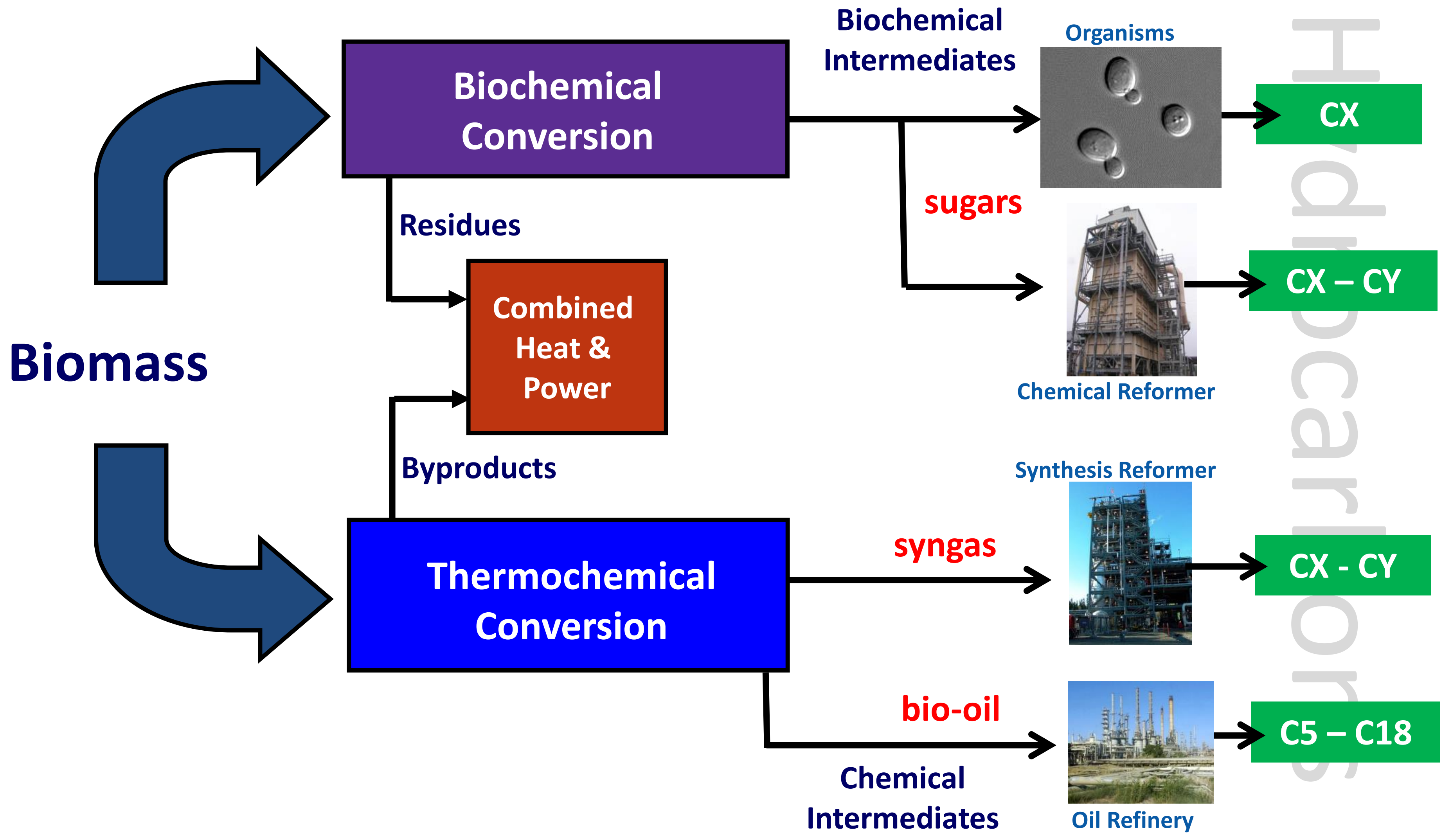
Biomass-based products

- **Potential Markets**
  - Plastics, solvents, alcohols, specialty chemicals
- **Technologies in Biomass Program Portfolio**
  - Biochemical
  - Thermochemical
  - Algal
- **Biomass Program Project Partners**
  - Targeted R&D
  - Integrated biorefinery demonstrations

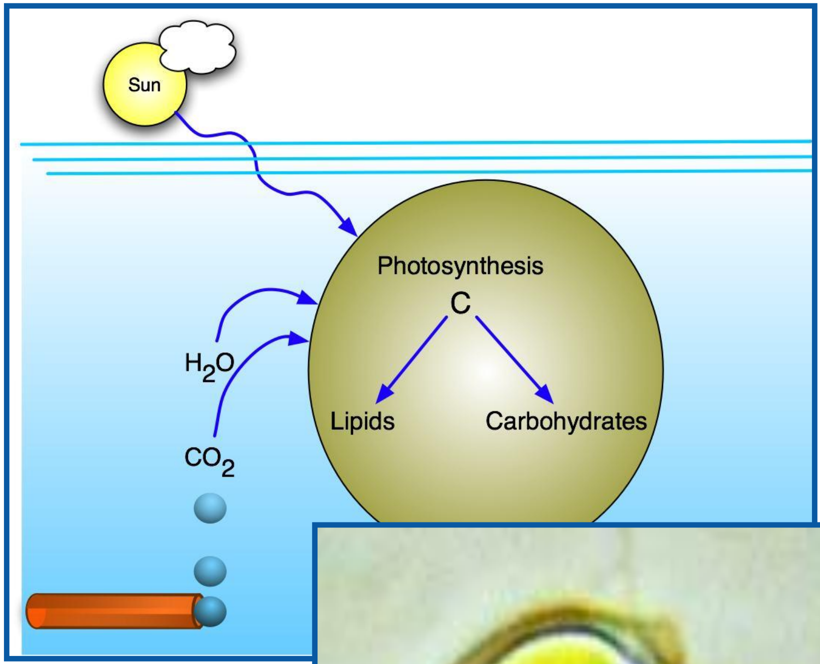
*Other Products include heating oil and other distillates, heavy fuel oil, liquefied petroleum gases, and more

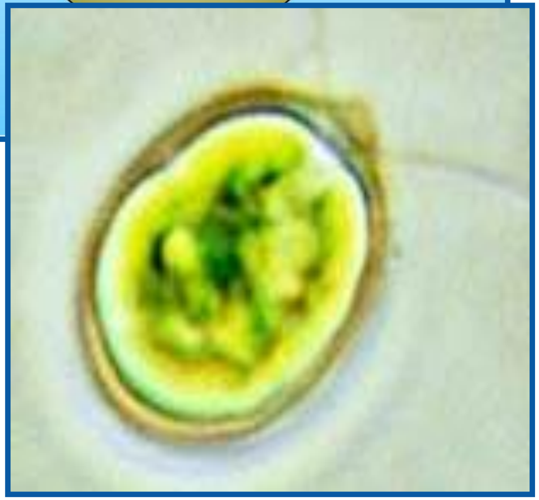
Diesel | Gasoline | Jet Fuel | Other Products

Biomass to Hydrocarbons



Algae as a Source of Biofuels

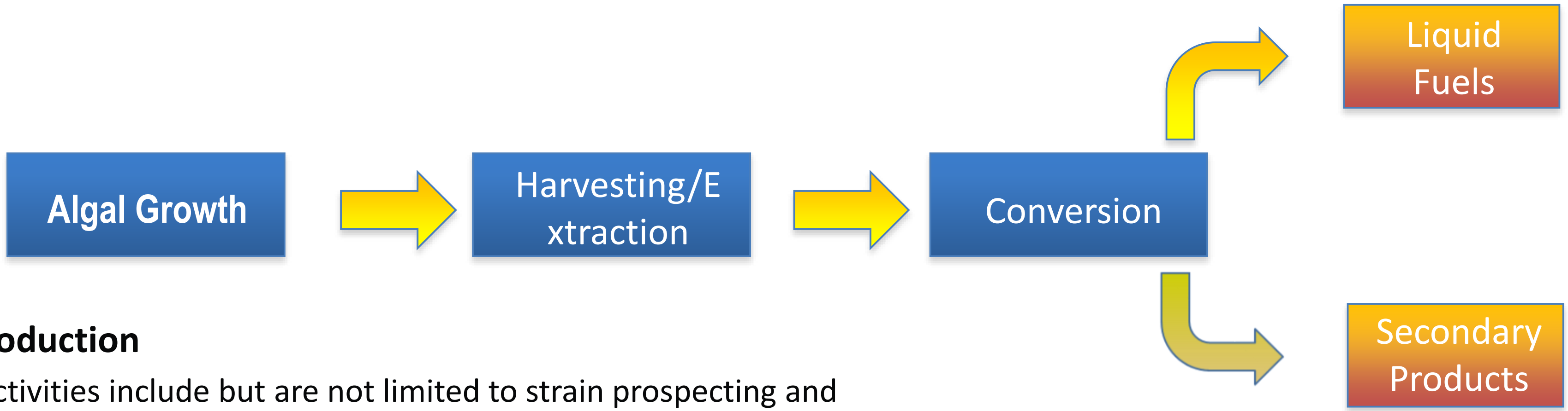




- **Source of additional lipids (oils) and/or carbohydrates**
- **Complements terrestrial biomass production**
    - Reduces pressure on land use
    - Avoids food vs fuel debate
    - Saline, brackish, waste water-compatible
    - Option to utilize large waste CO_2 resource (e.g. coal power plant)
- **Potential for greater productivity than their terrestrial cousins**
    - Up to <u>50 times</u> more productive than traditional oilseed crops
    - Very large resource potential for producing additional biodiesel or jet fuel

Algal Biofuels

Current RD&D projects are improving the growth, harvesting/extraction logistics and conversion of algal biomass into biopower or biofuels such as gasoline, diesel, and jet fuel.



Production

•Activities include but are not limited to strain prospecting and isolation, biological improvements, cultivation strategies and infrastructure engineering.

Harvesting

•Activities include but are not limited to collection, dewatering and concentration.

Conversion

•Activities include but are not limited to intermediate and final product production, purification and/or stabilization.

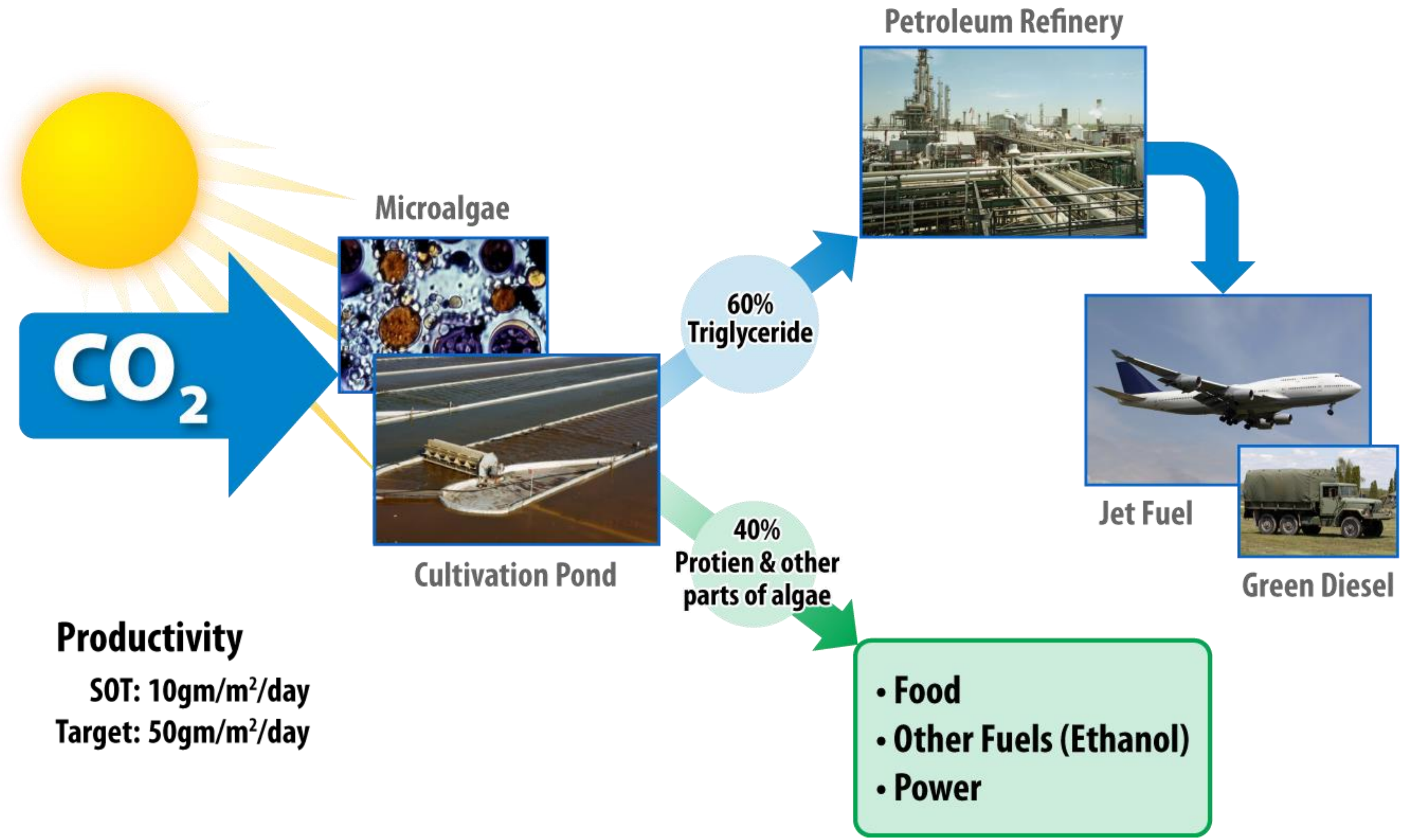
NREL Roles:

1) Technology Development

2) Demo at Bench to Pilot

Algae to Diesel or Jet Fuel

Offers oil source for utilization of existing refinery assets

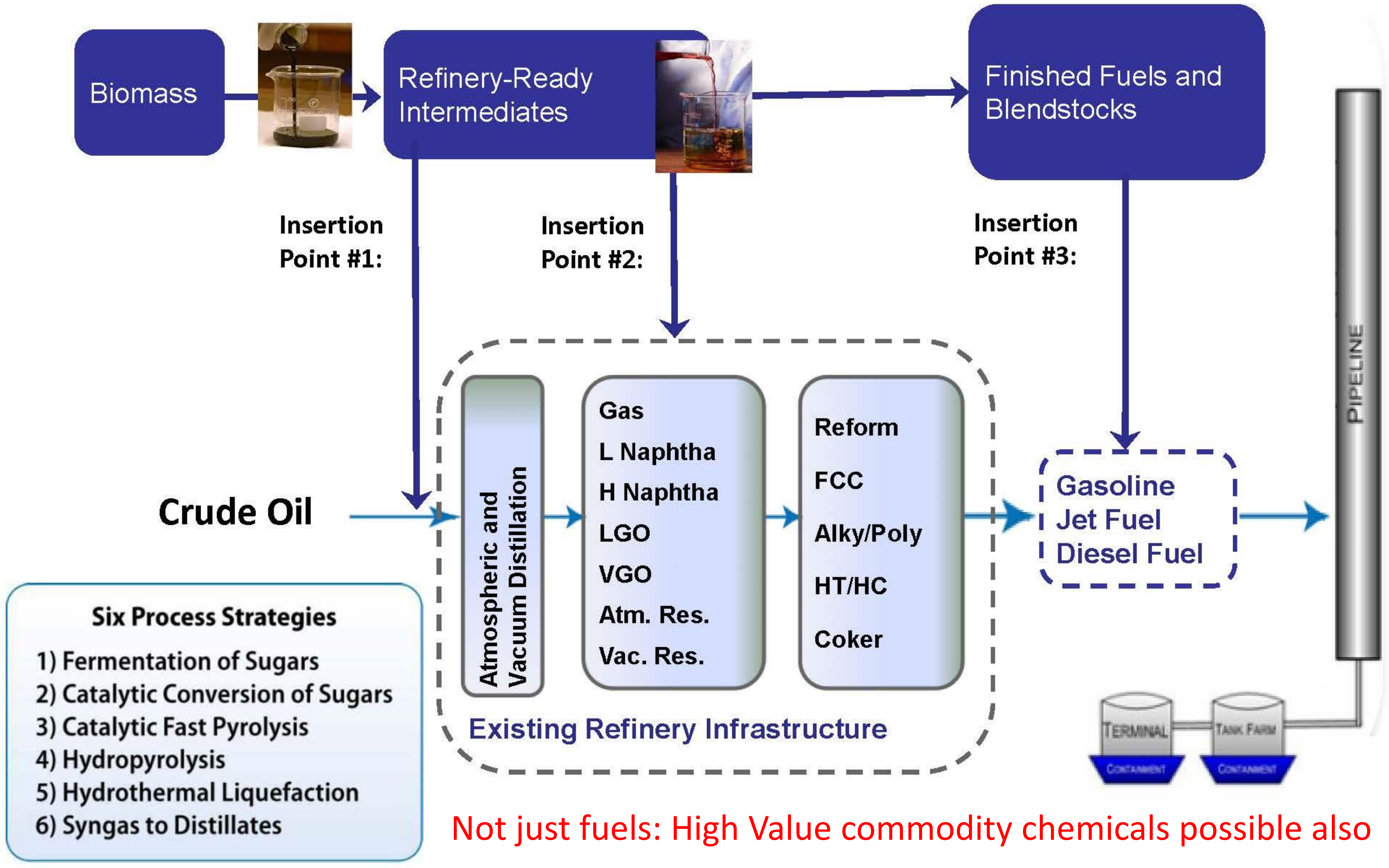


Productivity

SOT: 10gm/m²/day

Target: 50gm/m²/day

Biorefinery: Diverse Products and Infrastructure Compatibility



Not just fuels: High Value commodity chemicals possible also

Integrated Biorefinery Projects

Current IBR project investments will accelerate U.S. bioindustry growth and ramp up production of a range of biofuels and bioproducts.

A groundbreaking in April 2011 at the INEOS demonstration IBR.

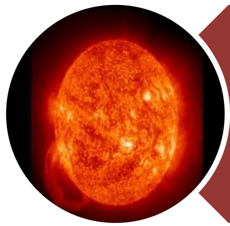
Over $1.1 B in DOE investments in 29 IBR projects:

11 hydrocarbon fuels - $326M
16 cellulosic ethanol - $766M
1 butanol - $30M
1 succinic acid - $50M
170 million gallons in planned capacity of biofuels and products by 2014

- $1.1 billion Biomass Program investment is being cost shared with over $1.7 billion from industry
- DOE investment has enabled equity investments, initial public offers (IPOs), venture capital (VC) funding, joint ventures (JVs), and joint development agreements (JDAs)

NREL Roles:

1) **Partnering to demonstrate Industrial technologies**
2) **Fuels Testing**



Fuels from Sunlight

Some considerations . . .

- Biomass will be an important, near to medium-term, renewable source of liquid and gaseous biofuels
  - Can probably never be a complete fossil fuel replacement
  - But, will be an important part of the future fuels "portfolio"
- To get there we need
  - Continued technology advancement and R&D
  - Policy measures which incentivize and accelerate implementation in the marketplace
- And, as technologies evolve, we must do thorough Life Cycle Assessments to understand the sustainability issues
- Although the task is difficult, the results will be worth the effort!

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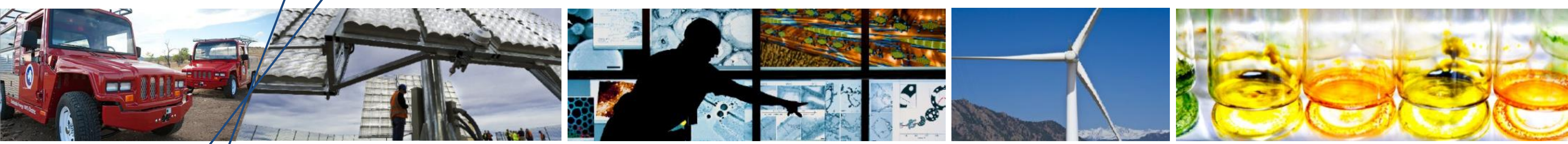
NREL
NATIONAL RENEWABLE ENERGY LABORATORY



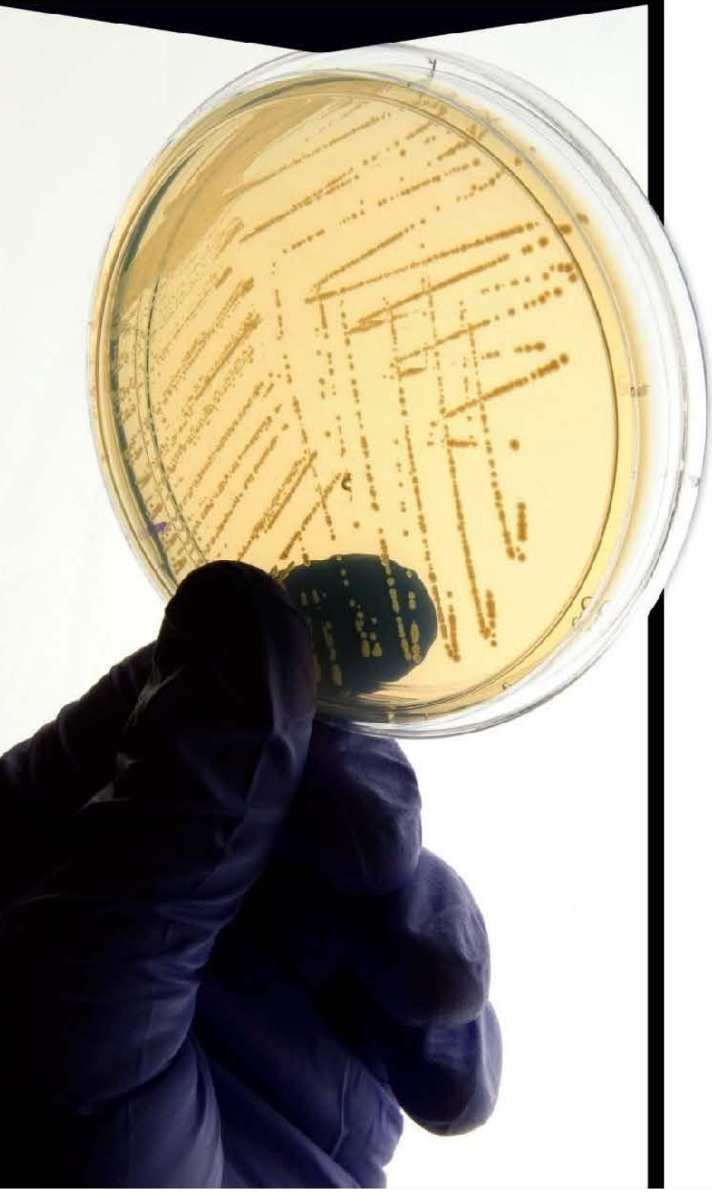
Thank You, for your kind attention!

(Gracias!)

Please contact me at: larry.taylor@nrel.gov innovation

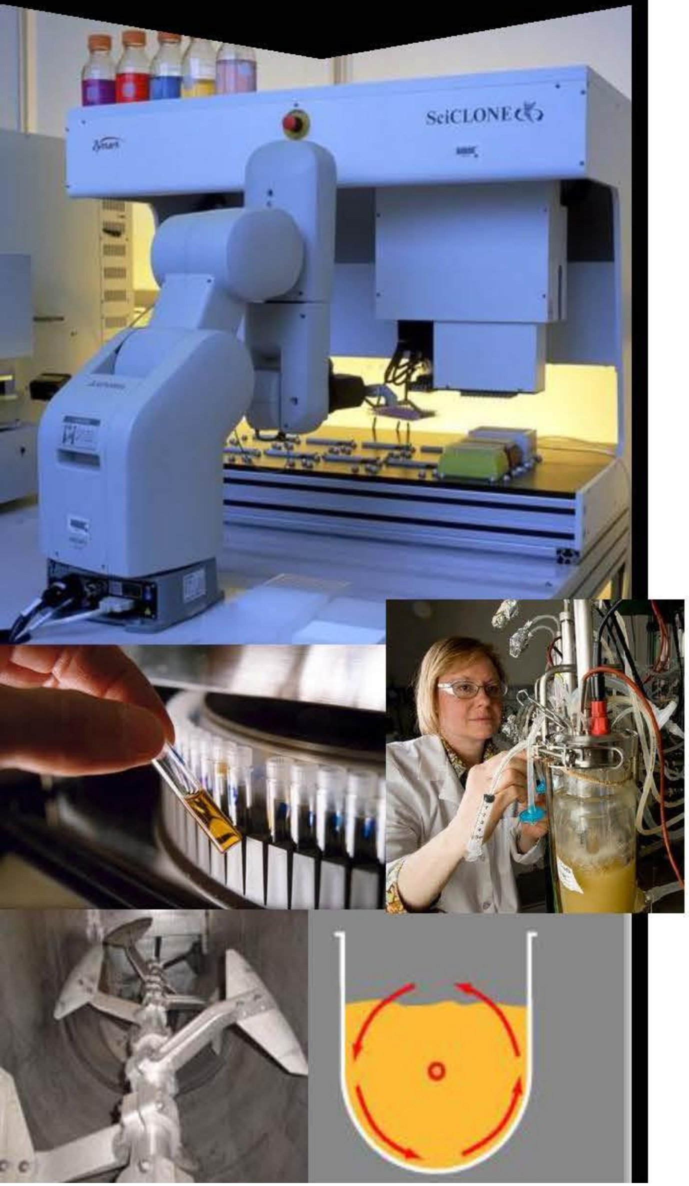
Biofuels

Driving Down the Cost of Biofuels



- Cellulosic ethanol prices tied to cost of enzymes used to convert biomass into fermentable sugars
- NREL partnered with Novozymes and Genencor to engineer new low-cost enzyme production
- Collaborated on biomass characterization, pretreatment, and process integration research
- Exceeded enzyme cost-reduction goal by 10x

innovation



Biomass Energy

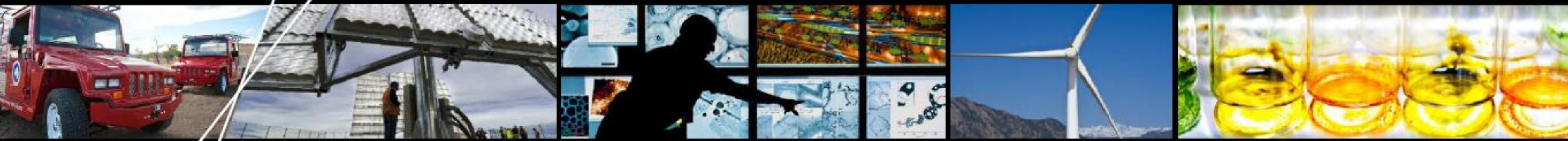
NREL's Focus

Biofuels: Converting biomass into liquid fuels for transportation

Biopower: Generating electricity by burning biomass directly, or converting it into gaseous or liquid fuels

Bioproducts: Converting biomass into chemicals for making plastics and other products that typically are made from petroleum

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

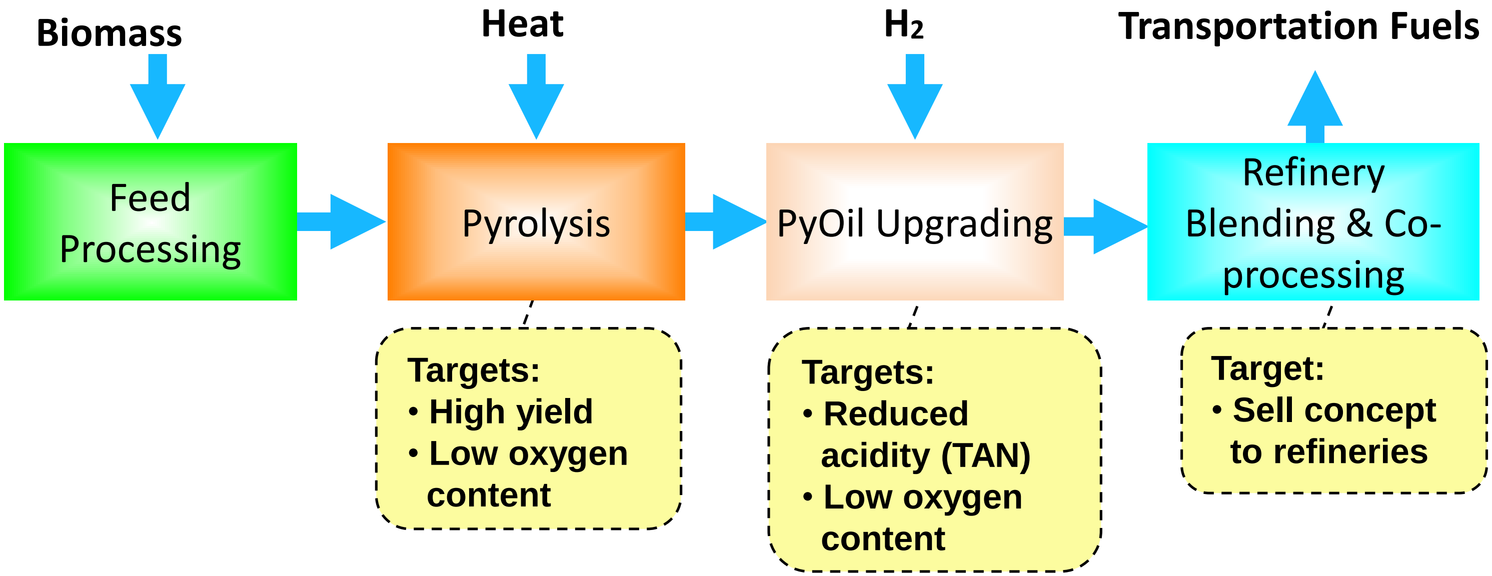


NREL Background

Thermochemical Conversion: Pyrolysis

Biomass via pyrolysis oils to fuels

- Partially deconstruct biomass to liquids
- Refine liquids to fuels



Biofuels: Current US State of Technology

Current Status:

U.S. produced 13.5 billion gallons of ethanol and 1.1 billion gallons of biodiesel (2011)

Biorefineries:

- 219 commercial corn ethanol plants
- 180 biodiesel refineries
- 28 cellulosic ethanol

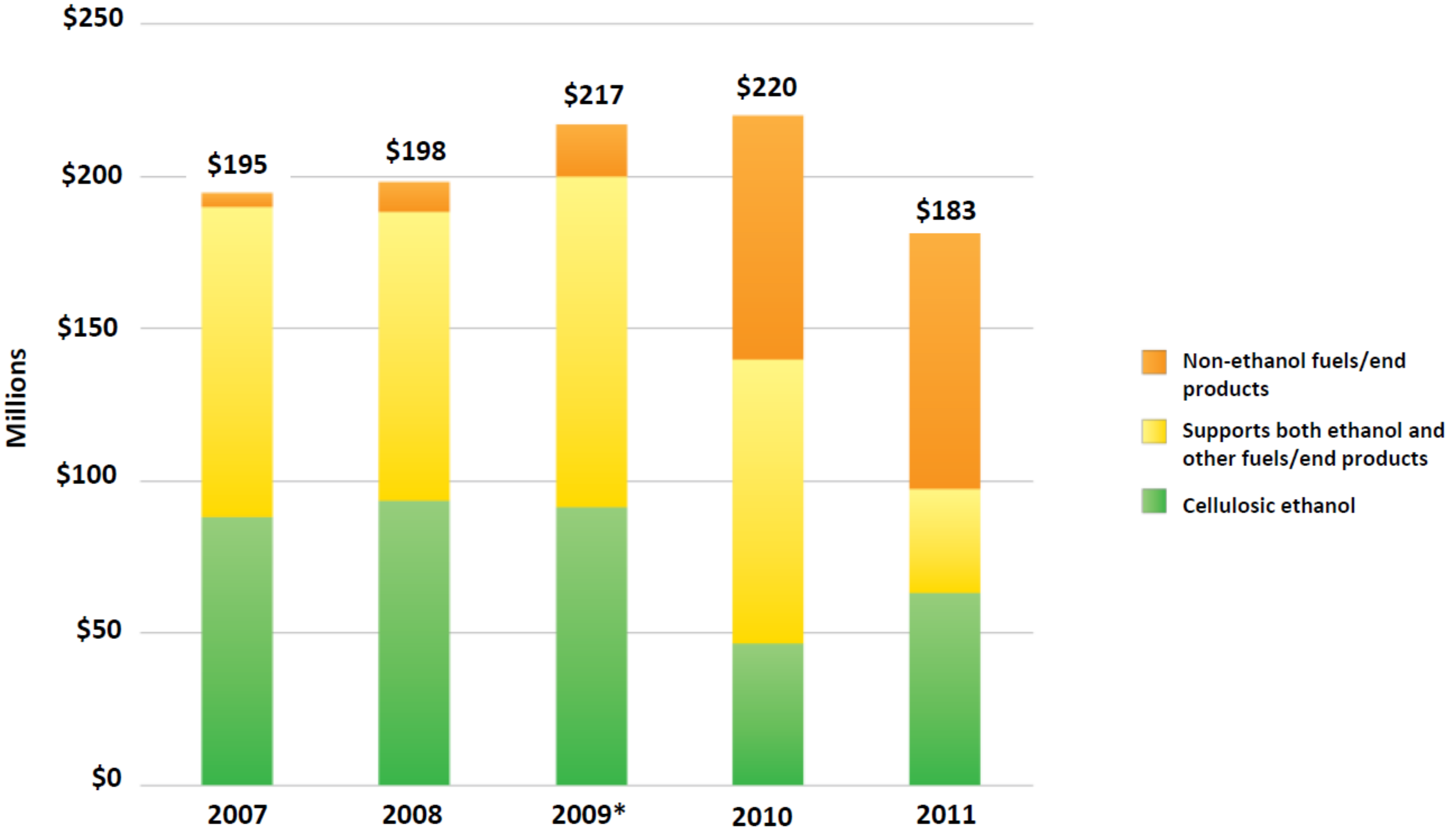
Cost goal:

Cellulosic ethanol—cost parity with gasoline by 2012

Major Technology Directions:

- Foundational Science: Enzymes, fermentation, understanding biomass and cell composition
- Feedstocks: Sustainable feedstock production systems
- Pretreatment and Conversion R&D: Biochemical and thermochemical conversion processes
- Advanced Biofuels and Algae: Broadening RD&D beyond cellulosic ethanol to address “drop in’ and high-energy content fuels from algae and other biomass resources

Biomass Program Annual Appropriations, FY07 through FY11



*Through the American Recovery and Reinvestment Act, the Biomass Program was appropriated an additional $800 million in FY2009. Learn more about the Program's Recovery Act investments.

Biomass Program

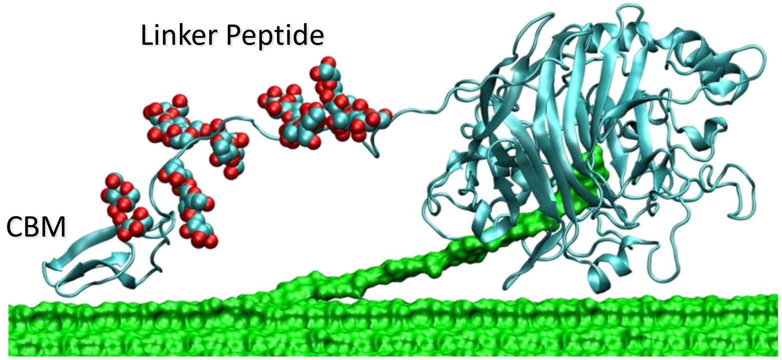
Improving Biocatalysts- Cel7A

Molecular Structure
(experimental parameters)

- X-ray crystallography
- Structure diversity (genomics)
- Homology modeling

Physical Biochemistry
(experimental parameters)

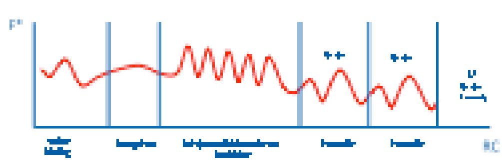
- Protein purification
- Physical chemical analyses
- MS and spectro. analyses
- Special and HTP activity testing



Numerical Models
(subsets to entire system)

- Molecular dynamics
- QM/MM
- Multi-scale modeling
- Code development
- Force fields
- Supercomputers

Mechanistic Model
(kinetic and Thermodynamic)



Biochemical Conversion to Ethanol