ARPA-E Portfolio of Fuels Investments

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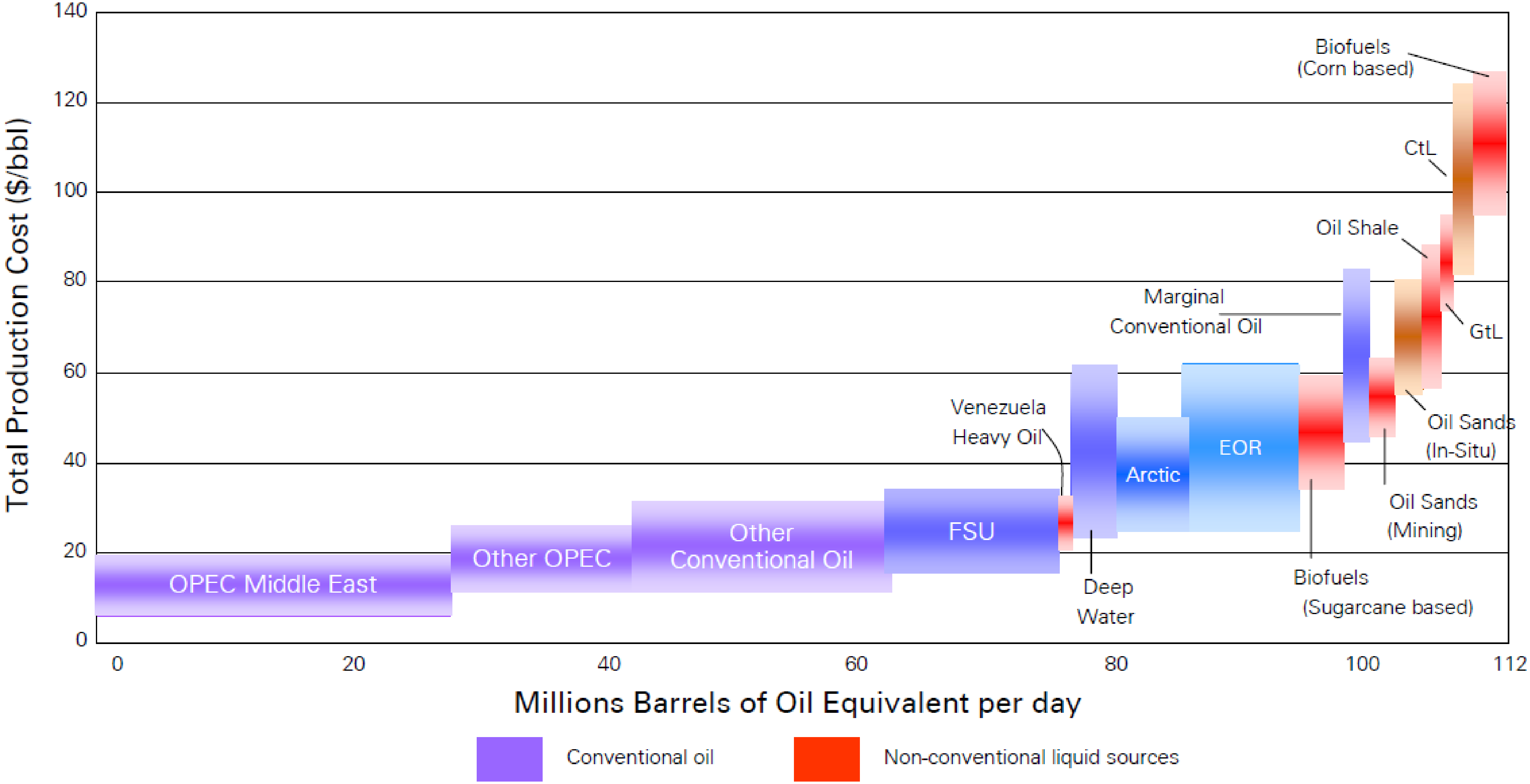
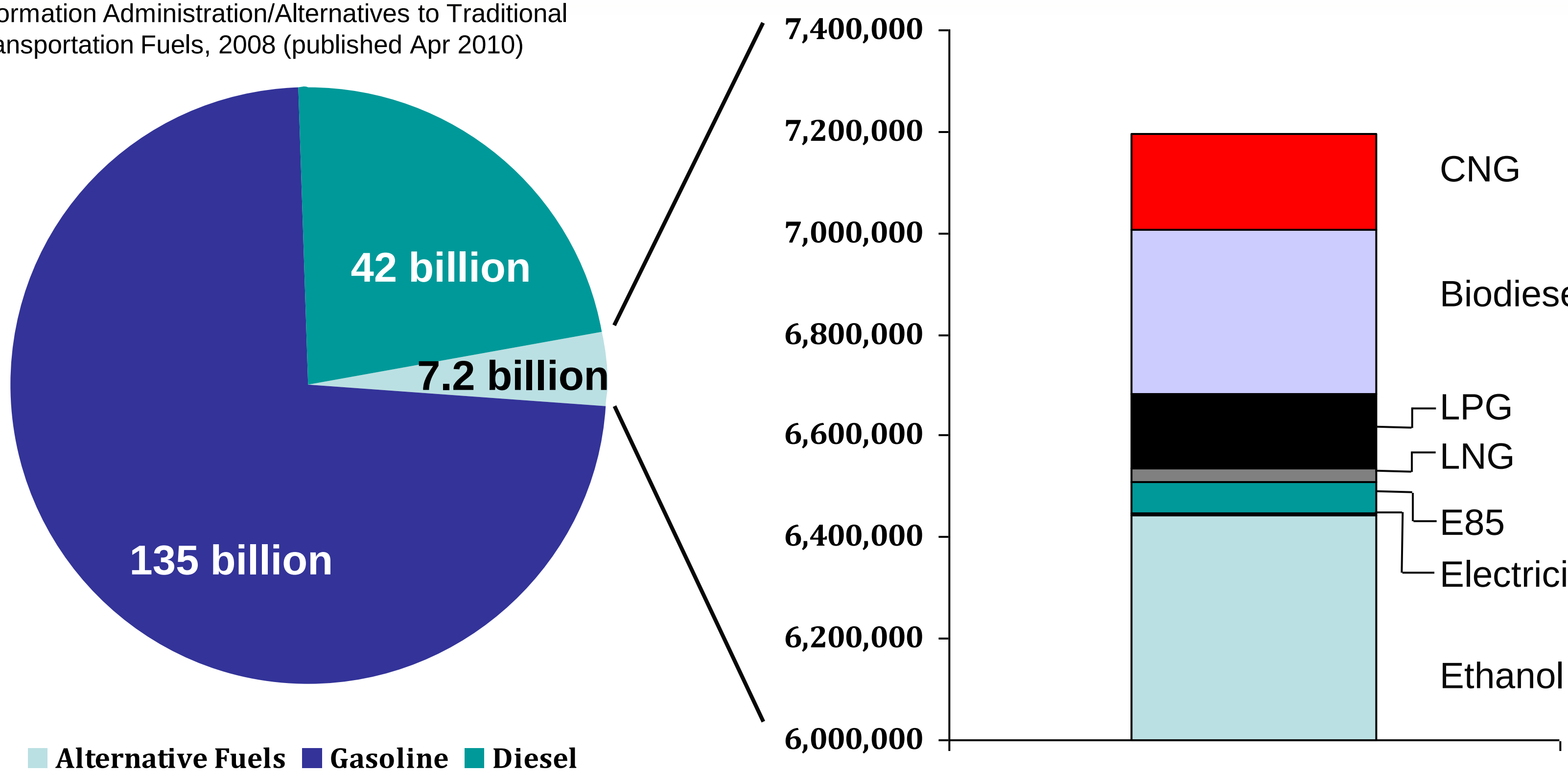
Biofuels: a tough nut to crack



Source: Booz Allen Hamilton analysis based on information from IEA, DOE and interviews with super-majors

Alternative fuels account for only 4% of fuels consumed, with ethanol leading the pack

2008 Fuel Consumption Estimates from U.S. Energy Information Administration/Alternatives to Traditional Transportation Fuels, 2008 (published Apr 2010)



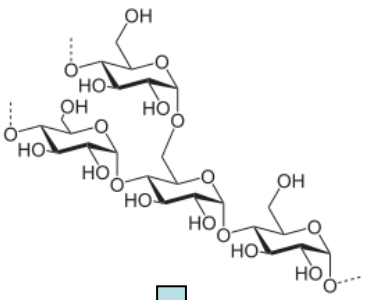
Values are reported in gasoline or equivalent gallons

Ethanol, as either E85 or in low concentration blends, accounts for 90% of alternative fuels consumed

1st Generation Biofuels: Relying on food commodities

- Raw biofuel feedstocks face upward price pressure due to increasing population and demand for food

- 1st generation biofuels face a volatile marketplace and production volumes are expected to plateau due to resource (available sugar or vegetable oil) and policy (RFS II) constraints.

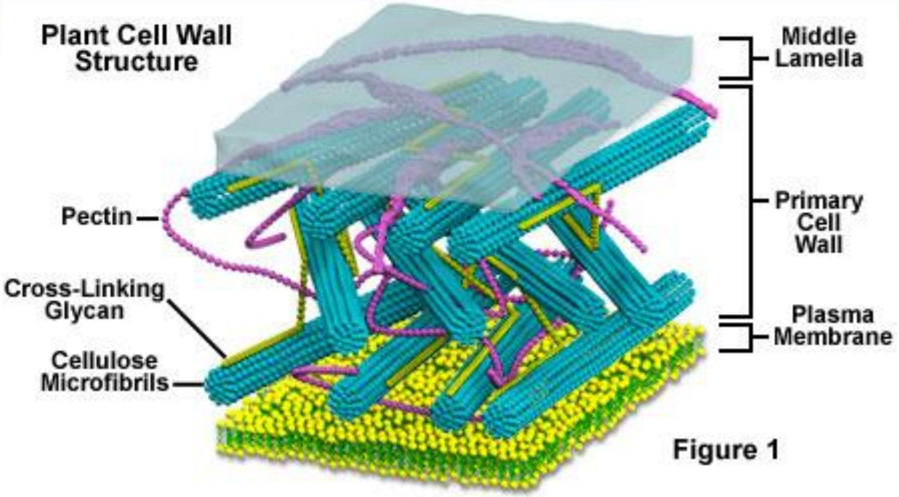


2nd Generation fuels: Utilize non-food feedstocks, not yet commercialized

2nd Generation biofuels rely on non-caloric polymers of glucose

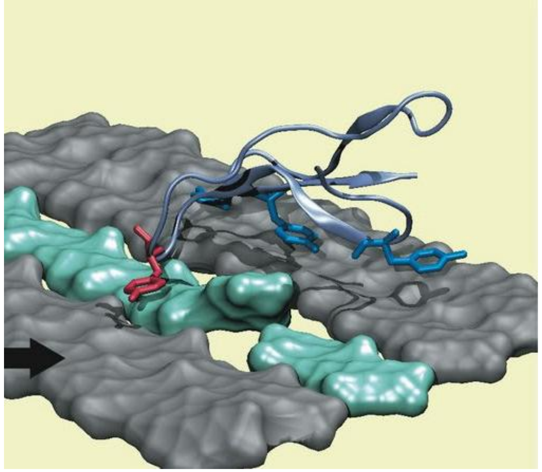
Recalcitrant cell walls make conversion to sugars complex

Non-carbohydrate components significant



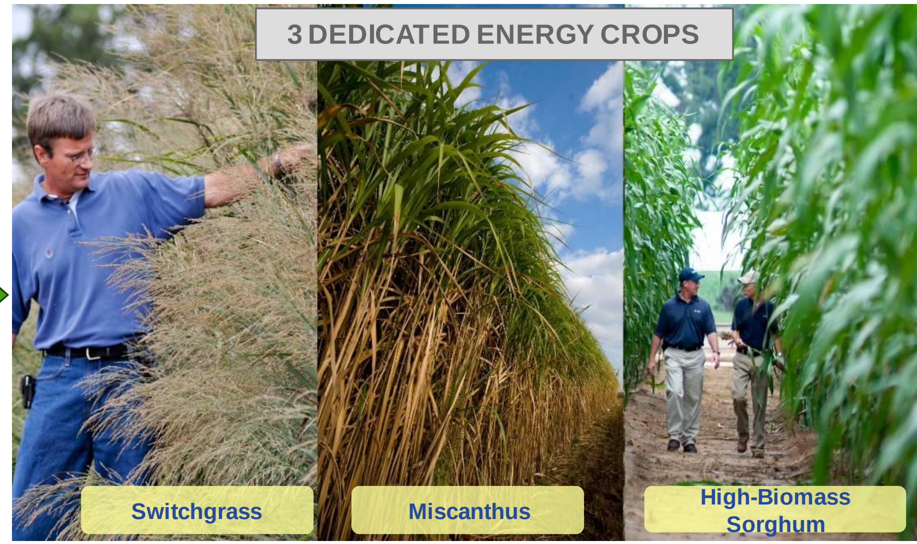
Primary research focii:

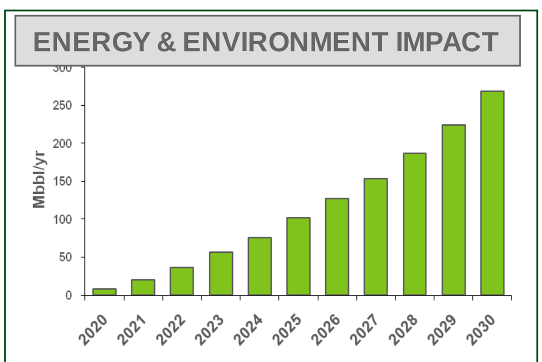
-Lignocellulose deconstruction
-Catalysts for pyrolysis
-Feedstock management

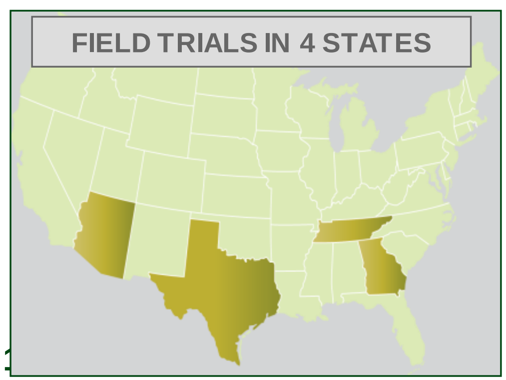


Developing high biomass dedicated energy crops with increased nitrogen use efficiency

Team Lead	Ceres – Thousand Oaks, CA	Project Budget	$6,116,430	POP	1/1/2010 - 12/31/2012 (36)



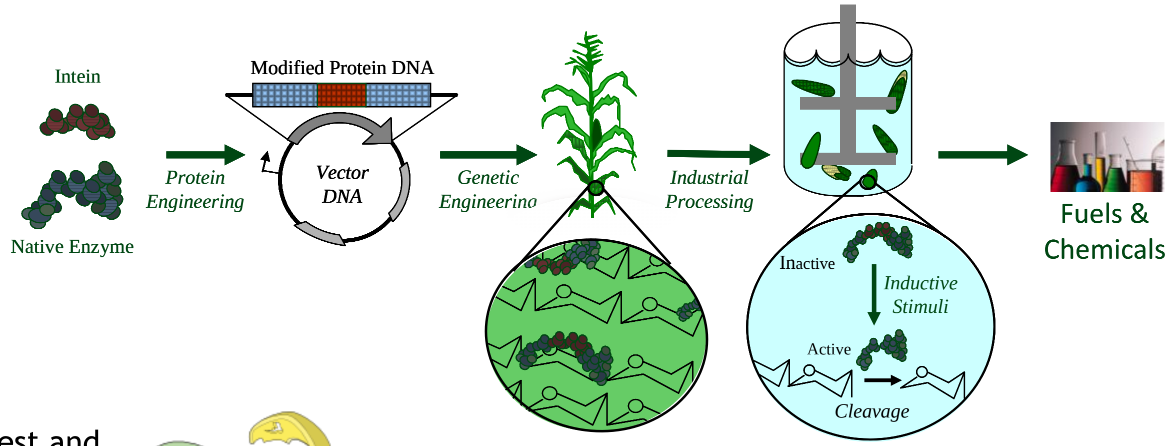


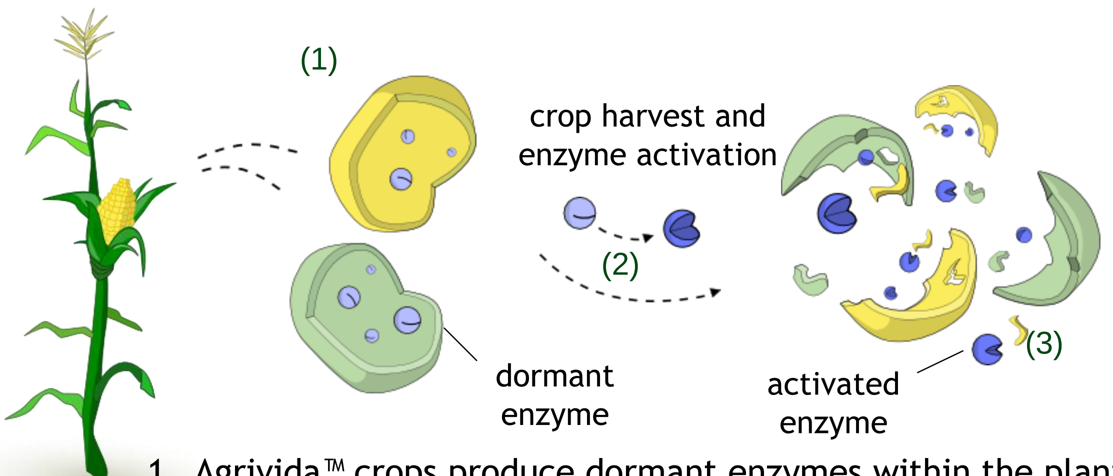


Intein-modified pro-enzymes which can be conditionally activated within plant biomass

Team Lead	Agrivida - Medford, MA	Project Budget	$5,707,250	POP	1/15/2010 - 1/14/2012 (24)

Molecular biology discovery platform





1. Agrivida™ crops produce dormant enzymes within the plant.
2. The dormant enzymes are activated after harvest.
3. The activated enzymes degrade the cell wall.

Macroalgae and biobutanol technology combined provide a sustainable biofuel

Team Lead	DuPont – Wilmington, DE	Project Budget	$17,769,396	POP	2/26/2010 - 2/25/2012 (24)

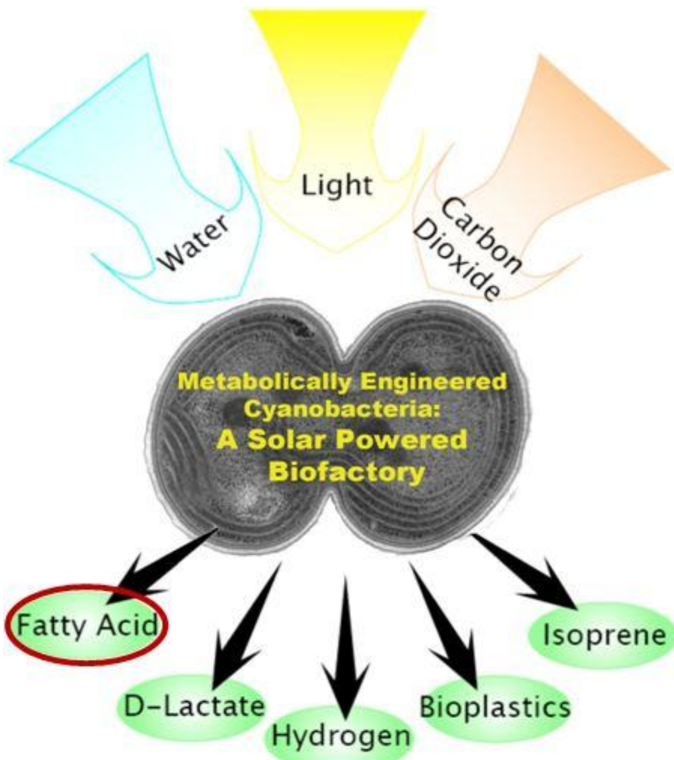
Approach:
- Technoeconomic Feasibility
- Biocatalyst Feasibility
- Commercialization via Butamax™ Advanced Biofuels (a DuPont/BP Joint Venture)

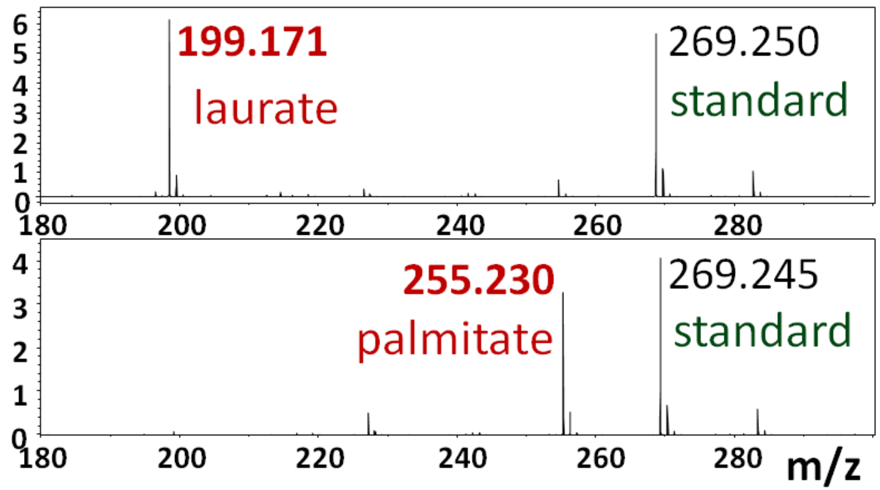
Seaweed:
- Scalable production
- Potential to reduce GHG emissions by >90% compared to petroleum based fuels
- Grown at large scale today

Biobutanol:
- Can be produced from a range of feedstocks
- Compatible with current infrastructure
- Physical properties which create value throughout the fuels supply chain
- Can be blended at 16% in gasoline

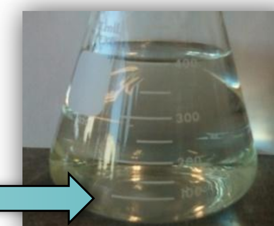
Cyanobacteria Designed for Solar-Powered Highly Efficient Production of Biofuels

Team Lead	Arizona State Univ. – Tempe, AZ	Project Budget	$6,509,931	POP	1/1/2010 - 12/31/2011 (24)





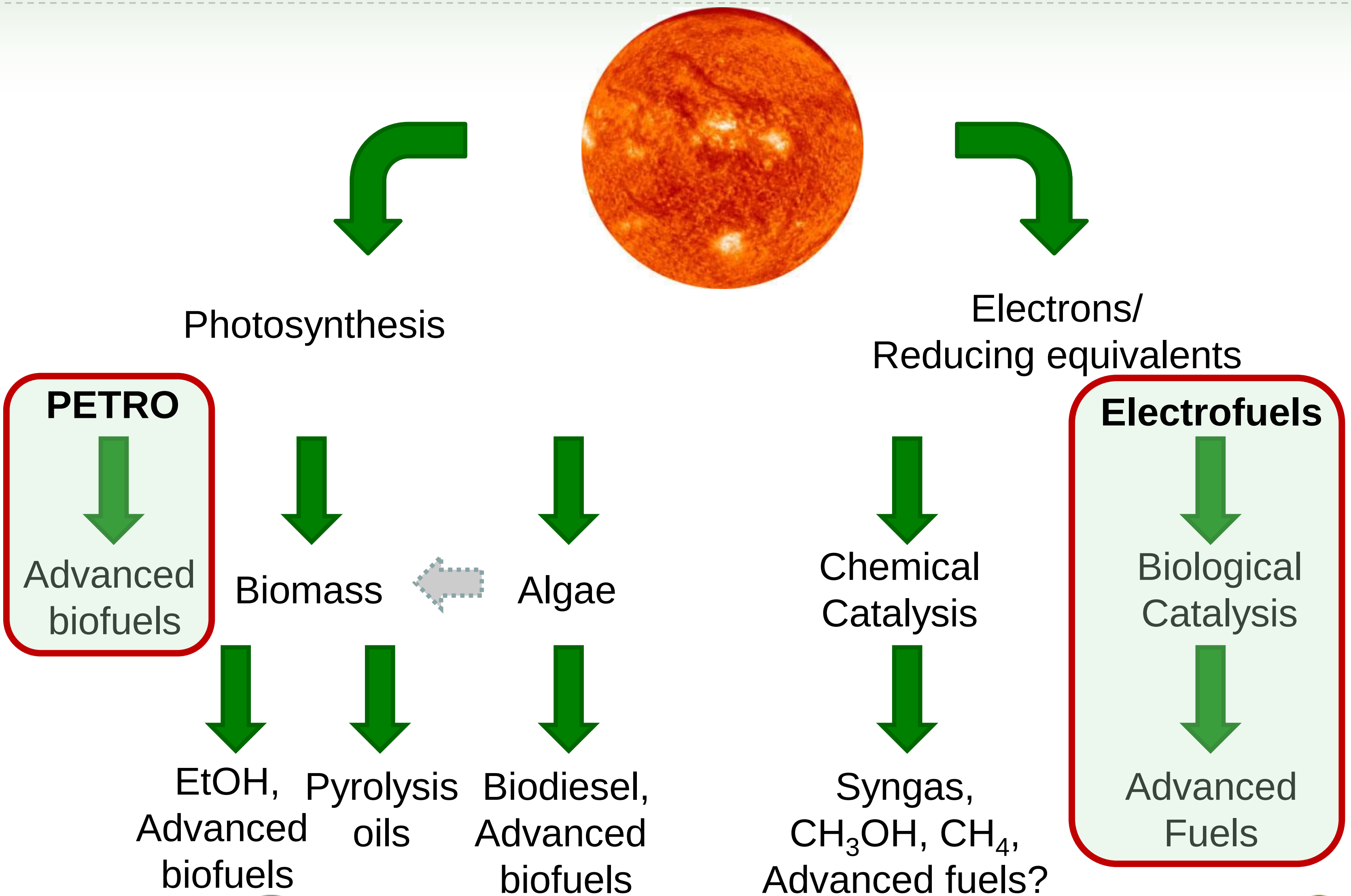
1. Harvest
2. Decarboxylate
3. Isomerize



Cyanobacteria + laurate

Jet Fuel

ARPA-E is funding biofuels which are fundamentally different from current approaches



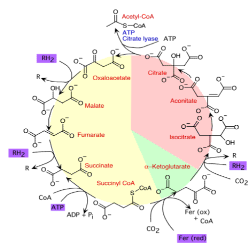
Electrofuels approach is non-photosynthetic, modular, and solutions can be mixed- and- matched

Assimilate Reducing Equivalents

Reducing equivalents: *other than reduced carbon or products from Photosystems I & II*

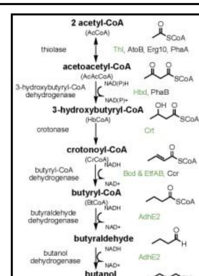
H_2S H_2 Direct Current NH_3 Fe^{2+}

Fix CO_2 for Biosynthesis



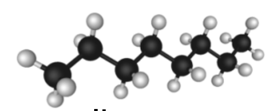
Pathway for carbon fixation: *reverse TCA, Calvin- Benson, Wood-Ljungdahl, hydroxpropionate/hydroxybutyrate, or newly designed biochemical pathways*

Generate Energy Dense Liquid Fuel



Fuel synthesis *metabolic engineering to direct carbon flux to fuel products*

butanol

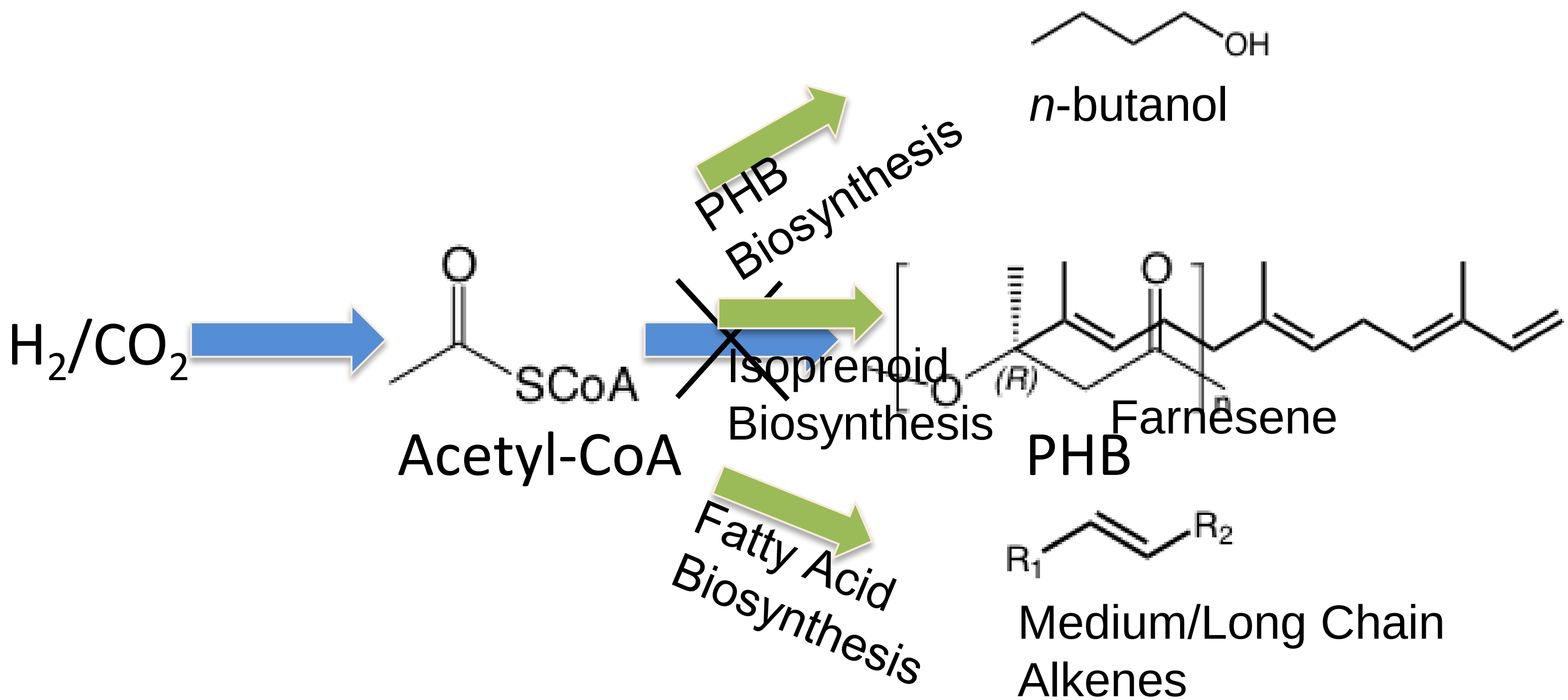


alkanes

+ numerous possibilities

Engineering *Ralstonia* to produce butanol

Team Lead	LBNL; Berkeley, CA	Project Budget	$5.0 Million	POP	7/16/2010 - 7/12/2013 (36)

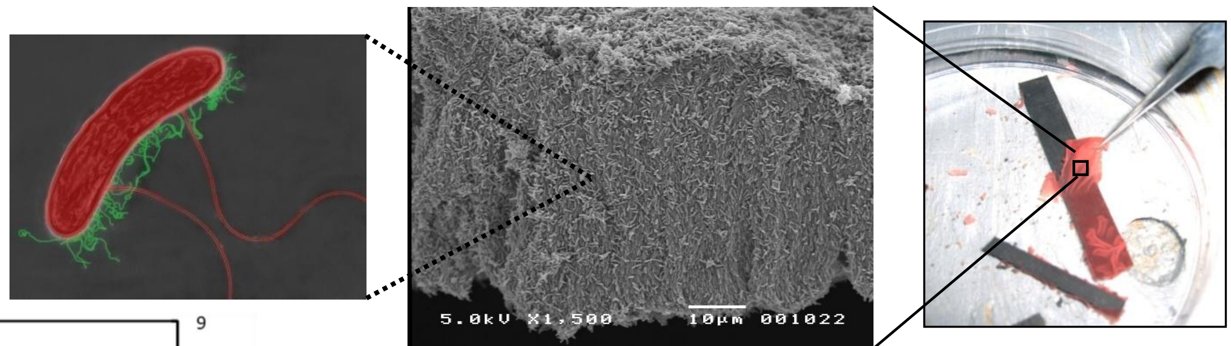


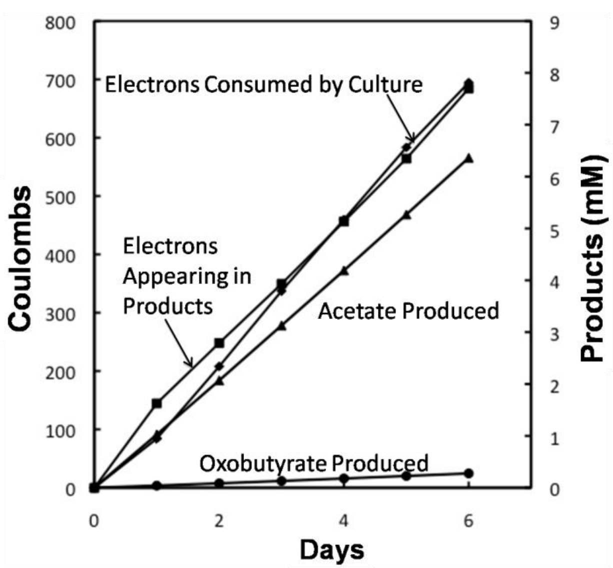
Carbon flux to PHB synthesis will be diverted to produce butanol, fatty-acid derived alkenes and isoprenoids from H_2/CO_2

Direct electron transfer: leveraging the ability of some microbes to make electrical contacts with electrodes

Team Lead	U. of Massachusetts; Amherst, MA	Project Budget	$4.1 Million	POP	7/01/2010 - 7/01/2013 (36)

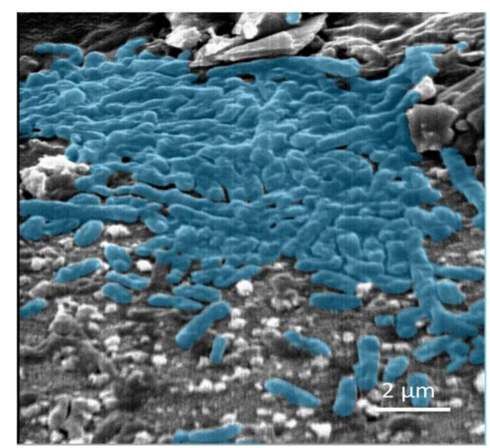
Geobacter metallireducens can form conductive biofilms on the surface of electrodes





Acetogenes such as *Sporomusa ovata* have demonstrated the ability to produce acetate directly from electrons with high coulombic efficiency

Clostridium ljungdahlii will be engineered to produce butanol from electrcity

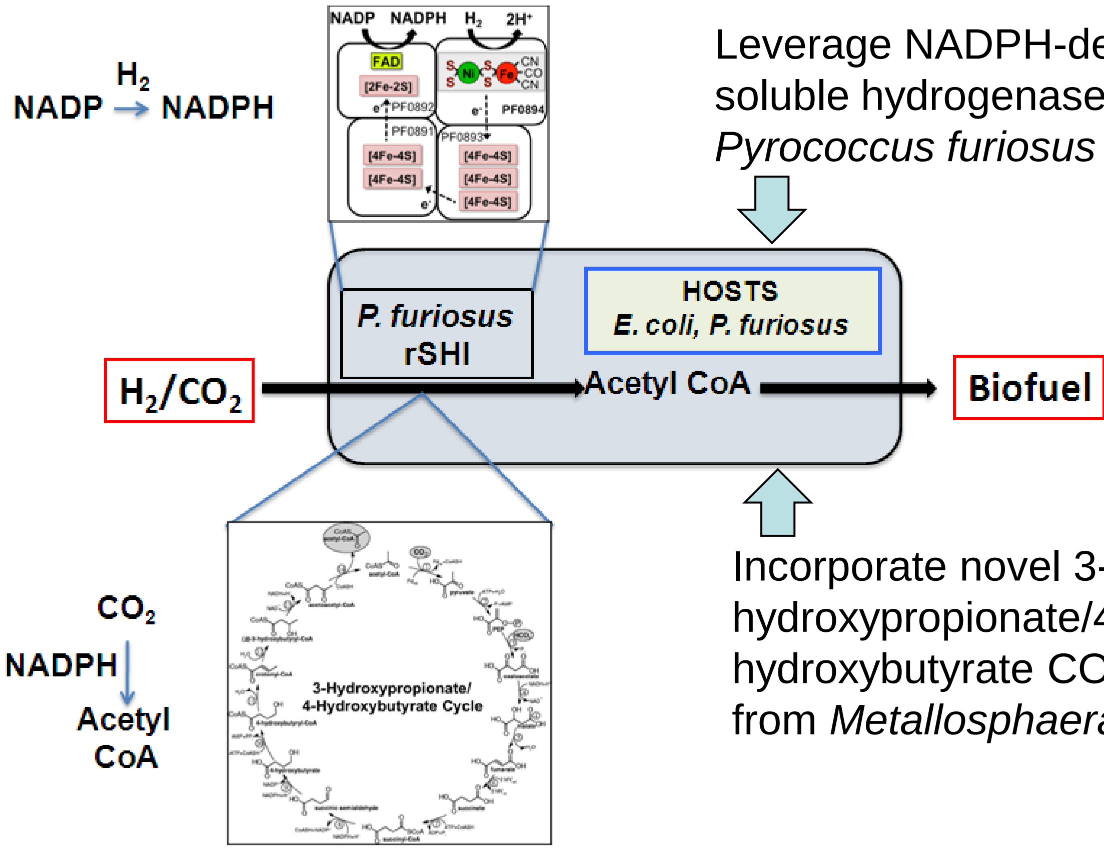


Transferring novel CO_2 fixation enzymes to convert heterotrophs into autotrophs

The University of Georgia

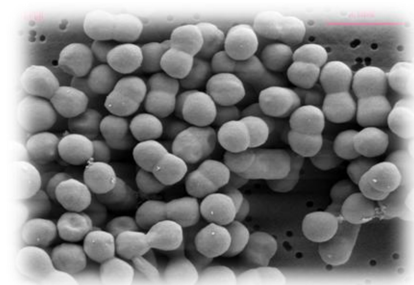
NC STATE UNIVERSITY

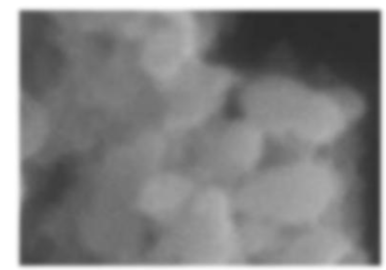
Team Lead	North Carolina State U.; Raleigh, NC	Project Budget	$3.3 Million	POP	7/01/2010 - 6/23/2013 (36)



Leverage NADPH-dependent soluble hydrogenase activity from *Pyrococcus furiosus*

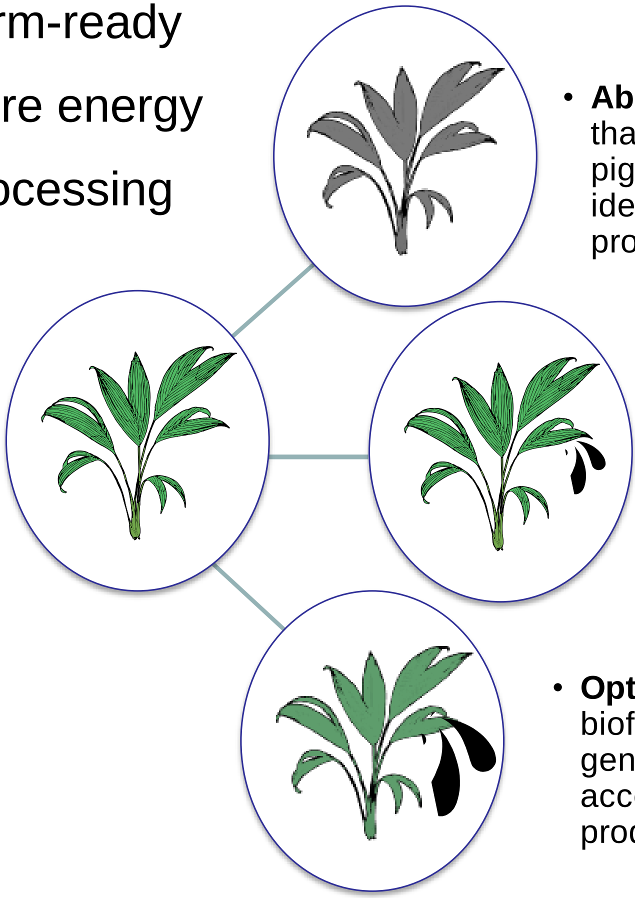
Incorporate novel 3-hydroxypropionate/4-hydroxybutyrate CO_2 fixation cycle from *Metallosphaera sedula*





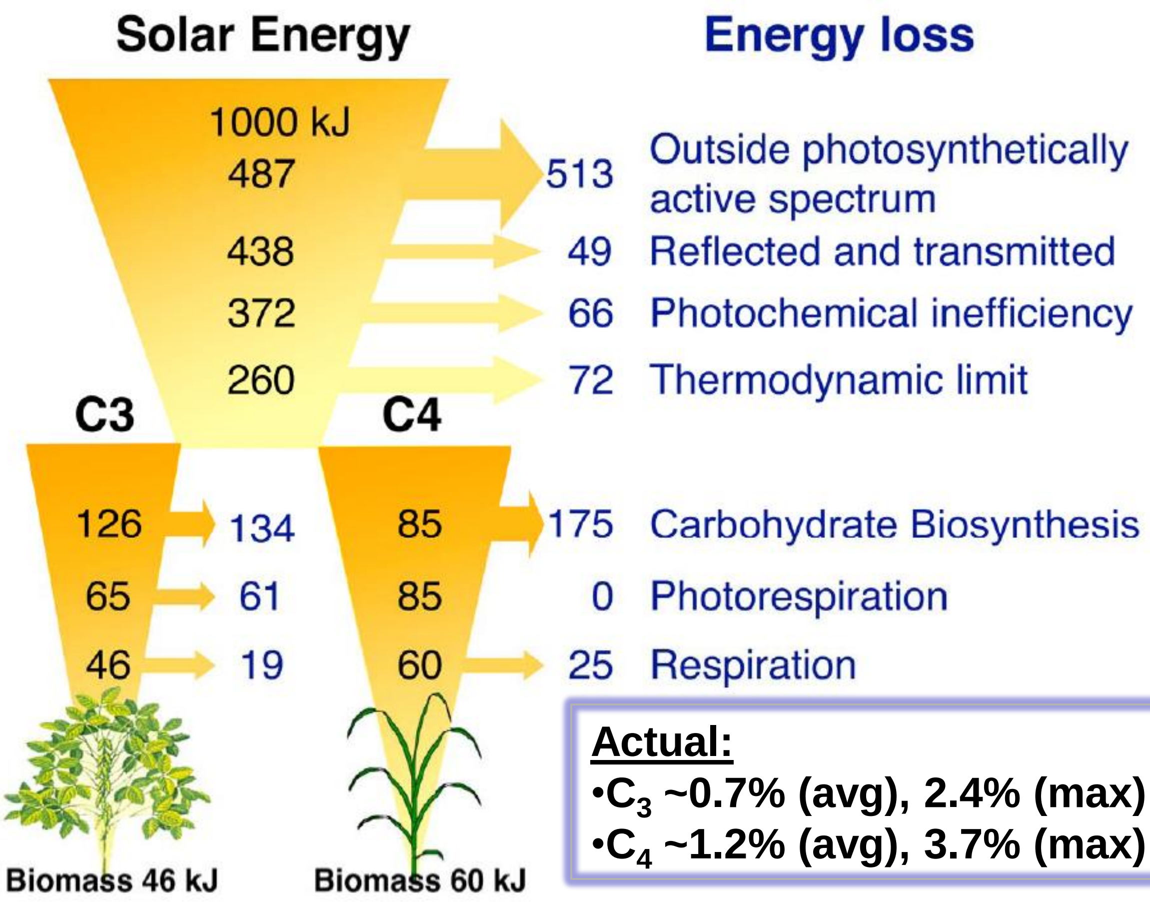
ARPA-E will soon announce awards for PETRO – Plants Engineered to Replace Oil

PETRO aims to create plants that capture more energy from sunlight and convert that energy directly into fuels. ARPA-E seeks to fund technologies that optimize the biochemical processes of energy capture and conversion to develop robust, farm-ready crops that deliver more energy per acre with less processing prior to the pump.



- **Absorption:** Ordinary photosynthesis uses less than half of the incident light energy. Biological pigments that absorb more energy have been identified, but have not used in biofuel production.
- **Metabolism:** Currently, biofuels are fermented from biologically created materials. The two biological processes are able to be combined into a single process to generate fuel directly.
- **Optimization:** A dedicated source of biofuel is an agricultural crop. Rapid genetic selection can be used to accelerate the development of viable production strains.

Motivation for PETRO: Losses in Biofuels



Actual:

- C_3 ~0.7% (avg), 2.4% (max)
- C_4 ~1.2% (avg), 3.7% (max)

(4.6%) **(6.0%)**

Zhu et al. *Current Opinion in Biotechnology* (2008) 19:153-159

Photosynthesis:

$$CO_2 + H_2O \Rightarrow C_6H_{12}O_6$$

Fermentation:

$$C_6H_{12}O_6 \Rightarrow 2CO_2 + 2\ C_2H_5OH$$

One third of the carbon captured is *not* converted into fuel.

In many regimes, carbon is *a limiting reagent*

Crops and fuels can be evaluated based on carbon incorporation for normalization

Table 1: Carbon flux from atmospheric CO_2 for current biofuel crops

[NOTE: Only carbon is counted as part of weight.]

	Maximum Photosynthetic Rate A_n 50 $t_C \cdot ha^{-1} \cdot y^{-1}$ [10] [based on carbon, mw=12]					
	Maize (*Midwest*) [11, 12, 13, 14, 15]		Soybean (*Midwest*) [11, 16, 17, 18, 19, 20, 21]		Sugarcane (*LA, TX, FL*) [22, 23, 24, 25, 26]	
	$t_C \cdot ha^{-1} \cdot y^{-1}$	Yield	$t_C \cdot ha^{-1} \cdot y^{-1}$	Yield	$t_C \cdot ha^{-1} \cdot y^{-1}$	Yield
Captured	7.7	15%	3.1	6.3%	24.	48.%
Harvested	3.9	7.8%	1.3	2.5%	16.	32.%
Purified	2.7	5.4%	0.38	0.77%	7.7	15.%
Processed	1.5	3.0%	0.34	0.69%	4.0	8.0%
Final Energy Content ($GJ \bullet t_C^{-1}$)	52 (Ethanol)		50 (FAME)		52 (Ethanol)	
Overall Fuel Yield ($GJ \bullet ha^{-1} \bullet y^{-1}$)	79		17		207	

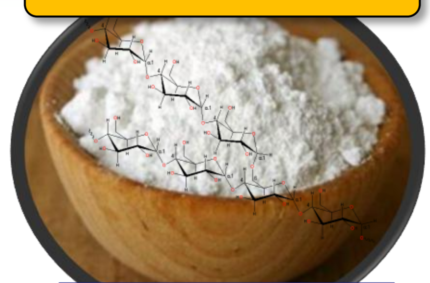
- Treats problem as organic synthesis, *not* thermodynamics
- Narrow range of “energy content” with carbon denominator
  - gasoline 54 $GJ \cdot t_C^{-1}$
  - methane 66 $GJ \cdot t_C^{-1}$

PETRO will produce crops capable of producing twice the energy yield of corn ethanol.

HARVESTED

3.9 $t_C \cdot ha^{-1} \cdot y^{-1}$

PURIFIED



2.7 $t_C \cdot ha^{-1} \cdot y^{-1}$

CAPTURED

7.7 $t_C \cdot ha^{-1} \cdot y^{-1}$

PROCESSED

1.5 $t_C \cdot ha^{-1} \cdot y^{-1}$

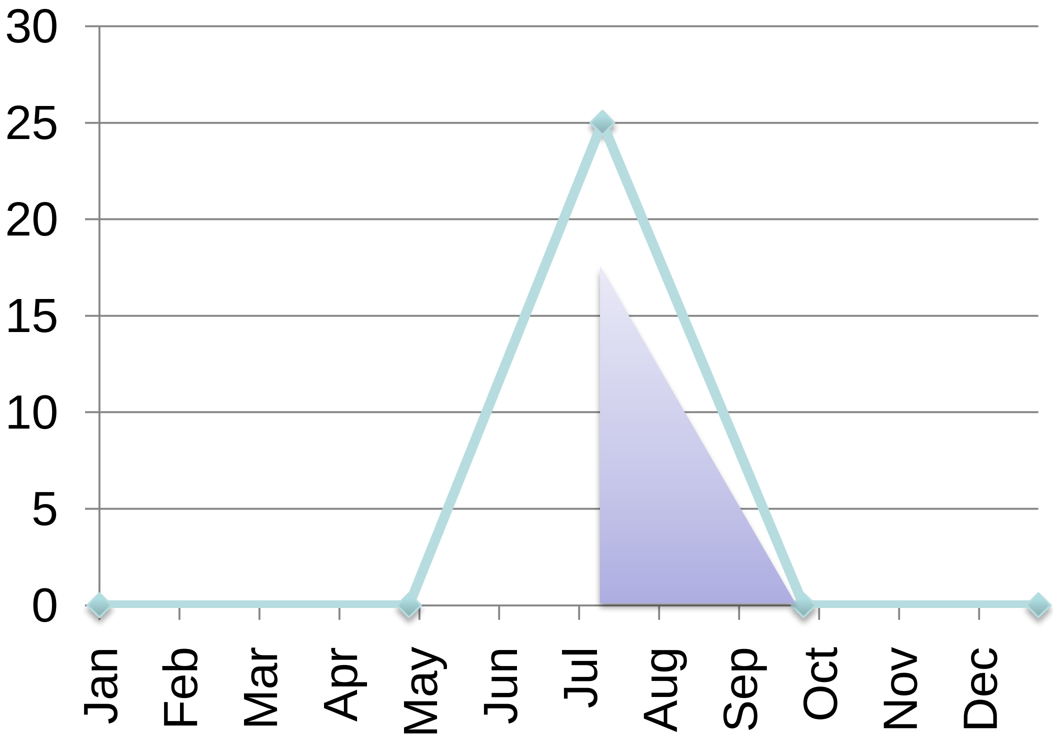
EtOH Energy Content: 52 $GJ \cdot t_C^{-1}$

Overall Carbon Yield
3.0 %

Overall Fuel Yield
79 $GJ \cdot ha^{-1} \cdot y^{-1}$

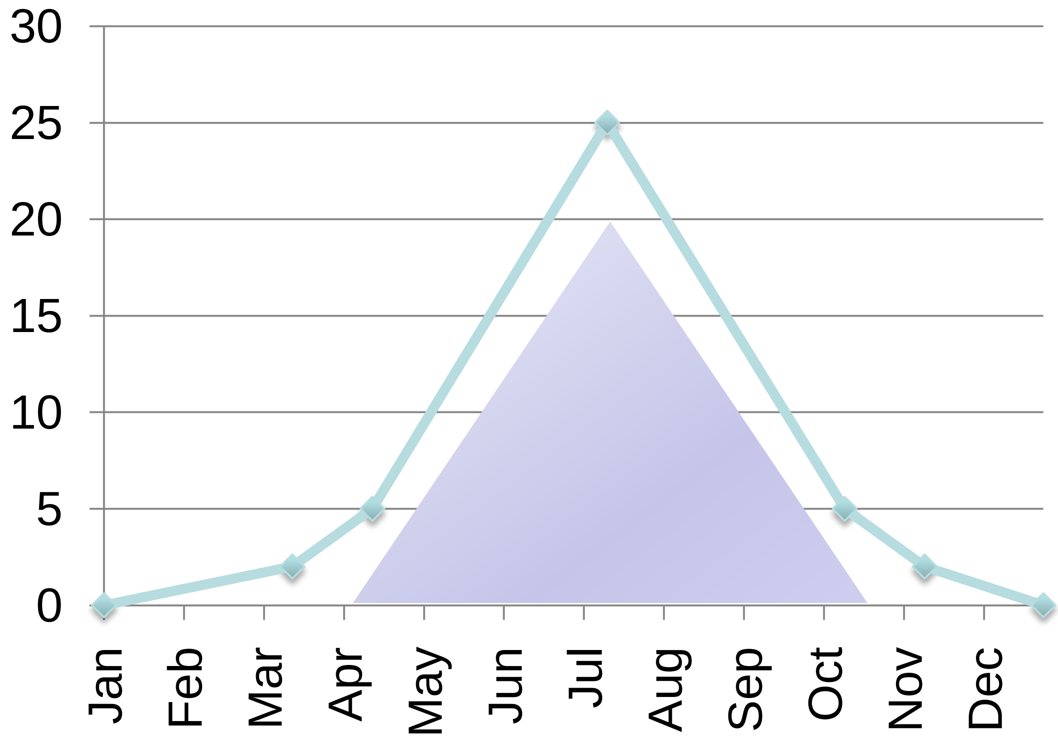
Photosynthetic energy utilized for existing biofuel production

Corn begins storing energy as starch, the precursor to ethanol, mid-way through its life cycle.



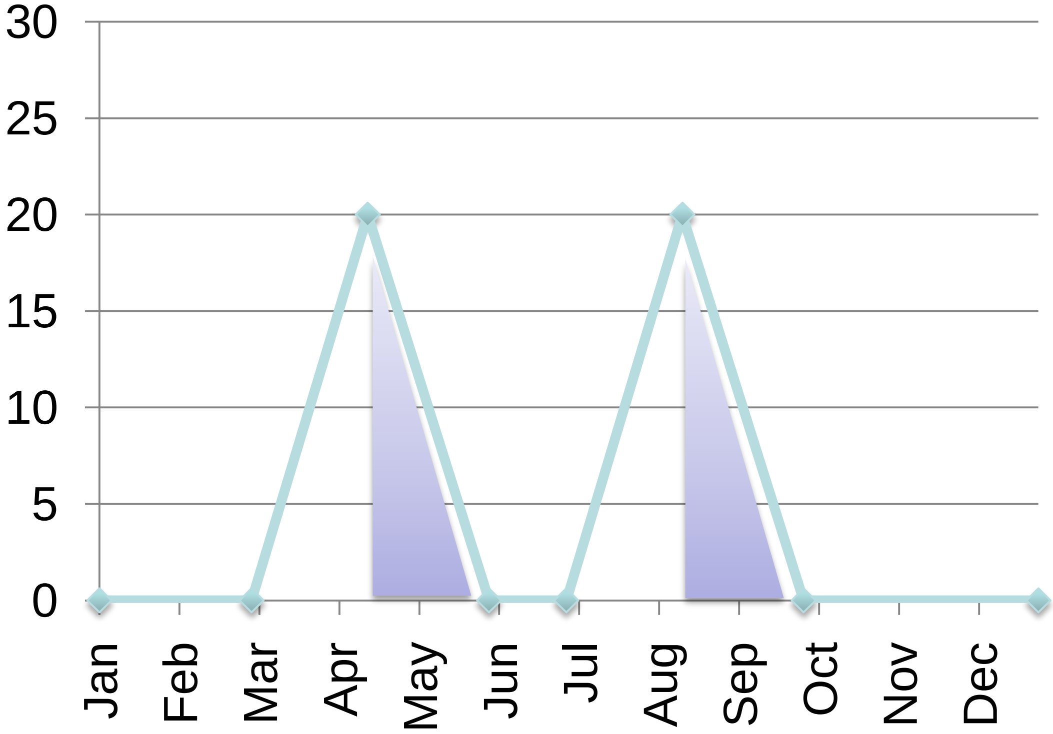
Photosynthetic energy utilized for next generation biofuel production

PETRO grasses will be engineered to produce fuel molecules throughout the life of the crop.



Photosynthetic energy utilized for next generation biofuel production

PETRO oilseed crops will be engineered to grow faster and incorporate more carbon into fuel molecules.



PETRO Program Metrics

- **Generate an innovative organism that:**
  - Is suited to the North American climate
  - Produces a **liquid fuel** directly from an agricultural process
  - Has a **per-acre** energy yield that is twice that of CBE
  - Uses primarily **atmospheric [CO_2]** as a C source
  - Can be **field-demonstrated in 3 years** (TRL 5-7 @ end)

- **The fuel:**
  - Has an energy density no less than isobutanol (≥ 26.5 MJ/L LHV)

- **The process cost at scale must be:**
  - ≤ $10/GJ fuel ($50/BOE), following a CBE financial model