CHANGING WHAT'S POSSIBLE

ARPA-E Overview & Bioenergy Update

to U.S. Biomass R&D Technical Advisory Committee

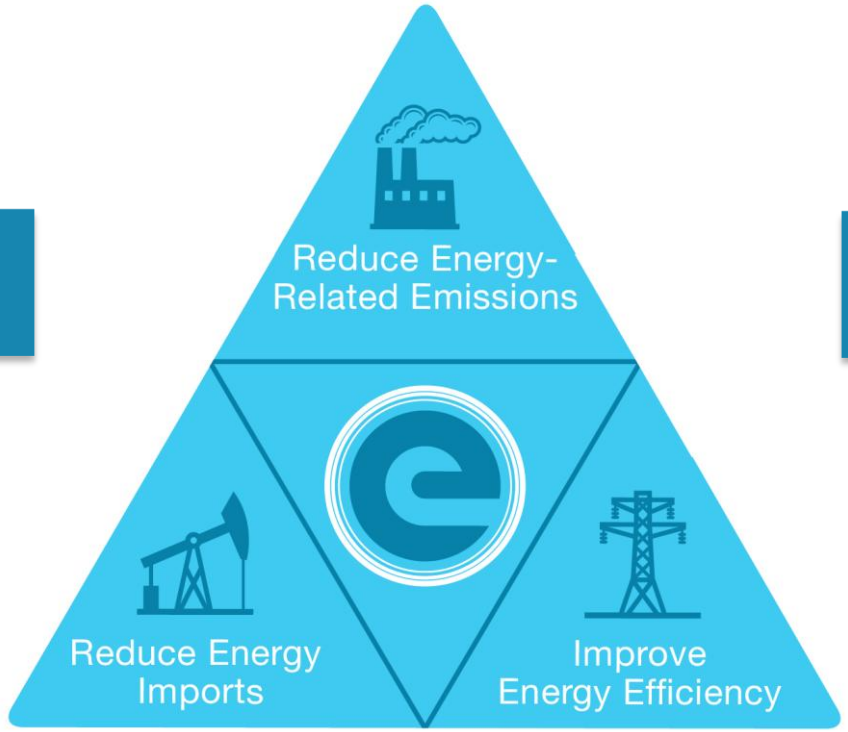
Chad Haynes

March 20, 2013

ARPA-E Mission

Catalyze the development of transformational, high-impact energy technologies

Promoting revolutionary advances in fundamental sciences



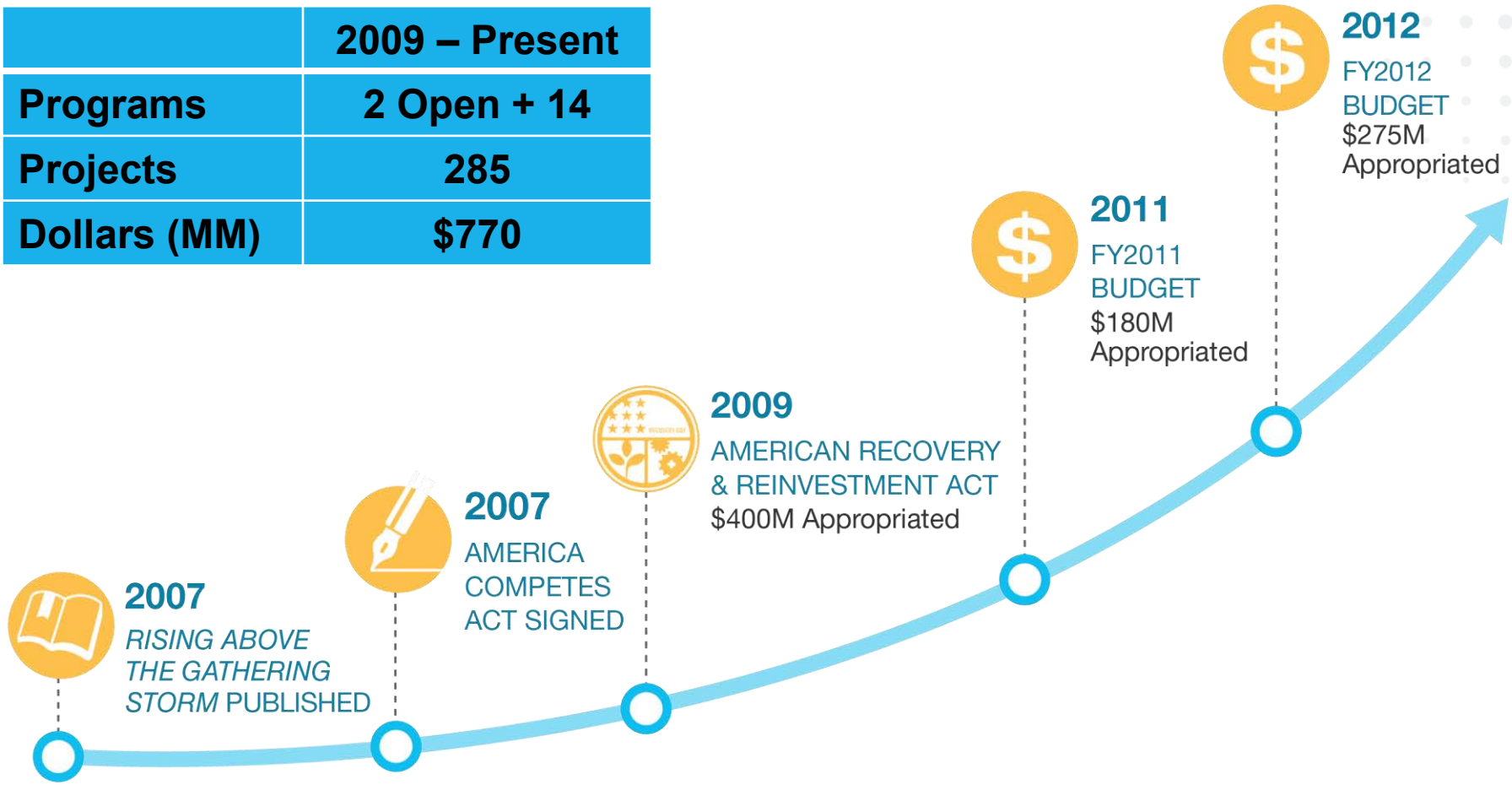
Translating scientific discoveries into technological innovations

Ensure the U.S. maintains a lead in the development and deployment of advanced technologies

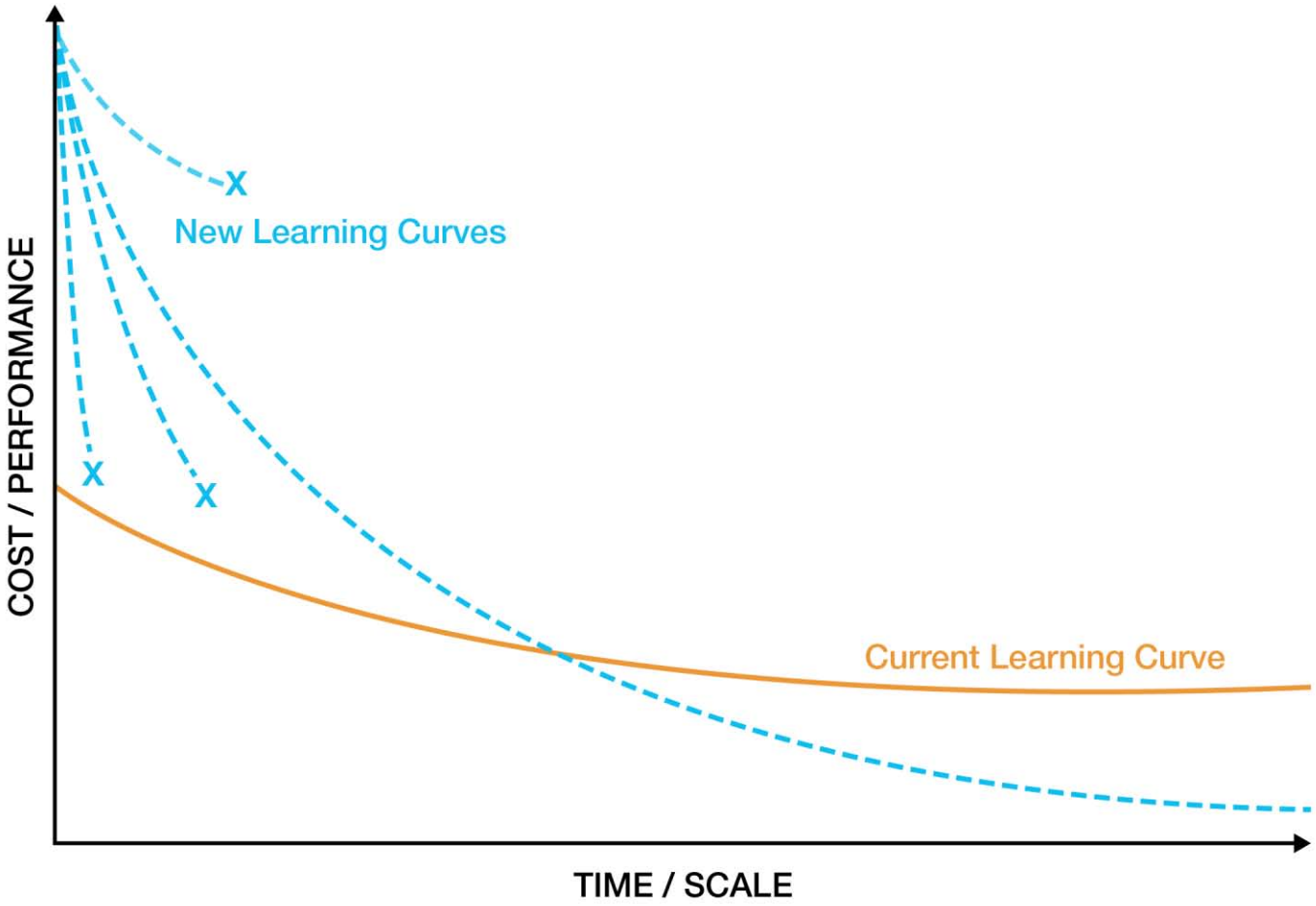
Accelerating transformational technological advances in areas that industry by itself is not likely to undertake

Evolution of ARPA-E

	2009 – Present
Programs	2 Open + 14
Projects	285
Dollars (MM)	$770



Creating New Learning Curves



What Makes an ARPA-E Project?

IMPACT

- High impact on ARPA-E mission areas
- Credible path to market
- Large commercial application

TRANSFORM

- Challenges what is possible
- Disrupts existing learning curves
- Leaps beyond today's technologies

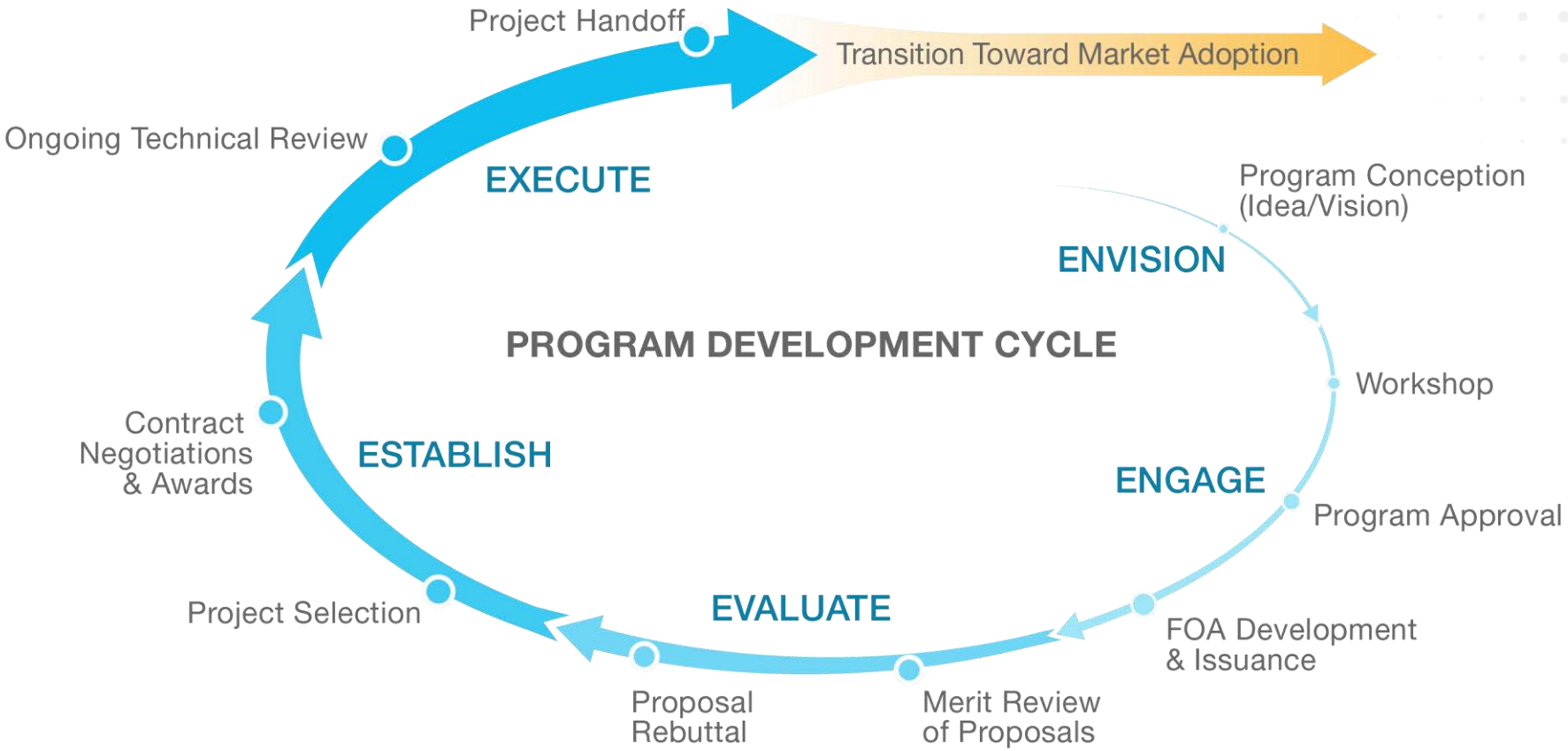
BRIDGE

- Translates science into breakthrough technology
- Not researched or funded elsewhere
- Catalyzes new interest and investment

TEAM

- Comprised of best-in-class people
- Cross-disciplinary skill sets
- Translation oriented

Technology Acceleration Model



Measuring ARPA-E's Success

MOVING TECHNOLOGY TOWARD MARKET

- Partnerships with Other Government Agencies
- Licensing/Acquisition by an Established Firm
- Licensing/Acquisition Resulting in a Spinoff
- Private-Sector Funding
- Growth of Existing Company (e.g., Organic Growth)

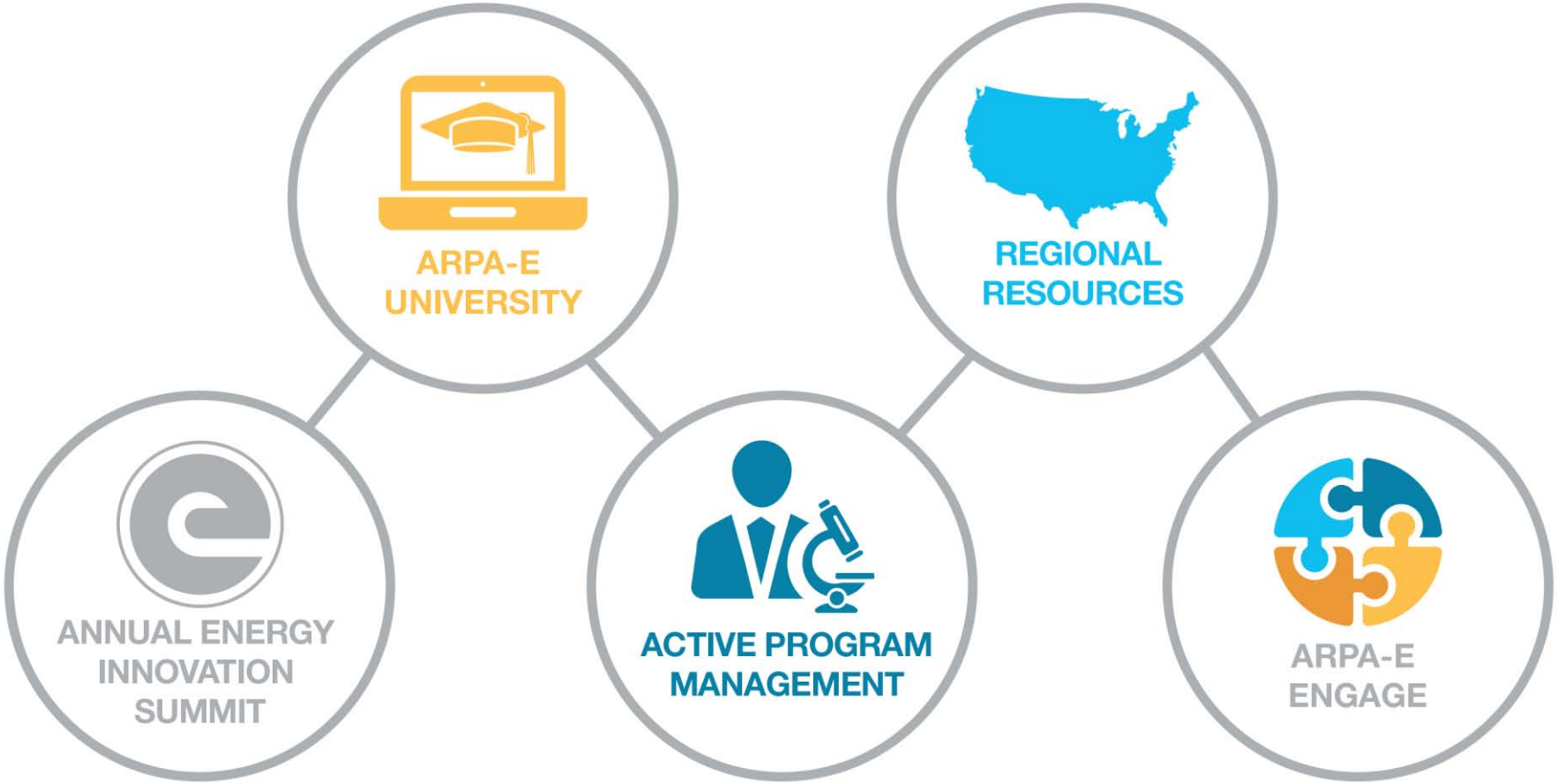
BREAKTHROUGH ACHIEVEMENTS

- Patents
- Publications

OPERATIONAL EXCELLENCE

- Expedited program development and project selection
- Aggressive performance metrics

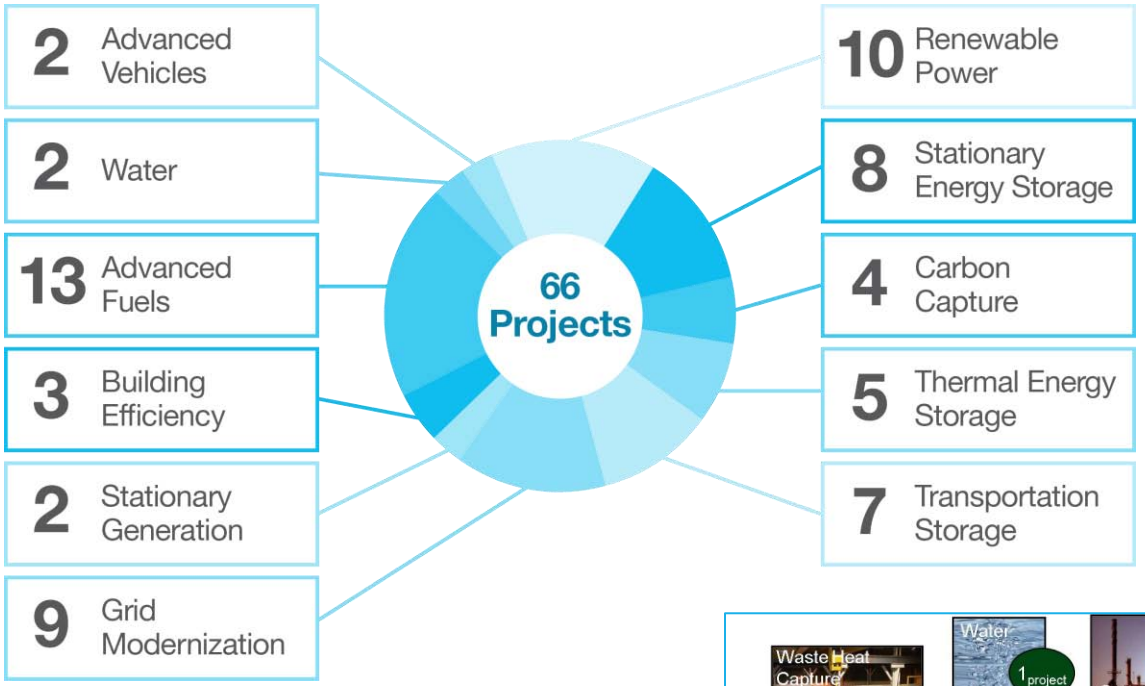
ARPA-E Resources

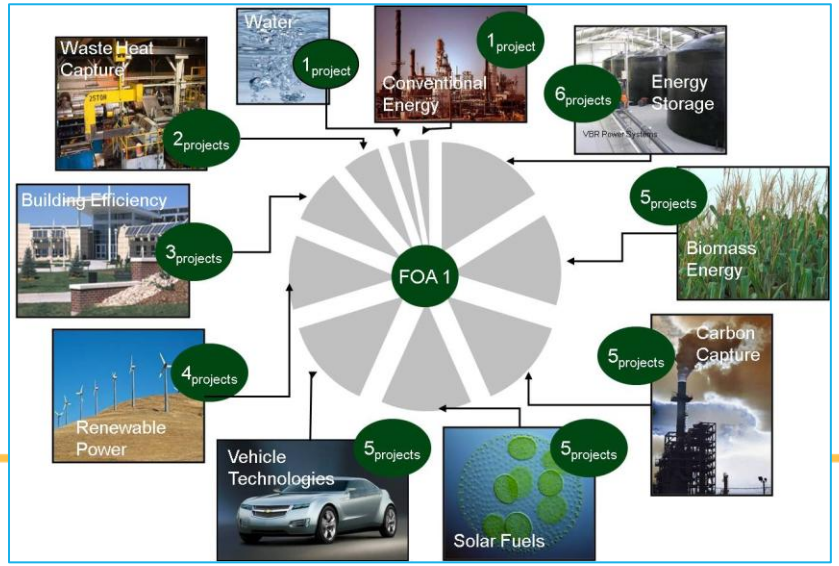


What is “Active Program Management”?

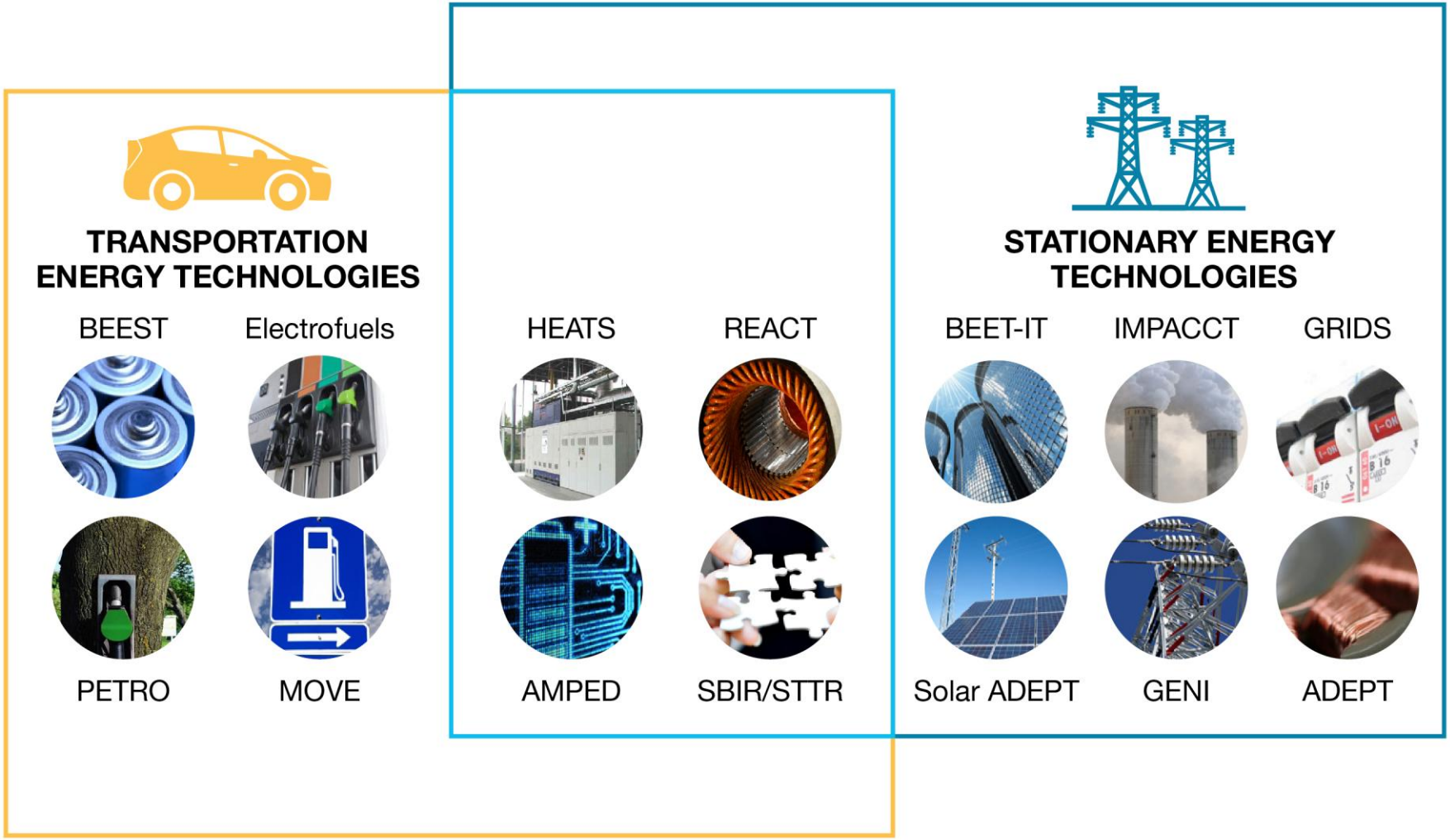
- Cooperative Agreements (vs. Grants) enable substantive involvement by the U.S.G.
- Contractually binding technical milestones are reported on quarterly and closely observed
- Site visits to R&D location for all-hands meetings twice a year
- T2M activities
- Contract modifications, plus-ups, and shut-downs

OPEN 2012: 66 Projects, 24 States, 11 Areas

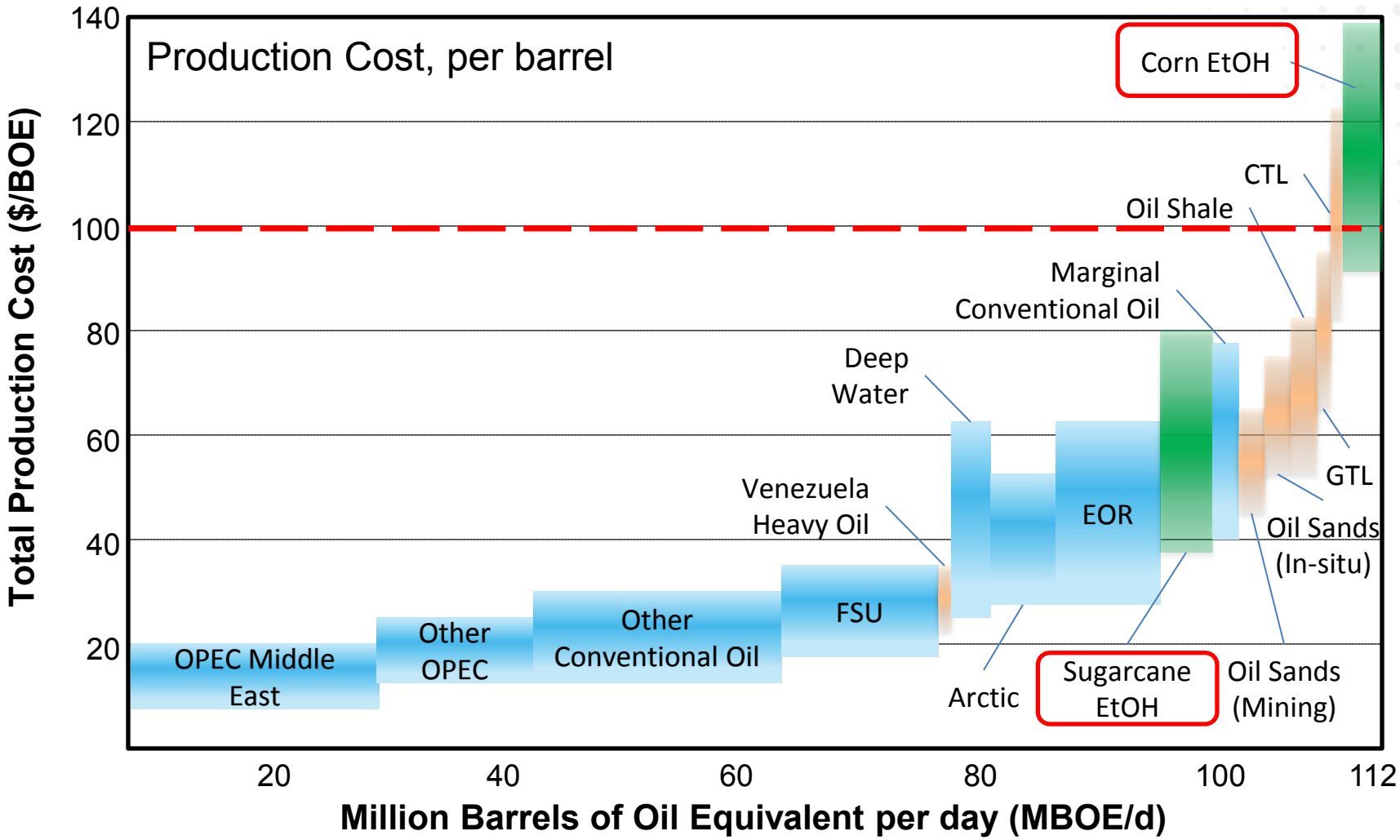




Focused Programs



Biofuels are an attractive alternative to fossil-based liquid fuels but production costs are a tough nut to crack



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

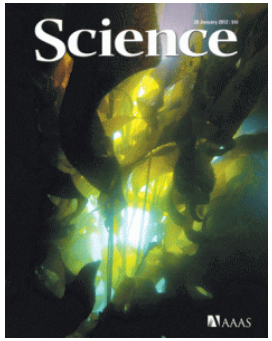
New technologies are required to drive cost reductions

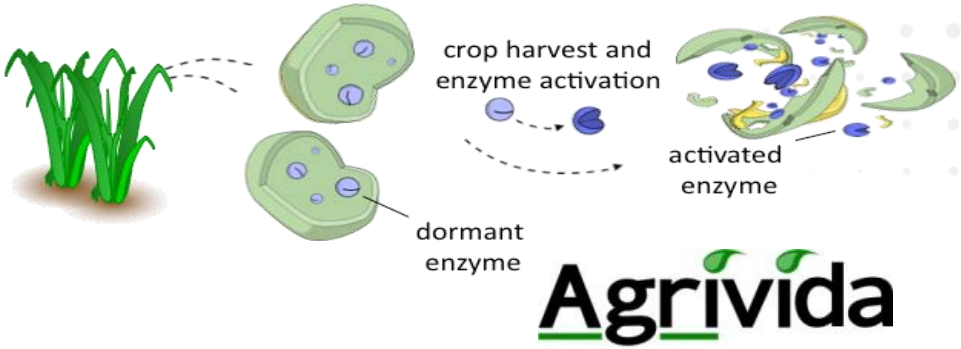
- Feedstocks improvements (non-commodity “crops”)
- Increase energy density of bioenergy crops
- Process improvements
- New processes

Feedstock R&D(&D)

bio architecture lab

DUPONT





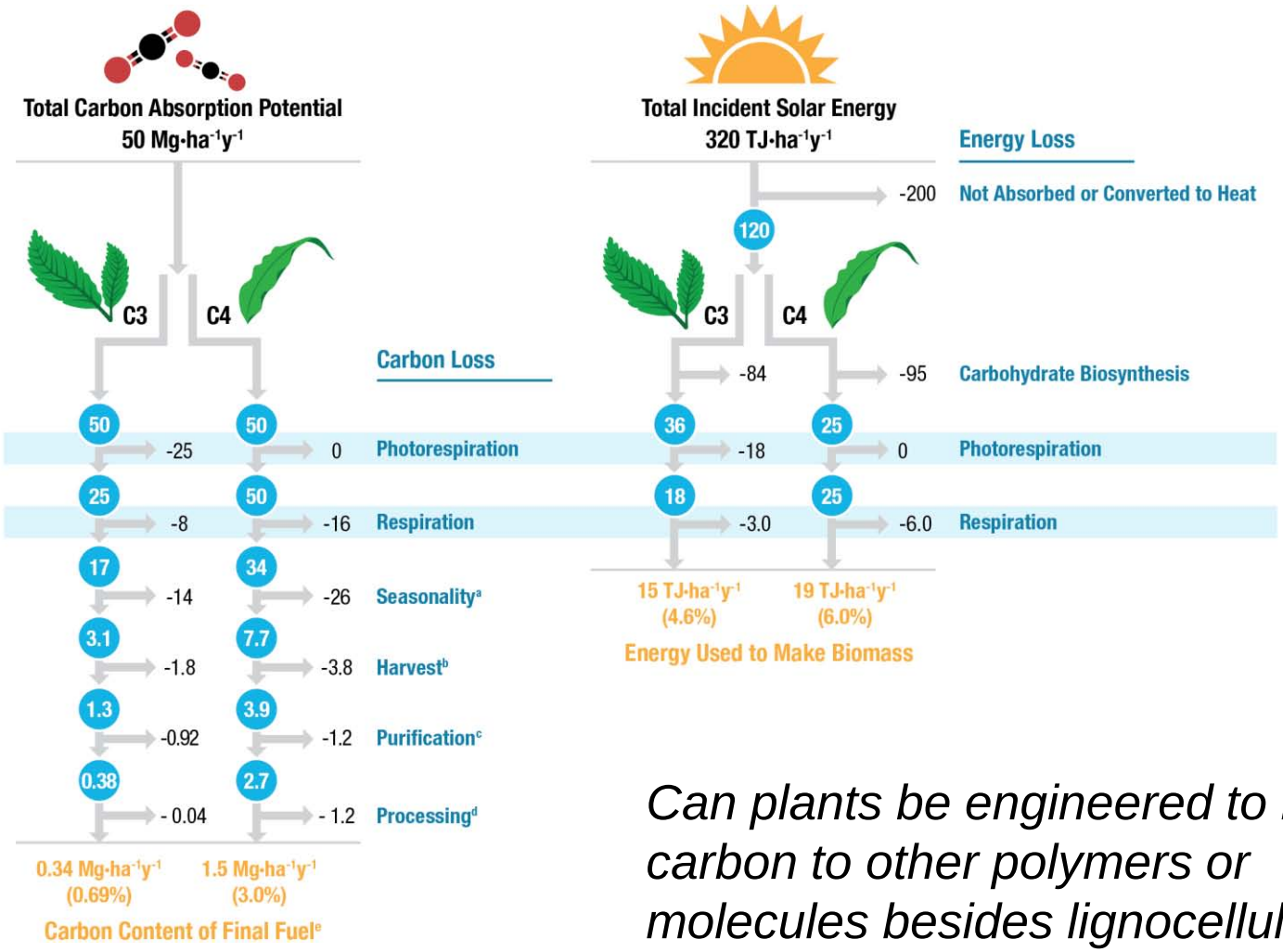
Agrivida

ceres

ASU
ARIZONA STATE UNIVERSITY

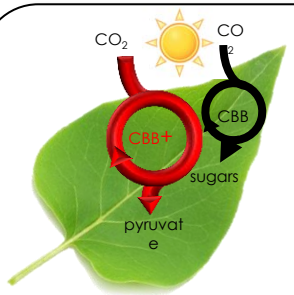
BIOCEE

Current pathways for liquid fuels from plants are inefficient

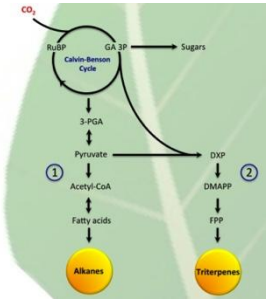


Can plants be engineered to move carbon to other polymers or molecules besides lignocellulose?

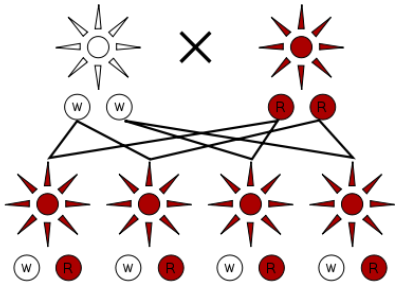
PETRO strategies to develop dedicated biofuel crops



Photosynthesis Optimization



Metabolic engineering



Heritable Traits

Yield: 160 GJ•ha^{-1}•y^{-1} (2x corn)
Cost: < $3 GGE

Plants being developed under PETRO

C_4 Grasses

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

(sugarcane, sorghum)

Arcadia BIOSCIENCES

(*Setaria*➔sorghum)

Chromatin, Inc.

(sorghum)

UCLA

(*Arabidopsis*➔Switchgrass/Camelina)

Oilseed

DONALD DANFORTH PLANT SCIENCE CENTER

NC STATE UNIVERSITY

UMASS AMHERST

(Camelina)

Trees

UF UNIVERSITY of FLORIDA

(loblolly pine)

Other

BERKELEY LAB

(tobacco)

Chromatin, Inc.

(Guayule)

TEXAS A&M UNIVERSITY

(tobacco➔Giant cane)

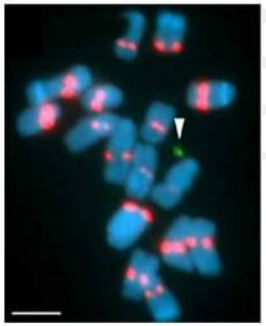
2012 - 2015
$36M, 36 months
10 projects

Producing hydrocarbons in sweet sorghum

- Sweet sorghum will be engineered to produce hydrocarbons instead of sugar.

- The fuel molecules can readily be solvent extracted from the crushed biomass.

- The engineered sorghum is projected to generate over 1000 gallons of fuel per acre



Chromatin, I

THE OHIO STATE UNIVERSITY OARDC

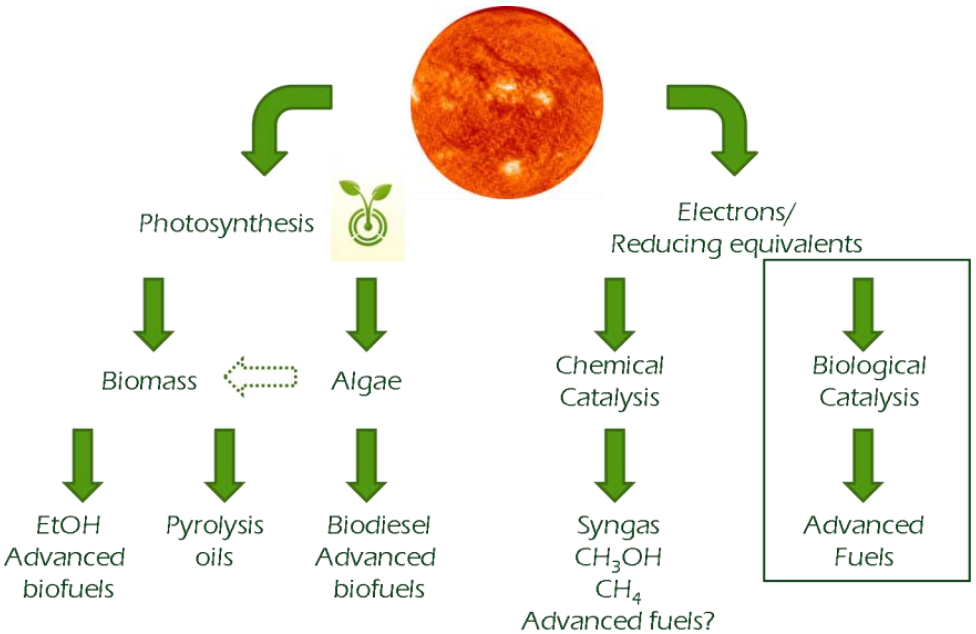
K·STATE.

Allylix

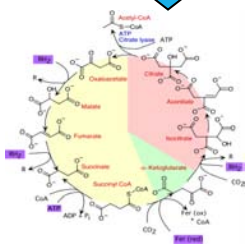
PETRO progress 1 yr in

- Launched work on a programmatic environmental impact assessment to preemptively address potential impacts of large scale deployment
- Preliminary results suggest improvements in photosynthesis efficiency
- Achieved confident analytical methods for highly accurate carbon flux measurements

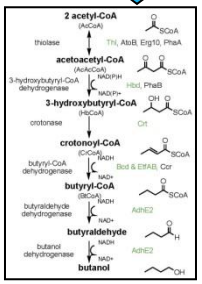
ARPA-E launched the "Electrofuels" program to address current biofuel production inefficiencies



Assimilate Reducing Equivalents: *other than reduced carbon or products from Photosystems I & II (ex. direct current, H_2, H_2S, etc.)*

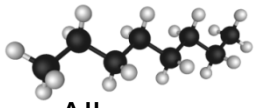


Pathways for Carbon Fixation: *reverse TCA, Calvin- Benson, Wood-Ljungdahl, Hydroxpropionate-hydroxybutyrate, or newly designed biochemical pathways*



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

Butanol



Alkanes

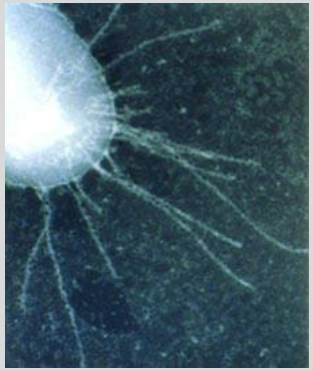
Etc.

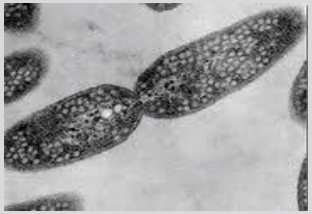
"Electrofuels" targets the first application of non-photosynthetic, autotrophic microorganisms for the production of infrastructure compatible biofuels.
13 projects, $45M ARPA-E, $56M Total

Chemolithoautotrophs are capable of assimilating energy directly from reduced inorganic compounds for CO_2 fixation

Chemoautotrophic Oxidation/ Energy Assimilation

$2H_2 + O_2 \rightarrow 2H_2O$ $\Delta G^{\circ\prime} = -474$ kJ
$2Fe(II) + 0.5O_2 + 2H^+ \rightarrow 2Fe(III) + H_2O$ $\Delta G^{\circ\prime} = -66$ kJ (pH 7)
$NH_4^+ + 1.5O_2 \rightarrow NO_2^- + 2H^+ + H_2O$ $\Delta G^{\circ\prime} = -275$ kJ
Direct current
$12HCOOH \rightarrow C_4H_{10}O + 8CO_2 + 7H_2O$ $\Delta G^{\circ\prime} = -760$ kJ





Requires development of an entirely new set of organisms for biofuel production.

NADH/NADPH and ATP + CO_2

Energy Assimilation

CO_2 Fixation (the chemical reduction of carbon to central metabolic intermediates)

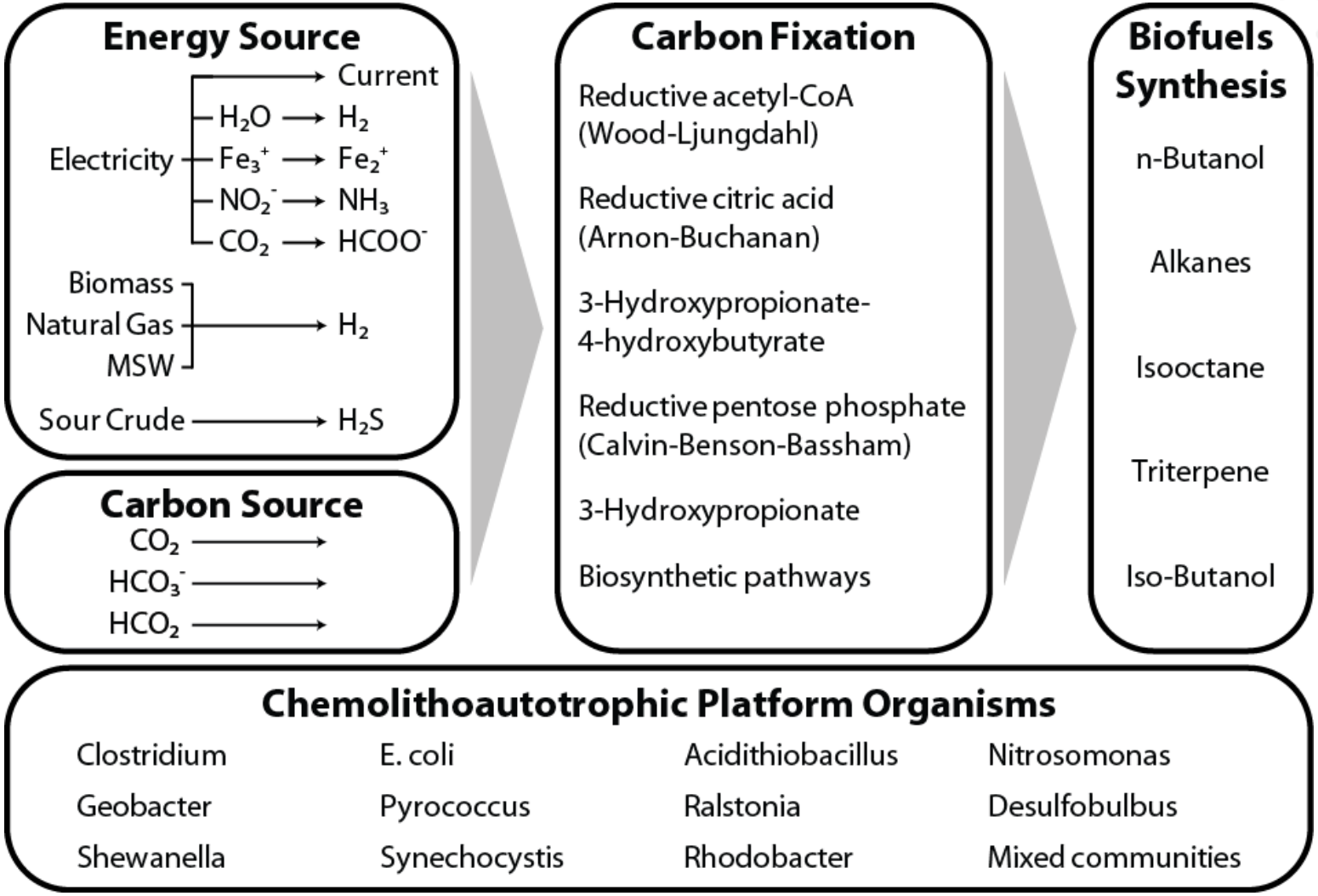
Acetyl-CoA

Carbon Fixation

Butanol

Fuel Synthesis

Numerous platform organisms, and energy pathways are being developed by Electrofuels performers



Source: Conrado, R.J., Haynes, C.A., Haendler, B.E., Toone, E.J.,"Electrofuels: A New Paradigm for Renewable Fuels" 2011, *Advanced Biofuels and Bioproducts (in press)* (Lee, J., ed.): Springer, U.S.

Many projects target the engineering of native H_2-consuming bacteria, but there is good balance across the program

H_2 consuming bacteria

- Endogenous hydrogenases
- Long history of H_2 fermentation and industrial unit operations are prevalent

Direct current/biocathodes

- "Electrotrophs" have been observed to convert CO_2 to acetate with >90% columbic efficiency

Electrochemical shuttles

- Can be relatively cost effective
- Can be electrochemically regenerated at high efficiency

Electrochemically produced formate

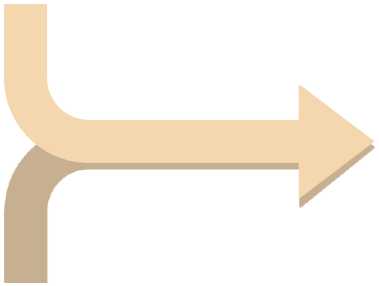
- Formate is readily soluble in aqueous media
- Is a source of both CO_2 and electrons

Hydrogen Sulfide, H_2S

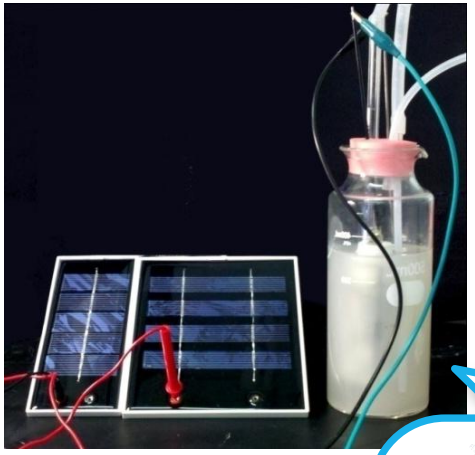
- Can be recovered as a waste product from oil refineries, or geological sources

Electrochemically produced formate as a source of both electrons and carbon dioxide for fuels

Electricity

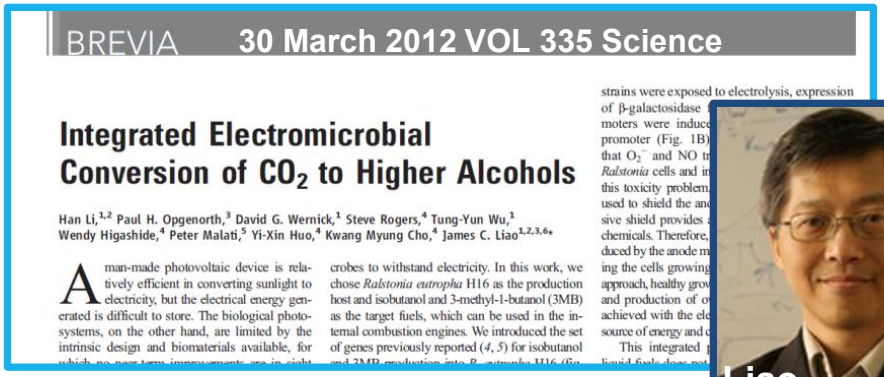


CO_2



UCLA

Isobutanol
3-MB



BREVIA 30 March 2012 VOL 335 Science

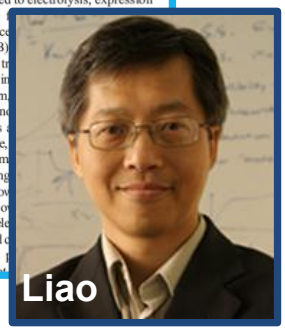
Integrated Electromicrobial Conversion of CO_2 to Higher Alcohols

Han Li,[1,2] Paul H. Opgenorth,[3] David G. Wernick,[1] Steve Rogers,[4] Tung-Yun Wu,[1] Wendy Higashide,[4] Peter Malati,[5] Yi-Xin Huo,[4] Kwang Myung Cho,[4] James C. Liao[1,2,3,6*]

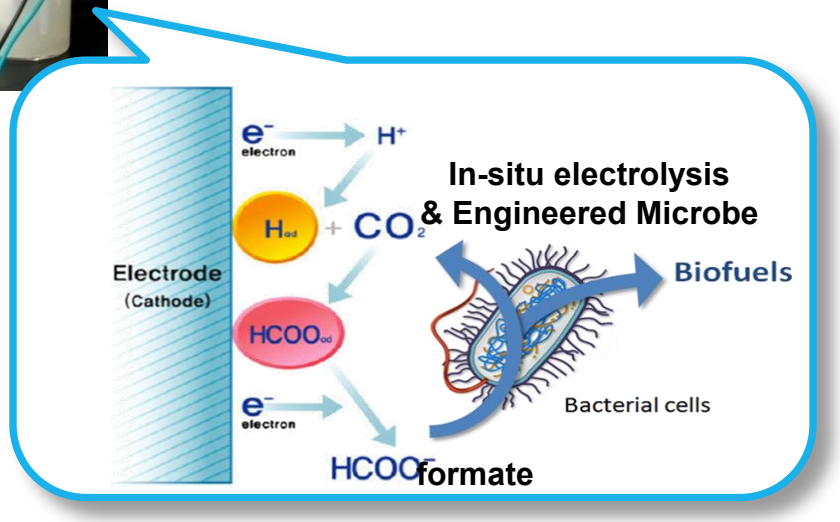
A man-made photovoltaic device is relatively efficient in converting sunlight to electricity, but the electrical energy generated is difficult to store. The biological photosystems, on the other hand, are limited by the intrinsic design and biomaterials available, for

crobes to withstand electricity. In this work, we chose *Ralstonia eutropha* H16 as the production host and isobutanol and 3-methyl-1-butanol (3MB) as the target fuels, which can be used in the internal combustion engines. We introduced the set of genes previously reported (*4*, *5*) for isobutanol

strains were exposed to electrolysis, expression of β-galactosidase

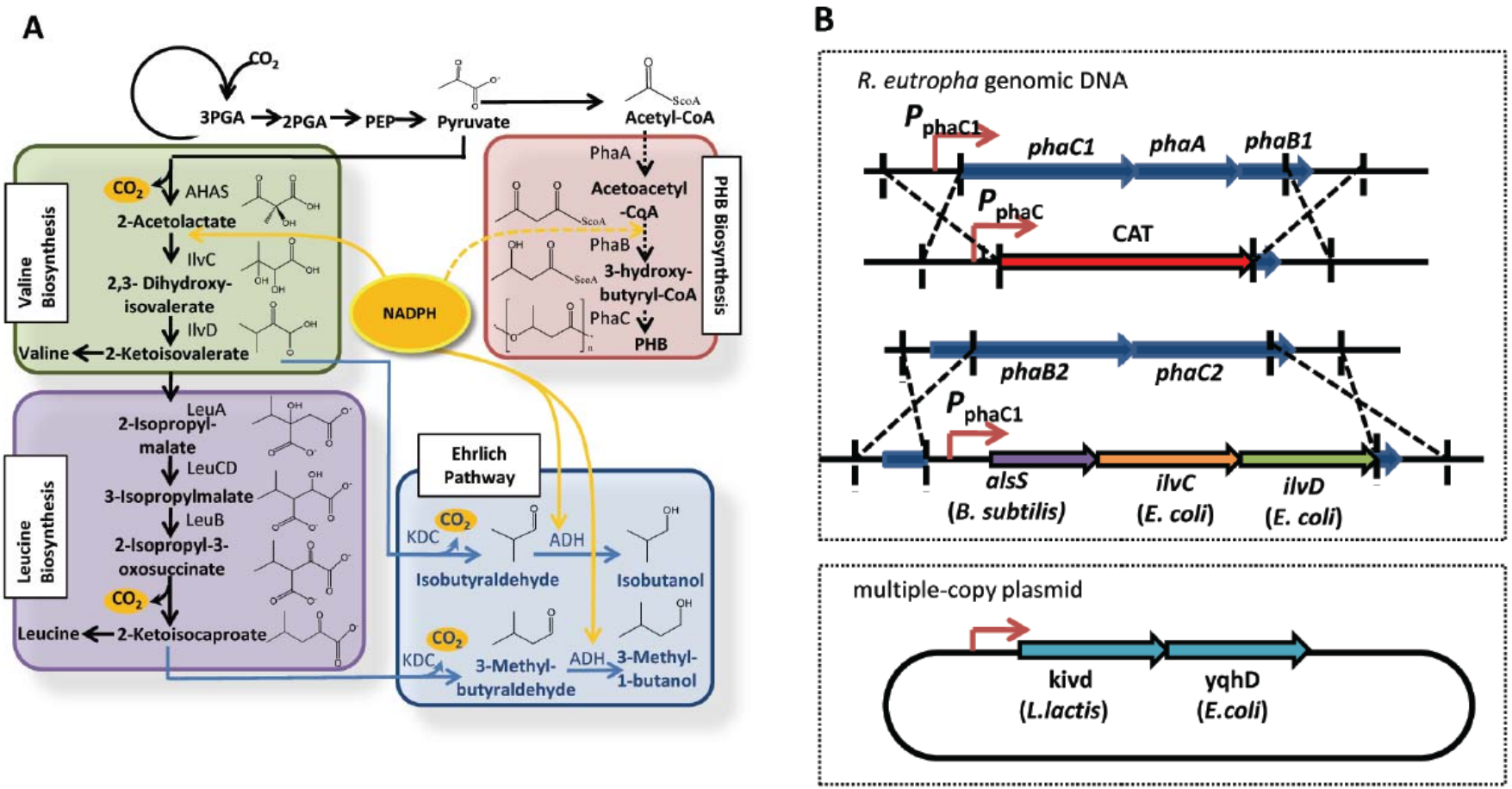


Liao

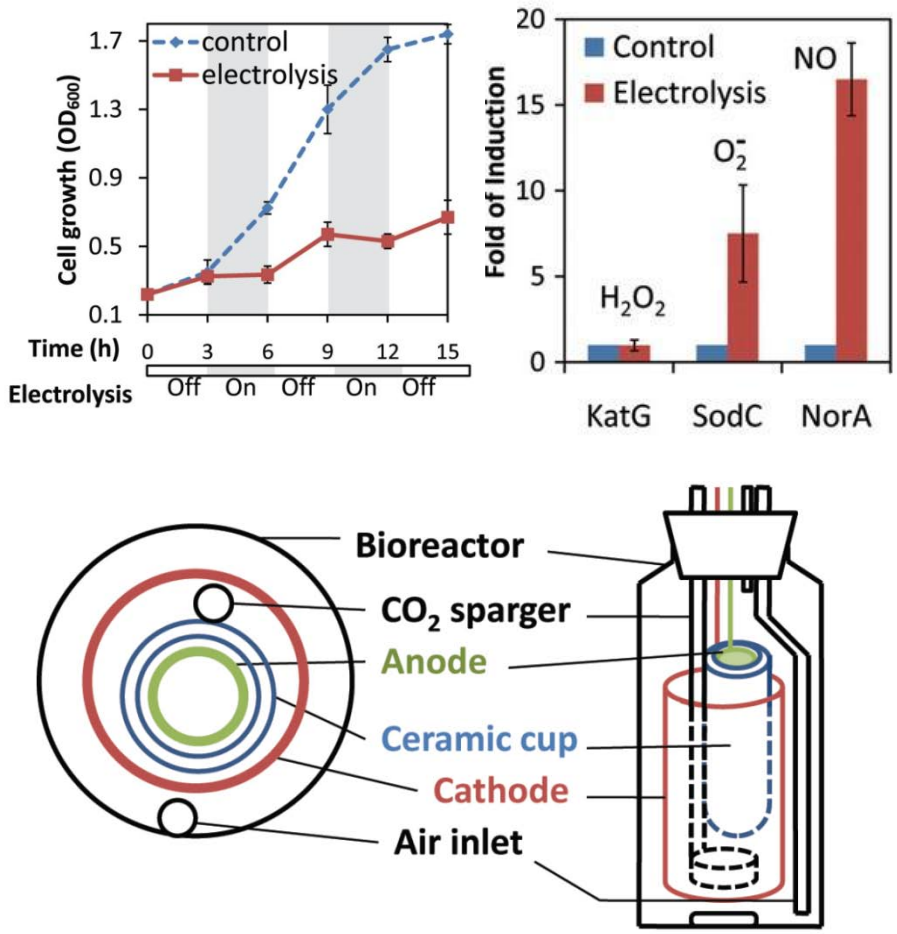


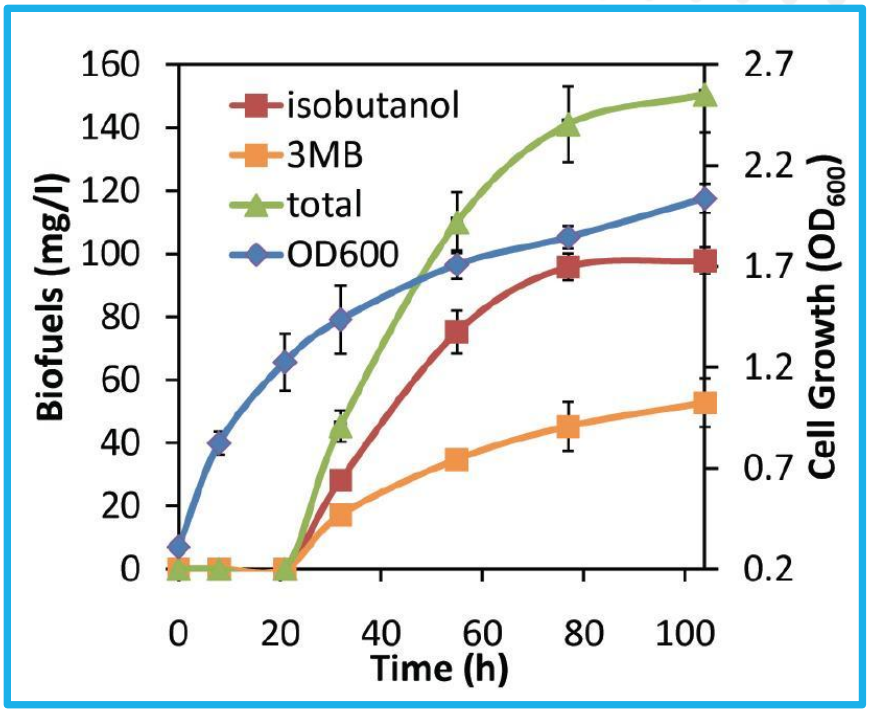
Key tech challenge: Electrochemical reduction of CO_2
Potential solution: New electrode materials, in situ production

UCLA's technology links genetic engineering to redirect amino acid biosynthesis…



…with innovative electrochemical reactor design for production of higher alcohols

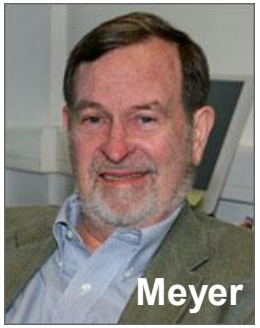




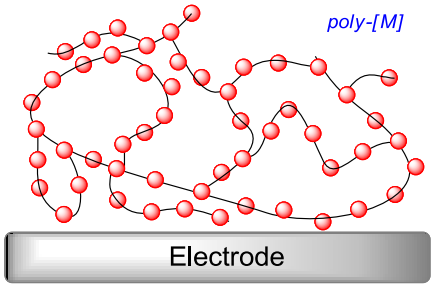
Formate production requires a large overpotential to force acceptable kinetics…new materials could be a gamechanger

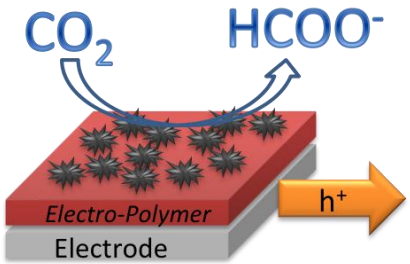
$$CO_2 + 2H^+ + 2e^- \rightarrow HCOOH$$

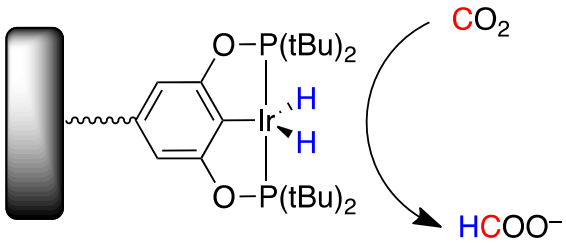
Plus up UCLA to bring on UNC for electrode material development



Suggested scope of work:







Electropolymerization to create active surfaces & Electrocatalysts

Strategic vision has evolved as the program has matured and new insights have come to light

Original Concept(s)
(e.g. standalone next to wind farm)

NEW INSIGHT →

Sourcing CO_2
Systems Level Analysis

"Near-term" Concept(s)
(e.g. "co-gen like")

Originally vision of CO_2 sourced from coal/NG electricity production
- Systems level analysis suggests this is an inefficient way to GTL/CTL
- Also not likely to qualify as a biofuel

Electricity & CO_2

1. Biofuels production releases up to 1/3 of total carbon feedstock as CO_2
   - e.g. Sugar-to-fuel fermentation releases 2/6 carbon from every sugar molecule
   - Extremely pure and concentrated CO_2 stream
2. CO_2 from geothermal could enable Iceland/Japan to become "oil" producers

H_2 & CO_2

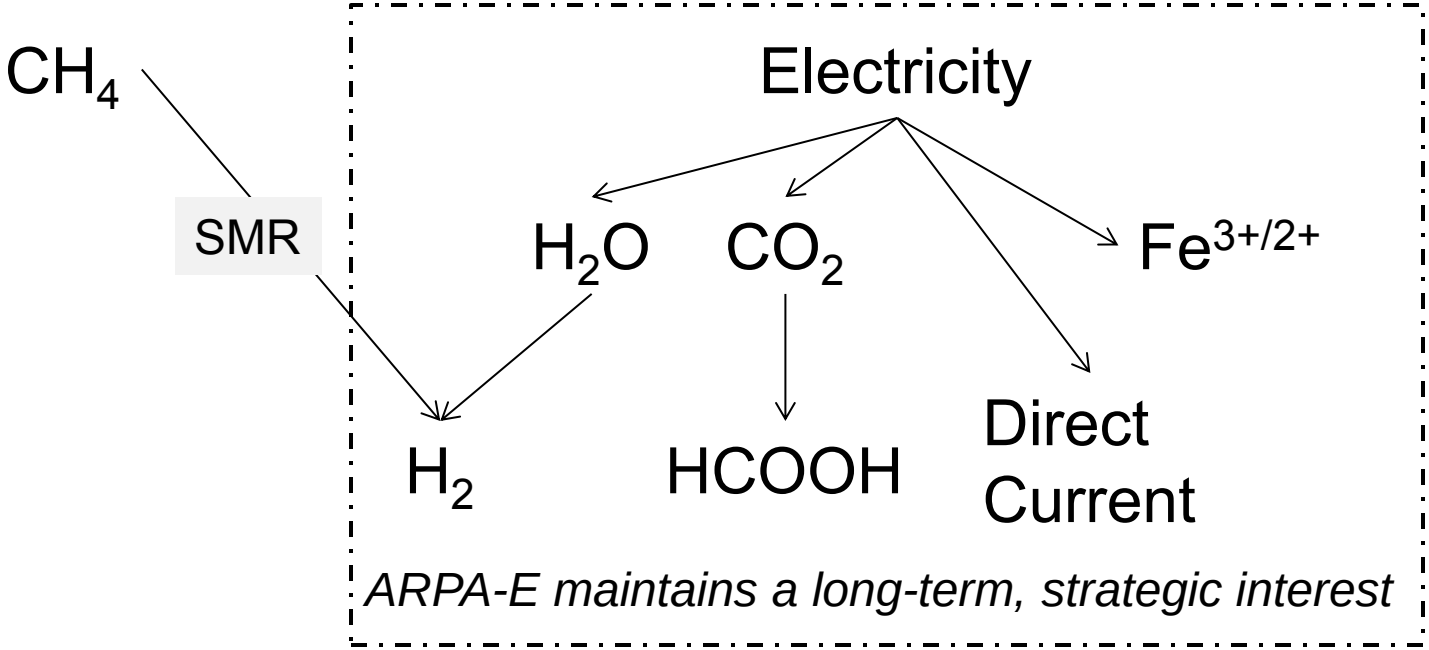
1. GTL/XTL using Electrofuels to convert CO_2/H_2 into fuel
2. Opportunity to couple fuel and ammonia production in same reactor

Certain feedstocks are advantaged and more near term due to particular market opportunities

South African Company to Build U.S. Plant to Convert Gas to Liquid Fuels

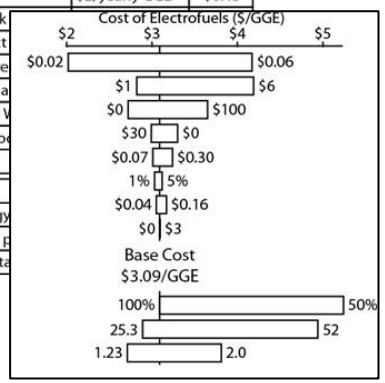
By CLIFFORD KRAUSS
Published: December 3, 2012

sasol
reaching new frontiers



ARPA-E conducted techno-economic analysis (TEA) to compare Electrofuels to other biofuel/fuel approaches

Item	Base Cost	Cost ($/GGE)
Electricity Feedstock	$0.04/kWh	$2.15
Capital Cost	$2/yearly GGE	$0.45
CO_2 Feedstock		
O_2 Co-product		
Labor and Ove		
Maintenance a		
Materials and V		
Water Feedsto		
Total Cost		
Item		
Cellular Energy		
e- Consumed p		
Delivered Volta		



ARPA-E built a preliminary model to explore operating costs

Selected representative examples where a process could be envisioned

Built general models to explore the diversity of the program

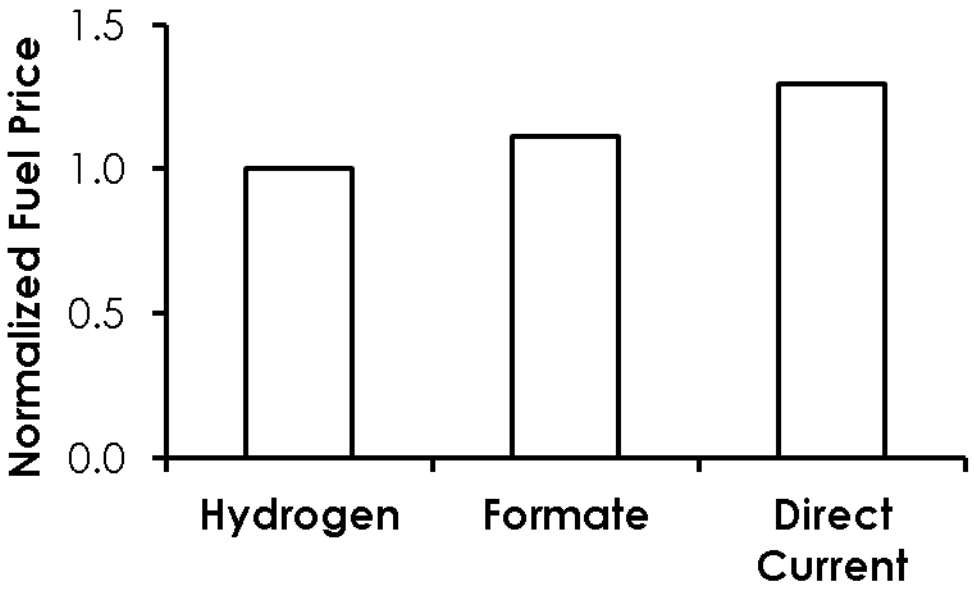
Expanded and improved the model to assess capital costs

Added precision around cost of reducing equivalents

ARPA-E and NREL specifically addressed hydrogen, formate, and direct electrosynthesis in first iteration of the models

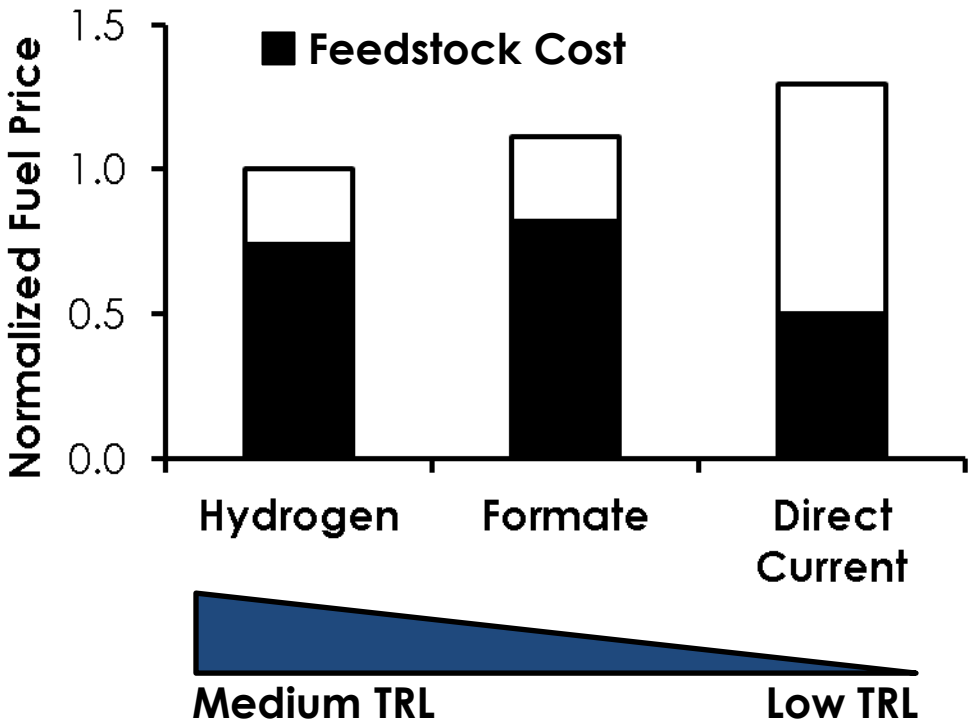
<u>Hydrogen:</u> H_2 → NADH, ATP + CO_2 → Calvin Benson Cycle	
H_2 can be generated from H_2O with high efficiency	High costs associated with improvements in gas mass transfer
<u>Formate:</u> $CO_2 + 2H^+ + 2e^- \rightarrow HCOOH \rightarrow CO_2 + NADH + H^+$ → Calvin Benson	
Formate is readily soluble and a source of energy and CO_2	CO_2 reduction to formate requires large overpotential and energetic cost
<u>Direct Current:</u> Direct current + CO_2 → Wood-Ljungdahl	
High columbic efficiency to acetate	Low current density and high CapEx cost

TEA comparison of representative approaches using electricity as feedstock



- Apples-to-apples comparison using the same feedstock and producing the same final fuel molecule
- Compares the cost of assimilating electrons and fixing carbon dioxide to a final fuel

Despite TRL disparity, the target cases show similar cost of production, however feedstock dominate



Technologies are needed to reduce the cost burden of feedstocks and improve performance

What technologies are needed to take advantage of low cost feedstock?

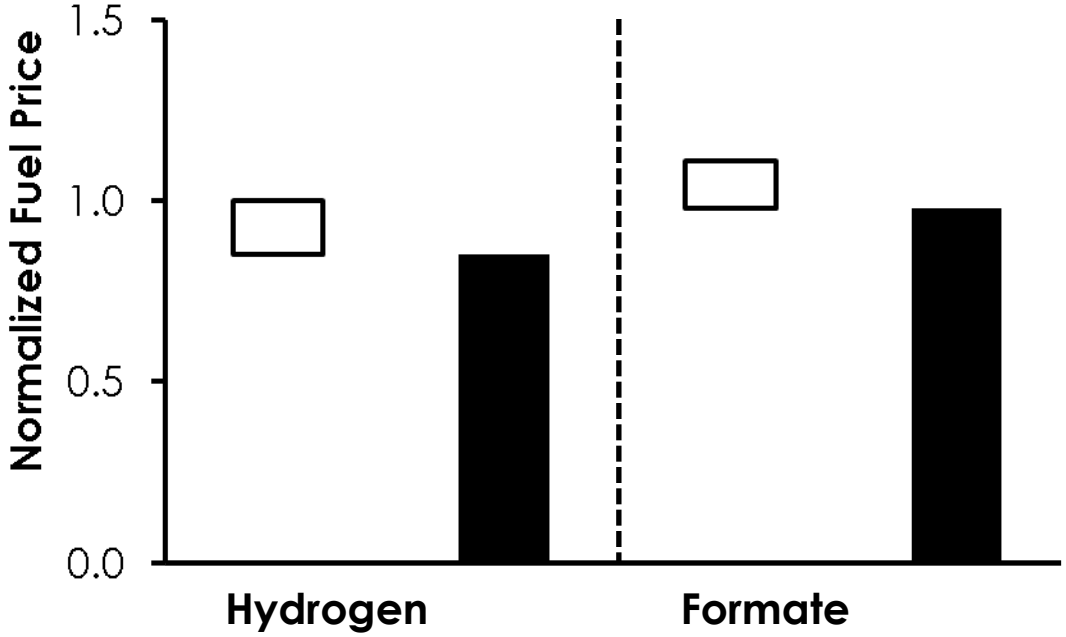
Efficient use of Feedstocks

- Efficient carbon fixation pathways
- Fuel assimilation pathways with minimal ATP requirements

Access to Cheap Feedstocks

- Cheap capital that can be deployed with low capacity factors
- “Energy storage” by accumulating acetate or formate with intermittent electricity supply for later conversion to fuel
- Small, modular deployment

Relative cost savings of switching to a more efficient carbon fixation pathway



By addressing these, we can go after niche opportunities in early deployment scenarios

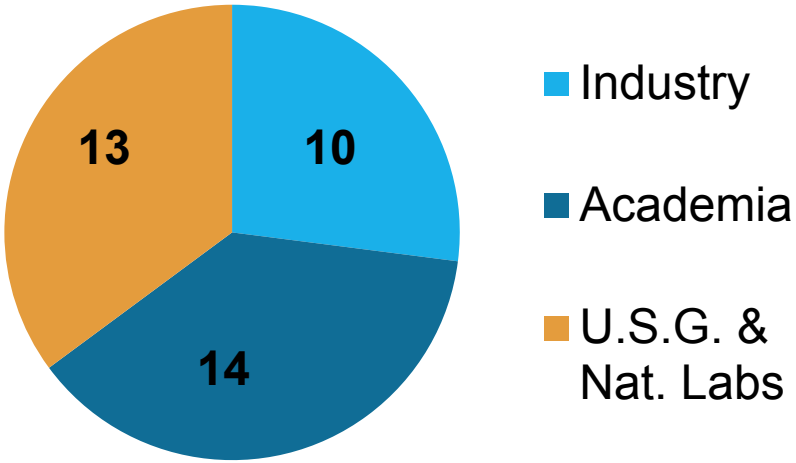
- **H_2/CO/CO_2 energy source**
  - Ethanol refinery bolt-on
  - Geographic niches with resource availability
    - TX = cheap wind e- & EOR CO_2
    - ND = natural gas processing with wind
    - Iceland & Japan = geothermal for e- and CO_2
- **Electricity as energy source**
  - Intermittent renewable electricity and opportunity for energy storage as formate/acetate

ARPA-E is currently evaluating next best investment opportunities for Efuels technologies

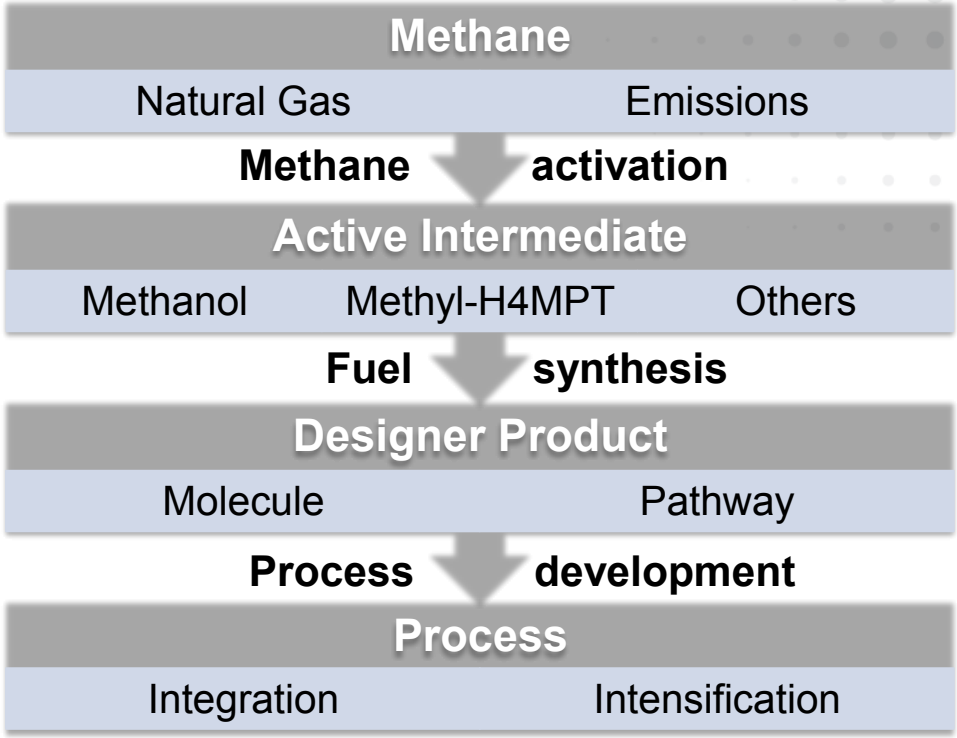
- Held a program review and workshop in Houston on Dec. 10, 2012
- Need to a different set of expertise
- Emergence of a need for emphasis on electrochemistry
- Techno-economics
- Reactor technologies

Bio-conversion of methane to liquid fuels workshop, Dec. 5, 2012

Workshop Participants



- **37 individuals participated in the workshop representing Industry, Academia, and the U.S.G. in roughly equal numbers.**
- **Representative expertise included methanogenesis, aerobic methanotrophs, anaerobic & C1 metabolism, electrosynthesis, synthetic biology & protein engineering, and industrial processing.**



Methane activation and fuel synthesis flow-diagram presented to workshop participants for additional context.

Workshop output and teaming list announcement

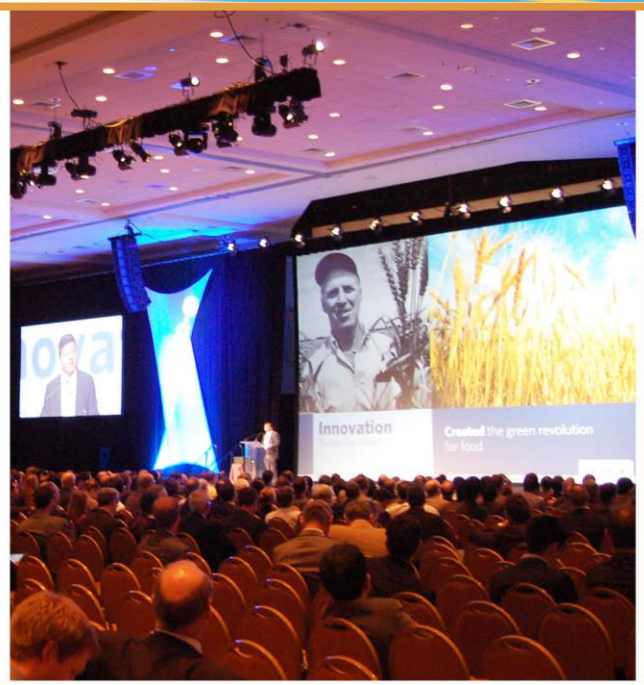
- Workshop output
  - http://arpa-e.energy.gov/?q=arpa-e-events/biological-technologies-methane-liquid-fuels

- Teaming List RFI Announcement
  - Targets three Focus Areas:
    - Efficient methane activation to a biological intermediate
    - Biological carbon-carbon bond formation & fuel synthesis
    - Biological process engineering and intensification
  - https://arpa-e-foa.energy.gov/

- Anticipate Funding Opportunity Announcement in March

arpa·e energy innovation summit

Unparalleled Showcase and Networking



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