ARPA-E Overview
IMPACCT Program & CO_2 Utilization

Dr. Ramon Gonzalez, Program Director
Advanced Research Projects Agency – Energy (ARPA-E)

July 11, 2013

Outline

ARPA-E Overview

CO_2 Separation

CO_2 Utilization

What's Next for ARPA-E in this Space?

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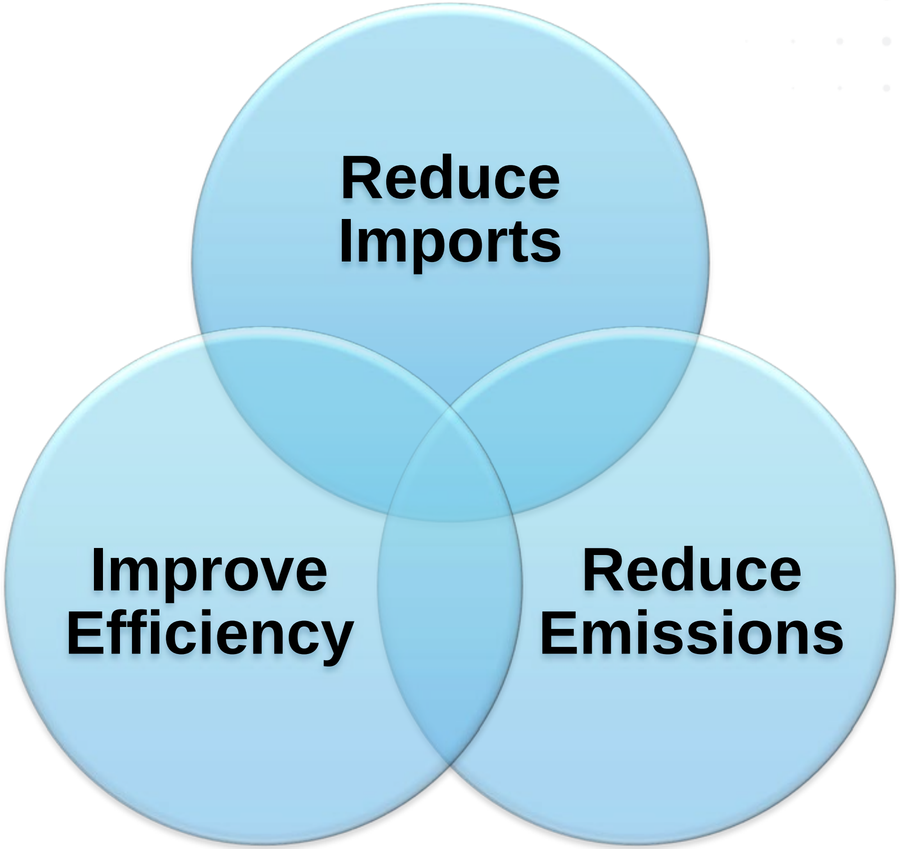
What's Next for ARPA-E?

The ARPA-E Mission

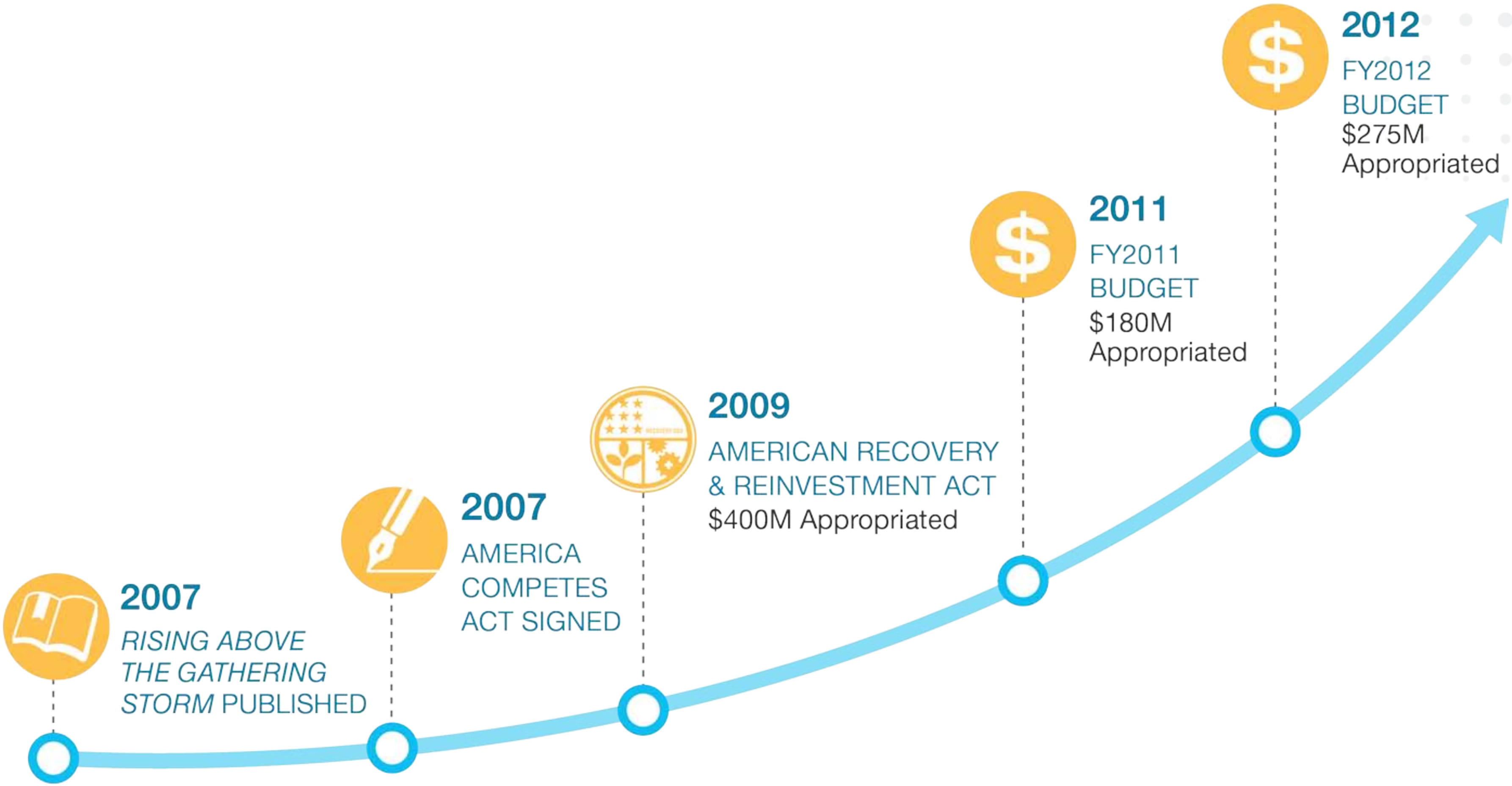
Catalyze and support the development of transformational, high-impact energy technologies

Ensure America's

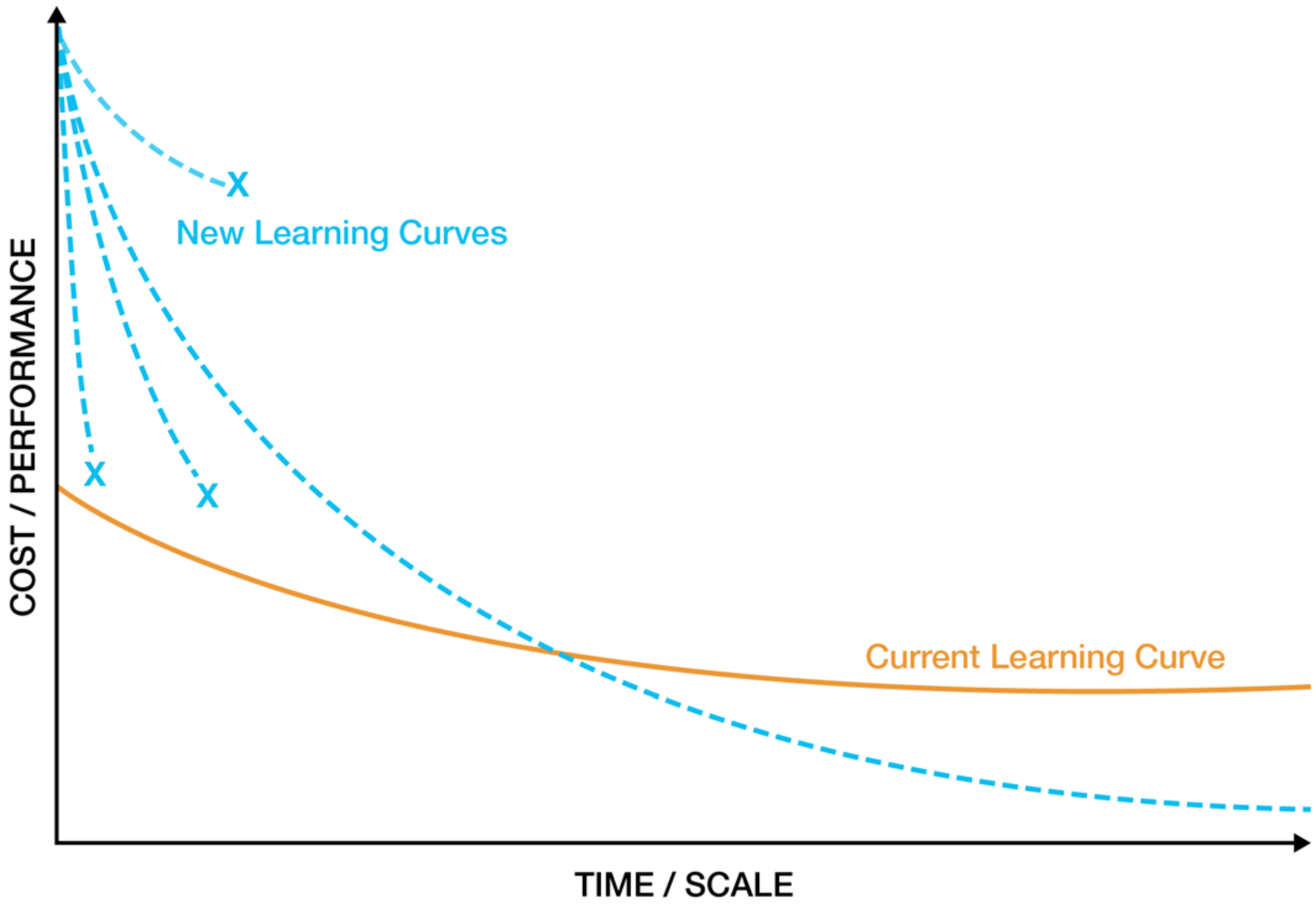
- National Security
- Economic Security
- Energy Security
- Technological Lead



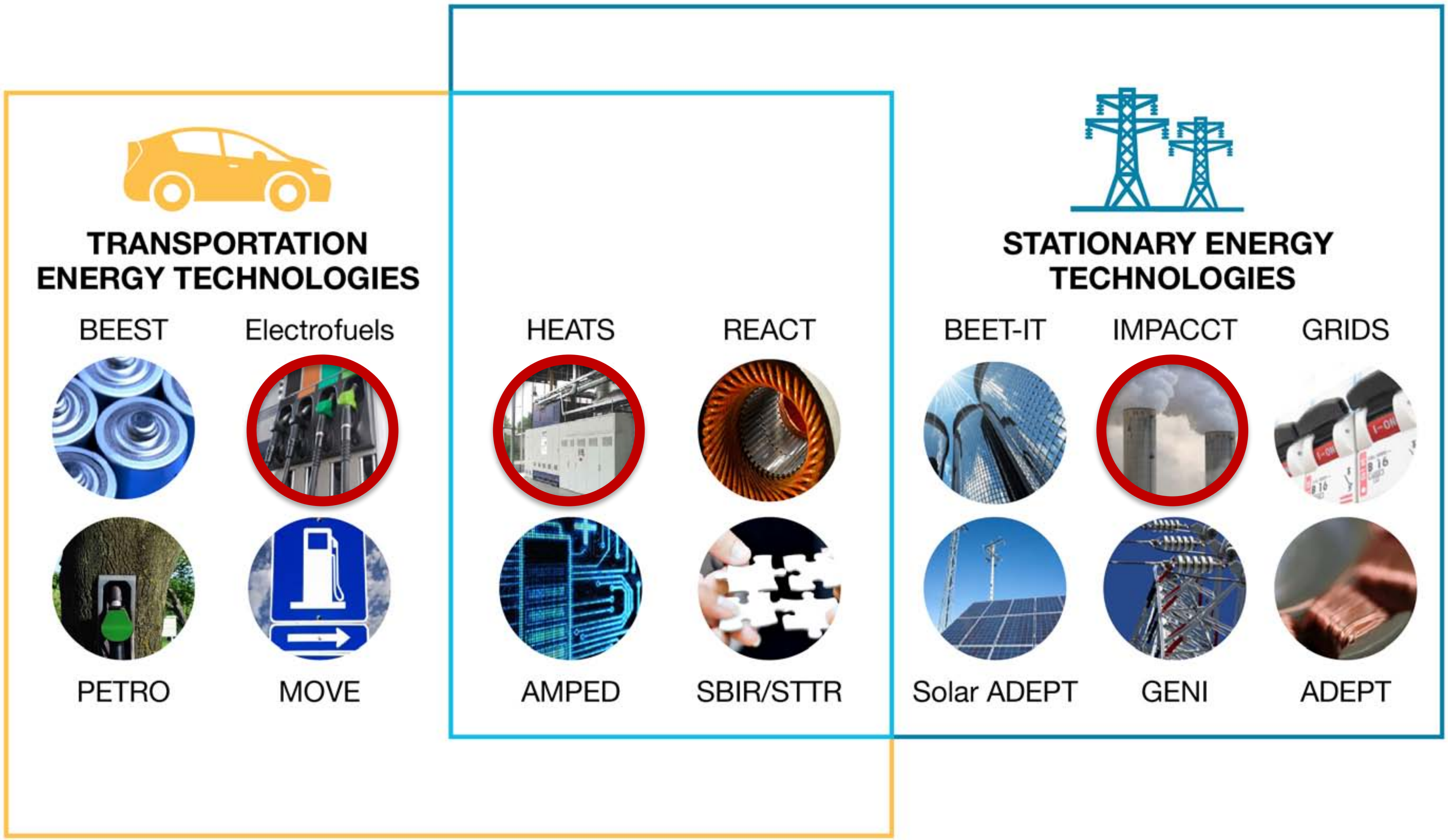
Evolution of ARPA-E



Creating New Learning Curves



Focused Programs



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ARPA-E CO_2 Separation Programs/Projects

OPEN 2009

2009 → 2014

5 projects, $13.3 M

IMPACCT

2010 → 2014

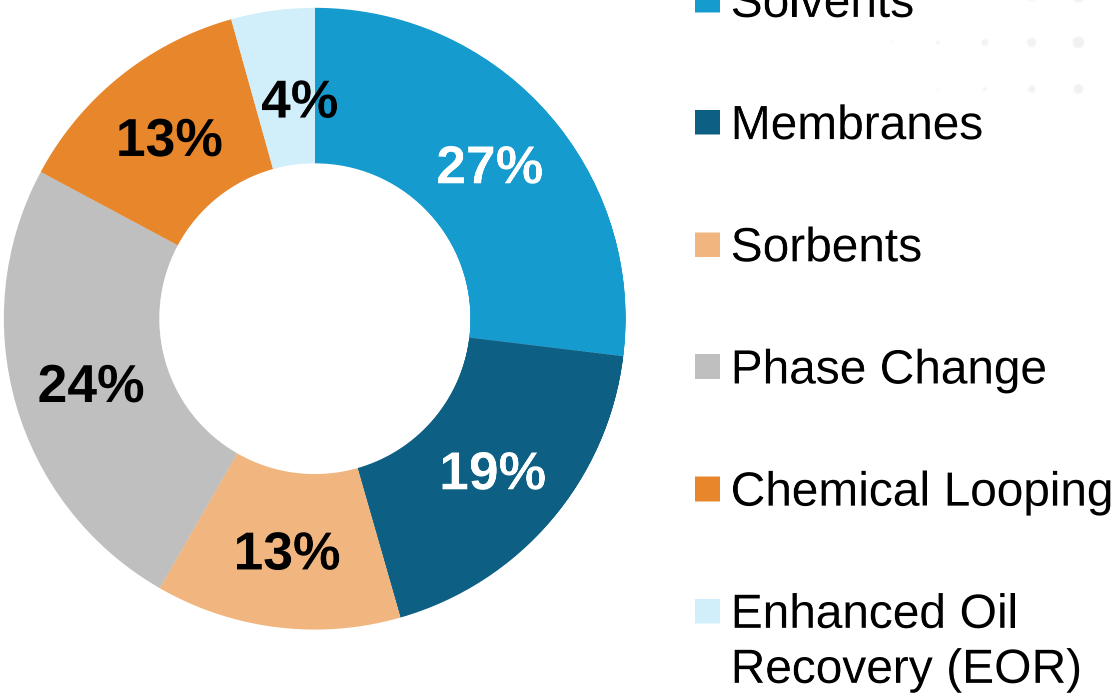
15 projects, $39.9 M

OPEN 2012

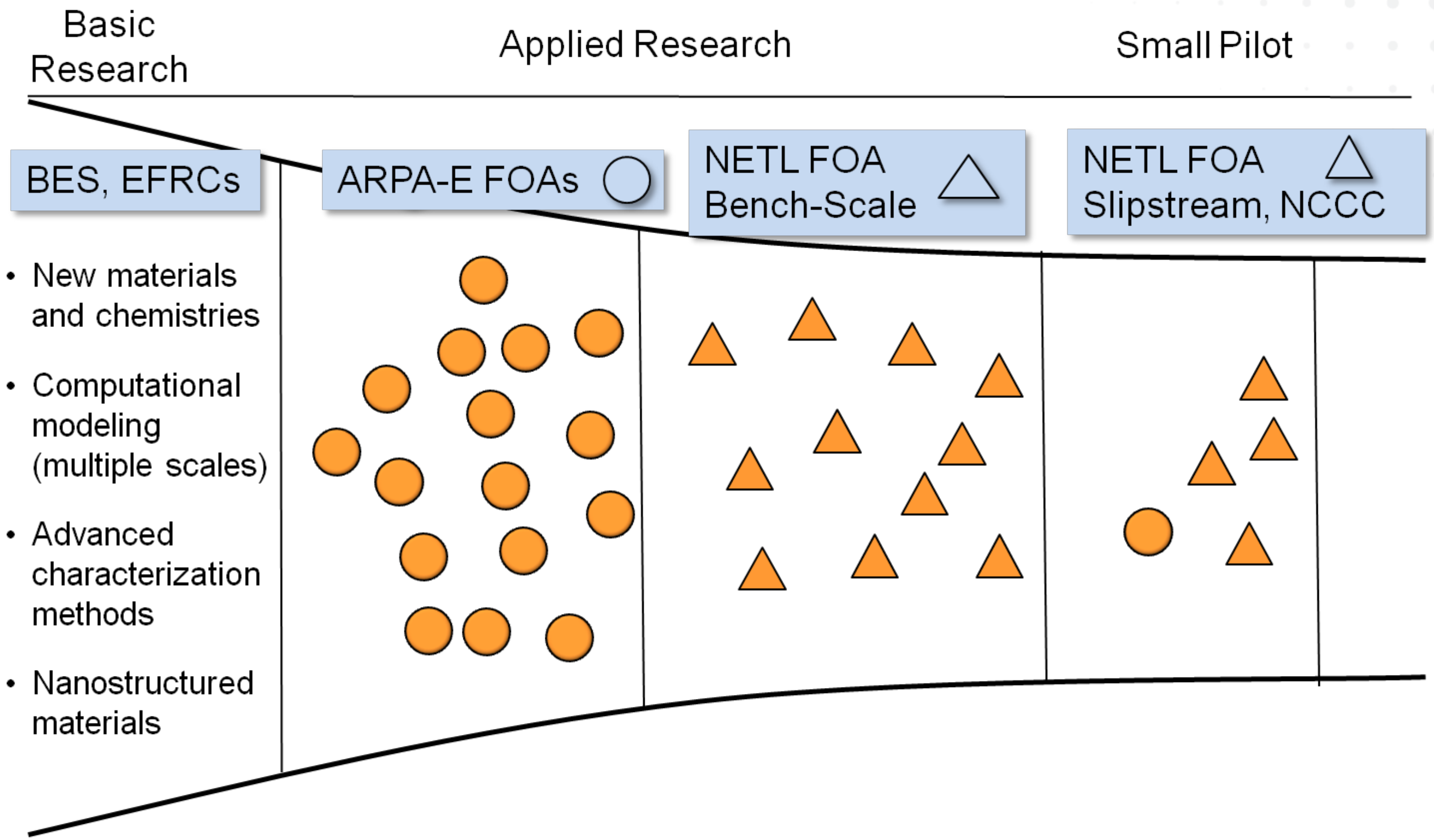
2013 → 2016

2 projects, $3.0 M

Funding by Technology



Development Pipeline: ARPA-E's Role



This presentation will be followed by 4 ARPA-E separation talks; several posters here as well

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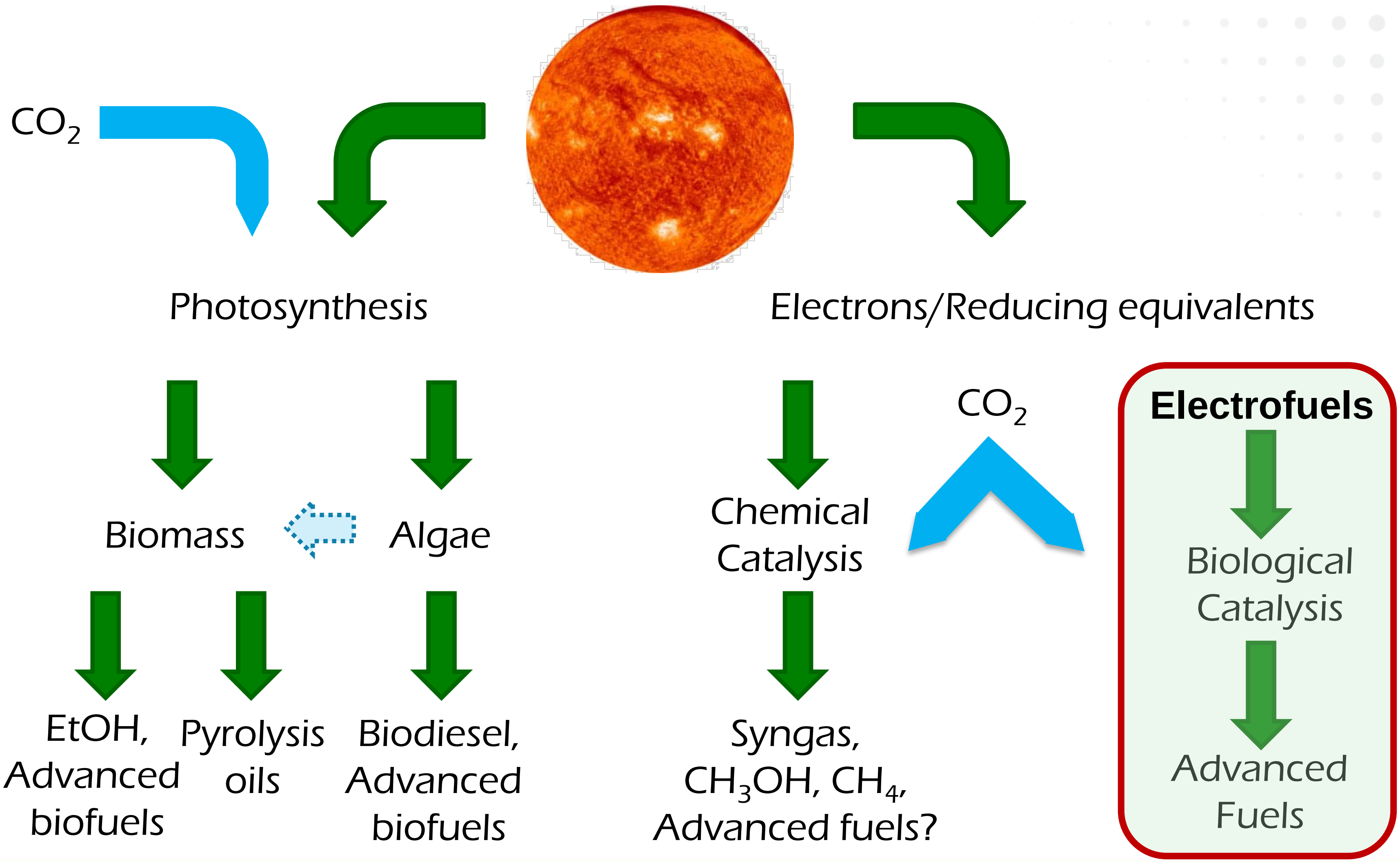
arpa·e
CHANGING WHAT'S POSSIBLE

The ‘U’ in CCUS

- Long-term: only geologic storage will make a dent in CO_2 levels in the atmosphere
- Nearer-term: utilization of CO_2 (e.g. enhanced oil recovery) could be a bridge until carbon pricing is enacted
- Fuel production could be a significant utilization of CO_2, however…

Communication between alternative fuels and power plant communities needs to be improved

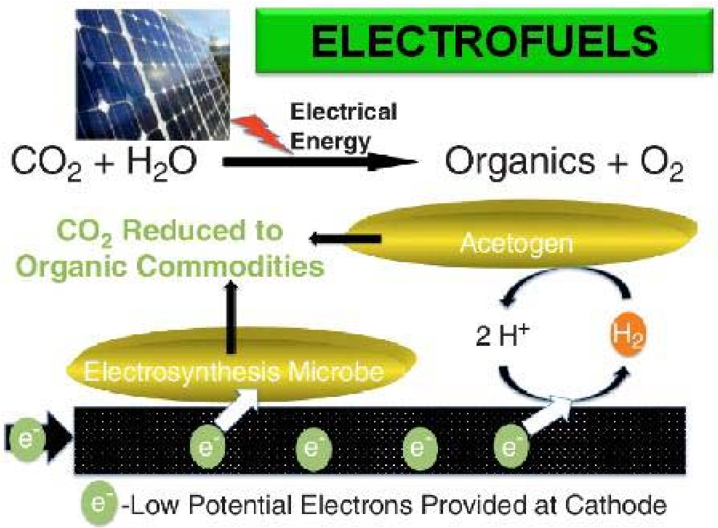
ARPA-E released the "Electrofuels" FOA in 2009 in recognition of the need for more efficient biofuel production technologies

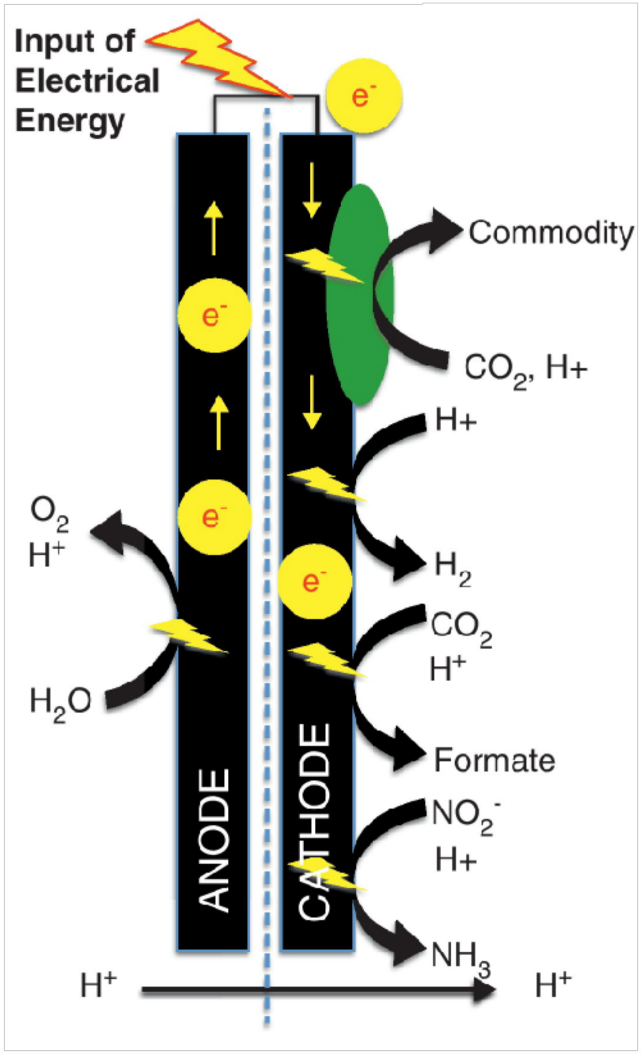


The FOA called for a first-of-kind non-photosynthetic, autotrophic fuel production from microorganisms

Area of Interest (Technical Category)

- **Organism development and integration for autotrophic/non-photosynthetic biological systems**





The Electrofuels portfolio

$$\text{Electrons} + CO_2 \xrightarrow[\text{microorganism}]{\text{chemoautotrophic}} \text{Biofuel}$$

INDIRECT ENERGY
$H_2 \rightarrow 2H^+ + 2e^-$

PENNSTATE 1855

MIT

BERKELEY LAB

THE OHIO STATE UNIVERSITY

opxbio good chemistry.

MIT

NC STATE UNIVERSITY

The University of Georgia 1785

$Fe^{2+} \rightarrow Fe^{3+} + 1e^-$

Columbia University

DIRECT ENERGY
Direct current/biocathode
$2H_2O \rightarrow 4H^+ + 4e^- + O_2$

MUSC MEDICAL UNIVERSITY of SOUTH CAROLINA

UMASS AMHERST

INDIRECT ENERGY & CARBON
$HCOOH \rightarrow CO_2 + 2H^+ + 2e^-$

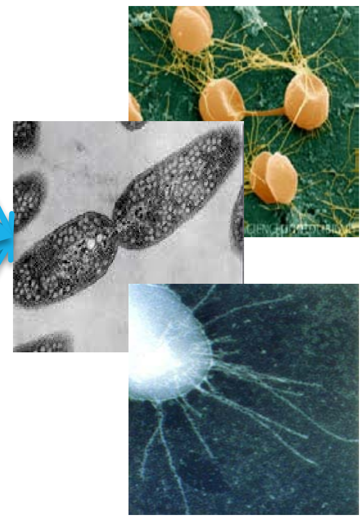
ginkgobioworks

UCLA

Harvard University

Early stage TRL investment provided insight and learning as the program matured

Microbiology
DNA sequencing data
New genetic tools
-omics
Metabolic engineering
Synthetic biology



Autotrophic biofuel production

H_2 → FFA → decane

CO_2 → formate → i-BuOH

Direct current → acetate → butyrate/butanol

> 40 papers; > 15 patents filed

- The core challenge has shifted from microorganism development to overall rates and efficiencies in the context of techno-economics
- New expertise is required to address challenges such as productivity and scalability of prototype reactors not covered by original FOA

INDIRECT ENERGY – Highlight

OPX Biotechnologies is producing jet fuel and diesel from hydrogen and carbon dioxide

H_2

CO_2

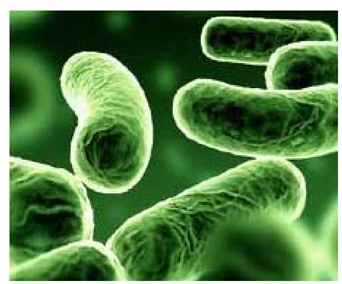
opxbio good chemistry.

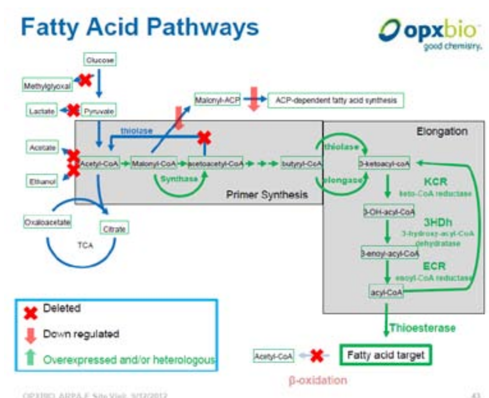
NREL NATIONAL RENEWABLE ENERGY LABORATORY

JM Johnson Matthey

Fatty Acids → Fuel

OPXBIO Engineered Microbe





Key tech challenge: Poor solubility of H_2 and mass transfer

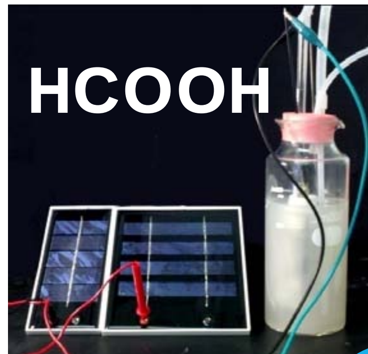
Potential solution: Innovations in reactor design

INDIRECT ENERGY & CARBON – Highlight

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

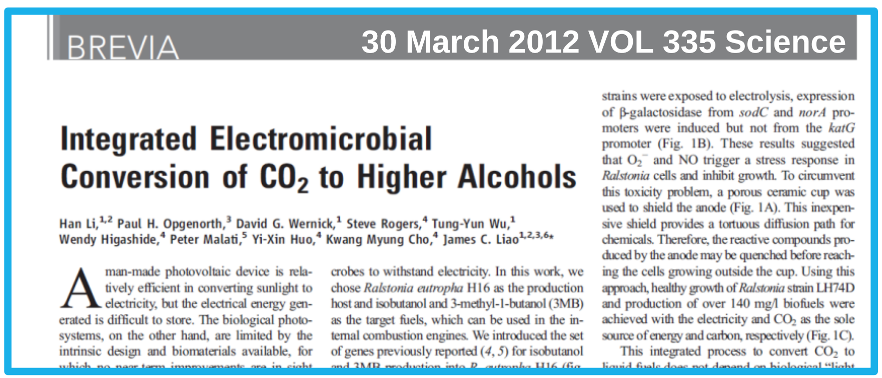
Electricity

CO_2



Isobutanol

3-MB


BREVIA 30 March 2012 VOL 335 Science

Integrated Electromicrobial Conversion of CO_2 to Higher Alcohols

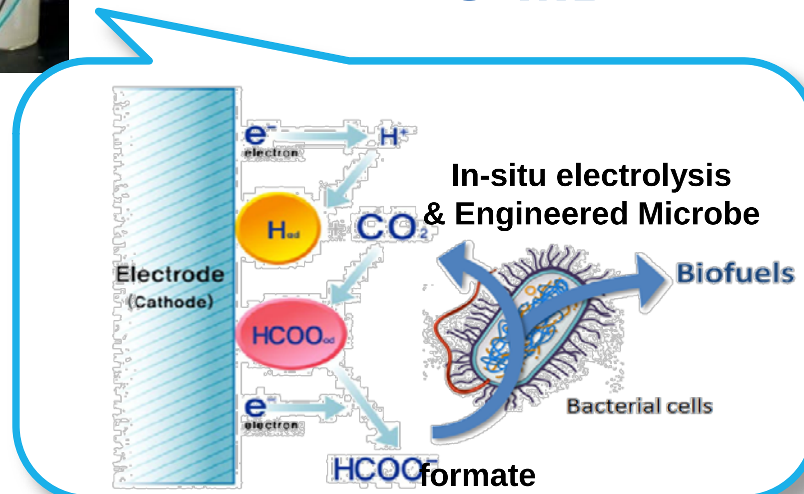
Han Li,[1,2] Paul H. Opgenorth,[3] David G. Wernick,[1] Steve Rogers,[4] Tung-Yun Wu,[1] Wendy Higashide,[4] Peter Malati,[5] Yi-Xin Huo,[4] Kwang Myung Cho,[4] James C. Liao[1,2,3,6*]

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 from *sodC* and *norA* promoters were induced but not from the *katG* promoter (Fig. 1B). These results suggested that O_2^- and NO trigger a stress response in *Ralstonia* cells and inhibit growth. To circumvent this toxicity problem, a porous ceramic cup was used to shield the anode (Fig. 1A). This inexpensive shield provides a tortuous diffusion path for chemicals. Therefore, the reactive compounds produced by the anode may be quenched before reaching the cells growing outside the cup. Using this approach, healthy growth of *Ralstonia* strain LH74D and production of over 140 mg/l biofuels were achieved with the electricity and CO_2 as the sole source of energy and carbon, respectively (Fig. 1C).

This integrated process to convert CO_2 to



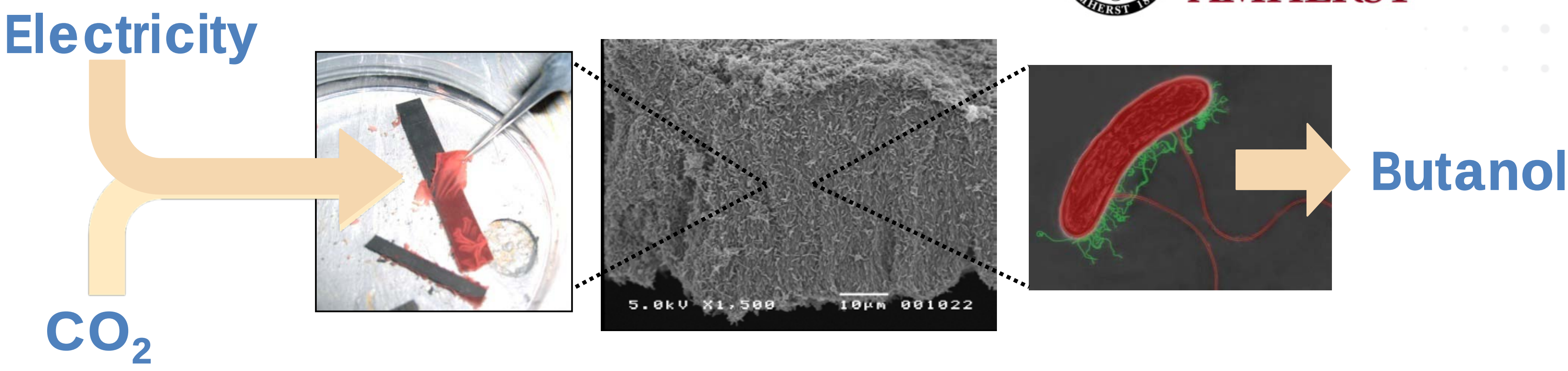
Key tech challenge: Electrochemical reduction of CO_2

Potential solution: New electrode materials, *in situ* production

DIRECT ENERGY – Highlight

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

UMASS AMHERST

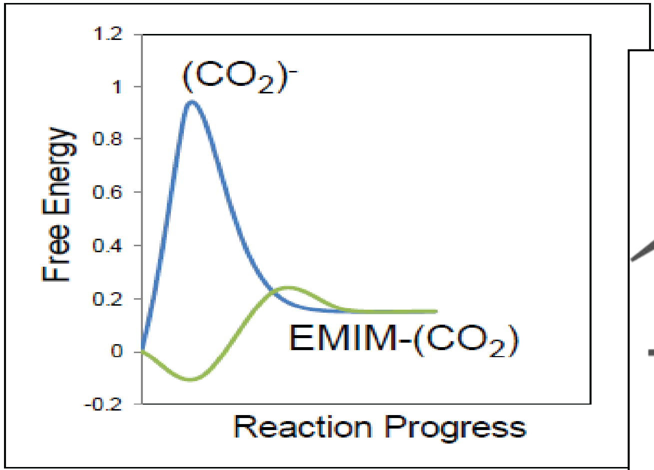


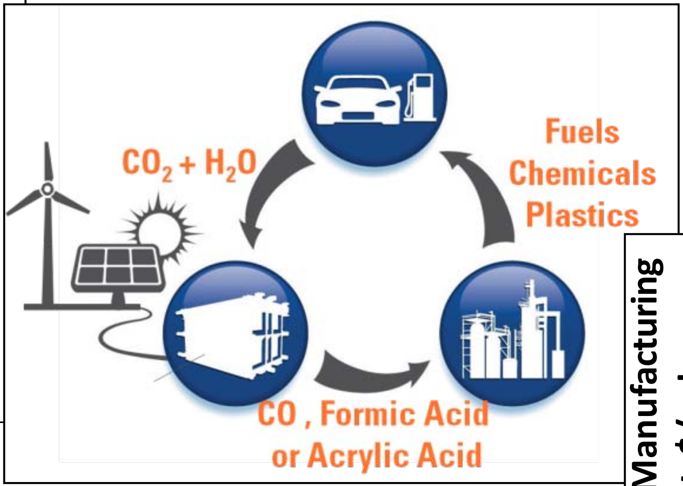
Sporomusa species, *Morella thermoacetica*, and *Clostridium* species are capable of electrosynthesis (conductive biofilms as a bioacathode on the surface of electrodes)

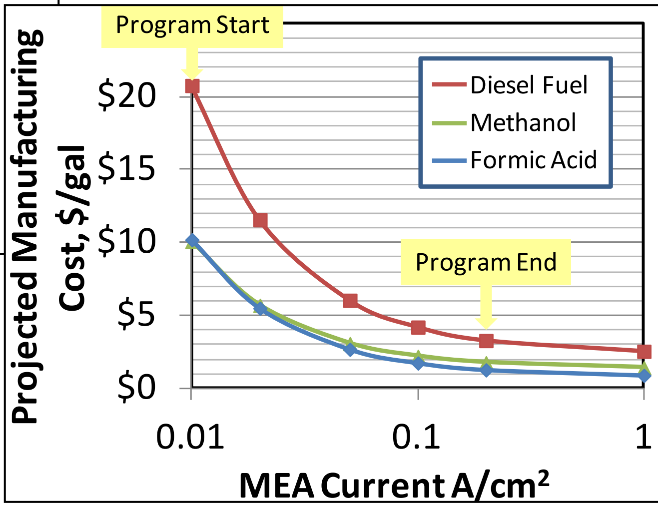
Key tech challenge: Current density (reaction rates), electrode surface area, reactor design
Potential solution: Improve mechanism, reactors for e- uptake

OPEN 2012: Dioxide Materials Project

- Energy Efficient Electrochemical Conversion of CO_2







- Operate cell at low over-potentials
- Increase electrolyzer current and lifetime to make cost competitive chemical products/fuel derivatives

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ARPA-E's Future in CO_2 Separation

- Most OPEN 2009 and IMPACCT projects are complete or winding down
- Recent focus has been understanding market opportunities and project handoffs
  - Compete in NETL FOA's
  - Other industrial CO_2 gas separations
- No current plans to launch a new CO_2 separation program…
- …but anything is possible
  - Open to new program ideas ("white space")
  - Would be championed by a new Program Director
  - Happy to discuss with attendees

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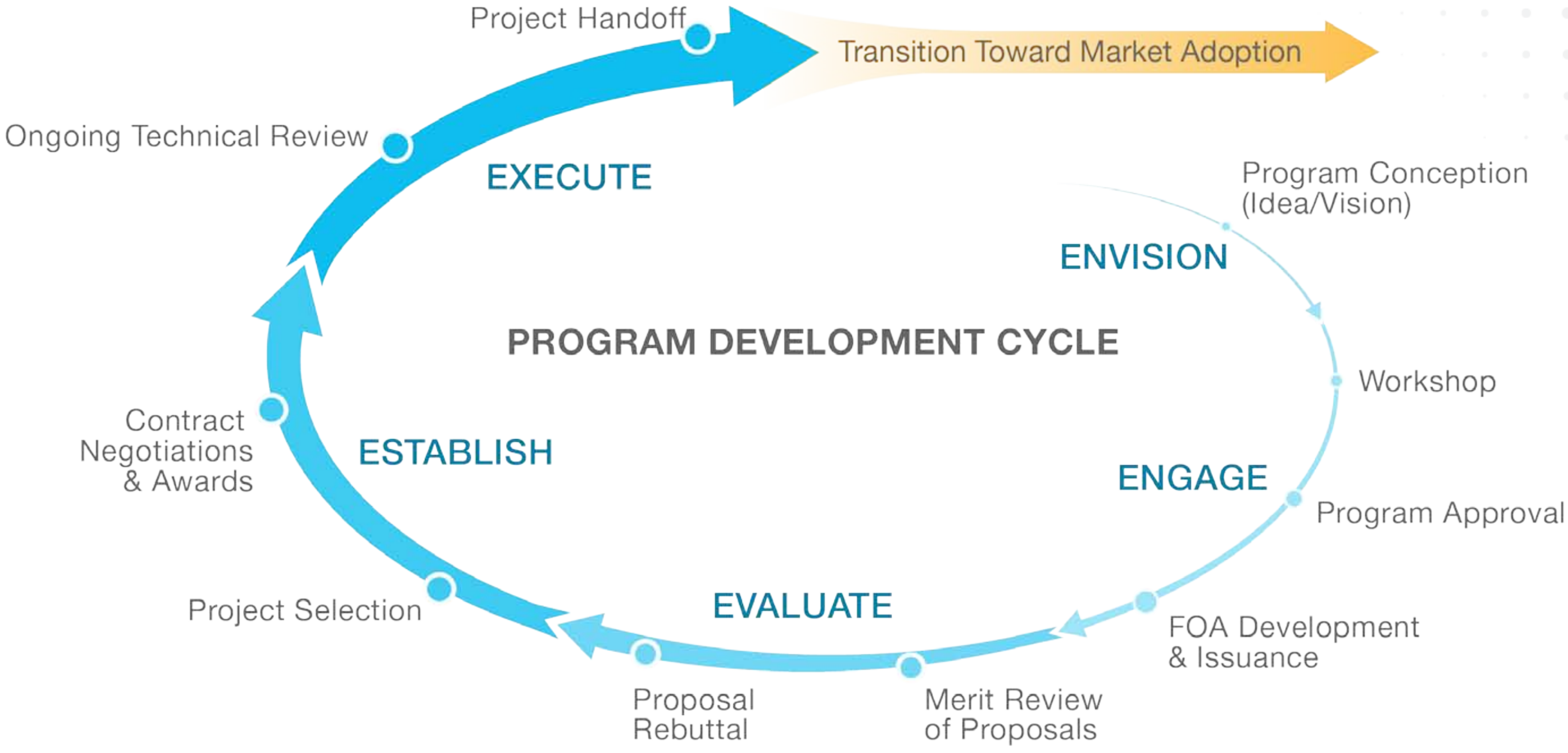
CHANGING WHAT'S POSSIBLE

Program Development Cycle



Thank you

- Ramon Gonzalez, PhD
  Ramon.gonzalez”at”hq.doe.gov