ARPA-E Electrofuels Program Meeting & Workshop

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ARPA-E

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Houston, Texas

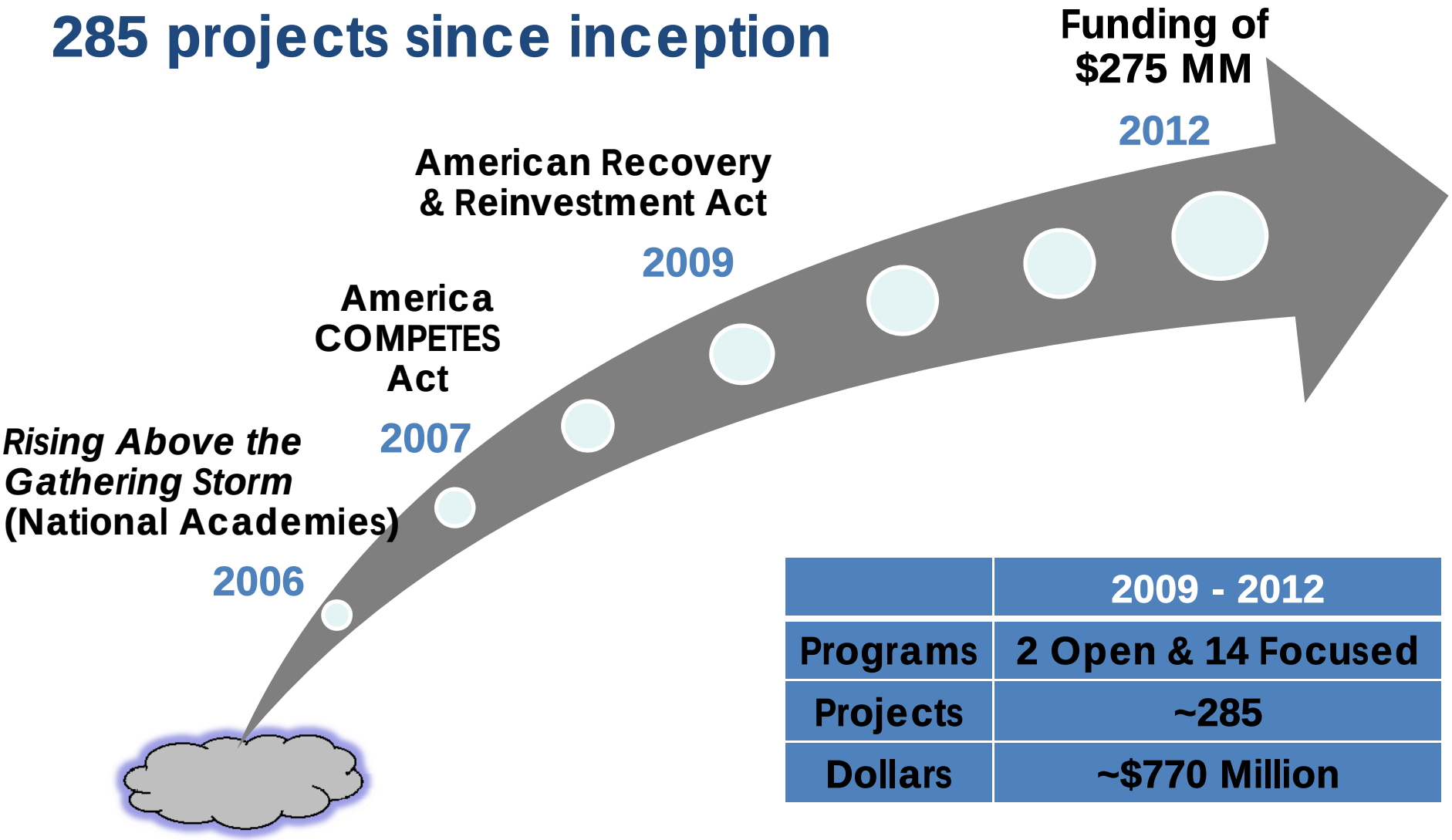
Introduction to ARPA-E

Liquid Fuel – A Brief History

FOA Rationale & Basics

Program Highlights & Learnings

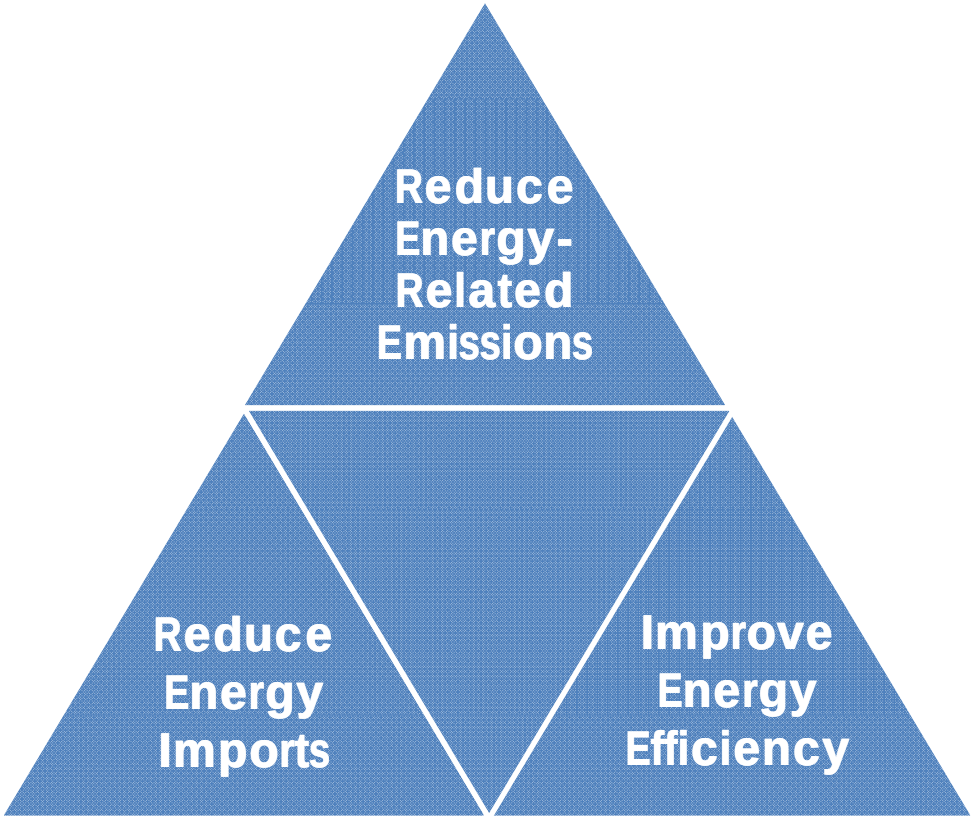
ARPA-E has funded approximately 285 projects since inception



	2009 - 2012
Programs	2 Open & 14 Focused
Projects	~285
Dollars	~$770 Million

The ARPA-E Mission

Enhance the economic and energy security of the U.S.

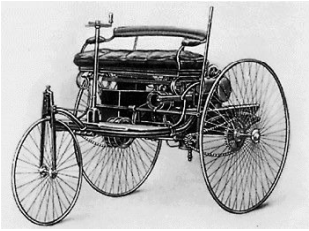


Ensure U.S. technological lead in developing and deploying advanced energy technologies

Moving to new learning curves

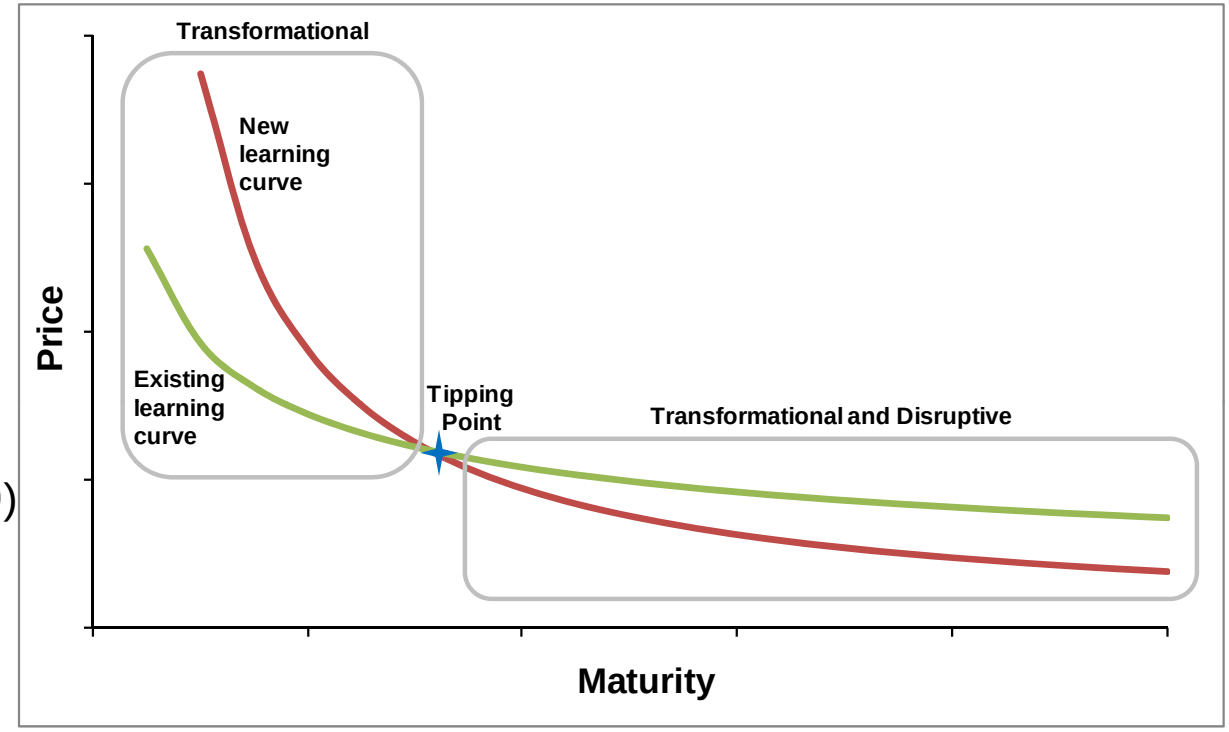
Pre-Mechanized Transportation

Steam-powered Cugnot (1769)



Benz Motorwagen (1885)

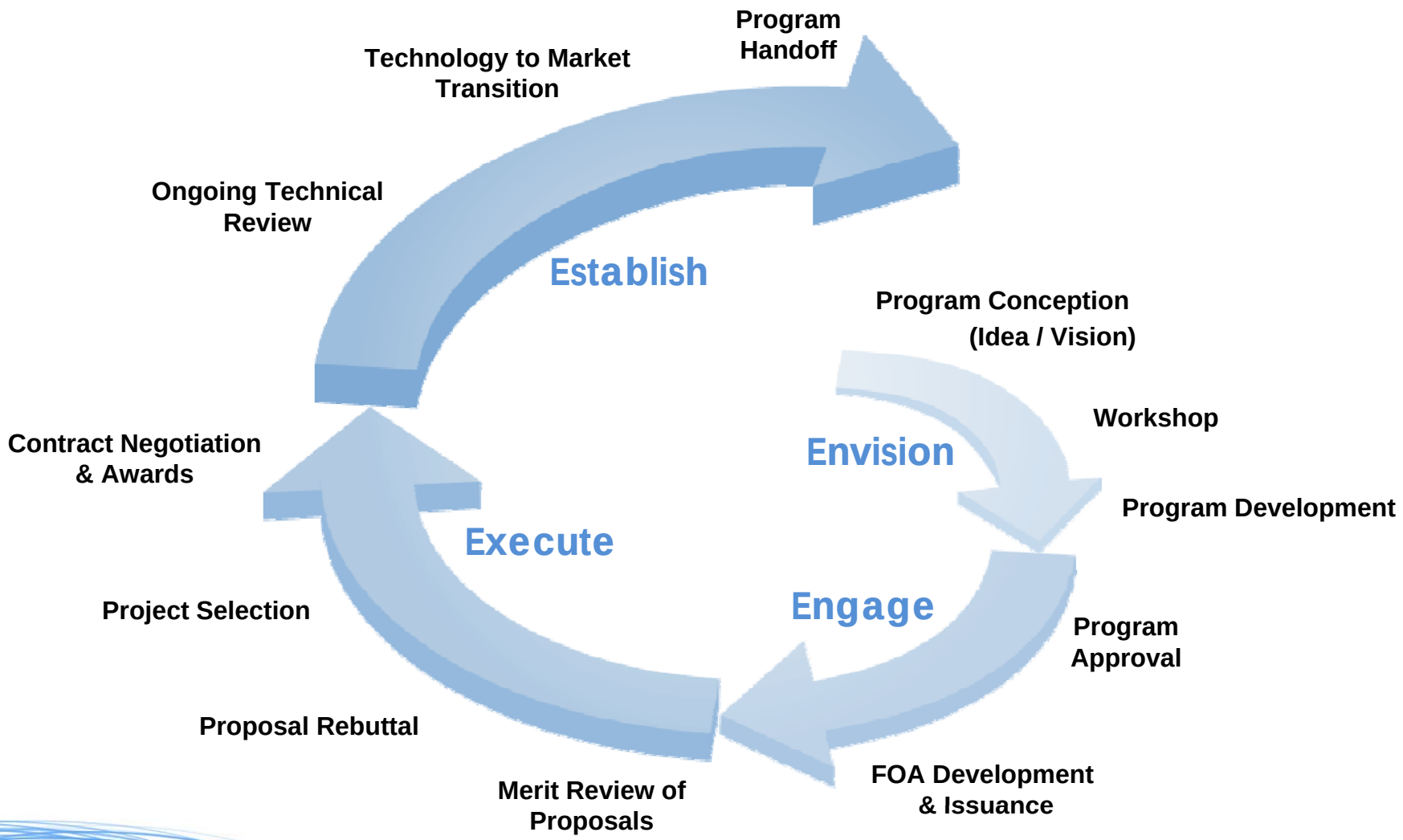
Ford Model T (1914)



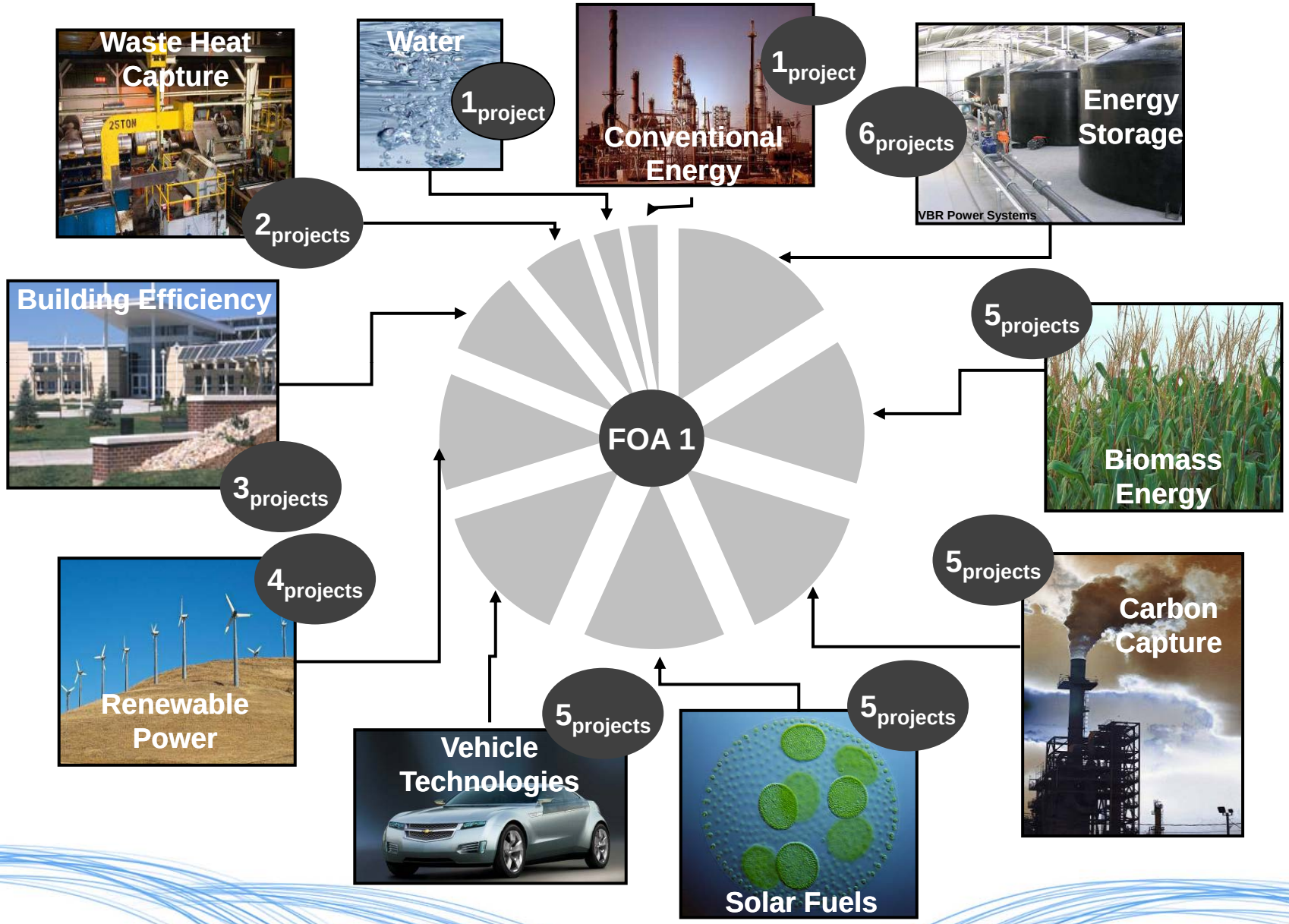
New energy technologies only matter if they are:

- Transformational and disruptive
- Adopted and deployed by private industry
- Meaningful to consumers
- Hit a key price tipping point

The program development cycle aspires to move applied technologies to market



First Open FOA 2009



Focused programs (2010-2012)

Transportation

Electrofuels

BEEST

PETRO

MOVE

Transportation and Stationary Power / Use

HEATS

REACT

AMPED

SBIR/STTR

Stationary Power / Use

BEETIT

IMPACCT

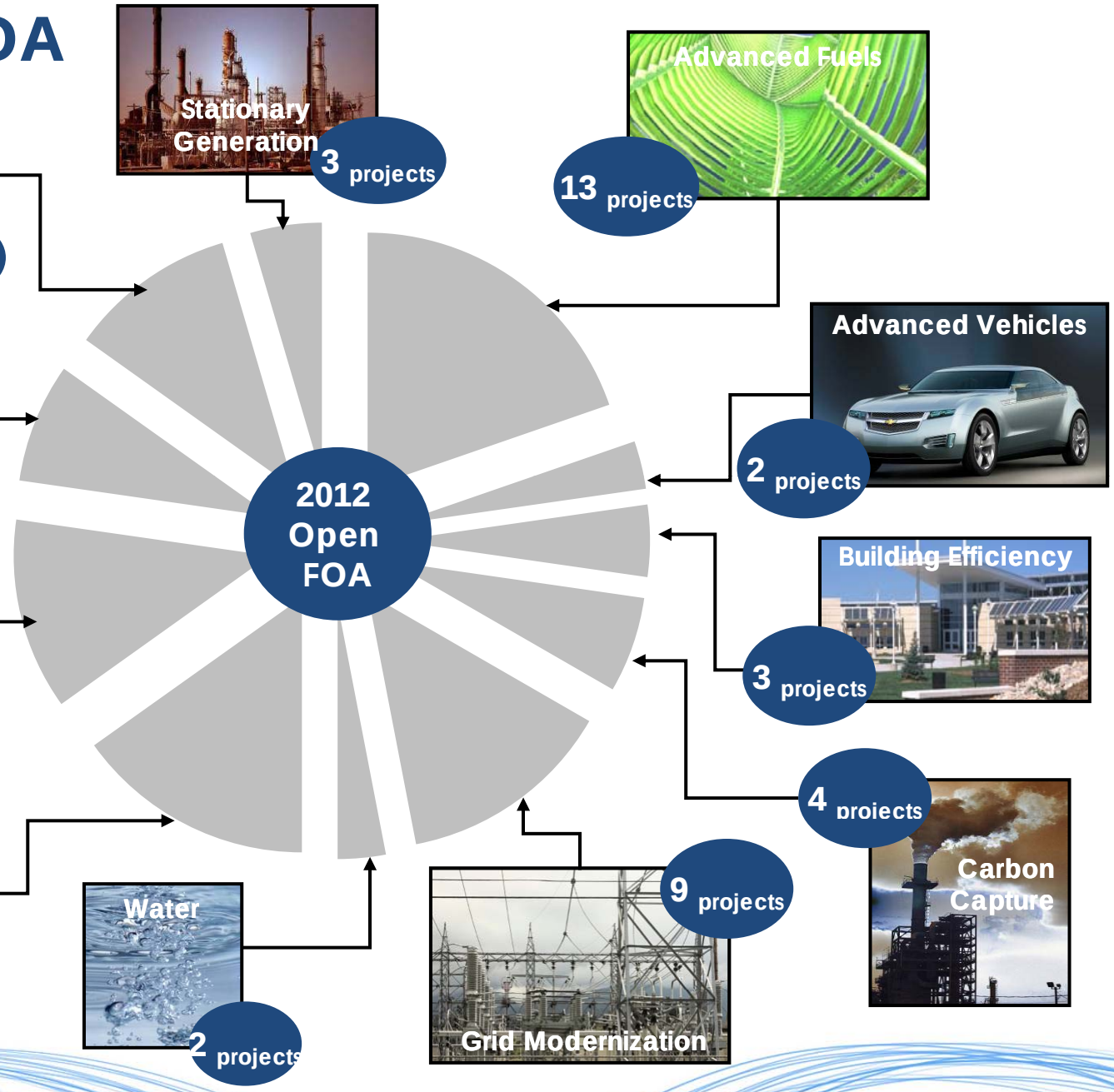
GRIDS

ADEPT

GENI

Solar ADEPT

2012 Open FOA



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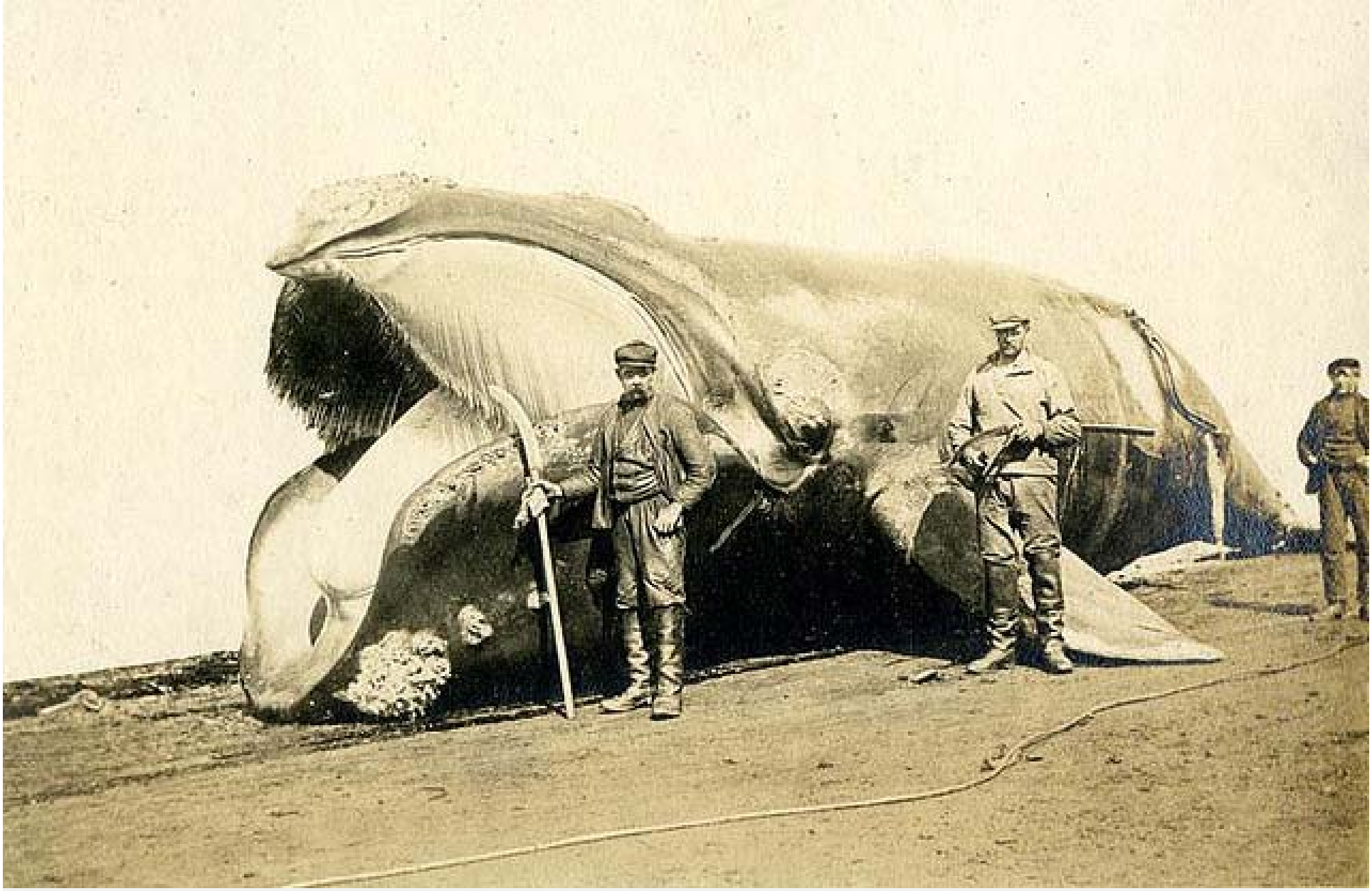
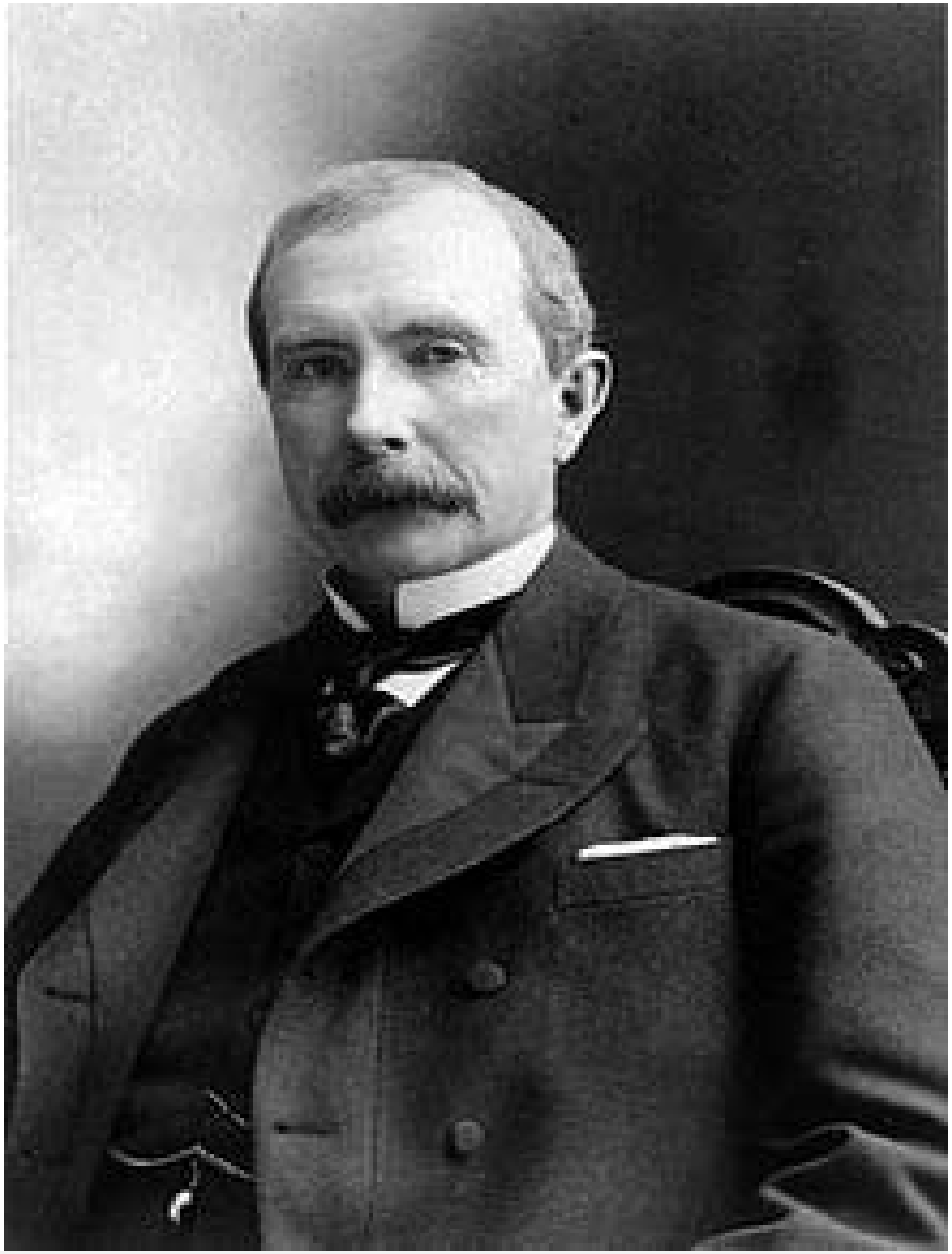
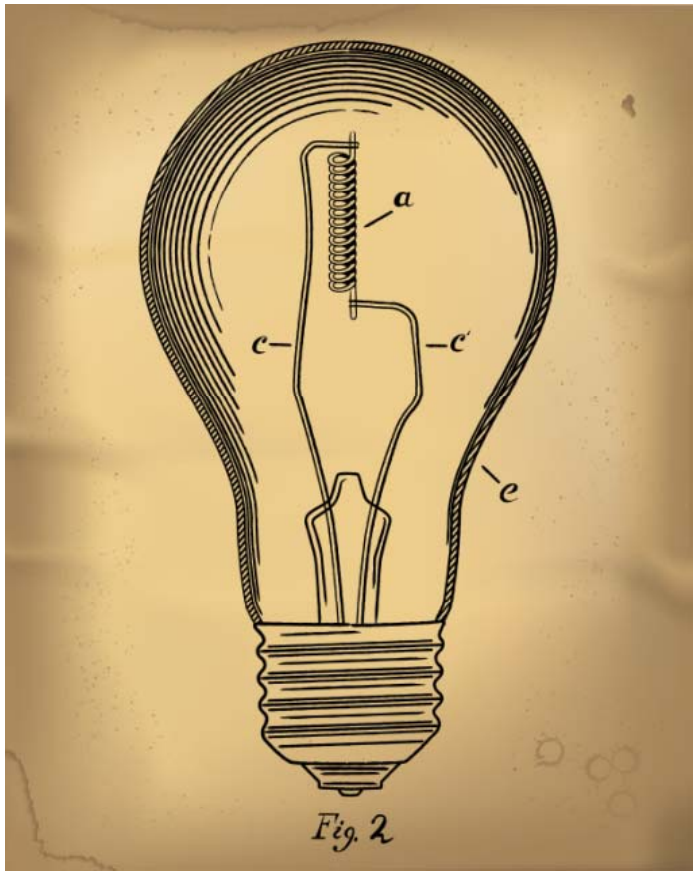
Pre-Industrial America



Whale Oil: 1850

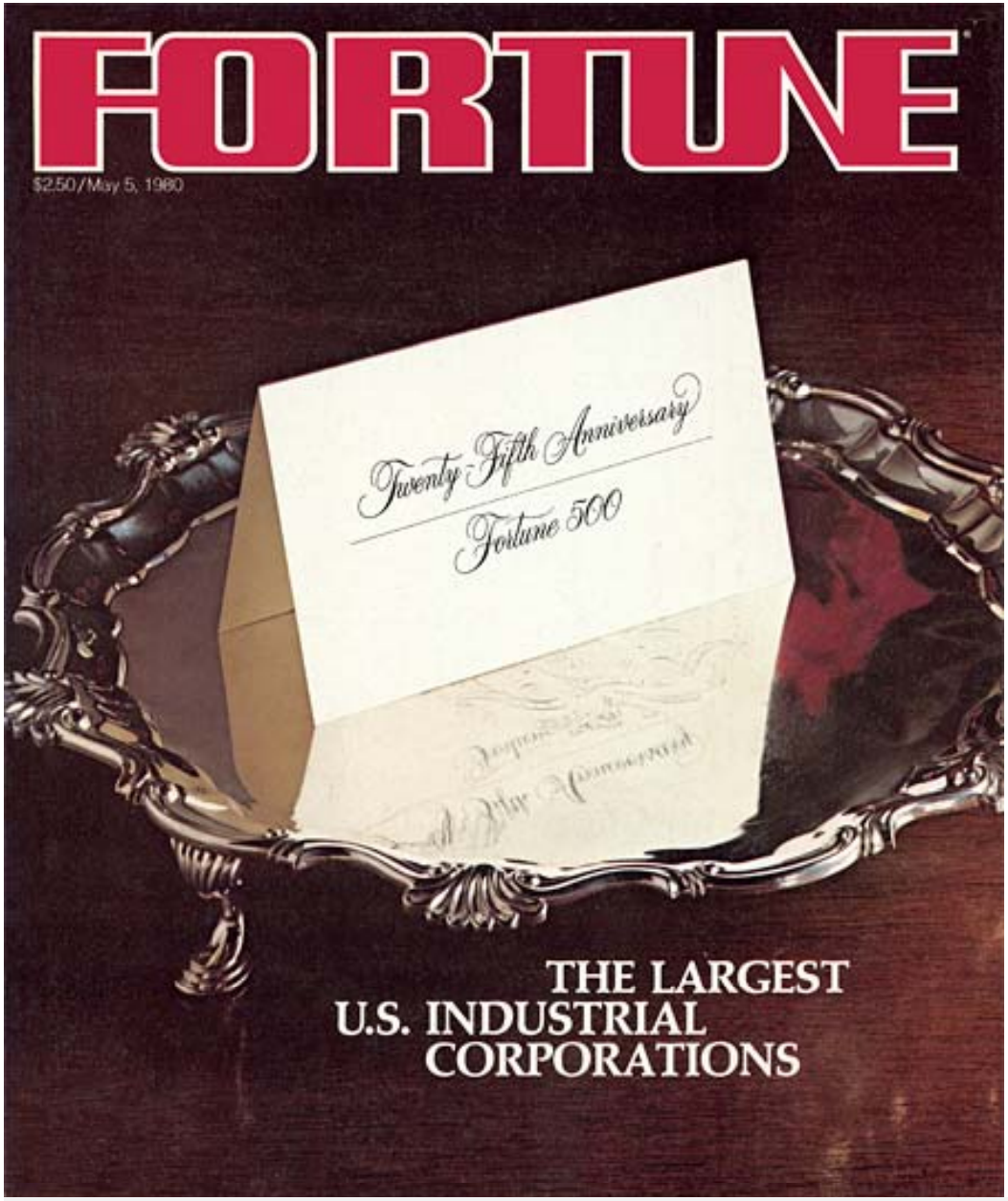


The Beginning of Oil: 1870



A Bump in the Road and New Possibilities: Late 1800s

Oil Takes Hold: Early 1900s



ExxonMobil

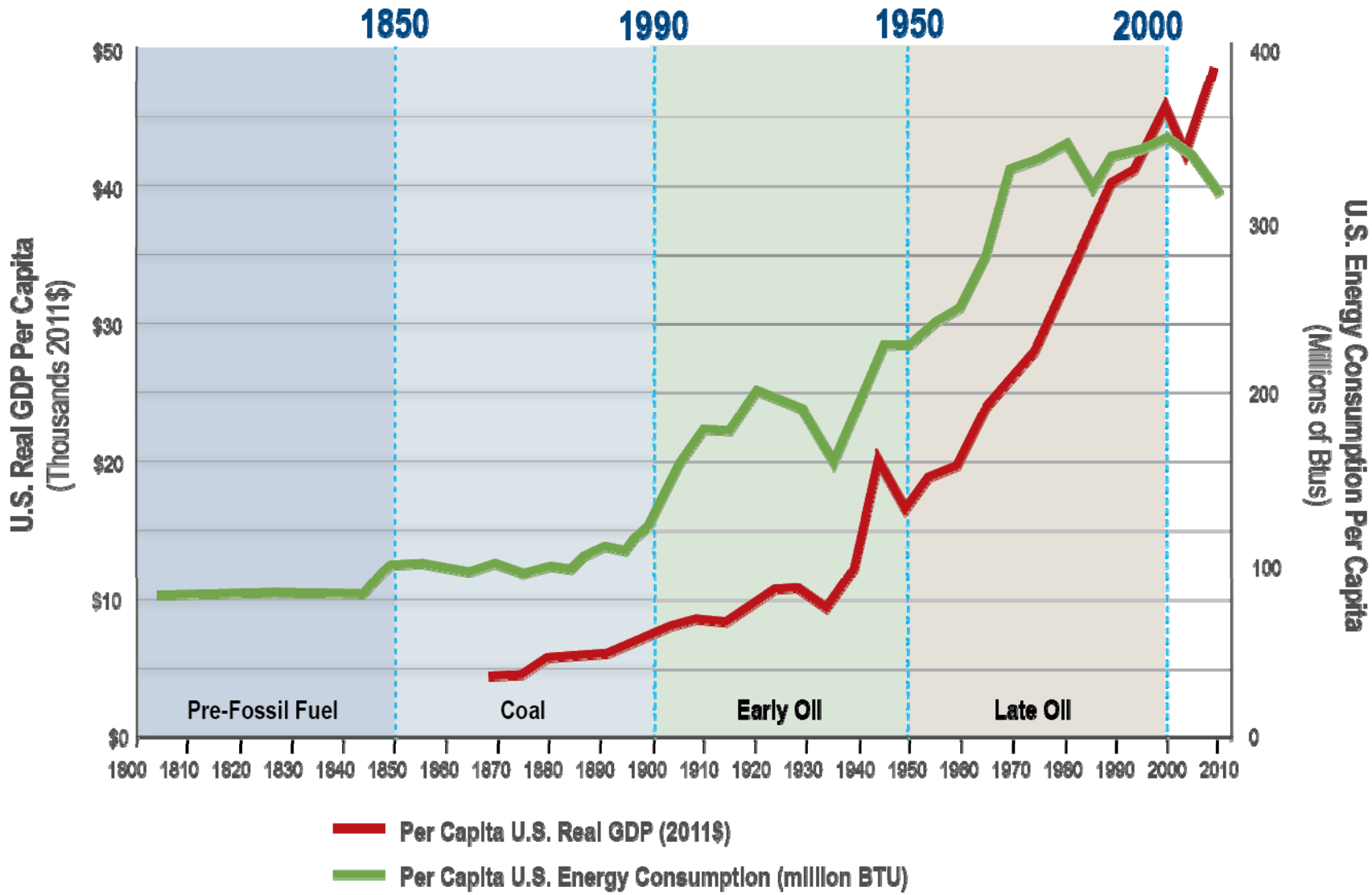
Mobil

Chevron

Gulf

AMOCO

A Mature Technology: Late 1900s



Energy Use and Prosperity (US, 1800-1900)

Our consumption of liquid fuel consumed is difficult to comprehend

arpa·e

Growing Global Demand

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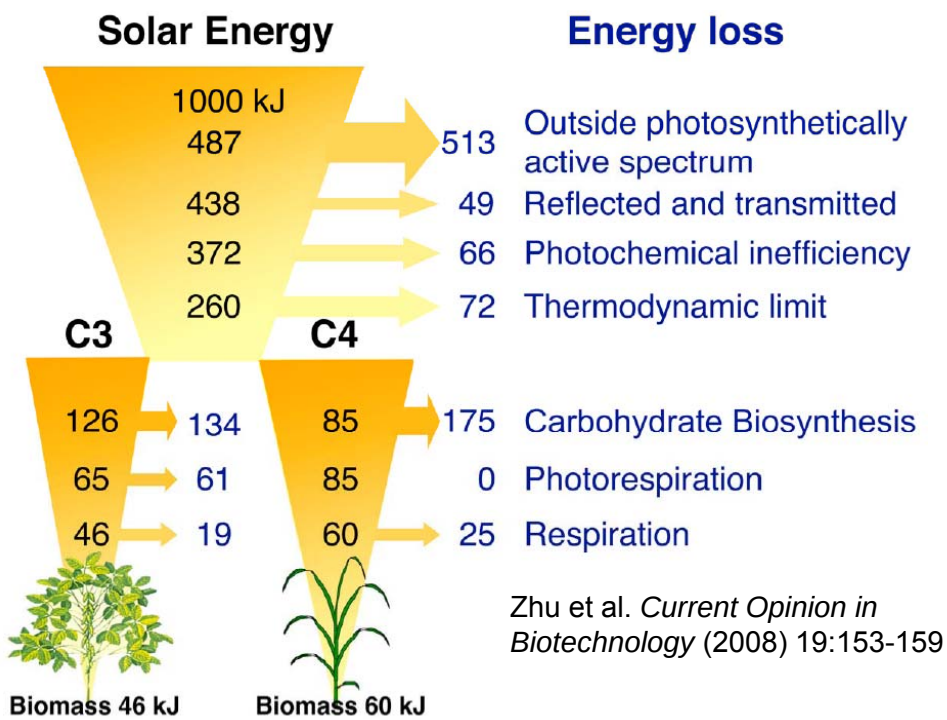
Both modern and ancient liquid fuels are stored solar energy, captured via photosynthesis, in C-C and C-H bonds



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

In practice, photosynthetic energy efficiency is 2-3%...

…which translates to the need for large land/surface area for solar energy collection.

Plants are very good at capturing dilute CO_2 from the atmosphere, but are terrible at capturing solar energy in chemical bonds.

Demonstration-scale projects are nearing the end of construction, cellulosic ethanol/butanol production '12/13

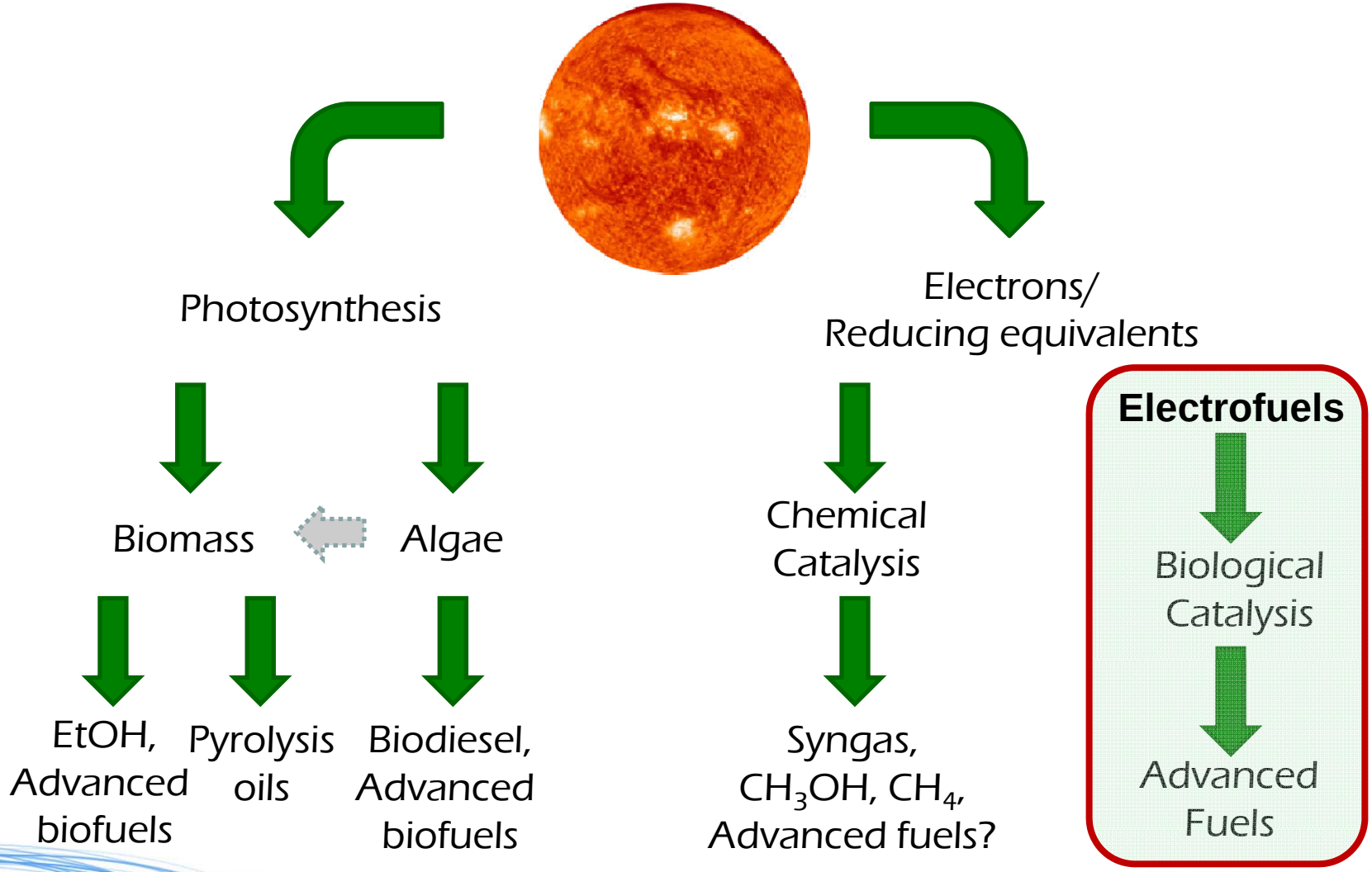
ABENGOA

Fermentation tanks, distillation columns, boiler structure
June 2012

Abengoa Bioenergy
- 25 MGY ethanol from biomass
- 20 MW gross power production
- Construction to be complete '13
- 1,100 dry ton corn stover/day
- Hughoton, KA

The challenge is scale – the average refinery output of the top 17 oil refineries in the U.S. is app. 350,000 barrels per day, or app. 4.5 billion gallons per year.

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



The FOA called for first-of-its-kind non-photosynthetic, autotrophic biofuels production from microorganisms

Primary Objective

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

Requirements

- Anticipated liquid fuel-energy-out to photon/electrical energy-in of the envisioned system; an overall energy efficiency > 1%
- Specify liquid fuel type (diesel fuel, JP-8 aviation fuel, and/or high octane fuels for four-stroke internal combustion engines); liquid fuels 85 research octane or 40 cetane
- Anticipated liquid fuel energy density 32 megajoules per kilogram
- Anticipated liquid fuel heat of vaporization < 0.5 megajoules per kilogram
- Rare earth elements or organic redox shuttles that cannot be deployed economically at scale should be avoided

Electrofuels technologies decouple biofuel production from biomass logistics, and may be more distributed

Current Biofuels	Electrofuels
Requires large, arable land areas; and, production agriculture	Chemoautotrophs assimilate energy directly, no need to “feed” sugar from plants; bypass agriculture
Biomass supply and logistics remain difficult to scale	Expands feedstock flexibility (electricity, H_2, etc.), and moves away from commodity prices
RFS policy has not effectively accelerated the deployment of “cellulosic” or “advanced” biofuels	Currently do not qualify under the RFS, but there are opportunities to influence policy change
Cellulosic refineries are difficult to finance considering economies of scale and uncertainty regarding adequate feedstock supply	Without the need for biomass, may be more distributed, potentially modular, and operate profitably at smaller scales

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ARPA-E contracted 13 projects for 36 months with $48 M Federal investment; $59 M total investment including cost share

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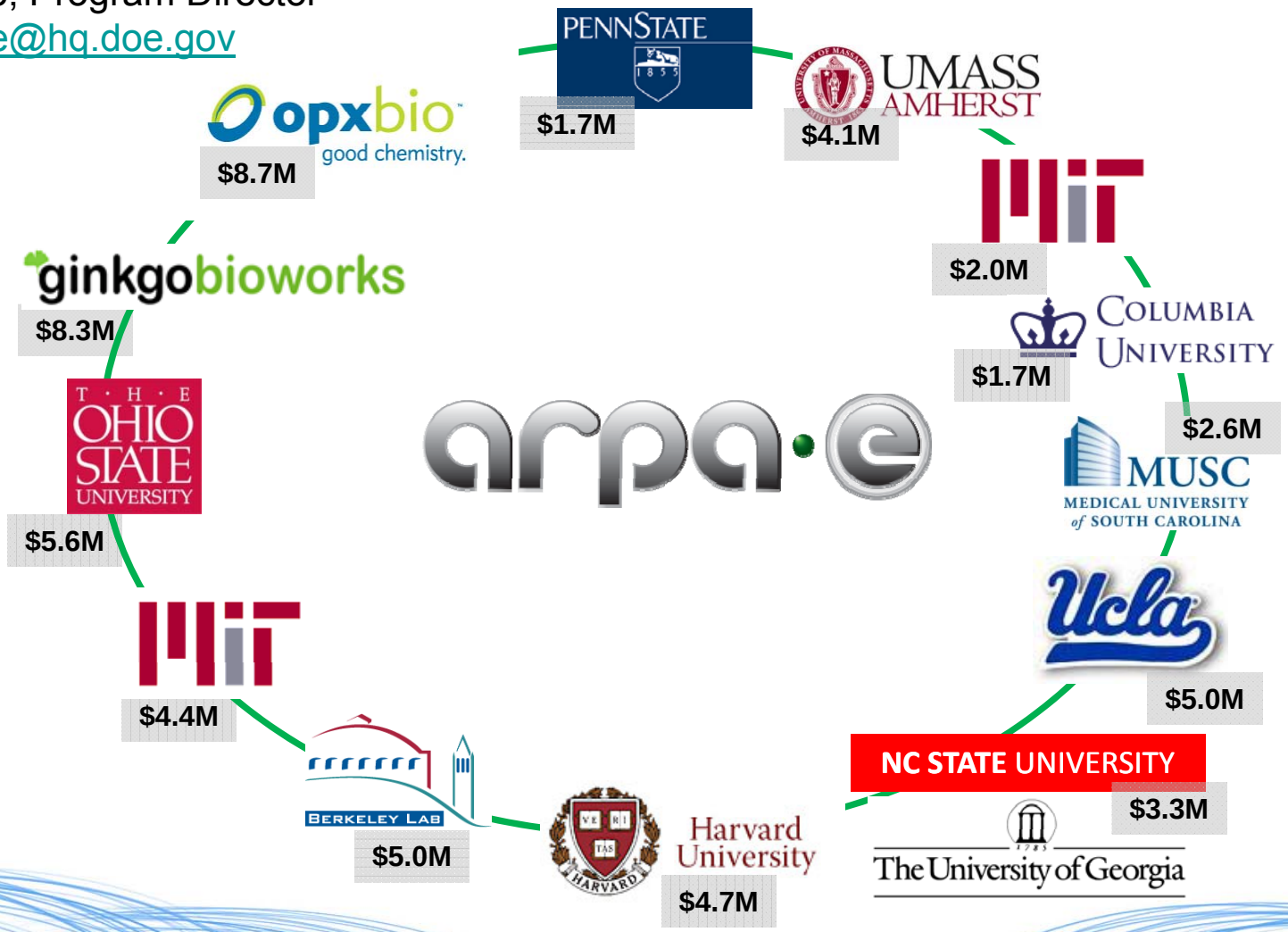
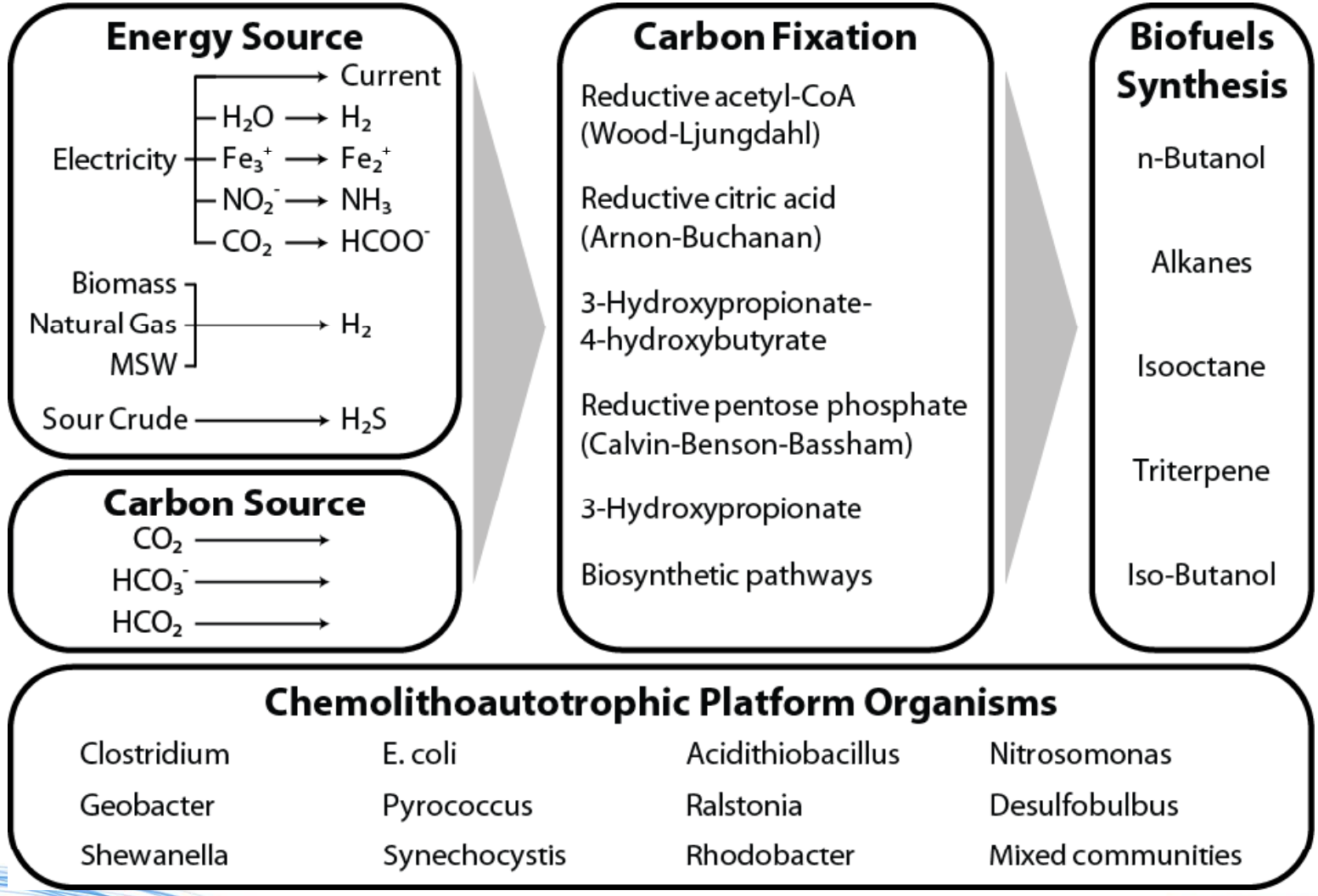


ARPA-E's Electrofuels program targets the use of multiple organisms, energy sources, and metabolic routes to fuels



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* (Lee, J., ed.): Springer, U.S.

ARPA-E funded a variety of approaches for energy assimilation by microorganisms

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

ARPA-E has proactively built a community, engaged stakeholders, and promoted ideas across many forums

Communications

- Advanced Biofuels and Bioproducts Book Chapter
- Numerous conferences presentations
- Popular press articles (e.g. C&E News)

U.S.G. Interagency Outreach & Coordination

- Bioenergy RD&D information sharing and discussion
  - Energy Efficiency and Renewable Energy
  - Office of Science
  - U.S.D.A.
- EPA (Renewable Fuel Standard)

Stakeholder Outreach & Feedback Solicitation

- AIChE SBE Conference on Electrofuels (Nov. 2011)
- DoD relationship building and information sharing
- Engagements with industry groups (e.g. BIO, EPRI)
- Discussions with for-profit industries
- ARPA-E Request for Information (RFI) to engage performers and others not directly in the program
- ARPA-E Energy Innovation Summits

Results

- Elevated the discussion around the potential impact of new, more efficient biofuel technologies
- Begun to expand the definition of what constitutes a biofuel within the U.S.G.
- Garnered interest and acceptance from the biofuels R&D community and industry writ large
- Positioned the ARPA-E program as an attractive area for additional funding

Project performance has rapidly moved beyond the original scope, enabling learning and shifting challenges

Original Scope of Work

- Development of microorganisms capable of chemoautotrophic growth and biofuel production

Primary Technical Needs & Expertise

- Sophisticated molecular biology and metabolic engineering
  - Scalable and high-throughput -omics
  - Microbiology
  - Rapid & cheap gene construction & sequencing
  - New genetic tools

Program Results to Date

- Challenges directly related to genetic tractability have been overcome
- Successful development of microorganism platforms capable of biofuel production from:
  - HCOOH, formate
  - H_2, hydrogen, and
  - Direct current
- Engineering of new, biosynthetic carbon fixation pathways
- The program has produced □ 30 papers
- Performers have filed □15 patent applications

Real Time Learning

- **Productivity & scale** are large, and extremely relevant challenges
- **Innovations are necessary** to improve fuel productivity, from g/L/day to ≥ 2 g/L/hr (such as energy assimilation, reactor design, feedstock technologies)
- **New expertise is necessary**; molecular biologists need chemical engineers, design engineers, cost modelers, plant operators, etc.
- **Energy efficiency** and cost relationship

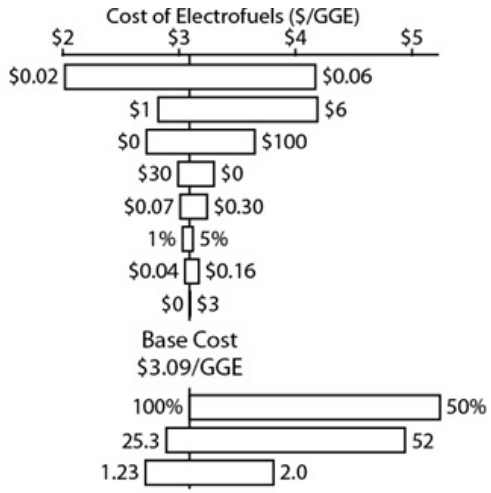
The Electrofuels program has required continuous application of new learning back to the program

- The Electrofuels program was an early-tech stage/technology readiness level (TRL) investment by ARPA-E
- Early stage TRL work involves community building and continuous evaluation of program performance
- ARPA-E has successfully built new technologies to support an entirely new field and has built a strong community to continue technology development.

Performance and cost are now the critical metrics for evaluating the future success of the program

Item	Base Cost	Cost ($/GGE)
Electricity Feedstock	$0.04/kWh	$2.15
Capital Cost	$2/yearly GGE	$0.45
CO_2 Feedstock	$40/ton CO_2	$0.37
O_2 Co-product	$20/ton O_2	-$0.20
Labor and Overhead	$0.15/GGE	$0.15
Maintenance and Taxes	4% of TPI	$0.09
Materials and Waste	$0.08/GGE	$0.08
Water Feedstock	$2/1000 gallons	$0.01
Total Cost	**Supp Calc 8**	**$3.09**

Item	Base Value
Cellular Energy Efficiency	100%
e- Consumed per Butanol Produced	28 e-
Delivered Voltage	1.5 V



- ARPA-E built a preliminary in-house cost model and shared this with performers
- ARPA-E has expanded the model through work with NREL & performers, to provide more precise cost modeling and develop a framework for comparison with cellulosic and algae-based approaches
- Cost modeling has identified many opportunities for cost reduction through further innovation and technology development

Where do we go next?