Bioenergy Research & ARPA-E

Purdue University, BioEnergy Day

Dr. Jonathan Burbaum, Program Director

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Evolution of ARPA-E

2006

Rising Above the Gathering Storm (National Academies)

2007

America COMPETES

2009

American Recovery & Reinvestment Act

2011

2012

$275 MM

<table>
<thead>
<tr>
<th>2009 - 2011</th>
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<tbody>
<tr>
<td>Programs</td>
</tr>
<tr>
<td>Projects</td>
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<tr>
<td>Dollars (MM)</td>
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</table>
Mission

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

- Reduce Energy-Related Emissions
- Reduce Energy Imports
- Improve Energy Efficiency

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

Creating New Learning Curves

R&D for Breakthrough Technologies to Create New Learning Curves

Cost
Performance

Current Learning Curve (Assured Path)

Time | Scale
What makes an ARPA-E project?

1. Impact
   - Aimed at ARPA-E mission areas
   - Shows a credible path to market
   - Has a large practical application

2. Transform
   - Challenges what is possible
   - Disrupts existing learning curves
   - Can leap beyond today’s technologies

3. Bridge
   - Translates science into breakthrough technology
   - The path lacks technical or financial resources
   - Catalyzes new interest and investment

4. Team
   - Comprised of best-in-class people
   - Brings skills from different disciplines
   - Focuses on translation of technologies to the market

Program Development Cycle

- Envision
- Establish
- Execute
- Engage
- Ongoing Technical Review
- Contract Negotiation & Awards
- Project Selection
- Proposal Rebuttal
- Merit Review of Proposals
- FOA Development & Issuance
- Program Conception (Idea / Vision)
- Workshop
- Program Development
- Program Approval
- Program Handoff
- Technology to Market Transition
First Open FOA (2009)

Improved high biomass energy crops

4 HIGH BIOMASS NUE TRAITS

DEDICATED ENERGY CROPS

FIELD TRIALS IN 4 STATES
Reduced pre-treatment costs

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.

Scalable production of macroalgae as a feedstock for isobutanol
### Focused Programs (2010-2012)

<table>
<thead>
<tr>
<th>Transportation</th>
<th>Stationary Power / Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrofuels</td>
<td>HEATS</td>
</tr>
<tr>
<td>BEEST</td>
<td>REACT</td>
</tr>
<tr>
<td>PETRO</td>
<td>AMPED</td>
</tr>
<tr>
<td>MOVE</td>
<td>SBIR/STR</td>
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<tr>
<td></td>
<td>BEETIT</td>
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<td></td>
<td>IMPACCT</td>
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<td></td>
<td>GRIDS</td>
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<td>ADEPT</td>
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<td>GENI</td>
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<td>Solar ADEPT</td>
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Programs focus on white spaces in fuel production:

- **Feedstock**
  - **Conversion**
  - **PETRO**
  - **Algae**
  - **Electrofuels**
  - **Alternative Fuels**

Conversion reactions:

- \( \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{CH}_3\text{OH} + \text{O}_2 \)
Alternative Fuels: A Snapshot

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

Current pathways for liquid fuels from solar energy have low energy efficiency

**Electrofuels**

Chemolithoautotrophs are at the core of a efficient and flexible Electrofuels platform

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Carbon Fixation</th>
<th>Biofuels Synthesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>Reductive acetyl-CoA (Wool-Ljungdahl)</td>
<td>n-butanol</td>
</tr>
<tr>
<td>Electricity</td>
<td>Reductive citric acid (Arnon-Buchanan)</td>
<td>Alkanes</td>
</tr>
<tr>
<td>Biomass</td>
<td>3-Hydroxypropionate</td>
<td>Isooctane</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>4-hydroxybutyrate</td>
<td>Triterpene</td>
</tr>
<tr>
<td>MSW</td>
<td>Reductive pentose phosphate (Calvin-Bensson Bassham)</td>
<td>Iso-lutanol</td>
</tr>
<tr>
<td>Sour Code</td>
<td>3-Hydroxypropionate</td>
<td>Biosynthetic pathways</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Carbon Source</th>
<th>Chemolithoautotrophic Platform Organisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>Clostridium, E. coli, Acidithiobacillus, Nitromonas</td>
</tr>
<tr>
<td>HCO₃⁻</td>
<td>Geobacter, Pyrococcus, Raistonia, Desulfovibus</td>
</tr>
<tr>
<td></td>
<td>Shevannia, Synechocystis, Rhodobacter, Mixed communities</td>
</tr>
</tbody>
</table>

**H₂ consuming bacteria**

Autotrophic production → Free fatty acid extraction → Final fuel upgrading

**Electrochemically produced formate**

Photovoltaic or Electricity → CO₂ → Gasoline substitutes

In-situ electrolysis & Engineered Microbe → Biofuel's → Bacterial cells → formate
Plants Engineered To Replace Oil

Programs focus on white spaces in fuel production

Feedstock → Conversion → PETRO → Electrofuels → Alternative Fuels

Conversion

PETRO

Alternatives

Algae

Conversion

Electrofuels
PETRO’s Approach Complements Other Programs

The Billion Ton Study projects that in excess of 200 million dry tons of biomass crops dedicated to energy will be needed by 2030.

Current pathways in terms of energy & carbon
Carbon efficiency in biofuel production

- Separation of key carbonaceous material from the total plant
- Corn cobs separated from residual plant biomass (leaves, stem, root) excluded
- Refinement of key harvested material into a processable substance
- Starch in corn kernels is made available for conversion
- Overall Carbon Yield: 3.0%
- Overall Fuel Yield: 79 GJ·ha⁻¹·y⁻¹

Photosynthesis Optimization
- Conversion of bioproducts into a liquid vehicle-compatible fuel
- Fermentation to ethanol

PETRO Targets

Developing Dedicated Biofuel Crops

- Yield: 160 GJ/Ha-year (2x corn)
- Cost: < $3 GGE

Heritable Traits

Metabolic engineering

Energy Content: 52 GJ·t⁻¹
PETRO’s impact will be felt in the next decade

**PETRO Funding**

- 3 Years
- 10-14 Years for complete deployment

- **Plant Development**
  - Genetic Transformation
- **Regulatory Approvals**
  - Field Trial Permits
  - Deregulation Petition
- **Intellectual Property**
  - Freedom to Operate
  - Technology Patents
- **Commercial Partners**
  - Cross License/Joint Development
  - Distribution/Strategic Partners
- **financing**
  - $2 Million
  - $30 Million
  - $75 Million

Plants will be ready for field testing at the end of the project period.

Plants being developed under PETRO

- **Oilseed**
  - (Camelina)
- **C₄ Grasses**
  - (Setaria)
- **Trees**
  - (loblolly pine)
- **Other**
  - (sugarcane, sorghum)
  - (tobacco)
  - (Guayule)
  - (tobacco, Giant cane)
Pine trees engineered to produce fuel molecules in addition to providing pulp for paper

Increase production, fuel quality & storage capacity for pine terpenes

Loblolly pine  Ancient source of turpentine  Processed on an industrial scale

Increasing Camelina Productivity for Drop-In Fuels

- Improved carbon capture by up to 60% over current plants.
- Production of high quantities of modified oils and terpenes.
- Enhanced heat and drought tolerance.
Sorghum engineered to produce fuel

- Sweet Sorghum
- ...engineered...
- to make fuel, instead of sugar

Higher yield Camelina with improved energy & CO₂ capture

- Higher light capturing efficiency
- Algae traits for improved fixation
- Higher yields of seed oils
Insightful Keynotes
Unparalleled Showcase and Networking
Compelling Discussions

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