Program Focus

The Biomass Program forms cost-share partnerships with key stakeholders to develop, demonstrate, and deploy technologies for advanced biofuels, bioproducts, and biopower from lignocellulosic and algal biomass.

Cellulosic Ethanol
2012 Cost Target
4 Commercial Facilities under construction

Decade of concentrated focus on RDD&D to convert lignocellulosic biomass to fuel ethanol and other products.

Alternative Light-Duty and Diesel Replacement Fuels

Expansion of scope to include other advanced biofuels such as hydrocarbon fuels (renewable gasoline, diesel, jet fuel), algae-derived biofuels, and biobutanol.
• Design Case:
  – Detailed, peer reviewed process simulation based on ASPEN or Chemcad
  – Establishes cost of production at biorefinery boundary
  – Provides estimate of nth plant capital and operating costs
  – Based on best available information at date of design case
  – Scope: feedstock cost (harvest, collection, storage, grower payment), feedstock logistics (handling, size reduction, moisture control), conversion cost, profit for biorefinery
  – Excludes: taxes, distribution costs, tax credits or other incentives

• State of technology (SOT): annual updates to measure progress
  – Assessment of the current state of development for a given technology pathway
  – Based on best available information from literature, bench scale tests, integrated pilot scale operations
BC Conversion to Cellulosic Ethanol

2012 Target and State of Technology

- Developed pretreatment/conditioning strategy (bench and pilot scale) capable of releasing 90% of the hemicellulosic sugars.
- Reduced Enzyme Costs >20x and developed strategy for further reductions.
- Developed Industrially Relevant Strains Capable of Converting C5 and C6 Cellulosic Sugars at conversion yields of 85-95% and tolerant of ethanol titers of >70 g/L.
- Built/adapted fully integrated pilot scale capability for 2012 demonstration.
- Developed peer reviewed model for extrapolation to commercial scale.
- Demonstrated Cost Reductions that make cellulosic ethanol production cost competitive with gasoline production at ~$110/bbl crude oil.
- Commercial demonstrations of similar design coming online (Poet, Abengoa).

### Minimum Ethanol Selling Price ($/gal)

<table>
<thead>
<tr>
<th>Year</th>
<th>2011 Target</th>
<th>2011 Washed Solids</th>
<th>2011 Whole Slurry</th>
<th>2012 Targets</th>
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<tbody>
<tr>
<td>2007</td>
<td>$2.56</td>
<td>$2.37</td>
<td>$2.15</td>
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<tr>
<td>2008</td>
<td>$3.57</td>
<td>$3.18</td>
<td>$2.77</td>
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<tr>
<td>2009</td>
<td>$4.27</td>
<td>$3.85</td>
<td>$3.64</td>
<td>$3.18</td>
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<tr>
<td>2010</td>
<td>$5.33</td>
<td>$4.70</td>
<td>$4.27</td>
<td>$3.85</td>
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<tr>
<td>2011</td>
<td>$6.90</td>
<td>$6.00</td>
<td>$5.33</td>
<td>$4.70</td>
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<tr>
<td>2012</td>
<td>$9.16</td>
<td>$8.00</td>
<td>$7.16</td>
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### Feedstock

<table>
<thead>
<tr>
<th>Value</th>
<th>2011 Target</th>
<th>2011 Washed Solids</th>
<th>2011 Whole Slurry</th>
<th>2012 Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedstock Cost ($/dry ton)</td>
<td>$59.60</td>
<td>$59.60</td>
<td>$59.60</td>
<td>$58.50</td>
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</table>

### Pretreatment

<table>
<thead>
<tr>
<th>Value</th>
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<th>2011 Washed Solids</th>
<th>2011 Whole Slurry</th>
<th>2012 Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solids Loading (wt%)</td>
<td>30%</td>
<td>30%</td>
<td>30%</td>
<td>30%</td>
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<tr>
<td>Xylan to Xylose (including enzymatic)</td>
<td>88%</td>
<td>88%</td>
<td>78%</td>
<td>90%</td>
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<td>Xylan to Degradation Products</td>
<td>5%</td>
<td>5%</td>
<td>6%</td>
<td>5%</td>
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</table>

### Conditioning

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<tr>
<th>Value</th>
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<th>2011 Washed Solids</th>
<th>2011 Whole Slurry</th>
<th>2012 Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia Loading (mL per L Hydrolyzate)</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Hydrolyzate solid-liquid separation</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Xylose Sugar Loss</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
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<tr>
<td>Glucose Sugar Loss</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>0%</td>
</tr>
</tbody>
</table>

### Enzymatic Hydrolysis & Fermentation

<table>
<thead>
<tr>
<th>Value</th>
<th>2011 Target</th>
<th>2011 Washed Solids</th>
<th>2011 Whole Slurry</th>
<th>2012 Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Solids Loading (wt%)</td>
<td>20%</td>
<td>17.5%</td>
<td>17.5%</td>
<td>20%</td>
</tr>
<tr>
<td>Combined Saccharification &amp; Fermentation Time (d)</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Corn Steep Liquor Loading (wt%)</td>
<td>0.60%</td>
<td>0.25%</td>
<td>0.25%</td>
<td>0.25%</td>
</tr>
<tr>
<td>Overall Cellulose to Ethanol</td>
<td>86%</td>
<td>89%</td>
<td>80%</td>
<td>86%</td>
</tr>
<tr>
<td>Xylose to Ethanol</td>
<td>85%</td>
<td>85%</td>
<td>85%</td>
<td>85%</td>
</tr>
<tr>
<td>Arabinose to Ethanol</td>
<td>80%</td>
<td>47%</td>
<td>47%</td>
<td>85%</td>
</tr>
</tbody>
</table>

#### 2012 Cellulosic Ethanol Successful Demonstration

- Developed pretreatment/conditioning strategy (bench and pilot scale) capable of releasing 90% of the hemicellulosic sugars.
- Reduced Enzyme Costs >20x and developed strategy for further reductions.
- Developed Industrially Relevant Strains Capable of Converting C5 and C6 Cellulosic Sugars at conversion yields of 85-95% and tolerant of ethanol titers of >70 g/L.
- Built/adapted fully integrated pilot scale capability for 2012 demonstration.
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- Demonstrated Cost Reductions that make cellulosic ethanol production cost competitive with gasoline production at ~$110/bbl crude oil.
- Commercial demonstrations of similar design coming online (Poet, Abengoa).
Pathway Selection Process

**Completed Activities**

- **March 2012**
  - 18 potential pathways identified, 13 selected to move forward with initial analysis
- **July 2012**
  - 8 pathways selected from original 13
- **September 2012**
  - PNNL/NREL completed joint milestone report detailing analysis effort
- **October 2012**
  - Pathways prioritized and timeline for analysis developed
- **September 2013**
  - Full design cases completed for 4 pathways (Fermentation of Lignocellulosic Sugars, ALU, AHTL, Fast Pyrolysis)

**Planned Activities**

- **September 2013**
  - Year-by-year targets completed for 2013 pathways. Full design cases completed for 4 additional pathways (ex situ and in situ Catalytic Pyrolysis, Catalytic Upgrading of Lignocellulosic Sugars, Syngas to Hydrocarbons).

**Criteria for downselect included:**

- Feasibility of achieving programmatic cost goal of $3/gal
- Near/Mid/Long-term techno-economic potential
- Potential national impact
- Feedstock availability/flexibility
- Data availability across the full pathway
- Co-product economics
- Potential volumetric impact in 2030
- Environmental Sustainability

**Planned Activities**

- **March 2013**
  - Preliminary cost goals published in MYPP and key areas of research identified
### Pathways included in initial analysis

<table>
<thead>
<tr>
<th>Technology Area</th>
<th>Pathway</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sugars</strong></td>
<td>Fermentation of Sugars to Hydrocarbons</td>
</tr>
<tr>
<td></td>
<td>Catalytic Upgrading of Sugars to Hydrocarbons</td>
</tr>
<tr>
<td></td>
<td>Fermentation of Sugars via Heterotrophic Algae to Hydrocarbons</td>
</tr>
<tr>
<td><strong>Oils</strong></td>
<td>Fast Pyrolysis and Upgrading</td>
</tr>
<tr>
<td></td>
<td>Catalytic Pyrolysis – ex situ</td>
</tr>
<tr>
<td></td>
<td>Catalytic Pyrolysis – in situ</td>
</tr>
<tr>
<td></td>
<td>Hydropyrolysis</td>
</tr>
<tr>
<td></td>
<td>Hydrothermal Liquefaction</td>
</tr>
<tr>
<td></td>
<td>Solvent Liquefaction</td>
</tr>
<tr>
<td><strong>Algae</strong></td>
<td>Whole Algae Hydrothermal Liquefaction (ABHTL)</td>
</tr>
<tr>
<td></td>
<td>Algal Lipid Extraction Upgrading to Hydrocarbons (ALU)</td>
</tr>
<tr>
<td><strong>Gaseous Intermediates</strong></td>
<td>Syngas to Methanol to Triptyls</td>
</tr>
<tr>
<td></td>
<td>Syngas Fermentation and Upgrading to Hydrocarbons</td>
</tr>
<tr>
<td></td>
<td>Landfill Gas Upgrading to Hydrocarbons</td>
</tr>
<tr>
<td></td>
<td>Gasification with Fermentation to Oxygenates</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td>Anaerobic digestion to CNG</td>
</tr>
<tr>
<td></td>
<td>Anaerobic digestion to Hydrocarbons via GTL</td>
</tr>
<tr>
<td></td>
<td>Coal Biomass to Liquids</td>
</tr>
<tr>
<td>Pathway</td>
<td>Description</td>
</tr>
<tr>
<td>---------------------------------------------</td>
<td>------------------------------------------</td>
</tr>
<tr>
<td>Fermentation of Lignocellulosic Sugars</td>
<td>fermentation of lignocellulosic sugars to HCs</td>
</tr>
<tr>
<td>Catalytic Conversion of Lignocellulosic Sugars</td>
<td>Catalytic conversion of lignocellulosic sugars to HCs</td>
</tr>
<tr>
<td>Ex situ Catalytic Pyrolysis</td>
<td>Pyrolysis, vapor-phase upgrading, liquid-phase finishing</td>
</tr>
<tr>
<td>In situ Catalytic Pyrolysis</td>
<td>Catalytic pyrolysis, liquid-phase finishing</td>
</tr>
<tr>
<td>Algal Lipid Upgrading (ALU)</td>
<td>Open pond algae, solvent extraction, hydrotreating</td>
</tr>
<tr>
<td>Algal Biofuels Hydrothermal Liquefaction (ABHTL)</td>
<td>Open pond algae, hydrothermal liquefaction, hydrotreating</td>
</tr>
<tr>
<td>Syngas to MeOH to High Triptyls</td>
<td>Syngas to MeOH to high Triptyls</td>
</tr>
</tbody>
</table>
Biofuel Production Costs
Detailed Example of renewable fuels via pyrolysis

Renewable gasoline and diesel via pyrolysis

Modeled minimum conversion cost ($/gal total fuel)

<table>
<thead>
<tr>
<th>Year</th>
<th>State of Technology</th>
<th>2012 Projection</th>
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</thead>
<tbody>
<tr>
<td>Feedstocks</td>
<td>$0.30</td>
<td>$0.29</td>
</tr>
<tr>
<td>Fast Pyrolysis</td>
<td>$0.82</td>
<td>$0.74</td>
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<tr>
<td>Upgrading</td>
<td>$4.69</td>
<td>$4.55</td>
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<tr>
<td>Fuel Finishing</td>
<td>$0.54</td>
<td>$0.99</td>
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<tr>
<td>Balance of Plant</td>
<td>$0.75</td>
<td>$0.52</td>
</tr>
</tbody>
</table>

49% overall cost reduction (2012 - 2017)

Pyrolysis costs by unit and projected cost reductions through R&D

- Feed Drying, Sizing, Fast Pyrolysis
- Upgrading to stable oil
- Fuel Finishing
- Balance of Plant

5% reduction
34% reduction
4% reduction
2% reduction

5% reduction
Fermentation of Sugars to Hydrocarbons

Rationale for Selecting Pathway

- Better utilization of biomass derived carbon sources (higher yields)
- Path to 2017 cost targets achievable via reasonable co-product credits
- Leverage previous front-end modeling and research through sugar production
- Back-integration and lessons-learned from IBR projects hasten process development
Catalytic Upgrading of Sugars to Hydrocarbons

Rationale for Selecting Pathway
• Better utilization of biomass derived carbon sources (higher yields)
• Path to 2017 cost targets achievable via reasonable co-product credits
• Leverage previous front-end modeling and research through sugar production
• Back-integration and lessons-learned from IBR projects hasten process development
**Rationale for Selecting Pathway**

- Raw algal oil intermediate is expected to require relatively mild upgrading (hydrotreating) to finished fuels at marginal cost.
- Algal biomass can be tailored to produce specific components for fuel and/or product markets (potential for high-value coproducts).
- Nutrient recycle and heat and power integration through anaerobic digestion improves process economics and sustainability profile.
Whole Algae Hydrothermal Liquefaction (ABHTL)

Heat Integration & Power Generation

Feed Handling → Hydrothermal Liquefaction (HTL) → Liquid Bio-Oil → Catalytic Hydrodeoxygenation → Product Fractionation

WWT

Hydrogen Plant Steam Reformer, Shift, PSA

Naphtha → Diesel

Wet Whole Algae

Rationale for Selecting Pathway
• HTL both extraction and conversion process (50-70% of carbon captured)
• Higher yield than other known extractions
• HTL is wet process using only water, no drying or solvent recovery needed
• Oil phase lower in oxygen content and easy to upgrade to hydrocarbons
• CHG is faster, smaller, and more complete than Anaerobic Digestion (AD)
• Leverages NABC, NAABB, and new AOP work in FY13
Fast Pyrolysis and Upgrading

Rationale for Selecting Pathway
- Continuation of existing pathway (rationale unchanged)
Rationale for Selecting Pathway
- Oil is lower in oxygen and likely easier to upgrade to hydrocarbons than fast pyrolysis derived bio-oil
- Greater control of gas/solid/liquid distribution as compared to fast pyrolysis
- May have a lower catalyst inventory
- Pathway R&D will facilitate upgrading step chemistry understanding and optimum catalyst/operating conditions
In situ Catalytic Pyrolysis

**Rationale for Selecting Pathway**
- Requires only one liquefaction reactor and will have lower CapEX
- May have a lower OpEx if larger size feedstock particles are acceptable
- Oil is lower in oxygen and likely easier to upgrade to hydrocarbons than fast pyrolysis derived bio-oil
- Leverages ex-situ Catalytic Pyrolysis R&D upgrading step chemistry understanding and optimum catalyst/operating conditions
Syngas to Methanol to High Triptyls

Rationale for Selecting Pathway
- Exploits mixed alcohol synthesis catalysts advances, leverages existing work in gasification and syngas cleanup
- Opportunity to improve catalyst performance (selectivity, lifetime, coking) to enable higher hydrocarbon yields
- Process intensification opportunity
Recent Budget History

Fiscal Year 2009-13 Budget

<table>
<thead>
<tr>
<th>Category</th>
<th>FY09</th>
<th>FY09 ARRA</th>
<th>FY10</th>
<th>FY11</th>
<th>FY12</th>
<th>FY13 Request</th>
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<tr>
<td>SBIR/STTR</td>
<td>$2,716</td>
<td>$4,281</td>
<td>$8,234</td>
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<td>Biopower/Stoves</td>
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<td>Analysis/Sustain</td>
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<td>Int Biorefineries</td>
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<td>Algal Conversion Tech.</td>
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<td>$21,440</td>
<td>$5,971</td>
<td>$6,787</td>
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Dollars in Thousands

Fiscal Year 2009-13 Budget
Fundamentals in Direct Liquefaction of Lignocellulose and Bio-Oil Upgrading – $15M
• Improve the fundamental understanding of how lignin, hemicellulose, and cellulose thermally depolymerized during biomass pyrolysis and how inorganic content impacts bio-oil production and upgrading processing to final fuels. Support all direct liquefaction technologies.

Algal Biomass Yield (ABY) – $4.4M – Supports algae pathways
• Improve downstream processing with the goal of lowering the cost of algae processing by improving process efficiency and scalability

Feedstock Logistics - $5.7M – Supports all pathways
• Design, build and demonstrate variable rate agriculture residue removal systems to increase sustainable volumes & improve feedstock quality
• Develop systems that produce infrastructure-compatible feedstock such as pre-conversion technologies that produce feedstocks that seamlessly integrate into existing solids and liquids handling infrastructure
• PDU deployment with partners