Bioenergy: Science, Technology, Sustainability

Tom Richard
Penn State University
www.bioenergy.psu.edu
Potential of underused renewable energy sources

From: Basic Research Needs for Solar Energy Utilization, DOE 2005
Imagineing a Sustainable World

Sustainable Resources
- Sunlight
- Wind
- Ocean/hydro
- Geothermal
- Nuclear
- Minerals

Primary Intermediates
- Biomass
- Electricity

Secondary Intermediates
- Animals
- Biofuels (Organic)
- Hydrogen
- Batteries

Human Needs
- Food
- Energy
- Motors/Lights
- Heat
- Transport
- Materials
  - Organic
  - Inorganic

Choices
- Blue lines

Sole Supply
- Red lines

Lee Lynd, Dartmouth College
Principal Biomass Conversion Pathways

- Production
- Collection
- Processing
- Storage
- Transportation

- Thermochemical Conversion
  - Combustion
  - Gasification
  - Pyrolysis
  - Refining

- Biochemical Conversion
  - Anaerobic/Fermentation
  - Aerobic Processing
  - Biophotolysis

- Physicochemical
  - Esters
  - Alkanes

- Energy
  - Heat
  - Electricity

- Fuels
  - Solids
  - Liquids
  - Gases

- Products
  - Chemicals
  - Materials

Biomass Feedstock → Integrated Biorefinery → Value added products

Bryan Jenkins, UC Davis
Thermochemical Technologies

Biomass

Gasification → Cleanup → Synthesis

Pyrolysis → Conversion or Collection → Purification

Other Conversion * → Separation → Purification

• Hydrogen
• Alcohols
• FT Gasoline
• FT Diesel
• Olefins
• Oxochemicals
• Ammonia
• SNG

• Hydrogen
• Olefins
• Oils
• Specialty Chem

* Examples: Hydrothermal Processing, Liquefaction, Wet Gasification

Bryan Jenkins, UC Davis
Brazil and the US are the leaders in ethanol fuel production. They use the “easy way” to make ethanol.

Dan Cosgrove, Penn State
Cell walls → fuel

Slow & expensive step

“recalcitrance”

sugars

enzyme digestion

chemical pretreatments

Parallel strands of glucose polymers

Fermentation

ethanol

Plant cell wall

Cellulose, Hemicellulose, + lignin

Cellulose microfibril

Dan Cosgrove, Penn State
Economic Drivers: Biological Processing of Lignocellulose

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Cost ($/kg)</th>
<th>Enzyme</th>
<th>Operating (non-enzyme)</th>
<th>Capital (non-enzyme)</th>
<th>Feedstock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn (dry mill)</td>
<td>$0.152</td>
<td>$0.05</td>
<td>$0.10</td>
<td>$0.15</td>
<td>$0.083</td>
</tr>
<tr>
<td>Cellulosic Biomass</td>
<td>$0.168</td>
<td>$0.05</td>
<td>$0.10</td>
<td>$0.15</td>
<td>$0.083</td>
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</tbody>
</table>

Laser and Lynd, 2007
Net energy and net greenhouse gases for gasoline, six studies, and three cases

The Carbon Debt Mortgage from Land Use Change

Maximum Nitrogen Load Changes for Biofuels

Millions of pounds per year of nitrogen delivered from the Chesapeake Bay watershed to the Bay under five modeling scenarios.

Assumptions for Alternative Scenarios:
- **Corn**: 300,000 additional acres of corn with typical levels of management practices
- **Soybeans**: 300,000 additional acres of soybeans with typical levels of management practices
- **300K Switchgrass**: 300,000 acres of switchgrass, converted primarily from hay and pastureland, with no fertilization
- **Corn with Cover Crops**: Cover crops on all existing and new (additional 300,000) corn acres and one quarter of all other row crops, watershed-wide.
- **1M Switchgrass**: 1 million acres of switchgrass, converted primarily from hay and pastureland, with no fertilization

SOURCE: U.S. EPA CHESAPEAKE BAY PROGRAM OFFICE
Five Sustainable Sources

- Organic Wastes
- Algae (?)
- Perennial Crops
- 21st Century Forestry
- Multi-functional Agriculture
Crop Yields (U.S. except Cane):
- Near-term cellulosic: 5 dry ton/acre
- Long-term cellulosic: 15 dton/acre
- Corn: 160 bushel/acre
- Cane: 3 tons sugar (dry)/acre
- Soy: 42 bushel/acre

Fuel Yields:
- Cellulosic ethanol 91 gal gasoline eq./ton (RBAEF)
- Corn ethanol: 2.8 gal/bushel
- Soy oil: 18% of bean (dry basis)
- 0.47 kg ethanol/kg sugar
- Biodiesel yield: 0.95 kg/kg soy oil
Quantitative evaluation of land use impacts (global)

- Double crops
- Pasture intensification
- Diet
- Land-efficient feed rations
- Increased crop productivity
- Forest and ag residues
- Feed/feedstock coproduction
- Marginal lands
- Vehicle efficiency, Smart growth

Population
- Per capita mobility
- Diet

Demand-Reducing
-3 -2 -1 0 +1 +2 +3 Demand-Increasing

Multiple of Current Transportation Fuel Demand
Global Sustainable Bioenergy: Feasibility & Implementation Paths - “GSB Project”

Project initiated (June, 2009)

- International Organizing Committee formed
- Joint statement in Issues in Science and Technology
- Web site launched

**Key Question:** Is it physically possible for bioenergy to meet a substantial fraction of future world mobility and/or electricity demand while our global society also meets other important needs.

**Staged structure**

1. Meetings, assemble international team, scope project, get support
2. Address key question posed above unconstrained by current realities
3. Work back to the present considering policy, economic, transition, and development issues

“High Beams” Approach
<table>
<thead>
<tr>
<th>Representation</th>
<th>Host Institutions, Location</th>
<th>Meeting Chairs/ Organizing Committee Members</th>
<th>Dates</th>
</tr>
</thead>
</table>
| European Union    | Kluyver Center for Genomics of Industrial Fermentations, Delft, The Netherlands | • Andre Faaij, Utrecht University  
• Patricia Osseweijer, Delft University of Technology | February, 24-26, 2010 |
| Africa            | University of Sellenbosch, Stellenbosch, South Africa | • Emile van Zyl, University of Stellenbosch  
• August Temu, World Agroforestry Centre, Nairobi | March, 17-19, 2010 |
| South America     | University of São Paulo, São Paulo, Brazil | • José Goldemberg, University of São Paulo  
• Carlos Henrique de Brito Cruz, FAPESP, São Paulo | March, 22-24, 2010 |
| North America     | ▪ University of Minnesota, Minneapolis/St. Paul, USA | • John Foley, University of Minnesota | May, 2010 |
| Asia, Oceania     | TBD                         | Reinhold Mann, Battelle Science and Technology, Malaysia | June 2010? |

**Steering Committee:** Nathanael Greene, Natural Resources Defense Council  
Lee Lynd (Chair), Dartmouth, Mascoma Corp.  
Tom Richard, Pennsylvania State University
• Sustainable forests and agricultural systems are a prerequisite for sustainable biomass energy systems