Liquid Transportation Fuels from Coal and Biomass

Technological Status, Costs, and Environmental Impacts

Panel on Alternative Liquid Transportation Fuels

DOE LDV Workshop  7-26-10
Mike Ramage and Jim Katzer
CHARGE TO THE ALTF PANEL

• Evaluate technologies for converting biomass and coal to liquid fuels that are deployable by 2020.
  • Current and projected costs, and CO$_2$ emissions.
  • Key R&D and demonstration needs.
  • Technically feasible supply of liquid fuels

• Estimate the potential supply curve for liquid fuels produced from coal or biomass.

• Evaluate environmental, economic, policy, and social factors that would enhance or impede development and deployment.

• Review other alternative fuels that would compete with coal-based and biomass-based fuels over the next 15 yr.

• No policy recommendations.
PANEL ON ALTERNATIVE LIQUID TRANSPORTATION FUELS

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G. DAVID TILMAN, Vice Chair        U.of Minnesota,
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ROBERT HALL                        Amoco Corporation (retired)
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CHRISTOPHER SOMERVILLE            Energy BioSciences Institute
GREGORY STEPHANOPOULOS             MIT
JAMES L. SWEENEY                   Stanford University
As Detailed in the Following Slides, the Panel’s Analyses Showed That

1. About 500 million tons/year of biomass can be sustainably produced in the US without incurring significant direct or indirect greenhouse gas emissions.

2. Liquid transportation fuels from coal and biomass have potential to supply 2-3 MBPD of oil equivalent fuels with significantly reduced CO₂ emissions by 2035.

3. Timely commercial deployment may hinge on adoption of fuel mandates and a carbon price, and on accelerated federal investment in essential technologies.
BIOMASS SUPPLY—Key Assumptions

• No indirect land use change and minimum competition with food.
• Corn stover—Adequate corn stover be left in the field to protect and maintain soil resources.
• Dedicated fuel crops—Biomass feedstock be produced on 24 million acres of CRP land in 2020.
• Woody biomass—Estimates based on reports by Milbrandt (2005) and Perlack et al. (2005).
• Hay and wheat straws—Yield increase over time = historic increase.
## Estimated Lignocellulosic Feedstock That Could Potentially Be Produced for Biofuel

<table>
<thead>
<tr>
<th>Feedstock Type</th>
<th>Current</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Millions of dry tons</td>
<td></td>
</tr>
<tr>
<td>Corn stover</td>
<td>76</td>
<td>112</td>
</tr>
<tr>
<td>Wheat and grass straw</td>
<td>15</td>
<td>18</td>
</tr>
<tr>
<td>Hay</td>
<td>15</td>
<td>18</td>
</tr>
<tr>
<td>Dedicated fuel crops</td>
<td>104</td>
<td>164</td>
</tr>
<tr>
<td>Woody residues(^a)</td>
<td>110</td>
<td>124</td>
</tr>
<tr>
<td>Animal manure</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>Municipal solid waste</td>
<td>90</td>
<td>100</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>416</strong></td>
<td><strong>548</strong></td>
</tr>
</tbody>
</table>

\(^a\)Woody residues currently used for electricity generation are not included in this estimate.
BIOMASS COSTS

Biomass costs include costs of:

• Nutrient replacement.
• Harvesting and maintenance.
• Transportation and storage.
• Seeding.
• Opportunity costs (for example, cropland rental costs).

The panel reviewed the literature and determined a low cost, a baseline cost, and a high cost. See Appendix H for list of references used.
## BIOMASS COSTS

<table>
<thead>
<tr>
<th>Biomass</th>
<th>Estimated in 2008&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Projected in 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn stover</td>
<td>110</td>
<td>86</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>151</td>
<td>118</td>
</tr>
<tr>
<td>Miscanthus</td>
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<td>Prairie grasses</td>
<td>127</td>
<td>101</td>
</tr>
<tr>
<td>Woody biomass</td>
<td>85</td>
<td>72</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>70</td>
<td>55</td>
</tr>
</tbody>
</table>

<sup>a</sup>2008 costs = baseline costs
BIOCHEMICAL CONVERSION STATUS

• Technology Ready for Deployment by 2020
  • Cellulosic biomass converted to sugars then ethanol
  • Key challenges freeing sugars from biomass structure
  • Conversion of cellulosic biomass to ethanol in early commercial scale-up

• Technologies Ready for Deployment After 2020
  • Catalytic conversion biomass sugars to biobutanol or hydrocarbon fuels – active development
  • Bacteria/based direct routes to fuels – active research
  • Algal biofuels - How and where to grow algae?
THERMOCHEMICAL CONVERSION STATUS

• Technology Ready for Deployment by 2020
  • Indirect Liquefaction
    • Gasification, followed by Fischer-Tropsch, or Methanol-to-Gasoline – commercially deployable now
    • Integrated Gasification, Fischer-Tropsch, or Methanol-to-Gasoline with CCS needs commercial demonstration now
  • Direct Liquefaction looks like a poor choice for the U.S.
  • Geologic Storage of CO₂ must be demonstrated by 2015, for 2020 deployment

• Feedstocks
  Coal, Biomass, and Coal + Biomass
BIOCHEMICAL\textsuperscript{a} AND THERMOCHEMICAL\textsuperscript{b} CONVERSION—KEY ASSUMPTIONS

The panel assumes in its analyses that

- Conversion plants that use biomass consume 4000 dry tons of biomass per day.
- Coal and biomass are combined at a ratio of 60:40 on an energy basis.
- Conversion plants that use coal only have a production capacity of 50,000 bbl/day of gasoline equivalent.
- Coal cost = $42/ton, and biomass cost = $101/dry ton.
- Capital costs were updated to 2007 dollars.

\textsuperscript{a}Modeling done with SuperPro Designer and estimates of a corn-grain ethanol plant cross-checked with literature values.
\textsuperscript{b}Modeling done with AspenPlus.
### COMPARISON OF LIFE-CYCLE COSTS—Effect of a $50/tonne CO₂ price

<table>
<thead>
<tr>
<th>Fuel Product</th>
<th>Cost without CO₂ Equivalent price ($/bbl of gasoline equivalent)</th>
<th>Cost with CO₂ Equivalent price of $50/tonne ($/bbl of gasoline equivalent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline at crude-oil price of $60/bbl</td>
<td>75</td>
<td>95</td>
</tr>
<tr>
<td>Gasoline at crude-oil price of $100/bbl</td>
<td>115</td>
<td>135</td>
</tr>
<tr>
<td>Cellulosic ethanol</td>
<td>115</td>
<td>110</td>
</tr>
<tr>
<td>Biomass-to-liquid fuels without carbon capture and storage</td>
<td>140</td>
<td>130</td>
</tr>
<tr>
<td>Biomass-to-liquid fuels with carbon capture and storage</td>
<td>150</td>
<td>115</td>
</tr>
<tr>
<td>Coal-to-liquid fuels without carbon capture and storage</td>
<td>65</td>
<td>120</td>
</tr>
<tr>
<td>Coal-to-liquid fuels with carbon capture and storage</td>
<td>70</td>
<td>90</td>
</tr>
<tr>
<td>Coal-and-biomass-to-liquid fuels without carbon capture and storage</td>
<td>95</td>
<td>120</td>
</tr>
<tr>
<td>Coal-and-biomass-to-liquid fuels with carbon capture and storage</td>
<td>110</td>
<td>100</td>
</tr>
</tbody>
</table>
COMPARISON OF CO$_2$ LIFE-CYCLE EMISSION
SUPPLY OF COAL-AND-BIOMASS-TO-LIQUID—TECHNICALLY FEASIBLE
SUPPLY OF ALTERNATIVE LIQUID FUELS—COMMERCIAL DEPLOYMENT

Cellulosic Ethanol
- 0.5 million bbl of gasoline eq./day by 2020,
- Then 1.7 million bbl of gasoline eq./day by 2035.
- CO₂ emissions close to zero

Coal-and-Biomass-to-Liquid (CBTL) Fuels
- CBTL fuels could reach 2.5 million barrels of gasoline eq./day by 2035.
- CO₂ emissions close to zero with CCS

Coal-to-Liquid (CTL) Fuels
- Then CTL fuels can reach 3 million bbl of gasoline eq./day by 2035, with a 50 percent increase in US coal production.
- If CCS used, CO₂ emission equivalent to petroleum fuels
BARRIERS TO DEPLOYMENT

• Developing a well-organized and sustainable cellulosic biofuel industry

• Implementing commercial demonstrations of conversion processes ASAP

• Completing megatonne geologic storage demonstrations ASAP

• Developing more efficient, economical pretreatment and improving enzymes to free up sugars

• Permitting and constructing tens to hundreds of conversion plants

• Approaches that recognize commodity prices, especially oil prices, vary widely.
CONCLUSION

Liquid transportation fuels from coal and biomass have potential to supply 2-3 MBPD of oil equivalent fuels with significantly reduced CO$_2$ emissions by 2035

• And thus play an important role in addressing issues of energy security, supply diversification, and CO$_2$ emissions

• But their commercial deployment by 2020 will require aggressive large-scale demonstration in the next few years.

• Investor confidence will most likely require a carbon price or fuel mandates with specified reductions in GHG emissions
Support for this Project was Provided by

- U.S. Department of Energy
- BP America
- Dow Chemical Company Foundation
- Fred Kavli and the Kavli Foundation
- GE Energy
- General Motors Corporation
- Intel Corporation
- W.M. Keck Foundation
- Presidents’ Circle Communications Initiative of the National Academies
- National Academy of Sciences through the following endowed funds
  - Thomas Lincoln Casey Fund
  - Arthur L. Day Fund
  - W.K. Kellogg Foundation Fund
  - George and Cynthia Mitchell Endowment for Sustainability Science
  - Frank Press Fund for Dissemination and Outreach.
Backup Slides
Additional Information on the America’s Energy Future Effort

www.nationalacademies.org/energy

October 2008

May 20, 2009

June 15, 2009

December 9, 2009

Final Report, July 28, 2009

America’s Energy Future: Technology and Transformation

Peter D. Blair
Executive Director
Division on Engineering & Physical Sciences
National Research Council
pblair@nas.edu
PANEL’S APPROACH

• Biomass Supply
  • Estimated supply and costs of different cellulosic feedstocks.

• Biochemical and Thermochemical Conversion
  • Estimated costs and performance of the conversion processes.
  • Estimated CO₂ emissions from the conversion processes and the burning of the fuel.
    Biochemical feedstock : biomass.
    Thermochemical feedstock : coal, biomass, or coal + biomass.
PANEL’S APPROACH (cont)

• Compared life-cycle costs and CO₂ emissions of biofuels, coal-to-liquid fuels, and coal+biomass-to-liquid fuels on a consistent basis.

• Estimated amount of fuels that is technically feasible to deploy by 2020.

• Estimated market penetration of fuels in 2020 and 2035.

The panel’s analyses include input from Princeton University, University of Minnesota, Massachusetts Institute of Technology, Purdue University, Iowa State University, USDA and others who presented to the panel.
Supply function for biomass feedstocks in 2020
## BIOCHEMICAL CONVERSION OF POPLAR TO ETHANOL—KEY ASSUMPTIONS AND COSTS

<table>
<thead>
<tr>
<th>Deployable year</th>
<th>Current</th>
<th>2020</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Capacity gal/yr</td>
<td>40 M</td>
<td>40 M</td>
<td>100 M</td>
</tr>
<tr>
<td>Feedstock rate dt/d</td>
<td>1.5k</td>
<td>1.5k</td>
<td>4 k</td>
</tr>
<tr>
<td>Pretreatment yield</td>
<td>80%</td>
<td>85%</td>
<td>85%</td>
</tr>
<tr>
<td>Cellulase cost $/gal</td>
<td>$0.40</td>
<td>$0.25</td>
<td>$0.25</td>
</tr>
<tr>
<td>Ethanol yield, gal/dt</td>
<td>67</td>
<td>78</td>
<td>78</td>
</tr>
<tr>
<td>Ethanol production cost ($/gal, gasoline equil)</td>
<td>4.00</td>
<td>3.00</td>
<td>2.70</td>
</tr>
</tbody>
</table>

- SuperPro Designer Modelling – Grain Ethanol Validated
<table>
<thead>
<tr>
<th></th>
<th>CTL FT With CCS</th>
<th>CBTL FT With CCS</th>
<th>BTL FT With CCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal, tons/day</td>
<td>26,700</td>
<td>3,030</td>
<td>0</td>
</tr>
<tr>
<td>Biomass, tons/day</td>
<td>0</td>
<td>3,950</td>
<td>3,950</td>
</tr>
<tr>
<td>Total liquid fuels, bbl/d</td>
<td>50,000</td>
<td>10,000</td>
<td>4,410</td>
</tr>
<tr>
<td>Specific total plant cost, $/bbl per day</td>
<td>98,900</td>
<td>134,000</td>
<td>147,000</td>
</tr>
<tr>
<td>Total liquid fuels cost, $/gal gasoline equivalent</td>
<td>1.64</td>
<td>2.52</td>
<td>3.32</td>
</tr>
<tr>
<td>Breakeven oil price, $/bbl</td>
<td>68</td>
<td>103</td>
<td>139</td>
</tr>
<tr>
<td>FT liquids per petroleum-derived diesel emissions</td>
<td>1</td>
<td>0</td>
<td>-1.4</td>
</tr>
</tbody>
</table>
COMPARISON OF LIFE-CYCLE COSTS
Cost of alternative liquid fuels produced from coal, biomass, or coal and biomass with a \( \text{CO}_2 \) equivalent price of $50/tonne.
## Effect of Life-Cycle Greenhouse Gas Price on Fuel Cost – for $0 and $50/tonne CO₂eq Price

<table>
<thead>
<tr>
<th>Fuel Product</th>
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<td>130</td>
</tr>
<tr>
<td>CTL with CCS</td>
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<td>120</td>
</tr>
<tr>
<td>CBTL with CCS</td>
<td>110</td>
<td>100</td>
</tr>
</tbody>
</table>
BARRIERS TO DEPLOYMENT—Conversion

Thermochemical Conversion
• Implementing commercial demonstration of conversion processes integrated with geologic storage ASAP
• Completing Megatonne geologic storage demonstrations to resolve siting, operating, monitoring and regulatory issues, and to establish safety and efficacy

Biochemical Conversion
• Implementing commercial demonstration
• Developing more efficient, economical pretreatment to free up sugars from cellulosics and hemicellulosics.
• Discovering better enzymes that are not subject to end-product inhibition.
BARRIERS TO DEPLOYMENT—Market Penetration

• Approaches that recognize commodity prices, especially oil prices, vary widely.

• Permitting and constructing tens to hundreds of conversion plants and the associated, water requirements, fuel transport and delivery infrastructure
## EFFECT OF LIFE-CYCLE GREENHOUSE GAS PRICE ON FUEL COST – for $0 and $50/tonne CO$_2$eq price

<table>
<thead>
<tr>
<th>Fuel Product</th>
<th>Cost without CO$_2$ Equivalent Price ($/bbl gasoline equivalent)</th>
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<tr>
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<td>110</td>
<td>100</td>
</tr>
</tbody>
</table>
# BIOMASS COSTS

<table>
<thead>
<tr>
<th>Biomass</th>
<th>Low Cost</th>
<th>50% Low (2020)</th>
<th>Baseline (2008)</th>
<th>50% High</th>
<th>High Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn stover</td>
<td>65</td>
<td>86</td>
<td>110</td>
<td>140</td>
<td>175</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>93</td>
<td>118</td>
<td>151</td>
<td>199</td>
<td>286</td>
</tr>
<tr>
<td>Miscanthus</td>
<td>82</td>
<td>101</td>
<td>123</td>
<td>150</td>
<td>186</td>
</tr>
<tr>
<td>Prairie grasses</td>
<td>79</td>
<td>101</td>
<td>127</td>
<td>179</td>
<td>273</td>
</tr>
<tr>
<td>Woody biomass</td>
<td>59</td>
<td>72</td>
<td>85</td>
<td>104</td>
<td>124</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>40</td>
<td>55</td>
<td>70</td>
<td>97</td>
<td>123</td>
</tr>
</tbody>
</table>
Geographic distribution of potential biomass supply for biofuel production. Shading shows the annual supply of all potential biomass feedstocks within a 40-mile radius of any point in the lower 48 states.
Number of sites in the United States with a potential to supply indicated daily amounts of biomass within a 40-mile radius.
## BIOCHEMICAL CONVERSION OF POPLAR TO ETHANOL—KEY ASSUMPTIONS AND COSTS

<table>
<thead>
<tr>
<th>Variable</th>
<th>Low Current</th>
<th>Medium 2020</th>
<th>High 2020+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of conversion plant</td>
<td>40 M gal/yr</td>
<td>40 M gal/yr</td>
<td>40 M gal/yr</td>
</tr>
<tr>
<td>Solids loading</td>
<td>18%</td>
<td>21%</td>
<td>25%</td>
</tr>
<tr>
<td>Pretreatment yield</td>
<td>80%</td>
<td>85%</td>
<td>95%</td>
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</tr>
<tr>
<td>Ethanol yield, gal/dt</td>
<td>67</td>
<td>78</td>
<td>87</td>
</tr>
<tr>
<td>Total capital ($ millions)</td>
<td>$223 M</td>
<td>$194 M</td>
<td>$174 M</td>
</tr>
<tr>
<td>Ethanol production cost ($/gal, gasoline equil)</td>
<td>4.00</td>
<td>3.00</td>
<td>2.30</td>
</tr>
</tbody>
</table>

- SuperPro Designer Modelling – Grain Ethanol Validated
- Biomass feed rate = 1,500,000 DT/Day
Analysis assumes that conversion plants sell net electricity to the grid. Electricity-related CO₂ emissions are dependent on the case: IGCC venting CO₂ for vent cases, and IGCC-CCS(90%) for CO₂ storage cases.
Estimated Biomass Input Costs in 2020
SUPPLY OF ALTERNATIVE LIQUID FUELS—COMMERCIAL DEPLOYMENT

Cellulosic Ethanol
- If commercial demonstration successful,
- Commercial deployment begins in 2015,
- Capacity growth = 50 percent each year,
- Then 0.5 million bbl of gasoline eq./day by 2020,
- Or 1.7 million bbl of gasoline eq./day by 2035.

Coal-and-Biomass-to-Liquid (CBTL) Fuels
- If commercial demonstration of CBTL with carbon capture and storage (CCS) is successful,
- First commercial plants start up in 2020,
- Capacity growth = 20 percent each year,
- Then CBTL fuels could reach 2.5 million barrels of gasoline eq./day by 2035.
SUPPLY OF ALTERNATIVE LIQUID FUELS—COMMERCIAL DEPLOYMENT

Coal-to-Liquid (CTL) Fuels

- If commercial demonstration of CTL plants with CCS is successful,
- First commercial plants start up in 2020,
- Growth capacity = 2-3 plants each year,
- Then CTL fuels can reach 3 million bbl of gasoline eq./day by 2035,
- U.S. coal production will increase by 50 percent.