Optimal Use of Biomass: Competition for Bioenergy Feedstocks Across the Energy System

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Overview

• EPA’s energy system modeling
• MARKAL background
• Bioenergy analysis
Total Energy Consumption ~ 36,000 PJ
Net Primary Resource Consumption 2050?

Emissions?

Source: Production and end-use data from Energy Information Administration, Annual Energy Review 2000

*Net fossil-fuel electrical imports

**Biomass/other includes wood and waste, geothermal, solar, and wind.
Energy & Environment in the Future?

The energy system and environmental quality are closely linked. There are many potential realizations of the energy system in the future. How the energy system evolves will have profound impacts on our environment.
The Big Picture: What Questions Are We Asking?

- How does feedstock end use vary by region?
- How do direct and indirect energy inputs plus criteria pollutant and GHG emissions vary across the biofuels supply chain?
- How does the coupling between energy and agricultural markets impact land use, natural resource consumption, and ecosystem services?
- How do assumptions about fossil energy prices, feedstock supplies, conversion technology development, and environmental and energy policy affect answers to these questions?
The Need for an Energy Systems Perspective

• Captures complexity:
  – Need to calculate both direct and indirect impacts across the energy economy (e.g., ag. is both an energy producer and consumer; biofuels both displace and use fossil energy)
  – Interactions must be considered, but they are not always intuitive
  – Trade-offs in technological and economic feasibility often emerge only at the systems level

• Complements life-cycle analysis
Modeling Energy System Interactions

- Oil Refining
- Biochemical Conversion
- Thermochemical Conversion
- Gasification
- Electricity Generation
- Transportation
- Residential
- Industrial/Commercial
- Agriculture (Future)

- Emissions
- MSW
- Livestock waste
- Agricultural biomass
- Forestry biomass
- Natural Gas
- Coal
- Uranium
- Forestry biomass
- Agricultural biomass
- Livestock waste
- MSW
- Emissions

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Energy System Evolution: Driving Forces

- Technological change
- Energy supply, demand, and price dynamics
- Region-specific factors
  - Demand patterns
    - Demographics
    - Industrial/economic activity
  - Land use
  - Technology preferences/suitability
  - Fuel availability, transport costs
  - Environmental, energy, and land use policies
The MARKAL Energy System Model

- Finds the **least cost set of technologies** that satisfies end-use energy service demands and user-specified constraints (linear optimization)

- Quantifies the **system-wide effects** of changes in resource supply, technology availability, and energy and environmental policies

- Database contains significant **technology detail** across economic sectors: electric power generation, transportation, industrial, residential, commercial, resource supply

- Model tracks CO$_2$, SO$_2$, NO$_x$, PM, and VOC **emissions**
MARKAL - How does it work?

• Selects the optimal mix of technologies and fuels at each time step to minimize the net present value of energy system capital and O&M costs

• Subject to:
  – Current and projected technology costs & efficiencies
  – Resource supply costs & competition for fuel across sectors
  – Resource supply constraints
  – Trade costs and constraints
  – Emission limits
  – Other constraints (e.g., policies)
Modeling Technology Change with MARKAL

MARKAL Inputs:
- Future-year energy service demands
- Primary energy resource supplies
- Current & future technology characteristics
- Emissions and energy policies

MARKAL Outputs:
- Technology penetrations for meeting industrial, residential, commercial, and transportation demands
- Fuel use by type and region
- Sectoral and system-wide emissions NOx, SO2, PM10 and CO2
- Marginal fuel and emissions reduction prices

• Through linear optimization MARKAL finds the least cost set of technologies
EPA Nine-Region MARKAL Model

- Based on U.S. Census Divisions
- Improve representation of:
  - Coal, oil, and gas supply plus transportation costs
  - Renewable energy resources
  - Existing technology stock
  - Technology suitability
  - End-use energy demands
  - Inter-region energy trading
  - Emissions regulations
- Public release summer 2008
Technology Detail: Light Duty Vehicles

Fuel
- Gasoline
- Ethanol
- E85
- Electricity

Technology
- Conventional ICE
- E85 Conventional ICE
- E85 Moderate ICE
- E85 Advanced ICE
- E85 Hybrid
- E85 Plugin-10
- E85 Plugin-40
- Diesel
- Diesel Hybrid
- CNG
- Electricity
- Hydrogen Fuel Cell

Class
- Mini
- Compact
- Full-size
- Minivan
- Pickup
- Small SUV
- Large SUV

Demand
- Airplanes
- Buses
- Heavy Duty
- Ships
- Rail
- Transportation

United States
Environmental Protection
Agency

U.S. EPA MARKAL 9-Region Database

Technology Detail: Light Duty Vehicles
Technology Detail: Electricity Production

Fuel

- 14 Coal Supply Regions
- Biomass for Co-firing

Technology

- Conventional
- Next Generation
- Supercritical
- Oxyfuel
- IGCC

Class

- Coal
- Natural Gas
- Oil
- Nuclear
- Hydro
- Wind
- Solar
- Geothermal
- Biomass

Controls

- NOx: LNB, SCR, SNCR
- SO₂: FGD
- CO₂: CCS
# U.S. EPA MARKAL 9-Region Database: End-use Energy Demands

## Sectors:
- Industrial
  - Electrochemical
  - Feedstock
  - Machine Drive
  - Process Heat
  - Steam
  - Other
- Commercial
  - Cooking
  - Lighting
  - Office Equipment
  - Refrigeration
  - Cooling
  - Ventilation
  - Water Heating
  - Other
- Residential
  - Freezing
  - Lighting
  - Refrigeration
  - Cooling
  - Heating
  - Water Heating
  - Other
- Transportation
  - Light duty
  - Heavy duty
  - Bus
  - Off-road
  - Passenger rail
  - Freight rail
  - Shipping

## Non-manufacturing
- Refineries
- Chemical
- Food
- Primary metals
- Minerals
- Pulp and paper
- Transportation equip.
- Non-manufacturing
- Other
## Technological Detail

<table>
<thead>
<tr>
<th>Standard</th>
<th>Optional</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Availability (Year)</td>
<td>• Capacity Factor</td>
</tr>
<tr>
<td>• Lifetime</td>
<td>• Growth Limit</td>
</tr>
<tr>
<td>• Capital Cost</td>
<td>• Learning Rate</td>
</tr>
<tr>
<td>• Operating Costs</td>
<td>• Discount Rate</td>
</tr>
<tr>
<td>– Fixed</td>
<td>• Time of Day Operation</td>
</tr>
<tr>
<td>– Variable (non-fuel)</td>
<td>• Market Penetration Constraints</td>
</tr>
<tr>
<td>• Efficiency</td>
<td>• Capacity Increment</td>
</tr>
<tr>
<td>• Fuel Inputs</td>
<td></td>
</tr>
<tr>
<td>• Emissions Factors</td>
<td></td>
</tr>
</tbody>
</table>
Constraints / Policy Variables

- System, sectoral and/or regional limits on:
  - Criteria pollutants (NOx, SO₂, PM₁₀)
  - CO₂
  - Fuel supplies
  - Technology penetration
    - Limiting
    - Forcing
- Incentives
  - Taxes on fuels or emissions
  - Subsidies on fuels or technologies
- Other
  - Renewable portfolio or efficiency standards
Current Technology Focus

• Electricity generation:
  – Advanced coal and natural gas plants
  – Biomass co-firing and gasification
  – Wind and solar
  – Advanced nuclear plants
  – Carbon capture and sequestration

• Transportation:
  – Biofuels
  – Conventional and plug-in hybrids
  – Hydrogen (and other) fuel cells
Scenario Analysis

- Scenarios do not predict the future
- Scenarios project internally consistent futures to posited storylines
  - “What if…” to forecast
  - “How could…” to backcast
- Scenarios allow visualization and assessment of:
  - Consequences of varying assumptions
  - Range of possible futures
  - Trade-offs and branch points between futures
Motivation for Bioenergy Work

• Examine how broader energy system drivers affect biomass feedstock demand and biofuels and bioenergy production
  – Capture the effects of EISA 2007 (Renewable Fuel Standard)
  – Model entire supply chain and interactions with larger energy system on a regional scale
  – Scenario analysis based on fossil energy prices, feedstock prices, conversion technology development, environmental and energy policy

• Evaluate resulting environmental impacts
  – Direct emissions changes of criteria pollutants and GHGs from biofuel/bioenergy production and use
  – Indirect emissions changes from fossil energy offsets
  – Ecosystem services, land use changes, natural resource consumption
Biomass Resources

- Corn grain
- Corn stover
- Agricultural residues
- Energy crops
- Forest residues
- Primary mill residues
- Urban wood waste
- Municipal solid waste
- Soybean oil
- Waste oil
### Biomass Conversion Technologies

**Liquid Fuels**

<table>
<thead>
<tr>
<th>Ethanol: Biochemical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Mill (corn grain)</td>
</tr>
<tr>
<td>(w/ and w/o CHP)</td>
</tr>
<tr>
<td>Wet Mill (corn grain)</td>
</tr>
<tr>
<td>Cellulosic (multiple feedstocks)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Biodiesel</th>
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</thead>
<tbody>
<tr>
<td>FAME (virgin soybean oil)</td>
</tr>
<tr>
<td>FAME (waste oil/grease)</td>
</tr>
<tr>
<td>Renewable diesel via thermochemical</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thermochemical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyrolysis to bio-oil</td>
</tr>
<tr>
<td>Gasification to syngas (to final fuel products)</td>
</tr>
</tbody>
</table>

**Heat and Power**

<table>
<thead>
<tr>
<th>Power Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass gasification</td>
</tr>
<tr>
<td>Coal/biomass co-firing</td>
</tr>
<tr>
<td>Biomass combustion</td>
</tr>
<tr>
<td>Landfill gas combustion</td>
</tr>
<tr>
<td>Waste-to-energy</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Industrial Heat and Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulp and paper (black liquor)</td>
</tr>
<tr>
<td>Other industrial heat/steam (lignocellulosic biomass)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Residential Heat/Hot Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood stoves</td>
</tr>
<tr>
<td>Outdoor wood boilers</td>
</tr>
</tbody>
</table>
## Bioenergy Consumption Across End-Use Economic Sectors

<table>
<thead>
<tr>
<th>Sector</th>
<th>Feedstock and Conversion Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transportation fuels</td>
<td>Corn-based ethanol</td>
</tr>
<tr>
<td></td>
<td>Cellulosic ethanol</td>
</tr>
<tr>
<td></td>
<td>Biodiesel</td>
</tr>
<tr>
<td>Industrial steam/power</td>
<td>Pulp and paper use of black liquor and biomass</td>
</tr>
<tr>
<td>Electric power</td>
<td>Dedicated combustion (steam), co-firing with coal, biomass gasification, combined heat and power (CHP)</td>
</tr>
<tr>
<td>Residential heat</td>
<td>Wood stoves</td>
</tr>
</tbody>
</table>
Energy, Emissions and Material Flows: Corn-Based Ethanol

Upstream processes

Co-products

Air Emissions

Corn production

Transport to refinery

Ethanol production

Transport to blender ...

Corn

Ethanol

corn

corn

CO2 uptake

Land

Water

Diesel

Gasoline

LPG

Electricity

Natural gas

Coal

Electricity

Natural gas

Gasoline

Water

Diesel

Gasoline
Importance of a Regional Perspective

• Need to understand how regional variation can affect the production, distribution, and use of biofuels
• Evaluate how bioenergy production systems may evolve differently in each region
  – Biomass feedstock potential
  – Bioenergy outputs – fuels, electricity, heat, etc.
  – Level of “investment” in fossil fuels needed to support a growing bioenergy system
  – Demand for biofuels and bioenergy – and competition with traditional fuels/energy
• Provide better estimates of transportation and distribution costs for both feedstocks and fuels
  – Assess energy requirements, emissions, and bottlenecks
Feedstock Use - National

National Feedstock Utilization by Type (MTonnes/y)

National Feedstock Utilization by Sector (MTonnes/y)

Run including the EISA corn ethanol and cellulosic ethanol volumes (but not the GHG thresholds)
Feedstock Use - Regional

Midwest

Feedstock Utilization by Type (MTonnes/y)

Feedstock Utilization by Sector (MTonnes/y)

Southeast

Feedstock Utilization by Type (MTonnes/y)

Feedstock Utilization by Sector (MTonnes/y)
Biofuels Supply Chain: Fossil Fuel Inputs

Run including the EISA corn ethanol and cellulosic ethanol volumes (but not the GHG thresholds)
# The Impact of CO₂ Emission Limits on Bioenergy Production

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Vehicle Fuel</th>
<th>Electricity (BkWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Corn-grain Ethanol (Bgal)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cellulosic Ethanol (Bgal)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Biodiesel (Bgal)</td>
<td></td>
</tr>
<tr>
<td>Base</td>
<td>15</td>
<td>23</td>
</tr>
<tr>
<td>CO₂ Policy</td>
<td>17</td>
<td>31</td>
</tr>
</tbody>
</table>

*C0₂ Policy* represents a 50% reduction in cumulative 2020-2050 aggregate emissions.
The Impact of CO₂ Emission Limits on Feedstock End Use

<table>
<thead>
<tr>
<th></th>
<th>Base Scenario</th>
<th></th>
<th>CO2 Policy Scenario</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Transport</td>
<td>Power</td>
<td>Transport</td>
<td>Power</td>
</tr>
<tr>
<td>Ag Residues</td>
<td>4.1</td>
<td>0.0</td>
<td>0.7</td>
<td>2.0</td>
</tr>
<tr>
<td>Corn Grain</td>
<td>154.8</td>
<td></td>
<td></td>
<td>172.4</td>
</tr>
<tr>
<td>Forest Residues</td>
<td>0.0</td>
<td></td>
<td></td>
<td>37.8</td>
</tr>
<tr>
<td>Primary Mill Residues</td>
<td>0.2</td>
<td></td>
<td></td>
<td>42.2</td>
</tr>
<tr>
<td>Stover (corn)</td>
<td>109.5</td>
<td></td>
<td></td>
<td>96.5</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>194.3</td>
<td></td>
<td></td>
<td>322.2</td>
</tr>
<tr>
<td>Urban Wood Waste</td>
<td>2.4</td>
<td></td>
<td></td>
<td>14.4</td>
</tr>
</tbody>
</table>

CO₂ Policy represents a 50% reduction in cumulative 2020-2050 aggregate emissions.
MARKAL Bioenergy Modeling: Take-away Points

• Goal is not to predict biofuels production trends, but to see interactions with the broader energy system
• Regional perspective is important for evaluating feedstock availability and end-use
• May see strong regional variation in which bioenergy products are most viable and cost effective – heat, electricity, or liquid fuels
EPA MARKAL Bioenergy Modeling: Next Steps

• Build out agriculture sector
• Account for water use across bioenergy supply chain
• Explore thermochemical pathway logistics and improve related infrastructure characterization
Related Work: Modeling Agriculture-Energy Feedbacks

With Iowa State, Southern Illinois University, NCA&T, and IFPRI, we are examining how regional crop and energy prices affect farm-level decision making and how the resulting land use choices impact the environment.

An integrated perspective is needed to understand:

- the linkages between agricultural and energy markets
- the impacts of those market dynamics on farm-level decision making
- how management of environmental impacts at the field level may constrain development of emerging biomass markets
Acknowledgements

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