Life Cycle Analysis

With examples from biofuel analysis

Sustainable Energy
18th November 2010
Outline of Presentation

• Introduction to Life Cycle Analysis (LCA)
• LCA Basics
• Examples and challenges to implementation
  – Corn Ethanol
  – Cellulosic Ethanol
  – Cellulosic Biofuels
• Illuminating Biofuel Trade-offs
• Consideration of Biofuel Policy
Introduction to LCA

• What is LCA?
  – A system analysis methodology (remember toolbox 4?)
  – “cradle-to-grave analysis”
Components of LCA

• Inventory
  – Quantification of energy and raw material requirements, emissions, effluents, and wastes
  – i.e. mass and energy balances are integrated over each process in system

• Impact Assessment
  – Values can be assigned to effects for quantification

• Improvement
  – Systems can then be optimized with respect to parameters from impact assessment
Why is LCA methodology Useful?

• Many parameters we are interested in don’t occur in just one step of a product’s lifecycle
  – Carbon dioxide emissions from Coal-to-Liquid fuels.
• Optimizing one production step doesn’t mean system is optimal.
  – Hydrogen as a transportation fuel
• Lifecycle analysis is intended to be used to optimize the aggregate outcomes
Allow for comparison of potential products: MacDonald’s - Styrofoam or paper?

Trees (natural?)

Paper (good?)

Oil (bad?)

Chemicals (worse)

Styrofoam (??)

Benzene + C2H4 + etc.

Pulp

Chlorine or Peroxide

Acid or Alkali

Hard to recycle

Plastic coating

Landfill

Trash

Recycle

PCBs + Dioxins

Water

Wastewater

McD

CFCs

CO2

Pentane

Styrene

Polystyrene foam
Life-Cycle Analysis - approach

- Define “cradle-to-grave” alternative systems
- Set system boundary conditions
- Set time basis (snapshot of industry in time vs. one life cycle of representative product)
- Identify impacts of interest to decision-makers
  - Costs, air pollution, GHG emissions, wastes, resource depletion, etc.
- For each portion of the life-cycle, estimate the impacts of interest
- Assess overall tradeoffs, considering uncertainties
- Identify major sources of adverse impact and assess improvements
Life Cycle Analysis Software

• Dedicated Packages
  – GaBi
  – Umberto

• DIY (for simple cases)
  – Excel
  – Matlab
Life Cycle Analysis for Energy Systems

- Major process steps
  - Resource extraction/production
  - Transport
  - Fuel/electricity production
  - Distribution
  - End-use

- Important Parameters
  - Emissions
  - Useful work
  - Costs

- Useful simplification
  - Most energy conversion facilities
  - Non-fuel resource use negligible.
LCA studies for biofuels are mandated

- Text of the Energy Independence and Security Act of 2007:
  - “GENERAL.—The term ‘advanced biofuel’ means renewable fuel, other than ethanol derived from corn starch, that has lifecycle greenhouse gas emissions, as determined by the Administrator, after notice and opportunity for comment, that are at least 50 percent less than baseline lifecycle greenhouse gas emissions.”
  - “CELLULOSIC BIOFUEL.—The term ‘cellulosic biofuel’ means renewable fuel derived from any cellulose, hemicellulose, or lignin that is derived from renewable biomass and that has lifecycle greenhouse gas emissions, as determined by the Administrator, that are at least 60 percent less than the baseline lifecycle greenhouse gas emissions.”
  - Baseline: average LCA GHG emissions from gasoline or diesel, whichever a particular biofuel replaces

- The act calls for 36 billion gallons of renewable fuel by 2022, with at least 21 billion gallons of this being “advanced biofuels”.
Life-Cycle Analysis – biofuels approach

• Define “cradle-to-grave” alternative systems
  – Choose alternate fuel options
• Set system boundary conditions
  – This is where the big fights have been/are going to be
• Identify impacts of interest to decision-makers
  – Costs, air pollution, GHG emissions, land-use change, Food Versus Fuel?
• Assess overall tradeoffs, considering uncertainties
• Identify major sources of adverse impact and assess improvements
System Boundaries for Biofuels

• Where do we draw the boundaries for our analysis? Why?
• This turns out to be a MAJOR point of contention.
  – The California Low Carbon Fuel Standard
• If there is a comprehensive carbon tax – won’t double counting then occur?
The California Low Carbon Fuel Standard (LCFS)

- The Governor's Executive Order directs the Secretary for Environmental Protection to coordinate the actions of the California Energy Commission, the California Air Resources Board (ARB), the University of California and other agencies to develop the protocols for measuring the "life-cycle carbon intensity" of transportation fuels...
California LCFS (Continued)

• In the California rule-making a large fight revolved around the quantification secondary land-use changes.
  – Argument for inclusion:
    • Will include deforestation caused by land use change to meet demand for food
  – Argument for exclusion:
    • Double counting
    • Measuring a counterfactual
    • Not applied to petroleum baseline
System Boundaries for Biofuels (Revisited)

• Policy is likely to play a major role in defining system boundaries
  – The term ‘advanced biofuel’ means renewable fuel, other than ethanol derived from corn starch, that has lifecycle greenhouse gas emissions, as determined by the Administrator, after notice and opportunity for comment, that are at least 50 percent less than baseline lifecycle greenhouse gas emissions."

• Assuming that system boundaries are “non-overlapping” could there still be double counting?
Identifying the Process Steps

• System contains a connected web of individual processing steps each with their own:
  – Energy balances
  – Mass balances
  – Cash flows
  – Emissions
  – Regulations
  – ...

• How do we determine the necessary amount of granularity?
  – Only major steps?
  – Every subprocess?
  – Down to the last valve?

• This is a matter of identifying goals of analysis (think back to SD lecture)
Key Issues

System Boundary

- Scale -- Biomass availability
- Performance -- Energy balance
- Economics today and tomorrow
- transitioning from corn–based to cellulosic fuel

Image by MIT OpenCourseWare.
Simplified Lifecycle of Biofuel Production

- Biomass Feedstock → Fuel Production
  - Heat and Electricity input

- Fuel Production → Fuel Distribution
  - Transportation Energy Requirements

- Fuel Distribution → End Use
  - Heat Loss, Incomplete Combustion

- End Use → Automotive Propulsion

- Byproducts, Heat Loss
Energy Inputs to Corn Ethanol

Total Ethanol
Distill/Dry
Electricity
Distribution
Other
Corn

MJ/kg EtOH

Courtesy of Jeremy Johnson. Used with permission.
Energy Inputs to Corn

- Machinery
- Seeds
- Electricity
- Pesticide
- Lime
- P-K
- Nitrogen
- Irrigation
- Fossil Fuels

Courtesy of Jeremy Johnson. Used with permission.
Corn Ethanol – comparison of estimated net energy ratio.

Effect of common system boundaries, coproduct credit

Courtesy of Jeremy Johnson. Used with permission.
Corn Ethanol

Key conclusions

- Corn grain ethanol has a slightly positive net energy on average, but is very dependent on
  - Ethanol production efficiency
  - Location and practices in corn production
  - Transportation distances

- Improved corn yield, conversion and purification technology can help, but most gains are incremental

- Expansion of corn production will probably lead to more energy intensity
Cellulosic Ethanol – Fossil fuel energy requirements

Monte Carlo LCA Results

NEV (MJ/Ethanol Liter)

- Iowa Corn Stover Ethanol
- Alabama Switchgrass Ethanol
- Iowa Switchgrass Ethanol
- 2025 Corn Stover Ethanol
- 2025 Switchgrass Ethanol

Tiffany Groode, PhD MIT 2008

Courtesy Tiffany Groode. Used with permission.
GHG Emissions – Cellulosic Ethanol

Monte Carlo LCA Results

GHG Emissions (gCO2-eq/MJ)

- Iowa Corn Stover Ethanol: 27.6
- Alabama Switchgrass Ethanol: 6
- Iowa Switchgrass Ethanol: 26.3
- 2025 Corn Stover Ethanol: 5
- 2025 Switchgrass Ethanol: 5.4
- Gasoline: 90

Tiffany Groode, PhD MIT 2008

Courtesy Tiffany Groode. Used with permission.
Net Energy Value - Cellulosic Ethanol

Previous Results
(Corn Grain Ethanol)

Monte Carlo LCA Results

Tiffany Groode, PhD MIT 2008

Courtesy Tiffany Groode. Used with permission.
GHG Cellulosic Ethanol

Previous Results
(Corn Grain Ethanol)

Monte Carlo LCA Results

GHG Emissions (gCO2-equ./MJ)


Iowa Corn Grain Ethanol
Iowa Corn Grain Ethanol
Iowa Corn Ethanol
Iowa Corn Ethanol Plus DDGS
Georgia Corn Grain Ethanol
Iowa Coal Powered Corn Grain Ethanol
2025 Iowa Corn Grain Ethanol
2025 Stover Ethanol
Alabama Switchgrass Ethanol
Iowa Switchgrass Ethanol
2025 Switchgrass Ethanol
Gasoline

Tiffany Groode, PhD MIT 2008

Courtesy Tiffany Groode. Used with permission.
Conclusions - Ethanol

• Corn grain ethanol:
  – Considering economics, energy balance, GHG abatement, not a bad idea, but limited by land constraints
  – Considerable expansion of corn production negates any benefits, so subsidies should be restructured to efficiency

• Lignocellulosic ethanol
  – Significantly better environmental performance plus more availability, but economic cost is a large barrier
  – Multiple technology advancements must be made to achieve commercialization, with feedstock logistics critical

• Overall
  – Potential for non-negligible (~20%) replacement of petroleum, but significant investment is required
Why Ethanol?

• If one is to use synthetic chemistry, one can make fuels that are not metabolic products:
  – Synthetic Hydrocarbons (Synthetic Natural Gas, Fischer-Tröpsch Diesel, MTG Gasoline)
  – Other Alcohols (methanol, propanol, butanol+)
  – Dimethyl Ether
  – Hydrogen?
## Properties of possible fuels

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Formula</th>
<th>Molecular Weight</th>
<th>Density (g/cm³)</th>
<th>Lower Heating Value (MJ/kg)</th>
<th>Heat of Vaporization (KJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methanol</td>
<td>CH₃OH</td>
<td>32.04</td>
<td>0.792</td>
<td>20</td>
<td>1103</td>
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<tr>
<td>Ethanol</td>
<td>CH₃CH₂OH</td>
<td>46.07</td>
<td>0.785</td>
<td>26.9</td>
<td>840</td>
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<tr>
<td>Propanol</td>
<td>CH₃(CH₂)₂OH</td>
<td>60.1</td>
<td>0.8</td>
<td>30.5</td>
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<td>Butanol</td>
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<td>0.81</td>
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<td></td>
<td>CH₁₈₅</td>
<td>~110</td>
<td>0.75</td>
<td>44</td>
<td>350</td>
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<tr>
<td>MTG Gasoline</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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<th>Lower Heating Value (MJ/kg)</th>
<th>Heat of Vaporization (KJ/kg)</th>
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</thead>
<tbody>
<tr>
<td>DME</td>
<td>CH₃OCH₃</td>
<td>46.07</td>
<td>0.668</td>
<td>28.7</td>
<td>467</td>
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<td>Fischer-Tröpsch</td>
<td>CH₁₈</td>
<td>170</td>
<td>0.8</td>
<td>43</td>
<td>270</td>
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<tr>
<td>Diesel</td>
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</table>
Life Cycle Energy Efficiency of Thermochemical Biofuels

Biomass-to-Wheel Efficiency utilizing best possible distribution method for each fuel

A. Stark MIT 2008
Biomass-to-Tank Efficiency of Thermochemical Biofuels

Biomass-to-Tank Efficiency utilizing best distribution method for each fuel

Efficiency %
Fuel Integrability

- A fuel’s properties will dictate whether it is accepted into the current fuel infrastructure
- This will greatly impact the economics of distribution

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Truck</th>
<th>Rail</th>
<th>Pipeline</th>
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<tbody>
<tr>
<td>Methanol</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Ethanol</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Mixed Alcohol</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>MTG</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Synthetic Gasoline</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FT Diesel</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>DME</td>
<td>Y</td>
<td>Y</td>
<td>Y/N</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fuel</th>
<th>cost of shipping per liter 1000km</th>
<th>cost of shipping per GJ 1000km</th>
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</thead>
<tbody>
<tr>
<td>methanol</td>
<td>$0.050</td>
<td>$3.141</td>
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<tr>
<td>ethanol</td>
<td>$0.050</td>
<td>$2.185</td>
</tr>
<tr>
<td>MTG</td>
<td>$0.003</td>
<td>$0.101</td>
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<tr>
<td>FTD</td>
<td>$0.003</td>
<td>$0.095</td>
</tr>
<tr>
<td>DME</td>
<td>$0.060</td>
<td>$3.130</td>
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</table>
End-Use emissions Regulations

• Existing emissions regulations will also play a role in dictating which fuels are used.
  – The Clean Air Act
  – Oxygenate requirements
  – Zero Emission Vehicles
  – California

<table>
<thead>
<tr>
<th></th>
<th>CO</th>
<th>NO\textsubscript{x}</th>
<th>Particulates</th>
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<td>methanol</td>
<td>Slight reduction</td>
<td>Significant reduction</td>
<td>N/A</td>
</tr>
<tr>
<td>ethanol</td>
<td>Slight reduction</td>
<td>Significant reduction</td>
<td>N/A</td>
</tr>
<tr>
<td>mixed alcohol</td>
<td>Slight reduction</td>
<td>Slight reduction</td>
<td>N/A</td>
</tr>
<tr>
<td>MTG synthetic gasoline</td>
<td>No change</td>
<td>Slight increase</td>
<td>N/A</td>
</tr>
<tr>
<td>FT Diesel</td>
<td>Moderate reduction</td>
<td>Moderate reduction</td>
<td>Moderate reduction</td>
</tr>
<tr>
<td>DME</td>
<td>No change</td>
<td>Moderate reduction</td>
<td>Significant Reduction</td>
</tr>
</tbody>
</table>
• Food Versus Fuel
• Land-use changes

ILLUMINATING THE TRADE-OFFS
Food Versus Fuel

• Increasing demand for biofuels may incentivize farmers to switch land away from food production
  – Decreasing food supplies
  – Increasing food prices

• Some argue that this was the case in 2008.
  – Data for making a conclusion either way is somewhat lacking.
  – Innovation in agriculture is far outpacing demand growth.
Land-use Changes

• Increasing demand for biofuels may incentivize farmers to put more land into production
  – The rainforests for soy/sugar cane
  – Jatropha in Indonesia

• How do we quantify these secondary effects?
  – Measuring a counterfactual
The Biofuel Policy Landscape

• Blender-Tax Credits (Volumetric Ethanol Excise Tax Credit, VEETC)
  – 45 cents per gallon tax credit for ethanol blenders.
  – This year ~9 billion gallons of ethanol were used
  – This subsidy creates a perverse incentive to produce low energy density fuels (ethanol instead of Fischer-Tröpsch Diesel)
Biofuel Policy Landscape (cont.)

• The Energy Independence and Security Act (EISA) requirements
  – In 2022 36 billion gallons of biofuel use is mandated
    • Of this, majority must be advanced/cellulosic
  – We are not meeting this target.

• EPA limits the percentage of ethanol which can be blended in RFG
  – Oxygenate requirements
  – Blending wall
General Conclusions

• No one fuel constitutes a silver-bullet
• Technology specific subsidies have not worked and are likely not to work
• US biofuel policy is very friendly to ethanol and will make it hard for other fuels to enter the market
• System thinking is necessary in analyzing such complex value chains