Dynamic Modeling of Learning in Emerging Energy Industries:
The Example of Advanced Biofuels in the United States

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Introduction to the Learning Model
What is industrial learning?

- Production cost reduction as a function of cumulative production volume (observed and assumed)
- Research distinguishes among different types of learning
- Quantitative metric is progress ratio, the relative cost after each doubling of cumulative production
Technology development, finance, and production are coupled

Industry Development
- Multiple Technologies/Multiple Regions
- Multiple Scales
  - Pilot
  - Demo
  - Pioneer
  - Commercial
- Learning Curve Dynamics
- Fuel Production

Maturity in terms of...
- Process Yield
- Input Capacity
- Capital Cost Growth
- Investor Risk Premium
- Debt Financing Access

Pioneer Scale Financials
- Multiple Technologies/Multiple Regions
- Pro Forma Financials
- Net Present Value of “Next” Plant

Commercial Scale Financials
- Multiple Technologies/Multiple Regions
- Pro Forma Financials
- Net Present Value of “Next” Plant

Industry Production and Capacity
- Multiple Technologies/Multiple Regions
- Pioneer and Commercial Scale
- Allocation of Plant Construction Capacity
- Initiation of Construction of Discrete Plants
- Net Present Value of “Next” Plant

Reinforcing feedback

Capacity Additions
Models use multiple stages in learning mechanism

- Learning Model (and BSM) divide technology development into pilot, demonstration, and commercial stages
- Experience accumulates with time (in pilot and demo) or production (commercial)
- Maturity and associated technical cost and performance metrics improve at each stage
Scenario Analysis of the Learning Model
Comparison of three pathways with different technology cost and performance

• Real-world biomass-to-biofuel conversion technology pathways vary in their relative
  o Maturity today
  o Expected process yield of a mature commercial biorefinery
  o Expected capital cost of a mature commercial biorefinery

• We performed a sensitivity analysis on cost and performance metrics
Comparison of three pathways with different technology cost and performance

<table>
<thead>
<tr>
<th>Pathway</th>
<th>Initial Maturity</th>
<th>Mature Process Yield</th>
<th>Mature Capital Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pathway A</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Pathway B</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Pathway C</td>
<td></td>
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</tbody>
</table>
Metrics show technology development, financial attractiveness, and production

- Baseline set so that all three pathways grow
- Model shows possible features of transition to commercial production
  - Oscillations in NPV reflect expiring subsidies
  - Relative production shares indicate potential for early technologies to plateau
Sensitivity analysis explores effects of pathway inputs through all combinations of selected variations

<table>
<thead>
<tr>
<th>Mature Industry Technoeconomics</th>
<th>Pathway A Baseline</th>
<th>Pathway B Baseline</th>
<th>Pathway C Baseline</th>
<th>Sensitivity Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedstock Input (dry short ton/day)</td>
<td>2,000</td>
<td>2,000</td>
<td>2,000</td>
<td>1.15 x baseline</td>
</tr>
<tr>
<td>Fixed Capital Investment ($)</td>
<td>300,000,000</td>
<td>300,000,000</td>
<td>400,000,000</td>
<td>1.15 x baseline</td>
</tr>
<tr>
<td>Fixed Operating Cost ($/yr)</td>
<td>15,000,000</td>
<td>15,000,000</td>
<td>15,000,000</td>
<td>1.05 x baseline</td>
</tr>
<tr>
<td>Other (non-feedstock) Variable Operating Cost ($/yr)</td>
<td>50,000,000</td>
<td>40,000,000</td>
<td>5,000,000</td>
<td>0.85 x baseline</td>
</tr>
<tr>
<td>Co-Product Sales Revenue ($/yr)</td>
<td>5,000,000</td>
<td>16,000,000</td>
<td>10,000,000</td>
<td>0.85 x baseline</td>
</tr>
<tr>
<td>Process Yield (gal/dry short ton)</td>
<td>100</td>
<td>90</td>
<td>66</td>
<td>0.85 x baseline</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Initial Technical Maturity (unit-less)</th>
<th>Pilot</th>
<th>Demonstration</th>
<th>Commercial</th>
<th>Pilot</th>
<th>Demonstration</th>
<th>Commercial</th>
<th>Pilot</th>
<th>Demonstration</th>
<th>Commercial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot</td>
<td>0.1</td>
<td>0.5</td>
<td>0.85</td>
<td>0.85 x baseline (pathway “B” only)</td>
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<tr>
<td>Demonstration</td>
<td>0</td>
<td>0.5</td>
<td>0.75</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Commercial</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<table>
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<tr>
<th>Progress Ratio (1/doubling)</th>
<th>Pilot</th>
<th>Demonstration</th>
<th>Commercial</th>
<th>Pilot</th>
<th>Demonstration</th>
<th>Commercial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>1.05 x baseline</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demonstration</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commercial</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
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<tr>
<th>Pre-Commercial Investment (projects/yr)</th>
<th>Pilot</th>
<th>Demo</th>
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</table>
Modeled system shows tendency for technology lock-in

- Things to watch over time series of this chart
  - Each point is a simulation
  - Position of points in chart shows technology shares
    - Single technology production dominance: points are at vertices
    - Two technologies producing: points are on legs of triangle
    - Three technology producing: equal shares are in middle
  - Size and color of circle shows amount of total production
- Large circles at vertices and on legs show lock-in tendency
Modeled system shows tendency for technology lock-in
Modeled system exhibits technology lock-in
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Modeled system exhibits technology lock-in

Total Biofuels Production [gal/yr]
- ≤ 60,000,000
- 2,000,000,000
- 4,000,000,000
- 6,000,000,000
- 8,000,000,000
- 9,000,000,000

60M 9B

2026
Modeled system exhibits technology lock-in

Total Biofuels Production [gal/yr]
- ≤ 60,000,000
- 2,000,000,000
- 4,000,000,000
- 6,000,000,000
- 8,000,000,000
- 9,000,000,000

2028
Modeled system exhibits technology lock-in

Total Biofuels Production [gal/yr]
- ≤ 60,000,000
- 2,000,000,000
- 4,000,000,000
- 6,000,000,000
- 8,000,000,000
- 9,000,000,000

2029
Modeled system exhibits technology lock-in

Base Case

2030
Mechanism for interactive effects based on learning and competition for investment

- Production A
- Maturity A
- Progress Ratio A

- Relative Attractiveness A : B

- Investment A
- Capacity A
- Delay

- Investment B
- Capacity B
- Delay

- Nth – plant attractiveness A
- Nth – plant attractiveness B

- Progress Ratio A

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Summary

- **Novel Learning Model** approach contrasts with single-factor learning
  - Progress toward mature performance instead of an implicit zero asymptote
  - Multiple technical attributes instead of only unit cost
  - Multiple development scales.
- **Parameters studied** exhibit highly interactive effects
  - Fixed capital investment
  - Process yield
  - Progress ratios
  - Pre-commercial investment
- **System shows tendency** towards market dominance of a single pathway
- **Result are not predictive** but illustrative
- **Broad applicability** to emerging industries to show interactions among:
  - Investment decisions
  - Cost reductions during development
  - Utilization and production