A Hierarchy of Models for R&D Planning and Policy Analysis

Options for a single facility (tech feasibility, efficiency, emissions, cost)

Multi-facility (or multi-sector) optimization or simulation (dynamic)

Integrated assessment models (including measures of impacts)
Areas of Modeling Research

• Performance, emissions and costs of fossil fuel power plants and environmental control options
  - Criteria air pollutants and consumptive water use
  - Carbon dioxide capture, transport and sequestration
  - Coal-to-liquids processes and polygeneration systems

• Energy storage options for solar-thermal power plants

• Environmental technology innovation and learning
The Research Team

- Mike Berkenpas
- Chris Frey (NCSU)
- Karen Kietze
- Hari Mantripragada
- Aaron Marks
- Sean McCoy
- Andrew Place
- Ed Rubin
- Sharon Wagner
- Peter Versteeg
- Sonia Yeh (UCD)
- Haibo Zhai
Power plant performance, emissions and cost

E.S. Rubin, Carnegie Mellon
The IECM Project: Power Plant Performance, Emissions & Costs

• A desktop/laptop computer model developed for DOE/NETL; free and publicly available at: www.iecm-online.com

• Provides systematic estimates of performance, emissions, costs and uncertainties for preliminary design of:
  ▪ PC, IGCC and NGCC plants
  ▪ All flue/fuel gas treatment systems
  ▪ CO₂ capture and storage options (pre- and post-combustion, oxy-combustion; transport, storage)
Modeling Approach

- Systems Analysis Approach
- Process Performance Models
- Engineering Economic Models
- Advanced Software Capabilities
  - Probabilistic analysis capability
  - User-friendly graphical interface
  - Easy to add or update models
IECM Software Package

**Fuel Properties**
- Heating Value
- Composition
- Delivered Cost

**Plant Design**
- Conversion Process
- Emission Controls
- Solid Waste Mgmt
- Chemical Inputs

**Cost Factors**
- O&M Costs
- Capital Costs
- Financial Factors

---

**Power Plant Models**

**Graphical User Interface**

**Plant and Fuel Databases**

---

**Plant & Process Performance**
- Efficiency
- Resource use

**Environmental Emissions**
- Air, water, land

**Plant & Process Costs**
- Capital
- O&M
- COE
IECM Technologies for PC Plants
(excluding CO₂ capture, transport and sequestration)

Boiler Types
- Subcritical
- Supercritical
- Ultra-supercritical

Furnace Firing Types
- Tangential
- Wall
- Cyclone

Furnace NOₓ Controls
- LNB
- SNCR
- SNCR + LNB
- Gas reburn

SO₂ Removal
- Wet limestone
  - Conventional
  - Forced oxidation
  - Additives
- Wet lime
- Lime spray dryer
- Combined SO₂/NOₓ systems

NOₓ Removal
- Hot-side SCR
- Combined SO₂/NOₓ systems

Mercury Removal
- Carbon/sorbent injection

Particulate Removal
- Cold-side ESP
- Fabric filter
  - Reverse Air
  - Pulse Jet

Solids Management
- Ash pond
- Landfill
- Stacking
- Co-mixing
- Byproducts
Models Account for Multi-Pollutant Interactions

- Criteria Air Pollutants: PM, SO₂, NOₓ
- Hazardous Air Pollutants: Hg, HCl, H₂SO₄
- Greenhouse Gas Emissions: CO₂, CH₄
### Some Recent IECM Users

<table>
<thead>
<tr>
<th>User Name</th>
<th>Company/Institution</th>
<th>City/Location</th>
<th>Industry/Field</th>
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<td>Clean Energy Systems Inc</td>
<td>Ann Arbor, MI</td>
<td>Energy, Power</td>
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<tr>
<td>Air Liquide</td>
<td>Coal in Sustainable Dev., Tech Transfer</td>
<td>Pittsburgh, PA</td>
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<td>Air Products plc</td>
<td>Coalex LLC / Jupiter Oxygen Corp.</td>
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<td>Cogentrix Energy, Inc</td>
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</table>

E.S. Rubin, Carnegie Mellon
Profile of Recent IECM Users

Type of Organization

- Company: 44%
- Education: 17%
- Utility: 28%
- Government: 11%

Geographic Region

- North America: 71%
- Europe: 23%
- Asia: 4%
- Australia: 2%
- South America: <1%

~ 500 organizations
Positive Feedback from Industry, Academia & Government

We've recently started using your IECM website to guide us in developing preliminary cost estimates for our operations. Refinery carbon capture has its own issues, but the information on the IECM website is extremely helpful. I just wanted to send along a note of thanks to you and Carnegie-Mellon for making this model available and the technical support behind it. We appreciate your work very much.

- George Schuette, Hydrogen - Carbon Dioxide Group, ConocoPhillips Technology Center

I'll be co-teaching a course … on carbon capture and sequestration. We're really eager to use your IECM software package throughout our course this fall. I'm hoping to use examples from both industry and research …It would be wonderful to get together in person sometime to share ideas and to share with you our experience for using your program directly in our new course.

- Jen Wilcox, Stanford University, Department of Energy Resources Engineering

“reviewers felt this contribution was …the ‘highlight’ of this year’s review meeting.”

IECM User Interface

Select Plant Type

New Session

Plant Type:
- Combustion (Boiler)
- Combustion (Boiler)
- Combustion (Turbine)
- IGCC

Ok
Cancel
PC Plant with Post-Comb. CCS

E.S. Rubin, Carnegie Mellon
NGCC Plant with CCS

E.S. Rubin, Carnegie Mellon
IGCC Plant with CCS

Gasification Options
- Gasifier: GE-quench O2-blown
- Gas Cleanup: Cold-gas
- CO2 Control: Sour Shift + Selexol

Combustion Controls
- NOx Control: None

Solids Management
- Slag: Landfill
- Sulfur: Sulfur Recovery

Configuration: Sour Shift + Selexol

E.S. Rubin, Carnegie Mellon
Specify Fuel Parameters

E.S. Rubin, Carnegie Mellon
Specify Technology Parameters

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<thead>
<tr>
<th>ID</th>
<th>Title</th>
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<th>Unc</th>
<th>Value</th>
<th>Calc</th>
<th>Min</th>
<th>Max</th>
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<td>2</td>
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<td>Total Carbon Loss</td>
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Process Type: Texaco
Set Financial Parameters

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<td>Fixed Charge Factor (FCE)</td>
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E.S. Rubin, Carnegie Mellon
Get Results for the Overall Plant

### Plant Mass Flows

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<th>Plant Inputs</th>
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<td>Coal</td>
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<tr>
<td>Oil</td>
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<td>Natural Gas</td>
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<tr>
<td>Petroleum Coke</td>
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<td>Other Fuels</td>
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<td>Total Fuels</td>
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<tr>
<td>Lime/Limestone</td>
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<td>Stronges</td>
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<tr>
<td>Ammonia</td>
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<tr>
<td>Activated Carbon</td>
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<tr>
<td>Other Chemicals, Solvents</td>
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<td>Total Chemicals</td>
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<td>Process Water</td>
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### Total Plant Costs

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<th>Capital Required ($/kW-h)</th>
<th>Revenue Required (M$)</th>
<th>Revenue Required ($/kW-h)</th>
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<td>4. Sulfer Control</td>
<td>54.38</td>
<td>110.7</td>
<td>12.23</td>
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<td>5. Mercury Control</td>
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<td>6. CO2 Capture</td>
<td>143.9</td>
<td>292.6</td>
<td>57.34</td>
<td>17.75</td>
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<td>7. Power Block</td>
<td>300.4</td>
<td>311.4</td>
<td>21.95</td>
<td>8.765</td>
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<td>8. Post-Comb. NOx Control</td>
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<td>9. Subtotal</td>
<td>801.6</td>
<td>1335</td>
<td>226.8</td>
<td>86.69</td>
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<td>10. Emission Taxes</td>
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<tr>
<td>11. Total</td>
<td>801.6</td>
<td>1335</td>
<td>226.8</td>
<td>86.69</td>
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</tbody>
</table>

Costs are in constant 2002 dollars.
Get Results for Specific Plant Components

E.S. Rubin, Carnegie Mellon
Example of Probabilistic Results

Probabilistic Results for a PC Plant with Amine-Based Capture

Uncertainty or Variability in:
- CO₂ capture efficiency
- steam-electric penalty
- compressor efficiency
- lean sorbent loading
- process facilities cost
- CO₂ storage cost
- variable operating costs
- gross plant heat rate
- plant capacity factor
- fixed charge factor

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Model Applications

- Process design
- Technology evaluation
- Cost estimation
- R&D management
- Risk analysis
- Environmental compliance
- Marketing studies
- Strategic planning
Recent IECM Applications:
Potential Cost Reductions from R&D

Cost of CO₂ Avoided ($/tonne CO₂)

- Plant Derate: 57
- Same Output: 52
- Cheaper Boiler: 49
- Future Amines: 34
- Heat Integr.: 31
- Amine Capex: 29

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Recent IECM Applications: Coal Quality Impacts on Technology Choice

(2005 $/MWh; dashed lines based on constant $/GJ for all coals)

All plants ~500 MW(net); 75% CF; Aquifer storage;
IGCC based on GE quench; PC=supercritical
Thermal storage options for solar power plants

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Research Questions

• What are the costs and benefits of adding a thermal storage system to a parabolic trough concentrated solar power plant?
  - Financial
  - Environmental

• How do life cycle impact with thermal storage compare to a PT system without storage?
Sharon Wagner and Plant Manager at SEGS - Kramer Junction

PT-CSP Model structure
PT-CSP Performance-Cost Model

- Builds on basics of NREL Solar Advisor Model (SAM) for solar field and power cycle performance
- More detailed representation of thermal storage:
  - Incorporates effect of storage heat exchanger area on plant performance and cost (indirect storage)
  - Calculates solar field area increase based on increased storage capacity
  - Calculates storage system cost based on component costs obtained from Kelly and Kearney (2006)
- Compares the cost of parabolic trough plants with and without storage
TES Performance Model

1. No TES

2. Two-Tank Direct

3. Two-Tank Indirect

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Preliminary Results

Compared to PT-CSP with no thermal storage:

- **Benefits:**
  - Higher capacity factor, greater annual output
  - Lower LCOE

- **Costs:**
  - Higher capital costs
  - Carbon tax necessary to compete with fossil fuels
  - Higher life cycle emissions, energy use and water use
Technology innovation and learning rates
Two Approaches to Estimating Future Technology Costs

- **Method 1**: Engineering-Economic Analysis
  - A “bottom up” approach based on engineering process models, informed by judgments regarding potential improvements in key process parameters

- **Method 2**: Use of Historical Experience Curves
  - A “top down” approach based on applications of mathematical “learning curves” or “experience curves” that reflect historical trends for analogous technologies or systems
Case Study Technologies

- Flue gas desulfurization systems (FGD)
- Selective catalytic reduction systems (SCR)
- Gas turbine combined cycle system (GTCC)
- Pulverized coal-fired boilers (PC)
- Liquefied natural gas plants (LNG)
- Oxygen production plants (ASU)
- Hydrogen production plants (SMR)
## Case Study Learning Rates

<table>
<thead>
<tr>
<th>Technology</th>
<th>“Best Estimate” Learning Rates</th>
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<tbody>
<tr>
<td></td>
<td>Capital Cost</td>
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<td>Flue gas desulfurization (FGD)</td>
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<tr>
<td>Selective catalytic reduction (SCR)</td>
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<td>Gas turbine combined cycle (GTCC)</td>
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<td>Pulverized coal (PC) boilers</td>
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<tr>
<td>LNG production</td>
<td>0.14</td>
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<td>Oxygen production (ASU)</td>
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<tr>
<td>Hydrogen production (SMR)</td>
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</table>
Apply to CCS Plant Designs

PC Plant
Steam Turbine Generator
Steam
PC Boiler
Coal
Air
Air Pollution Controls (SCR, ESP, FGD)
CO₂ Capture System
Mostly N₂
Amine/CO₂ Separation
CO₂ Compression
CO₂ to storage
CO₂ to atmosphere

Oxyfuel Plant
Steem Turbine Generator
Steam
PC Boiler
Coal
O₂
CO₂ to recycle
Air Pollution Controls (ESP, FGD)
CO₂ Capture System
CO₂ Compression
CO₂ Storage

NGCC Plant
Combustor
Steam Turbine Generator
Steam
Natural Gas
Air Compressor
Air
CO₂ Capture System
Mostly N₂
Amine/CO₂ Separation
CO₂ Compression
CO₂ Storage

IGCC Plant
Gasifier
Quench System
Gas Turbine
Steam
Shift Reactor
Sulfur Removal System
H₂
H₂O
CO₂ Capture System
H₂
Gas Turbine Combined Cycle System
CO₂ Compression
CO₂ Storage

E.S. Rubin, Carnegie Mellon
Select learning rate analogues for each plant component

<table>
<thead>
<tr>
<th>Plant Type &amp; Technology</th>
<th>FGD</th>
<th>SCR</th>
<th>GTCC</th>
<th>PC boiler</th>
<th>LNG prod</th>
<th>O₂ prod</th>
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<td>IGCC Plant</td>
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<td>Air separation unit</td>
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<td>Gasifier area</td>
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<td>Sulfur removal/recovery</td>
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<td>CO₂ capture system</td>
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<td>CO₂ compression</td>
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<td>GTCC (power block)</td>
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Summary of COE Results
(Based on 100 GW of cumulative CCS capacity)
Work in Progress: Characterizing Radical Technological Innovation

**Motivation**
R&D programs and policies are targeting “radical” change

**Literature Review**
of “radical innovation”

**Implications**
for R&D planning and evaluation to accomplish “radical” change in fossil-energy

**Case Studies**
of instances of “radical” change in fossil-energy

**Interviews**
With experts from fossil-energy R&D community
Thank You

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