Economic Input-Output Life Cycle Assessment for Power Plant Construction

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Energy Life Cycle Analysis
Cradle-to-grave environmental footprint of energy systems

Mission
Develop and utilize the LCA framework and methods to support the evaluation of sustainable energy systems both in and outside of the Department of Energy

Vision
A world-class research and analysis team that integrates results which inform and recommend sustainable energy strategy and technology development

Tim Skone – 18 years
Federal Team Lead
BS Chemical Engineering
Joe Marriott – 12 years
Contractor Team Lead
PhD Environmental Eng. & Public Policy
James Littlefield – 16 years
Natural gas, system & process design
BS Chemical Engineering
Chung Shih – 12 years
GIS, Subsurface, Software Dev.
PhD Advanced Infrastructure Systems
Matt Jamieson – 8 years
Power systems, CO2-EOR
BS Mechanical Engineering
Michele Mutcheck – 5 years
Loan program office, CO2 Utilization
MS Civil/Env/Sust Engr | BS Env Sciences
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Natural gas, fuel cells, coal
BS Civil/Env Engr & Public Policy
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I/O LCA, Efficiency, CO2 capture
PhD/MS Civ/Env Engr | B.S. Chemistry
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Natural gas, visual analytics
BS Energy Engineering
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Energy analysis; transportation fuels
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Recent and Ongoing LCA Studies

**Petroleum**

- Evaluating the Climate Benefits of CO₂-Enhanced Oil Recovery Using Life Cycle Analysis
- Updating the U.S. Life Cycle GHG Petroleum Baseline to 2014 with Projections to 2040 Using Open-Source Engineering-Based Models

**Natural Gas**

- Synthesis of recent ground-level methane emission measurements from the US natural gas supply chain

**Coal**

- Identifying/Quantifying Environmental Trade-offs Inherent in GHG Reduction Strategies for Coal-Fired Power
- Understanding the Contribution of Mining and Transportation to the Total Life Cycle Impacts of Coal Exported from the United States

**Ongoing Work**

- Establishing an Electricity Baseline for the U.S.
- Full environmental inventory for the Petroleum Baseline
- Creating a 2016 baseline for natural gas produced in the U.S.
- Creating a regionalized 2017 baseline for coal produced in the U.S.
- Using field EOR data to inform LCA results
- Collaboration with ONE Future for natural gas characterization
- Options for energy in the North Slope of Alaska
- Updated advanced power plant design LCAs

**Collaborators**

- University of Calgary
- ONE Future
- Wyoming Department of Environmental Quality
- EDF
Scope

• LCA at NETL
  • Largely process based, over 450 unit processes
  • www.netl.doe.gov/lca

• Power plant construction modeling has been incomplete
  • Small impacts relative to operation
  • “In case of insufficient input data or data gaps for a unit process, materials and processes can be omitted, if the process contributes with less than 1% of mass or renewable or non-renewable primary energy of the total, and all excluded materials and processes do not exceed 5% of total energy use and mass.” – EeBGuide Project

• Can we improve?

Reference: DOE/NETL-2015/1723 “Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3”
<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Parameter Formula</th>
<th>Units</th>
<th>Min. Value</th>
<th>Max. Value</th>
<th>Description</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>McD, N, CsCO3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>NCO2, N, CsCO3</td>
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<tr>
<td>NCO2, N, CsCO3</td>
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<tr>
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<td>NCO2, N, CsCO3</td>
<td></td>
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<tr>
<td>NCO2, N, CsCO3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Flow Name**
- Concrete, ready mix, R-5-0 (Valuable substances)
- Steel cold rolled (St) (Metals)
- Steel pipe (Metals)
- Cast iron part (Metal parts)
- Aluminum sheet (Metals)
- Stainless steel (cold rolled) (Metals)

*Select this entire row, then insert new row*
Moving Beyond Raw Material Inputs
Engineering, Architectural, Chemical, Construction, Design, Government, etc.

Power Plant Construction

Raw Materials
(current modeling)
- Steel
- Aluminum
- Concrete
- Iron

Additional Components
(proposed additions)
- Manufacturing
- Construction
- Services

- NETL baseline reports for coal and gas plants
- CMU Green Design Institute’s EIO-LCA
Data & Plan

- Detailed Cost Engineering Data
  - Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3 (NETL)

- Map to NAICS (EIO sectors)

- Input to EIO-LCA model – Carnegie Mellon University Green Design Institute – 2002 Producer model
### Plant Cost Details (Supercritical PC e.g.)

#### Table: Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Description</th>
<th>EIO-LCA Sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRSG, Ducting, &amp; Stacks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.3</td>
<td>Ductwork</td>
<td>Air purification and ventilation equipment manufacturing</td>
</tr>
<tr>
<td>7.4</td>
<td>Stack</td>
<td>Air purification and ventilation equipment manufacturing</td>
</tr>
<tr>
<td>7.9</td>
<td>HRSG, Duct &amp; Stack Foundations</td>
<td>Ready-mix concrete manufacturing</td>
</tr>
<tr>
<td>Steam Turbine Generator</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.1</td>
<td>Steam TG &amp; Accessories</td>
<td>Turbine and turbine generator set units manufacturing</td>
</tr>
<tr>
<td>8.2</td>
<td>Turbine Plant Auxiliaries</td>
<td>Turbine and turbine generator set units manufacturing</td>
</tr>
<tr>
<td>8.3</td>
<td>Condenser &amp; Auxiliaries</td>
<td>Turbine and turbine generator set units manufacturing</td>
</tr>
<tr>
<td>8.4</td>
<td>Steam Piping</td>
<td>Turbine and turbine generator set units manufacturing</td>
</tr>
<tr>
<td>8.9</td>
<td>TG Foundations</td>
<td>Iron, steel pipe and tube manufacturing from purchased steel</td>
</tr>
<tr>
<td></td>
<td><strong>Subtotal</strong></td>
<td>$110,073 $1,247 $24,647 $0 $135,967 $13,597</td>
</tr>
</tbody>
</table>

- **Map each line of the cost tables to EIO-LCA (NAICS) sectors**
  - Quick, reliable, & easy way to model small components (vs. full UP)
  - Full UPs are not warranted given size of construction impacts
- Offers much more detail than raw material UPs
Expansion of Impact Categories (EIO-LCA)

<table>
<thead>
<tr>
<th>Economic Activity ($ millions)</th>
<th>Conventional Air Pollutants (metric tons)</th>
<th>Greenhouse Gasses (t CO2e)</th>
<th>Energy (TJ)</th>
<th>Toxic Releases (kg)*</th>
<th>Transportation (ton-km)</th>
<th>TRACI LCIA</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Economic Activity</td>
<td>CO</td>
<td>Total</td>
<td>Total Energy</td>
<td>Fugitive Air</td>
<td></td>
<td>Glob Warm CO2e</td>
<td>HazWaste Gen</td>
</tr>
<tr>
<td>Total Value Added</td>
<td>NH₃</td>
<td></td>
<td>Coal</td>
<td>Stack Oil Pipe</td>
<td></td>
<td>Acidif Air SO₂e</td>
<td>Water Withdrawls</td>
</tr>
<tr>
<td>Employee Comp VA</td>
<td>NOx</td>
<td></td>
<td>CO₂ Fossil</td>
<td>Natural Gas Gas Pipe</td>
<td></td>
<td>HH Crit Air PM10e</td>
<td>Land Use</td>
</tr>
<tr>
<td>Net Tax VA</td>
<td>PM10</td>
<td></td>
<td>CO₂ Process</td>
<td>Total Air Rail</td>
<td></td>
<td>Eutro Air Ne</td>
<td></td>
</tr>
<tr>
<td>Profits VA</td>
<td>PM2.5</td>
<td></td>
<td>CH₄</td>
<td>Surface Water Truck</td>
<td></td>
<td>Etro Water Ne</td>
<td></td>
</tr>
<tr>
<td>Direct Economic</td>
<td>SO₂</td>
<td></td>
<td>N₂O</td>
<td>Underground Water Water</td>
<td></td>
<td>OzoneDep CFC-11e</td>
<td></td>
</tr>
<tr>
<td>Direct Economic (%)</td>
<td>VOC</td>
<td></td>
<td>HFC/PFCs</td>
<td>Land Offsite</td>
<td></td>
<td>Smog Air O₃e</td>
<td></td>
</tr>
</tbody>
</table>

* The table above summarizes toxic emissions by sector by aggregating across all toxic substances regardless of impact. That is not a very good way of summarizing toxics.

Assumptions
Primarily for scaling up current UPs to total construction impact rather than per MWh

- 30 year lifetime for power plant
- 85% capacity factor
- 550 MWh NGCC plant
- 630 MWh SCPC plant
- 3% discount rate (to match the report year [2011 USD] and the EIO model year [2002 USD])
  - Consistent with national average Consumer Product Index
- **Eng. H.O. and Fee** is 10% of the bare erected cost – modeled as the ‘architectural and engineering services’ sector
  - Architectural
  - landscape architectural
  - engineering, drafting
  - building inspection
  - geophysical surveying and mapping
  - surveying and mapping (except geophysical) services
  - testing laboratories
- **Labor** is modeled as other nonresidential construction
### Results – Construction (SCPC)

UPs have mostly underestimated impacts

<table>
<thead>
<tr>
<th>Selective Releases</th>
<th>UP kg per MWh</th>
<th>UP kg per Plant</th>
<th>EIO-LCA kg per Plant</th>
<th>Ratio EIO to UP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>1.2 E-06</td>
<td>1.3 E04</td>
<td>3.5 E05</td>
<td>2.5</td>
</tr>
<tr>
<td>Barium</td>
<td>1.4E-08</td>
<td>1.7</td>
<td>11</td>
<td>6.6</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>0.94</td>
<td>1.1E08</td>
<td>4.0E08</td>
<td>3.5</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>0.01</td>
<td>1.1E08</td>
<td>2.6E08</td>
<td>2.3</td>
</tr>
<tr>
<td>NOx</td>
<td>1.0 E-05</td>
<td>1.2E03</td>
<td>1.8E04</td>
<td>14</td>
</tr>
<tr>
<td>Sulphur dioxide</td>
<td>0.0017</td>
<td>2.1E05</td>
<td>1.3E06</td>
<td>6.1</td>
</tr>
<tr>
<td>Organic emissions to air (group VOC)</td>
<td>0.0026</td>
<td>3.2E05</td>
<td>3.7E05</td>
<td>1.1</td>
</tr>
<tr>
<td>Methane</td>
<td>0.0025</td>
<td>3.1E05</td>
<td>1.6E06</td>
<td>5.4</td>
</tr>
<tr>
<td>Particles to air</td>
<td>0.001</td>
<td>1.3E05</td>
<td>5.7E05</td>
<td>4.3</td>
</tr>
</tbody>
</table>
### Results – NGCC (Construction)

UPs have mostly underestimated impacts

<table>
<thead>
<tr>
<th>a</th>
<th>UP kg per MWh</th>
<th>UP kg per Plant</th>
<th>EIO-LCA kg per Plant</th>
<th>Ratio EIO to UP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>5.84E-07</td>
<td>14,886</td>
<td>23,800</td>
<td>1.6</td>
</tr>
<tr>
<td>Barium</td>
<td>7.91E-09</td>
<td>1.1</td>
<td>1.1</td>
<td>1.0</td>
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<tr>
<td>Carbon dioxide</td>
<td>0.43</td>
<td>6.0E07</td>
<td>2.4E08</td>
<td>3.9</td>
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<tr>
<td>Carbon monoxide</td>
<td>0.0036</td>
<td>5.1E05</td>
<td>1.3E06</td>
<td>2.5</td>
</tr>
<tr>
<td>NOx</td>
<td>3.76E-06</td>
<td>530</td>
<td>8,722</td>
<td>16</td>
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<tr>
<td>Sulphur dioxide</td>
<td>0.00080</td>
<td>1.1E05</td>
<td>6.1E05</td>
<td>5.5</td>
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<tr>
<td>Organic emissions to air (group VOC)</td>
<td>0.0012</td>
<td>1.6E05</td>
<td>2.2E05</td>
<td>1.4</td>
</tr>
<tr>
<td>Methane</td>
<td>0.0011</td>
<td>1.5E05</td>
<td>1.2E06</td>
<td>7.8</td>
</tr>
<tr>
<td>Particles to air</td>
<td>0.00043</td>
<td>6.1E04</td>
<td>3.8E05</td>
<td>6.2</td>
</tr>
</tbody>
</table>
Does Construction Matter?
Old UP vs. New UP

### NGCC 630 Construction Impacts / Total Impacts

<table>
<thead>
<tr>
<th>Output</th>
<th>% of Impacts (Old UP)</th>
<th>% of Impacts (EIO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>0.4%</td>
<td>0.6%</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>0.1%</td>
<td>0.5%</td>
</tr>
<tr>
<td>NOx</td>
<td>0.9%</td>
<td>15%</td>
</tr>
</tbody>
</table>

### SCPC 550MW Construction Impacts/Operation Impacts

<table>
<thead>
<tr>
<th>Output</th>
<th>% of Impacts (Old UP)</th>
<th>% of Impacts (EIO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>4.8%</td>
<td>12%</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>0.1%</td>
<td>0.4%</td>
</tr>
<tr>
<td>NOx</td>
<td>0.2%</td>
<td>3.0%</td>
</tr>
<tr>
<td>Particulate Matter</td>
<td>2.1%</td>
<td>9.1%</td>
</tr>
</tbody>
</table>
Fossil Scenarios with CCS?

SCPC Plant with CCS

• CCS represents a 40% increase in cost over a power plant without CCS
  • Some uncertainty with the exact numbers as these data are proprietary
  • The 40% adder to construction impacts is a good starting point

<table>
<thead>
<tr>
<th>SCPC 550MW Construction Impacts/Operation Impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output</td>
</tr>
<tr>
<td>Ammonia</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>NOx</td>
</tr>
<tr>
<td>Particulate Matter</td>
</tr>
</tbody>
</table>

• Construction is approximately 5% of operational lifetime CO$_2$ emissions
GHGs Scale with Construction Costs

\[ y = 0.6812x + 4.3417 \]

\[ R^2 = 0.9528 \]

- NGCC
- Subcritical PC
- Supercritical PC
- LR IGCC

Construction and Manufacturing GHGs (Thousand Tons CO2e)

Total Cost ($Million 2002)
Conclusions

- EIO-LCA offers an easy and reliable method to estimate construction emissions for power plants and expand inventory.
- Construction, design, processing, and other services are important to the construction impacts (3x -4x increase in CO$_2$ emissions).
  - Other impacts vary, but ignoring construction or modeling as raw material inputs misses the mark.
- While construction represents <1% of many impacts for the life cycle of a fossil power plant, this is unlikely to be true with the adoption of CCS and renewables.
  - For SCPC w/ CCS – construction emissions are ~5% of the operational CO$_2$ emissions.
Future Work

• Is this scalable beyond coal and natural gas?
  • Nuclear, Hydro
  • Wind, Solar

• Decommissioning
  • Data sources
  • Recycling of materials

• Update to USEEIO
Contact Information

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Life Cycle Analysis
environmental | economic | social

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Preliminary Results – NGCC w/CCS

UPs have mostly underestimated impacts – note that these impacts are uncertain.

<table>
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<th>Ratio EIO to UP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>1.2E-06</td>
<td>1.5E+02</td>
<td>2.0E+04</td>
<td>130</td>
</tr>
<tr>
<td>Barium</td>
<td>1.5E-08</td>
<td>2.0E+00</td>
<td>2.0E+01</td>
<td>11</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>1.5E+00</td>
<td>1.8E+08</td>
<td>6.9E+08</td>
<td>3.8</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>1.2E-02</td>
<td>1.5E+06</td>
<td>4.3E+06</td>
<td>2.9</td>
</tr>
<tr>
<td>Nitrogen (N-compounds)</td>
<td>1.6E-12</td>
<td>0.0E+00</td>
<td>1.7E+06</td>
<td>6.6</td>
</tr>
<tr>
<td>Nitrogen dioxide</td>
<td>1.1E-05</td>
<td>1.4E+03</td>
<td>3.2E+04</td>
<td>24</td>
</tr>
<tr>
<td>Sulphur dioxide</td>
<td>2.6E-03</td>
<td>3.2E+05</td>
<td>2.2E+06</td>
<td>6.9</td>
</tr>
<tr>
<td>Organic emissions to air (group VOC)</td>
<td>3.9E-03</td>
<td>4.8E+05</td>
<td>6.4E+05</td>
<td>1.3</td>
</tr>
<tr>
<td>Methane</td>
<td>3.7E-03</td>
<td>4.6E+05</td>
<td>2.9E+06</td>
<td>6.3</td>
</tr>
<tr>
<td>Particles to air</td>
<td>1.3E-03</td>
<td>1.7E+05</td>
<td>9.7E+05</td>
<td>5.9</td>
</tr>
</tbody>
</table>