Life-cycle Greenhouse Gas And Energy Balance Of Community-scale Wind Powered Ammonia Production

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The WCROC Research Facility

- One of several locations around the state that researches agriculture.
- In addition to traditional agricultural topics, we focus on energy and agricultural systems.
- Our energy focus is covers community scale agricultural energy issues.
Several Industrial Uses for Ammonia

- Refrigeration
- Chemical Manufacture
- Agriculture
  - Largest Current use in the US
- As an energy storage medium
Traditional Production of Ammonia

- Large Facilities
  - High capital costs
  - Large Resource Demand
    - Production must be located near feedstocks
- Fossil Based- cost linked
  - Natural gas
  - Coal gasification
- Transported great distances

Natural Gas Prices 1997 to 2013

- Commercial Prices
- Industrial Prices
Issues with Traditional production

- Fossil Energy Use
  - Both coal and natural gas

- Shortages
  - Transportation bottlenecks
  - Demand Spikes in fall and spring

- Cost
Wind Powered Ammonia Production

- Uses electricity for entire process
  - Commercial scale turbines with grid backup
  - Nitrogen isolated from the air
  - Hydrogen from electrolysis of water

- Done at ‘community’ scale, where needed
  - Less capital
  - Limited transport needed
University of Minnesota Ammonia Facility

Wind Electricity

Grid Electricity

Air

Ammonia Production Facility

Water

Anhydrous Ammonia
Hydrogen Storage Tanks

Hydrogen, Nitrogen, and Ammonia Production Buildings

Nitrogen Storage Tank

Safety Equipment & Shower Building

12.5 kV to 480 V Transformer

Ammonia Product Storage (3000 Gallons)

Ammonia Pump and Loadout
Status of Pilot Facility

- Operating and studying the system since early 2013.
- Production chemistry and reactor appear to function well.
- Production capacities seem to be accurate.
- Some issues with supporting equipment systems
  - Modified from off the shelf industrial equipment
    - Little prior experience on how these should be set up
  - Valve and sensor materials
    - Not always compatible with ammonia
    - Sometimes not correct for temperatures seen.
How Electricity is Used In The System

Approximate Electrical Use in Ammonia Production

- Electricity Input 60 MJ
- Hydrogen Production 50%
- Nitrogen Production 5%
- Ammonia Generation 31%
- Ammonia Cooling 14%

1 Kg Nitrogen (in ammonia)

- This is the point the work was at last year at this time
Environmental Impacts of Wind Based Ammonia Production

- Environmental impacts are an important consideration
  - Wind based ammonia not likely to be adopted if not a ‘green’ technology
  - Agriculture under pressure to be more sustainable

*Research Question:* Does using wind energy for ammonia production have less environmental impacts than the traditional fossil methods?
- Fossil energy depletion
- Releases of greenhouse gases
Using LCA Modeling To Study Impacts

- Limited life cycle assessment
- ‘Cradle to Grate’
  - All resources going into energy production
    - Wind infrastructure construction energy
    - Grid fossil energy and infrastructure construction energy
  - Units of ammonia production
- Analysis ends at production storage tanks
  - At this point wind ammonia and fossil ammonia are identical
Ammonia Production System Modeled

- **Community-scale facility**
  - Serve a county sized mid-western agricultural area
    - Based on a Midwestern agricultural coop size
    - Around 150,000 acres of corn
    - 5500 tonnes anhydrous ammonia per year
    - Roughly 630 kg per hour NH3 (520 Kg N)

- **Energy demand**
  - 7.4 MW constant
  - 8-15 Turbines depending on scenario
Scenarios Examined

- Location
  - Sweden
  - United States

- Net percent of system electricity produced by wind
  - 75% From Wind (25% purchased)
  - 100% From Wind (Net 0)
  - 125% From Wind (25% excess sold)
Data Analyzed

- **Electrical flows**
  - Power purchased from the grid
  - Power sold to the grid

- **Environmental footprint for electricity**
  - Types of power generation
  - Percentage of each power type
  - Fossil energy used by power type
  - GHG released by each power type
Overall Method of Calculating Emissions*

\[
\begin{align*}
\frac{\text{Emissions}}{\text{Grid}} \times \frac{\text{Quantity of Electricity From Grid}}{} \\
+ \frac{\text{Emissions}}{\text{Turbine}} \times \frac{\text{Quantity of Electricity From Turbine}}{} \\
- \frac{\text{Emissions Credit For Electricity sold}}{} \times \frac{\text{Quantity of Electricity Sold}}{}
\end{align*}
\]

Emissions Per Kg of Ammonia Produced

*Same Basic Idea for Fossil Energy Use
Flows of Power

Tallaksen et al. 2014

Ammonia Production Facility

Turbine Electricity

Grid Electricity

Turbine Electricity

Grid Electricity
Modeling Power Flows

• Began with a wind energy model
  ◦ Actual data vs mathematical estimates

• Models provided:
  ◦ Energy production by the wind farm
  ◦ Frequency of specific production levels.

• Data was turned into an average for each hour of operation

• The end result was a set of number for each scenerio.
Modeling Power Flows

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  - Energy production by the wind farm
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<table>
<thead>
<tr>
<th>Average Hourly Power Flows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minnesota</td>
</tr>
<tr>
<td>125% production model</td>
</tr>
</tbody>
</table>

- 13.4 turbines (1.65MW) needed
- Wind Production: 9.3 MWhr
- Grid Purchases: 2.6 MWhr
- Net Sales: 4.5 MWhr
- Power to Facility 7.4 MWhr
## Regional Electricity Grids Compared

- Minnesota has significant coal generations with nuclear and wind making up most of the rest.
- Sweden has mostly hydropower and nuclear. Very little fossil generation.

<table>
<thead>
<tr>
<th>Source</th>
<th>Minnesota</th>
<th>Swedish</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind power</td>
<td>13%</td>
<td>5%</td>
</tr>
<tr>
<td>Hydro power</td>
<td>1%</td>
<td>51%</td>
</tr>
<tr>
<td>Gas turbines</td>
<td>6%</td>
<td>0.06%</td>
</tr>
<tr>
<td>Coal</td>
<td>53%</td>
<td>-</td>
</tr>
<tr>
<td>Nuclear</td>
<td>23%</td>
<td>39%</td>
</tr>
<tr>
<td>Solar/other renew.</td>
<td>1%</td>
<td>-</td>
</tr>
<tr>
<td>Crude Oil</td>
<td>1%</td>
<td>-</td>
</tr>
<tr>
<td>Biomass and other</td>
<td>3%</td>
<td>5%</td>
</tr>
</tbody>
</table>

Note: regional electricity imports/exports not included in modeling.
Fossil Energy and Emissions In Electrical Production

- Fossil energy use for ‘green’ technologies was in construction of the systems
- In conventional fossil-based electricity, fossil energy use was much greater (as expected)
- Greenhouse gas emissions followed the same patterns

<table>
<thead>
<tr>
<th>Technology</th>
<th>Primary energy factors</th>
<th>Associated GHG emissions (g CO₂-eq/MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind power</td>
<td>1.03</td>
<td>1.81</td>
</tr>
<tr>
<td>Coal</td>
<td>5.7</td>
<td>331</td>
</tr>
</tbody>
</table>

Primary energy roughly translates to “natural Energy” - Wind, water, biomass, solar, atoms
Grid Electricity Footprint

- Power plant infrastructure construction
- Fossil energy use
- For Minnesota estimates:
  - Database of footprints for each power type
  - Percentages of each type of power
- Estimates for Sweden:
  - Each type of power has documents data
  - Looked at the percentage each contributes

<table>
<thead>
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<th></th>
<th>MJ primary energy per MJ electricity</th>
<th>g CO₂ –eq per MJ electricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweden</td>
<td>1.87</td>
<td>4.88</td>
</tr>
<tr>
<td>Minnesota</td>
<td>4.90</td>
<td>206</td>
</tr>
</tbody>
</table>
Wind Power Footprint

- Used Data From Wind Turbine Manufacturer (Vestas)
  - A complete life cycle assessment had been done of construction of a 1.65MW turbine
- Combined manufacture data with local capacity factors
- Energy required to build the turbine per kW hour of power produced by the turbine.

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<td>1.81</td>
</tr>
<tr>
<td>Sweden</td>
<td>1.03</td>
<td>2.01</td>
</tr>
</tbody>
</table>

Primary energy of wind includes 1 MJ of actual energy in the wind and 0.03 MJ of energy needed for construction
Overall Method of Calculating Emissions*

\[
\frac{\text{Emissions From Grid}}{\text{Grid}} \times \frac{\text{Quantity of Electricity From Grid}}{} + \frac{\text{Emissions From Turbine}}{\text{Turbine}} \times \frac{\text{Quantity of Electricity From Turbine}}{} - \frac{\text{Emissions Credit For Electricity sold}}{\text{Electricity sold}} \times \frac{\text{Quantity of Electricity Sold}}{\text{Sold}}
\]

Emissions Per Kg of Ammonia Produced

*Same Basic Idea for Fossil Energy Use
Fossil Energy Use

Minnesota
Significant fossil energy reduction at 100% and 125%
More fossil energy with only 25% from the grid.

Sweden
Significant fossil energy saving at all levels of production

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Minnesota</th>
<th></th>
<th></th>
<th>Sweden</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>75%</td>
<td>100%</td>
<td>125%</td>
<td>75%</td>
<td>100%</td>
<td>125%</td>
</tr>
<tr>
<td>Fossil based Ammonia</td>
<td>33.1</td>
<td>33.1</td>
<td>33.1</td>
<td>33.1</td>
<td>33.1</td>
<td>33.1</td>
</tr>
<tr>
<td>Wind based ammonia</td>
<td>49.4</td>
<td>6.69</td>
<td>-35.8</td>
<td>1.71</td>
<td>1.48</td>
<td>1.25</td>
</tr>
<tr>
<td>Comparison</td>
<td>149%</td>
<td>20%</td>
<td>-108%</td>
<td>5%</td>
<td>4%</td>
<td>3%</td>
</tr>
</tbody>
</table>
Greenhouse Gases

Minnesota
Significant GHG reduction at 100% and 125%
More GHG than fossil ammonia with only 25% from the grid.

Sweden
Significant fossil saving at all levels of production

<table>
<thead>
<tr>
<th>Greenhouse Gas Emissions g CO2 Equiv. Per KG N</th>
<th>Minnesota</th>
<th>Sweden</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Net Wind Production:</strong></td>
<td>75%</td>
<td>100%</td>
</tr>
<tr>
<td>Fossil based Ammonia</td>
<td>2150</td>
<td>2150</td>
</tr>
<tr>
<td>Wind based ammonia</td>
<td>2890</td>
<td>413</td>
</tr>
<tr>
<td>Comparison</td>
<td>136%</td>
<td>19%</td>
</tr>
</tbody>
</table>
Sensitivity Analysis

Examined model variables that could have important impact on the results

● Energy needed to make Ammonia
   ◆ Increase - linear response
   ◆ Decrease - linear response

● Reduced Capacity Factor
   ◆ Set both countries capacity factor to 25%
   ◆ Significant increases in fossil energy and GHG emissions
Conclusions

● Electricity source and its associated emissions is critical
   ◆ A heavily fossil dependent grid quickly increases fossil use and carbon emissions in ammonia production
   ◆ Grid power backup should be minimized in some regions do to the fossil energy use

● More attention should be paid to precursor storage.
   ◆ Hydrogen production can be ramped up and down quickly
   ◆ Can be stored in times of high wind energy production
Future Steps

- Model other base load renewable energy sources
  - Anaerobic digestion
  - Hydro electric
  - Gasification

- Model systems with hydrogen storage

- More data on facility energy use
Acknowledgment

- **Swedish Energy Agency**
  (International Collaboration Funding)

- Many sponsors for ammonia system

- **Ongoing Funding from LCCMR**
  (Legislative-Citizens Commission on Minnesota Resources)

- [http://commons.wikimedia.org/wiki/Commons:GNU_Free_Documentation_License](http://commons.wikimedia.org/wiki/Commons:GNU_Free_Documentation_License)
Wind to Ammonia LCA System Boundaries

Wind Power (V82 Vestas)
- Water Electrolysis
- Hydrogen Compression
- Nitrogen Separation
- Nitrogen Compression

Ammonia Production
- 1 KG Ammonia
- Oxygen
- Heat
- Other Outputs to Environmental

Alternate Power

Wind
Water
Coal
NG

Ammonia Storage

Water

Grid Power

Electrolysis
Compressors
Separators
Storage