Overview

- Why Ammonia?
- Relevant Ammonia Properties
- (Green) Ammonia Synthesis
- Current Ammonia Storage and Delivery Infrastructure
- Cost Comparison
- Safety
Why Ammonia?

- Transmission and firming storage for renewables
- Large existing market and delivery infrastructure
- Energy dense
- Clean burning direct fuel: no carbon
- Hydrogen carrier
- Is liquid at moderate pressure/temperature
- Widespread use/experience (#2 chemical)
  - 130 million tons produced annually worldwide
  - US consumes 20 million tons per year
Forms of Ammonia

- **Anhydrous Ammonia**—NH₃
  Only form suitable for fuel
- **Aqueous Ammonia**—NH₃ in water
- **Urea**—2NH₃ + CO₂
- **Ammonium Nitrate**—NH₄N0₃
- **UAN**—Aqueous Urea + Ammonium Nitrate
Relevant Ammonia Properties

- Fuel is same as fertilizer, NH3, anhydrous ammonia
- 18% hydrogen by weight
- Liquid at >125 psi at room temperature
- About half energy density of gasoline, by volume
- About 50% more energy dense than LH2 *
- At point of use can be used as direct fuel or cracked to provide GH2 **

* LH2: Liquid Hydrogen
** GH2: Gaseous Hydrogen
Zero-Emission Combustion

- Only hydrogen and ammonia burn without emitting greenhouse gases (contain no carbon)
- Also, no CO, SOx, or NOx
- Hydrogen combustion--
  \[ H_2 + O_2 \rightarrow H_2O \]
  (water only combustion product)
- Ammonia combustion--
  \[ 4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O \]
  (nitrogen and water only combustion products)
H$_2$ and Energy Density for Various Fuels

Hydrogen density and HHV energy content of ammonia and selected synthetic liquid hydrocarbon fuels

Note--
Liq CH4 = 116 kgH2/m3
Liq C3H8 = 106 kgH2/m3

Bossel et al., *The Future of the Hydrogen Economy: Bright or Bleak?*, Oct 28, 2004
http://www.oilcrash.com/articles/h2_eco.htm
Getting Power Out Of Ammonia

- Spark-Ignited Internal Combustion Engines
- Gasoline or ethanol blend ICEs
- Hydrogen-spiked
  - Diesel Engines
  - Combustion Turbines
- Converted Biogas Generators
- Direct Ammonia Fuel Cells

Reform to liberate H2 \[2\text{NH}_3 \rightarrow 3\text{H}_2 + \text{N}_2\]
Ammonia fueled vehicle – Rjukan 1933

Source: Et forsøk verdt. Forskning og utvikling i Norsk Hydro gjennom 90 år. Oslo 1997, s. 125
Green Ammonia Synthesis

1. **Wind Generators**
2. **Electrolyzers**
3. **Air Separation Plant**
   - Air
   - Electricity
   - N₂
4. **Haber-Bosch Ammonia Synthesis**
   - H₂
   - H₂O
5. **Liquid Ammonia Tank Storage**
6. **Liquid Ammonia Transmission Pipeline**
7. **Generators ICE, CT, FC**
8. **End users Retail**
9. **Cars, Buses, Trucks, Trains**
10. **AC grid Wholesale**
11. **Aircraft Fuel**
Norsk Hydro Electrolyzers
2 MW each
Ammonia Pipelines

- ~3000 miles currently used
- Operate at 250 psi and above; Ammonia liquid
- Mild steel construction
- No corrosion or embrittlement problems
- Smaller diameter than NG or H2
- Approximately 4.5 million tons of large-tank ammonia storage
U.S. Ammonia Pipeline

3000 Miles Total
Easily Stored in Refrigerated Liquid Tanks
Cost Comparison

Cases considered:
2,000 MW (nameplate) Great Plains Windplant

1. HVDC electricity: 50% of 3,000 MW line
2. Elec → GH2 → Gas Pipeline → City gate wholesale
   a. Without firming storage
   b. With firming storage
3. Elec → GH2 → NH3 → Liquid Pipeline → City gate wholesale
   a. Without firming storage
   b. With firming storage
4. Elec → GH2 → NH3 → Liquid Pipeline → Reform to H2
   a. Without firming storage
   b. With firming storage
The Great Plains Wind Resource
Key Assumptions

1. 2,000 MW windplant = 2,000 MWh / hr at full output
2. AEP: 2,000 MW (nameplate) Great Plains windplant
   @ 40% CF, 100% energy equivalent:
   • 7,008,000 MWh / yr
   • 195,754 tons H2 / yr
   • 1,087,523 tons NH3 / yr
3. 1,000 mile transmission to city gate market
   • 20” GH2 pipeline
   • 10” NH3 pipeline
4. Installed capital costs year 2020 @ year ’05 $US:
   • Wind generators: $1,000 / kW
   • Electrolyzers: $350 / kW
5. Benchmark: actual Xcel Energy wind-generated electric energy, at wind plant gate:
   • $ 0.057 / kWh unsubsidized
   • $ 0.038 / kWh with PTC = $ 0.019 / kWh
Key Assumptions

6. NH3 delivered as liquid; no reforming to H2
7. NH3 tank storage at sources; maximize pipeline CF
8. 500 and 1,000 mile pipelines (2 cases) (only 1,000 mile here)
9. Large-scale for all components:
   • GW sources and conversions (synthesis, cracking)
   • >10,000 ton liquid NH3 storage
10. 150 tph pipeline, 10” diam, .25” wall thick, 1,300 psi nominal, 1,500 MAOP
11. X42 or Grade B carbon steel line pipe, welded, 35 – 42,000 psi
12. 150 tph flow = 300,000 lbs / hr = 52,817 gal / hr
13. Annual capital cost @ 15% CRF
# 2,000 MW Windplant Output

## 100 % Capacity Factor

<table>
<thead>
<tr>
<th></th>
<th>MWh/day</th>
<th>tons/hr</th>
<th>tons/day</th>
<th>tons/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>As electricity</td>
<td>48,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>As H2</td>
<td></td>
<td>311</td>
<td>1,342</td>
<td>489,776</td>
</tr>
<tr>
<td>As NH3</td>
<td></td>
<td>1,726</td>
<td>7,455</td>
<td>2,720,980</td>
</tr>
<tr>
<td>10” NH3 pipeline capacity as NH3</td>
<td>150</td>
<td>3,600</td>
<td>1,314,000</td>
<td></td>
</tr>
<tr>
<td>10” NH3 pipeline capacity as H2</td>
<td>27</td>
<td>648</td>
<td></td>
<td>236,520</td>
</tr>
</tbody>
</table>

## 40 % Capacity Factor

<table>
<thead>
<tr>
<th></th>
<th>MWh/day</th>
<th>tons/hr</th>
<th>tons/day</th>
<th>tons/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>As electricity</td>
<td>19,200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>As H2</td>
<td></td>
<td>124</td>
<td>537</td>
<td>195,910</td>
</tr>
<tr>
<td>As NH3</td>
<td></td>
<td>690</td>
<td>2,982</td>
<td>1,088,392</td>
</tr>
<tr>
<td>10” NH3 pipeline capacity as NH3</td>
<td>60</td>
<td>1,440</td>
<td>525,600</td>
<td></td>
</tr>
<tr>
<td>10” NH3 pipeline capacity as H2</td>
<td>11</td>
<td>259</td>
<td></td>
<td>94,608</td>
</tr>
</tbody>
</table>
# Cost Comparison Summary
(2,000 MW Wind Energy Plant at 40% CF)

<table>
<thead>
<tr>
<th>Energy Carrier</th>
<th>Capital Cost Synthesis ($M)</th>
<th>Capital Cost Transmission ($M)</th>
<th>Capital Cost Firming ($M)</th>
<th>Cost per kg H2 ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVDC Electric</td>
<td>2,000</td>
<td>500</td>
<td>-0-</td>
<td>0.54</td>
</tr>
<tr>
<td>GH2 not firmed</td>
<td>3,000</td>
<td>930</td>
<td>-0-</td>
<td>1.96</td>
</tr>
<tr>
<td>GH2 firmed</td>
<td>3,000</td>
<td>930</td>
<td>160</td>
<td>2.01</td>
</tr>
<tr>
<td>NH3 not firmed</td>
<td>3,760</td>
<td>800</td>
<td>-0-</td>
<td>2.57</td>
</tr>
<tr>
<td>NH3 firmed</td>
<td>3,760</td>
<td>800</td>
<td>100</td>
<td>2.65</td>
</tr>
</tbody>
</table>
New “Green” Ammonia

- New technology for “solid state” ammonia is expected to:
  - Increase synthesis efficiency by ~50%
  - Lower capital cost requirements significantly
  - Produce ammonia at prices competitive with brown ammonia in places where renewable energy is abundant and competitive in cost
Ammonia Safety

- Toxic, so must be handled with respect
- Millions of tons are stored, transported, and handled every year with an excellent safety record
- Not corrosive
- Not explosive nor highly flammable
- Can be stored at moderate pressures
- Lighter than air
- Trapped by water
- Not a greenhouse gas
Ammonia Fuel Network

- Proceedings of first three conferences at [http://www.energy.iastate.edu/becon/ammonia.html](http://www.energy.iastate.edu/becon/ammonia.html)
Back-up Slides
Ammonia is easy to crack

<table>
<thead>
<tr>
<th></th>
<th>Cracking Reaction to Produce Hydrogen</th>
<th>Energy Lost (or Cost)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>(2\text{NH}_3 \rightarrow 3\text{H}_2 + \text{N}_2)</td>
<td>12-15%</td>
</tr>
<tr>
<td>Methane</td>
<td>(\text{CH}_4 + 2\text{H}_2\text{O} \rightarrow 4\text{H}_2 + \text{CO}_2)</td>
<td>25-30%</td>
</tr>
<tr>
<td>Methanol</td>
<td>(\text{CH}_3\text{OH} + \text{H}_2\text{O} \rightarrow 3\text{H}_2 + \text{CO}_2)</td>
<td>~45%</td>
</tr>
<tr>
<td>Ethanol</td>
<td>(2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2)</td>
<td>25-35%</td>
</tr>
<tr>
<td>Water</td>
<td>(\text{H}_2\text{O} \rightarrow \text{H}_2 + \text{O}_2)</td>
<td></td>
</tr>
</tbody>
</table>
Ammonia Is Easy To Store
“Leighty Summary” draft

- Following slide needs checking and revision
## Cost Comparison Summary

<table>
<thead>
<tr>
<th>Energy Carrier</th>
<th>Capital Cost Synthesis ($M)</th>
<th>Capital Cost Transmission ($M)</th>
<th>Capital Cost Firming ($M)</th>
<th>Cost per kg H2 ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVDC Electric</td>
<td>2,000</td>
<td>500</td>
<td>-0-</td>
<td>0.54</td>
</tr>
<tr>
<td>GH2 not firmed</td>
<td>3,000</td>
<td>930</td>
<td>-0-</td>
<td>1.96</td>
</tr>
<tr>
<td>GH2 firmed</td>
<td>3,000</td>
<td>930</td>
<td>160</td>
<td>2.01</td>
</tr>
<tr>
<td>NH3 not firmed</td>
<td>3,760</td>
<td>800</td>
<td>-0-</td>
<td>2.57</td>
</tr>
<tr>
<td>NH3 firmed</td>
<td>3,760</td>
<td>800</td>
<td>100</td>
<td>2.65</td>
</tr>
</tbody>
</table>