Comparing Fuels For Energy Transmission, Storage, and Integration

Ammonia Fuel
1-2 October 2012, San Antonio

Bill Leighty
Director, The Leighty Foundation
Principal, Alaska Applied Sciences
Juneau, AK
wleighty@earthlink.net
907-586-1426  206-719-5554 cell
Volumetric Energy Density of Fuels (Fuels in their Liquid State)

- Diesel (Cetane)
- Gasoline (Octane)
- Heptane
- Hexane
- Pentane
- Butane
- Ethane
- Propane
- Methane
- Ethanol
- Methanol
- Ammonia
- Hydrogen

C-free
<table>
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*Corrected for optimal engine efficiency due to increased compression ratio.*
## NH3 Fuel Association Website

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(All Energy, More Properties)

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Compressed fuel tank costs

- Dynetek
- Quantum
- Lincoln
- Toyota
- Baytech Landi-Renzo, Torrance, CA
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Volumetric Fuel Energy versus Gasoline
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<th>Ethanol</th>
<th>Propane</th>
<th>Gasoline</th>
<th>Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Formula</strong></td>
<td>CH4</td>
<td>C30H</td>
<td>CH4</td>
<td>C2H50H</td>
<td>C3H8</td>
<td>C8H16</td>
<td>C12H26</td>
</tr>
<tr>
<td><strong>Research Octane #</strong></td>
<td>130</td>
<td>112</td>
<td>130</td>
<td>111</td>
<td>112</td>
<td>91-98</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Motor Octane #</strong></td>
<td>130</td>
<td>91</td>
<td>130</td>
<td>92</td>
<td>97</td>
<td>82-90</td>
<td></td>
</tr>
<tr>
<td><strong>Cetane #</strong></td>
<td>-10</td>
<td>3</td>
<td>-10</td>
<td>8</td>
<td>5-10</td>
<td>8-14</td>
<td>40-60</td>
</tr>
<tr>
<td><strong>Boiling Point</strong></td>
<td>-259/-162</td>
<td>N/A</td>
<td>-259/-162</td>
<td>N/A</td>
<td>-44/-42</td>
<td>(81-464)/ (27-240)</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Energy Content (volume) (BTU/ft³) / (kJ/L)</strong></td>
<td>213,300/7,875</td>
<td>425,000/15,688</td>
<td>569,200/21,013</td>
<td>570,000/21,027</td>
<td>637,500/25,535</td>
<td>862,100/31,825</td>
<td>950,400/35,082</td>
</tr>
<tr>
<td><strong>Energy vs Gasoline %</strong></td>
<td>25</td>
<td>49</td>
<td>66</td>
<td>66</td>
<td>74</td>
<td>100</td>
<td>110</td>
</tr>
<tr>
<td><strong>Stoich A/F Ratio (mass)</strong></td>
<td>17.3</td>
<td>6.5</td>
<td>17.3</td>
<td>9.0</td>
<td>15.7</td>
<td>14.7</td>
<td>15.0</td>
</tr>
<tr>
<td><strong>Autoignition Temperature °F/°C</strong></td>
<td>842/450</td>
<td>N/A</td>
<td>842/450</td>
<td>N/A</td>
<td>1,004/540</td>
<td>428/220</td>
<td>437/225</td>
</tr>
<tr>
<td><strong>Peak Flame Temperature °F/°C</strong></td>
<td>3,254/1,790</td>
<td>N/A</td>
<td>3,254/1,790</td>
<td>3,614/1,990</td>
<td>3,591/1,977</td>
<td>3,729/2,054</td>
<td></td>
</tr>
<tr>
<td><strong>Flammability Lower Limit (volume %)</strong></td>
<td>5.3</td>
<td>4.0</td>
<td>N/A</td>
<td>N/A</td>
<td>2.1</td>
<td>1.4</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Flammability Upper Limit (volume %)</strong></td>
<td>15.0</td>
<td>75.0</td>
<td>N/A</td>
<td>N/A</td>
<td>10.4</td>
<td>7.6</td>
<td>N/A</td>
</tr>
</tbody>
</table>
**Context: Fuel Definitions**

**Attributes:**
- Transportable
- Energy storage
- Convertible (energy $\rightarrow$ exergy)
- Safe, convenient, economical
- USA Fed designation

**Electricity?**
- Flow of electrons
- 100% exergy
- No storage
- Real-time
- “Smart Grid” symptom
Phyllis Cuttino
Pew Environment

“Electrification of transportation is the only way to get off foreign oil”
**Greenhouse Gas Pollution** (Light duty vehicles only)
(Billion/ tonnes CO2-equivalent/year)

- **GHG Goal: 60% below 1990 Pollution**
- **GHG Goal: 80% below 1990 Pollution**

**Scenarios**
- Base Case: Gasoline Hybrid Scenario
- Gasoline Plug-In Hybrid Scenario
- Ethanol Plug-In Hybrid Scenario
- Fuel Cell Vehicle Scenario
- 100% Gasoline ICVs

**1990 LDV GHG**
**Context: Fuel Definitions**

1. A material consumed to produce energy, especially:
   a. Burned to produce heat or electricity
   b. Fissionable or fusible material used in a nuclear reactor
   c. Nutritive, food metabolized by a living organism

2. A substance that produces useful energy when it undergoes a chemical or nuclear reaction: burning, combustion, oxidation or reduction, metabolism.

3. Some radioactive substances:
   - Uranium, plutonium, thorium via fission
   - Deuterium and tritium via fusion

4. USA Fed designation

5. Electricity? No
Energy Storage System Characteristics
Hydrogen and Ammonia off the charts

- Storage capacity (Mwh, scf, nM3, Mt, gallons ....)
- Power (MW, scfm ....)  In / Out rate
- Costs
  - Capital
  - O&M
  - Conversion losses
- Efficiency
- Response time
- Durability (cycling capacity)
- Reliability
- Autonomy
- Self-discharge
- Depth of discharge
- Adaptation to the generating source
- Mass and volume densities of energy
- Monitoring and control equipment
- Operational constraints
- Feasibility
- Environmental
Storage System Ratings

Gaseous Hydrogen (GH2)
Anhydrous Ammonia (NH3)
GH2 and NH3
MONTHS: GH2, NH3
Context: Complete energy systems

• Photons + moving molecules $\rightarrow$ energy services
• Extraction: Non-renewable
  – Fossil
  – Nuclear
• Production: Renewable generation, conversion
• Transmission
• Storage
• Supply integration
• Markets, niches
Solar Hydrogen Energy System

Sunlight from local star

Electrolyzer

O₂

H₂

Fuel Cell

Electricity

Electricity

Work

2H₂O + Energy → 2H₂ + O₂

2H₂ + O₂ → 2H₂O + Energy
EIA estimated 2025 energy use

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>2025 Energy Use (Quads)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear</td>
<td>76.4</td>
</tr>
<tr>
<td>Coal</td>
<td>26.89</td>
</tr>
<tr>
<td>Gas</td>
<td>34.88</td>
</tr>
<tr>
<td>Oil</td>
<td>56.7</td>
</tr>
<tr>
<td>Hydro</td>
<td>0.96</td>
</tr>
<tr>
<td>Bio/Geo</td>
<td>5.94</td>
</tr>
<tr>
<td>Wind</td>
<td>0.11</td>
</tr>
<tr>
<td>Solar</td>
<td>0.01</td>
</tr>
<tr>
<td>Nuclear</td>
<td>7.64</td>
</tr>
</tbody>
</table>

**Estimated Future U.S. Energy Requirements - 133.1 Quads**

- **Electricity Generation**: 45.74 Quads
- **Residential**: 14.09 Quads
- **Commercial**: 12.31 Quads
- **Industrial**: 34.81 Quads
- **Automotive**: 25.83 Quads
- **Freight**: 13.18 Quads
- **Airlines**: 5.06 Quads
- **Rejected Energy**: 73.47 Quads
- **Useful Energy**: 59.64 Quads
Context: Why Ammonia?
Fertilizer and Fuel

Only liquid fuel embracing:

- **Carbon-free**: clean burn or conversion; no CO$_2$
  - Excellent hydrogen carrier
  - Easily “cracked” to H$_2$
- **Reasonably high energy density**
- **Energy cycle inherently pollution free**
  - Potentially all RE-source: elec + water + Nitrogen
  - Cost competitive with hydrocarbon fuels?
- **Decades of global use, infrastructure**
  - Practical to handle, store, and transport
  - End-use in ICE, Combustion Turbine, fuel cell
  - Safety: self-odorizing; safety regs; hazard
Markets: Supply, Demand, Price

- Supply Push
- Demand Pull
- Price
  - Competition
  - Substitutes
  - Volume
  - Condition changes
Market: Transportation

- Land
  - Truck
  - Rail
  - Personal vehicle
  - Military
- Air
- Marine
  - Pleasure, utility
  - Commercial
  - Shipping
  - Military: USCG, Navy
Market: Transportation

• Land, Marine
  – Liquid HC’s
  – CNG, LNG
  – LPG
  – Hydrogen: GH2, LH2
  – Other: Al-Ga, Zinc

• Air
  – Liquid HC’s
  – LH2
Compressed Natural Gas (CNG) Fueling: ~ 3,000 psi
Market: Ag + Construction + Industrial

- Liquid HC’s
- CNG, LNG
- LPG
- Hydrogen: GH2, LH2
- Other: Al-Ga, Zinc
John Deere “LP” tractor
Market: Combined Heat and Power (CHP)

- Firm, quality “power”
  - Elec grid backup
  - Elec grid replace
  - Sub-cycle response

- 80% + fuel energy recovery

- Stationary, on-site
  - Genset (ICE, CT, Fuelcell)
  - Byproduct heat (HI, LO temp)
    - Heat and cool
    - Process

- Fuels
  - Natural gas (pipeline)
  - Liquid HC’s (pipeline and / or tank)
  - Ammonia (pipeline and / or tank)
  - Nuclear SMR (small modular reactor)
Market: Combined Heat and Power (CHP)

- Firm, quality “power”
  - Elec grid backup
  - Elec grid replace
  - Sub-cycle response
- 80% + fuel energy recovery
- Stationary, on-site
  - Genset (ICE, CT, Fuelcell)
  - Byproduct heat (HI, LO temp)
    - Heat and cool
    - Process
- Fuels
  - Natural gas (pipeline)
  - Liquid HC’s (pipeline and / or tank)
  - Ammonia (pipeline and / or tank)
  - Nuclear SMR (small modular reactor)
Market: Military

- Land
- Sea
- Air

- Scale
  - Major Base
  - Forward Base
  - Ship
  - Aircraft
  - Mini, Micro 1 W → 1 kW
Market: RE Systems “Big 3”
(RE = Renewable Energy)

1. Gathering and Transmission
2. Storage
   - Firming
   - Seasonal, annual
   - Dispatchable
   - Cure “intermittent”
3. Supply Integration
   - Extant energy systems
   - Cure “intermittent”
Market: Fertilizer

• N:
  – Embodied energy
  – “Corn ethanol is recycled natural gas”
  – NH3 and products: Urea, DAP, AN, other

• K, P
  – Embodied energy
  – Enables solar harvest via photosynthesis

• Trace minerals
  – Enables solar harvest via photosynthesis
Market: Chemicals + Explosives

- Feedstock
- Explosives
Context:
Markets - Where NH$_3$ Compete?

- Transportation
- Combined Heat and Power (CHP)
- Ag + Construction + Industrial
- Military
- Complete RE systems
- Fertilizer
- Chemicals + Explosives

Fuel, fertilizer, feedstock?
Distributed, centralized, networked?
Determines salient “fuel” properties
<table>
<thead>
<tr>
<th>Energy Demand</th>
<th>Volumetric demand</th>
<th>Gravimetric demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH₃ energy demand per day, using NH₃ to replace fossil fuels only</td>
<td>90,711,825</td>
<td>61,856,394</td>
</tr>
</tbody>
</table>

### Annual (MMtonnes) (Million metric tons)

#### Assuming Solid State Ammonia Synthesis

<table>
<thead>
<tr>
<th>Energy Demand</th>
<th>Volumetric demand</th>
<th>Gravimetric demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Separation Unit input, air</td>
<td>95,519,027</td>
<td>65,134,424</td>
</tr>
<tr>
<td>Air Separation Unit output, nitrogen</td>
<td>74,585,077</td>
<td>50,859,564</td>
</tr>
<tr>
<td>Air Separation Unit output, oxygen</td>
<td>20,933,950</td>
<td>14,274,860</td>
</tr>
</tbody>
</table>

#### SSAS input, water

<table>
<thead>
<tr>
<th>Volumetric demand</th>
<th>Gravimetric demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>59,744,604</td>
<td>40,739,845</td>
</tr>
<tr>
<td>18,729,770</td>
<td>12,771,830</td>
</tr>
</tbody>
</table>

#### SSAS input, nitrogen

<table>
<thead>
<tr>
<th>Volumetric demand</th>
<th>Gravimetric demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>74,585,077</td>
<td>50,859,564</td>
</tr>
<tr>
<td>23,382,218</td>
<td>15,944,334</td>
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</table>

#### Total inputs

<table>
<thead>
<tr>
<th>Volumetric demand</th>
<th>Gravimetric demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>134,329,681</td>
<td>91,599,409</td>
</tr>
<tr>
<td>42,111,988</td>
<td>28,716,165</td>
</tr>
</tbody>
</table>

#### SSAS output, NH₃ per day (fossil fuel replacement only)

<table>
<thead>
<tr>
<th>Volumetric demand</th>
<th>Gravimetric demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>90,711,825</td>
<td>61,856,394</td>
</tr>
<tr>
<td>28,437,910</td>
<td>19,391,811</td>
</tr>
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</table>

#### SSAS output, oxygen

<table>
<thead>
<tr>
<th>Volumetric demand</th>
<th>Gravimetric demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>43,617,856</td>
<td>29,743,016</td>
</tr>
<tr>
<td>13,674,079</td>
<td>9,324,354</td>
</tr>
</tbody>
</table>

#### Total outputs

<table>
<thead>
<tr>
<th>Volumetric demand</th>
<th>Gravimetric demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>134,329,681</td>
<td>91,599,409</td>
</tr>
<tr>
<td>42,111,988</td>
<td>28,716,165</td>
</tr>
</tbody>
</table>
Complete energy systems

- Photons + moving molecules → energy services
- Extraction: Non-renewable
  - Fossil
  - Nuclear
- Production: Renewable generation, conversion
- Transmission
- Storage
- Supply integration
- Markets, niches
NH₃ Ag Fertilizer Tanks, Wind Generators, NW Iowa
Energy as a Complete System: Generation, Usage, Storage, Transmission

**OFFSHORE 500MW WIND FARM**
- 157 3 MW turbines
- 3 offshore substations
- 1 onshore substation

**GENERATION**
- 400 kV offshore cable connecting O/S
- Offshore substation
- Step up to 130-150 kV transmission voltage

**ONSHEL SUBSTATION**
- 120 kV transmission grid

**STORAGE**
- Pumped Hydro Storage
  - Using off-peak or surplus wind generation

**TRANSMISSION**
- Super Smart Grid
  - Dynamically balances generation and demand, eliminates issues of intermittency and seasonality for wind power

**USAGE**
- All-climate heat pumps
  - Geothermal & air
  - 3x efficiency of resistive electric heat

**NH3 Storage**
- Ammonia Production (NH3)
  - For diesel engines using off-peak and surplus wind generation
Valero LP Operations

Liquid ammonia pipeline

NOLA
The NATURALHY approach: EC, R+D

NATURALHY:
• Breaks “chicken-egg” dilemma
• Bridge to sustainable future

Prepared by
O. Florisson
Gasunie
5,000 MW alternatives: HVAC vs HVDC superconductor

25 ft Pipeline ROW:
- 36” Gaseous Hydrogen
- 24” Liquid Ammonia
- 36” Superconductor (SC)

Out of Sight, Out of Harm’s Way
The Atlantic Wind Connection transmission backbone would connect 6,000 MW of wind turbine capacity, built on the broad, windy spaces of the mid-Atlantic continental shelf, to population centers and transmission nodes on land.
Hydrogen and Ammonia Fuels

• Solve electricity’s RE problems:
  – Transmission
  – Firming storage
  – Grid integration: time-varying output
• Carbon-free
• Underground pipelines
• Low-cost storage: < $ 1.00 / kWh capital
  – Pipelines
  – GH2 salt caverns
  – NH3 tanks
• Sec’y Chu: reconsidering hydrogen (WREF)
Annual Fresh Water for Energy

- USA today
- All energy

- 17,000 billion liters
  - “Withdrawn”
  - “Consumed”
  - Include all NG “fracking”?

- If all via GH2 + NH3 feedstock:
  - Dissociated, disintegrated: $H_2O \rightarrow H_2 + O_2$
  - 900 billion liters
“There’s a better way to do it... Find it.”
Comparing Fuels For Energy Transmission, Storage, and Integration

Ammonia Fuel
1-2 October 2012, San Antonio

Bill Leighty
Director, The Leighty Foundation
Principal, Alaska Applied Sciences
Juneau, AK
wleighty@earthlink.net
907-586-1426 206-719-5554 cell

Bill Leighty, Principal
Alaska Applied Sciences, Inc.
Box 20993, Juneau, AK 99802
wleighty@earthlink.net
907-586-1426 206-719-5554 cell
Wind Power Class

<table>
<thead>
<tr>
<th>Power</th>
<th>Class</th>
<th>Speed</th>
<th>Power Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0-5.6 m/s</td>
<td>0-200 W/m²</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5.6-6.4 m/s</td>
<td>200-300 W/m²</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>6.4-7.0 m/s</td>
<td>300-400 W/m²</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>7.0-7.5 m/s</td>
<td>400-500 W/m²</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>7.5-8.0 m/s</td>
<td>500-600 W/m²</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>8.0-8.8 m/s</td>
<td>500-800 W/m²</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>&gt;8.8 m/s</td>
<td>&gt;800 W/m²</td>
<td></td>
</tr>
</tbody>
</table>
Superconducting (SC) electric line would leave TAPS at Fairbanks, follow Alaska Railroad to Anchorage.

Fuel Cell Gen Plant: NG fuel
Opportunity: Alaska Applications

1. Village energy “independence”: degree
   a. Internal, external energy economies
   b. Diverse renewable sources
   c. Low-cost tank storage
   d. CHP, transportation fuels

2. Firming storage: annual scale
   a. Susitna hydro
   b. Other

3. Export large, diverse, stranded renewables
   a. Cryo tankers: global trade
   b. “Green” NH3 premium? C-tax required?
   c. SE AK “Cluster Industry”
   d. Aleutians cargo ship fueling

4. Military fuel: ground, marine
   a. USCG, Navy
   b. Other services
   c. DOD Assistant Secretary Sharon Burke visit 3-7 Aug 12
1. Decrease Cash OUT: Village “Energy Independence” via RE Generation + Storage

- What’s Annual Average RE Cost of Energy (COE) ?
- Competitive ?
- What degree of “energy independence” ?
- Is SSAS required ?
2. Increase Cash **IN**: Export AK GW-scale RE as “Green” Ammonia

- Can RE compete with “brown”? 
- What would C-tax need to be? 
- What would global NG price need to be?
Project Fundamentals

1. Does SSAS system “work”?
2. Competitive with EHB?
3. Useful in Alaska?
<table>
<thead>
<tr>
<th>Source</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>EETF via AEA</td>
<td>$ 750 K</td>
</tr>
<tr>
<td>NHThree LLC in-kind</td>
<td>$ 100 K</td>
</tr>
<tr>
<td>Wind2Green (W2G) in-kind</td>
<td>$ 100 K</td>
</tr>
<tr>
<td>AASI in-kind</td>
<td>$  50 K</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>$  1 M</td>
</tr>
</tbody>
</table>
SSAS Pilot Plant Schedule

1. Test PCC tubes; accept
2. Build and test multi-tube reactor
3. Build and test BOS
4. Instrument with SCADA, remote read at UAF
5. Add regeneration: NH3 → electricity to grid
6. Package in insulated CONEX
7. Acceptance test
8. Transport to Juneau, AK for demo
9. Demo at other AK sites as budget allows
10. Upgrade as budget allows
Project Fundamentals

1. Anhydrous ammonia (NH3) is a fuel and transmission and low-cost energy storage medium.

2. NH3 made from renewable energy (RE) electricity, water, and air (Nitrogen, N2) by:
   a. Electrolysis + Haber-Bosch (EHB)
   b. Solid State Ammonia Synthesis (SSAS)

3. SSAS should best EHB in:
   a. Capital cost per kWe in, kg NH3 out
   b. Energy conversion efficiency
   c. System simplicity, low O&M cost
   d. AK value
4. **SSAS unproven**: needs proof-of-concept, small pilot plant

5. **Design and build pilot plant:**
   a. Complete
   b. SCADA instrumented
   c. Containerized & transportable
   d. Upgradeable

6. **Success:**
   a. Great value to AK, beyond
   b. Next steps to commercial
   c. SA AK “RE Cluster Industry” via USFS, JEDC
**PROJECT: Complete RE - NH₃ SSAS Storage System**

- NH₃ synthesis from RE electricity, water, air (N₂)
- Liquid NH₃ tank storage
- Regeneration + grid feedback
- SCADA instrumentation → UAF - ACEP
RE Ammonia Transmission + Storage Scenario: Electrolysis + Haber-Bosch (EHB)

- Wind Generators
- Electrolyzers
- Air Separation Plant
- Haber-Bosch Ammonia Synthesis
- Liquid Ammonia Tank Storage
- Liquid Ammonia Transmission
- Pipeline
- Electricity
- Air
- N₂
- H₂
- H₂O
- Generators ICE, CT, FC
- End users Retail
- Cars, Buses, Trucks, Trains
- AC grid Wholesale
- Aircraft Fuel
Inside the Black Box: HB Plus Electrolysis

\[ 3 \text{H}_2\text{O} \rightarrow 3 \text{H}_2 + \frac{3}{2} \text{O}_2 \]
\[ 3 \text{H}_2 + \text{N}_2 \rightarrow 2 \text{NH}_3 \]

Energy consumption \(\sim 12,000\) kWh per ton \(\text{NH}_3\)
RE Ammonia Transmission + Storage Scenario

Solid State Ammonia Synthesis (SSAS)

Electrolyzers

Air Separation Plant

Haber-Bosch Ammonia Synthesis

Liquid Ammonia Transmission + Storage Scenario

Wind Generators

Electrolyzers

H₂

N₂

H₂O

Liquid Ammonia Tank Storage

Generators

ICE, CT, FC

AC grid Wholesale

End users Retail

Cars, Buses, Trucks, Trains

Aircraft Fuel
Solid State Ammonia Synthesis (SSAS)
Inside the Black Box: Solid State Ammonia Synthesis

6 H₂O + 2 N₂ → 3 O₂ + 4 NH₃

Energy consumption 7,000 – 8,000 kWh per ton NH₃

Benchtop
Proof-of-concept
Solid State Ammonia Synthesis (SSAS)
NHThree LLC patent
**RE Ammonia Transmission + Storage Scenario**

- **Wind Generators**
- **Electrolyzers**
- **Haber-Bosch Ammonia Synthesis**
  - **H2**
  - **N2**
- **Liquid Ammonia Tank Storage**
- **Electrolyzers**
- **Haber-Bosch Ammonia Synthesis**
- **Liquid Ammonia Transmission Pipeline**
- **Liquid Ammonia Tank Storage**
- **Wind Generators**
- **Haber-Bosch Ammonia Synthesis**
- **Liquid Ammonia Transmission Pipeline**
- **Liquid Ammonia Tank Storage**
- **Generators ICE, CT, FC**
- **Cars, Buses, Trucks, Trains**
- **Aircraft Fuel**
- **AC grid Wholesale**
- **End users Retail**
Inside the Black Box: HB Plus Electrolysis

3 H₂O → 3 H₂ + 3/2 O₂
3 H₂ + N₂ → 2 NH₃

Energy consumption ~12,000 kWh per ton NH₃
“Atmospheric” Liquid Ammonia Storage Tank (corn belt)

30,000 Tons
190 GWh
$15M turnkey
$80 / MWh
$0.08 / kWh

-33 C
1 Atm

’09 ARPA-E “Grids” Goal: $100 / kWh
Why SSAS?

- Electrolysis + Haber-Bosch too costly
  - From RE electricity
  - Capital components at low capacity factor (CF)
  - Energy conversion losses
- Proton conducting ceramics (PCC) now
- Solid oxide fuel cell (SOFC) success
- Need stranded RE transmission
- Need RE storage
**EHB vs SSAS prelim estimates**

**EHB:**
- 11-12 kWh / kg
- $1,000 / kWe input capital cost

**SSAS:**
- 7-8 kWh / kg
- $500 / kWe input capital cost
- $200K / Mt / day capital cost
Great Reward, and Risk

Project success: SSAS “works”
- Reactor, multi-tube
- Power electronics drive
- Regeneration from stored NH3
- SCADA: UAF - ACEP download
- Complete system functions, efficient
- Complete system durable, reliable
- Cost estimates: capital, O&M

Next steps?
Great Reward, and Risk

AK renewable energy (RE) opportunities:

1. Village energy “independence”
2. Annual-scale firming storage
3. Transmission for:
   a. Intrastate AK
   b. RE export
4. Fuel for military land and sea
5. Incubator, test sites, commercial rollout

Scales: Village → Susitna Hydro → Global export
Liquid Anhydrous Ammonia (NH3) -33 °C, 1 atmosphere
Project Objectives

• Run AK, world on RE: all energy, beyond electricity
• Discover and demo SSAS potential
• Demo complete RE storage system
• Begin commercialization
• Attract funding
**Project Goals**

1. Estimate efficiency
2. Estimate capital cost:
   a. PCC tube area, tube
   b. Reactor
   c. Power electronics drive
3. Dynamics
4. TRL 5 – 6
5. Attract RE industry: AK, US, global, ARPA-E
State of the Art; Competition

- Electrolysis + “Haber-Bosch” = EHB
  - NH3 United, TX + Canada NH3
  - Proton Ventures
  - Freedom Fertilizer
- Other “SSAS”
EHB vs SSAS prelim estimates

EHB:

- 11-12 kWh / kg
- $1,000 / kWe input capital cost

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- 7-8 kWh / kg
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Community:

Wind Generators

Electricity -> Air Separation Unit (ASU)

Air -> SSAS reactor

N₂

Electricity -> SSAS reactor

H₂O

Liquid Ammonia Transmission Pipeline

SSAS reactor

Liquid Ammonia Tank Energy Storage

Generators ICE, CT, FC

AC grid Wholesale

End users Retail

Cars, Buses, Trucks, Trains

Aircraft Fuel

Solid State Ammonia Synthesis (SSAS)
NH3: “The other hydrogen”

Hydrogen Hub
10 Megawatt Capacity Site
Site Area: 4.57 acres

Preston Michie, Jack Robertson: 2009
Former BPA; Northwest Hydrogen Alliance
Hydrogen Hub Concept

- Water
- Air
- Off-Peak Power

Ammonia Synthesis

Control Electronics

NH₃

Ammonia Storage

NH₃

Excess NH₃ Sales

Oxygen Sales

Electric Power Production

Power To Grid

Power for Local Use

NH₃

Simplification for clarity in representing the workflow.
Liquid Ammonia Tank Storage

Cost per Gallon: 250 psi Ammonia Tanks

Largest highway-transportable
Military:  *Land* + *sea fuel*

- USCG, Navy ships
- Land vehicles: road, rail
- Recip engines modify: multifuel, Sturman
- Mini + micro app’s
State of the Art; Competition

- Electrolysis + “Haber-Bosch” = EHB
  - Proton Ventures
  - Freedom Fertilizer
  - NH3 United, TX + Canada NH3
- Other “SSAS” suppliers
- Do not deploy novel, complex systems in Alaska villages: EHB too risky?
3 Mt/day Electrolysis + Haber-Bosch (EHB) NH3 plant by Proton Ventures

Input $\approx 1.5$ MW @ 11 kWe / kg NH3
Quoted at $4M. Delivered?
Contact: Steve Gruhn sgruhn@freedomfertilizer.com
Village-scale
3 Mt / day Mini-NH3 Plant
RE Electricity Haber-Bosch

Source: Kellogg-Brown-Root (KBR)
Opportunity: Alaska Applications

1. Village energy “independence”: degree
   a. Internal, external energy economies
   b. Diverse renewable sources
   c. Low-cost tank storage
   d. CHP, transportation fuels

2. Firming storage: annual scale
   a. Susitna hydro
   b. Other

3. Export large, diverse, stranded renewables
   a. Cryo tankers: global trade
   b. “Green” NH3 premium? C-tax required?
   c. SE AK “Cluster Industry”
   d. Aleutians cargo ship fueling

4. Military fuel: ground, marine
   a. USCG, Navy
   b. Other services
   c. DOD Assistant Secretary Sharon Burke visit 3-7 Aug 12
Markets: Supply, Demand, Price

- Supply Push
- Demand Pull
- Alaska incubator, rollout
- Price
  - Competition
  - Substitutes
  - Volume
  - Condition changes

Bill Leighty, Principal
Alaska Applied Sciences, Inc.
Box 20993, Juneau, AK 99802
wleighty@earthlink.net
907-586-1426       206-719-5554 cell
Comparing Fuels For Energy Transmission, Storage, and Integration

Ammonia Fuel
1-2 October 2012, San Antonio

Bill Leighty
Director, The Leighty Foundation
Principal, Alaska Applied Sciences
Juneau, AK
wleighty@earthlink.net
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