
EUEC, Phoenix, 3 - 5 Feb 14

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Kivalina, Alaska
Inupiat people
Arctic
Angoon, Alaska
Tlingit people
Southeast
Comparing the world’s energy resources*

Where should we invest for the long-haul??

- Annual Income
- Capital

SOLAR

World energy use

© Richard Perez, et al.

*yearly potential is shown for the renewable energies. Total reserves are shown for the fossil and nuclear “use-them, lose-them” resources. Word energy use is annual.
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>0.0-5.6m/s</td>
<td>0-200W/m²</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5.6-6.4m/s</td>
<td>200-300W/m²</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>6.4-7.0m/s</td>
<td>300-400W/m²</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>7.0-7.5m/s</td>
<td>400-500W/m²</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>7.5-8.0m/s</td>
<td>500-600W/m²</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>8.0-8.8m/s</td>
<td>500-800W/m²</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>&gt;8.8m/s</td>
<td>&gt;800W/m²</td>
<td></td>
</tr>
</tbody>
</table>
OCEAN: wave, tidal
Hydro
Geothermal: hot water, surface recharge
“Enhanced”, “Engineered” Geothermal Mt. Spurr, Alaska

Hot dry rock: flash injected water to steam
Analogy: HDR geothermal borehole (well) requires only surface casing and full-depth hot water insulated return line (‘‘production casing’’), typically to 6,000 m depth. Compare: Typical oil well completion, with several casings.
2003: EPB Drilling Full Scale in Granite

311 mm = 12.25”
Alaska’s Renewable Energy (RE) Goals

• 150+ community “energy islands”:
  – Affordable
  – Indigenous; independence
  – Survival: outmigration
  – All energy, all uses: elec, heat, transport
  – Annual-scale, low-cost storage

• “Firm” large RE: Susitna Dam electricity
• Export large RE: “green” ammonia fuel
• Cluster industry: employment
• Prevent:
  1. Rapid climate change: warming
  2. Ocean acidification
  3. Sea level rise
  4. Species extinction
Trouble with Renewables

- Diffuse, dispersed: gathering cost
- Richest are remote: “stranded”
  - High intensity
  - Large geographic extent
- Time-varying output:
  - “Intermittent”
  - “Firming” integration + storage required
- “Energy island” communities, Alaska
Trouble with Renewables: Big Three

1. Transmission and gathering
2. Storage: Annual-scale firming
3. Integration
   - Extant energy systems
   - Electricity grid
   - Fuels: CHP, transportation
   - Macro: “centralized plants”
   - Micro: distributed gen (DG), microgrids
Trouble with Renewables: Electricity Transmission

- Grid nearly full: who pays?
- Integration
  - Distributed AND centralized: utilities squeezed
  - Continental energy system
  - Quality
  - Time-varying
- Costly “firming” storage: CAES, VRB, pump hydro
- Low capacity factor (CF) or curtailment
- Overhead vulnerable: God or man
- Underground: only HVDC, 6x cost
- Wide ROW
- NIMBY: delay + cost, site + ROW
"There's a better way to do it... Find it"

Thomas Edison
Solar Hydrogen Energy System

Sunlight from local star

Electrolyzer

H₂

O₂

Fuel Cell

Electricity

Work
• AEA: Alaska Energy Authority, State of Alaska
• EETF: Emerging Energy Technology Fund
• AASI: Alaska Applied Sciences, Inc.
• Anhydrous ammonia (NH3) fuel from RE
• SSAS: Solid State Ammonia Synthesis
• PCC: Proton Conducting Ceramic
• AEA grants $750K from EETF to AASI: Aug ‘12
• AASI in-kind $250K
• Total $1M
AEA EETF AASI Project

- Deliver: Containerized, transportable, SSAS pilot plant “ammonia microgrid” system
- Produce NH3 from RE-electricity, water, air
- Store NH3 in small tank
- Recover via CHP in ICE genset
- SCADA data export for public
- Demo around Alaska
Solid State Ammonia Synthesis (SSAS)
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
150 microgrids
Opportunity: Alaska Microgrid Applications

1. Village energy “independence”
   a. Diverse renewable sources
   b. Low-cost tank storage
   c. 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
Military: Land + sea fuel

- USCG, Navy ships
- Land vehicles: road, rail
- Recip engines modify: multifuel, Sturman
- Mini + microgrid app’s
Anhydrous Ammonia  \( \text{NH}_3 \)

N  Nitrogen
H  Hydrogen

Molecular weight = \( \sim 17 \)

18\% H by weight: “other hydrogen”

\( \text{NH}_3 + \text{O}_2 = \text{N}_2 + \text{H}_2\text{O} \)
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

KWh per Gallon (LHV)

- Hydrogen Energy
- Carbon Energy

C-free
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: fertilizer
  - End-use in ICE, CT, fuel cell
  - Safety: self-odorizing; safety regs; hazard; toxic
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
- 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
System Ratings

Gaseous Hydrogen (GH2)
Anhydrous Ammonia (NH3)
MONTHS: GH2, NH3
Ammonia fueled – Norway

Ammonia fuel tank

1933
Ammonia + Gasoline Powered

• Idle: gasoline
• Full power: 80% ammonia

University of Michigan

Summer ’07 Detroit → San Francisco

2007
X-15 rocket plane: NH3 + LOX fuel
Mach 6.7 on 3 Oct 67
199 missions
1959 - 68
1,000 hours, ICE, 6 cyl, 100 hp
75% ammonia, 25% propane

Irrigation pump
Central Valley, CA

2008
NH₃ Ag Fertilizer Tanks, Wind Generators, NW Iowa
Liquid Ammonia Tank Storage

Cost per Gallon: 250 psi Ammonia Tanks

Tank cost per gallon

Tank capacity, gallons

Largest highway-transportable
Hydro “Dispatchable” with NH3 storage
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
Haber-Bosch Process
1909 – 1913 BASF

- NH$_3$ synthesis
- Coal gasification $\rightarrow$ H$_2$
- WW I explosives
- 40% humanity: N fertilizer

Haber-Bosch Reactor
1921
Ludwigshafen, Germany

Fritz Haber
Inside the Black Box: Steam Reforming + Haber-Bosch (H-B)

\[3 \text{ CH}_4 + 6 \text{ H}_2\text{O} + 4 \text{ N}_2 \rightarrow 3 \text{ CO}_2 + 8 \text{ NH}_3\]

Energy consumption \(~33\) MMBtu (9,500 kWh) per ton \(\text{NH}_3\)
Tons \(\text{CO}_2\) per ton \(\text{NH}_3\) = 1.8
Burrup Peninsula, NW Australia, Natural Gas to Ammonia Plant
760,000 Mt / year
$US 650 million capital cost ‘06

The Competition
Natural gas input
80,000 Mt liquid storage - 33°C
To wharf
Ammonia or LPG Tanker
To 35,000 Mt
Refrigerated
USA NH3 Infrastructure

- USA imports ~60% of 14 MMt / year
- ~ 3,000 miles pipelines
  - ~ 250 psi liquid
  - Smaller diameter than NG or hydrogen
- ~ 4.5 MMt large “atmospheric” tank storage
- Mild steel construction
  - Low cost
  - No corrosion or embrittlement
Liquid ammonia pipeline

NOLA
# Capital Cost per GW-mile

## Electricity:

<table>
<thead>
<tr>
<th>KV</th>
<th>MW</th>
<th>$M / GW-mile</th>
</tr>
</thead>
<tbody>
<tr>
<td>765</td>
<td>5,000</td>
<td>1.3</td>
</tr>
<tr>
<td>345</td>
<td>1,000</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Consensus ? 2.5</td>
</tr>
</tbody>
</table>

- SEIA: 765 5,000 1.3
- AEP-AWEA 765 5,000 3.2

## Hydrogen pipeline:

- 36”, 100 bar, 500 miles, no compress 0.3

## Ammonia pipeline:

- 10”, liquid, 500 miles, with pumping 0.2
RE Ammonia Transmission + Storage Scenario

Wind Generators

Electrolyzers

Haber-Bosch Ammonia Synthesis

Liquid Ammonia Tank Storage

Liquid Ammonia Transmission Pipeline

Air Separation Plant

Electricity

Air

N₂

H₂

H₂O

Generators ICE, CT, FC

End users Retail

Cars, Buses, Trucks, Trains

Aircraft Fuel

AC grid Wholesale
Ammonia from hydrogen from zero-cost off-peak hydro
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
Input $\sim 1.5$ MW @ 11 kWe / kg NH$_3$
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)
**RE Ammonia Transmission + Storage Scenario**

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**Solid State Ammonia Synthesis (SSAS)**

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

$6 \text{H}_2\text{O} + 2 \text{N}_2 \rightarrow 3 \text{O}_2 + 4 \text{NH}_3$

Energy consumption 7,000 – 8,000 kWh per ton NH$_3$

Benchtop Proof-of-concept
Solid State Ammonia Synthesis (SSAS)
NHThree LLC patent
Tube assembly installed in test fixture.

Nickel oxide cathode coating (tube interior) reduced by hydrogen to metallic nickel, ready for subsequent tests.
Center: PCC tube 33 cm$^2$ active area. Current collectors installed. Sealed to alumina support tubes. Setup is leak-free.
50x PCC tube cross-section, anode layer (exterior)
2,000x cathode (interior)
**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
Beyond Alaska Microgrids

- Success: global application
- “Electrofuels” microgrids
- Merging RE microgrids
  - Ammonia microgrid → macrogrid
- Continental scale RE systems
- RE for all energy, all purposes
- “Run world on renewables”
- “Green” ammonia compete? C-tax?
320,000 MWh storage
Annual firming 1,000 MW Great Plains wind

• Electricity
  – VRB (Vanadium Redox Battery)
    • O&M: 80% efficiency round-trip
    • Capital: $500 / kWh = $160 Billion
  – CAES (Compressed Air Energy Storage)
    • O&M: $46 / MWh typical
    • Iowa Stored Energy Park:
      – Power = 268 MW
      – Energy capacity = 5,360 MWh
      – Capital: 268 MW @ $1,450 / kW = $390 M
        @$40 / kWh = $13 Billion
        @ $1 / kWh = $325M

• GH2 (3 hydrogen caverns) Capital $70 Million
• NH3 (2 ammonia tanks) Capital $30 Million
“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
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
“Americans can be counted on to always do the right thing – but only after they have tried everything else.”

Winston Churchill

The dog caught the car.

Dan Reicher
Beyond “microgrids” --

1. Village energy independence
2. Firming large variable RE
3. Export diverse, large-scale RE as “green” NH₃
Renewable Source Electricity

SSAS

Merging microgrids
Liquid Anhydrous Ammonia (NH3)
-33 C, 1 atmosphere
Alaska Energy Authority
Emerging Energy Technology Fund
Project Fundamentals

1. Does SSAS system “work”?
2. Competitive with EHB?
3. Useful in Alaska?

SSAS: Solid State Ammonia Synthesis
Alaska Energy Authority
Emerging Energy Technology Fund
$750K grant to
Alaska Applied Sciences, Inc.

- SSAS Proof-of-concept pilot plant
- Alaska applications
  - Village energy independence
  - Hydro firming, annual-scale
  - RE export as NH3 fuel
  - ALL energy: elec, heat, transport
- 2-year project
Project Fundamentals

1. Anhydrous ammonia (NH3) is a:
   a. Fuel: ICE, CT, fuel cell
   b. Transmission medium
   c. Low-cost energy storage medium: liquid, 15 bar

2. NH3 made from 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. Alaska value
Project Fundamentals

4. SSAS unproven: needs proof-of-concept, kW-scale pilot plant

5. Design and build pilot plant:
   a. Complete system: convert, store, regenerate
   b. SCADA instrumented: public
   c. Containerized & transportable
   d. Upgradeable

6. Success:
   a. Great value to Alaska, beyond
   b. Scaleup to commercial
   c. SE Alaska “RE Cluster Industry” via USFS, JEDC
L to R: John Holbrook, NTHThree       Bill Leighty, AASI       Greg Coffey, PNNL

Test reactor is above Bill’s left shoulder
**Project Status**

- PCC tube section in test at PNNL, Richland, WA
- AEA 1 Dec deadline: “use or lose” $750K grant
- Alternative technology proposed
  - “Nafion” membrane reactor: TRL = 0
- Fundamentals persist:
  - Alaska, global need

Project cancelled; $750K grant lost

Milestone 1: failed to demonstrate technology at PNNL

Handouts + DVD’s

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