Running the World on Renewables: Alternatives to Electricity for Transmission and Low-cost Firming Storage of Stranded Renewables as Hydrogen and Ammonia Fuels via Underground Pipelines

ASME – IMECE Paper: IMECE2012-87097

American Society of Mechanical Engineers, International Mechanical Engineering Congress and Exposition

15 Nov 12, Houston

Bill Leighty, Director
The Leighty Foundation
Juneau, AK
wleighty@earthlink.net
907-586-1426       206-719-5554 cell
Mendenhall Glacier, Juneau, AK
June ‘71
Mendenhall Glacier, Juneau, AK
10 October 10
Rapid climate change

Spruce bark beetle kill, Alaska
Shishmaref, Alaska
Winter storms coastal erosion
MUST Run the World on Renewables – plus Nuclear?

- Climate Change
- Ocean acidification
- Demand growth
- Water for energy
- War
- Depletion of Oil and Gas
- Only 200 years of Coal left
- Only Source of Income:
  - Sunshine
  - Tides
  - Spending our capital
Comparing the world's energy resources*

Where should we invest for the long-haul??

©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. World energy use is annual.
Hydro
Geothermal: hot water, surface recharge
“Enhanced”, “Engineered” Geothermal  Mt. Spurr, Alaska
Hot dry rock: flash injected water to steam
Trouble with Renewables

• Diffuse, dispersed: gathering cost
• Richest are remote: “stranded”
  – High intensity
  – Large geographic extent
• Time-varying output:
  – “Intermittent”
  – “Firming” integration + storage required
• Distributed AND centralized
Trouble with Renewables: Big Three

1. Transmission and gathering
2. Storage: Annual-scale firming
3. Integration
   • Extant energy systems
   • Electricity grid
   • Fuels: CHP, transportation
Trouble with Renewables: Electricity Transmission

- Grid nearly full: who pays?
- Integration
  - 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
- FERC no interstate jurisdiction
- Wide ROW
- NIMBY: delay + cost, site + ROW
10,000 MW alternatives: HVAC vs HVDC superconductor

Out of Sight, Out of Harm's Way

Superconductor (SC) Pipeline
25 ft ROW

600 ft ROW
Zion, IL
Near Zion nuclear plant, Oct 02
Beyond “Smart Grid”

- Primarily DSM
- More vulnerable to cyberattack?
- Adds no physical:
  - Transmission, gathering, distribution
  - Storage
- Next big thing; panacea
- Running the world on renewables?
- Must think:
  - Beyond electricity
  - Complete energy systems
  - ALL energy: Dr. Grob, Hermann Scheer
“Transmission”

- Electrofuels
- Renewable-source electricity
- Underground pipelines
- Carbon-free fuels: hydrogen, ammonia
- Low-cost storage: $0.10 – 0.20 / kWh capital
- CHP, transport, industrial
- GW scale
Solar Hydrogen Energy System

Sunlight from local star

- Electrolyzer
- Fuel Cell
- Electricity
- Work

Chemical reactions:

- $2H_2O + \text{Energy} \rightarrow 2H_2 + O_2$
- $2H_2 + O_2 \rightarrow 2H_2O + \text{Energy}$
DOE-EIA: 2005 estimated US annual energy:
~ 100 quads = 100 TWh

Estimated Future U.S. Energy Requirements - 96.8 Quads

- Hydro: 0.94
- Bio/Geo: 3.81
- Wind: 0.06
- Solar: 0
- Nuclear: 7.48
- Coal: 20.83
- Gas: 24.73
- Oil: 38.96

Electricity Generation: 33.91

Useful Energy: 44.76

Rejected Energy: 52.06

Projection Year 2005
From Year 2005
Efficiency Year 2005
Energy Distribution Year 2005
EIA estimated 2025 annual energy:
~ 130 quads = 130 TWh
“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
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
Hydrogen and Ammonia Fuels

- Delivering fuels: distribution
- ICE, CT, Fuel cell
- CHP on-site
- Utility substation wholesale
- Transportation
  - Rail
  - Truck
  - Personal
- Emissions: $H_2O$, $N_2$
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
System Ratings

Gaseous Hydrogen (GH2)  
Anhydrous Ammonia (NH3)
GH2 and NH3
MONTHS: GH2, NH3
The Great Plains Wind Resource
## Exporting From 12 Windiest Great Plains States

Number of GH2 pipelines or HVDC electric lines necessary to export total wind resource. Capacity at 500 miles length. Capacity Factor (CF) = 30%.

<table>
<thead>
<tr>
<th>State</th>
<th>Annual Energy Production (TWh)</th>
<th>Nameplate Installed Capacity (GW)</th>
<th>Nameplate Installed Capacity (GW)</th>
<th>6 GW 36&quot; GH2 Hydrogen Pipelines</th>
<th>$ Billion Total Capital Cost</th>
<th>3 GW 500 KV HVDC Electric Lines</th>
<th>$ Billion Total Capital Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Texas</td>
<td>6,528</td>
<td>1,901,530</td>
<td>1,902</td>
<td>317</td>
<td></td>
<td>634</td>
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<td>South Dakota</td>
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<td>157</td>
<td></td>
<td>315</td>
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<tr>
<td>North Dakota</td>
<td>2,984</td>
<td>770,196</td>
<td>770</td>
<td>128</td>
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<td>257</td>
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<td>Iowa</td>
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<td>571</td>
<td>95</td>
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<td>190</td>
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<tr>
<td>Wyoming</td>
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<td>552,073</td>
<td>552</td>
<td>92</td>
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<td>184</td>
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<td>Oklahoma</td>
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<td>516,822</td>
<td>517</td>
<td>86</td>
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<tr>
<td>Minnesota</td>
<td>1,679</td>
<td>489,271</td>
<td>489</td>
<td>82</td>
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<tr>
<td>New Mexico</td>
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<td>Colorado</td>
<td>1,288</td>
<td>387,220</td>
<td>387</td>
<td>65</td>
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<td>129</td>
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<td><strong>TOTALS</strong></td>
<td><strong>33,711</strong></td>
<td><strong>9,376,694</strong></td>
<td><strong>9,377</strong></td>
<td><strong>1,563</strong></td>
<td><strong>$1,500</strong></td>
<td><strong>3,126</strong></td>
<td><strong>$2,000</strong></td>
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</tbody>
</table>

Wind energy source: Archer, Jacobson 2003
Total solar: $\sim 3 \times 10^{14} \text{ kg / yr}$
Total wind: $\sim 3 \times 10^{11} \text{ kg / yr}$

Synergy:
- Diurnal + Seasonal
- Minimize “firming” storage
**Major Electricity Transmission Studies**

- **EWITS-NREL**: 225 - 330 GW
- **WWSIS-NREL**: 30 GW
- **Brattle Group**: 24 GW
- **SEIA-AWEA**: 300 GW
- **JCSP**: 745 GW
- **AEP-AWEA**: 350 GW
- **Frontier + Transwest**: 115 GW
- **ICFI Wyoming**: 12 GW

**Total**: ~ 1,000 GW

**Great Plains Potential**: 3,000 GW wind, nameplate
3,000,000 GW solar, nameplate

**Total USA energy @ 33% CF**: ~ 3,460 GW

@ 5 GW / 765 kv AC or HVDC line: ~ 700 new lines
SEIA – AWEA  Feb 09
“Green Power Superhighways: Building a Path to America’s Clean Energy Future”
Mega Project Scenario

Legend:
Final Wind MW (Change from In-Area MW)
New Transmission MW (GW-miles)

Total Wind MW:
24040 (801 sites) [$48.1B]
Change from in-area MW:
-5940 (-197 sites) [-$11.8B]
Total Solar MW:
5700 MW (-100 MW) [-$0.4 B]
Total Additional Transmission:
+ 6900 GW-miles [+ $11 B]
Total Change in Capital Cost:
- $1.2B
Frontier Line

- Proposed transmission corridor to interconnect Wyoming, Utah, Nevada, California and possibly other states
- MOU signed on April 4, 2005

TransWest Express

Several alternatives proposed, including:

Statement of Robert Smith on behalf of Arizona Public Service Company and the TransWest Express Project before the House Subcommittee on Water and Power and the House Subcommittee on Forests and Forest Health, June 27, 2006.
NOTE: Approximate relationship based on Surge Impedance Loading (i.e. reactive power balance point) 345 kV single circuit tower lines with two conductors per phase compared to 765 kV single circuit lines with six conductors per phase.

<table>
<thead>
<tr>
<th>Transmission Voltage (kV)</th>
<th>Cost per Mile ($/mile)</th>
<th>Capacity (MW)</th>
<th>Cost per Unit of Capacity ($/MW-mile)</th>
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</thead>
<tbody>
<tr>
<td>230</td>
<td>$2.077 million</td>
<td>500</td>
<td>$5,460</td>
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<tr>
<td>345</td>
<td>$2.539 million</td>
<td>967</td>
<td>$2,850</td>
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<td>500</td>
<td>$4.328 million</td>
<td>2040</td>
<td>$1,450</td>
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<tr>
<td>765</td>
<td>$6.578 million</td>
<td>5000</td>
<td>$1,320</td>
</tr>
</tbody>
</table>

(Sources: Edison Foundation\(^2\), AEP\(^3\))

**SEIA – AWEA**  **Feb 09**
**“Green Power Superhighways: Building a Path to America’s Clean Energy Future”**
Transmission Line Construction Cost

$ million per Mile

Southwest Power Pool ‘07
AWEA 20% Wind by 2030

“Never be built ...”
AWEA: 20% Electricity from Wind by 2030
~ 7% US energy
## Electricity Capital Cost per GW-mile

<table>
<thead>
<tr>
<th>Capacity</th>
<th>KV</th>
<th>Capacity</th>
<th>MW</th>
<th>$M / GW-mile</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEIA:</td>
<td>765</td>
<td>5,000</td>
<td>1.3</td>
<td></td>
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<tr>
<td></td>
<td>345</td>
<td>1,000</td>
<td>2.6</td>
<td></td>
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<tr>
<td>AEP-AWEA</td>
<td>765</td>
<td>5,000</td>
<td>3.2</td>
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<tr>
<td>Consensus?</td>
<td></td>
<td></td>
<td></td>
<td>2.5</td>
</tr>
</tbody>
</table>
350 miles
5 GW
$ 5B

1,750 GW-miles @ $5,000M = $2.8M / GW-mile
Atlantic Wind Connection
Offshore Submarine Cable

Superconducting

GH2 Pipeline: 36” Composite

Clean Line: Rock Island, Grain Belt

Clean Line: Tallgrass, Plains & Eastern

NH3 Pipeline: 36” Steel

Alaska Gasline

Keystone XL Oil
“Firm” Energy Essential

- Every hour, every year
- Dispatchable
- Strategically: indigenous, secure
- Market price: worth more
- Bankable large projects
- Risk avoidance:
  - Rapid climate change
  - Economic chaos
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
WWSIS: April week: ~30% RE
WWSIS: July week: ~10% RE
Wind seasonality, Great Plains

Normalized to 1.0

- Winter 1.20
- Spring 1.17
- Summer 0.69
- Autumn 0.93

Source: D. Elliott, et al, NREL
Wind Seasonality, Northern Great Plains

Normalized to 1.0 per season

Seasonality Factor

Winter | Spring | Summer | Fall

0.0 | 0.2 | 0.4 | 0.6

normalized to 1.0 per season
Wind Seasonality, Northern Great Plains

1,000 MW windplant: AEP = 3,500 GWh / yr

“Firm” goal = 875 GWh / season

Storage: 320 GWh per 1,000 MW wind

Source: NREL, D. Elliott
320 GWh
Annual firming, 1,000 MW wind

- CAES (compressed air energy storage)
  - O&M: $46 / MWh typical
  - Iowa: Power = 268 MW
  - Energy capacity = 5,360 MWh
  - Capital: $214 M
  - Storage @ $40 / kWh = $13 Billion
  - Storage @ $1 / kWh = $325 Million

- VRB flow battery
  - O&M: 80% efficiency round-trip
  - Capital: $160 Billion
“There’s a better way to do it... Find it”
Why Hydrogen, Ammonia?

- Transmission via underground pipeline
  - Easier to site, permit
  - Lower NIMBY
  - Protected: acts of God and man
  - FERC interstate jurisdiction
  - High capacity: 5 - 10 GW
  - Lower capital cost / GW - mile
- Affordable storage:
  - Annual-scale firming
  - Dispatchable fuel supply
- Zero-carbon fuels: RE
- Nascent markets: transport fuel, other
- Integration
  - Continental energy system
  - Elec grid quality
  - Elec grid generation O+M: fatigue, wear, efficiency
Annual Fresh Water for Energy

- USA today
- All energy

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

- If all via GH2 + NH3 fuels, required feedstock:
  - Dissociated, disintegrated: \( \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{O}_2 \)
  - 900 billion liters
Continental Supergrid – EPRI concept “Energy Pipeline”

- ~ 100 GW elec LVDC +
- ~ 100 GW LH2
- ~ 190 MWh / mile storage

* SC: MgB2 magnesium diboride superconductor
** LH2: liquid hydrogen coolant, energy transmit
Energy System of the Future

Frank Novachek, Director Corporate Planning
Utsira Island, Norway
The wind – hydrogen plant at Utsira

A vision becoming reality
ALL Denmark’s energy from windpower

• Prof Bent Sorensen, Roskilde Univ, DK
• WHEC, Montreal, June 02
• ALL Denmark’s energy from wind –
  - Elec, oil, gas
  - Transport, space heat-cool, industry
• IF convert ~ 15% to H2, store in extant salt caverns
• Can USA do same?
• Start with transport fuel?
Hydrogen Transmission Scenario

- Low-pressure electrolyzers
- “Pack” pipeline: ~ 120 GWh

- Wind Generators
- Electrolyzers
- Compressors
- Storage: 120 GWh
- 1,000 miles Hydrogen Gas Pipeline
  36" diameter
  ~ 1,000 psi

- AC grid Wholesale
- Generators ICE, CT, FC
- End users Retail
- Cars, Buses, Trucks, Trains
- Liquefy
- Aircraft Fuel
Norsk Hydro Electrolyzers 2 MW each
Norsk Hydro electrolyzer, KOH type
560 kW input, 130 Nm3 / hour at 450 psi (30 bar)
Compressorless system: No geologic storage

Transmission

City gate

Distribution

Wind Generators

High-pressure Electrolyzers

Wind Generators

Pipeline Energy Storage

1,500 psi → 500 psi

500 miles

Hydrogen Gas

Pipeline

20" diameter

1,500 -- 500 psi

Generators

ICE, CT, FC

End users

Retail

AC grid

Wholesale

Cars, Buses, Trucks, Trains

Liquefy

Aircraft Fuel

Transmission Distribution

Compressorless system: No geologic storage

Wind Generators

High-pressure Electrolyzers

Wind Generators

Pipeline Energy Storage

1,500 psi → 500 psi

500 miles

Hydrogen Gas

Pipeline

20" diameter

1,500 -- 500 psi

Generators

ICE, CT, FC

End users

Retail

AC grid

Wholesale

Cars, Buses, Trucks, Trains

Liquefy

Aircraft Fuel
Electrolyzer

H₂O

H₂

O₂

Power Electronics

To Compressor or Hydrogen Pipeline

Renewable-source Electricity Generation

PE: Power Electronics

To Compressors or Pipelines: Hydrogen and Oxygen

Topology Options: H₂ and O₂ Production and Gathering from Renewable Energy Generation
Polymer-metal linepipe avoids hydrogen embrittlement
Gaseous Hydrogen (GH2)

36” diam, 800 km
No compression
8,000 MW

CRLP™ is a trademark of NCF Industries, Inc.
Hydrogen Energy Storage

1,000 miles Hydrogen Gas
Pipeline 36'' diameter, 1,500 - 500 psi

Pipeline Storage = 120 GWh

Geologic Storage?
Domal Salt Storage Caverns
- 860,000 m$^3$ physical
- 150 bar = 2,250 psi
- 2,500 Mt net = 92,500 MWh
- $15M$ avg cap cost / cavern
- $160 / MWh = $0.16 / kWh
- Cavern top ~ 700m below ground
Renewable-source GH2 geologic storage potential. Candidate formations for manmade, solution-mined, salt caverns.
(8 x 13) = 104 + (8 x 12) = 96  Total = 200 caverns per square mile
Each cavern is 200 ft diam, with minimum 200 ft web separation.

"Firm" 4,000 MW Great Plains wind
14 caverns

Maximum Cavern Packing Density
### Optimistic: Total Installed Capital Cost

1,000 mile Pipeline

“Firming” GH2 cavern storage

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost [million]</th>
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</thead>
<tbody>
<tr>
<td>Wind generators</td>
<td>$1,000</td>
</tr>
<tr>
<td>Electrolyzers</td>
<td>500</td>
</tr>
<tr>
<td>Pipeline, 20”</td>
<td>1,100</td>
</tr>
<tr>
<td># storage caverns</td>
<td>[4]</td>
</tr>
<tr>
<td>Caverns @ $10M ea</td>
<td>40</td>
</tr>
<tr>
<td>Cushion gas @ $5M ea</td>
<td>20</td>
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<tr>
<td><strong>TOTAL</strong></td>
<td><strong>$2,660</strong></td>
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Cavern storage: ~ 3 % of total capital cost
The NATURALHY approach: EC, R+D

NATURALHY:
- Breaks “chicken-egg” dilemma
- Bridge to sustainable future
Hydrogen - fueled
2005 Prius
ICE Hybrid
Carmakers Commit to Hydrogen Fuel Cell Cars?

• 9 Sept 09 “Letter of Understanding”
• Carmakers:
  - Daimler
  - Ford
  - GM/Opel
  - Honda
  - Hyundai/Kia
  - Renault
  - Nissan
  - Toyota
• Serial production ~ 2015: “… quite significant number” of electric vehicles powered by fuel cells
• Vague; lobbying for fed FCV funds restore?
• Will need H2 fuel: “… hydrogen infrastructure has to be built up with sufficient density …”
Greenhouse Gas Pollution (Light duty vehicles only)
(Billion/ tonnes CO2-equivalent/year)

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

Scenarios:
- 100% Gasoline ICVs
- Base Case: Gasoline Hybrid Scenario
- Gasoline Plug-In Hybrid Scenario
- Ethanol Plug-In Hybrid Scenario
- BEV Scenario
- H2 ICE HEV Scenario
- Fuel Cell Vehicle Scenario

1990 LDV GHG

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

100% Gasoline ICVs
Base Case: Gasoline Hybrid Scenario
Gasoline Plug-In Hybrid Scenario
Ethanol Plug-In Hybrid Scenario
BEV Scenario
H2 ICE HEV Scenario
Fuel Cell Vehicle Scenario
CA: 20% of “cars” hydrogen fueled by 2030

- 20% of 45M vehicles = 9M
- @ 78 mpg = 78 miles / kg H₂
- 12,000 miles / year = 150 kg H₂ / year
- 1,800 M kg H₂ / year = 1.65 MMt H₂ fuel
- @ 50 kWh / kg at windplant gate:
  - 82,500 GWh / year
  - @ 40% CF = 23,000 MW nameplate wind
  - Requires 3 GH₂ pipelines, 36”, 500 miles long
  - PLUS @ 4 caverns / GW = 92 storage caverns, to firm the supply at annual scale
GH2 Transmission Pipeline

Wind Potential ~ 10,000 GW
12 Great Plains states
Wind Potential ~ 10,000 GW
12 Great Plains states
AWEA 20% Wind Electricity by 2030

Wind Potential ~ 10,000 GW
# Capital Cost per GW-mile

## Electricity:

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

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

Consensus: 2.5

## Hydrogen pipeline:

- 36”, 100 bar, 500 mi, no compress: 0.3

(100 bar = 1,500 psi)
Pilot plant needed

- Every major new industrial process
- Renewables-source systems
- Diverse, large-scale, stranded
- US, Japan, Canada, IPHE → “ IRHTDF “
Pilot-scale Hydrogen Pipeline System: Renewables

- **Diverse**
- **Dispersed, diffuse**
- **Large-scale**
- **Stranded**
  - Remote
  - No transmission
IRHTDF: generation, conversion, collection, storage CORRIDOR, SYSTEM

Biomass, Wind, Other Catchment Areas, with Delivery Points to GH2 pipeline

GH2 geologic storage

O2 pipeline

Ames
Anhydrous Ammonia \( \text{NH}_3 \)

N Nitrogen
H Hydrogen

Molecular weight = \(~17\) mass units

18\% \text{H} by weight: “other hydrogen”

\( \text{NH}_3 + \text{O}_2 = \text{N}_2 + \text{H}_2\text{O} \)
Why Ammonia?  
Fertilizer and Fuel

Only liquid fuel embracing:

- Carbon-free: clean burn or conversion; no CO₂
  - Excellent hydrogen carrier
  - Easily “cracked” to H₂
- 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
Ammonia Fuel Uses

1. Internal Combustion Engine (ICE)
   - Diesel: NH$_3$ gas mixed with intake air
   - Spark-ignition: 70%+ NH$_3$ plus gasoline, ethanol, propane, NG, hydrogen
   - NOx ~ ¼ gasoline engines

2. Combustion Turbines

3. Direct Ammonia Fuel Cells:
   - Combined heat + power (CHP)
   - No NOx

4. Reform (“crack”) to liberate hydrogen for fuel cells:
   $2\text{NH}_3 \rightarrow 3\text{H}_2 + \text{N}_2$
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

Cost per Gallon (LHV)

- Hydrogen Energy
- Carbon Energy

C-free
Ammonia fueled - Norway

Ammonia fuel tank

1933
Ammonia Fueled Bus: Thousands of Problem-free Miles

Belgium

Ammonia fuel tank

Ammonia Fueled Bus: Thousands of Problem-free Miles

1943
X-15 rocket plane: NH₃ + LOX fuel
Mach 6.7 on 3 Oct 67
199 missions
1959 - 68
Ammonia + Gasoline Powered

- Idle: gasoline
- Full power: 80% ammonia

University of Michigan

Summer ’07 Detroit → San Francisco

2007
NH₃ Ag Fertilizer Tanks, Wind Generators, NW Iowa
“Atmospheric” Liquid Ammonia Storage Tank (corn belt)

- 30,000 Tons
- 190 GWh
- $15M turnkey
- $80 / MWh
- $0.08 / kWh
- -33 C
- 1 Atmosphere

'09 ARPA-E “Grids” Goal: $100 / kWh
95% Global Ammonia Synthesis Plant
Natural Gas 1 – 3,000 tpd
Haber-Bosch process
The Competition

Burrup Peninsula, NW Australia, Natural Gas to Ammonia Plant
760,000 Mt / year
$US 650 million capital cost ‘06

Natural gas input
80,000 Mt liquid storage
- 33°C

To wharf
Haber-Bosch Process
1909 – 1913  BASF
• NH₃ synthesis
• Coal gasification → H2
• WW I explosives
• 40% humanity: N fertilizer

Haber-Bosch Reactor
1921
Ludwigshafen, Germany
Inside the Black Box: Steam Reforming + Haber-Bosch (H-B)

3 CH₄ + 6 H₂O + 4 N₂ → 3 CO₂ + 8 NH₃

Energy consumption ~33 MMBtu (9,500 kWh) per ton NH₃
Tons CO₂ per ton NH₃ = 1.8
Ammonia Tanker
Burrup Peninsula
Western Australia
Ammonia or LPG Tanker
To 35,000 Mt
Refrigerated
10” NH3 liquid pipeline cost

- Industry sources, all costs:
  - $750 – 900 K per mile, 10”, “uncongested area”
  - $250K per mile “small diameter”
- 1,000 mile pipeline @ 10” = $400M
- Capacity 2 GW
- Capital cost = $200K / GW-mile
# Capital Cost per GW-mile

## Electricity:

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

## Hydrogen pipeline:

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

## Ammonia pipeline:

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

- Wind Generators
- Electrolyzers
  - Wind Generators
  - H₂O
- Air Separation Plant
  - N₂
- Haber-Bosch Ammonia Synthesis
  - H₂
  - H₂O
- Liquid Ammonia Transmission + Storage
- Liquid Ammonia Tank Storage
- AC grid
  - Wholesale
  - Generators
    - ICE, CT, FC
- End users
  - Retail
  - Cars, Buses, Trucks, Trains
  - Aircraft Fuel
Norsk Hydro
Electrolyzers
2 MW each

Ammonia from hydrogen from zero-cost off-peak hydro
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 ~12,000 kWh per ton NH$_3$
RE Ammonia Transmission + Storage Scenario

Solid State Ammonia Synthesis (SSAS)

Wind Generators

Electrolyzers

Haber-Bosch Ammonia Synthesis

Air Separation Plant

Electricity

Air

N₂

H₂

H₂O

Liquid Ammonia Transmission Pipeline

Liquid Ammonia Tank Storage

Generators ICE, CT, FC

End users Retail

AC grid Wholesale

Cars, Buses, Trucks, Trains

Aircraft Fuel
SSAS reactor

Air Separation Unit (ASU)

Wind Generators

Electricity

Air

N₂

SSAS reactor

Liquid Ammonia Pipeline

Liquid Ammonia Tank Energy Storage

Wind Generators

Electricity

H₂O

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

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

Energy consumption 7,000 – 8,000 kWh per ton NH\textsubscript{3}

**Benchtop**

**Proof-of-concept**
Solid State Ammonia Synthesis (SSAS) NHThree LLC patent
**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
320,000 MWh storage
Annual firming 1,000 MW 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
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
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 Proof-of-concept pilot plant
Two-year project
Alaska Applied Sciences, Inc.
“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
Humanity’s Goal

A global, sustainable, benign-source, equitable, energy economy

• CANNOT with only electricity transmission
“Transmission”

- Beyond “Smart Grid”, GW scale
- Electrofuels
- Renewable-source electricity
- Underground pipelines
- Carbon-free fuels: hydrogen, ammonia
- Low-cost storage:
  $ 0.10 – 0.20 / kWh  capital
- CHP, transport, industrial
Beyond “Smart Grid”

- Primarily DSM
- More vulnerable to cyberattack?
- Adds no physical:
  - Transmission, gathering, distribution
  - Storage
- Next big thing; panacea
- Running the world on renewables?
- Must think:
  - Beyond electricity
  - Complete energy systems
MUST Run the World on Renewables – plus Nuclear?

- Global
- Indigenous
- Firm: available
- C-free
- Benign
- Abundant
- Affordable
- Equitable
- Perpetual:
  - solar
  - geothermal
  - tidal
Comparing the world’s energy resources*

Where should we invest for the long-haul??

©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. World energy use is annual.
Running the World on Renewables: Alternatives to Electricity for Transmission and Low-cost Firming Storage of Stranded Renewables as Hydrogen and Ammonia Fuels via Underground Pipelines

Handouts, DVD’s

ASME - IMECE
15 Nov 12, Houston

Bill Leighty, Director
The Leighty Foundation
Juneau, AK
wleighty@earthlink.net
907-586-1426 206-719-5554 cell
Running the World on Renewables: Alternatives to Electricity for Transmission and Low-cost Firming Storage of Stranded Renewables as Hydrogen and Ammonia Fuels via Underground Pipelines

ASME – IMECE Paper: IMECE2012-87097

American Society of Mechanical Engineers, International Mechanical Engineering Congress and Exposition

15 Nov 12, Houston

Bill Leighty, Director
The Leighty Foundation
Juneau, AK
wleighty@earthlink.net
907-586-1426 206-719-5554 cell
End 15 Nov 12 presentation;
22 minutes videorecorded live.

The following slides are supplemental.
Annual Fresh Water for Energy

- USA today
- All energy

- 17,000 billion liters in today’s “energy” system
  - “Withdrawn”
  - “Consumed”
  - Include all oil & gas “fracking” ?

- If all via GH2 + NH3 fuels, required feedstock:
  - Dissociated, disintegrated: $\text{H}_2\text{O} \rightarrow \text{H}_2 + \text{O}_2$
  - 7,650 billion liters “consumed”
International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF)
Pilot plant

Global opportunity: IPHE project
Humanity’s Goal

- International Collaboration
- Alternatives to electricity
- R & D
- Pilot plant demonstrations

Funding?
- China, Korea, others
- Big oil
- Military spending
- Global C-tax
- Capital markets
GW-scale Transmission + Storage Options

- **Electricity:** HVAC, HVDC
  - CAES compressed air energy storage
  - Vanadium Redox battery (VRB Power Systems)
  - Sodium-sulfur battery
  - PHEV, BEV (distributed)
- **Gaseous Hydrogen (GH2)**
  - Pipeline
  - Geologic: salt caverns (man-made)
  - Geologic: natural formations? *Terra incognita*
- **Liquid Hydrogen (LH2)**
  - Pipeline, truck, rail car, ship
  - 1/3 energy to liquefy Ammonia (NH3) liquid
  - Tank, refrigerated, 10K – 60K ton
  - Truck, rail car, ship
- **Liquid anhydrous ammonia (NH3)**
  - Pipelines
  - Tanks
- **Liquid synthetic HC’s – zero net C**
  - Pipeline
  - Tank, truck, rail car, ship
  - Geologic: salt caverns (man made)
- “Energy Pipeline”, EPRI: LH2 in pipeline, SC LVDC electric
- **Chemicals**
  - Hydrides
  - Al – Ga ← → Alumina
OPTIMISTIC
City-gate GH2 cost @ 15% CRF, 20” pipeline, from 2,000 MW Great Plains windplant

Competitive cost?
Anhydrous Ammonia (NH₃) wholesale price, NOLA (New Orleans, LA)
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 \textbf{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?
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
  – RE export as NH3 fuel
  – Hydro firming, annual-scale
• 2-year project
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

Community grid; Renewable-source Electricity

240 vac 1-phase Line

Consume NH₃; Produce electricity

Produce NH₃; Consume electricity

Air Flow

Air Separation Unit (ASU)

O₂ to air or market

N₂

Power electronics

Cell voltages

SSAS reactor

NH₃

Compressor

Steel Storage Tank

Liquid level

P, T

Water

Flow

NH₃ Flow

RA

Flow

Compress

ICE Genset

Rev: 6 Mar 11 W. Leighty
Alaska Applied Sciences, Inc.
Humanity’s Goal

A global, sustainable, benign, equitable, energy economy
Humanity’s Goal

- International Collaboration
- Alternatives to electricity
- R & D
- Pilot plant demonstrations

Funding?
- China, Korea, others
- Big oil
- Military spending
- Global C-tax
- Capital markets: Mike Eckhart, 19 Oct
Airbus Industrie concept: liquid hydrogen fueled
Flexibility Supply Curve

NREL: Systems Integration
# Exporting From 12 Windiest Great Plains States

Number of GH2 pipelines or HVDC electric lines necessary to export total wind resource

Wind energy source: PNL-7789, 1991

* at 500 miles average length

<table>
<thead>
<tr>
<th>State</th>
<th>AEP, TWh</th>
<th>Wind Gen MW (nameplate) (40% CF)</th>
<th>6 GW 36” GH2 export pipelines</th>
<th>$ Billion Total Capital Cost *</th>
<th>3 GW export HVDC lines</th>
<th>$ Billion Total Capital Cost *</th>
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</thead>
<tbody>
<tr>
<td>North Dakota</td>
<td>1,210</td>
<td>345,320</td>
<td>50</td>
<td>50</td>
<td>100</td>
<td>60</td>
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<tr>
<td>Texas</td>
<td>1,190</td>
<td>339,612</td>
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<td>48</td>
<td>100</td>
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<td>Kansas</td>
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<td>43</td>
<td>100</td>
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<td>South Dakota</td>
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<td>41</td>
<td>100</td>
<td>60</td>
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<td>247,717</td>
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<td>80</td>
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<td>Wyoming</td>
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<td>213,185</td>
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<td>Oklahoma</td>
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<td>157,249</td>
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<tr>
<td>Colorado</td>
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<td>137,272</td>
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<td>New Mexico</td>
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<td><strong>TOTALS</strong></td>
<td><strong>9,984</strong></td>
<td><strong>2,849,316</strong></td>
<td><strong>401</strong></td>
<td><strong>$ 401</strong></td>
<td><strong>890</strong></td>
<td><strong>$ 534</strong></td>
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</table>
Stanford wind energy study: 2003

- Underestimated: PNNL, NREL
- 80 m hub height
- 1.3 – 1.7 m / s faster windspeed
- IF transmission network:
  steady, reliable, abundant supply

“Spatial and temporal distributions of U.S. winds and wind power at 80 m derived from measurements”

# Jan '09 Transmission Backlog

<table>
<thead>
<tr>
<th>Region</th>
<th>Capacity (GW)</th>
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<tbody>
<tr>
<td>California</td>
<td>13 wind</td>
</tr>
<tr>
<td></td>
<td>30 solar</td>
</tr>
<tr>
<td>Upper Midwest</td>
<td>70 wind</td>
</tr>
<tr>
<td>Lower Midwest</td>
<td>40 wind</td>
</tr>
<tr>
<td>Great Lakes + Mid Atlantic</td>
<td>40 wind</td>
</tr>
<tr>
<td>Texas</td>
<td>50 wind</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>243 GW</strong></td>
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</table>

**Potential Great Plains Wind** 3,000 GW
SSAS Pilot Plant Budget

EETF via AEA $ 750 K
NHThree LLC in-kind $ 100 K
Wind2Green (W2G) in-kind $ 100 K
AASI in-kind $ 50 K
TOTAL $ 1 M

EETF  Emerging Energy Technology Fund, State of Alaska
AEA  Alaska Energy Authority, State of Alaska
AASI  Alaska Applied Sciences, Inc.
SSAS Pilot Plant Schedule:
24 months from ~ Dec ‘12

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
Comparing the world’s energy resources*

Where should we invest for the long-haul??

*yearly potential is shown for the renewable energies. Total reserves are shown for the fossil and nuclear “use-them, lose-them” resources. World energy use is annual.
Gaseous Hydrogen (GH2)
36” diam, 500 miles
No compression
8,000 MW
Vision: Remote renewable energy sources
connected to loads by DC grid
Figure III-6: Hourly supply and demand with storage, January 1-7, 2007. Source: IEER.
Ammonia reformer

Oct '09  Ammonia Fueled V-8 with Hydrogen Injection: Reformed from NH₃
Hydrogen Engine Center, Algona, IA

2009