Alternatives to Electricity for Transmission and Annual-scale Firming Storage for Diverse Renewable Energy Resources: Hydrogen and Ammonia Fuels

ASME Power
14 July 10, Chicago

Bill Leighty, Director
The Leighty Foundation
Juneau, AK
wleighty@earthlink.net
907-586-1426  206-719-5554 cell
COP 15 Failure

- No adequate global vision
- Cap-and-trade neither acceptable nor adequate
- UN process inadequate: such enormous problem

BP Gulf Tragedy

- Spending capital
- External costs
Humanity’s Goal

A global, sustainable, benign-source, equitable, energy economy
MUST Run the World on Renewables – plus Nuclear?

- Climate Change
- Demand growth
- Depletion of Oil and Gas
- Only 200 years of Coal left
- Only Source of Income:
  - Sunshine
  - Tides
  - Meteors and dust
- Spend our capital?
Comparing the world’s energy resources*

Where should we invest for the long-haul??

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.
Comparing the world’s energy resources*

Where should we invest for the long-haul??

SOLAR

World energy use

Annual

Capital

WIND

Natural Gas

Petroleum

Uranium

COAL

OTECH

BIO

HYDRO

*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.
# 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>
</tr>
</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>
<td>60</td>
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<td>Kansas</td>
<td>1,070</td>
<td>305,365</td>
<td>43</td>
<td>43</td>
<td>100</td>
<td>60</td>
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<tr>
<td>South Dakota</td>
<td>1,030</td>
<td>293,950</td>
<td>41</td>
<td>41</td>
<td>100</td>
<td>60</td>
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<td>Montana</td>
<td>1,020</td>
<td>291,096</td>
<td>41</td>
<td>41</td>
<td>90</td>
<td>54</td>
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<tr>
<td>Nebraska</td>
<td>868</td>
<td>247,717</td>
<td>35</td>
<td>35</td>
<td>80</td>
<td>48</td>
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<tr>
<td>Wyoming</td>
<td>747</td>
<td>213,185</td>
<td>30</td>
<td>30</td>
<td>70</td>
<td>42</td>
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<td>Oklahoma</td>
<td>725</td>
<td>206,906</td>
<td>29</td>
<td>29</td>
<td>60</td>
<td>36</td>
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<tr>
<td>Minnesota</td>
<td>657</td>
<td>187,500</td>
<td>26</td>
<td>26</td>
<td>60</td>
<td>36</td>
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<tr>
<td>Iowa</td>
<td>551</td>
<td>157,249</td>
<td>22</td>
<td>22</td>
<td>50</td>
<td>30</td>
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<tr>
<td>Colorado</td>
<td>481</td>
<td>137,272</td>
<td>19</td>
<td>19</td>
<td>40</td>
<td>24</td>
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<tr>
<td>New Mexico</td>
<td>435</td>
<td>124,144</td>
<td>17</td>
<td>17</td>
<td>40</td>
<td>24</td>
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<tr>
<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>
</tr>
</tbody>
</table>
Total solar: $\sim 3 \times 10^{14}$ kg / yr
Total wind: $\sim 3 \times 10^{11}$ kg / yr

Rich, stranded Resources
Total solar: $\sim 3 \times 10^{14}$ kg / yr

Total wind: $\sim 3 \times 10^{11}$ kg / yr

Synergy:
- Diurnal + Seasonal
- Minimize “firming” storage
## Jan ’09 Transmission Backlog

<table>
<thead>
<tr>
<th>Region</th>
<th>Power Generation (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>13 GW wind</td>
</tr>
<tr>
<td></td>
<td>30 GW solar</td>
</tr>
<tr>
<td>Upper Midwest</td>
<td>70 GW wind</td>
</tr>
<tr>
<td>Lower Midwest</td>
<td>40 GW wind</td>
</tr>
<tr>
<td>Great Lakes + Mid Atlantic</td>
<td>40 GW wind</td>
</tr>
<tr>
<td>Texas</td>
<td>50 GW wind</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>243 GW</strong></td>
</tr>
<tr>
<td>Potential Great Plains Wind</td>
<td>3,000 GW</td>
</tr>
</tbody>
</table>
“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
# Major Electricity Transmission Studies

<table>
<thead>
<tr>
<th>Study</th>
<th>Capacity (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EWITS-NREL</td>
<td>225 - 330</td>
</tr>
<tr>
<td>WWSIS-NREL</td>
<td>30</td>
</tr>
<tr>
<td>Brattle Group</td>
<td>24</td>
</tr>
<tr>
<td>SEIA-AWEA</td>
<td>300</td>
</tr>
<tr>
<td>JCSP</td>
<td>745</td>
</tr>
<tr>
<td>AEP-AWEA</td>
<td>350</td>
</tr>
<tr>
<td>Frontier + Transwest</td>
<td>115</td>
</tr>
<tr>
<td>ICFI Wyoming</td>
<td>12</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>~ 1,000</td>
</tr>
</tbody>
</table>

**Great Plains Potential:**
- Wind, nameplate: 3,000 GW
- Solar, nameplate: 3,000,000 GW

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

**@ 5 GW / 765 kv AC line:** ~ 700 new lines
SEIA – AWEA  Feb 09
“Green Power Superhighways: Building a Path to America’s Clean Energy Future”
Emerging Energy Research LLC
“Green Power Express” ITC Holdings

12,000 MW
3,000 miles
765 kv AC
$10 – 12 B
WWSIS: Wind + PV + CSP
**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

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>
</tr>
</thead>
<tbody>
<tr>
<td>230</td>
<td>$2.077 million</td>
<td>500</td>
<td>$5,460</td>
</tr>
<tr>
<td>345</td>
<td>$2.539 million</td>
<td>967</td>
<td>$2,850</td>
</tr>
<tr>
<td>500</td>
<td>$4.328 million</td>
<td>2040</td>
<td>$1,450</td>
</tr>
<tr>
<td>765</td>
<td>$6.578 million</td>
<td>5000</td>
<td>$1,320</td>
</tr>
</tbody>
</table>

(Sources: Edison Foundation\(^2\), AEP\(^3\))
Transmission Line Construction Cost
$ million per Mile
Southwest Power Pool ‘07
## Electricity Capital Cost per GW-mile

<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>
</tr>
<tr>
<td></td>
<td>345</td>
<td>1,000</td>
<td>2.6</td>
</tr>
<tr>
<td>AEP-AWEA</td>
<td>765</td>
<td>5,000</td>
<td>3.2</td>
</tr>
<tr>
<td>Consensus?</td>
<td></td>
<td></td>
<td>2.5</td>
</tr>
</tbody>
</table>
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
“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
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 $\leftrightarrow$ Alumina
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
Trouble with Renewables: Electricity Transmission

- Grid nearly full
  - New must pay for transmission
  - Costly: AC or DC
- Integration
  - Continental energy system
  - Quality
  - Generation O+M: fatigue, wear, low efficiency
- Low capacity factor (CF) or curtailment
- Costly “firming” storage: CAES, VRB
- Overhead vulnerable: God or man
- Underground: Only HVDC, 6x cost
- FERC no interstate jurisdiction
- Wide ROW
- NIMBY: site, ROW delay + cost
WWSIS: April week: ~30% RE
WWSIS: July week: ~10% RE
“There’s a better way to do it... Find it”
ABB, ISET Kassel “Huge Catchment Area”

Wind – Electricity only: almost “Firm”

Windpower 01
Vision: Remote renewable energy sources
connected to loads by DC grid
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
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

Normalized to 1.0 per season
Wind Seasonality, Northern Great Plains

1,000 MW windplant: \( AEP = 3,500 \text{ GWh / yr} \)

“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: 268 MW @$800 / kW = $214 M
    Storage @ $40 / kWh = $13 Billion
    Storage @ $1 / kWh = $325 Million

• VRB flow battery
  – O&M: 80% efficiency round-trip
  – Capital: $500 / kWh = $160 Billion
Continental Supergrid – EPRI concept “Energy Pipeline”

- Thermal Insulation
- Vacuum
- Electrical Insulation
- SC*: MgB_2 magnesium diboride superconductor
- LH2**: liquid hydrogen coolant, energy transmit

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

* SC: MgB_2 magnesium diboride superconductor
** LH2: liquid hydrogen coolant, energy transmit

Continental Supergrid – EPRI concept “Energy Pipeline”
Energy System of the Future

Potential Hydrogen Delivery System

H₂ Production/Use (Lg/Sm)

Frank Novachek, Director Corporate Planning
Hydrogen Utility Group (HUG)
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

1,000 miles Hydrogen Gas Pipeline
36" diameter ~ 1,000 psi

Storage: 120 GWh
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**

- Wind Generators
- High-press Electrolyzers

**Pipeline Energy Storage**

- Wind Generators

**Distribution**

- Generators CD, CT, FC
- End users Retail
- Cars, Buses, Trucks, Trains
- Liquefy
- Aircraft Fuel

500 miles
Hydrogen Gas Pipeline
20" diameter
1,500 -- 500 psi

City gate

AC grid Wholesale

1,500 psi

500 psi
Renewable-source Electricity Generation

Electrolyzer

\[ \text{H}_2 \text{O} \rightarrow \text{H}_2 + \text{O}_2 \]

To Compressors or Hydrogen Pipeline

Power Electronics

PE: Power Electronics

Topology Options: \( \text{H}_2 \) and \( \text{O}_2 \) Production and Gathering from Renewable Energy Generation
Compressorless 20”, 36” GH2 Pipeline Capacity

1,500 psi IN / 500 psi OUT

Pipeline Length, Miles

Capacity, GW

20" diameter

36" diameter

200 300 500 1,000

20" diameter 36" diameter
Gaseous Hydrogen (GH2)
36” diam, 500 miles
No compression
8,000 MW
## Capital Cost per GW-mile

### Electricity:

<table>
<thead>
<tr>
<th></th>
<th>KV</th>
<th>MW</th>
<th>$M / GW-mile</th>
</tr>
</thead>
<tbody>
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<td>Consensus?</td>
<td></td>
<td></td>
<td>2.5</td>
</tr>
</tbody>
</table>

### Hydrogen pipeline:

36”, 100 bar, 500 mi, no compress 0.3

(100 bar = 1,500 psi)
Hydrogen Energy Storage

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

Pipeline Storage = 120 GWh

Wind Generators

Electrolyzers

Wind Generators

Storage

Generators
ICE, CT, FC

AC grid Wholesale

End users Retail

Cars, Buses, Trucks, Trains

Liquefy

Aircraft Fuel

Storage

Geologic Storage?
- 860,000 m³ physical
- 150 bar = 2,250 psi
- 2,500 Mt net = 92,500 MWh
- $15 M avg cap cost / cavern
- $160 / MWh = $0.16 / kWh
- Cavern top ~ 700 m 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>Description</th>
<th>Cost (million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windplant size</td>
<td>1,000 MW</td>
</tr>
<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>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>$2,660</td>
</tr>
</tbody>
</table>

Cavern storage: ~3% of total capital cost
Hydrogen “sector” of a benign, sustainable, equitable, global energy economy
The NATURALHY approach: EC, R+D

NATURALHY:
• Breaks “chicken-egg” dilemma
• Bridge to sustainable future
Hydrogen-fueled 2005 Prius ICE Hybrid

www.qtww.com
Carmakers Commit to Hydrogen Fuel Cell Cars?

- **9 Sept 09** “Letter of Understanding”
- Carmakers:
  - Daimler
  - GM/Opel
  - Hyundai/Kia
  - Nissan
  - Ford
  - Honda
  - Renault
  - 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 ...”
Carmakers’ letter Oct 09: FCV’s production 2015, Need H$_2$ fuel!
Greenhouse Gas Pollution (Light duty vehicles only)
(Billion/ tonnes CO2-equivalent/year)

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
"Never be built ..."
Wind Potential $\approx 3,000$ GW
12 Great Plains states
Wind Potential $\approx 3,000$ GW

12 Great Plains states
Wind Potential \( \approx 3,000 \text{ GW} \)

12 Great Plains states
“There’s a better way to do it... Find it”
Pilot plant needed

- Every major new industrial process
- Renewables-source systems
- Diverse, large-scale, stranded
- US, Japan, Canada, IPHE → " IRHTDF "

International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF) Pilot plant

Global opportunity: IPHE project
Pilot-scale Hydrogen Pipeline System: Renewables

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

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

GH2 geologic storage

O2 pipeline
OPTIMISTIC

City-gate GH2 cost @ 15% CRF, 20” pipeline, from 2,000 MW Great Plains windplant

2005 $US / kg GH2

B1: Unsubsidized
B2: US fed PTC only
B3: PTC + Oxygen sales
B4: PTC + O2 sale + C-credit

Competitive cost?
Anhydrous Ammonia $\text{NH}_3$

N Nitrogen
H Hydrogen

Molecular weight = ~ 17

18% 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
Streetcar
New Orleans

“Ammoniacal Gas Engine”

1871
Ammonia fueled – Norway

Ammonia fuel tank

1933
Ammonia Fueled Bus: Thousands of Problem-free Miles

Belgium

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

Summer ’07 Detroit → San Francisco

University of Michigan
1,000 hours, ICE, 6 cyl, 100 hp
75% ammonia, 25% propane

Irrigation pump
Central Valley, CA

2008
Oct '09  Ammonia Fueled V-8 with Hydrogen Injection: Reformed from NH₃
Hydrogen Engine Center, Algona, IA
Ammonia Fuel Uses

1. Internal Combustion Engine (ICE)
   - Diesel: \( \text{NH}_3 \) gas mixed with intake air
   - Spark-ignition: 70%+ \( \text{NH}_3 \) plus gasoline, ethanol, propane, NG, hydrogen
   - NOx \( \sim \frac{1}{4} \) 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**

**C-free**
Ammonia Properties

- C-free fuel: unique physical, chemical properties
- Carbon-free energy cycle, system
- Liquid at >125 psi at room temperature
- ~ Half energy density gasoline or diesel, volume or weight
- Low flammability, flame spread
- Easily “cracked” to \( \text{H}_2 + \text{N}_2 \) at end-use
- # 2 global industrial chemical trade
- Now 95% from stranded natural gas
  - ~ $1.00 / MMbtu
  - Trinidad, Australia, Quatar, Algeria, Russia
  - 5% from coal gasification \( \rightarrow \) hydrogen + Haber-Bosch
Ammonia Properties

- Fertilizer forms:
  - “Anhydrous” NH₃ (only useful fuel)
  - Urea: (2) NH₃ + CO₂
  - Ammonium nitrate: NH₄NO₃
  - UAN: aqueous urea + ammonium nitrate
- Decades infrastructure + safety record
  - ~14 MMt / year in USA, mostly fertilizer
  - Inhalation hazard; detected @ 5 ppm
  - OSHA, NIOSH regs + exposure limits
  - Toxic to aquatic life
MONTHS: GH2, 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
95% Global Ammonia Synthesis Plant Natural Gas 1 – 3,000 tpd Haber-Bosch process
Haber-Bosch Process
1909 – 1913  BASF

- NH₃ synthesis
- Coal gasification → H₂
- WWI explosives
- 40% humanity: N fertilizer

Haber-Bosch Reactor
1921
Ludwigshafen, Germany
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
Ammonia Tanker
Burrup Peninsula
Western Australia
Ammonia or LPG Tanker
To 35,000 Mt
Refrigerated
Valero LP Operations

Liquid ammonia pipeline

NOLA
## 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>
</tr>
<tr>
<td></td>
<td>345</td>
<td>1,000</td>
<td>2.6</td>
</tr>
<tr>
<td>AEP-AWEA</td>
<td>765</td>
<td>5,000</td>
<td>3.2</td>
</tr>
<tr>
<td>Consensus?</td>
<td></td>
<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
Ammonia Storage Terminal
Mississippi River
Winona, MN
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
Global Ammonia = 140 million Mt / year

- #2 chemical
- 200 plants, nat gas + coal
- ~ 500 Million Bbl oil
- ~ 2% oil
- ~ 0.5% energy

14 million Mt / yr USA; 60% imported; corn ethanol
Cost: Ammonia from Stranded Natural Gas (NG)

- Burrup, Australia Plant: 750,000 Mt / year
- $650M capital @ 15% capital recovery factor (CRF)
- 34 MMBtu NG / Mt NH₃
- NG cost $1.20 / MMBtu long-term
- Tanker shipping to New Orleans, LA (NOLA) $50 / Mt
- CO₂ emission 1.8 Mt / Mt NH₃

<table>
<thead>
<tr>
<th></th>
<th>C-tax</th>
<th>C-tax</th>
<th>C-tax</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>$50 / Mt CO₂</td>
<td>$100 / Mt CO₂</td>
</tr>
<tr>
<td>Capital</td>
<td>98</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>NG</td>
<td>41</td>
<td>41</td>
<td>41</td>
</tr>
<tr>
<td>Shipping</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>C-tax</td>
<td>0</td>
<td>90</td>
<td>180</td>
</tr>
<tr>
<td>Plant O&amp;M</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Total NOLA / Mt</td>
<td>$191</td>
<td>$281</td>
<td>$371</td>
</tr>
</tbody>
</table>
Anhydrous Ammonia (NH3) wholesale price, NOLA (New Orleans, LA)
Fertilizer Prices in Illinois ($ per ton)

Wholesale at Terminal

- Anhydrous Ammonia NH₃
- Diammonium Phosphate

- New Orleans Landed: $425
- Corn Belt Wholesale: $447
- Corn Belt Farmer: $560

May 10

$447

Source: Agricultural Marketing Services, U.S.D.A.
Wind – to – Ammonia Potential, NW Iowa
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
**RE Ammonia Transmission + Storage Scenario**

**Solid State Ammonia Synthesis (SSAS)**

- **Wind Generators**
- **Electrolyzers**
- **Haber-Bosch Ammonia Synthesis**
  - **Air Separation Plant**
  - **N₂**
  - **H₂O**
  - **H₂**
- **Liquid Ammonia Transmission Pipeline**
- **Liquid Ammonia Tank Storage**
- **Generators ICE, CT, FC**
- **Cars, Buses, Trucks, Trains**
- **Aircraft Fuel**
- **End users Retail**
- **AC grid Wholesale**
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
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
“Green” Ammonia (NH₃) Output
> 2,000 MW Adak Wind-to-ammonia Plant
> $5 B total capital @ $2,500 / kW
> 45% Capacity Factor (CF)

Windplant Annual Energy Production: 7,884,000 MWh / year

Convert to NH₃ by:

Electrolysis + H-B  @ 12 MWh / Mt
SSAS  @ 7.5 MWh / Mt

Mt (tons) / year  657,000  1,050,000

Sales @ $300 / Mt (plant gate)  $197 M  $315 M

Simple ROI  4%  6%
### “Green” Ammonia (NH3) Output

- **2,000 MW Adak Wind-to-ammonia plant**
- **$5 B total capital @ $2,500 / kW**
- **45% Capacity Factor (CF)**
- **15% Capital Recovery Factor (CRF)**

Windplant Annual Energy Production: 7,884,000 MWh / year

<table>
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<tr>
<th>Electrolysis</th>
<th>+ H-B</th>
<th>SSAS</th>
</tr>
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<tbody>
<tr>
<td>Sales: Mt (tons) / year</td>
<td>657,000</td>
<td>1,050,000</td>
</tr>
<tr>
<td>Total Cost of Sales:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital @ 15% CRF</td>
<td>$750M</td>
<td>$750M</td>
</tr>
<tr>
<td>Plant O&amp;M @ $0.03 / kWh</td>
<td>24M</td>
<td>24M</td>
</tr>
<tr>
<td>Input energy</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$774M</td>
<td>$774M</td>
</tr>
<tr>
<td>Cost / Mt NH3 (plant gate)</td>
<td><strong>$1,178</strong></td>
<td><strong>$ 737</strong></td>
</tr>
<tr>
<td>Shipping @ $50 / Mt</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Total NOLA / Mt</td>
<td><strong>$1,228</strong></td>
<td><strong>$ 787</strong></td>
</tr>
</tbody>
</table>
“Green” Ammonia (NH3) Output
- 2,000 MW Adak Wind- to- ammonia plant
- $5 B total capital @ $2,500 / kW
- 45% Capacity Factor (CF)
- 12% Capital Recovery Factor (CRF)

Windplant Annual Energy Production: 7,884,000 MWh / year

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<td>SSAS</td>
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</tr>
<tr>
<td>Total Cost of Sales:</td>
<td></td>
</tr>
<tr>
<td>Capital @ 12% CRF</td>
<td>$600M</td>
</tr>
<tr>
<td>Plant O&amp;M @ $0.03 / kWh</td>
<td>24M</td>
</tr>
<tr>
<td>Input energy</td>
<td>0</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$624M</td>
</tr>
</tbody>
</table>

Cost / Mt NH3
- $ 949 | $ 594
Shipping @ $50 / Mt
- 50 | 50
Total NOLA / Mt
- $ 999 | $ 644
Anhydrous Ammonia (NH3) wholesale price, NOLA (New Orleans, LA)
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
“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” → GH2, NH3, other
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??

SOLAR

Annual

Capital

Natural Gas

Petroleum

Uranium

COAL

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. World energy use is annual.
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

- Nascent markets: transport fuel, other

- Integration
  - Continental energy system
  - Elec grid quality
  - Elec grid generation O+M: fatigue, wear, efficiency
Alternatives to Electricity for Transmission and Annual-scale Firming Storage for Diverse Renewable Energy Resources: Hydrogen and Ammonia Fuels

DVD’s available

ASME Power
14 July 10, Chicago

Bill Leighty, Director
The Leighty Foundation
Juneau, AK
wleighty@earthlink.net
907-586-1426  206-719-5554 cell
END presentation

Following slides are supplemental
Jon Wellinghof  
FERC* Chairman

About new coal + nuclear plants:

“ We may not need any, ever ”

NY Times, 22 Apr 09

* FERC = Federal Energy Regulatory Commission
Hydrogen Fuel Cell
Proton Exchange Membrane (PEM) type

Hydrogen (H2) combines with Oxygen (O2) to make electricity + heat + water (H2O)
MUST Run the World on Renewables – plus Nuclear?

- Emergencies:
  - Climate change
  - Energy prices
  - Energy security
- Quickly invest:
  - Conserv + efficiency
  - GW-scale renewables
  - Beyond electricity grid
  - Hydrogen, ammonia, ?
WE’RE HERE: 385.92 ppm

WE NEED TO GET BELOW: 350 ppm

CO₂ in the Atmosphere

www.350.org
MUST Run the World on Renewables – plus Nuclear?

- Global
- Indigenous
- Firm: available
- C-free
- Benign
- Abundant
- Affordable
- Equitable
- Perpetual:
  - Solar
  - Geothermal
  - Tidal
Solid State Ammonia Synthesis (SSAS)

- **Goals:**
  - Renewables-source ammonia (NH₃)
  - Compete with natural gas source NH₃
- **High energy conversion efficiency**
  - ~50% better than electrolysis → hydrogen + H-B
  - No hydrogen production
- **Electricity + water + nitrogen → ammonia**
- ~ 50% lower capital cost
- **SSAS reactor: SOFC * in reverse**

* SOFC: Solid oxide Fuel Cell
Liquid Anhydrous Ammonia (NH₃) -33 C, 1 atmosphere
Electricity Capital Cost per GW-mile

- ICF International “Wyoming Collector and Transmission System Conceptual Design”
-