RUNNING THE WORLD ON RENEWABLES VIA HYDROGEN TRANSMISSION PIPELINES WITH FIRMING GEOLOGIC STORAGE

Fuel Cell 2008
Long Beach, CA
Bill Leighty, The Leighty Foundation
wleighty@earthlink.net
Run the World on Renewables

- EREC: 20% by 2025
- 25 x ’25
- Only 200 years of coal; less O+G
- Emergencies?
  - Climate change
  - Energy cost
  - Energy security
Run the World on Renewables

• Richest renewables stranded
  – High intensity
  – Large geographic extent – dispersed
  – Far from markets
  – No transmission

• Time-varying output – except
  – Except geothermal, currents
  – Seconds to seasons

• ABB, ISET “huge catchment area”
Vision: Remote renewable energy sources
connected to loads by DC grid
Composite Wind Resource Map

The remaining states use data from the 1987 "Wind Energy Atlas of the United States".

Wind Power Classification

<table>
<thead>
<tr>
<th>Wind Power Class</th>
<th>Resource Potential</th>
<th>Wind Power Density at 50 m W/m²</th>
<th>Wind Speed at 50 m m/s</th>
<th>Wind Speed at 50 m mph</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Marginal</td>
<td>200 - 300</td>
<td>5.6 - 6.4</td>
<td>12.5 - 14.3</td>
<td></td>
</tr>
<tr>
<td>3 Fair</td>
<td>300 - 400</td>
<td>6.4 - 7.0</td>
<td>14.3 - 15.7</td>
<td></td>
</tr>
<tr>
<td>4 Good</td>
<td>400 - 500</td>
<td>7.0 - 7.5</td>
<td>15.7 - 16.8</td>
<td></td>
</tr>
<tr>
<td>5 Excellent</td>
<td>500 - 600</td>
<td>7.5 - 8.0</td>
<td>16.8 - 17.9</td>
<td></td>
</tr>
<tr>
<td>6 Outstanding</td>
<td>600 - 800</td>
<td>8.0 - 8.8</td>
<td>17.9 - 19.7</td>
<td></td>
</tr>
<tr>
<td>7 Superb</td>
<td>800 - 1600</td>
<td>8.8 - 11.1</td>
<td>19.7 - 24.8</td>
<td></td>
</tr>
</tbody>
</table>

*Wind speeds are based on a Weibull k value of 2.0

Source: POWERmap, powermap.platts.com, ©2007 Platts, a division of the McGraw-Hill Companies

U.S. Department of Energy
National Renewable Energy Laboratory

19-APR-2007 1.5.0
Proposed Transmission Projects in the West

- John Day-McNary
- MT-AB intertie
- Northern Lights
- Northwestern AMPS
- Seabreeze
- Frontier Line
- TransBay
- Robinson Summit-Harry Allen
- TransWest Express
- Tehachapi
- Green Path
- Navajo Transmission Project
- Palo Verde-Devers II
- WAPA/TransElect/WIA
- Miracle Mile-Ault
- Colorado-New Mexico Interconnection Project
- Sunrise Powerlink
- Tucson-Nogales
Run the World on Renewables

- Distributed + centralized
- Transmission + storage
- Need “Firm” unless MO and lifestyle changes
- Firm: deliver contracted energy every hour of every year
Run the World on Renewables

• Can’t do it with electricity alone
  – NIMBY delays, costs
  – Vulnerable: acts of God or man
  – High capital costs:
    ▪ Gathering
    ▪ Access -- substations
  – Low CF
  – O&M cost, losses
  – No affordable annual-scale storage

• Bigger markets than grid?
  ▪ Transportation fuel
  ▪ DG fuel, CHP
Of 10,000 CA total

Whence the hydrogen?
CA Annual Hydrogen Fuel Demand

- 20% of 45M vehicles H2 fueled -- by 2030?
- 9M vehicles @ 78 mpg = 78 miles / kg H2
- 12,000 miles / year → 150 kg H2 / year
- 1,350 M kg H2 / year = 1.35 M tons H2 fuel
- @ 50 kWh / kg at windplant gate:
  - 90 x 10^9 kWh / year = 67,500 GWh / year
  - @ 40% CF → 19 GW nameplate wind
  - 3 GH2 pipelines, 36”, 500 miles long
  - @ 4 caverns / GW = 80 storage caverns: firm
- OR: 6 electric lines, biggest: not firm
- How fuel the other 80%?
Hydrogen - fueled
2005 Prius
ICE Hybrid

www.qtww.com
Renewables Focus

- Centralized production
  - Electricity
  - Direct hydrogen (bio, photochem)
- GW (Gigawatt = 1,000 MW) scale
  - Economy of scale
  - Run the world
- Gaseous hydrogen (GH2)
- Anhydrous ammonia (NH₃)
  ✓ Better than hydrogen?
  ✓ Need hydrogen
Hypothesis:

Hydrogen’s greatest value to humanity:
- Not fuel for fuel cell cars
- Means to gather, transmit, firm, deliver, use
- Diverse, large-scale, stranded renewables
Solar Hydrogen Energy System

Sunlight from local star

Solar panel

Electrolyzer
H\textsubscript{2}O\rightarrow H\textsubscript{2} + O\textsubscript{2}

Electrolyzer

Fuel Cell

H\textsubscript{2} + O\textsubscript{2} \rightarrow 2H\textsubscript{2}O + Energy

Work

Electricity

Electricity
Hydrogen Transmission Scenario

- **Low-pressure electrolyzers**
- “Pack” pipeline: ~ 1-2 days’ storage = 120 GWh

![Diagram](image)
Compressorless system: No firming storage

Transmission

Wind Generators

High-press Electrolyzers

City gate

Pipeline Energy Storage

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

1,500 psi

500 psi

Distribution

Generators ICE, CT, FC

End users Retail

AC grid Wholesale

Cars, Buses, Trucks, Trains

Liquefy

Aircraft Fuel

1,500 psi
1,500 psi output
Electrolyzers

Generators
ICE, CT, FC

Wind Generators

1,000 miles Hydrogen Gas Pipeline, 36" diameter, 1,500 psi input, 500 psi output
Pipeline Storage = 240 GWh

AC grid Wholesale

End users Retail

Cars, Buses, Trucks, Trains

Liquefy

Aircraft Fuel

Compressorless Renewables - Hydrogen System with Annual Firming storage

Geologic Storage
Solar Hydrogen Energy System

- Sunlight from local star
- Electricity
- Electrolyzer
- O₂
- H₂
- Fuel Cell
- Electricity
- Work

Reaction:

2H₂O → Energy → 2H₂ + O₂

2H₂ + O₂ → 2H₂O + Energy
Storage: Hour – Week Scale

• Distributed
  – Buildings to blocks
    • Thermal: space heat + cool, DHW
    • Chemical – Hydrogen, ammonia
    • Reversible fuel cells – Hydrogen, ammonia
    • Battery, flywheel, VRB-ESS *
  – Vehicles
    • BEV (battery electric)
    • Hydrogen-fueled FCEV, HICE

• Centralized
  – VRB-ESS *
  – Compressed Air (CAES)
  – Concentrated Solar Power CSP thermal

* Vanadium Redox Battery Energy Storage System
Storage: Annual-scale “Firm”

- Every hour of every year: contracted amount
- Adds great value: strategic, market price
  - “Run world on renewables”
  - Without MO, lifestyle changes
    - Manufacture when sun shines
    - Vacation on winter wind
- Except:
  - Geothermal
  - Biomass stockpiled
  - OTEC
  - Ocean current
- Requires large storage
  - GW scale
  - Hydrogen: pipelines + caverns
  - Ammonia: pipelines + tanks
### Exporting From 12 Windiest Great Plains States

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

* at 500 miles average length

Wind energy source: PNL-7789, 1991

<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>
</tr>
<tr>
<td>Texas</td>
<td>1,190</td>
<td>339,612</td>
<td>48</td>
<td>48</td>
<td>100</td>
<td>60</td>
</tr>
<tr>
<td>Kansas</td>
<td>1,070</td>
<td>305,365</td>
<td>43</td>
<td>43</td>
<td>100</td>
<td>60</td>
</tr>
<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>
</tr>
<tr>
<td>Montana</td>
<td>1,020</td>
<td>291,096</td>
<td>41</td>
<td>41</td>
<td>90</td>
<td>54</td>
</tr>
<tr>
<td>Nebraska</td>
<td>868</td>
<td>247,717</td>
<td>35</td>
<td>35</td>
<td>80</td>
<td>48</td>
</tr>
<tr>
<td>Wyoming</td>
<td>747</td>
<td>213,185</td>
<td>30</td>
<td>30</td>
<td>70</td>
<td>42</td>
</tr>
<tr>
<td>Oklahoma</td>
<td>725</td>
<td>206,906</td>
<td>29</td>
<td>29</td>
<td>60</td>
<td>36</td>
</tr>
<tr>
<td>Minnesota</td>
<td>657</td>
<td>187,500</td>
<td>26</td>
<td>26</td>
<td>60</td>
<td>36</td>
</tr>
<tr>
<td>Iowa</td>
<td>551</td>
<td>157,249</td>
<td>22</td>
<td>22</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>Colorado</td>
<td>481</td>
<td>137,272</td>
<td>19</td>
<td>19</td>
<td>40</td>
<td>24</td>
</tr>
<tr>
<td>New Mexico</td>
<td>435</td>
<td>124,144</td>
<td>17</td>
<td>17</td>
<td>40</td>
<td>24</td>
</tr>
<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: $\sim 3 \times 10^{14} \text{ kg / yr}$

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

Rich, stranded Resources
North Dakota wind needs 115 new lines at 3,000 MW each

Twelve Plains states wind needs 890 new lines at 3,000 MW each

SIEMENS HVDC line +/- 500 kv
The NATURALHY approach

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

Prepared by
O. Florisson
Gasunie
Compressorless 20”, 36” GH2 Pipeline Capacity

1,500 psi IN / 500 psi OUT

Diagram showing the pipeline capacity in GW for different pipeline lengths and diameters.
Compressorless 20”, 36” GH2 Pipeline Capacity

1,500 psi IN / 450 psi OUT
Compressorless 20”, 36” GH2 Pipeline Capacity
1,500 psi IN / 450 psi OUT
Wind seasonality, Great Plains

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

Source: D. Elliott, et al, NREL
The Great Plains Wind Resource
Wind Seasonality, Northern Great Plains
Normalized to 1.0 per season

Seasonality Factor

Winter
Spring
Summer
Fall
Annual – scale “Firming”
Great Plains Wind

• Potential, 12 states, ~50% land area:
  – 10,000 TWh = 100 quads = entire USA energy
  – 2,800,000 MW nameplate

• Seasonality:
  – Summer minimum
  – Spring – Summer maximum storage
  – “Firming” energy storage, per 1,000 MW wind:
    • as electricity = 300 GWh
    • as GH2 = 15,000 Mt @ 2,500 tons / cavern = 6 caverns
  – “Firming” energy storage, all great Plains wind:
    • as GH2 = 17,000 caverns @ $15M each = $264 billion
Great Plains Windplant, Pipeline
Hourly Output for Typical Week

Hourly Hydrogen Pipeline Input and Output

- **Input**
- **Output**
Texas hydrogen caverns
- Chevron-Phillips, 1986
- Praxair, 2007

Domal Salt Storage Caverns
$5-15M each
Wellhead, new Gaseous Hydrogen Storage Cavern

- PRAXAIR
- Commissioned 2007
- In domal salt, in Texas

Instantaneous hydrogen supply with cavern storage
Solution-mined Salt Caverns assume

• “Clemens Terminal”
  – 6.4 M ft$^3$ = 580,000 m$^3$ gross
  – 2,200 psi MAOP $\rightarrow$ 1,000 psi min
  – 2,300 ft to cavern top
• Arrays of 10 – 100 caverns
• Same pressure: manifold
• Low input / output flowrate
• Minimum BOS
• Favorable conditions:
  – geography
  – geology
  – water supply
  – brine disposal
**Optimistic: Total Installed Capital Cost**

1,000 mile Pipeline

“Firming” GH2 cavern storage

Windplant nameplate

Wind generators

Electrolyzers

Pipeline, 20”

# storage caverns

Caverns @ $10M ea

Cushion gas @ $5M ea

TOTAL

Cavern storage: ~ 3% of total capital cost

- Windplant nameplate: 2,000 MW
- Wind generators: $2,000 million
- Electrolyzers: 1,000
- Pipeline, 20”: 1,100
- # storage caverns: [8]
- Caverns @ $10M ea: 80
- Cushion gas @ $5M ea: 40
- TOTAL: $4,220
Pessimistic: Total Installed Capital Cost

1,000 mile Pipeline
“Firming” GH2 cavern storage

Windplant nameplate 2,000 MW

Wind generators $2,000 million
Electrolyzers 1,000
Pipeline, 20” 1,100
# storage caverns [8]
Caverns @ $50M ea 400
Cushion gas @ $5M ea 60
TOTAL $4,560

Cavern storage: ~10% of total capital cost
Optimistic: “Firming” Storage Capital Cost for ALL Great Plains Wind

Adds VALUE: strategic, market

- Salt caverns: ~ 17,000
  - Excavate: $10 M each $ 170 B
  - Cushion gas: $5 M each $ 85 B
  Total $ 255 B

- Ammonia (NH₃) tanks: ~ 5,000
  - Capital $25 M each $125 B
Pessimistic: “Firming” Storage Capital Cost for ALL Great Plains Wind

Adds VALUE: strategic, market

- Salt caverns: ~ 17,000
  - Excavate: $50 M each $ 850 B
  - Cushion gas: $5 M each $ 85 B
  Total $ 935 B

- NH3 tanks: ~ 5,000
  - Capital $25 M each $125 B
Other

- EPRI “Energy Pipeline”
- Aluminum – gallium
- Fischer – Tropsch Liquids (FTL’s)
- Hythane ™
- Nuclear nexus
Continental Supergrid – EPRI concept “Energy Pipeline”

* SC: MgB\textsubscript{2} magnesium diboride superconductor
** LH2: liquid hydrogen coolant, energy transmit
Hypothesis:

• Hydrogen’s greatest value to humanity:
  – Not fuel for fuel cell cars
  – Means to gather, transmit, firm, deliver, use
  – Diverse, large-scale, stranded renewables

• Test: build pilot plants
  – Induce upstream R+D
  – Discover tech + econ feasibility
  – Assure public, business
  – Ready solutions: emergencies
International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF)
Pilot plant

Global opportunity: IPHE project
Hydrogen Embrittlement of Pipeline Steel
Scientists at HDI have invented new methods of tube design and component/facility construction that greatly reduce: (i) the diffusive flux of hydrogen through the walls of hollow cylinders, and (ii) the escape of hydrogen from hydrogen pipelines where connections are made.

The techniques involve use of one or more layers of homogeneous or laminated polymeric material and a thin metal interlayer to create multiple equilibrium and kinetic barriers to hydrogen diffusion.
HDI Polymer/Metal Pipe Technology: Longitudinal Cross-Section
Hydrogen Discoveries, Inc. (HDI)
Seeing is believing!

A close-up photograph of a 3” long, 4” I.D. pipe specimen consisting of two layers of HDPE with a thin aluminum interlayer.
Anhydrous Ammonia (NH₃) for Transmission and Storage of Renewable Energy: Fertilizer and Fuel

Jason C. Ganley

Howard University
Department of Chemical Engineering
Washington, DC
(202) 806-4796
jganley@howard.edu
Facts About Ammonia (NH$_3$)

- One of the most widely used chemicals worldwide
  - > 100 million tons/year
  - 80% used as fertilizer
  - Refrigeration and cleaning
  - Purification of water supplies
  - Manufacture of plastics, dyes...

- Easily stored as a liquid
  - Compressed (~10 atm at 25°C)
  - Refrigerated (-33°C at 1 atm)

- Strong odor, easy to detect leaks
Ammonia as a Fuel

\[ 2 \text{NH}_3 \rightarrow 3 \text{H}_2 + \text{N}_2 \ \Delta H^\circ = 46 \text{ kJ / mol} \]

- Very mild enthalpy of reforming, if \( \text{H}_2 \) is required
- \( \text{NH}_3 \) is typically stored and transported as a liquid
  - Power density is comparable to other liquid fuels
  - Vaporizes when throttled (no flash line required)
- Classified as non-flammable, non-explosive
- Suitable fuel for internal combustion engine
  - Spark ignition
  - High-compression diesel
- Suitable fuel for fuel cells
  - Cracked ammonia for PEMFC, AFC, PAFC
  - Direct ammonia for SOFC, PCFC, MCFC, MSAFC
Ammonia Manufacturing:

The Haber-Bosch Process

\[ 3 \text{CH}_4 + 6 \text{H}_2\text{O} + 4 \text{N}_2 \rightarrow 3 \text{CO}_2 + 8 \text{NH}_3 \]
A Renewable Alternative: Electrolysis + Haber-Bosch

$$3\ H_2O \rightarrow 3\ H_2 + 3/2\ O_2$$
$$3\ H_2 + N_2 \rightarrow 2\ NH_3$$
Alternative to Haber-Bosch: Solid State Ammonia Synthesis

\[ 6 \text{H}_2\text{O} + 2 \text{N}_2 \rightarrow 3 \text{O}_2 + 4 \text{NH}_3 \]
NH₃ Transport: Pipelines

- Pipelines provide much of the NH₃ used in the Midwest
  - Local production: 47%
  - Pipeline: 33%
  - River barge: 14%
  - Rail shipment: 6%
- Service is unique
  - Many local markets
  - High seasonal demand
- Pipeline construction: mild carbon steel
Wind-to-Ammonia Concept

Only requirements for renewable NH₃: Air, Water, Electricity.
A Vision for Renewable Ammonia

**Electrolyzers**

- Wind Generators
- H₂
- H₂0

**Air Separation Plant**

- Air
- N₂

**Haber-Bosch Ammonia Synthesis**

- Electricity

**Liquid Ammonia Transmission Pipeline**

- Liquid Ammonia Tank Storage

**Pressurized or refrigerated tank ammonia storage to firm supply**

**End users Retail**

- Cars, Buses, Trucks, Trains

**Aircraft Fuel**

**Generators ICE, CT, FC**

**AC grid Wholesale**
Sec. 9019 “Renewable Nitrogen Fertilizer”

• Research initiative

• “… identify key tech and econ barriers to producing commercial-scale quantities of nitrogen fertilizer from renewable energy sources.”
Summary

- “Transmission” must include alternatives to electricity
  - Gaseous hydrogen, GH2
  - Liquid anhydrous ammonia, NH₃
  - Others
- “Run the World on Renewables” requires:
  - Annual-scale firming storage
  - Synergy among renewables
- Think energy systems
Transmission + Storage = System

- System optimize
- Long-term COE
- GW scale
- Diversity $\rightarrow$ Synergy $\rightarrow$ Minimum storage $\rightarrow$ Firm $\rightarrow$
  Add value $\rightarrow$ COE
RUNNING THE WORLD ON RENEWABLES VIA HYDROGEN TRANSMISSION PIPELINES WITH FIRMING GEOLOGIC STORAGE

Fuel Cell 2008
22 May 08
Long Beach, CA
Bill Leighty, The Leighty Foundation
wleighty@earthlink.net