Running the World on Renewables via Gaseous Hydrogen Pipeline Transmission and Firming Geologic Storage

Electricity Storage Association
Anaheim, CA
21 May 08

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The Leighty Foundation
Juneau, AK
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907-586-1426    206-719-5554 cell
MUST Run the World on Renewables – plus Nuclear?
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:
  - Photons and Particles from Sun
  - Meteors and dust
MUST Run the World on Renewables – plus Nuclear?

- Beyond Electricity Grid
- Energy: beyond electricity
- “Hydricity”
- GW scale
- Emergencies:
  - Climate change
  - Energy prices
  - Energy security
The Trouble with Renewables

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

• Time-varying output
  – Except geothermal, currents
  – Seconds to seasons
  – ABB, ISET Kassel “huge catchment area”
  – Synergy reduces storage: wind + solar
The Great Plains Wind Resource
• Great Plains Wind: Huge, Stranded

• Total USA energy: 100 quads = 10,000 TWh

• Big Market: Hydrogen Fuel, not Grid Electricity

• Accelerate Conversion from Fossil Fuel
Total solar: $\sim 3 \times 10^{14}$ kg / yr
Total wind: $\sim 3 \times 10^{11}$ kg / yr

Rich, stranded Resources
# 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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<tbody>
<tr>
<td>North Dakota</td>
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<td><strong>TOTALS</strong></td>
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<td><strong>$ 401</strong></td>
<td><strong>890</strong></td>
<td><strong>$ 534</strong></td>
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</table>
Wind seasonality, Great Plains

Source: NREL, D. Elliott, et al

- Winter = 1.20
- Spring = 1.17
- Summer = 0.69
- Autumn = 0.93
Wind Seasonality, Northern Great Plains
Normalized to 1.0 per season
450 GWh per 1,000 MW wind

Source: NREL, D. Elliott
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 = 450 GWh
    • as GH2 = 15,712 tons, metric @ 2,500 tons / cavern = 6 caverns
  – “Firming” energy storage, all great Plains wind:
    • as GH2 = 17,000 caverns @ $15M each = $264 billion
“There’s a better way to do it... Find it”
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?
The NATURALHY approach

NATURALHY:

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

Prepared by
O. Florisson
Gasunie
Hydrogen and electricity become the primary currencies in the future energy economy

Utility electrolysis vision

- MW-scale utility electrolyzers
- Affordable capital investment:
  - Total system cost considerations
- Off-peak, wholesale electricity: Operated by utility
- Distributed, substation level operation
- Tightly integrated with electrical grid

Dan Smith
GE Global Research, 2004
Continental Supergrid – EPRI concept “Energy Pipeline”

- Thermal Insulation
- Vacuum
- Electrical Insulation
- SC* (MgB₂ magnesium diboride superconductor)
- LH2** (liquid hydrogen coolant, energy transmit)

* SC: MgB₂ magnesium diboride superconductor
** LH2: liquid hydrogen coolant, energy transmit
Hydrogen - fueled
2005 Prius
ICE Hybrid

www.qtww.com
“Hydricity”

- Nexus of electricity + hydrogen: twin currencies
- $\text{GH}_2$, $\text{NH}_3$ for annual-scale “firming” storage
- Long-term:
  - Clear: energy currencies
  - Fuzzy: sources
- Climate Change: drive *transition* faster than:
  - Wood-to-coal
  - Coal-to-oil
  - Oil-to-natural gas
  - Coal-to-nuclear
  - Fossil-to-electricity
Hydrogen “sector” of a benign, sustainable, equitable, global energy economy
1: Adequate Renewables

- Run the world; humanity’s needs
- “Distributed” and “Centralized”
- Affordable, benign
- Diverse, synergistic
- Richest are “stranded”
  - Far from markets
  - No transmission
2: When we realize these as emergencies:

- Global Warming, Rapid Climate Change
- Energy Security and Cost
- Peak Oil and Natural Gas

We must quickly invest in:

- Energy conservation, efficiency
- Large, new energy supplies:
  - CO₂ – emissions - free
  - Indigenous
  - Both distributed, centralized
3: Shortest path to benign, secure, abundant energy

- Renewables
  - Diverse
  - Diffuse
  - Dispersed
- Centralized:
  - large, rich; lower cost than distributed?
  - but stranded (no transmission)
- Gaseous hydrogen (GH2) pipelines
  - Conversion, gathering
  - Transmission
  - Storage
  - Distribution
- Geologic storage “firms”
- Pilot plant needed:
  - every major new industrial process
  - IRHTDF
4: Hydrogen’s principal value

• NOT fuel cell cars
• Gather, transmit, store:
  – Large-scale, diverse, stranded renewables
  – FIRM time-varying-output renewables
    • Pipeline transmission, storage
    • Geologic storage
    • “Renewables – nuclear Synergy …”, C. Forsberg
• Benign, if from renewables
• Global opportunity
• Hydrogen “sector”, not “economy”
  – Transportation fuel: ground, air
  – DG electricity, CHP, retail value
5: *Pilot plant needed*

- Every major new industrial process
- Diverse, large-scale, stranded
- Renewables-source systems
- IRHTDF
- Posters: Japan, Canada, IPHE
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
Energy System of the Future

Frank Novachek, Director Corporate Planning
Dick Kelly (Xcel) and Dan Arvizu (NREL) shake hands after pushing button to light H2 sign and dedicate system

Mark Udall (US Rep CO) discusses project with Dan Arvizu (NREL), Dick Kelly (Xcel), and John Mizroch (DOE)

National Wind Technology Center
Golden, CO
2006
Hydrogen Utility Group (HUG)
Value from Collaboration

- DC/DC Interface
- Coordinated “Wind Storage”
- Re-deployable

- Larger Scale “Wind Storage”
- Vehicle Applications

- Parallel timetables
- Inter-project collaboration and data sharing

- Larger Scale “Wind Storage”
- Anhydrous Ammonia Production
- Vehicle & Hybrid Applications

- High-Pressure Electrolysis
- Vehicle Fueling Station & Fuel Cell
- Hydrogen/Natural Gas Mixing
Hydrogen Transmission Scenario

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

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

H2O

H2

O2

Power Electronics

To Compressor or Hydrogen Pipeline

Renewable-source Electricity Generation

To Compressors or Pipelines: Hydrogen and Oxygen

PE: Power Electronics

Topology Options: H2 and O2 Production and Gathering from Renewable Energy Generation
Norsk Hydro electrolyzer, KOH type
560 kW input, 130 Nm3 / hour at 450 psi (30 bar)
Compressorless system: No firming storage

Transmission

City gate

Distribution

Wind Generators

High-press Electrolyzers

1,500 psi

Pipeline Energy Storage

500 miles

Hydrogen Gas Pipeline

20" diameter

1,500 -- 500 psi

500 psi

Generators ICE, CT, FC

End users Retail

AC grid Wholesale

Liquefy

Aircraft Fuel

Cars, Buses, Trucks, Trains
Great Plains Windplant, Pipeline
Hourly Output for Typical Week

Hourly Hydrogen Pipeline Input and Output

MWh

0 200 400 600 800 1000 1200 1400 1600 1800

1 25 49 73 97 121 145

Hours

Input
Output
Great Plains Windplant: Actual Hourly Output

August Hourly Pipeline Input and Output

Days

MW

Input

Output
Hydrogen Transmission Scenario

Storage: Pipeline smoothing, geologic firming

PE: Power Electronics

Wind Generators

Electrolyzer

H₂O

H₂

O₂

Gaseous Hydrogen (GH₂) Transmission Pipeline

GH₂ Fuel Market: City Gate

Energy Storage in Pipeline

GH₂ Geologic Storage?

Oxygen Sales to Nearby Gasification Plants
Hydrogen Energy Storage

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

Pipeline Storage = 240 GWh

Storage
Generators
ICE, CT, FC

AC grid Wholesale
End users Retail

Cars, Buses, Trucks, Trains

Storage
Liquefy
Aircraft Fuel

Storage

Geologic Storage?
Solar Hydrogen Energy System

Sunlight from local star

Electrolyzer

Electricity

O₂

H₂

Fuel Cell

Electricity

Work

Solar Hydrogen System

2H₂O + Energy → 2H₂ + O₂

2H₂ + O₂ → 2H₂O + Energy
Hydrogen Fuel Cell

Proton Exchange Membrane (PEM) type

Hydrogen (H2) combines with Oxygen (O2) to make electricity + heat + water (H2O)
Electrolyzers

Compressors

Generators

ICE, CT,
FC

AC grid

Wholesale

End users
Retail

Wind
Generators

Bioma\n or
Coal
Gasification

Syngas

Reactors

CT, ICE

Generator

Electricity
Grid

Water-shift
Reaction

H20

H2

O2

H2

CO2

Sequestration

H20

1,600 km
GH2
Pipeline

Generators
ICE, CT,
FC

Cars, Buses,
Trucks, Trains

Liquefy

Aircraft Fuel

Geologic Oxygen storage ?

Geologic Hydrogen
storage ?

Biomass or
Coal
Gasification

H20

Wind
Generators

Electrolyzers

Compressors

H20

H2

CO2

Sequestration
“Domal” salt storage caverns, solution-mined
Meters below ground level
Texas gaseous hydrogen (GH2) caverns

- Chevron-Phillips, 1986
- Praxair, 2007
Per cavern:
- 800,000 m³ physical volume
- 2,500 tons GH2 net
- 90,000 MWh net
- Power: > 100 MW
- Capital costs:
  - $5 - 15M each “solution mining”
  - $5M cushion GH2
  - $2 - 5M each surface facility
Surface facility
- Compressor: 2,500 psi typical MAOP
- Drying withdrawn GH2
Wellhead, new Gaseous Hydrogen Storage Cavern

- PRAXAIR
- Commissioned 2007
- In domal salt, in Texas
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 = 450 GWh
    • as GH2 = 15,712 tons, metric @ 2,500 tons / cavern = 6 caverns
  – “Firming” energy storage, all Great Plains wind:
    • as GH2 = 17,000 caverns @ $15M each = $264 billion
(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
Renewable-source GH2 geologic storage potential. Candidate formations for manmade, solution-mined, salt caverns
“Bedded” salt

Solution-mining of storage caverns typical of New Mexico and west Texas

Solution Mining Research Institute (SMRI)
Major “bedded” salt basins

Gaseous hydrogen storage may be feasible
Coal or Biomass Gasification Plant

H20

O2

Syngas

Electrolyzers

H2

Wind Separation Plant

Air

Electricity

H20

Haber-Bosch Ammonia Synthesis

Water-shift Reaction

Liquid Ammonia Transmission Pipeline

Liquid Ammonia Tank Storage

H20

Geologic Oxygen storage?

CO2 Sequestration?

CT, ICE

Generator

Grid

Chemicals

AC grid Wholesale

End users Retail

Generators ICE, CT, FC

Cars, Buses, Trucks, Trains

Aircraft Fuel

Wind Generators

H20

H2

N2

Air Separation Plant

Sequestration?
Anhydrous Ammonia, NH₃
Fertilizer → Fuel

Business case:

- Market size, share:
  - 15 MT / yr ag fertilizer
  - 5 MT / yr other
  - ? MT / yr NH₃ fuel
  - ICE, fuel cell

- RE-NH₃ competes with coal, imports
NH₃ Ag Fertilizer Tanks, Wind Generators, NW Iowa
Regional ammonia prices paid by U.S. farmers in April

Red: Northwest
Green: North Central
Yellow: South Central

Year

$ per ton NH3
"Ammonia Nation?"

Anhydrous ammonia (NH₃)

- Low-cost transmission, storage: liquid
- Transportation fuel
- Stationary generation, CHP
- Total USA annual energy ’02 - 06
  - 100 quads
  - 10,000 TWh
- More renewables than coal
- Coal limits:
  - Only 200 year supply?
  - CCS limits: where to put the CO₂?
Ammonia (\( NH_3 \))
Synthesis Plant
Natural Gas Feed
1 – 3,000 tpd

Haber-Bosch “Synloop”
Inside the Black Box: Steam Reforming + Haber-Bosch

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

Energy consumption \(~33\) MBtu (9500 kWh) per ton \(\text{NH}_3\)
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 \(\text{NH}_3\)
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 7000 - 8000 kWh per ton NH\textsubscript{3}

Benchtop
Proof-of-concept
Green Ammonia Cycle
Renewable-source, C-free

Renewable Energy Input
(Electricity or Heat & Electricity)

NH₃ Synthesis
3 H₂ + N₂ \rightarrow 2 \text{NH}_3

(N Combustion or Fuel Cell)

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

N₂ & H₂O
Return to Environment

NH₃ Storage

Electricity Generation

Energy Recovery
• Electricity
• Byproduct heat
Liquid ammonia pipeline

Valero LP Operations
Liquid Ammonia Storage Tank

60,000 Tons

-28 F
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 = 450 GWh
    - As GH2 = 15,712 tons, metric @ 2,500 tons / cavern = 6 caverns
    - As NH3 = 87,291 tons, metric @ 60,000 tons / tank = 1.4 tanks
  - “Firming” energy storage, all great Plains wind:
    - As GH2 = 17,000 caverns @ $15M each = $264 billion
    - As NH3 = 5,000 tanks @ $25M each = $127 billion
’08 Farm Bill Title IX: Energy

- Passed by US Senate, House May 08
- Sec 9015
- “Renewable nitrogen fertilizer research”
- Anhydrous ammonia: $NH_3$
- Commercialization of RE-$NH_3$
- $1M$ recommended appropriation
## Total Installed Capital Cost

<table>
<thead>
<tr>
<th>Windplant size</th>
<th>1,000 MW</th>
<th>2,000 MW</th>
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<tbody>
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<td>Wind generators</td>
<td>$1,000</td>
<td>$2,000</td>
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<tr>
<td>Electrolyzers</td>
<td>500</td>
<td>1,000</td>
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<tr>
<td>Pipeline, 20” *</td>
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<td>1,100</td>
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<td><strong>TOTAL</strong></td>
<td><strong>$2,600</strong></td>
<td><strong>$4,100</strong></td>
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* $1.1 M / mile
Hydrogen Energy Storage

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

Pipeline Storage = 240 GWh

Wind Generators
Electrolyzers

Generators
ICE, CT, FC

End users
Wholesale Retail

Cars, Buses,
Trucks, Trains

Liquefy

Aircraft Fuel

Storage

Geologic
Storage?
Low Cost Electrolyzer Technology for Industrial Hydrogen Markets

National Hydrogen Association
Annual Hydrogen Conference
April 2008

Richard Bourgeois\textsuperscript{1}
Dana Swalla\textsuperscript{1}
Todd Ramsden\textsuperscript{2}

\textsuperscript{1}GE Global Research Center, Niskayuna NY
\textsuperscript{2}National Renewable Energy Laboratory, Golden CO

\[ 2 \text{H}_2\text{O} + \text{ELECTRICITY} \rightarrow \text{O}_2 + 2 \text{H}_2 \]
Industrial Hydrogen Markets

Global consumption: 42 million tons H₂ per year

Large scale: 90%

Mid-scale Industrial

Site capacity, kg H₂ / day

Number of sites in USA

Global consumption: 42 million tons H₂ per year
Plastic Stack Construction

Stack end assembly (machined from molded blanks)

Diaphragm cartridge

Electrode Assembly

Diaphragm cartridge

Stack end assembly (machined from molded blanks)

Plastic weld

9 cell stack core

10-cell Stack module
(shell, bolts, current straps not shown)

15 bar pressure stack under construction for 2008 test
Stack Module Costs

Cost scenarios based on actual cost of demonstration stack, projected assembly and labor costs.

Balance of system costs are additional, and depend on system size.

50 kWh in per kg H₂ = 72% efficiency, plus Byproduct heat

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<th>Size</th>
<th>Power*</th>
<th>Module Cost</th>
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<td>5 kgph</td>
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<td>$45,800</td>
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<tr>
<td>20 kgph</td>
<td>1 MW</td>
<td>$150,000</td>
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* Assumes 50 kWh/kg H₂
Electrolysis Cost of Hydrogen

Basis is the NREL H2A model, modified from the 1500 kgpd case.

- Industrial point-of-use case:
  No dispensing or distribution costs.

### Cost per kg H₂ Plant Gate

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<th>Cost of Electricity, ¢/kWh</th>
<th>Capital Cost, $/kW</th>
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<td>8.0</td>
<td>$8.30</td>
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</table>
### Total Installed Capital Cost

**1,000 mile pipeline, $US million**

**GH2 Delivery to City Gate**

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<td>1,000</td>
</tr>
<tr>
<td>Pipeline, 20&quot;</td>
<td>1,100</td>
<td>1,100</td>
</tr>
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</table>

**TOTAL**  
$2,600  
$4,100

* $1.1 M / mile
# 2,000 MW Windplant Output

## 100% Capacity Factor

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<tr>
<th></th>
<th>MWh/day</th>
<th>tons/hr</th>
<th>tons/day</th>
<th>tons/yr</th>
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<td>As electricity</td>
<td>48,000</td>
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<td></td>
<td></td>
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<tr>
<td>As H2</td>
<td></td>
<td>311</td>
<td>1,342</td>
<td>489,776</td>
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<td>As NH3</td>
<td></td>
<td>1,726</td>
<td>7,455</td>
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<td>10” NH3 pipeline capacity as NH3</td>
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<td>150</td>
<td>3,600</td>
<td>1,314,000</td>
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<tr>
<td>10” NH3 pipeline capacity as H2</td>
<td></td>
<td>27</td>
<td>648</td>
<td>236,520</td>
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</tbody>
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## 40% Capacity Factor

<table>
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<tr>
<th></th>
<th>MWh/day</th>
<th>tons/hr</th>
<th>tons/day</th>
<th>tons/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>As electricity</td>
<td>19,200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>As H2</td>
<td></td>
<td>124</td>
<td>537</td>
<td>195,910</td>
</tr>
<tr>
<td>As NH3</td>
<td></td>
<td>690</td>
<td>2,982</td>
<td>1,088,392</td>
</tr>
<tr>
<td>10” NH3 pipeline capacity as NH3</td>
<td></td>
<td>60</td>
<td>1,440</td>
<td>525,600</td>
</tr>
<tr>
<td>10” NH3 pipeline capacity as H2</td>
<td></td>
<td>11</td>
<td>259</td>
<td>94,608</td>
</tr>
</tbody>
</table>
City-gate GH2 cost @ 15% CRF, 20” pipeline, from 2,000 MW Great Plains windplant

Competitive cost?
Compressorless 20”, 36” GH2 Pipeline Capacity
1,500 psi IN / 500 psi OUT
### Optimistic: Total Installed Capital Cost

**1,000 mile Pipeline**

“Firming” GH2 cavern storage

<table>
<thead>
<tr>
<th>Windplant size</th>
<th>1,000 MW [million]</th>
<th>2,000 MW [million]</th>
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</thead>
<tbody>
<tr>
<td>Wind generators</td>
<td>$1,000</td>
<td>$2,000</td>
</tr>
<tr>
<td>Electrolyzers</td>
<td>500</td>
<td>1,000</td>
</tr>
<tr>
<td>Pipeline, 20”</td>
<td>1,100</td>
<td>1,100</td>
</tr>
<tr>
<td># storage caverns</td>
<td>[4]</td>
<td>[8]</td>
</tr>
<tr>
<td>Caverns @ $10M ea</td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>Cushion gas @ $5M ea</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$2,660</td>
<td>$4,220</td>
</tr>
</tbody>
</table>

Cavern storage: ~3% 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

- NH3 tanks: ~ 5,000
  - Capital $25 M each $125 B
**Pessimistic: Total Installed Capital Cost**

**1,000 mile Pipeline**

“Firming” GH2 cavern storage

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</tr>
<tr>
<td># storage caverns</td>
<td>[4]</td>
<td>[8]</td>
</tr>
<tr>
<td>Caverns @ $50M ea</td>
<td>200</td>
<td>400</td>
</tr>
<tr>
<td>Cushion gas @ $5M ea</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>$ 2,830</strong></td>
<td><strong>$ 4,560</strong></td>
</tr>
</tbody>
</table>

Cavern storage: ~ 10 % of total capital cost
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
DOE-EIA: Estimated 2005 US energy use

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

H2 Production: 0

Residential: 11.89
Commercial: 8.96
Industrial: 26.36
Automotive: 16.18
Freight: 9.19
Airlines: 2.8

Useful Energy: 44.76
Rejected Energy: 52.06

Projection Year 2005
From Year 2005
Efficiency Year 2005
Energy Distribution Year 2005
Estimated **2050** energy use

(H₂ fleet using wind electrolysis)
Pilot-scale Hydrogen Pipeline System: Renewables

- Diverse
- Dispersed, diffuse
- Large-scale
- Stranded
  - Remote
  - No transmission
The wind – hydrogen plant at Utsira

A vision becoming reality
Hydrogen “sector” of a benign, sustainable, equitable, global energy economy
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 7000 - 8000 kWh per ton $\text{NH}_3$
“Hydricity”

- Nexus of electricity + hydrogen: twin currencies
- GH2, NH₃ for annual-scale “firming” storage
- Long-term:
  - Clear: energy currencies
  - Fuzzy: sources
- Climate Change: drive transition Wood-to-coal
- Conversion costs:
  - Capital
  - O&M
  - Energy losses:
    - 50 – 70% round-trip efficiency
    - CHP → 100%
Running the World on Renewables via Gaseous Hydrogen Pipeline Transmission and Firming Geologic Storage

DVD available: your card

Electricity Storage Association
Anaheim, CA
21 May 08

Bill Leighty, Director
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907-586-1426  206-719-5554 cell
21 May 08

Energy Storage Association, Anaheim