Wind - source Hydrogen: Transmission and Firming via Pipeline and Geologic Storage

NHA Renewables to Hydrogen Forum
Albuquerque, NM
4 - 5 October 06

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1: 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
• Benign, if from renewables
• Global opportunity
• Hydrogen “sector”, not “economy”
  – Transportation fuel: ground, air
  – DG electricity, CHP, retail value
2: 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) pipeline systems
  - Conversion, gathering
  - Transmission
  - Storage
  - Distribution
- Geologic storage “firms”
- Pilot plant needed:
  - every major new industrial process
  - IRHTDF
**If --**

- Build hydrogen, natural gas pipelines for same cost:
  - Capital: diameter, pressure, NOT energy capacity
  - Hydrogen embrittlement controlled
  - O&M
- High-pressure-output electrolyzers
  - 1,500 psi
  - Attractive incremental cost
- Pressure drop acceptable:
  - 1,500 → 500 psi
  - 200 – 1,000 miles
- Disregard distribution costs within “city”
- No opposition: public, codes, standards, insurance
- Market for GH2 fuel (vehicles, retail DG in CHP)

**Then --**

*Deliver renewable-source GH2 fuel:*
- To city-gate or plant-gate market
- 200 – 1,000 miles via pipeline
- Cost competitive with fossil fuels
- No costly compressors
- FIRM supply (geologic storage)
International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF) Pilot plant

Global opportunity: IPHE project
EIA: Estimated 2050 energy use (H₂ fleet using wind electrolysis)

Estimated Future U.S. Energy Requirements - 143.3 Quads

- Hydro: 1.21
- Bio/Geo: 7.28
- Wind: 16.27
- Solar: 0.01
- Nuclear: 7.84
- Coal: 25.99
- Gas: 41.83
- Oil: 42.92
- Electricity Generation: 60.3
- H₂ Production: 14.76

Energy Distribution:
- Residential: 17.22
- Commercial: 16.91
- Industrial: 45.97
- Automotive: 10.71
- Freight: 18.45
- Airlines: 7.77
- Rejected Energy: 63.09
- Useful Energy: 80.22

Projection Year 2050
From Year 2025
Efficiency Year 2025 Modified
Energy Distribution Year 2025 Modified
Great Plains Wind

- **Huge:**
  - 3,000 GW = 10,000 TWh AEP
  - Total USA annual energy: 100 quads = 10,000 TWh
  - USA installed ’06 ~ 10 GW (nameplate)

- **Lowest-cost renewable -- at plant gate**

- **Stranded: little transmission**

- **Big Market:** Hydrogen Fuel, not Grid Electricity

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

Rich, stranded Resources
How shall we bring the large, stranded, Great Plains diverse renewables to market?
"There's a better way to do it... Find it"
The NATURALHY approach

NATURALHY:

- Breaks “chicken-egg” dilemma
- Bridge to sustainable future
Proposed Northeast Asia Natural Gas Pipeline
Pilot-scale Hydrogen Pipeline System: Renewables

- Diverse
- Dispersed, diffuse
- Large-scale
- Stranded
  - Remote
  - No transmission
International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF) Pilot plant

Global opportunity: IPHE project
Panacea?

Solar Hydrogen Energy System

Sunlight from local star

Electrolyzer

H₂

O₂

Electricity

Fuel Cell

Electricity

Work

Solar Hydrogen Energy System
Pilot plant: Every new industrial process
Renewables-hydrogen system
- Generation
- Conversion
- Collection
- Transmission
- Storage
- Distribution, end users
- Synergy: $O_2$, seasonal
IRHTDF: generation, conversion, collection, storage corridor

- GH2 geologic storage
- O2 pipeline
- Biomass, Wind, Other Catchment Areas, with Delivery Points to GH2 pipeline
IRHTDF
International Renewable Hydrogen Transmission Demonstration Facility

Des Moines
Ames

Iowa Energy Center

This map was generated from data collected by the Iowa Wind Energy Institute under Iowa Energy Center Grant No. 93-04-02. The map was created using a model developed by Brower & Company, Andover, MA.

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ISE H2-fueled ICE Hybrid, V10
April 05, NHA, Washington DC
GW-scale Transmission Options: Stranded Renewables

- **Electricity:**
  - Overhead: HVAC, HVDC
  - Underground: HVDC
- **Gaseous Hydrogen (GH2) pipeline**
  - 100% GH2; purity
  - “Hythane”; “NaturalHY”, EC, Gasunie Research NL
- **Liquid Hydrogen (LH2) pipeline, truck, rail car, ship**
- **Ammonia (NH3) liquid: pipeline, truck, rail car, ship**
- **Liquid synthetic HC’s – zero net C**
  - SNG, “synthane” CH4
  - FTL’s: Fischer – Tropsch liquids
  - CH3OH (methanol); DME (dimethyl ether)
  - Cyclohexane – benzene (2 pipelines)
  - Silanes: Si₁₀H₂₂
- **“Energy Pipeline”: EPRI**
  - SC, LVDC: ~ 100 GW
  - LH2: ~ 100 GW
- **Al – Ga ↔ Alumina**
# 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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<td>Texas</td>
<td>1,190</td>
<td>339,612</td>
<td>48</td>
<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>
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<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>
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<td>291,096</td>
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<td>Nebraska</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>30</td>
<td>70</td>
<td>42</td>
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<tr>
<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>
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.
Trouble with Electricity Transmission

• Grid nearly full
  – New wind must pay for transmission
  – Costly: AC or DC
• NIMBY
• Low capacity factor or curtailment
• No storage: smoothing or firming
• Overhead towers vulnerable: God or man
• Underground: Only HVDC
Trouble with GW-scale Wind

• Grid nearly full
  – New wind must pay for transmission
  – Costly: AC or DC
• “Cherry-picked” windplants, to date
  – Best wind sites
  – Low-cost transmission access
• Depend on PTC: $0.019 / kWh
• No storage: smoothing or firming
"Hydrogen Transmission Scenario"

Collection Topology Options:

**Electrolyzer and Rectifier Location**

- PE: Power Electronics

PE: Electrolyzer

**H2O**

**H2**

**O2**

To Compressor or Hydrogen Pipeline

- **PE**: Power Electronics
Norsk Hydro
Electrolyzers
2 MW each
Electrolyzers

Compressors

Generators

ICE, CT, FC

AC grid

Wholesale

End users
Retail

Wind Generators

Electrolyzers

Biomass or Coal Gasification

Reactors

Syngas

CT, ICE

Generator

Electricity Grid

Water-shift Reaction

H₂O

H₂

O₂

1,600 km GH₂ Pipeline

1000 km GH₂ Pipeline

1000 km GH₂ Pipeline

1000 km GH₂ Pipeline

1000 km GH₂ Pipeline

1000 km GH₂ Pipeline

1000 km GH₂ Pipeline

1000 km GH₂ Pipeline

1000 km GH₂ Pipeline

1000 km GH₂ Pipeline

CO₂ Sequestration

CO₂ Sequestration

Geologic Oxygen storage?

Geologic Hydrogen storage?

Generators Ice, CT, FC

Cars, Buses, Trucks, Trains

Liquefy

Aircraft Fuel
Norsk Hydro electrolyzer, KOH type
560 kW input, 130 Nm3 / hour at 450 psi (30 bar)
High-pressure Electrolyzers

Generators
ICE, CT, FC

AC grid
Wholesale

End users
Retail

Wind Generators

High-pressure Electrolyzers

Pipeline Energy Storage

City gate

1,500 psi

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

500 psi

Cars, Buses, Trucks, Trains

Liquefy

Aircraft Fuel

Transmission

Distribution
20”, 36” GH2 Pipeline Capacity
1,500 psi IN → 500 psi OUT, no compressors

Pipeline Length, Miles

Capacity, MMScfd

20” diameter
36” diameter
## Total Installed Capital Cost

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

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<thead>
<tr>
<th>Windplant size</th>
<th>1,000 MW</th>
<th>2,000 MW</th>
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<tr>
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<td>$1,000</td>
<td>$2,000</td>
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<tr>
<td>Electrolyzers</td>
<td>500</td>
<td>1,000</td>
</tr>
<tr>
<td>Pipeline, 20”</td>
<td>930</td>
<td>930</td>
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<tr>
<td><strong>TOTAL</strong></td>
<td><strong>$2,430</strong></td>
<td><strong>$3,930</strong></td>
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Wind-Hydrogen 1,000 Mile Pipeline Optimization Simulation

- Delivered Cost $/kg H₂
- Wind Gen Utilization
- Pipeline Utilization
- Electrolyzer Utilization

Graph showing the relationship between Wind Gen Capacity / Pipeline Capacity and Delivered Cost $/kg H₂, with utilization levels indicated.
City-gate GH2 cost @ 15% CRF, 20” pipeline, from 2,000 MW Great Plains windplant

Competitive cost?
Air Products Company

REFINERY ACTIVITY

LOS ANGELES BASIN, CALIFORNIA

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Industrial \( \text{H}_2 \) Pipelines

- 3,000 km worldwide
- Industrial corridors; on-site
- 30% SMYS typical *
- Constant pressure; low cyclic fatigue
- Low-alloy, low-strength steel
- Re-purposed oil pipelines

* Specified Minimum Yield Strength
Renewables-Hydrogen Service for Pipelines

• Diverse, Diffuse, Dispersed
• Time-varying output: seconds, seasons, decades
• Pipeline pressure fluctuations: frequent, severe
• Hydrogen embrittlement (HE) of steel
  – must be controlled
  – storage ameliorates: firms
  – pipeline energy storage
Hydrogen Energy Storage

Wind Generators → Electrolyzers → Wind Generators

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

Pipeline Storage = 240 GWh

Storage

Generators
ICE, CT, FC

End users
Wholesale
Retail

Cars, Buses, Trucks, Trains

Liquefy
Aircraft Fuel

Geologic Storage?

Storage
Great Plains Windplant, Pipeline
Hourly Output for Typical Week

Hourly Hydrogen Pipeline Input and Output

MWh

Input
Output

Hours
Hydrogen Can Be Stored Underground At Low Costs

**Current Hydrogen Storage**
- Shaft
- Salt Formation

**Natural Gas Stored Underground**
- Shaft
- Water compensation column
- Other rock strata
- Impervious caprock
- Porous rock air storage

From: Charles W. Forsberg, ORNL, 17th NHA Conference, 12-16 Mar 06
Renewable-source GH2 geologic storage potential. Candidate formations for manmade, solution-mined, salt caverns.
### Total Installed Capital Cost

1,000 mile pipeline, $US million

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### Total Installed Capital Cost

**1,000 mile Pipeline**

“Firming” GH2 cavern storage

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<td>1,000</td>
</tr>
<tr>
<td>Pipeline</td>
<td>930</td>
<td>930</td>
</tr>
<tr>
<td># storage caverns</td>
<td>[4]</td>
<td>[8]</td>
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<tr>
<td>Caverns @ $5M ea</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Cushion gas @ $5M ea</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$2,470</td>
<td>$4,010</td>
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</tbody>
</table>

Cavern storage: 1.6% total capital cost
“Firming” GH2 Cavern Storage for ALL Great Plains Wind

~ 12,000 caverns

Excavate: $5 M each $ 60 B
Cushion gas: $5 M each $ 60 B

Total $120 B

Adds VALUE: strategic, market
International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF)

Pilot plant

Global opportunity: IPHE project
2: Shortest path to benign, secure, abundant energy

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• 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
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Wind - source Hydrogen: Transmission and Firming via Pipeline and Geologic Storage

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3: When we realize these as emergencies:

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

We must quickly invest in:

- Energy conservation, efficiency
- Large, new energy supplies:
  - CO$_2$-emissions-free
  - Indigenous
  - Both Distributed, Centralized
Ammonia Conferences:
Anhydrous Ammonia (NH₃) as an energy and hydrogen carrier and energy storage medium

• First two annual conferences archives at: http://www.energy.iastate.edu/renewable/

• 28 Oct 04 Proceedings: http://www.energy.iastate.edu/renewable/biomass/AmmoniaMtg.html

• 13-14 Oct 05 Proceedings: http://www.energy.iastate.edu/renewable/biomass/AmmoniaMtg05.html


"Ammonia, the Key to U.S. Energy Independence"
Summary

• Agree with hypotheses ?
• Preparing for Carbon Price
• “Firming” renewables with storage
• Compressorless pipeline systems: Renewables-GH2 fuel, competitive cost
• Pilot plant: the IRHTDF as IPHE project