International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF)

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International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF)

Bill Leighty, The Leighty Foundation, USA
Prof. M. Hirata, University of Tokyo, Science Council of Japan
Dr. K. O’Hashi, Nippon Steel, Japan
Jacques Benoit, AMEC Earth & Environmental, Canada
The Great Plains Wind Resource

How shall we bring the large, rich, stranded, Great Plains wind to market?
# Total USA Wind Resource Estimate: PNL-7789 (1991)

*USA total energy use, year 2000 ~= 10,000 TWh (billion kWh)*

<table>
<thead>
<tr>
<th>State</th>
<th>TWh / year</th>
<th>MW (nameplate, at 40% CF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Dakota</td>
<td>1,210</td>
<td>345,320</td>
</tr>
<tr>
<td>Texas</td>
<td>1,190</td>
<td>339,612</td>
</tr>
<tr>
<td>Kansas</td>
<td>1,070</td>
<td>305,365</td>
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<td>1,030</td>
<td>293,950</td>
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<tr>
<td>Montana</td>
<td>1,020</td>
<td>291,096</td>
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<td>Nebraska</td>
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<td>247,717</td>
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<tr>
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<td>187,500</td>
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<td>Missouri</td>
<td>52</td>
<td>14,840</td>
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</tbody>
</table>

**TOTALS**  

| 10,500 TWh | 3,000,000 MW |
Total solar: $\sim 3 \times 10^{14}$ kg / yr
Total wind: $\sim 3 \times 10^{11}$ kg / yr

“Rich”
Geothermal Resources

- Good - Excellent
- Fair - Moderate
GW-scale Transmission Options: Stranded Renewables

- Electricity:
  - Overhead: HVAC, HVDC
  - Underground: HVDC
- Gaseous Hydrogen (GH2) pipeline
- Liquid Hydrogen (LH2) pipeline
- Liquid Hydrogen (LH2) rail car, ship
- Liquid synthetic HC’s – zero net C
  - CH3OH (methanol); DME (dimethyl ether)
  - Cyclohexane – benzene (2 pipelines)
  - Silanes: Si_{10}H_{22}
- “Energy Pipeline”: EPRI
  - SC, LVDC: ~ 100 GW
  - LH2: ~ 100 GW
Superconducting “Energy Pipeline”
Paul Grant, EPRI
~ 100 GW electrical + 100 GW LH2
Natural Gas Pipelines in Shield Tunnel, from "Energy Engineering", Nippon Steel, 2001
* SC: MgB$_2$ magnesium diboride superconductor
** LH2: liquid hydrogen coolant, energy transmit

Continental Supergrid - EPRI
Materials Challenges

GW-scale Transmission

- Electricity
- Overhead
- Underground cable
- SC “Energy Pipeline”, EPRI
- Hydrogen pipelines for renewables
- Linepipe
- Components
Materials Challenges

Hydrogen pipeline systems for renewables

- Linepipe
- “H2 attack” on steel: HIC, HCC, HE
- Transmission: High capacity
  - High pressure
  - Large diameter
  - Long distance
  - Economical
- Components
- Synergy: diverse sources, storage
GH2 Pipeline is Lowest-cost Hydrogen Transport Method, at Long Distance and High Power  (W. Amos, NREL, USA)
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
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>
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<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>
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</tbody>
</table>
"Electricity Transmission" Scenario

Wind Generators

Collection System

AC to HVDC Converter Station

1,000 miles
+/- 500 kv HVDC

HVDC to AC Converter Station

"STIFF" AC grid

End users

Wind Generators

North Dakota

Chicago
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

High Voltage Direct Current Transmission

SIEMENS HVDC line +/- 500 kV
Vision: Remote renewable energy sources
connected to loads by DC grid
Hydrogen Transmission Scenario

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

Wind Generators

Electrolyzers

Compressors

Storage: 120 GWh

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

Generators ICE, CT, FC

End users Retail

AC grid Wholesale

Cars, Buses, Trucks, Trains

Liquefy

Aircraft Fuel
Wind Powering America

NW Iowa 190 MW windplant
Norsk Hydro Electrolyzers 2,000 kW each
"Hydrogen Transmission" Scenario

Hydrogen Fuel Delivery
High-pressure electrolyzers

Wind Generators
High-pressure Electrolyzers
Wind Generators

Storage: 120 GWh

1,000 miles
Hydrogen Gas Pipeline
18 - 36" diameter
~ 1,000 psi

Generators
ICE, CT, FC

AC grid
Wholesale

End users
Retail

Cars, Buses, Trucks, Trains
Liquefy
Aircraft Fuel
"Hydrogen Transmission" Scenario

Hydrogen Storage

Wind Generators

Electrolyzers

Compressors

Generators

ICE, CT, FC

AC grid Wholesale

End users Retail

Cars, Buses, Trucks, Trains

Storage

Liquefy

Aircraft Fuel

Storage

36" Pipeline Storage = 120 GWh

1,000 miles Hydrogen Gas Pipeline 18 - 36" diameter ~ 1,000 psi

Geologic Storage ?

- Improves pipeline CF
- Reduces cyclic loading
10 MW Windplant + Electrolyzers

5 MW Biomass Plant

H₂

Compressor

Meter, gas quality control

Shutoff Valve

Pipe Flange

12” Hydrogen Gas Pipeline

Pipeline Delivery Nodes

- Simple
- Low cost
- Large or small
- Closely spaced
### Hydrogen Fuel Cost in Chicago

**No PTC subsidy**

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind-generated electricity in ND</td>
<td>$0.045 / kWh</td>
</tr>
<tr>
<td>Hydrogen conversion and 1,000 miles transmission</td>
<td>$0.052 / kWh</td>
</tr>
<tr>
<td><strong>Wholesale price of GH2 fuel at Chicago city gate</strong></td>
<td>$0.097 / kWh</td>
</tr>
<tr>
<td>Equivalent per-gallon-gasoline-energy price *</td>
<td>$3.49 / gal</td>
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<tr>
<td>Distribution and retail “gas” station cost</td>
<td>$0.79 – 1.45 / gal</td>
</tr>
<tr>
<td><strong>Retail price of GH2 fuel in Chicago</strong></td>
<td>$4.28 – 4.94 / gal</td>
</tr>
<tr>
<td>Drive train efficiency ratio: FCEV / ICEV = 2</td>
<td></td>
</tr>
<tr>
<td>Equivalent retail price GH2 fuel per vehicle-mile</td>
<td>$2.14 – 2.47 / gal</td>
</tr>
</tbody>
</table>

* 1 GJ = 278 kWh; 1 gallon gasoline = 0.13 GJ (HHV) = 36 kWh @ $0.08 / kWh = $2.89 / gallon

HHV means higher heating value of hydrogen.
GH2 means compressed gaseous hydrogen
Hydrogen Fuel Cost in Chicago
With PTC subsidy

Wind-generated electricity in ND $ 0.045 / kWh
Fed PTC (production tax credit subsidy) ( .017 )
Subsidized wind energy in ND 0.028
Hydrogen conversion and 1,000 miles transmission 0.052

Wholesale price of GH2 fuel in Chicago, end-of-pipe $ 0.08 / kWh
Equivalent per-gallon-gasoline-energy price * $ 2.89 / gal
Distribution and fuel station cost $ 0.79 – 1.45 / gal

Retail price of GH2 fuel in Chicago $ 3.68 – 4.34 / gal
Drive train efficiency ratio: FCEV / ICEV = 2
Equivalent retail price GH2 fuel per vehicle-mile $ 1.84 – 2.17 / gal

* 1 GJ = 278 kWh; 1 gallon gasoline = 0.13 GJ (HHV) = 36 kWh @ $ 0.08 / kWh = $ 2.89 / gallon
HHV means higher heating value of hydrogen.
GH2 means compressed gaseous hydrogen.
Hydrogen Fuel Cell Hybrid
Hydrogen Fuel Cell - Electric
Long Term Vision

A transportation system powered by hydrogen from renewable resources
Distributed Generation (DG)
Twelve Great Plains states wind needs

\( \sim 400 \) H2 gas Pipelines

Each: 2,500 tons GH2 / day = 6,000 MW

36” diameter

14 MPa = 1000 psi = 65 bar
LARGE STRANDED RENEWABLES:
the International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF)

A pilot-scale gaseous hydrogen (GH2) transmission pipeline system optimized to bring large-scale, remote, diverse, dispersed, stranded, renewable resources to distant markets, in "renewables-hydrogen service"

- No pipelines for renewables-hydrogen service exist.
- Major new industrial processes require pilot plants like IRHTDF.
- Electricity lines and GH2 pipelines are comparable in capital and O&M costs.
- GH2 transmission provides valuable storage in the pipeline and in geological formations.
- New underground GH2 pipelines may be more secure, socially acceptable, permittable, and bankable than new overhead electric lines.

Global Energy Strategy Challenge

- How shall we bring Earth’s huge, stranded, renewable resources to distant markets?
- Ingenious options for long-distance stranded renewables:
  - Reversing high voltage direct current (HVDC) electric lines and gas pipelines
  - Using gaseous hydrogen (GH2) transmission pipelines
  - Synthetic liquid hydrocarbons, with net zero C emissions
  - Superconducting "Energy Pipelines" (EHP, USA patent)
  - Pipeline GH2 "Gases" (GH2G)

  - GH2G Natural gas options:
    - Low temperature energy density of hydrogen as low as that of nuclear energy.
    - Pipeline systems must be safe from hydrogen attack, corrosion, and containment.
    - Special ventilation, valves, and meters required.
    - GH2 gases may have mineralized pigments to be a major part of humanity’s sustainable energy future? Under what circumstances? Dan paper presented renewable-gases density compared with hydrogen from other sources.

Pipelines, purpose

- We need to utilize humanity’s energy sources for renewable resources.
- Earth’s largest, richest renewable resources are stranded.
- For rural populations and load centers.
- GH2 pipelines and hydrogen processing systems are needed worldwide, for these large, remote, stranded resources.
- GH2 pipeline routes compete with HVDC corridor transmission lines. Capital and O&M costs, conversion and transportation fossil.
- GH2 pipeline transmission routes make long-distance transmission and high-power (1000MW) feasible.
- GH2 pipeline systems must be optimized for renewable-hydrogen services:
  - High capacity, high pressures, large diameter, long distance.
  - Acceptable flow, large pressure swings.
  - Avoid hydrogen toxic, corrosive, caustic, embrittles.
  - Low fluid leakage: containment, control, and safety.
  - Balance renewable-power source (GH2) and petrochemical costs.
  - Allow flexibility in hydrogen reserve among diverse renewable resources.

- No GH2 pipelines for renewables-hydrogen service exist.
- The process for fueling infrastructure (GH2) pipeline systems is not capable of renewable-hydrogen services.
- No major new processes require pilot plants.
- Benefits costs, savings, technical obstacles must be identified and quantified. GH2 and HVDC technology for large-scale pipelines.
- IRHTDF is the ideal test and demonstration facility for renewable-hydrogen services, for GH2.

The future of renewable electricity and hydrogen’s sustainable energy future? Under what circumstances? IRHTDF as an initial critical path to identifying these elements.

IRHTDF status

- Concept only; no detailed engineering or economics studies.
- No funding or sponsorship in place; no leadership opportunities.
- Possible R&D (R&D) investment, but saw limited interest.
  - IP: Project Partnership: Advancing Transition to Hydrogen.
  - IRHTDF status: Paper, poster, presentation.

19th World Energy Congress
Sydney, AUS
5-9 Sept ’04
IRHTDF
paper, poster
The NATURALHY approach

NATURALHY:
• Breaks “chicken-egg” dilemma
• Bridge to sustainable future
Renewables-Hydrogen Sector of a Sustainable Energy Economy

International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF)
Line pipe for GH2 - RHS

- Resist HE under 100% GH2, cyclic loading
- Low cost: fab, transport, install, maintain
  - Low-alloy, low-strength steel (X42, below)
  - “Sour service” X65
  - Other steel?
  - CRLP (composite reinforced line pipe)
  - Ameron SSL process
  - Fiberspar process
  - Continuous on-site manufacturing?
    - Composites? Capital cost vs. diameter
  - Plastic internal H2 barrier: Dynetek tanks
Composite Reinforced Line Pipe (CRLP)

42” diameter
3,400 psi
.75” X70 steel
.75” composite

NCF Industries and TransCanada Pipelines

ASME International Pipeline Conference and Exposition, Calgary, AB, Canada, October 02.
Composite – Reinforced Line Pipe (CRLP)

3,400 psi, .75” X70 steel plus .75” composite

NCF Industries and TransCanada Pipelines
ASME International Pipeline Conference and Exposition,
Calgary, AB, Canada, October 02.
Typical Stress-Strain Curves

- **X70 steel pipe**
- **composite reinforcement**

CRLP™ & GTM™ - Manufactured under license from NCF Industries, Inc.
Canadian, US & Foreign Patents Issued & Pending.
Operating Stresses

Graph showing the relationship between internal pressure (MPa) and hoop stress (MPa) for composite and steel materials.

- **Composite**
- **Steel**

TransCanada
TransCanada Installs Demonstration Section Of Composite Reinforced Line Pipe
CRLP™ is a trademark of NCF Industries, Inc.

CRLP™ is manufactured under license from NCF Industries, Inc. U.S. and Foreign patents have been issued and are pending.
CRLP™ is a trademark of NCF Industries, Inc. CRLP™ is manufactured under license from NCF Industries, Inc. U.S. and Foreign patents have been issued and are pending.
CRLP™ is a trademark of NCF Industries, Inc. CRLP™ is manufactured under license from NCF Industries, Inc. U.S. and Foreign patents have been issued and are pending.
Wrapper, composite splice

CRLP™ is a trademark of NCF Industries, Inc. CRLP™ is manufactured under license from NCF Industries, Inc. U.S. and Foreign patents have been issued and are pending.
Fracture arrest by 2 CRLP sections: 1
Fracture arrest by 2 CRLP sections: 2
Intelligent “Pig” for Pipeline Inspection
Steel Strip Laminate (SSL) Pipe
To 40 MPa (5,700 psi), 40” diam

- Glass Reinforced Epoxy Outer Jacket
- Helically Wound Steel Strip Layers
- Glass Reinforced Epoxy Inner Liner
Fiberspar
Composite
Line pipe
4.5” Canada
Fiberspar Composite Line pipe

3.5” and 4.5” Canada
### Existing Hydrogen Pipelines

<table>
<thead>
<tr>
<th>Company</th>
<th>Location</th>
<th>Mscf / day</th>
<th>Length km</th>
<th>Diameter inches</th>
<th>Pressure psi</th>
<th>Years Installed</th>
<th>Material</th>
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<td>Praxair</td>
<td>Texas</td>
<td>100</td>
<td>8</td>
<td>70's</td>
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<td></td>
<td>NewJersey</td>
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<td></td>
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<td></td>
<td>Indiana</td>
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<td>Air Products</td>
<td>Texas</td>
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<td>200</td>
<td>4 - 12</td>
<td>50 - 800</td>
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<td>ChemischeWerk Huls</td>
<td>Germany</td>
<td>100</td>
<td>220</td>
<td>4 - 12</td>
<td>360</td>
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<td>ICI, Teeside</td>
<td>England</td>
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<td>16</td>
<td></td>
<td>750</td>
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<td>France, Belgium</td>
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<td>340</td>
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<td>1,470</td>
<td>80's</td>
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<td>Shell Canada</td>
<td>Scotford, AB</td>
<td>88</td>
<td>9</td>
<td>30</td>
<td>65</td>
<td>2002</td>
<td>X42</td>
</tr>
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</table>

**Total ~500 miles USA, ~3,000 miles worldwide**

- Low, constant pressure: ~ 30% SMYS
- 80% captive; 20% merchant; worldwide 90M tons / yr
- Short, small diameter, low flowrate
- Mild steel; low strength
- 100 Mscf / day = 266 tons / day = 397 MW
Gulf Coast and Mississippi River Pipeline Network

The world leader in industrial and medical gases
Air Products Company

REFINERY ACTIVITY

LOS ANGELES BASIN, CALIFORNIA
“We know how to pipeline hydrogen”  Air Products
~ 10,000 miles of GH2 pipeline, worldwide

Air Products H₂/ CO Pipeline - Texas Gulf Coast

- HYDROGEN
- CO
- SYNGAS
- Air Products Facilities

CITY OF HOUSTON
MONT BELVIEU
BATTLEGROUND
BAYTOWN
LAPORTE
LAKE CHARLES
GULF OF MEXICO

Approx. 60 Miles
## Carbon Steel Properties for H2

<table>
<thead>
<tr>
<th></th>
<th>2005 IDEAL</th>
<th>1970’s API 5L</th>
<th>1940’s Grade B</th>
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<tbody>
<tr>
<td>Hardness</td>
<td>&lt;250 HB</td>
<td>225</td>
<td>178</td>
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<tr>
<td>Carbon Equivalent</td>
<td>&lt;0.43</td>
<td>0.63</td>
<td>0.325</td>
</tr>
<tr>
<td>Grade</td>
<td>&lt;X56</td>
<td>X60</td>
<td>Gr.B</td>
</tr>
<tr>
<td>Sulphur</td>
<td>&lt;0.01%</td>
<td>0.03</td>
<td>0.036</td>
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<tr>
<td>Phosphorus</td>
<td>&lt;0.015%</td>
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<tr>
<td>Charpy Impact</td>
<td>&gt;35J</td>
<td>&gt;27J</td>
<td>6J</td>
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<tr>
<td>Heat treatment</td>
<td>Normalized</td>
<td>NA</td>
<td>NA</td>
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</table>

Metallurgy may require de-rating MOP <30 SMYS*

* Specified Minimum Yield Strength
Natural Gas Pipeline Capacity, 2001

USDOE, EIA

Capacity (in Million Cubic Feet per Day)
as of December 2000

Direction of Flow

Bi-directional
Challenges of GH2 Pipeline Transmission

- Recognize, confront:
  - Global warming, global climate change (GW / GCC)
  - Security: energy supply
  - Security: human threats
  - International pressure: Kyoto Protocol; beyond
  - External costs of energy

- Indigenous, C-emissions-free energy
  - Large demand, quickly
  - Higher price
  - Renewable sources
    - Distributed: on-site generation, use
    - Centralized: large plants; transmission
    - Largest, richest: Diverse, dispersed, remote
    - Time-varying output: minute to seasonal, cyclic to random

- Transmission pipelines for GH2, for RHS: not ready
Challenges of GH2 Pipeline Transmission

- Cost 1.5 – 2 x NG per Nm3 – km (energy – distance)
  - GH2 one-third energy density of NG, volume
  - H2 attack
    - Line pipe, other steel components
    - RHS exacerbates: cyclic loading, fatigue
  - Compression: more power, energy, per Nm3 - km
  - Special compressors, valves, meters, sensors

- Deliver GH2 plant-gate to city-gate at competitive price
  - Long distance
  - High capacity: economy of scale (>36”, >2,000 psi)

- Competition
  - Transmission: electricity, liquids, EPRI SC “Energy Pipeline”
  - Sources: Nuclear; With CCS: NG-SMR, coal gasification

- Large capital projects: $US 10B +
- Financing, permitting, ROW
Challenges of GH2 Pipeline Transmission

- New components, materials; Fab, construction methods
  - Line pipe: steel, hybrids, composites, on-site fab
  - High capacity: economy of scale (>36”, >2,000 psi)
  - Electrolyzers, compressors, valves, meters
- Gathering, distribution: topology
- Systems design, optimization
- GH2 purity: PEMFC grade = 99.999 +
- Cannot now design, build GH2 - RHS pipeline systems
- All new NG pipelines RHS-capable?
- Public perception: hydrogen “dangerous”, NIMBY
Challenges of GH2 Pipeline Transmission

Will Renewables-Hydrogen pipeline systems be important?

– Define Renewables-Hydrogen Service (RHS)
– Pilot plant: IRHTDF
  • Technical challenges
  • Synergies, diverse sources
  • Benefits, costs: city-gate COE
– Start now
Hindenberg
May, 1937
Lakehurst, NJ

Safer than gasoline?
Renewables – Hydrogen Service (RHS) for GH2 pipelines - A

- 100% GH2: low energy density (volume)
- Large-scale:
  - ~ 2,500 tons / day = 25 Million Nm3 / day = 6,000 MW
    - 36” diam @ 7 MPa (1,000 psi)
    - > 36” diam
    - > 14 MPa (2,000 psi)
- From diverse, dispersed, renewable energy sources:
  - Remote:
    - Gathering, feedpoints, topology
    - Long distance, cross-country transmission
  - Time-varying output scales:
    - Minute – to – hourly
    - Daily
    - Seasonal
    - Random, unpredictable
Renewables – Hydrogen Service (RHS) for GH2 pipelines - B

• Frequent, large pressure cycling
  – ~ 2:1, ~ daily
  – Cyclic loading, steel → fatigue → H2 attack → fracture
  – Mitigated by other storage: geological, end-user

• Valuable pipeline energy storage
• New codes, standards, specs
• Pipeline is part of complex system
  – “Corridor”, not “transmission line”
  – Must be optimized: technically, economically
  – Must be low-cost: compete
    • Other sources
    • Other transmission: Electricity

• Transmission cost a large % of delivered price
Renewables – Hydrogen Service (RHS) for GH2 pipelines - C

- Gathering, transmission, delivery
- Many input, output nodes, wide size range
- High purity: 99.999, for PEMFC
- Frequent inspections: pigging; other
- Low cost needed: capital, O+M, on-ramps
- Public apprehension: permitting, siting
Pilot-scale GH2 Pipeline System

International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF)
Prospects for Hydrogen Pipeline Transmission

• Metallurgists:
  – Few generalizations are meaningful in the study of hydrogen effects
  – Unexpected failures too common

• Gaseous hydrogen ≠ natural gas
  – Any metal component subjected to mechanical loads in a gaseous hydrogen environment is potentially susceptible to hydrogen effects

• Operational hydrogen pipelines exist
  – Expensive/conservative designs and materials

• Important hydrogen-related concerns for pipelines:
  – Fatigue cracking
  – Fracture behavior
  – Performance of welds
  – High pressure hydrogen (up to 34MPa/5 ksi)
  – Gas purity
Convergence: Prepare now

- Serious concern, emergency
  - GW / GCC
  - Security: energy, national
  - Equity, access
- Rapid development, indigenous, C-free energy
  - Fossil
  - Nuclear
  - Renewables
- Transmission expansion: upgrade, new
  - Electricity
  - Gaseous hydrogen (GH2) pipelines
  - Other: liquids, EPRI “Energy Pipeline”
- Renewables-hydrogen service (RHS) (GH2) unknown
  - Fast track to above?
  - R+D: lab, pilot-scale
  - Demonstration system: IRHTDF
  - Technical and economic prospects; significance
  - Benefits, costs, synergies: systems analysis
Renewables - Hydrogen service (RHS) (GH2) pipelines

• Fast track to;
  – Indigenous, C-free energy
  – New transmission expansion
  – Serious concern, emergency
    • GW / GCC
    • Security: energy, national
    • Global equity, access

• Need pilot plant: IRHTDF
  – These pipeline systems important?
  – How to design, build them
**International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF)**

- Pilot-scale gaseous hydrogen (GH2) pipeline *system*
- From diverse, dispersed, renewables
- To diverse, distant, concentrated end-users
- Optimized for “Renewables – Hydrogen Service” (RHS)
- Systems analysis platform, laboratory:
  - Design >>> Test >>> Demonstration
- ~ 10 years, $US 50 - 100 M: international
- Discover, value, demonstrate, extrapolate to large-scale:
  - Costs: capital, O+M, environmental
  - Synergies
  - Value-adding benefits: IRR, NPV
- Will GH2 - RHS pipeline systems be competitive, important? How?
- Prove acceptance:
  - Public, industry, finance
  - One demonstration = 1,000 studies
- Ideal project for IPHE, IEA - HIA, EC, PATH, NEDO, METI
IRHTDF: generation, conversion, collection, storage corridor

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

GH2 geologic storage
O2 pipeline
Estimated Average Annual Wind Speeds
Typical average wind speeds on well exposed sites at 50 m above ground

Iowa Energy Center, 2521 Elwood Dr., Suite 124, Ames, IA  50010-8263  515-294-8819  FAX -9912

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 Brewe & Company, Andover, MA.

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Iowa Energy Center, 2521 Elwood Dr., Suite 124, Ames, IA  50010-8263  515-294-8819  FAX -9912
LARGE STRANDED RENEWABLES: the International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF)

A pilot-scale gaseous hydrogen (GH2) transmission pipeline system optimized to bring large-scale, remote, diverse, dispersed, stranded, renewable resources to distant markets, in "renewables-hydrogen service"

- No pipelines for renewables-hydrogen service exist.
- Major new industrial processes require pilot plants like IRHTDF.
- Electricity lines and GH2 pipelines are comparable in capital and O&M costs.
- GH2 transmission provides valuable storage, in the pipeline and in geological formations.
- New underground GH2 pipelines may be more secure, socially acceptable, permissible, and bankable than new overhead electric lines.

Global Energy Strategy Challenge

- How shall we bring Earth’s high-cost, stranded, renewable resources to distant markets?
- "Renewables options for large-scale stranded renewable:"
  - New high-voltage direct current (HVDC) electric lines
  - New GH2 transmission (H2G2) transmission pipelines
  - Synthetic fuels (e.g., methanol, methanol-based electricity)
  - Superconducting "Energy Pipelines" (SEP, USA patent)
  - Pipelining GH2 to convert to electricity at the consumption site
  - Various storage energy density of hydrogen: sea at 2.47 kWh/kg
  - Pipeline systems must be safe from hydrogen atomic, combustion, cracking, containment.
  - Special components, valves, and nozzles required.
- Will greenhouse gas (GHG) emission control significate be a major part of humanity’s sustainable energy future? Under what circumstances? Can piped renewable energy systems compete with hydrogen from other sources?

- To discover, quantify, and demonstrate answers, we should begin, now, to:
  - Assist and fund an international consortium
  - Design, build, and operate the IRHTDF
  - Operate GH2 pipelines as an MFC test, then as a test facility, then as a demonstration facility.
- Take use (global energy strategy).

Rationale, purpose

- We need to build bulk utility-scale energy centers for renewable resources.
- Earth’s largest, richest renewable resources are stranded.
- For high population and high demand.
- GH2 is not a prime gathering and transmission systems to deliver their energy.
- Many new, new high-capacity transmission systems will be needed.
- For these large, remote, stranded resources.
- GH2 pipelines will provide a long-distant transmission line, in capital and O&M costs, conversion and transmission’s feasibility.
- GH2 pipelines will have a lower energy transmission cost (for long distance and high power transfers).

- GH2 pipeline transmission systems must be optimized for renewables-hydrogen services:
  - High capacity, high pressure, large diameter, long distance
  - Accurate, fast, precise, smooth transitions
  - Avoid hydraulic, thermal, erosion, corrosion, embrittlement.
  - Deliver needs and costs of GH2 from pipeline to cost.
  - Avoid buffer inventories among diverse renewable resources
  - Use vertical, horizontal, or diagonal pipelines, among diverse renewable muscles.
- GH2 pipeline transmission systems are a prime gathering and transmission system for renewables-hydrogen service.

- GH2 pipeline transmission systems are a prime gathering and transmission system for renewables-hydrogen service.

IRHTDF status

- Concept only; no site selection or economics studies.
- No funding or deployment in place; new a leadership opportunity.
- Possible $300 – $500M cost, phases, megawatts, international effort.

- IRHTDF International Partnership for the Hydrogen Economy
- IEA Hydrogen Implementation Agreement (HIA)
- EC PRIN (Partnership Advancing Transition to Hydrogen)

19th World Energy Congress
Sydney, AUS
5-9 Sept '04
IRHTDF paper, poster
Why IRHTDF? (A)

- Largest, richest renewables are stranded, remote
- Assume GH2 - RHS pipelines
- Pioneer:
  - No GH2 - RHS system on Earth
  - No experience with RHS
- Major new industrial process: always pilot plant
- Initiates
  - **Systems** engineering
  - R+D
    - Line pipe, components
    - Source equipment
    - Geologic storage
- Systems analysis →
  Design → Test facility →
  Demonstration → Extrapolate to large-scale
- Define “Renewables – Hydrogen Service” (RHS)
- Design and prove line pipe, system components:
  H2 attacks steel in RHS
**Why IRHTDF? (B)**

- Prove acceptance, understanding, support
  - Renewables are ready
  - Hydrogen is ready
  - Public
  - Energy industry
  - Insurance & finance

- Discover, value, demonstrate,
  - Costs: capital, O+M, environmental
  - *System* synergies
  - Value-adding benefits: IRR, NPV for typical systems

- RHS pipelines must compete: H2 fuel market
  - Electricity, efficiency
  - GH2 pipelines costly: capital, O&M
  - RHS long distance: costly

- Important part of “hydrogen economy”?
  - Acceptable to public?
  - Insurable? Bankable?
  - Fail? Proceed, abandon, demur?
  - “No regrets” investment
  - Avoid blind alleys
Why IRHTDF? (C)

Value-adding benefits:

- Energy storage: time-varying renewables
  - Pipeline
  - Source devices
  - End use devices
  - Smoothing: improve CF, cyclic loading
  - Geologic: seasonal; dispatchable
  - Biomass stockpiling

- Wind - electrolysis:
  - Share power electronics
  - Eliminate redundant power electronics
  - Store GH2 in towers
Why IRHTDF? (D)

Value-adding benefits:

- Share transmission among sources
  - Higher CF
  - Fewer transmission systems, ROW’s
- Topology
  - Gathering & transmission
  - On-ramps: simple, low-cost, wide size range
- Underground
  - Permitting, acceptance
  - Security
- By-product O2 from electrolysis
  - Adjacent plants
  - Biomass, coal
- Affect system IRR, NPV
Pilot-scale GH2 Pipeline System

International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF)
International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF)

ASM

Materials Solutions Conference and Expo
18 – 20 October 04
Columbus, OH

Bill Leighty, The Leighty Foundation, Juneau, AK
wleighty@earthlink.net

Presentation, papers on CD: your card, please.
Handout, poster
End of ASM presentation, 19 Oct 04

The following 12 slides were not used in ASM presentation; were intended for presentation if time had allowed.
2,000 delegates
89 countries

19th World Energy Congress, Sydney
4 – 9 September 04

World Energy Council
CONSEIL MONDIAL DE L’ENERGIE
19th World Energy Congress
Sydney, AUS, Sept 04

• ~ 2,000 delegates, 89 countries
• Energy demand triples by 2100: IEA
• Most from fossil fuels, mostly coal
• Carbon capture + sequestration (CCS):
  – Great hope: Sleipner, DGC
  – No proven technology: combustion, gasification
• No one questions GW / GCC
• Kyoto: “beyond”; flawed, inadequate; Russia?
• GW / GCC response inadequate
  – No sense of emergency
  – Overwhelming
19th World Energy Congress
Sydney, AUS, Sept 04

- Major energy companies respond, slowly
- Reject no energy source or technology
- Renewables little emphasis
- Very large capital required
- R+D underfunded
- New nuclear electricity:
  - Resigned to this CO2-free source
  - China, Japan, Korea, India, Finland
  - France? South Africa? Russia?
  - $4,000 / kW capital cost
  - U fuel limited; breeders necessary
  - Proliferation, waste unsolved
  - Fusion mentioned
Vision: skeptical reports, backlash

• “The Hydrogen Economy…”
  National Academies, USA, Feb ‘04
• “The Hype about Hydrogen …” J.J. Romm, ‘04
• “Energy and the Hydrogen Economy”
  U. Bossel, B. Eliasson, Jan ‘03
• “The Hydrogen Illusion”, Ulf Bossel, Mar ‘04
• “Twenty Hydrogen Myths”, A.B. Lovins, June ’03
• Recent magazines: from “E” optimism (Jan-Feb ’03) to current caution and reaction
“Can Hydrogen Fuel Deliver us from Oil, War, and Terrorism?”
Renewables should displace coal-source electricity, not make H2 fuel for FC cars decades in future
13 Aug 04

“Toward a Hydrogen Economy”
Spring '04
National Academies

“The Hype about Hydrogen”
“The Hope for Hydrogen”
“Do Fuel Cells make Environmental Sense?”
May-June ’04

“Is a Hydrogen Energy Economy the Right Goal?”
GLOBAL WARMING
Why Business Is Taking It So Seriously
BY JOHN CAREY (P. 60)

“Why Business Is Taking It So Seriously”
Sept '04

“Bulletins from a Warmer World”
International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF)

ASM
Materials Solutions Conference and Expo
18 – 20 October 04
Columbus, OH

Bill Leighty, The Leighty Foundation, Juneau, AK
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Presentation, papers on CD: your card, please.
Handout, poster
End of ASM presentation, 19 Oct 04, Columbus, OH

The following slides are supplementary to the podium presentation by Bill Leighty, The Leighty Foundation.

Thank you.
The Great Plains Wind Resource
4,000 MW of Nameplate Wind Generation
53 x 53 grid 500 m spacing
2,809 wind generators at 1,400 kW each
~ 850 sq km
~ 350 sq mi
Alliance Pipeline: CDN-USA
$3.5 billion (‘97-00)
1 Dec 00 startup
2,988 km (1857 miles)
36", 1740 psi (115 bar)
1.5 Bcf/d (16 GW)
Compression = 407 MW
Proposed Alaska Highway ANS Gas Pipeline Project

"ALCAN" Route

Foothills Pipe Lines Ltd.

Canada
Renewable-source energy, converted to GH2, feeds new NG pipeline system
Forum Outcomes

- Your notes and suggestions: summary report
- Presentations on CD, for panelists, others
- Consensus: RHS, GH2 transmission pipelines promising?
- Prepare to design, build, RHS pipelines
- Codes, standards for RHS
- Fatigue test linepipe materials for RHS
- New linepipe materials: hybrid, composite
- IRHTDF for IPHE project proposal: Improve it
- All new NG pipelines RHS – capable?
- Propose a “Conversion Project” to H2ICEHV’s?
- New international association?
- Another forum? Occasion?
“Hydrogen Transmission” Scenario
High-pressure electrolyzers
Wholesale electricity delivery

Wind Generators

High-pressure Electrolyzers

Storage: 120 GWh

1,000 miles

Hydrogen Gas Pipeline
18 - 36" diameter
~ 1,000 psi

Generators
ICE, CT, FC

End users
Retail

Cars, Buses, Trucks, Trains

Liquefy

Aircraft Fuel

AC grid
Wholesale
Capital Cost per Installed kW

4,000 MW Total System
2,670 Wind Generators, 1,500 kW each

Wind Generators
Electrolyzers
H2-PipelineSystem
HVDC-ElecSystem
Collection Infrastructure
Cost of Dakotas Wind Energy in Chicago
$US per kWh in year 2010

[Bar chart showing the cost of Dakotas Wind Energy in Chicago with different categories labeled as H2-A, H2-B, H2-C, ELEC-D, ELEC-E, ELEC-F, and ELEC-G.]

- Total Transmission Costs and Losses
- Wind Generated Unsubsidized COE
Annual Transmission Costs and Energy Losses, $ Million

- Fixed Charge: Capital Recovery
- Electrolyzers O+M
- Electrolyzer Losses
- Compressor Energy
- Electric Transmission System O+M
- Pipeline System O+M
- Electric Transmission Losses

Ch 5
Annual Profit / Loss
Wind Energy Generation, Transmission
Wholesale Delivery of Electricity
With PTC; Wind Capital Cost = $700 / kW
“Zero Emissions” Coal Synergy

- ND, MT, WY are wind and coal states
- Oxygen byproduct of electrolysis to “zero emissions” coal gasification plants
- 4,000 MW windplant produces –
  - ~ 3.1 million tons O2 per year
  - Value ~ $ 19.17 / ton at coal plant
  - $ 59 million per year delivered O2
- Share transmission; CF improve?
- Will CO2 sequestration work?
Hydrogen Fuel Cost in Minneapolis
From Dakotas Gasification Company (DGC) Lignite

Lignite – source GH2 * at DGC plant, Beulah, ND @ 1 atm $ 4.44 / Mscf

GGEE * = $ 1.58 / gal

Volume: 55 billion scf / year = 56 million gallons gasoline
(Assume C-sequestration, included in cost)

Annual and 400 miles transmission pipeline and compression costs

- $350 M pipeline @ 12% CRF = $ 42 M
- Pipeline O&M = $ 5 M
- Compression energy = $10 M

Total annual cost = $ 57 M / 56 M gallons = $ 1.02 / gal

Wholesale price of GH2 fuel in Minneapolis, end-of-pipe $ 2.60 / gal

Distribution and fuel station cost $ 0.79 – 1.45 / gal

Retail price of GH2 fuel in Minneapolis $ 3.39 – 4.05 / gal

Drive train efficiency ratio: FCEV / ICEV (gasoline) = 2

Equivalent retail price GH2 fuel per vehicle-mile $ 1.70 – 2.03 / gal

*GH2 means compressed gaseous hydrogen

*GGEE = gallon of gasoline energy equivalent: H2 = 325 Btu / scf; gasoline = 116,000 Btu / gal
International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF)

ASM
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Bill Leighty, The Leighty Foundation, Juneau, AK
wleighty@earthlink.net

Presentation, papers on CD: your card, please.
Handout, poster
250 hydrogen “gas stations”

Of 10,000 CA total

Whence the hydrogen?
Superconducting “Energy Pipeline”
Paul Grant, EPRI
~ 100 GW electrical + 100 GW LH2
Natural Gas Pipelines in Shield Tunnel, from “Energy Engineering”, Nippon Steel, 2001
Bishop, CA

Left: 3,000 MW HVDC (Pacific DC Intertie, PDCI)  Right: HVAC
Zion, IL
Near Zion nuclear plant, Oct 02
How much can we upgrade capacity of extant ROW and structures, with “no net loss of perceived or real safety or tranquility”?

Zion nuclear plant: 2 of 3 tower systems

HVDC potential: 6 bipoles @ 3,000 MW = 18,000 MW
500 MW HVDC Converter Station
Scotland, by Siemens
Stuart Energy
“Hydrogen Energy Station”
Hunterston Hydrogen Limited

Winner IEE “New Spirit Challenge 2002”

- 53 MW wind project.
- 4 MW electrolysis plant, operating 12 hours per day (most nights).
- 10 MW gas engine gensets.
- Short, medium & long term hydrogen storage.

Source: Wind Hydrogen Ltd., Sept 03
Competition for renewable-source hydrogen fuel

- From NG by SMR (steam methane reformation)
- From coal by gasification, with CO2 sequestration
- Nuclear: electricity, heat
Denmark’s energy from windpower

- 14th WHEC, Montreal, June 02
- Prof. Bent Sørensen, Roskilde Univ, DK
Focus

• Diverse, large, rich, stranded, renewable energy
• Gaseous hydrogen (GH2) pipelines
• Renewables – hydrogen service (RHS)
• Design, build, now, GH2 – RHS system:
  – Unique
  – Pilot-scale pipeline system

International
Renewable Hydrogen
Transmission
Demonstration Facility
Large, Stranded Renewables

- Largest, richest “deposits” remote, stranded
- Enough for humanity
- Time-varying:
  - Minute – to – seasonal scales
  - Unpredictable, stochastic
  - Non dispatchable, firm
- Transmission: city gate cost double plant gate
- Capacity factor (CF) challenge
- Storage challenge (power, energy):
  - GH2 pipeline
  - GH2 geologic:
    - “Wet” salt caverns; others unknown
    - Geographic availability
    - Cost: capital, energy loss (Nm3 – month)
  - Benefits:
    - Multiple-renewables synergy
    - Pipeline CF improved
GH2 Pipeline Interest

- National Academies, USA, Feb ’04, “Hydrogen Economy”
- ASME, International Pipeline Conference, Calgary, Oct 04
- Far East Pipeline Forum:
  - Northeast Asia Pipeline Network
  - Eastern Siberia to Far East Pipeline
- European Commission “NaturalHy”
- UK: Wind Hydrogen Ltd.
- IPHE (International Partnership for Hydrogen Economy)
- IEA Annex 18, Subtask B
- Renewables 2004, Bonn, June 04
Renewables-Hydrogen Service (RHS)

• Gathering and transmission
• Diverse, distant, dispersed, diffuse sources
• Many input, output nodes, wide size range
• Long-distance, high-capacity: diam, pressure
• Time-varying output
  – Hourly, daily
  – Seasonally
  – Severe pressure cycling: frequency, magnitude
• H2 attack on steel: HIC, HCC, HE
• Frequent inspections: pigging; other
• Storage valuable
• Low cost needed: capital, O+M, on-ramps
• Public apprehension: permitting, siting
• New spec needed?
IRHTDF

International Renewable Hydrogen Transmission Demonstration Facility

• International:
  – Global application
  – > $ 50 M : cost share
  – Technology share
  – IPHE project
• Pilot scale GH2 pipeline system optimizing:
  – Production – diverse renewable sources
  – Conversion
  – Gathering and Transmission
  – Storage
  – Delivery
  – End-use
  – Oxygen byproduct sale
• 30 – 100 km long, buried
• 12” diam for frequent “pigging”
• 1,000 – 2,000 psi operating pressure, P
• Daily pressure swings to ½ P
• Demonstration facility
  – Beyond “test”
  – Reliable fuel delivery
Conclusion: IRHTDF

- Concept, only
- > 5 years, $50 M
- Pilot-scale GH2 – RHS pipeline CORRIDOR
  - System design
  - Synergies, Benefits, Costs
  - Storage firms renewables: adds value
  - “Renewables – Hydrogen Service” (RHS)
- Acceptance: Public, insurance, finance, industry
- Next:
  - Fund, consortium: credibility
  - Craft RFP
  - Lab-scale R+D
  - Design, build, operate
- GH2 pipeline transmission long-term COE:
  - Lower than alternatives?
  - Competitive?
- Will GH2 – RHS pipelines likely succeed? If not?
- All new NG pipelines built “GH2 - capable”?
- Urgent?
Why IRHTDF? (E)

- Consensus on “ultimate” sustainable energy system:
  - Renewable-source, carbon-free, H2 fuel
  - Centralized production
19th World Energy Congress
Sydney, AUS, Sept 04

- Pragmatic market reforms
- Regional integration, energy supply systems
- Earn and keep public trust
Compressor
Reciprocating
Natural gas

3,000 hp
Electric Motor
Drive
“Hydrogen Transmission” Scenario

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

![Diagram of hydrogen transmission system]

Storage: 120 GWh at 1000 - 500 psi

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

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

**Storage: 120 GWh**

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

Wind Generators

Electrolyzers

Compressors

Wind Generators

Generators ICE, CT, FC

AC grid Wholesale

End users Retail

Cars, Buses, Trucks, Trains

Liquefy

Aircraft Fuel
“Hydrogen Transmission” Scenario

Hydrogen Fuel Delivery
High-pressure electrolyzers
Mid-line Compressors

Wind Generators
High-press Electrolyzers
Wind Generators

Storage: 120 GWh

1,000 miles
GH2 Pipeline
18 - 36" diameter
~ 2,000 psi

Mid-line Compressors Needed?

Generators
ICE, CT, FC

End users
Retail

AC grid
Wholesale

Cars, Buses,
Trucks, Trains

Liquefy
Aircraft Fuel
“Distributed Collection”

4,000 MW of Nameplate Wind Generation
150 x 19 grid
500 m spacing

2,850 wind generators at
1,400 kW each

~ 750 sq km
~ 300 sq mi
The gas is only $1.39. The aircraft carrier is $470, the tank is $125, the Stealth fighter is $330, the gas mask is $45 and the gun adds $30 a gallon.
ALL Denmark’s energy from windpower

- WHEC, Montreal, June 02
- Prof Bent Sorensen, Roskilde Univ, DK
Percent of Land Area > Wind Class 3
Existing ASME Codes and Standards Applicable to H₂ Infrastructure

- Tanks:
  - Boiler & Pressure Vessel Code (BPVC) Section VIII
    - Division 1 – Pressure Vessels
    - Division 2 – Alternative Rules
    - Division 3 – High Pressure Vessels
  - Code Case 2390
    - BPVC Section VIII, Div.3 - Composite Reinforced Pressure Vessels
  - BPVC Section X
    - Fiber-Reinforced Plastic Pressure Vessels
  - BPVC Section XII
    - Rules for Construction of Transport Tanks (1ˢᵗ edition July’04)

- Piping and Pipelines:
  - B31.1 - Power piping
  - B31.3 - Process piping
  - B31.8 - Gas pipelines
  - B31.8S - Managing gas pipeline integrity

- Valves, Flanges, and Fittings:
  - B16.34 - Valves
  - B16.5 - Pipe flanges and fittings
  - Many others
Existing ASME Codes and Standards Applicable to H₂ Infrastructure

Piping and Pipelines:
- B31.1 - Power piping
- B31.3 - Process piping
- B31.8 - Gas pipelines
- B31.8S - Managing gas pipeline integrity

Valves, Flanges, and Fittings:
- B16.34 - Valves
- B16.5 - Pipe flanges and fittings
- Many others
Challenges of Hydrogen Pipeline Transmission

Forum Cochairmen:
- Bill Leighty, Director, Alaska Applied Sciences, Inc. (AASI)
- John Koehr, Director, Codes and Standards Technology Institute, ASME
- Dr. Mo Mohitpour, President, Tempsys Pipeline Solutions Inc

Moderator: Louis E Hayden ASME Chairman H2 Code Committee
Panel Participants and Topics of Presentations

Forum: “Challenges of Hydrogen Pipeline Transmission”
ASME International Pipeline Conference, 4-8 Oct 04, Calgary

Gopala Kirshna Vinjamuri, US Department of Transportation (DOT), Research and Special Program Administration, Washington DC. “Development of DOT Regulations for Hydrogen Transportation Systems”

Onno Florisson Gasunie Research, N.V. Nederlandse Gasunie, The Netherlands “Investigations of the conditions under which the existing natural gas system can be used for hydrogen-natural gas mixtures (NATURALHY-project)” The EU “NaturalHy” project

Bill Leighty, Director, The Leighty Foundation (TLF) & Principal, Alaska Applied Sciences, Inc. (AASI), Juneau, Alaska "Renewable-hydrogen service for large gaseous hydrogen transmission pipelines”

Chris San Marchi, Brian P. Somerday and Steve Robinson, Gas Transfer Systems and H-Gear Sandia National Laboratories Livermore CA, USA” Hydrogen Pipelines and Material Compatibility Research at Sandia”


Dr O’Hashi, General Manager, Nippon Steel Corporation, Energy Eng. Division, and Professor M. Hirata, Shibaura Institute of Technology, Tokyo, “Potential Hydrogen Capability for the Proposed Northeast Asia Natural Gas Pipeline Network”

Louis E. Hayden Jr. PE.. Bethlehem PA, USA. “ASME Hydrogen Pipeline Codes and Standards for the Hydrogen Infrastructure”.

John J. Koehr, Director, ASME Codes and Standards Technology Institute. “Research and ASME Codes in Support of The Emerging Hydrogen Infrastructure

Thomas Joseph, Air Products and Chemicals Inc. Allentown PA, USA “Below Grade Storage and Distribution of Hydrogen”

Jim Campbell. P.Eng Manager, Pipeline Construction Air Liquide Process & Construction, Houston, Texas, "Conversion of Existing Hydrocarbon Pipelines for Hydrogen Service"
Design Requirements

\[ P = (2 \frac{S \cdot t}{D}) \cdot F \cdot E \cdot T \]

- **P** = Design Pressure
- **S** = Specified Minimum Yield Stress
- **t** = Nominal wall thickness
- **D** = Nominal outside Diameter
- **F**, **E**, **T** = Design, weld joint & temperature derating factors.
Material Qualification


Materials for pipe and components must be:

(a) Able to maintain structural integrity of the pipeline...

(b) Chemically compatible with any gas that they transport..., and

(c) Qualified in accordance with the applicable requirements of this subpart ...
# Existing Hydrogen Pipelines

<table>
<thead>
<tr>
<th>Company</th>
<th>Location</th>
<th>Mscf / day</th>
<th>Length km</th>
<th>Diameter inches</th>
<th>Pressure psi</th>
<th>Years Installed</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Praxair</td>
<td>Texas</td>
<td>100</td>
<td>8</td>
<td>70's</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NewJersey</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Indiana</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air Products</td>
<td>Texas</td>
<td>40</td>
<td>200</td>
<td>4 - 12</td>
<td>50 - 800</td>
<td>70's</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Louisiana</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ChemischeWerk Huls</td>
<td>Germany</td>
<td>100</td>
<td>220</td>
<td>4 - 12</td>
<td>360</td>
<td>1938</td>
<td></td>
</tr>
<tr>
<td>ICI, Teeside</td>
<td>England</td>
<td>20</td>
<td>16</td>
<td></td>
<td>750</td>
<td>70's</td>
<td></td>
</tr>
<tr>
<td>AirLiquide</td>
<td>France, Belgium</td>
<td>17</td>
<td>340</td>
<td>4</td>
<td>1,470</td>
<td>80's</td>
<td></td>
</tr>
<tr>
<td>Shell Canada</td>
<td>Scotford, AB</td>
<td>88</td>
<td>9</td>
<td>30</td>
<td>65</td>
<td>2002</td>
<td>X42</td>
</tr>
</tbody>
</table>

- **Low, constant pressure: ~ 30% SMYS**
- **Short, small diameter, low flowrate**
- **Mild steel; low strength**
- **100 Mscf / day = 266 tons / day = 397 MW**
- **80% captive; 20% merchant; worldwide 90M tons / yr**
“Hydrogen Transmission Scenario”
Collection Topology Options:
Electrolyzer and Rectifier Location

PE: Power Electronics
Hydrogen-Assisted Fracture Mechanisms in Metals

Hydrogen attack:
chemical reaction of atomic hydrogen with microstructural features

Hydrogen solute effects:
solute hydrogen enhanced failure of interfaces and deformation mechanisms

- Hydrogen accumulation at interfaces affects strength of interface (grain boundaries, second phases, inclusions)
- Hydrogen enhanced shear localization

[Diagram of hydrogen attack and solute effects]
Material variables: effect of yield strength on performance in hydrogen gas

- Notched tensile strength
- Reduction in Area (smooth tensile)

Material variables: effect of composition on hydrogen-assisted fracture

4340 (σₚ = 1450 MPa)

N. Bandyopadhyay et al., Metallurgical Transactions A, 1983
Mechanical variables: effect of frequency on hydrogen-assisted fatigue crack growth

SA-105 Grade II steel ($P_{H2} = 103$ MPa)

Environmental variables: effect of gas pressure on hydrogen-assisted fracture

**Pressure Vessel Steels**

- 4130 steel ($\sigma_{YS}=634$ MPa [92 ksi])
- 4145 steel ($\sigma_{YS}=669$ MPa [97 ksi])
- 4147 steel ($\sigma_{YS}=724$ MPa [105 ksi])

![Graph showing the effect of gas pressure on hydrogen-assisted fracture](image)
Environmental variables: effect of gas purity on hydrogen-assisted fracture

All Conceivable Variables Can Result in Hydrogen Effects

- Material Variables
  - Yield strength
  - Composition
  - Microstructure (welds)
- Mechanical Variables / Test Method
  - Frequency (Fatigue)
  - Presence of preexisting flaws
  - Strain rate effects (i.e., static load versus rising load)
  - Mixed mode loading
- Environmental Variables
  - Gas pressure and purity
  - Temperature
  - Hydrogen source: internal versus environmental

How should laboratory scale tests be translated into meaningful design data for hydrogen compatibility?