Running Alaska and the World on Renewables via Hydrogen and Ammonia Pipelines and Fuels

DVD available

Alaska Renewable Energy Fair 08
Anchorage, AK
9 August 08

Bill Leighty, Director
The Leighty Foundation
Juneau, AK
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907-586-1426  206-719-5554 cell
Solar Hydrogen Energy System

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

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)
Windpower - Hydrogen Hybrid Systems

By Dr. K. O’Hashi 20 Dec 99

Source: “Overview of the Transportation of Wind-Generated Hydrogen Using Natural Gas Pipeline Network in Northeast Asia” August, 2000
By: Asian Pipeline Research Center, Shibaura Institute of Technology
Proposed Northeast Asia Natural Gas Pipeline
The Fossil Fuel Age:
A “Blink of an Eye” between the First and Second Solar Civilizations

Coal, Oil, Gas

The First Solar Civilization

The Second Solar Civilization
The First Solar Civilization

One-fourth of farm’s solar energy harvest goes to the draft animals
The Second Solar Civilization

Japan and USA should begin to build it
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**

- Residential: 11.89
- Commercial: 8.96
- Industrial: 26.36
- Automotive: 16.18
- Freight: 9.19
- Airlines: 2.9

**H2 Production: 0**

**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)
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.
IT WASN’T HIS DRIVING
THAT CAUSED THE
ALASKAN OIL SPILL.
IT WAS YOURS.

It would be easy to blame the Valdez oil spill on one man. Or one company. Or even one industry.

Too easy.

Because the truth is, the spill was caused by a nation drunk on oil. And a government asleep at the wheel.

Did you know that if the government raised efficiency standards for cars just 1 MPG it would save 420,000 barrels of oil a day, or about twice the oil lost in the spill?

And that heat escaping through leaky windows wastes more oil than the Alaskan pipeline supplies in a year?

What it comes down to is this: As long as we are so dependent on fossil fuels and so wasteful of the oil we have, more offshore drilling and disastrous oil spills are inevitable.

But together we can curb our dependency on oil.

We can shelve Bush’s plan to lease the continental shelf to offshore drillers. We can put pressure on Washington to tighten auto efficiency standards and restore the funding for renewable energy sources Reagan took away.

And we can convince U.S. automakers to stop pushing large cars and muscle cars, and get back to marketing more fuel efficient automobiles.

Support Greenpeace.

Because it’s time we put the brakes on our nation’s oil dependency.

GREENPEACE
Pogo

“We have met the enemy...

“Here’s to each and all; Bless ’em!

C’mon, Albert, toast up!

I’m still broodin’ about pollution!”

Hear! Hear!

All them characters what dumps anything anywhere... they is enemies of the people!

Albert!

We have met the enemy and he is us.

Lemonade
YO! AMIGO!!
WE NEED THAT TREE TO PROTECT US FROM THE GREENHOUSE EFFECT!
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, particles from Sun
  - Meteors and dust
- Spend our capital?
MUST Run the World on Renewables – plus Nuclear?

• Emergencies:
  • Climate change
  • Energy prices
  • Energy security
• GW scale
• Beyond Electricity Grid
• Energy: beyond electricity
• “Hydricity”
HB 152, ’08 AK Legis

- $50M / year for 5 years, capital funds
- Leverage AK $ for other $
- RE grant fund; recommendation program
  - New project
  - Transmission must link to “grid”
  - [ “Commercial”, not R+D ] -- REAP
- Identify and evaluate long-term fuel resources
- Natural gas “last resort”
- Advisory Committee of 7 + DNR
- AK Heating Assistance program, H&SS
Alaska Energy Authority (AEA)
- Recommends grants
- Methodology
- Annual report to Legislature
- FY09:
  - Distribute grants;
  - Notify LB&A Committee
The Troubles 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” firms
  – Synergy reduces storage: wind + solar
GW-scale Transmission + Storage Options

- Electricity: HVAC, HVDC
  - CAES compressed air energy storage
  - Vanadium Redox battery (VRB Power Systems)
  - Sodium-sulfur battery
  - PHEV (distributed)

- Liquid Hydrogen (LH2)
  - Pipeline, truck, rail car, ship
  - 1/3 energy to liquefy

- Gaseous Hydrogen (GH2)
  - Pipeline
  - Geologic: salt caverns (man-made)
  - Geologic: natural formations

- Ammonia (NH3) liquid
  - Tank, refrigerated, 10K – 60K ton
  - Truck, rail car, ship

- Liquid synthetic HC’s – zero net C
  - Pipeline
  - Tank, truck, rail car, ship
  - Geologic: salt caverns (man made)

- “Energy Pipeline”, EPRI: LH2 in pipeline, SC LVDC electric

- Chemicals
  - Hydrides
  - Al – Ga ← → Alumina
“Firm” energy worth more

- Every hour, every year
- Strategically: indigenous, secure
- Market price
- Dispatchable
- Bankable large projects
- Risk avoidance: rapid climate change
ABB, ISET Kassel “Huge Catchment Area”

Windpower 01
Compressed air energy storage (CAES)

Iowa geology
Hourly to Weekly Storage

- Compressed air energy storage (CAES)
- Sodium – sulfur battery
- VRB: vanadium redox battery
- Pumped hydro
GW-scale Transmission + Annual Firming

Storage Options

- **Electricity**: HVAC, HVDC
  - CAES compressed air energy storage
  - Vanadium Redox battery (VRB Power Systems)
  - Sodium-sulfur battery
  - PHEV (distributed)

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- **Chemicals**
  - Hydrides
  - Al – Ga ← → Alumina
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
# 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>
<td>1,210</td>
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<td>124,144</td>
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<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>
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
“Firm” energy worth more

- Every hour, every year
- Strategically: indigenous, secure
- Market price
- Dispatchable
- Bankable large projects
- Risk avoidance: rapid climate change
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
Total solar: $\sim 3 \times 10^{14}$ kg / yr
Total wind: $\sim 3 \times 10^{11}$ kg / yr

Rich, stranded Resources
“There’s a better way to do it... Find it”
“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
Hydrogen Energy

GE Tomorrow = Electricity + Hydrogen Infrastructure

GE Today = Electricity Infrastructure
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

• Breaks “chicken-egg” dilemma
• Bridge to sustainable future
Continental Supergrid – EPRI concept “Energy Pipeline”

Thermal Insulation

Vacuum

Electrical Insulation

SC*

LH2**

~ 100 GW elec LVDC + ~ 100 GW LH2

* SC: MgB$_2$ magnesium diboride superconductor

** LH2: liquid hydrogen coolant, energy transmit

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

Frank Novachek, Director Corporate Planning

H₂ Production/Use (Large / Small)
Potential Hydrogen Delivery System
Dick Kelly (Xcel) and Dan Arvizu (NREL) shake hands after pushing button to light H2 sign and dedicate system

National Wind Technology Center
Golden, CO
2006

Xcel – NREL
Wind – Hydrogen Demo

DVD available

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

Wind – Hydrogen
Autonomous System

Replaces aging electricity cable from mainland
The wind – hydrogen plant at Utsira

A vision becoming reality
Airbus Industrie concept: liquid hydrogen fueled
“Firm” Energy Essential

- Rural Alaska, Islands, Humanity
- Risk avoidance:
  - Rapid climate change
  - Death
- Every hour, every year
- Strategically: indigenous, secure
- Market price
- Dispatchable
- Bankable large projects
“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 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
1: Adequate Renewables

- “Run” the world; humanity’s “needs”
- “Distributed” and “Centralized”
- Affordable, benign
- Diverse, synergistic
- Richest are “stranded”
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:
  - CO$_2$ – 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) pipeline systems
  - Conversion, gathering
  - Transmission
  - Storage
  - Distribution

- Geologic storage “firms”

- Pilot plant needed:
  - every major new industrial process
  - IRHTDF
4: 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

*
5: 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
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
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

Pipeline Energy Storage

1,500 psi

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

Generators
ICE, CT, FC

End users
Retail

AC grid
Wholesale

Cars, Buses,
Trucks, Trains

Liquefy

Aircraft Fuel

Liquefy
“We know how to pipeline hydrogen” Air Products
~ 10,000 miles of GH2 pipeline, worldwide

Air Products H₂/ CO Pipeline - Texas Gulf Coast
Air Products Company
REFINERY ACTIVITY
LOS ANGELES BASIN, CALIFORNIA
Hydrogen Embrittlement (HE) of Pipeline Steel
Industrial H2 Pipelines

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

* Specified Minimum Yield Strength
Line Pipe Material Options

• Control Hydrogen Embrittlement (HE)
• Minimize energy-distance cost (kg-km)
• Nippon Steel
  – “Sour service” X65 steel
  – HTUFF : microstructure
• CRLP * by TransCanada and NCF
• Polymer – metal (HDPE + foil + FRP)
  * Composite Reinforced Line Pipe
Composite Reinforced Line Pipe (CRLP)
TransCanada Pipelines & NCF Industries
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.
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.
CRLPTM is a trademark of NCF Industries, Inc.

CRLPTM is manufactured under license from NCF Industries, Inc. U.S. and Foreign patents have been issued and are pending.
HDPE + Al foil GH2 barrier

Hydrogen Discoveries, Inc. (HDI)

3” long
4” ID
Hydrogen Transmission Scenario
Storage: Pipeline smoothing, geologic firming

Gaseous Hydrogen (GH2) Transmission Pipeline

GH2 Fuel Market: City Gate

Energy Storage in Pipeline

GH2 Geologic Storage?
Hydrogen Energy Storage

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

Pipeline Storage = 240 GWh

Wind Generators
Electrolyzers
Wind Generators

Geologic Storage?

Storage
Generators ICE, CT, FC
Cars, Buses, Trucks, Trains
Liquefy
Aircraft Fuel

AC grid Wholesale
End users Retail

Storage
Solar Hydrogen Energy System

Sunlight from local star

Solar panel

Electrolyzer

H₂

O₂

Fuel Cell

Electricity

Electricity

Work

2H₂O + Energy → 2H₂ + O₂

2H₂ + O₂ → 2H₂O + Energy
Great Plains Windplant, Pipeline
Hourly Output for Typical Week
August Hourly Pipeline Input and Output

Great Plains Windplant: Actual Hourly Output
Wind-Hydrogen 1,000 Mile Pipeline Optimization Simulation

Delivered Cost $ / kg H2

Utilization

Delivered Cost - WindGen Utilization - Pipeline Utilization - Electrolyzer Utilization
“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 GWh 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

Instantaneous hydrogen supply with cavern storage
Annual – scale “Firming”
Great Plains Wind

- Potential, 12 states, ~50% land area:
  - 10,000 TWh = 100 quads / yr = 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 mt @ 2,500 tons / cavern = 6 caverns
  - “Firming” energy storage, all Great Plains wind:
    - as GH2 = 17,000 caverns @ $15M each = $264 billion
The diagram shows a grid of caverns with a total of 104 caverns in the 8 x 13 grid and 96 caverns in the 8 x 12 grid, totaling 200 caverns per square mile. Each cavern is 200 ft in diameter, with a minimum 200 ft web separation. The total area covered is 5,280 ft = 1 mile. The label on the right side of the diagram indicates "Firm" 4,000 MW Great Plains wind with 14 caverns and a 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
Anhydrous Ammonia, NH$_3$ Fertilizer $\rightarrow$ Fuel

Business case:

- Market size, share:
  - 15 mt / yr ag fertilizer
  - 5 mt / yr other
  - ? mtT / yr NH$_3$ fuel
  - ICE, CT, fuel cell

- RE - NH$_3$ 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: 1990-2008
$ per ton NH3: 0-1000
“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 (NH₃) 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 $\sim$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$_3$
Green Ammonia Cycle
Renewable-source, C-free

Renewable Energy Input
(Electricity or Heat & Electricity)

NH₃ Synthesis

3 H₂ + N₂ → 2 NH₃

(NCombustion or Fuel Cell)

4 NH₃ + 3 O₂ → 2 N₂ + 6 H₂O

Energy Recovery
- Electricity
- Byproduct heat

N₂ & H₂O Return to Environment

Electricity Generation

NH₃ Storage
Asset Portfolio

Liquid ammonia pipeline
Liquid Ammonia Storage Tank

60,000 Tons

-28 F
Annual – scale “Firming”
Great Plains Wind

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• Seasonality:
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  – “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 9003
- “Renewable fertilizer study”
- Anhydrous ammonia: \( \text{NH}_3, \text{nitrogen} \)
- Commercialization of RE - \( \text{NH}_3 \)
- $1M recommended appropriation
- July 08: no approp; try FY10
### Total Installed Capital Cost

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

<table>
<thead>
<tr>
<th>Windplant size</th>
<th>1,000 MW</th>
<th>2,000 MW</th>
</tr>
</thead>
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<td>Pipeline, 20” *</td>
<td>1,100</td>
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</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>$2,600</td>
<td>$4,100</td>
</tr>
</tbody>
</table>

* $1.1 M / mile
Hydrogen Energy Storage

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

Pipeline Storage = 240 GWh

Electrolyzers

Wind Generators

AC grid Wholesale

Generators
ICE, CT, FC

End users
Retail

Cars, Buses,
Trucks, Trains

Storage

Liquefy

Aircraft Fuel

Storage

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

Geologic Storage ?
Low Cost Electrolyzer Technology for Industrial Hydrogen Markets

National Hydrogen Association Annual Hydrogen Conference April 2008

Richard Bourgeois¹
Dana Swalla¹
Todd Ramsden²

©GE Global Research Center, Niskayuna NY
• National Renewable Energy Laboratory, Golden CO

2 H₂O + ELECTRICITY → O₂ + 2 H₂
Industrial Hydrogen Markets

Global consumption: 42 million tons H₂ per year

Number of sites in USA

Large scale: 90%

Mid-scale Industrial

Site capacity, kg H₂ / day

Global consumption: 42 million tons H₂ per year
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

<table>
<thead>
<tr>
<th>Size</th>
<th>Power*</th>
<th>Module Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 kgph</td>
<td>250 kW</td>
<td>$45,800</td>
</tr>
<tr>
<td>20 kgph</td>
<td>1 MW</td>
<td>$150,000</td>
</tr>
</tbody>
</table>

* 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**

<table>
<thead>
<tr>
<th>Cost of Electricity, ¢/kWh</th>
<th>Capital Cost, $/kW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$4,000</td>
</tr>
<tr>
<td>1.0</td>
<td>$4.79</td>
</tr>
<tr>
<td>2.0</td>
<td>$5.29</td>
</tr>
<tr>
<td>3.0</td>
<td>$5.79</td>
</tr>
<tr>
<td>4.0</td>
<td>$6.30</td>
</tr>
<tr>
<td>5.0</td>
<td>$6.80</td>
</tr>
<tr>
<td>6.0</td>
<td>$7.30</td>
</tr>
<tr>
<td>7.0</td>
<td>$7.80</td>
</tr>
<tr>
<td>8.0</td>
<td>$8.30</td>
</tr>
</tbody>
</table>
**Total Installed Capital Cost**

*1,000 mile pipeline, $US million*

**GH2 Delivery to City Gate**

<table>
<thead>
<tr>
<th>Windplant size</th>
<th>1,000 MW</th>
<th>2,000 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind generators</td>
<td>$1,000</td>
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</tr>
</tbody>
</table>

**TOTAL**

|             | $2,600   | $4,100   |

* $1.1 M / mile
## 2,000 MW windplant output

### 100 % Capacity Factor

<table>
<thead>
<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>48,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>As H2</td>
<td></td>
<td>311</td>
<td>1,342</td>
<td>489,776</td>
</tr>
<tr>
<td>As NH3</td>
<td></td>
<td>1,726</td>
<td>7,455</td>
<td>2,720,980</td>
</tr>
<tr>
<td>10” NH3 pipeline capacity as NH3</td>
<td>150</td>
<td>3,600</td>
<td>1,314,000</td>
<td></td>
</tr>
<tr>
<td>10” NH3 pipeline capacity as H2</td>
<td>27</td>
<td>648</td>
<td>236,520</td>
<td></td>
</tr>
</tbody>
</table>

### 40 % Capacity Factor

<table>
<thead>
<tr>
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<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>60</td>
<td>1,440</td>
<td>525,600</td>
<td></td>
</tr>
<tr>
<td>10” NH3 pipeline capacity as H2</td>
<td>11</td>
<td>259</td>
<td>94,608</td>
<td></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
“Firming” Cavern Storage

Hydrogen Energy Storage

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

Pipeline Storage = 240 GWh

AC grid
Wholesale

End users
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Cars, Buses, Trucks, Trains

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Geologic Storage?
### Optimistic: Total Installed Capital Cost

**1,000 mile Pipeline**

“Firming” GH2 cavern storage

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<tr>
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<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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<td>1,100</td>
</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>TOTAL</td>
<td>$2,830</td>
<td>$4,560</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
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 $\rightarrow$ 100%
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?

• Global
• Indigenous
• Firm: available
• C-free
• Benign
• Abundant
• Affordable
• Equitable
• Perpetual: solar, geothermal
Running Alaska and the World on Renewables via Hydrogen and Ammonia Pipelines and Fuels

DVD available

Alaska Renewable Energy Fair 08
Anchorage, AK
9 August 08

Bill Leighty, Director
The Leighty Foundation
Juneau, AK
wleighty@earthlink.net
907-586-1426 206-719-5554 cell
9 August 08

REAP
Alaska Renewable Energy Fair 08
Anchorage
Value from Collaboration

Xcel Energy & NREL
- DC/DC Interface
- Coordinated “Wind Storage”
- Re-deployable

Basin Electric & NREL
- Larger Scale “Wind Storage”
- Vehicle Applications

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

Fort Collins Utilities & Colorado OEMC
- High-Pressure Electrolysis
- Vehicle Fueling Station & Fuel Cell
- Hydrogen/Natural Gas Mixing

• Parallel timetables
• Inter-project collaboration and data sharing