Running the World on Renewables: Gaseous Hydrogen Pipeline Transmission with Firming Geologic Storage

SMRI, Basel, CH, 30 April 07

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SMRI Quest:

1. Is “firming” renewables, as high-pressure gaseous hydrogen (GH2) in salt caverns, technically feasible?
2. Economically attractive, competitive, bankable?
3. R+D path? Bedded special for GH2?
4. Worldwide potential?
5. SMRI
   - Interest, support?
   - Pilot plant required
1: Adequate Renewables

- Run the world; humanity’s needs
- “Distributed” and “Centralized”
- Affordable, benign
- Diverse, synergistic
- Richest are “stranded”
Global Opportunity
Wind Powering America

NW Iowa 190 MW windplant
Hydro

Hoover Dam
Geothermal:
Nesjavellir Power Plant, Iceland; 90 MW
Photobiological
*Rhodobacter sphaeroides*
Algae: *Chlamydomonas reinhardtii*

Photo: Tasios Melis, PhD, UC Berkeley, USA
Dry Biomass
Wet Biomass: Anaerobic Digester
Solar thermal
Stirling Energy Systems, Inc.

Model solar thermal power plant, NM    Completed May 05
Parabolic Trough
Concentrating Solar Power (CSP)
CA, Spain
Photovoltaic (PV)

Small
Medium
Large
Example: Vision of a bright future

The Silk Road Genesis Project*
*proposed by Sanyo

Vision of solar farms in China along the historic silk road to cover $\frac{1}{3}$ of China's energy demand in 2030
GW-scale Transmission Storage Options

- **Electricity**
  - Vanadium Redox battery (VRB Power Systems)
- **Gaseous Hydrogen (GH2) pipeline**
  - Pipeline
  - Geologic: salt caverns (man-made)
  - Geologic: natural formations
- **Liquid Hydrogen (LH2)**
  - Pipeline, truck, rail car, ship
- **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**
- **Chemicals**
  - Hydrides
  - Al – Ga ← → Alumina
Trouble with Renewables

- Diffuse, dispersed: gathering cost
- Richest are remote: “stranded”
- Time-varying output:
  - “intermittent”
  - “firming” storage required
- Transmission:
  - low capacity factor (CF) or curtailment
  - NIMBY
- Distributed or centralized?
Trouble with Electricity Transmission

• Grid nearly full
  – New wind must pay for transmission
  – Costly: AC or DC
• NIMBY: generators, lines
• Low capacity factor or curtailment
• No storage: smoothing or firming
• Overhead towers vulnerable: God or man
• Underground: Only HVDC, ~ 6x cost
SMRI Quest: Help me --

1. Get cavern storage right:
   - Concepts
   - Costs
   - Geography
   - Systems analysis

2. Avoid hydrogen error, exaggeration:
   - “Clean, abundant energy source”
   - “Running our cars on water”
   - “Hydrogen economy”
   - Confusion: public, industry, banking

3. Capital flows:
   - Avoid misplaced
   - Attract new

4. New SM opportunity?
1. Great Plains wind could provide all USA energy: \((100 \text{ quads} = 100 \text{ EJ}) / \text{ year}\)

2. “Firming” wind at annual scale requires \(~ 15,000\) salt caverns plus GH2 pipelines; diversity = fewer

3. \(2,500 \leftrightarrow 1,000\) psi

4. ConocoPhillips “Clemens Terminal”:
   - \(160 \times 1,000 \text{ ft} = 6.4 \text{ Mft}^3\)
   - \(580,000\) m\(^3\)
   - \(2,500\) tons GH2 net \(~= 940\) mmmscf GH2
   - replacement cost ?
“Firm” energy worth more

- Strategically: indigenous, secure
- Market price
- Dispatchable
- Bankable large projects
- Risk avoidance: rapid climate change
1: Adequate Renewables

- “Run” the world; humanity’s “needs”
- “Distributed” and “Centralized”
- Affordable, benign
- Diverse, synergistic
- Richest are “stranded”
### 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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<td><strong>401</strong></td>
<td><strong>$ 401</strong></td>
<td><strong>890</strong></td>
<td><strong>$ 534</strong></td>
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</table>
Total solar: $\sim 3 \times 10^{14} \text{ kg / yr}$

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

Rich, stranded Resources
1: Adequate Renewables

- “Run” the world; humanity’s “needs”
- “Distributed” and “Centralized”
- Affordable, benign
- Diverse, synergistic
- Richest are “stranded”
"Stranded"

~ 3,200 miles, 52", $25 B

4 bcf/d NG delivered: 50 GW

ANS Gasline
Hydrogen-capable linepipe?
The Great Plains Wind Resource

2001: 4,000 MW windplant, ND → Chicago
- Great Plains Wind: Huge, Stranded
- Total USA energy: 100 quads = 10,000 TWh
- 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?
Hydrogen - fueled
2005 Prius
ICE Hybrid

www.qtww.com
Total solar: \( \sim 3 \times 10^{14} \text{ kg / yr} \)

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

Rich, stranded Resources
The Great Plains Wind Resource

How shall we bring the large, stranded, Great Plains renewables to market?
1: Adequate Renewables

- “Firming” adds value
  - Strategic: security, indigenous
  - Market price
- Seasonal-scale storage
- Salt caverns lowest cost:
  Forsberg, ORNL: renewables - nuclear
- Need nuclear? Through 2100?
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) pipelines
  - Conversion, gathering
  - Transmission
  - Storage
  - Distribution

- Geologic storage “firms”

- Pilot plant needed:
  - every major new industrial process
  - IRHTDF
4: *Hydrogen’s principal value*

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

- Every major new industrial process
- Diverse, large-scale, stranded
- Renewables-source systems
- IRHTDF
- Posters: Japan, Canada, IPHE
International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF) Pilot plant

Global opportunity: IPHE project
Pilot-scale Hydrogen Pipeline System: Renewables

- Diverse
- Dispersed, diffuse
- Large-scale
- Stranded
  - Remote
  - No transmission
Solar Hydrogen Energy System

- Sunlight from local star
- Electrolyzer
- Fuel Cell
- Electricity
- Work
- H₂
- O₂
Hydrogen Fuel Cell
Proton Exchange Membrane (PEM) type

Hydrogen (H2) combines with Oxygen (O2) to make electricity + heat + water (H2O)
IRHTDF: generation, conversion, collection, storage corridor

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

GH2 geologic storage

O2 pipeline

*
5: Pilot plant needed

• Every major new industrial process
• Diverse, large-scale, stranded
• Renewables-source systems
• IRHTDF: papers
• SMRI interest, help?
Compressorless system: No firming storage

Transmission

Wind Generators
High-pressure Electrolyzers

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

City gate

500 psi

Distribution

AC grid
Generators
ICE, CT, FC
End users
Retail
Cars, Buses, Trucks, Trains
Liquefy
Aircraft Fuel

Pipeline Energy Storage
1,500 psi
Topology Options: \( H_2 \) and \( O_2 \) Production and Gathering from Renewable Energy Generation
Norsk Hydro electrolyzer, KOH type
560 kW input, 130 Nm3 / hour at 450 psi (30 bar)
# 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>
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</thead>
<tbody>
<tr>
<td>Wind generators</td>
<td>$1,000</td>
<td>$2,000</td>
</tr>
<tr>
<td>Electrolyzers</td>
<td>500</td>
<td>1,000</td>
</tr>
<tr>
<td>Pipeline, 20” *</td>
<td>1,100</td>
<td>1,100</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>$2,600</td>
<td>$4,100</td>
</tr>
</tbody>
</table>

* $1.1 M / mile
City-gate GH2 cost @ 15% CRF, 20” pipeline, from 2,000 MW Great Plains windplant

Competitive cost?
Great Plains Windplant, Pipeline
Hourly Output for Typical Week

Hourly Hydrogen Pipeline Input and Output
Great Plains Windplant: Actual Hourly Output

August Hourly Pipeline Input and Output

Days

MW

Input  Output
Hydrogen Energy Storage

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

Pipeline Storage = 240 GWh

Storage

AC grid Wholesale
End users Retail

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

Storage

Geologic Storage?
# Total Installed Capital Cost

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

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* @ $1.1 M / mile
Wind seasonality, Great Plains

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

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

Seasonality Factor

Winter: 1.2
Spring: 1.2
Summer: 0.7
Fall: 1.0
Energy storage reduced by diverse renewables synergy

• Solar
  – Concentrating Solar Power (CSP)
  – PV
• Biomass
  – Dry: forests, farms
  – Wet: manure
Annual – scale “Firming”
Great Plains Wind

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

• Seasonality:
  – Summer minimum
  – Spring – Summer maximum storage
  – “Firming” energy storage, per 1,000 MW wind:
    • as electricity = 450 GWh
    • as GH2 = 15,712 tons, metric @ 2,500 tons / cavern = 6 caverns
    • as NH3 = 87,291 tons, metric @ 60,000 tons / tank = 1.4 tanks
  – “Firming” energy storage, all great Plains wind:
    • as GH2 = 17,000 caverns @ $15M each = $264 billion
    • as NH3 = 5,000 tanks @ $25M each = $127 billion
## Optimistic: Total Installed Capital Cost

### 1,000 mile Pipeline

“Firming” GH2 cavern storage

<table>
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<tr>
<th>Windplant size</th>
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<td>Pipeline, 20”</td>
<td>1,100</td>
<td>1,100</td>
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<tr>
<td># storage caverns</td>
<td>[4]</td>
<td>[8]</td>
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<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>
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<td>TOTAL</td>
<td>$2,660</td>
<td>$4,220</td>
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</table>

Cavern storage: ~3% of total capital cost
**Pessimistic: Total Installed Capital Cost**

**1,000 mile Pipeline**

“Firming” GH2 cavern storage

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<thead>
<tr>
<th></th>
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<td>1,000</td>
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<tr>
<td>Pipeline, 20”</td>
<td>1,100</td>
<td>1,100</td>
</tr>
<tr>
<td># storage caverns</td>
<td>[4]</td>
<td>[8]</td>
</tr>
<tr>
<td>Caverns @ $50M ea</td>
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<td>400</td>
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<tr>
<td>Cushion gas @ $5M ea</td>
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<td>60</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$2,830</td>
<td>$4,560</td>
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</table>

Cavern storage: ~10% of total capital cost
Solution-mined Salt Caverns assume

- “Clemens Terminal”
  - 6.4 M ft$^3$ = 580,000 m$^3$ gross
  - 2,200 psi MAOP $\rightarrow$ 1,000 psi min
  - 2,300 ft to cavern top
- Arrays of 10 – 100 caverns
- Same pressure: manifold
- Low input / output flowrate
- Minimum BOS
- Favorable conditions:
  - geography
  - geology
  - water supply
  - brine disposal
Optimistic: “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: “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
Hydrogen Can Be Stored Underground At Low Costs

Current Hydrogen Storage

Salt Formation

Shaft

Storage caverns in hard-rock formation

Natural Gas Stored Underground

Surface lake

Water compensation column

Shaft

Other rock strata

Impervious caprock

Porous rock air storage

Water
Working Gas in Underground Storage Compared with 5-Year Range

Total USA Natural Gas Underground Storage

Source: USDOE, EIA  http://tonto.eia.doe.gov/oog/info/NGS/ngs.html
"Domal" salt storage caverns, solution-mined
Meters below ground level
"Bedded" salt

Solution-mining of storage caverns typical of New Mexico and west Texas
Major “bedded” salt basins

Gaseous hydrogen storage may be feasible
Depth to Top of Bedded Salt (ft)
Thickness of bedded salt strata (ft)
Wellhead, new Gaseous Hydrogen Storage Cavern

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

Instantaneous hydrogen supply with cavern storage
ChevronPhillips GH2 Storage Cavern

- Near Freeport, TX, Clemens Terminal
- Solution-mined: 3 – 5 years
- Estimated capital cost ’05 ~ $5 M / MMbbl
- 20 years old
- 2,200 psi design -- 2,000 psi operating
- Cavern roof 2,800 ft below surface
  \[ d = \frac{\text{psi}}{0.78} \]
- 160 ft diam x 1,000 ft high
  - 580,000 m³
  - 6.4 million ft³
- New Praxair cavern ‘07, TX: cost?
Gulf of Mexico Coast

- Huge salt structures are offshore
- Sea water leachant, sea brine disposal
- Offshore drilling, string adjustment costs
- Minimum distance offshore
- Hydrogen safety, acceptability
- Mature offshore, seafloor industry
- Breakthroughs needed
- Firm TX wind for petro market: onshore, offshore
- Best wind is offshore
Assumptions: A

AHP chem plant
Alaska Applied Sciences, Inc., Jan 07

- Firm GH2 ~290 MMscfd (~680,000 kg / day) at 1,010 psi
- No backup hydrogen supply (NG via SMR)
- Windplant CF = 35%
- 4,300 MW (nameplate) windplant
- Windplant installed capital cost $1,500 / kW
- Windplant owned by AHP project or by merchant
- Windplant / electrolyzer nameplate = 125%
- Electrolyzer installed capital cost per kWe input:
  - $ 855 Hydro Hydrogen Technologies estimate
  - $ 450 optimistic estimate
  - $ 350 USDOE goal
- Electrolyzer efficiency = 75%
Assumptions: B

AHP chem plant

- 360 mile GH2 pipeline: windplant → chem plant
- Large reciprocating GH2 compressors, elec motor drive
- GH2 supply “firmed” at annual scale in salt caverns:
  - ~ 280 million cubic feet gross volume
  - ~ 14 to 20 caverns required
  - Man-made, solution-mined caverns in eastern NM
  - NM bedded salt caverns will be adequately GH2-tight (?)
- Electricity transmission of wind energy rejected:
  - New 4,000 MW transmission line costs > GH2 pipeline
  - Provides no affordable “firming” energy storage
  - Low CF: same as windplant
- Simple CRF method for annualizing capital costs
- Suitable geology for salt caverns in eastern NM
Assumptions: C
AHP chem plant

• Oxygen byproduct is stranded; has no value
• Electrolysis feedwater required for 3-train AHP plant:
  ~ 1,800 acre-feet per year
• GH2 pipeline is 20” diam, ¾” wall, 1,500 psi max,
  at nearly-constant pressure, X42 carbon steel
• GH2 pipeline installed cost ~ $1.25 M per mile
• GH2 pipeline length = 360 miles, including caverns
  access stub
• Federal production tax credit (PTC) = $0.019 / kWh
• GH2 salt storage caverns ~ 6.5 million ft³ each
• Windplant land rent = $2,000 / MW nameplate / year
## Cases Considered

### AHP chem plant

<table>
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<tr>
<th>Case</th>
<th>CRF%</th>
<th>PTC</th>
<th>Windplant Owner</th>
<th>AHP value or Merchant $ / MWh</th>
<th>Electrolyzer $ / kWe</th>
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<td>Yes</td>
<td>Merchant</td>
<td>$ 50</td>
<td>$ 450</td>
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CRF: capital recovery factor  
PTC: USA federal production tax credit for wind energy, other renewables  
AHP value: value to AHP of owning the windplant  
Merchant $ / MWh: price paid to merchant plant for wind energy
## Cases Considered: Results

**Cost per kg GH2 $ US**

*AHP chem plant*

<table>
<thead>
<tr>
<th>CASE</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
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<td>6.03</td>
<td>4.74</td>
<td>3.74</td>
<td>3.92</td>
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<tr>
<td>AHP plant gate</td>
<td>7.39</td>
<td>5.38</td>
<td>7.44</td>
<td>6.00</td>
<td>4.99</td>
<td>5.28</td>
<td>4.88</td>
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<tr>
<td>GH2 transmission cost</td>
<td>1.32</td>
<td>1.31</td>
<td>1.41</td>
<td>1.27</td>
<td>1.26</td>
<td>1.36</td>
<td>1.26</td>
</tr>
</tbody>
</table>

Windplant gate: output of wind generator – electrolyzer system; no O₂ value

AHP plant gate: delivery end of GH2 pipeline, at 1,010 psi, firmed

GH2 transmission cost: gaseous hydrogen (GH2) pipeline and compression, capital and O&M costs
A - C: Chem plant owns windplant
D - G: Merchant windplant

Capital Costs, Cases A - G, AHP Plant

- Wind: plant or purchased
- Electrolyzers
- H2 Pipeline
- H2 storage caverns
- H2 Compressors
- Backup H2 supply
- ASU
- TSA
Topology Options: H₂ and O₂ Production and Gathering from Renewable Energy Generation
4,300 MW wind

Renewable Electricity Generators

Electrolyzers

O2 vent to atmosphere

~ 300 mile Transmission Pipeline

AHP Coal plant

ASU

Electricity

O2

H2

1,500 psi

1,010 psi

H2O

Geologic Hydrogen storage in salt caverns

~ 290 MMscfd (~680,000 kg / day) at 1,010 psi
4,300 MW wind

Renewable Electricity Generators

Electrolyzers

H₂O → H₂

H₂ → O₂ vent to atmosphere

Transmission Pipeline ~ 300 mile

Compressor

ASU

Electricity O₂

AHP Coal plant

Firm GH₂ ~290 MMscfd (~680,000 kg / day) at 1,010 psi

Geologic Hydrogen storage in salt caverns
4,300 MW wind

Renewable Electricity Generators

Electrolyzers

O2 vent to atmosphere

450 psi

H2

H20

Compressor

1,500 psi

~ 300 mile GH2 Transmission Pipeline

1,010 psi

ASU

Electricity

O2

AHP Coal plant

Geologic Hydrogen storage in salt caverns

Firm GH2 ~290 MMscfd (~680,000 kg / day) at 1,010 psi
Renewable Electricity Generators

Electrolyzers

\[ H_2O \rightarrow H_2 \]

\[ H_2 \]

Comp #1

\[ 450 \text{ psi} \]

\[ 1,500 \text{ psi} \]

Comp #2

\[ 1,010 \text{ psi} \]

Geologic Hydrogen storage in salt caverns

Transmission Pipeline

\[ \sim 300 \text{ mile} \]

Comp: GH2 compressor

ASU: air separation unit

AHP: advanced hydrogasification process

O2 vent to atmosphere

ASU

O2

AHP Coal plant

Electricity
Renewable Electricity Generators

Electrolyzers

H2O → H2

Comp #1: 812 MMscfd H2, 450 → 1,500 psi

Comp #2: 300 MMscfd H2, 150 → 1,010 psi

ASU

AHP Coal plant

O2 vent to atmosphere

~ 300 miles
GH2 Transmission Pipeline

Electricity

Comp: GH2 compressor
TSA: temperature swing adsorber
AHP: advanced hydrogasification process

Geologic Hydrogen storage in salt caverns
Renewable Electricity Generators

Electrolyzers

H₂O

Electrolyzers

H₂

Comp #1 450 psi

Comp #2 1,500 psi

Comp #3 1,800 psi

TSA: temperature swing adsorber

Comp: GH₂ compressor

AHP: advanced hydrogasification process

Comp #1: 812 MMscfd H₂, 450 → 1,500 psi
Comp #2: 300 MMscfd H₂, 150 → 1,010 psi
Comp #3: 600 MMscfd H₂, 750 → 1,800 psi

Geologic Hydrogen storage in salt caverns

~ 300 miles

GH₂ Transmission Pipeline

Electricity

ASU

O₂

Comp #2

1,010 psi

Comp #3

Withdraw

Fill

Electricity

O₂ vent to atmosphere

Electricity

Coal plant
Dresser-Rand Large Reciprocating Compressors for Natural Gas and Hydrogen

5 – 13,000 hp
(8 x 13) = 104 + (8 x 12) = 96  Total = 200 caverns per square mile
Each cavern is 200 ft diam, with minimum 200 ft web separation.

Maximum Cavern Packing Density: 14 caverns

(8 x 13) = 104 + (8 x 12) = 96  Total = 200 caverns per square mile
Each cavern is 200 ft diam, with minimum 200 ft web separation.
DOE-EIA: Estimated 2005 US energy use

Estimated Future U.S. Energy Requirements - 96.8 Quads

- Hydro: 0.94
- Bio/Geo: 3.81
- Wind: 0.06
- Solar: 0
- Nuclear: 7.48
- Coal: 20.83
- Gas: 24.73
- Oil: 38.96
- Electricity Generation: 33.91
- H2 Production: 0
- Residential: 11.89
- Commercial: 8.96
- Industrial: 26.36
- Automotive: 16.18
- Freight: 9.19
- Airlines: 2.8
- Rejected Energy: 52.06
- Useful Energy: 44.76
Estimated 2050 energy use
(50 mpg hybrid, 50% efficient grid)
Estimated 2050 energy use
(H₂ fleet using wind electrolysis)
Estimated 2050 energy use
(H₂ fleet using nuclear thermochemical)

Estimated Future U.S. Energy Requirements - 153 Quads

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Use</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro</td>
<td></td>
<td>0.97</td>
</tr>
<tr>
<td>Bio/Geo</td>
<td></td>
<td>7.06</td>
</tr>
<tr>
<td>Wind</td>
<td></td>
<td>0.12</td>
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<tr>
<td>Solar</td>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td>Nuclear</td>
<td></td>
<td>30.72</td>
</tr>
<tr>
<td>Coal</td>
<td></td>
<td>28.38</td>
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<tr>
<td>Gas</td>
<td></td>
<td>42.83</td>
</tr>
<tr>
<td>Oil</td>
<td></td>
<td>42.9</td>
</tr>
</tbody>
</table>

Electricity Generation 47.11

H₂ Production 22.85

Residential 17.22
Commercial 16.91
Industrial 45.97
Automotive 10.71
Freight 18.45
Airlines 7.77

Useful Energy 80.22
Rejected Energy 72.77
“There’s a better way to do it... Find it”
The NATURALHY approach

NATURALHY:

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

Prepared by
O. Florisson
Gasunie
Proposed Northeast Asia Natural Gas Pipeline
Continental Supergrid – EPRI concept “Energy Pipeline”

Thermal Insulation

Vacuum

Electrical Insulation

SC*

LH2**

* SC: MgB₂ magnesium diboride superconductor

** LH2: liquid hydrogen coolant, energy transmit

Continental Supergrid – EPRI concept “Energy Pipeline”
Hydrogen - fueled
2005 Prius
ICE Hybrid

www.qtww.com
High Temperature Gas Reactor (HTGR)

Both electricity and hydrogen
Three studies: large-scale, stranded renewables

- Compressorless GH2 pipelines: wind at competitive cost
- Comparing electricity, GH2, NH3 transmission and “firming” storage
- Firm renewables-GH2 supply: chem plant
- Prove 5 hypotheses?

www.leightyfoundation.org/earth.php
If --

• Build hydrogen, natural gas pipelines for same cost:
  – Capital: diameter, pressure, NOT energy capacity
  – O&M
  – Hydrogen embrittlement controlled
• 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)
Running the World on Renewables: Gaseous Hydrogen Pipeline Transmission with Firming Geologic Storage

SMRI, Basel, CH, 30 April 07

DVD’s, posters

Bill Leighty, Director
The Leighty Foundation
Juneau, AK
wleighty@earthlink.net
907-586-1426 206-719-5554 cell
The following slides are notes and supplemental

Bill Leighty
wleighty@earthlink.net
Sustainable

“Meeting our needs without compromising the ability of future generations to meet their own needs”

United Nations Commission on Environment and Development (UNCED)
“Our Common Future”, 1987
Humanity’s Goal?

A sustainable, benign-source, equitable, global energy economy

Rapid Climate Change (GCC)
Global Warming (GW)
Sustainable

“Meeting our needs without compromising the ability of future generations to meet their own needs”

United Nations Commission on Environment and Development (UNCED)
“Our Common Future”, 1987
Earth’s only source of income: Solar radiation, dust
Aldo Leopold
1887 - 1948
There are two spiritual dangers in not owning a farm:

One is supposing that breakfast comes from the grocery;

The other is supposing that heat comes from the furnace.

Aldo Leopold, “A Sand County Almanac”
Mendenhall Glacier
Juneau, Alaska  2005
Composite Reinforced Line Pipe (CRLP)
TransCanada Pipelines & NCF Industries
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.
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.
IRHTDF startup

Phase 1
- Funding
- Credibility
- Consortium
- Project manager

Preliminary R & D
- Systems engineering
- Geologic storage
- Pipeline hydraulics
- Source equipment

Draft RFP
- Design
- Permit
- Build
- Operate

Candidate site selection
Mature consortium; outreach

Phase 2
- Define, design
- Scope, outcomes
- Budget, funding
- Management

Final RFP
- Site
- Sources
- End uses
- Design, build
- Operate

Proced ?

- Publish report
- Reject RHS pipelines
- Resume under conditions

Consortium
Funding
Build, own, operate
Ammonia as Hydrogen Carrier, Fuel

- Anhydrous, NH₃
- C – free; H source?
- ~18% H, weight
- ~100 liters = 500 mile range, car
- ~15 M tons/year USA, 5 M as NH₃
- Good safety record: ag, industry
- Infrastructure in place
- Liquid storage: -10 C, 1 atm
- 60,000 ton tanks common
- Self-odorized
- ICE operates at 50% efficiency, low emissions
- Toxic
Ammonia Conferences: Anhydrous Ammonia ($NH_3$) 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“
Electrolyzers

Haber-Bosch Ammonia Synthesis

Air Separation Plant

Air

N₂

H₂

H₂O

Wind Generators

Electrolyzers

Liquid Ammonia Transmission Pipeline

Liquid Ammonia Tank Storage

Generators ICE, CT, FC

End users Retail

Cars, Buses, Trucks, Trains

Aircraft Fuel

AC grid Wholesale

End users Retail

Wholesale

End users Retail

Retail

Wind Generators

Electricity
EIA estimated 2025 energy use

Estimated Future U.S. Energy Requirements - 133.1 Quads

- Hydro: 0.96
- Bio/Geo: 5.94
- Wind: 0.11
- Solar: 0.01
- Nuclear: 7.64
- Coal: 26.89
- Gas: 34.88
- Oil: 56.7

Energy Distribution Year 2025

Electricity Generation: 45.74

Residential: 14.09
Commercial: 12.31
Industrial: 34.81
Automotive: 25.83
Freight: 13.18
Airlines: 5.06

H2 Production: 0

Useful Energy: 59.64
Rejected Energy: 73.47
Estimated **2050** energy use

(H₂ fleet using coal gasification)

Estimated Future U.S. Energy Requirements - 149.3 Quads

- Hydro: 0.97
- Bio/Geo: 7.06
- Wind: 0.12
- Solar: 0.01
- Nuclear: 7.87
- Coal: 47.57
- Gas: 42.83
- Oil: 42.9

Electricity Generation: 47.11

H₂ Production: 19.19

Residential: 17.22
Commercial: 16.91
Industrial: 45.97
Automotive: 10.71
Freight: 18.45
Airlines: 7.77
2005 World Hydrogen Economy

- 90 million tons / yr
- 90% from natural gas via SMR
  \[ CH_4 + H_2O \rightarrow H_2 + CO_2 \]
  \[ 16 + 36 \rightarrow 8 + 44 \]
- 95% captive (local, in-plant)
  - oil refining
  - nitrogen fertilizer
  - electronics, metals

SMR (steam methane reforming)
100 MMscfd