

Solar Hydrogen Energy System

## Hydrogen Fuel Cell Proton Exchange Membrane (PEM) type

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



## 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"

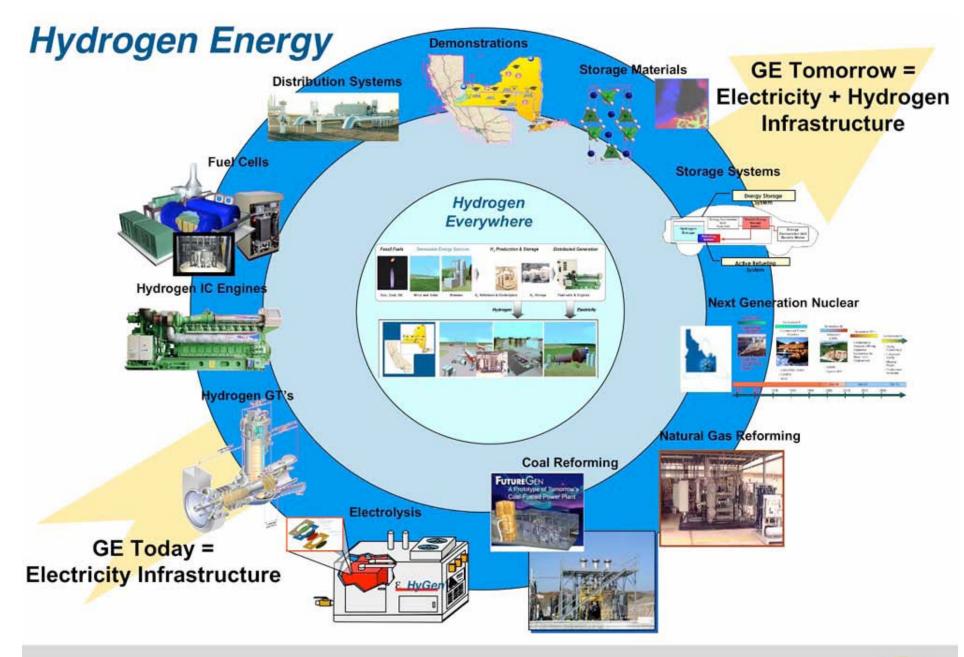


## "Hydrogen and electricity become the primary currencies in the future energy economy"

#### **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



## The Trouble with Renewables

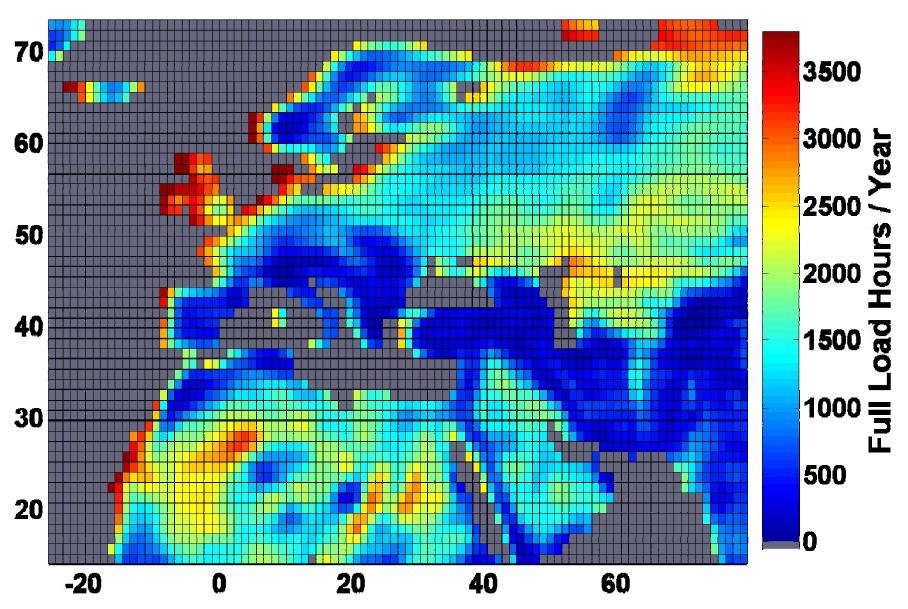
- Richest renewables stranded
  - High intensity
  - Large geographic extent dispersed
  - Far from markets
  - No transmission
- Time-varying output
  - Except geothermal, currents
  - Seconds to seasons
  - ABB, ISET Kassel "huge catchment area" firms
  - Synergy reduces storage: wind + solar

## 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
  - AI Ga ← → Alumina

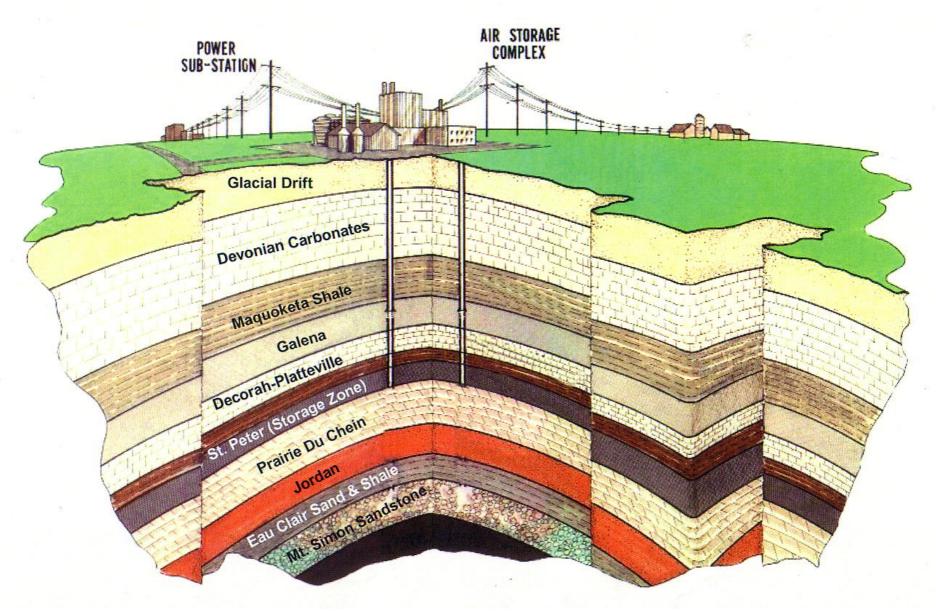
## ABB, ISET Kassel "Huge Catchment Area"

Windpower 01



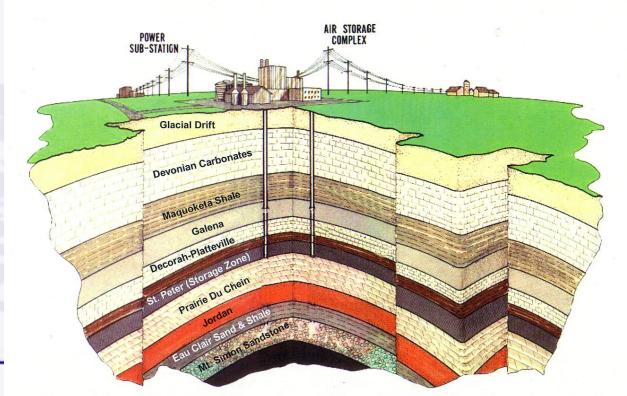
## Compressed air energy storage (CAES)

lowa geology



## Hourly to Weekly Storage

- Compressed air energy storage (CAES)
- Sodium sulfur battery
- VRB: vanadium redox battery
- Pumped hydro

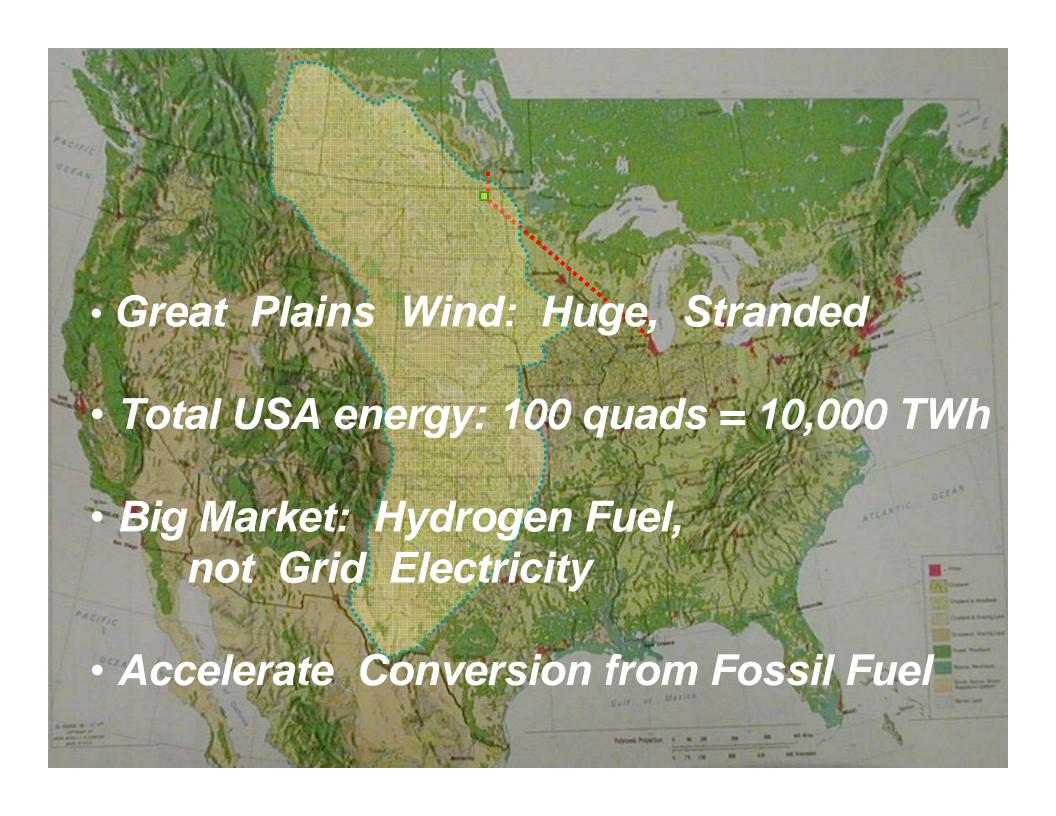


el Energy\*

## 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)
- 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
  - AI Ga ← → Alumina





### **Exporting From 12 Windiest Great Plains States**

Number of GH2 pipelines or HVDC electric lines necessary to export total wind resource Wind energy source: PNL-7789, 1991 \* at 500 miles average length

| State        | AEP,<br>TWh | Wind Gen MW (nameplate) (40% CF) | 6 GW<br>36" GH2<br>export<br>pipelines | \$ Billion<br>Total<br>Capital<br>Cost * | 3 GW<br>export<br>HVDC<br>lines | \$ Billion<br>Total<br>Capital<br>Cost * |
|--------------|-------------|----------------------------------|--|--|---------------------------------|--|
| North Dakota | 1,210       | 345,320                          | 50                                     | 50                                       | 100                             | 60                                       |
| Texas        | 1,190       | 339,612                          | 48                                     | 48                                       | 100                             | 60                                       |
| Kansas       | 1,070       | 305,365                          | 43                                     | 43                                       | 100                             | 60                                       |
| South Dakota | 1,030       | 293,950                          | 41                                     | 41                                       | 100                             | 60                                       |
| Montana      | 1,020       | 291,096                          | 41                                     | 41                                       | 90                              | 54                                       |
| Nebraska     | 868         | 247,717                          | 35                                     | 35                                       | 80                              | 48                                       |
| Wyoming      | 747         | 213,185                          | 30                                     | 30                                       | 70                              | 42                                       |
| Oklahoma     | 725         | 206,906                          | 29                                     | 29                                       | 60                              | 36                                       |
| Minnesota    | 657         | 187,500                          | 26                                     | 26                                       | 60                              | 36                                       |
| lowa         | 551         | 157,249                          | 22                                     | 22                                       | 50                              | 30                                       |
| Colorado     | 481         | 137,272                          | 19                                     | 19                                       | 40                              | 24                                       |
| New Mexico   | 435         | 124,144                          | 17                                     | 17                                       | 40                              | 24                                       |
| TOTALS       | 9,984       | 2,849,316                        | 401                                    | \$ 401                                   | 890                             | \$ 534                                   |

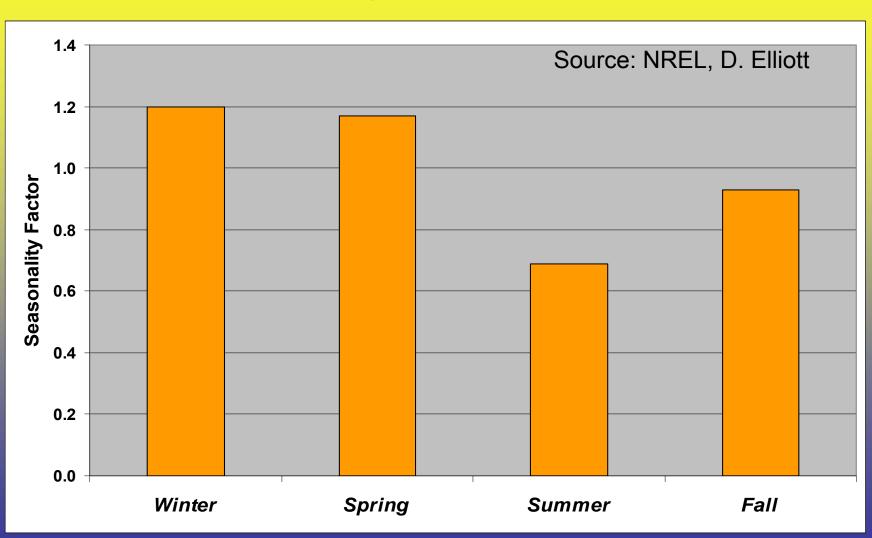
## Wind seasonality, Great Plains

Source: NREL, D. Elliott, et al

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

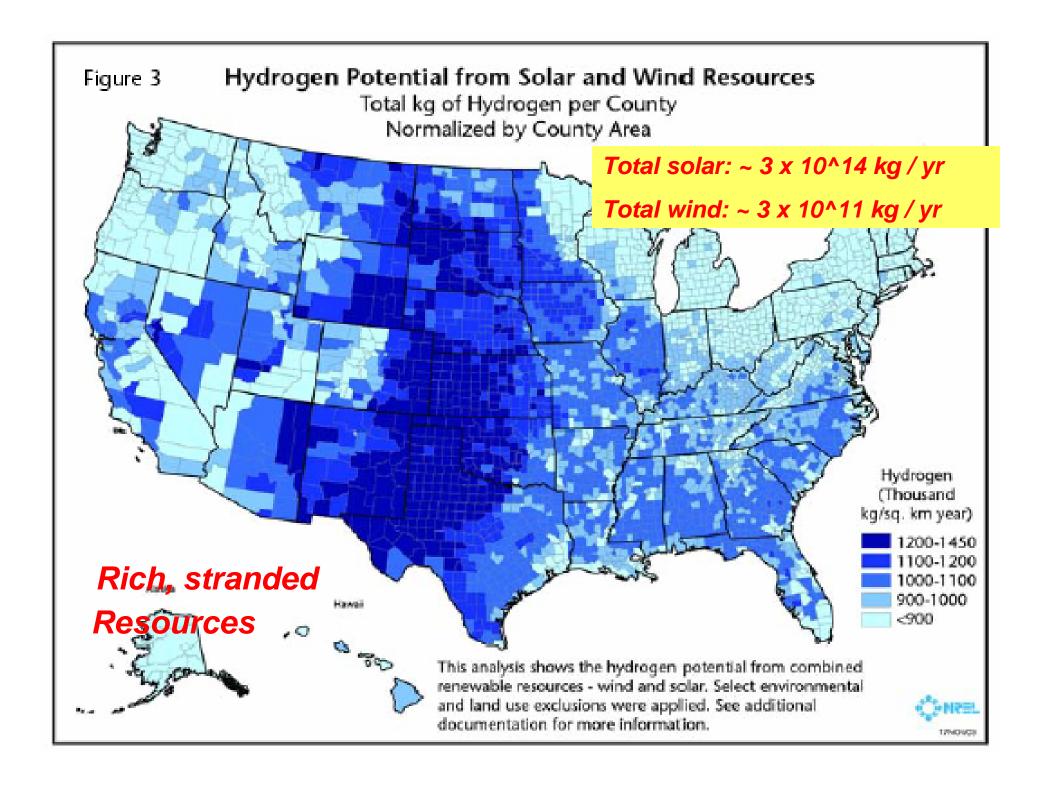
## Wind Seasonality, Northern Great Plains

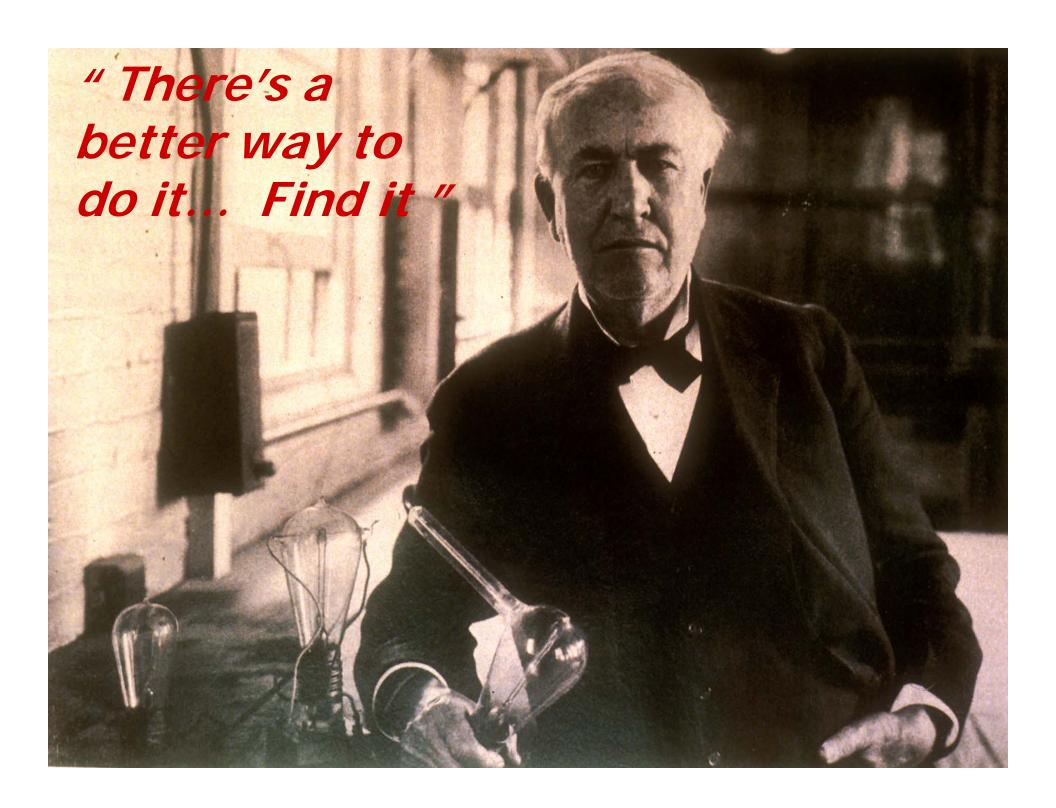
Normalized to 1.0 per season 450 GWh per 1,000 MW wind

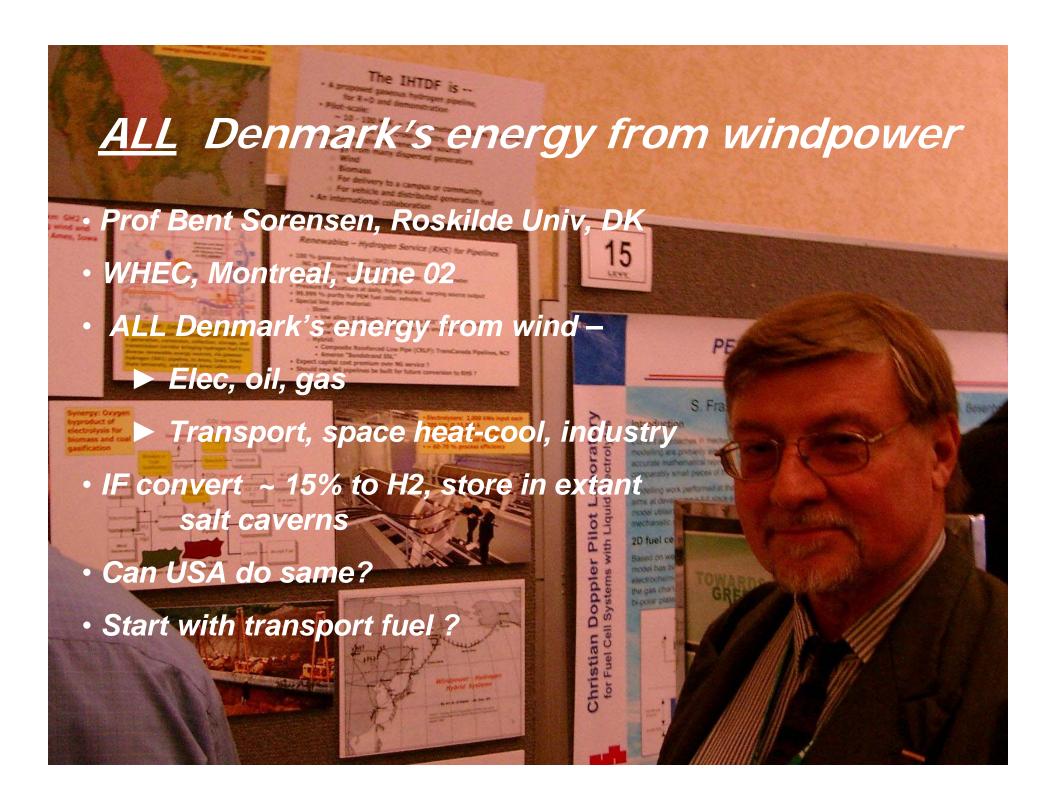


## Annual – scale "Firming" Great Plains Wind

- 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

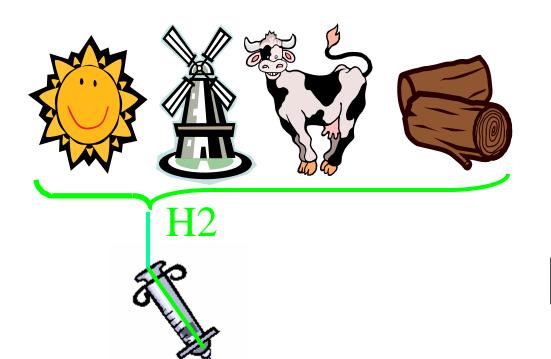






#### The NATURALHY approach











#### **NATURALHY:**

- Breaks "chicken-egg" dilemma
- Bridge to sustainable future







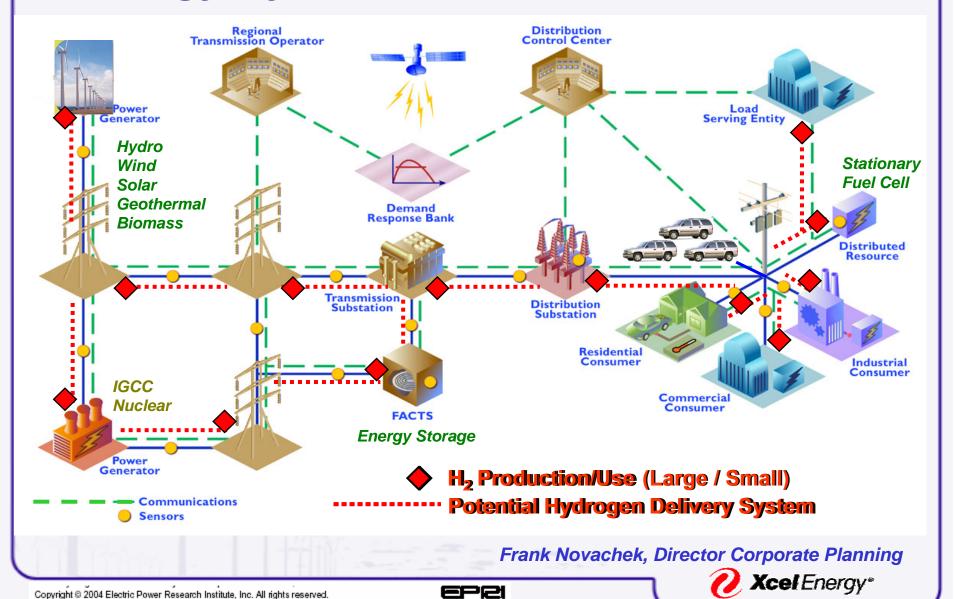
N.G.



Continental Supergrid – EPRI concept "Energy Pipeline"



## Energy System of the Future





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)



## Hydrogen Utility Group (HUG)



















**ENTERGY NUCLEAR** 

















## "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



## 1: Adequate Renewables

- Run the world; humanity's needs
- "Distributed" and "Centralized"
- Affordable, benign
- Diverse, synergistic
- Richest are "stranded"
  - Far from markets
  - No transmission

## 2: When we realize these as emergencies:

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

## We must quickly invest in:

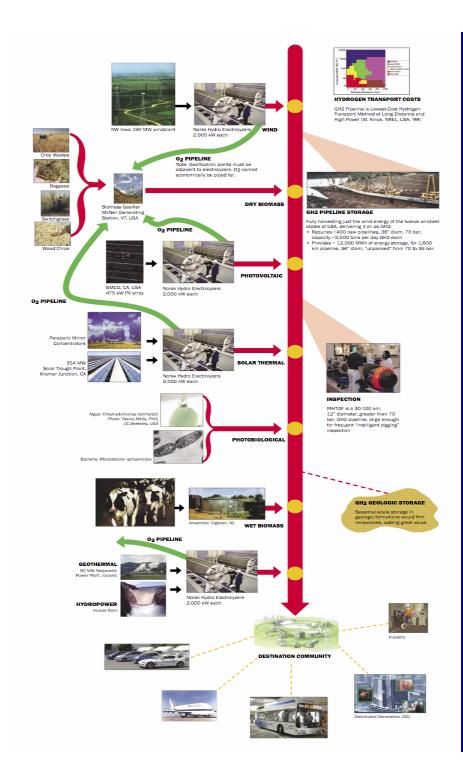
- Energy conservation, efficiency
- Large, new energy supplies:
  - CO<sub>2</sub> emissions free
  - Indigenous
  - Both distributed, centralized

# 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

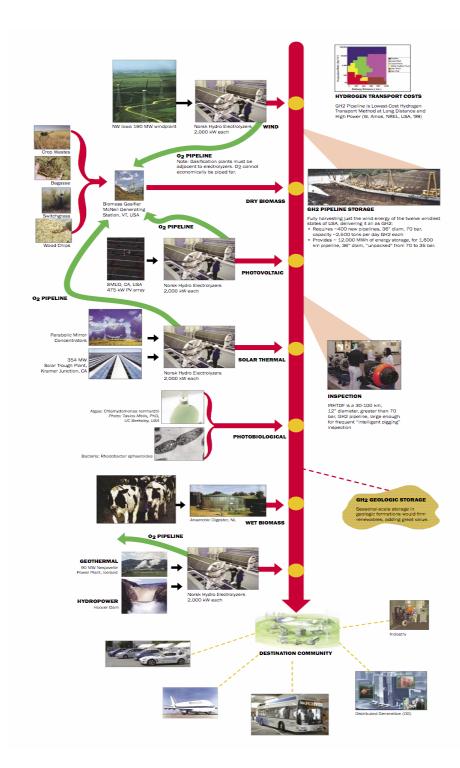
## 4: Pilot plant needed

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



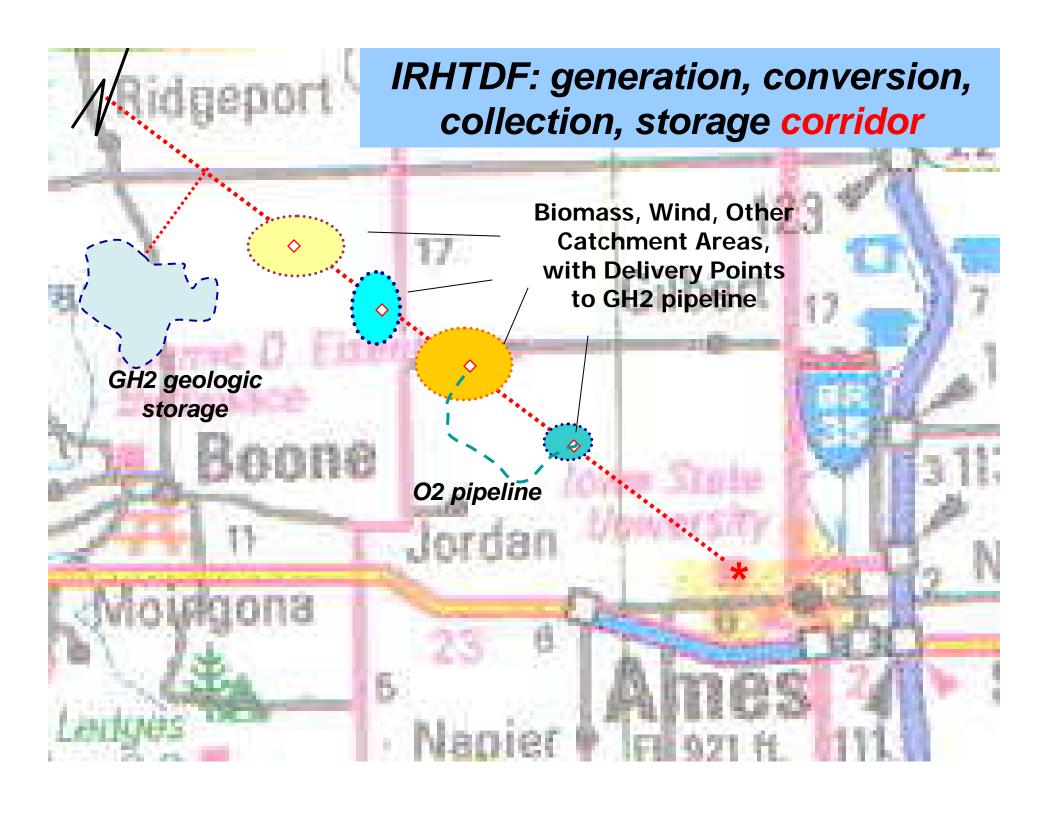
# International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF) Pilot plant

Global opportunity: IPHE project



# Pilot-scale Hydrogen Pipeline System: Renewables

- Diverse
- Dispersed, diffuse
- Large-scale
- Stranded
  - Remote
  - No transmission

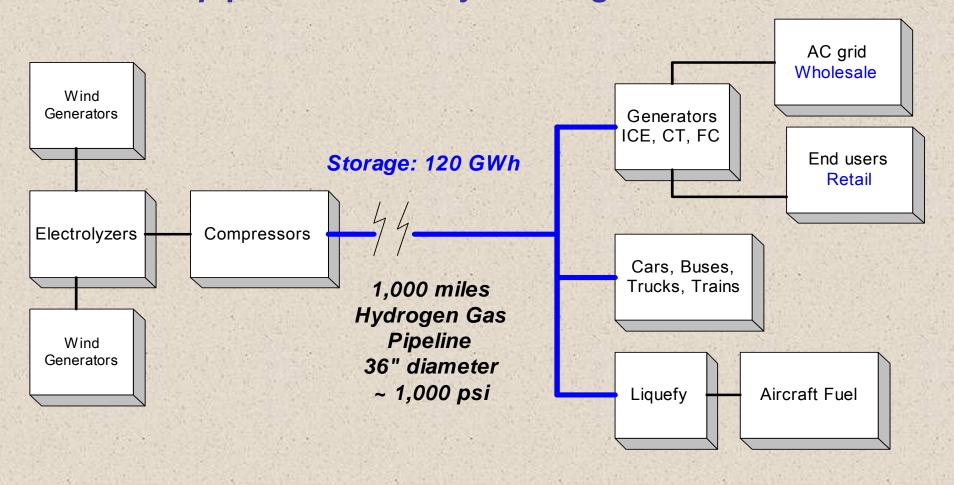


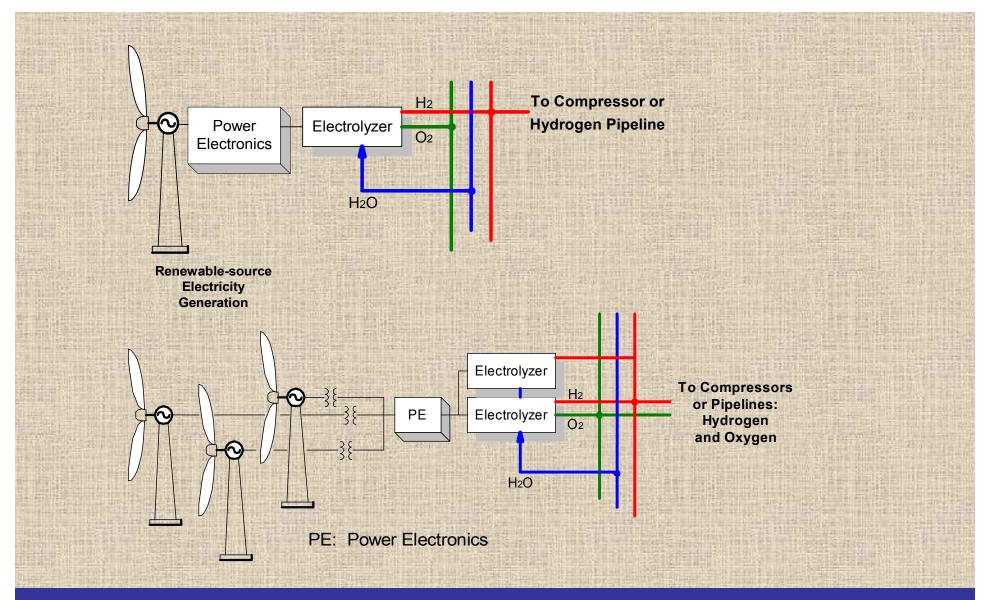
# 5: Hydrogen's principal value

- 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

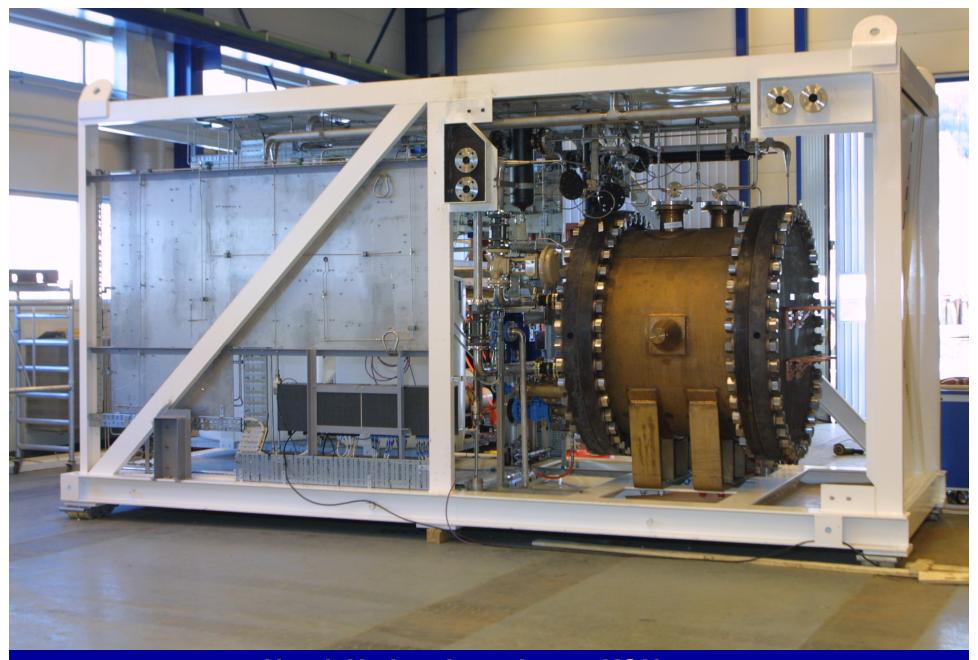
## Hydrogen Transmission Scenario

- Low-pressure electrolyzers
- "Pack" pipeline: ~ 1-2 days' storage = 120 GWh



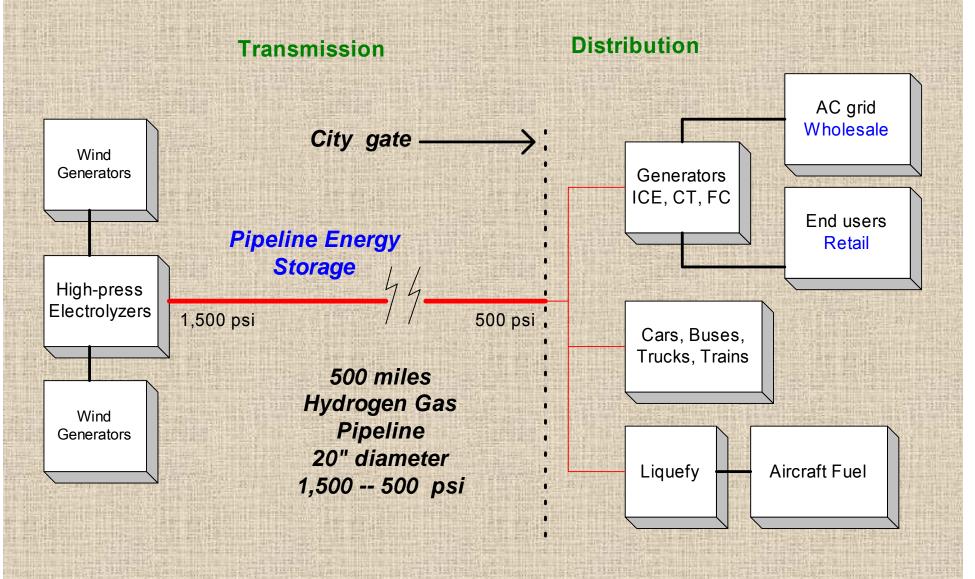


Topology Options: H<sub>2</sub> and O<sub>2</sub> Production and Gathering from Renewable Energy Generation



Norsk Hydro electrolyzer, KOH type 560 kW input, 130 Nm3 / hour at 450 psi (30 bar)

#### Compressorless system: No firming storage



# "We know how to pipeline hydrogen" Air Products ~ 10,000 miles of GH2 pipeline, worldwide

### Air Products H<sub>2</sub>/ CO Pipeline - *Texas Gulf Coast*

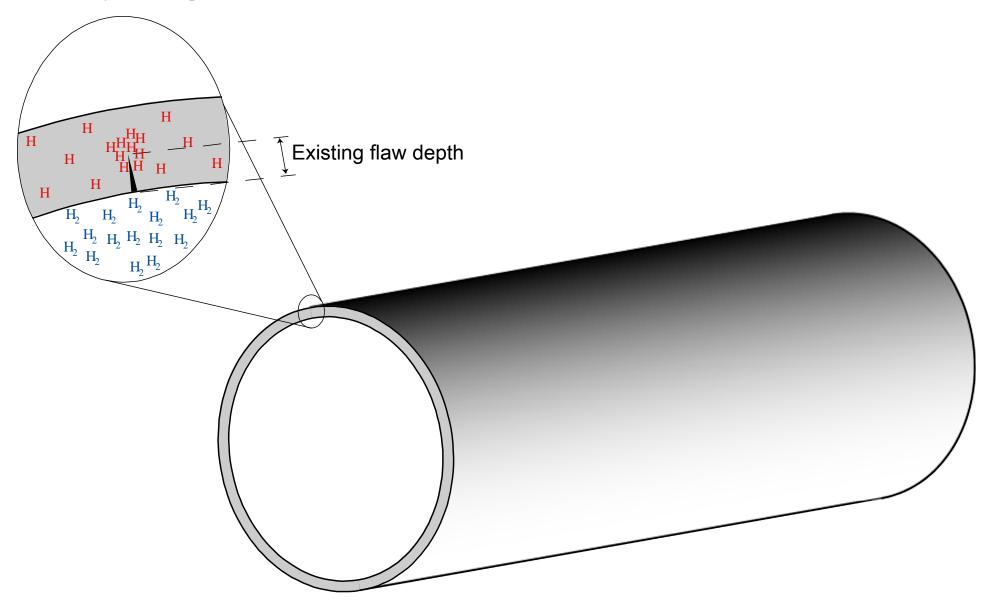


## Air Products Company

REFINERY ACTIVITY
LOS ANGELES BASIN, CALIFORNIA



#### Hydrogen Embrittlement (HE) of Pipeline Steel



# Industrial H2 Pipelines

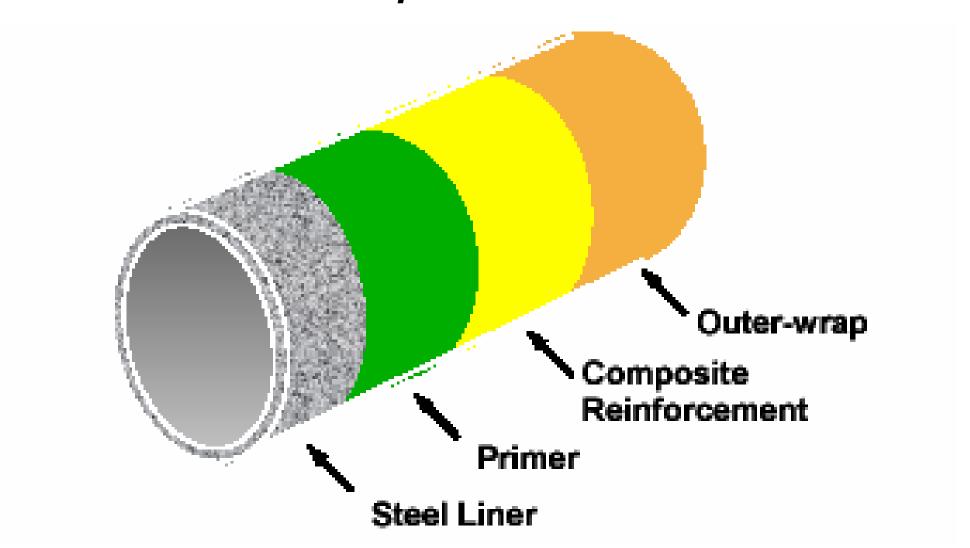
- 3,000 km worldwide
- Industrial corridors; on-site
- 30% SMYS typical \*
- Constant pressure; low fatigue
- Low-alloy, low-strength steel
- Re-purposed oil pipelines

<sup>\*</sup> 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

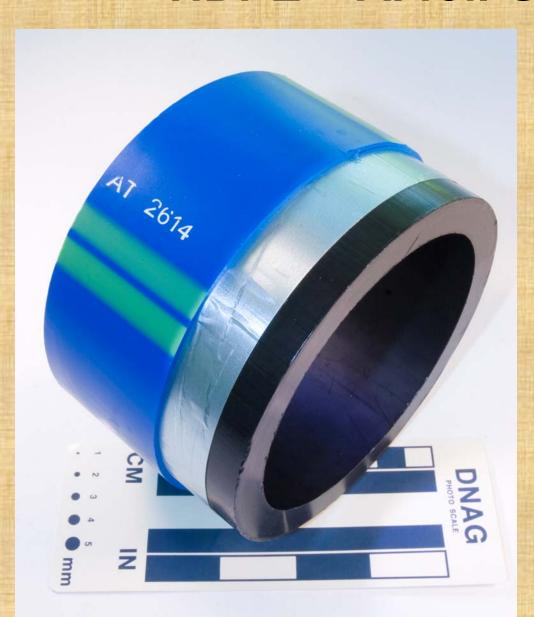
ASME International Pipeline Conference and Exposition, Calgary, AB, Canada, October 02.



CRLP™ is a trademark of NCF Industries, Inc.

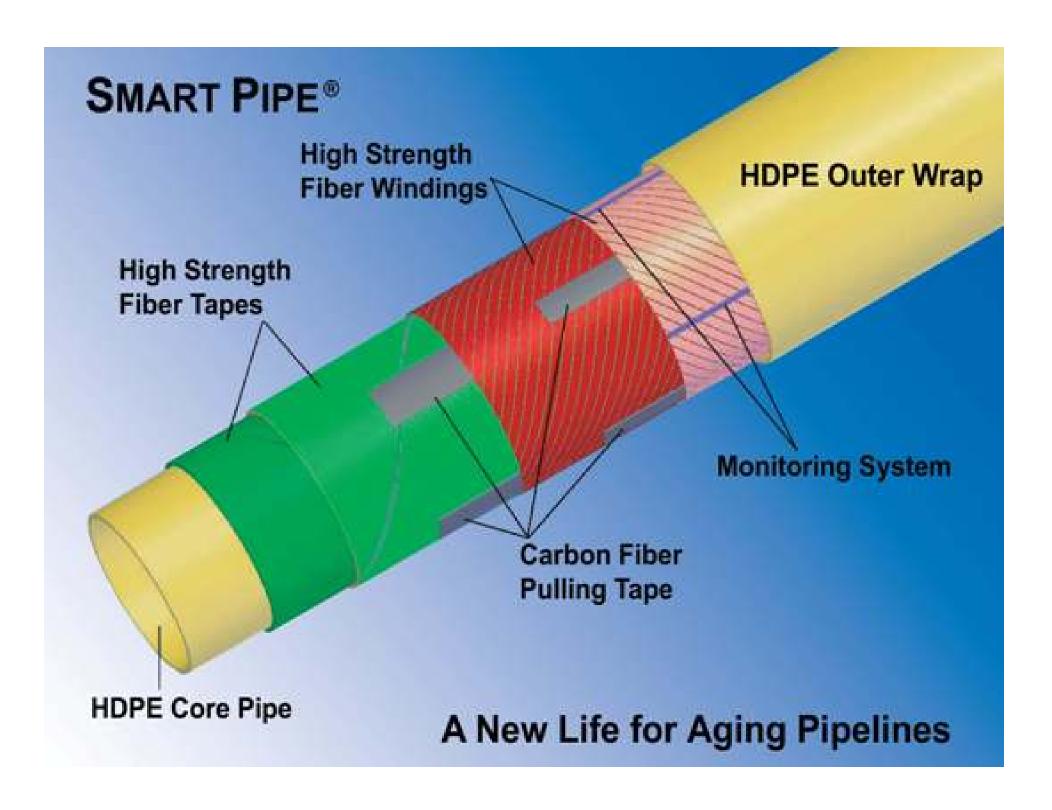
CRLP™ is manufactured under license from NCF Industries, Inc. U.S. and Foreign patents have been issued and are pending.

## HDPE + Al foil GH2 barrier



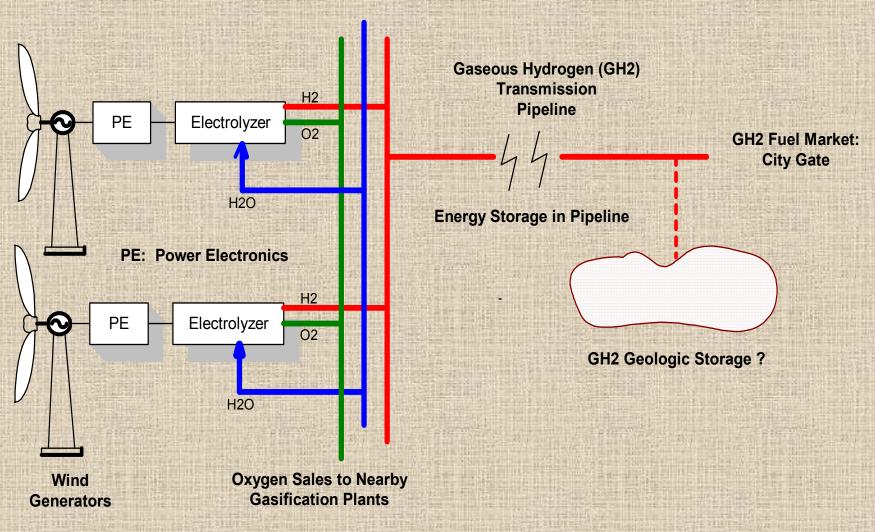
**Hydrogen Discoveries, Inc. (HDI)** 

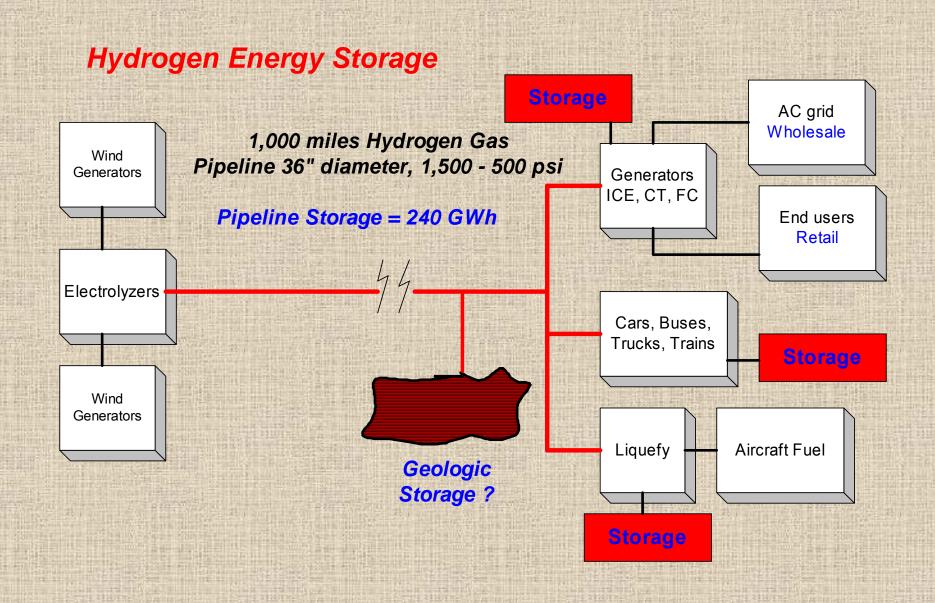
3" long 4" ID

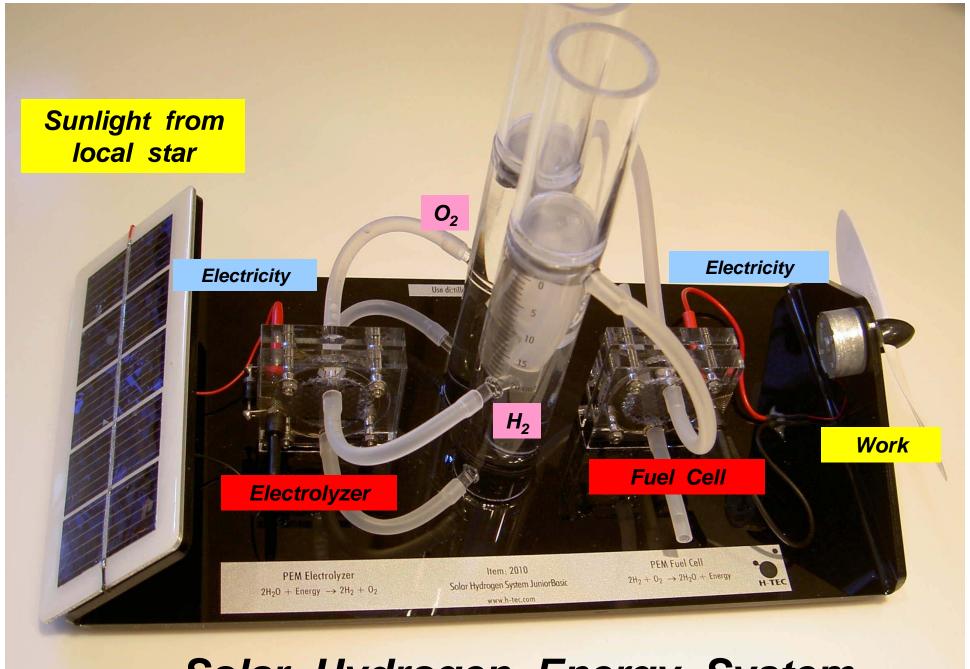




#### Hydrogen Transmission Scenario Storage: Pipeline smoothing, geologic firming

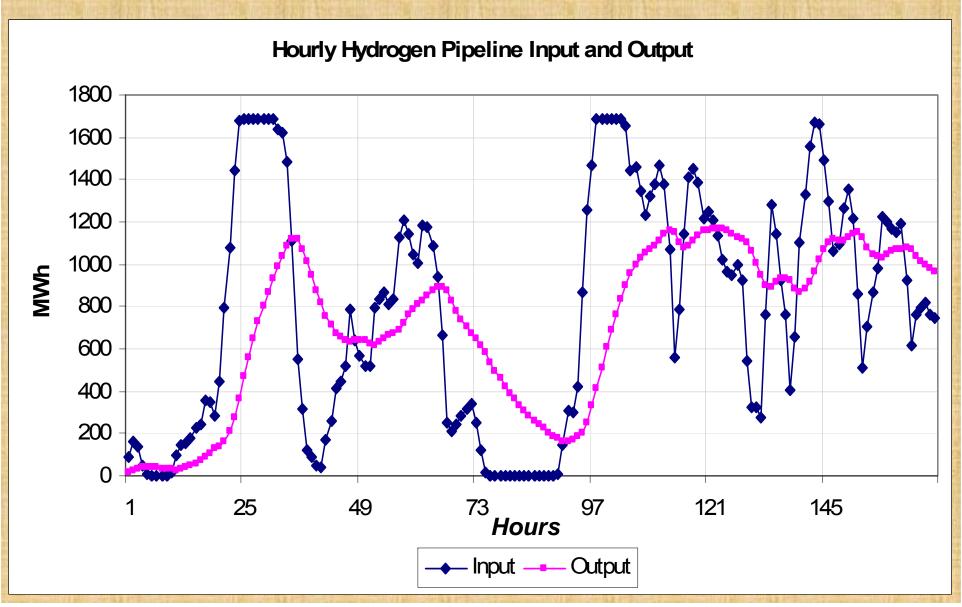




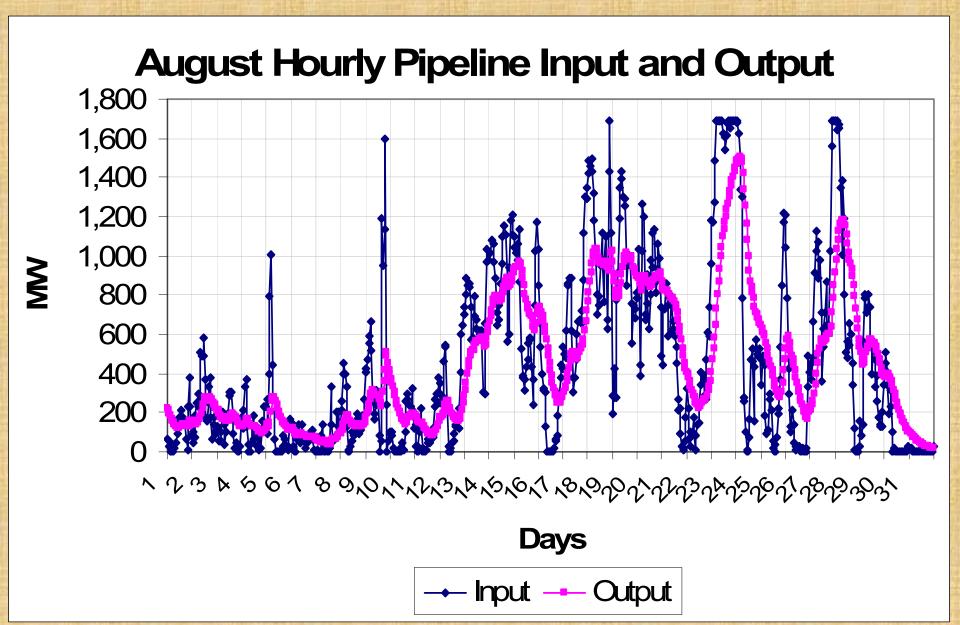


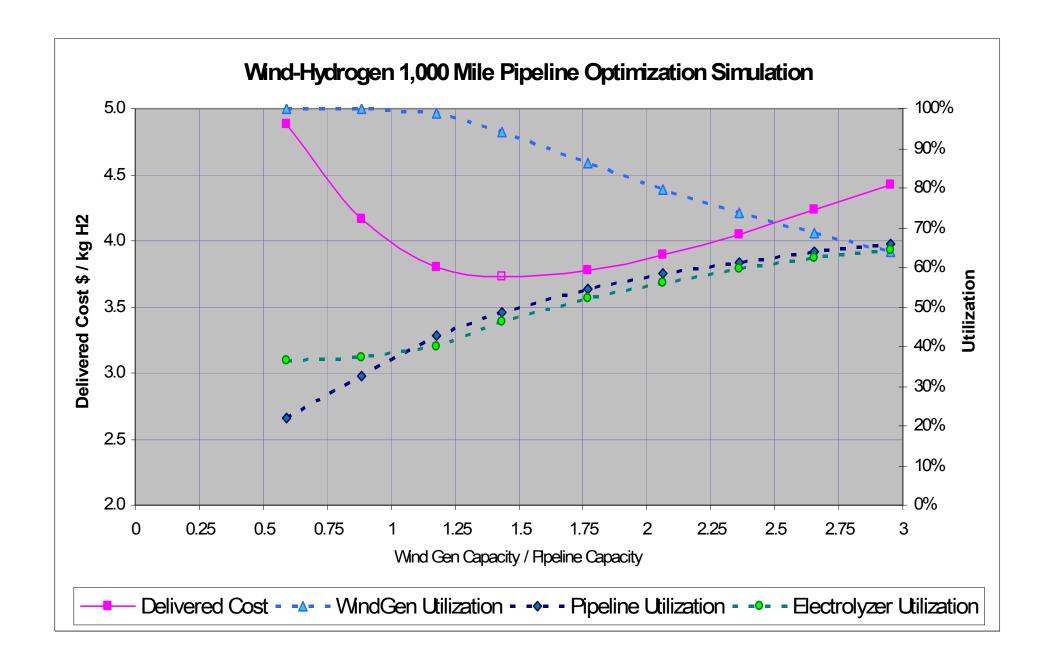
Solar Hydrogen Energy System

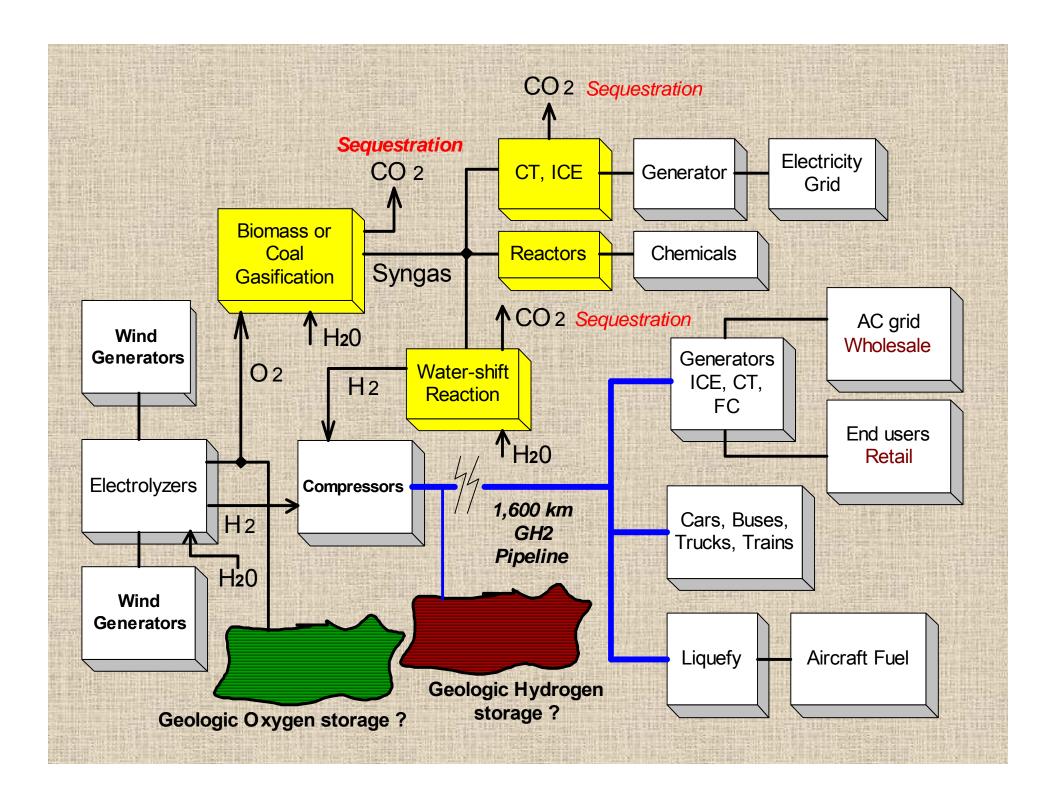
# Great Plains Windplant, Pipeline Hourly Output for Typical Week

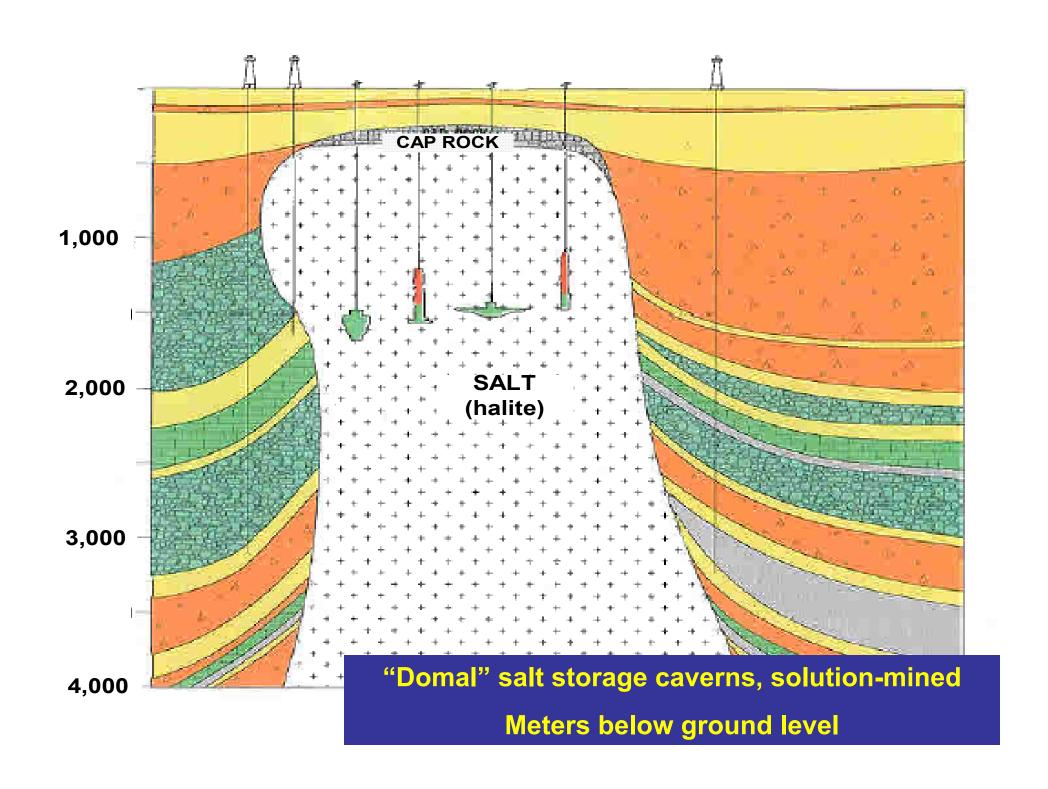


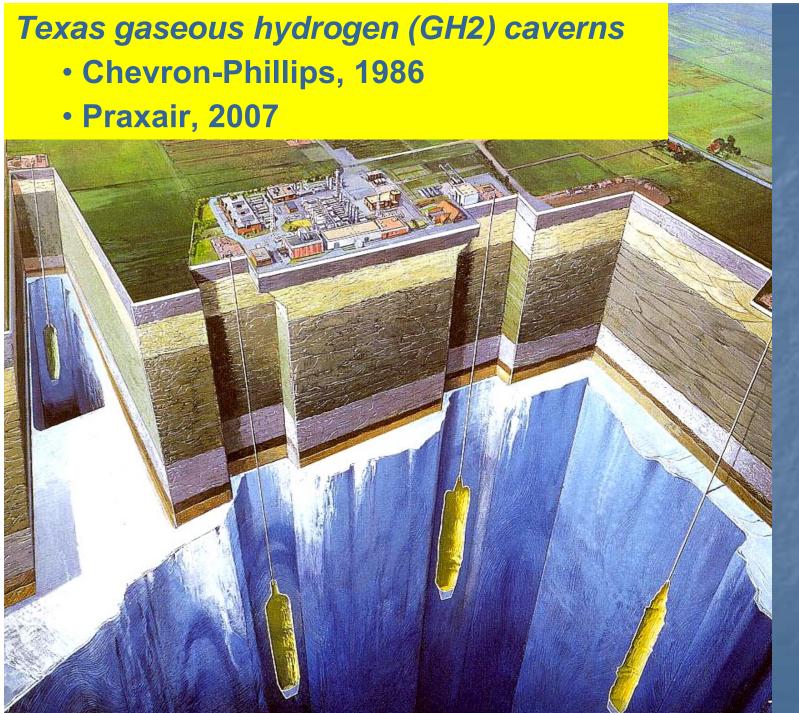
#### Great Plains Windplant: Actual Hourly Output











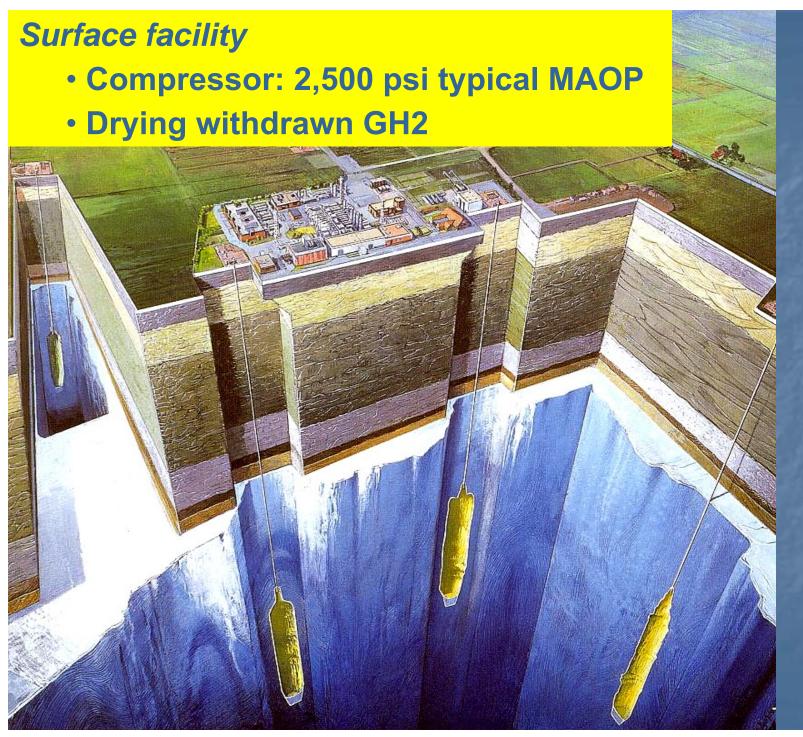
Domal Salt Storage Caverns

**PB ESS** 



Domal Salt Storage Caverns

**PB ESS** 



Domal Salt Storage Caverns

**PB ESS** 

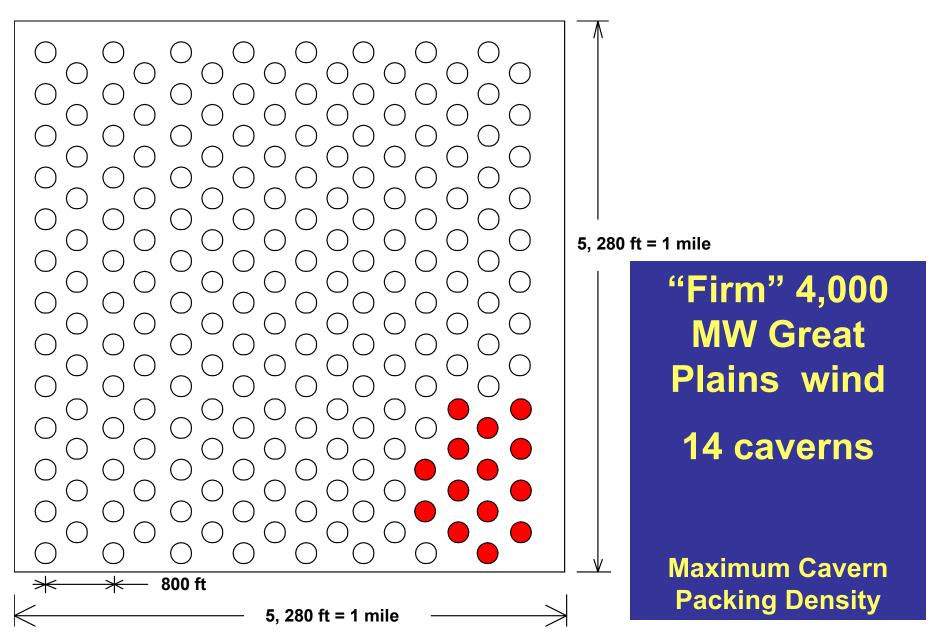
# Wellhead, new Gaseous Hydrogen Storage Cavern

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



#### Annual – scale "Firming" Great Plains Wind

- Potential, 12 states, ~50% land area:
  - 10,000 TWh = 100 quads / 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

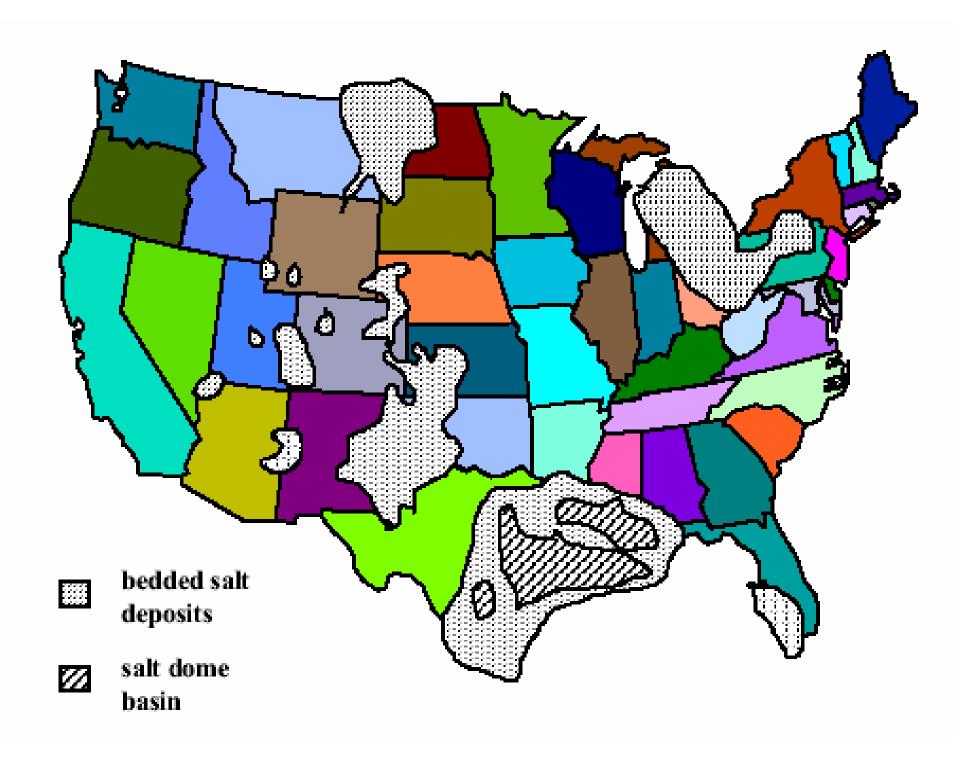


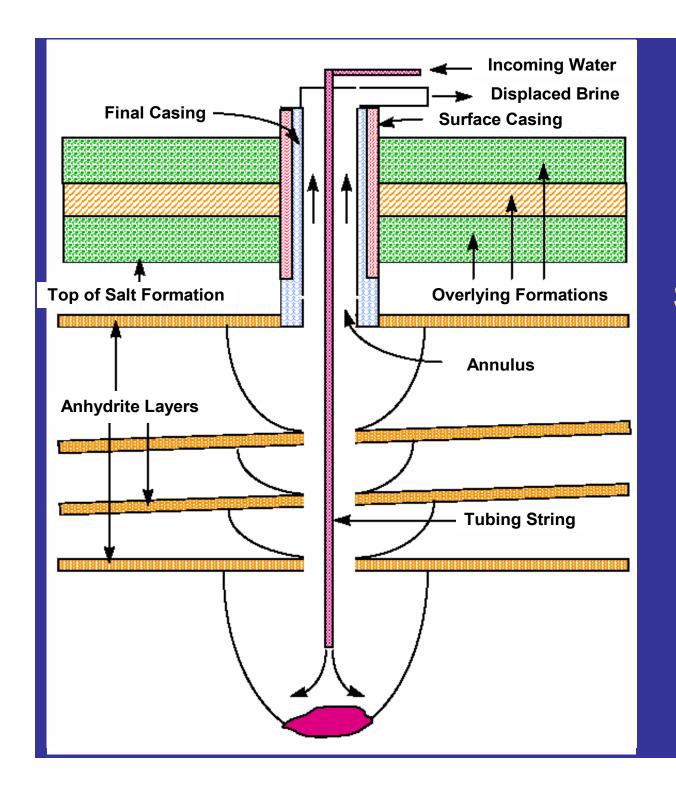
 $(8 \times 13) = 104 + (8 \times 12) = 96$  Total = 200 caverns per square mile Each cavern is 200 ft diam, with minimum 200 ft web separation.



Renewable-source GH2 geologic storage potential.

Candidate formations for manmade, solution-mined, salt caverns

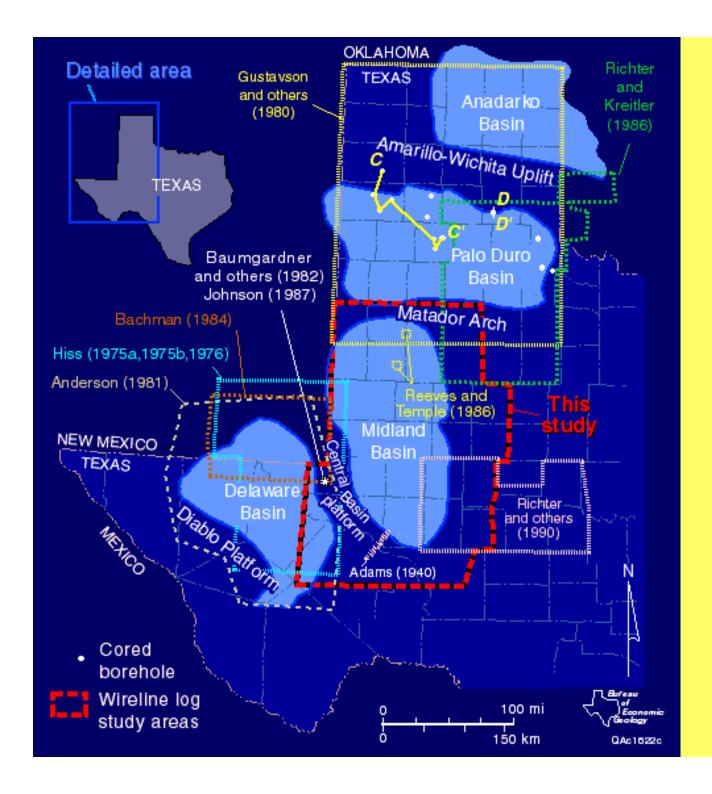




"Bedded" salt

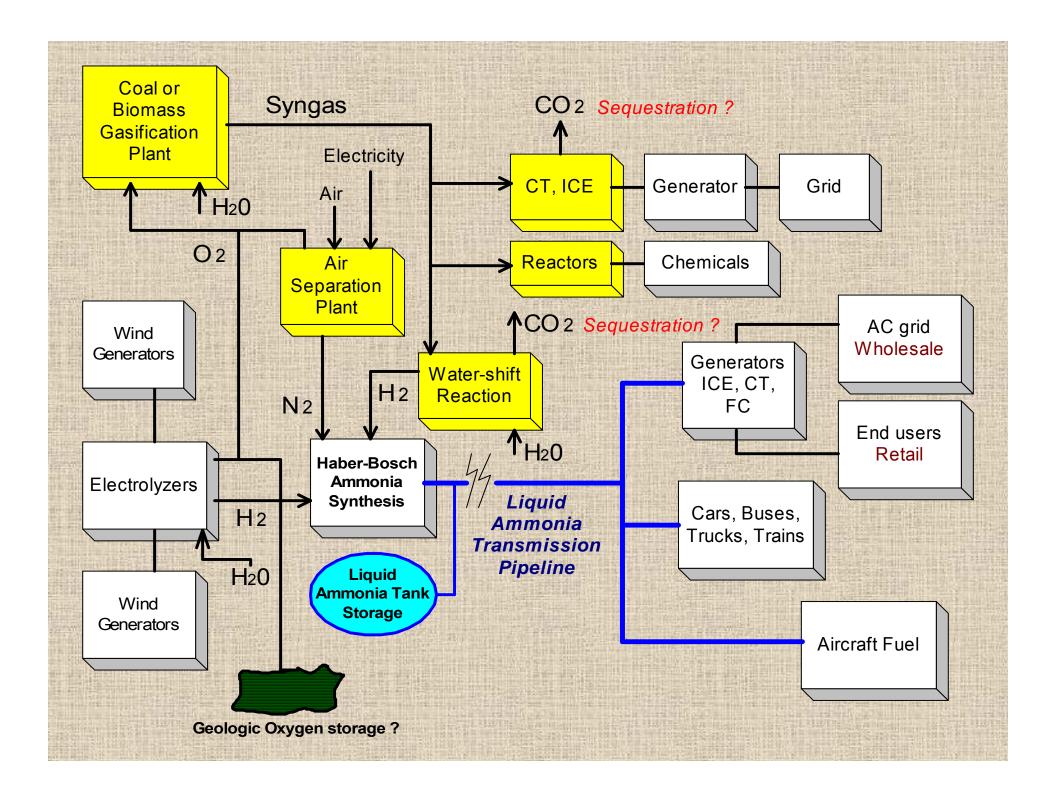
Solution-mining of storage caverns typical of New Mexico and west Texas

Solution Mining Research Institute (SMRI)



Major "bedded" salt basins

Gaseous
hydrogen
storage may be
feasible



## Anhydrous Ammonia, NH<sub>3</sub> Fertilizer -> Fuel

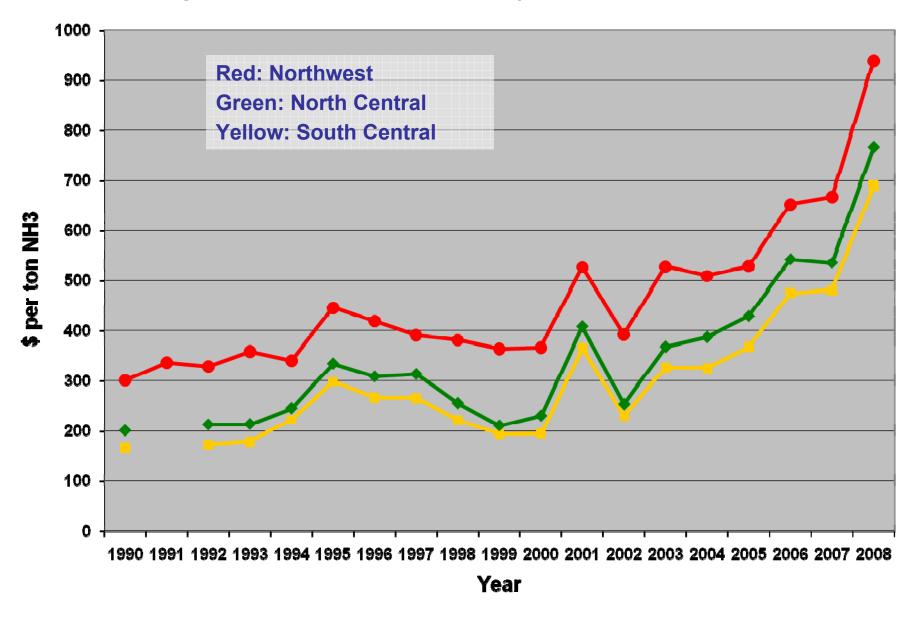
#### **Business case:**

- Market size, share:
  - 15 mt / yr ag fertilizer
  - 5 mt / yr other
  - ? mtT / yr NH3 fuel
  - ICE, CT, fuel cell
- RE NH3 competes with coal, imports

### NH<sub>3</sub> Ag Fertilizer Tanks, Wind Generators, NW Iowa



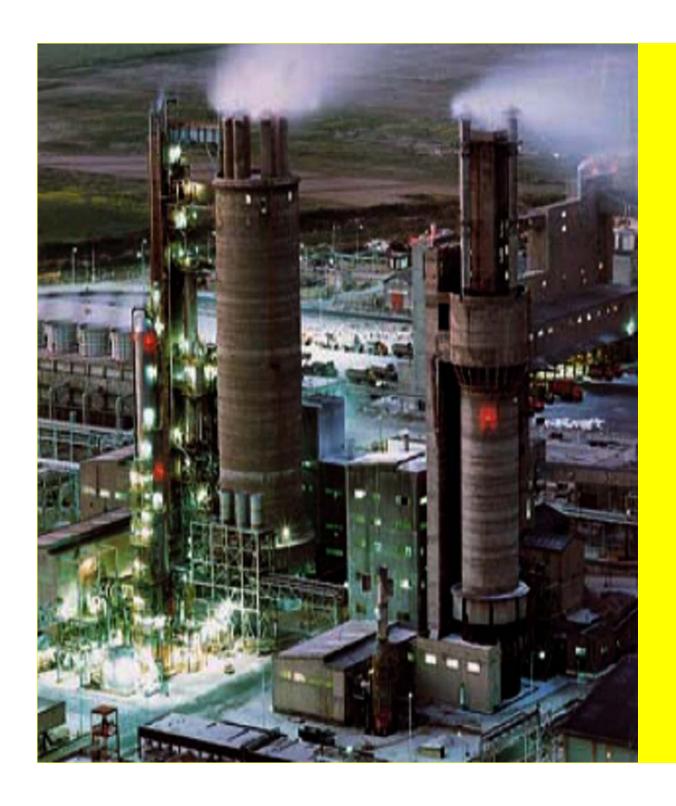
#### Regional ammonia prices paid by U.S. farmers in April



### "Ammonia Nation?"

Anhydrous ammonia (NH3)

- Low-cost transmission, storage: liquid
- Transportation fuel
- Stationary generation, CHP
- Total USA annual energy '02 06
  - 100 quads
  - 10,000 TWh
- More renewables than coal
- Coal limits:
  - Only 200 year supply ?
  - CCS limits: where to put the CO2 ?



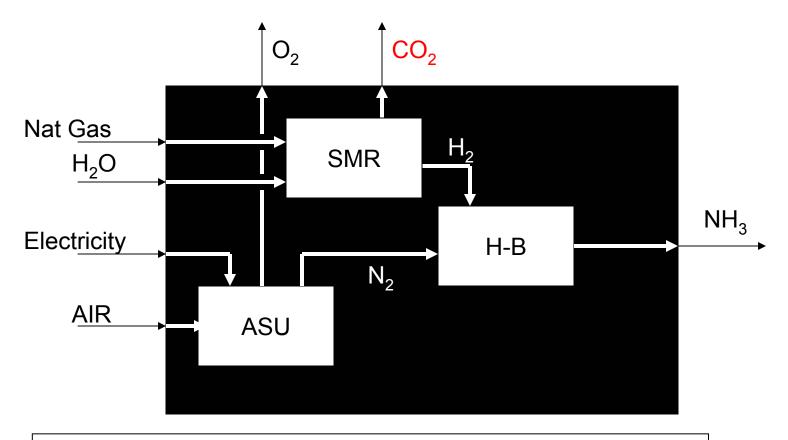
Ammonia (NH<sub>3</sub>) Synthesis Plant Natural Gas Feed

1 - 3,000 tpd

Haber-Bosch "Synloop"

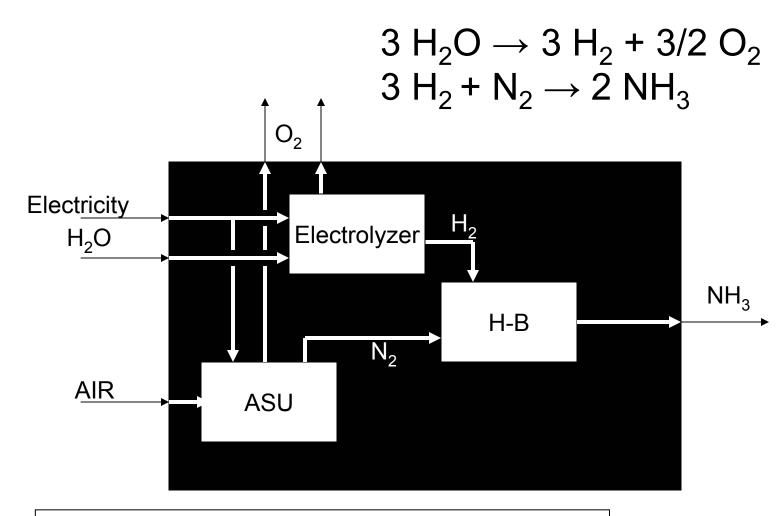
### Inside the Black Box: Steam Reforming + Haber-Bosch

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



Energy consumption ~33 MBtu (9500 kWh) per ton NH<sub>3</sub>

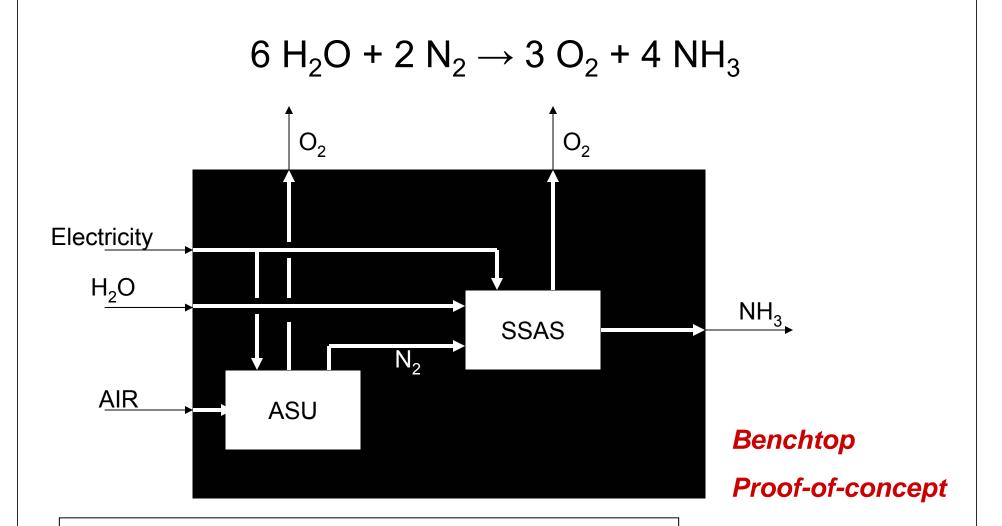
### Inside the Black Box: HB Plus Electrolysis



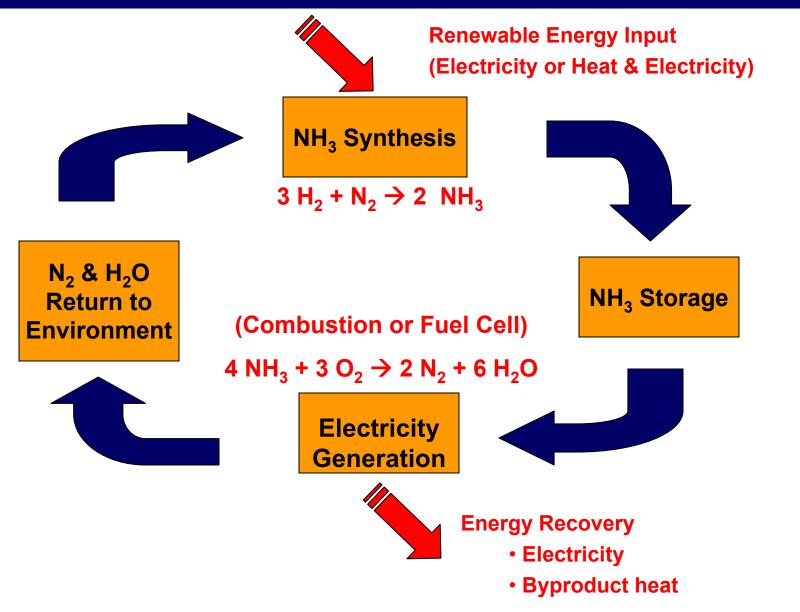
Energy consumption ~12,000 kWh per ton NH<sub>3</sub>

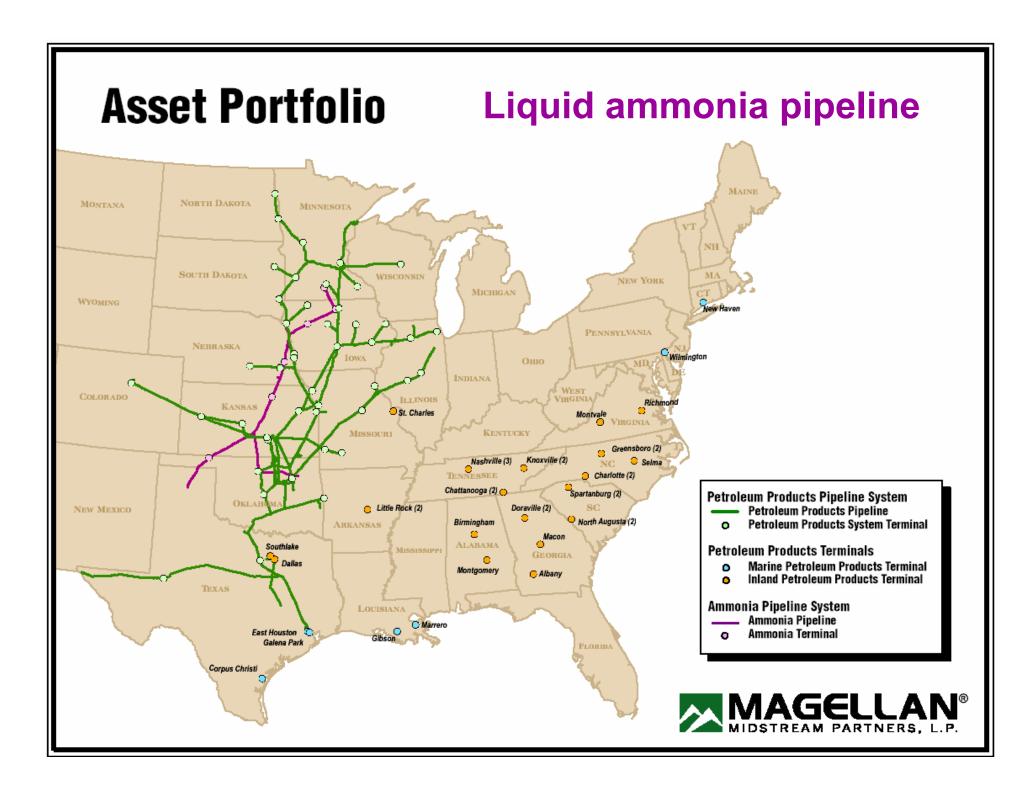
### Inside the Black Box: Solid State Ammonia Synthesis

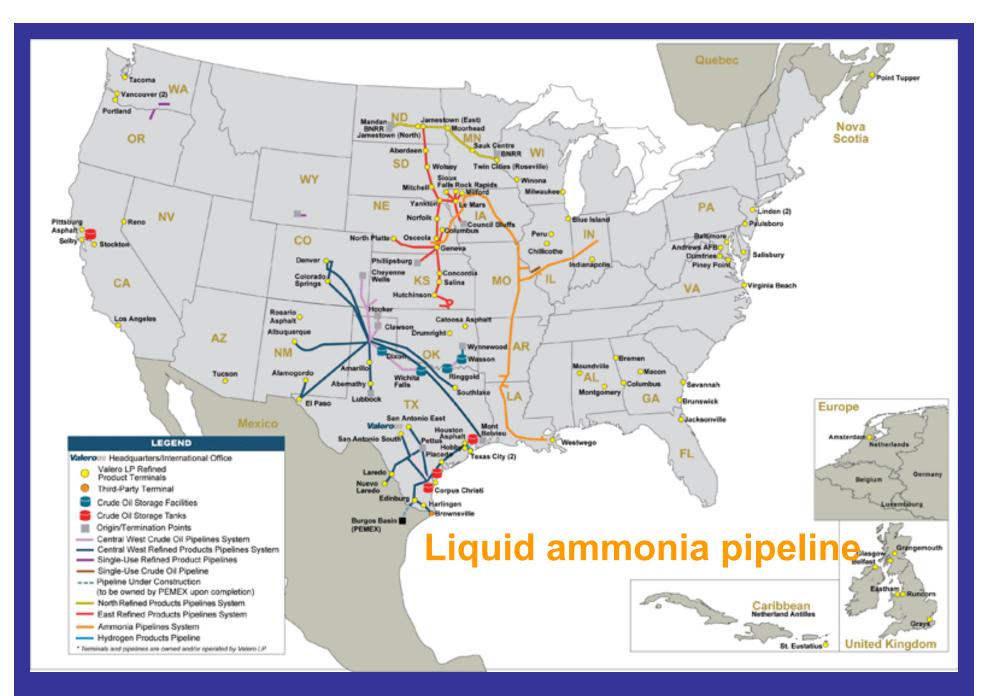
Energy consumption 7000 - 8000 kWh per ton NH<sub>3</sub>

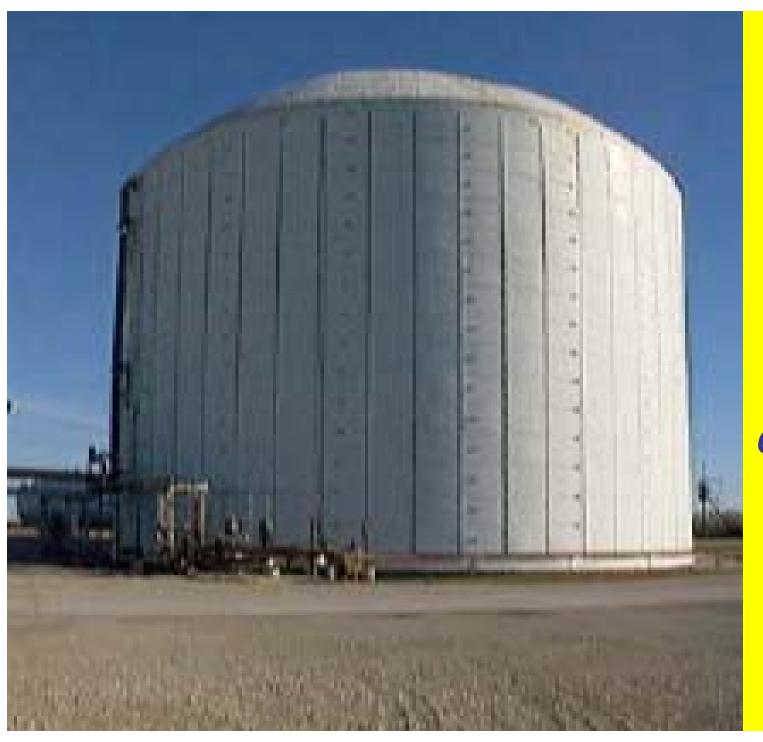


### Green Ammonia Cycle Renewable-source, C-free









Liquid Ammonia Storage Tank

60,000 Tons

-28 F

### Annual – scale "Firming" Great Plains Wind

- Potential, 12 states, ~50% land area:
  - 10,000 TWh = 100 quads = entire USA energy
  - 2,800,000 MW nameplate
- Seasonality:
  - Summer minimum
  - Spring Summer maximum storage
  - "Firming" energy storage, per 1,000 MW wind:
    - As electricity = 450 GWh
    - As GH2 = 15,712 tons, metric @ 2,500 tons / cavern = 6 caverns
    - As NH3 = 87,291 tons, metric @ 60,000 tons / tank = 1.4 tanks
  - "Firming" energy storage, all great Plains wind:
    - As GH2 = 17,000 caverns @ \$15M each = \$264 billion
    - As NH3 = 5,000 tanks @ \$25M each = \$127 billion

### '08 Farm Bill Title IX: Energy

- Passed by US Senate, House May 08
- Sec 9003
- "Renewable fertilizer study"
- Anhydrous ammonia: NH<sub>3,</sub> nitrogen
- Commercialization of RE NH<sub>3</sub>
- \$1M recommended appropriation
- July 08: no approp; try FY10

# Total Installed Capital Cost 1,000 mile pipeline, \$US million

Windplant size

1,000 MW

2,000 MW

Wind generators

**Electrolyzers** 

Pipeline, 20" \*

\$ 1,000

500

1,100

\$ 2,000

1,000

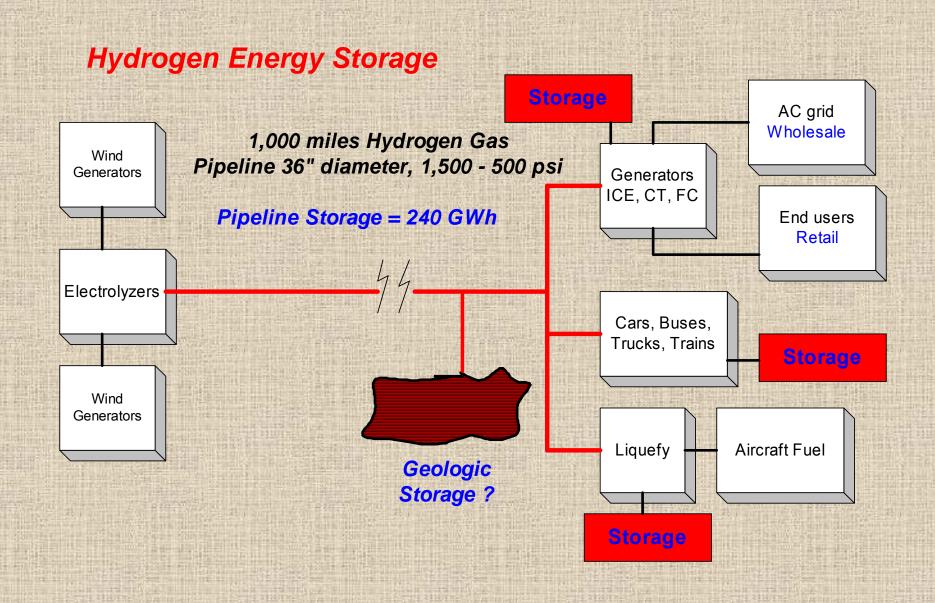
1,100

TOTAL

\$ 2,600

\$ 4,100

\* \$ 1.1 M / mile



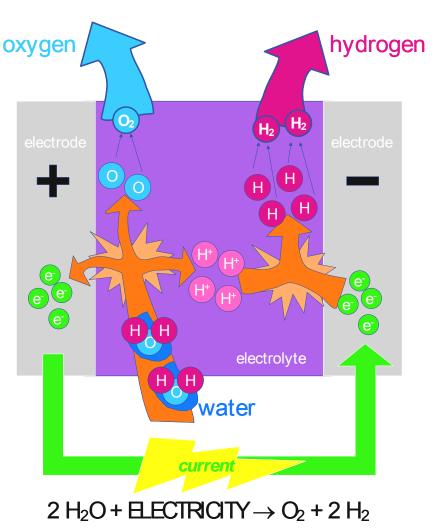
# Low Cost Electrolyzer Technology for Industrial Hydrogen Markets

National Hydrogen Association Annual Hydrogen Conference April 2008

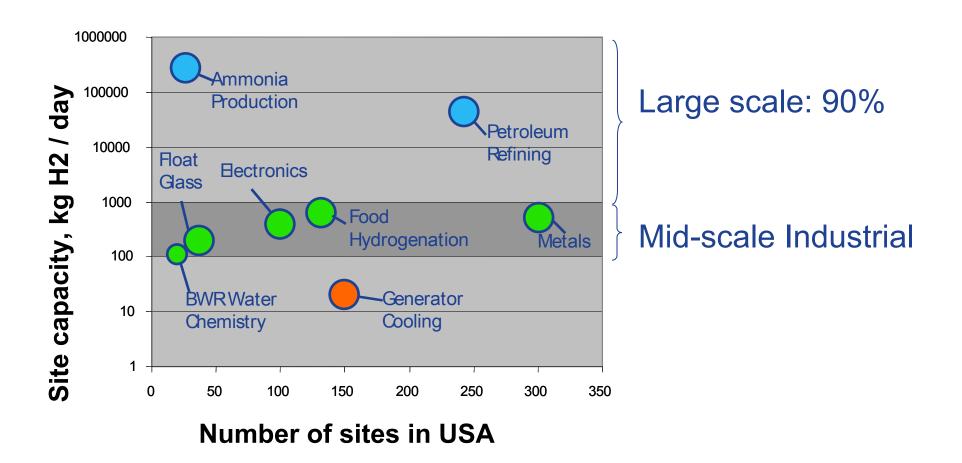
Richard Bourgeois<sup>1</sup> Dana Swalla<sup>1</sup> Todd Ramsden<sup>2</sup>

- •GE Global Research Center, Niskavuna NY
- National Renewable Energy Laboratory, Golden CO





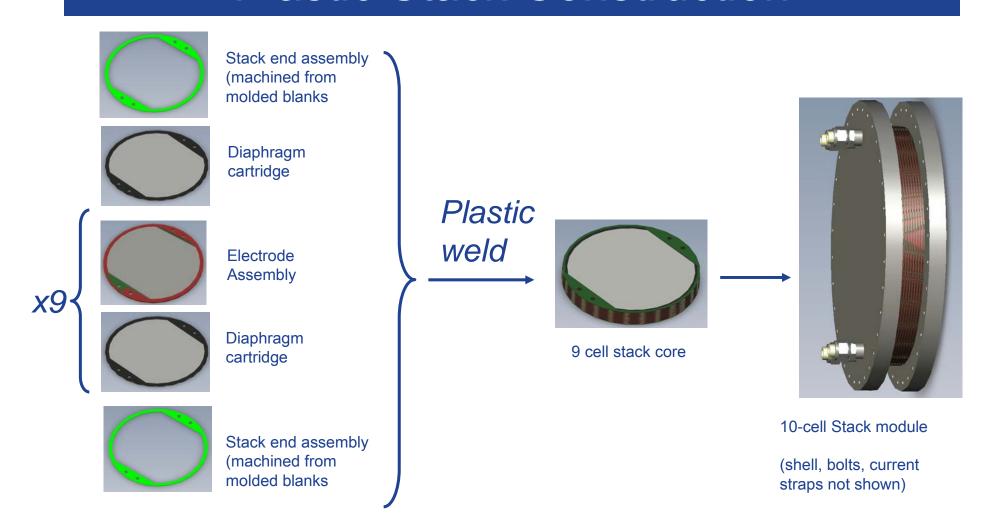
### Industrial Hydrogen Markets



Global consumption: 42 million tons H<sub>2</sub> per year



#### Plastic Stack Construction



15 bar pressure stack under construction for 2008 test



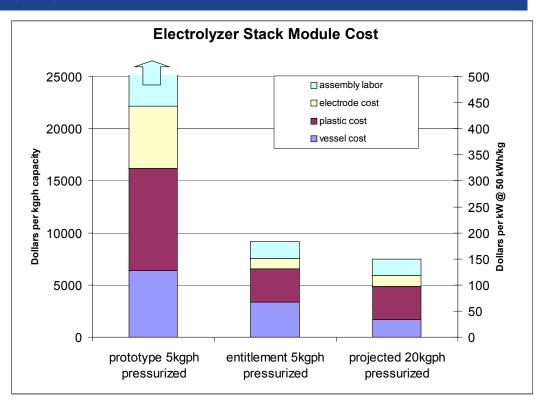
### Stack Module Costs

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  $H_2$  = 72% efficiency, plus byproduct heat





| Size    | Power* | Module<br>Cost |
|---------|--------|----------------|
| 5 kgph  | 250 kW | \$45,800       |
| 20 kgph | 1 MW   | \$150,000      |

### Electrolysis Cost of Hydrogen

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

 Industrial point-ofuse case:
 No dispensing or distribution costs.

### Cost per kg H<sub>2</sub> Plant Gate

| Cost of Electricity, | Capital Cost, \$/kW |        |        |  |
|----------------------|---------------------|--------|--------|--|
| ¢/kWh                | \$4,000             | \$800  | \$400  |  |
| 1.0                  | \$4.79              | \$1.51 | \$1.10 |  |
| 2.0                  | \$5.29              | \$2.01 | \$1.60 |  |
| 3.0                  | \$5.79              | \$2.51 | \$2.10 |  |
| 4.0                  | \$6.30              | \$3.01 | \$2.60 |  |
| 5.0                  | \$6.80              | \$3.52 | \$3.11 |  |
| 6.0                  | \$7.30              | \$4.02 | \$3.61 |  |
| 7.0                  | \$7.80              | \$4.52 | \$4.11 |  |
| 8.0                  | \$8.30              | \$5.02 | \$4.61 |  |



### Total Installed Capital Cost 1,000 mile pipeline, \$US million GH2 Delivery to City Gate

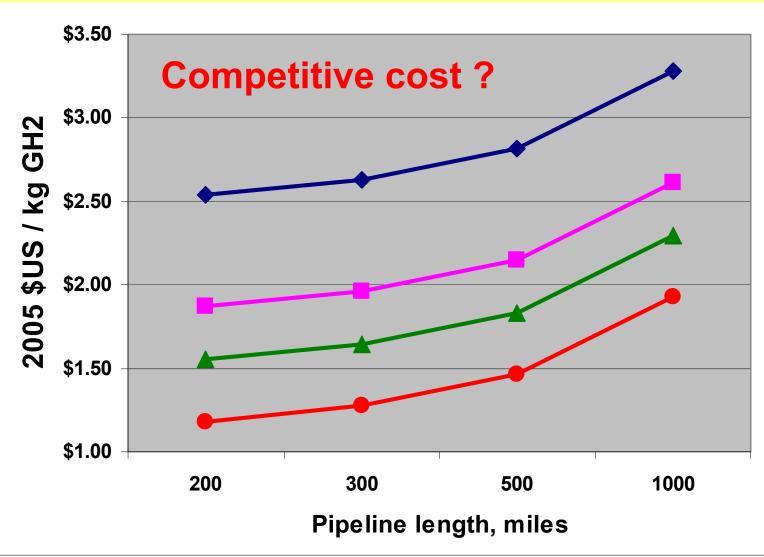
| Windplant size    | 1,000 MW     | 2,000 MW     |
|-------------------|--------------|--------------|
| Wind generators   | \$ 1,000     | \$ 2,000     |
| Electrolyzers     | 500          | 1,000        |
| Pipeline, 20" *   | <u>1,100</u> | <u>1,100</u> |
| TOTAL             | \$ 2,600     | \$ 4,100     |
| * \$ 1.1 M / mile |              |              |

### 2,000 MW windplant output

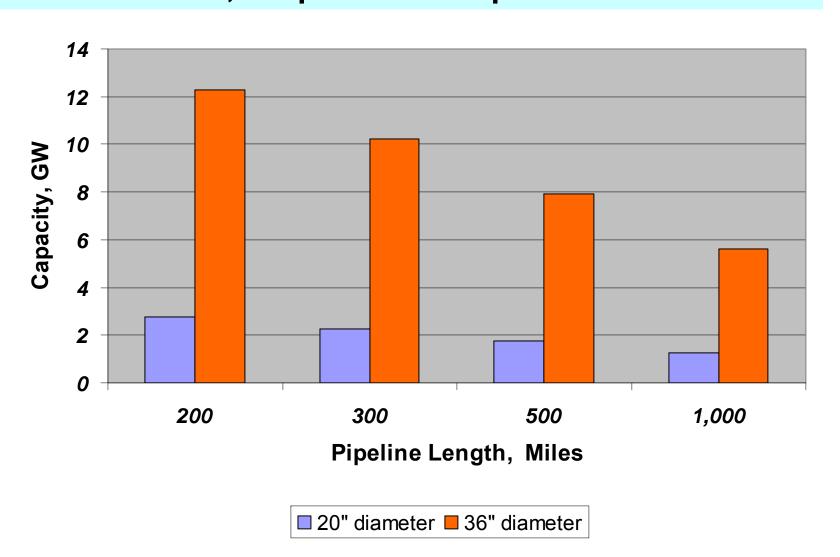
| 100 | % | Capa | acity | <b>Factor</b> |
|-----|---|------|-------|---------------|
|-----|---|------|-------|---------------|

| 100 % Supudity Fusion |             |         |         |           |
|-----------------------|-------------|---------|---------|-----------|
|                       | MWh/day     | tons/hr | tons/da | y tons/yr |
| As electricity        | 48,000      |         |         |           |
| As H2                 |             | 311     | 1,342   | 489,776   |
| As NH3                |             | 1,726   | 7,455   | 2,720,980 |
| 10" NH3 pipeline capa | city as NH3 | 150     | 3,600   | 1,314,000 |
| 10" NH3 pipeline capa | city as H2  | 27      | 648     | 236,520   |
| 40 % Capacity Factor  |             |         |         |           |
|                       | MWh/day     | tons/hr | tons/da | y tons/yr |
| As electricity        | 19,200      |         |         |           |
| As H2                 |             | 124     | 537     | 195,910   |
| As NH3                |             | 690     | 2,982   | 1,088,392 |
| 10" NH3 pipeline capa | city as NH3 | 60      | 1,440   | 525,600   |
| 10" NH3 pipeline capa | city as H2  | 11      | 259     | 94,608    |

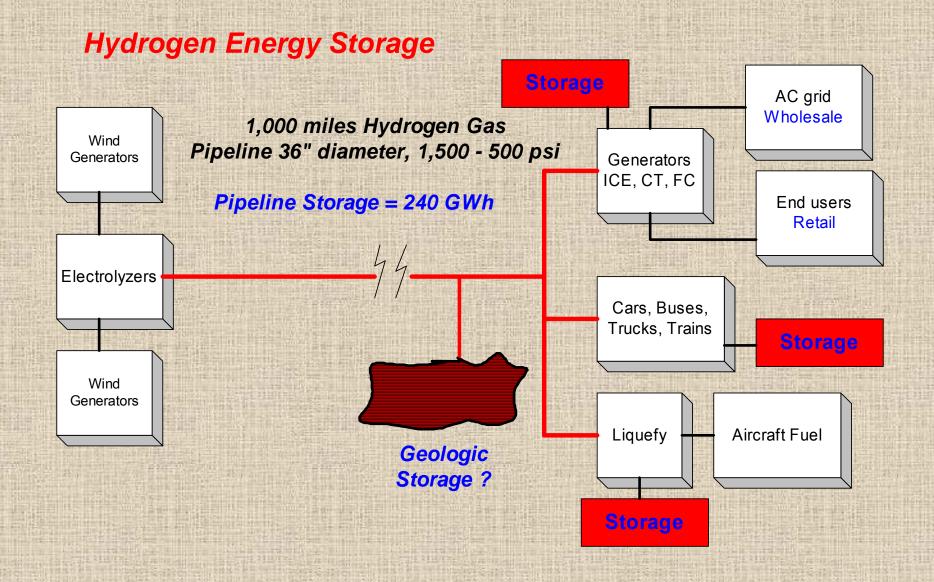
### City-gate GH2 cost @ 15% CRF, 20" pipeline, from 2,000 MW Great Plains windplant



### Compressorless 20", 36" GH2 Pipeline Capacity 1,500 psi IN / 500 psi OUT



### "Firming" Cavern Storage



### Optimistic: Total Installed Capital Cost 1,000 mile Pipeline "Firming" GH2 cavern storage

| Windplant size       | 1,000 MW     | 2,000 MW  |
|----------------------|--------------|-----------|
|                      | [million]    | [million] |
| Wind generators      | \$ 1,000     | \$ 2,000  |
| Electrolyzers        | 500          | 1,000     |
| Pipeline, 20"        | 1,100        | 1,100     |
| # storage caverns    | [4]          | [8]       |
| Caverns @ \$10M ea   | 40           | 80        |
| Cushion gas @ \$5M e | ea <u>20</u> | 40        |
| TOTAL                | \$ 2,660     | \$ 4,220  |

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

| Windplant size       | 1,000 MW     | 2,000 MW  |
|----------------------|--------------|-----------|
|                      | [million]    | [million] |
| Wind generators      | \$ 1,000     | \$ 2,000  |
| Electrolyzers        | 500          | 1,000     |
| Pipeline, 20"        | 1,100        | 1,100     |
| # storage caverns    | [4]          | [8]       |
| Caverns @ \$50M ea   | 200          | 400       |
| Cushion gas @ \$5M e | ea <u>30</u> | 60        |
| TOTAL                | \$ 2,830     | \$ 4,560  |

Cavern storage: ~ 10 % of total capital cost

### Pessimistic: "Firming" Storage Capital Cost for ALL Great Plains Wind

Adds VALUE: strategic, market

Salt caverns: ~ 17,000

Excavate: \$50 M each \$850 B

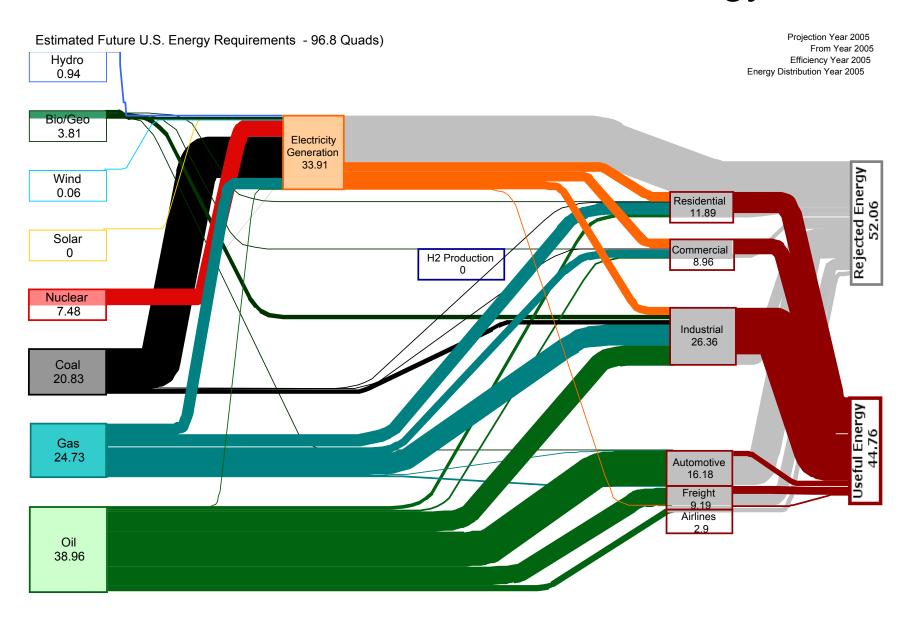
Cushion gas: \$5 M each \$85 B

Total \$ 935 B

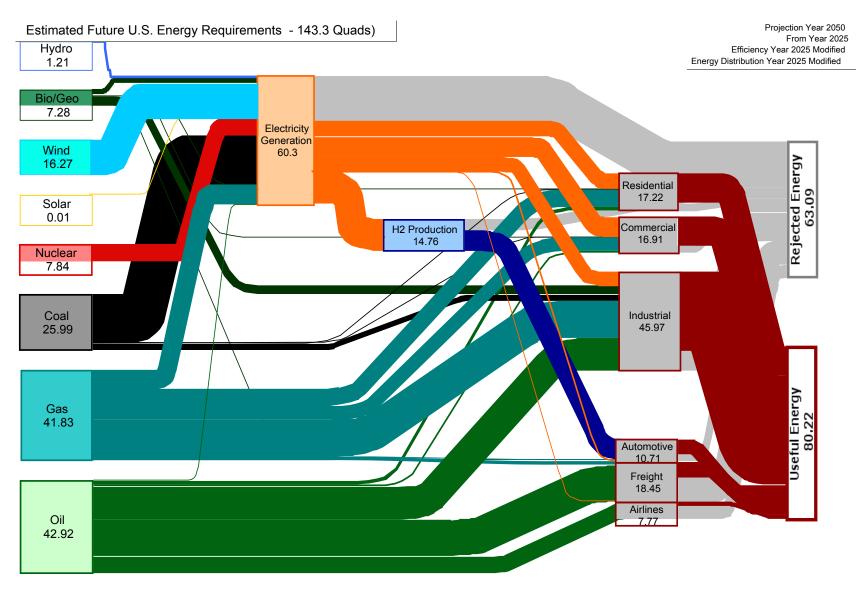
• NH3 tanks: ~ 5,000

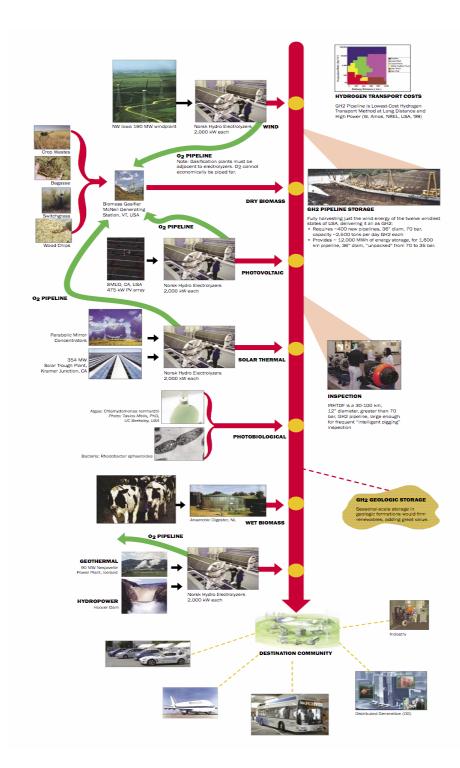
Capital \$25 M each \$125 B

### DOE-EIA: Estimated 2005 US energy use



## Estimated **2050** energy use (H<sub>2</sub> fleet using wind electrolysis)





# Pilot-scale Hydrogen Pipeline System: Renewables

- Diverse
- Dispersed, diffuse
- Large-scale
- Stranded
  - Remote
  - No transmission

#### The wind - hydrogen plant at Utsira

A vision becoming reality

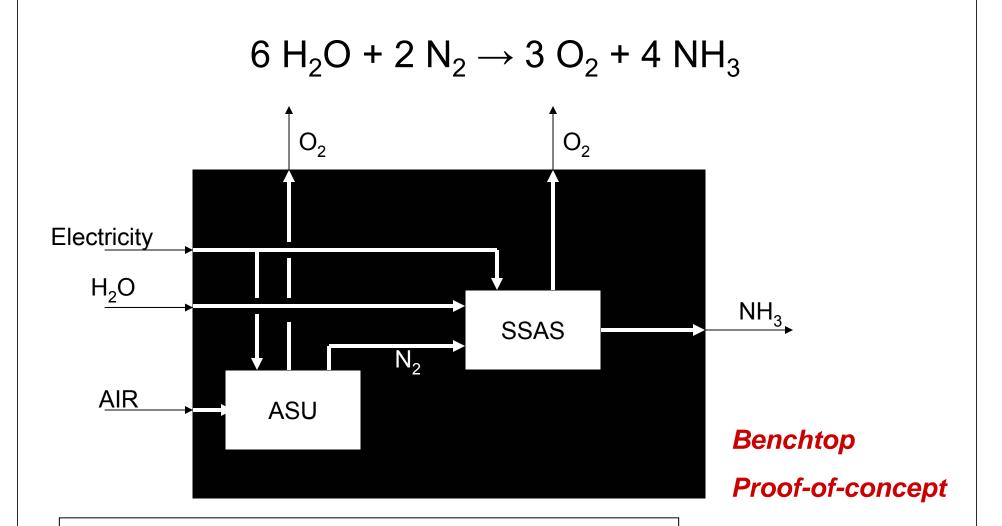






### Inside the Black Box: Solid State Ammonia Synthesis

Energy consumption 7000 - 8000 kWh per ton NH<sub>3</sub>



### "Hydricity"

- Nexus of electricity + hydrogen: twin currencies
- GH2, NH<sub>3</sub> for annual-scale "firming" storage
- Long-term:
  - Clear: energy currencies
  - Fuzzy: sources
- Climate Change: drive transition Wood-to-coal
- Conversion costs:
  - Capital
  - **O&M**
  - Energy losses:
    - 50 70% round-trip efficiency
    - CHP → 100%

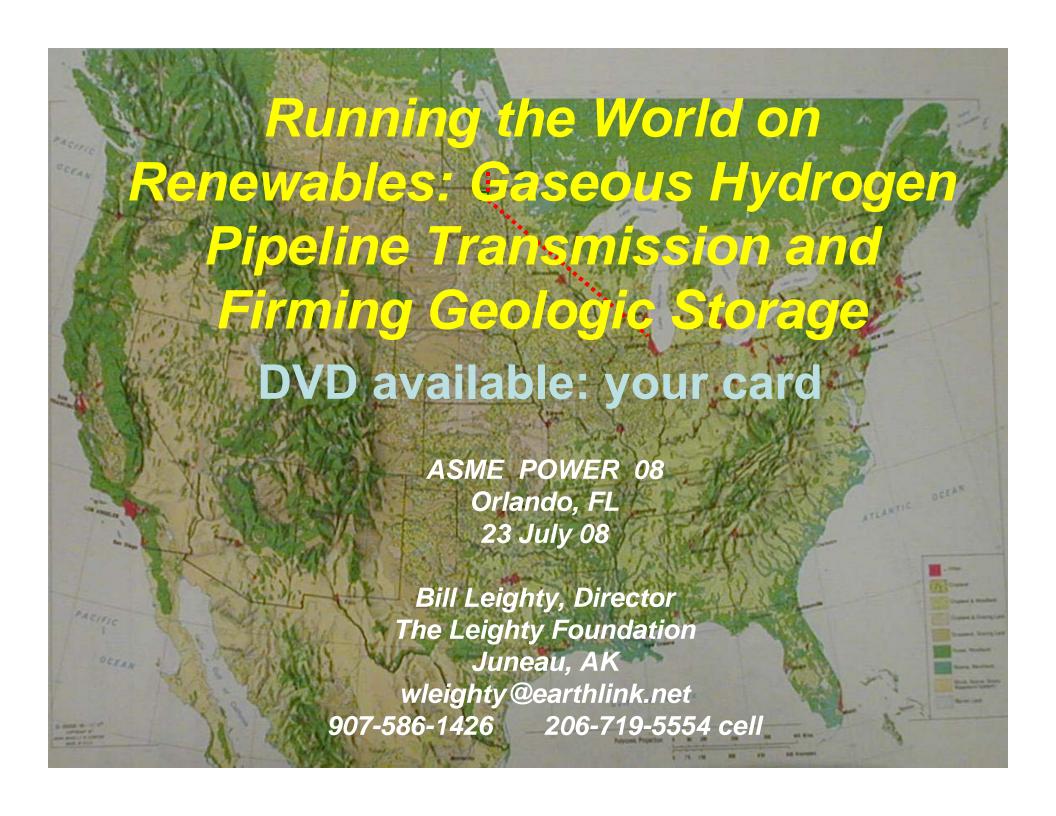
#### MUST Run the World on Renewables – plus Nuclear?

- 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





### 23 July 08

ASME
POWER 08
Orlando

#### Value from Collaboration

 Larger Scale "Wind Storage" **Basin Electric Xcel Energy**  Vehicle Applications & NREL & NREL DC/DC Interface Coordinated "Wind Storage" Re-deployable **Fort Collins** University Parallel timetables **Utilities &** of Minnesota Inter-project **Colorado OEMC** collaboration and data sharing Larger Scale "Wind Storage" High-Pressure Electrolysis

- Anhydrous Ammonia Production
  - Vehicle & Hybrid Applications

- Vehicle Fueling Station & Fuel Cell
  - Hydrogen/Natural Gas Mixing

