

Run the World on Renewables

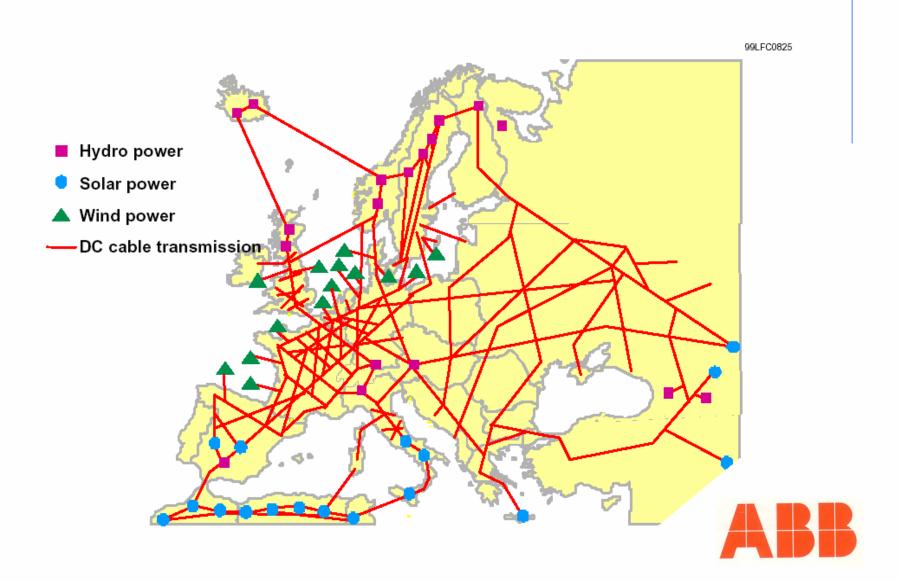
- EREC: 20% by 2025
- 25 x '25
- Only 200 years of coal; less O+G
- Emergencies ?
 - Climate change
 - Energy cost
 - Energy security

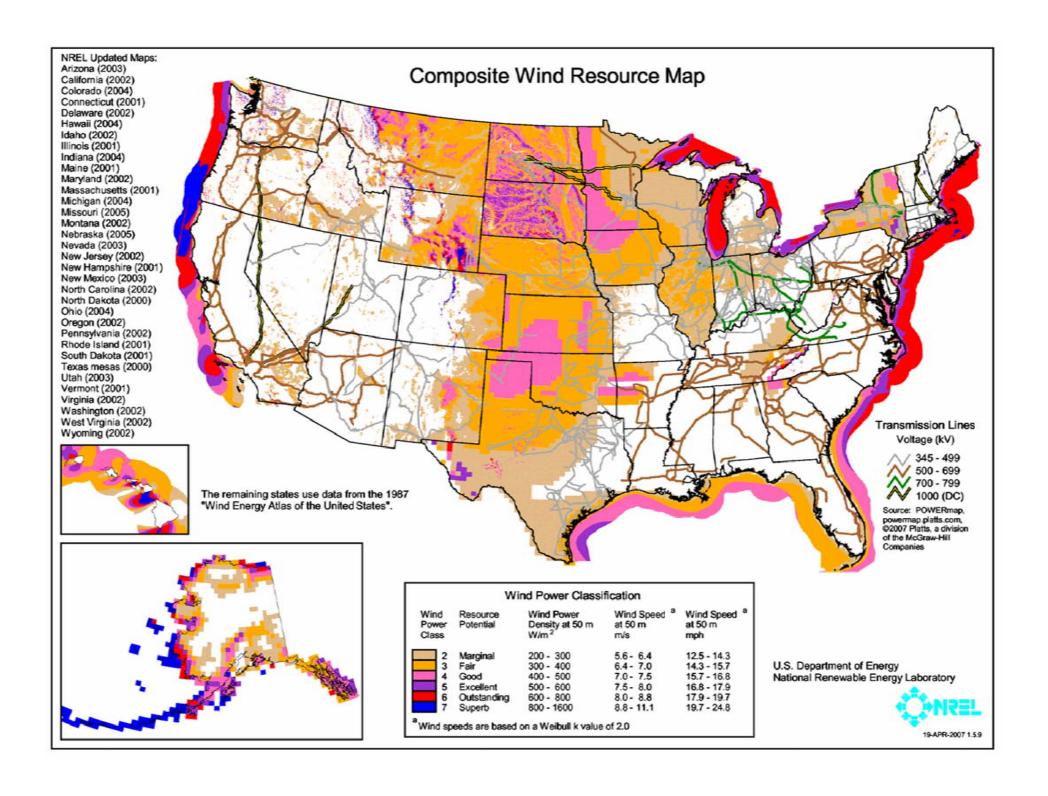
Run the World on Renewables

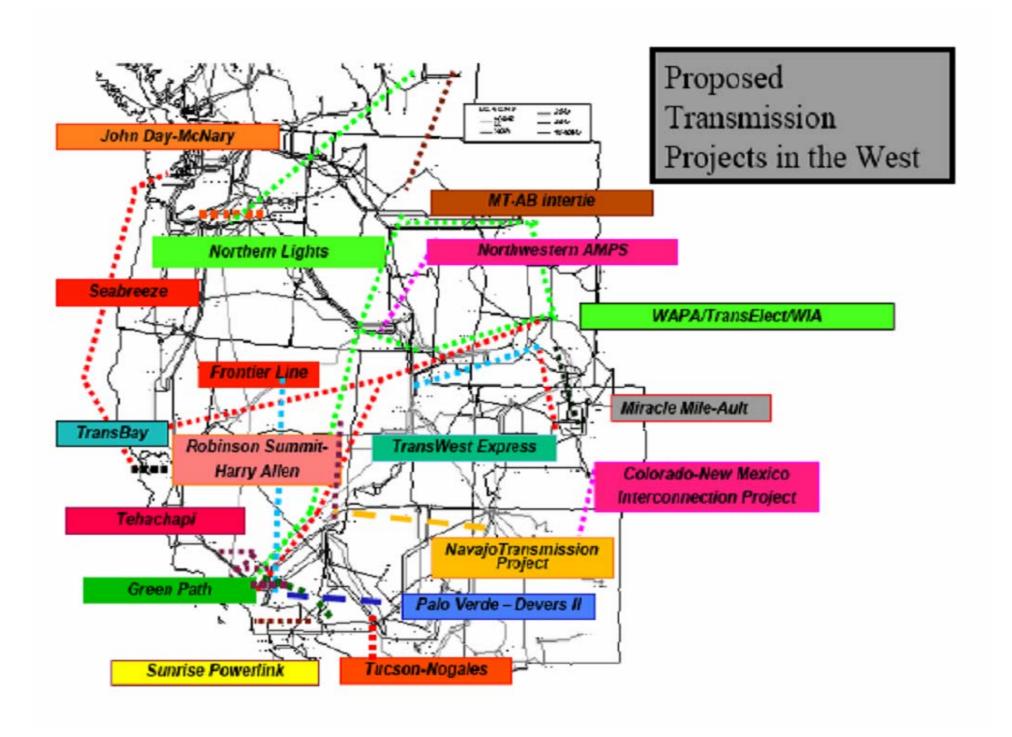
- Richest renewables stranded
 - High intensity
 - Large geographic extent dispersed
 - Far from markets
 - No transmission
- Time-varying output except
 - Except geothermal, currents
 - Seconds to seasons
- ABB, ISET "huge catchment area"

Vision: Remote renewable energy sources

connected to loads by DC grid







Run the World on Renewables

- Distributed + centralized
- Transmission + storage
- Need "Firm" unless MO and lifestyle changes
- Firm: deliver contracted energy every hour of every year

Run the World on Renewables

- Can't do it with electricity alone
 - -NIMBY delays, costs
 - -Vulnerable: acts of God or man
 - –High capital costs:
 - Gathering
 - Access -- substations
 - -Low CF
 - -O&M cost, losses
 - –No affordable annual-scale storage
- Bigger markets than grid?
 - Transportation fuel
 - DG fuel, CHP

California Hydrogen Highways ENERGY Hydrogen Fuel Stations (count)* Existing Station (12) Planned Station (13) "2010 Vision" Station (184)** Transportation and Population Major California or Interstate Highway Other Route County Line Urban Area * The primary sources of existing and planned hydragen station locations are the South Coast Air Quality Management District (SCAQMD) and Fuel Cells 2000. ** "2010 Vision" stations are located approximately every 20 miles along major freeway corridors throughout California. Los Angeles Area NOTE: This is a droft map and is intended for illustrative purposes only. Existing and planned dollars date may not be complete.

250 hydrogen "gas stations"

Of 10,000 CA total

Whence the hydrogen?

CA Annual Hydrogen Fuel Demand

- 20% of 45M vehicles H2 fueled -- by 2030 ?
- 9M vehicles @ 78 mpg = 78 miles / kg H2
- 12,000 miles / year → 150 kg H2 / year
- 1,350 M kg H2 / year = 1.35 M tons H2 fuel
- @ 50 kWh / kg at windplant gate:
 - $-90 \times 10^9 \text{ kWh / year} = 67,500 \text{ GWh / year}$
 - @ 40% CF → 19 GW nameplate wind
 - 3 GH2 pipelines, 36", 500 miles long
 - @ 4 caverns / GW = 80 storage caverns: firm
- OR: 6 electric lines, biggest: not firm
- How fuel the other 80%?





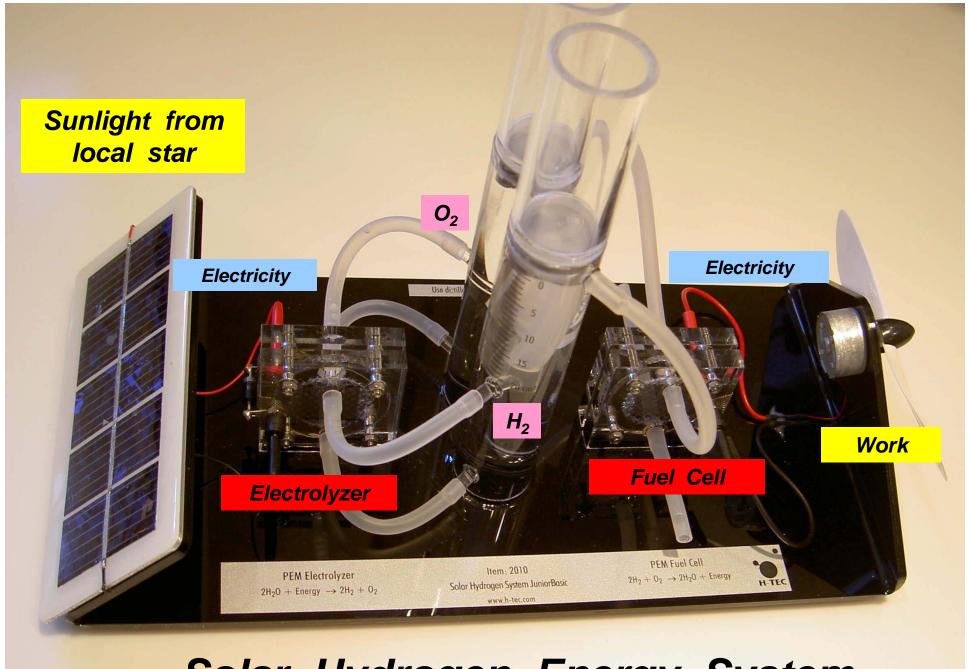
Renewables Focus

- Centralized production
 - Electricity
 - Direct hydrogen (bio, photochem)
- GW (Gigawatt = 1,000 MW) scale
 - Economy of scale
 - Run the world
- Gaseous hydrogen (GH2)
- Anhydrous ammonia (NH₃)
 - ✓ Better than hydrogen?
 - ✓ Need hydrogen

Hypothesis:

Hydrogen's greatest value to humanity:

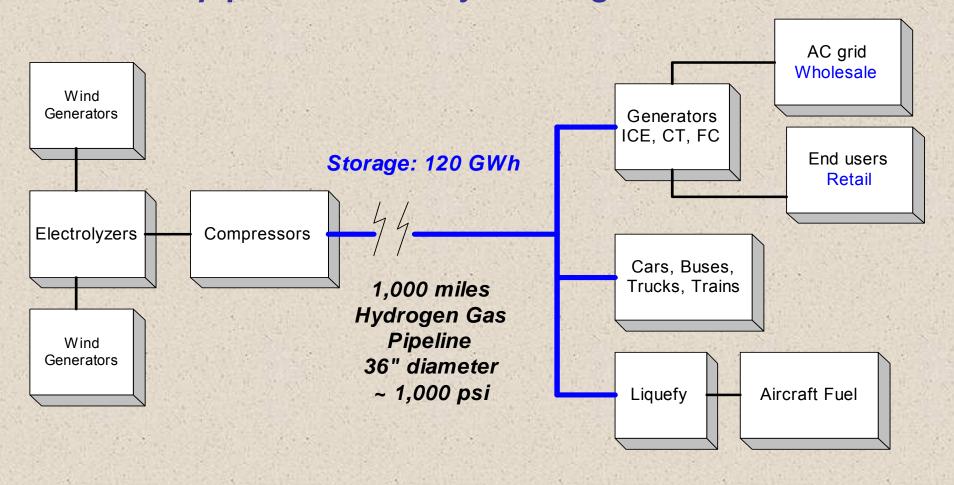
- Not fuel for fuel cell cars
- Means to gather, transmit, firm, deliver, use
- Diverse, large-scale, stranded renewables



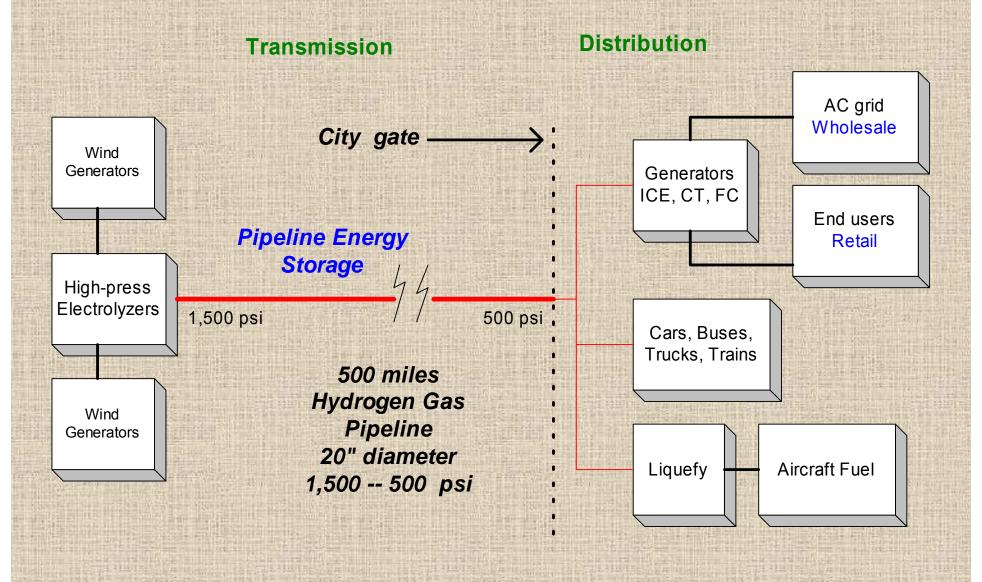
Solar Hydrogen Energy System

Hydrogen Transmission Scenario

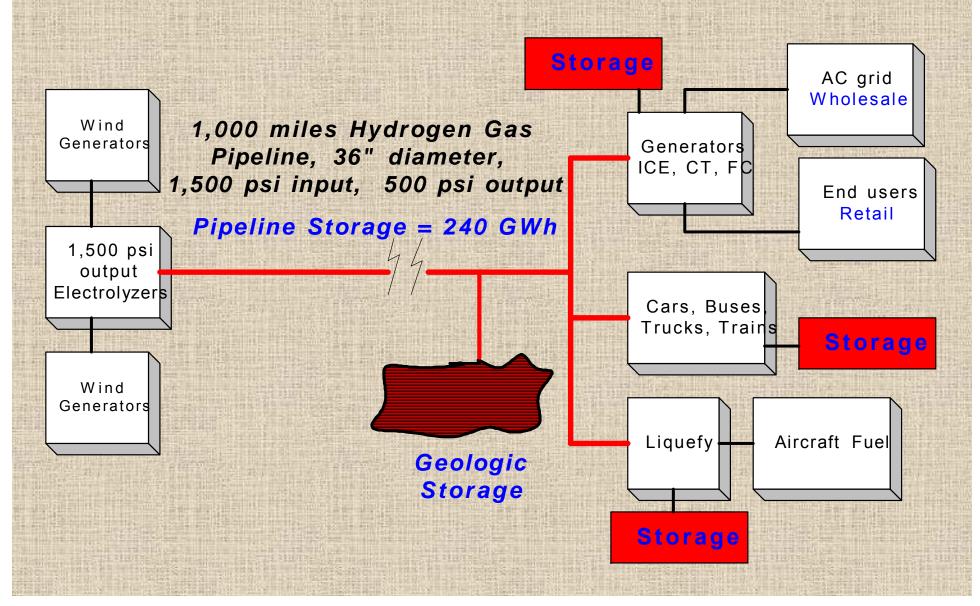
- Low-pressure electrolyzers
- "Pack" pipeline: ~ 1-2 days' storage = 120 GWh

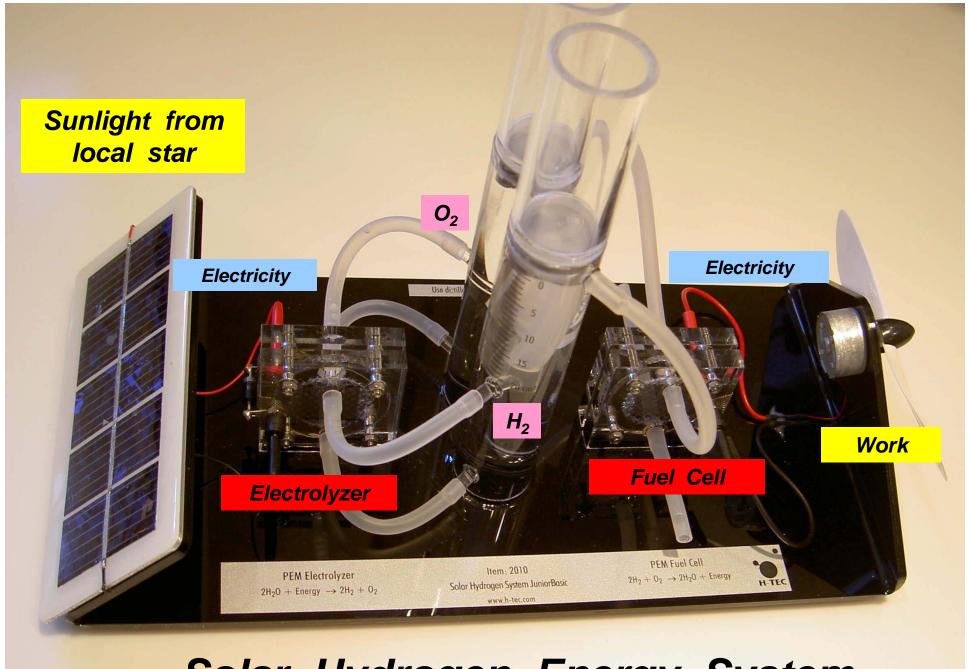


Compressorless system: No firming storage



Compressorless Renewables - Hydrogen System with Annual Firming storage





Solar Hydrogen Energy System

Storage: Hour - Week Scale

- Distributed
 - Buildings to blocks
 - Thermal: space heat + cool, DHW
 - Chemical Hydrogen, ammonia
 - Reversible fuel cells Hydrogen, ammonia
 - Battery, flywheel, VRB-ESS *
 - Vehicles
 - BEV (battery electric)
 - Hydrogen-fueled FCEV, HICE
- Centralized
 - VRB-ESS *
 - Compressed Air (CAES)
 - Concentrated Solar Power CSP thermal
 - * Vanadium Redox Battery Energy Storage System

Storage: Annual-scale "Firm"

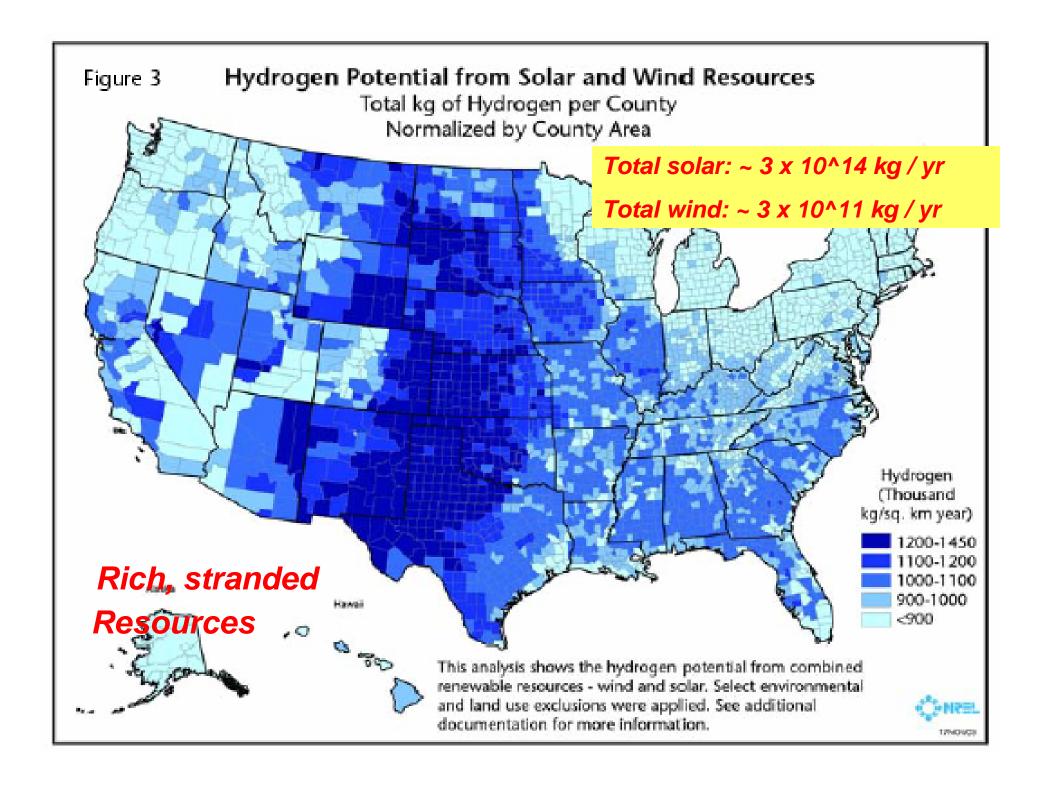
- · Every hour of every year: contracted amount
- Adds great value: strategic, market price
 - "Run world on renewables"
 - Without MO, lifestyle changes
 - Manufacture when sun shines
 - Vacation on winter wind
- Except:
 - Geothermal
 - Biomass stockpiled
 - OTEC
 - Ocean current
- Requires large storage
 - GW scale
 - Hydrogen: pipelines + caverns
 - Ammonia: pipelines + tanks



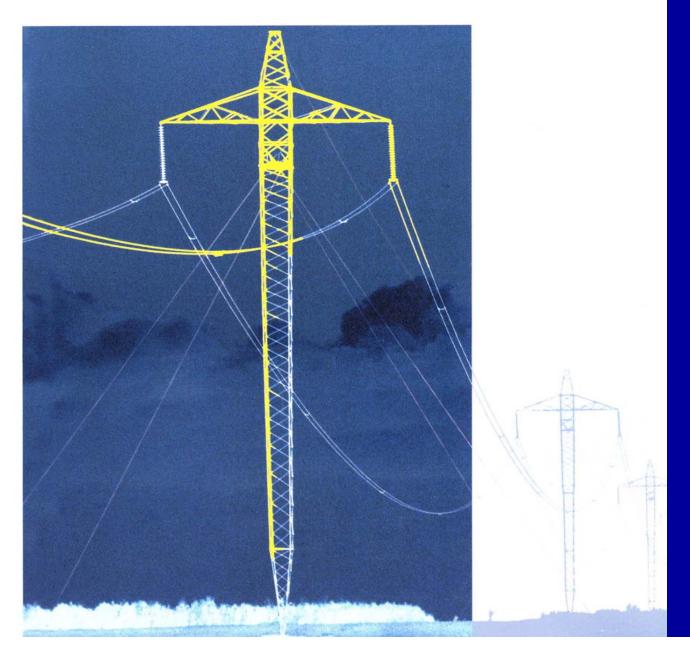
Exporting From 12 Windiest Great Plains States

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, TWh	Wind Gen MW (nameplate) (40% CF)	6 GW 36" GH2 export pipelines	\$ Billion Total Capital Cost *	3 GW export HVDC lines	\$ Billion Total Capital 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



High Voltage Direct Current Transmission



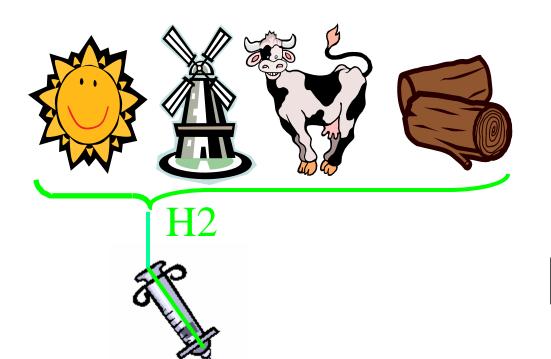
North Dakota wind needs 115 new lines at 3,000 MW each

Twelve Plains
states
wind needs
890 new lines
at 3,000 MW
each

SIEMENS HVDC line +/- 500 kv

The NATURALHY approach











NATURALHY:

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

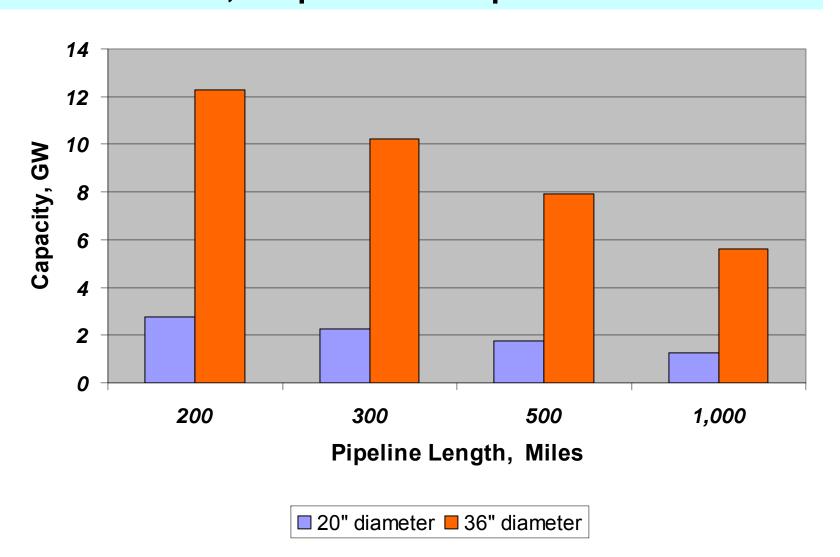




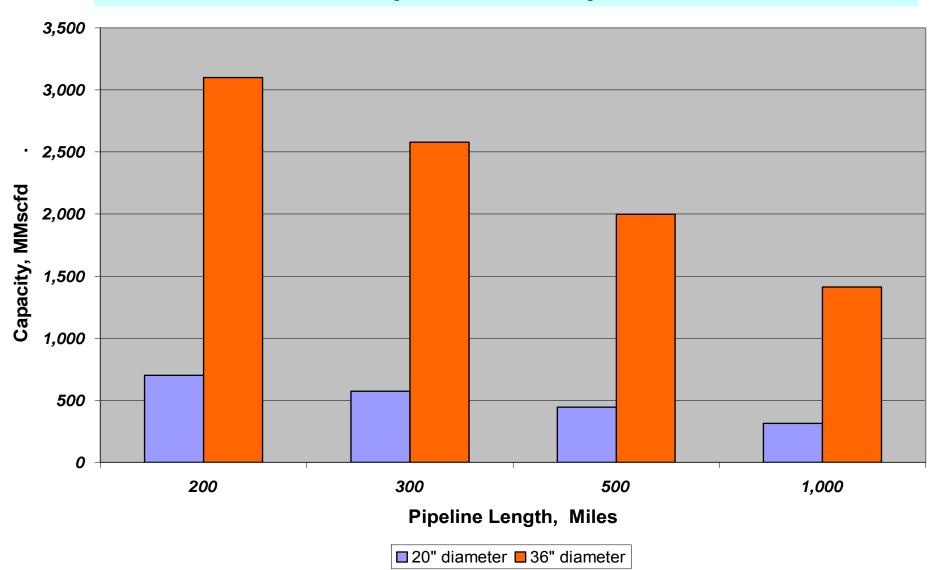


N.G.

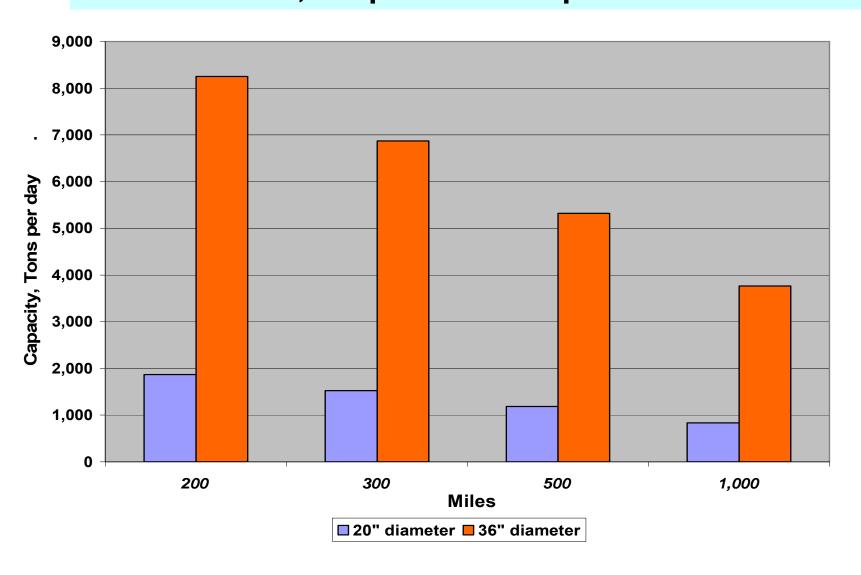
Compressorless 20", 36" GH2 Pipeline Capacity 1,500 psi IN / 500 psi OUT



Compressorless 20", 36" GH2 Pipeline Capacity 1,500 psi IN / 450 psi OUT



Compressorless 20", 36" GH2 Pipeline Capacity 1,500 psi IN / 450 psi OUT



Wind seasonality, Great Plains

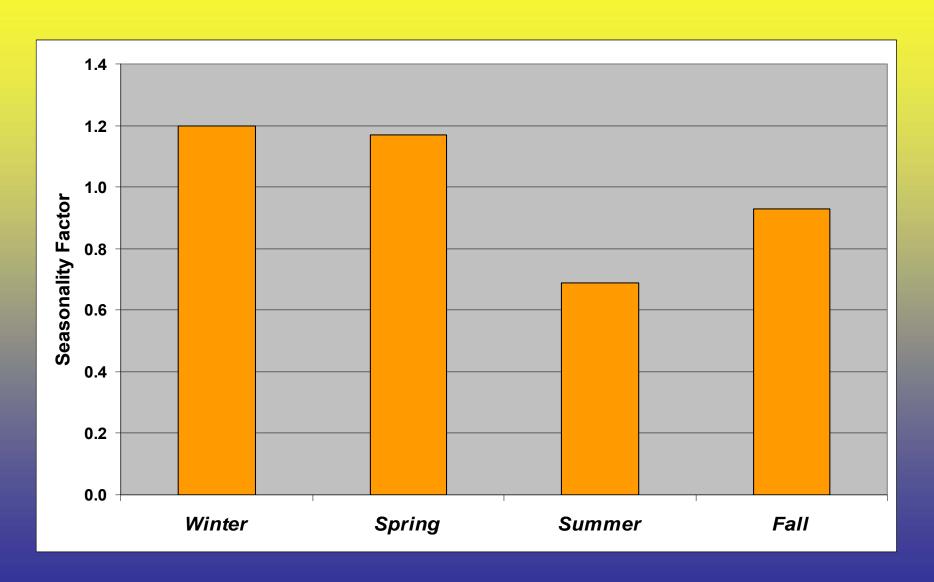
- Winter = 1.20
- Spring = 1.17
- Summer = 0.69
- Autumn = 0.93

Source: D. Elliott, et al, NREL



Wind Seasonality, Northern Great Plains

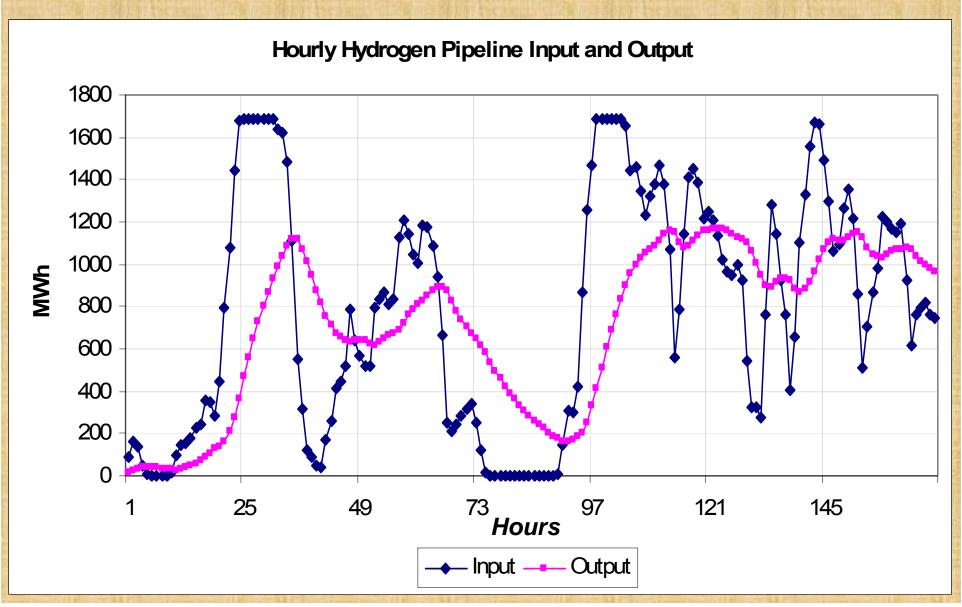
Normalized to 1.0 per season

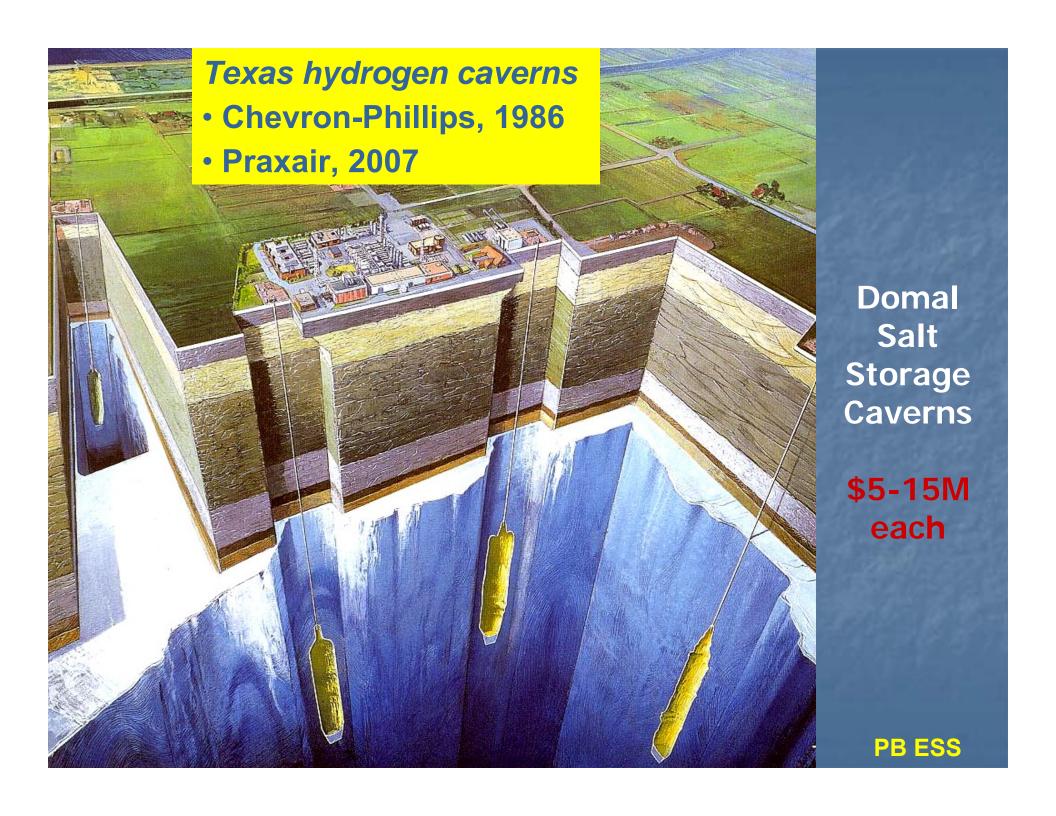


Annual – scale "Firming" Great Plains Wind

- 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 = 300 GWh
 - as GH2 = 15,000 Mt @ 2,500 tons / cavern = 6 caverns
 - "Firming" energy storage, all great Plains wind:
 - as GH2 = 17,000 caverns @ \$15M each = \$264 billion

Great Plains Windplant, Pipeline Hourly Output for Typical Week

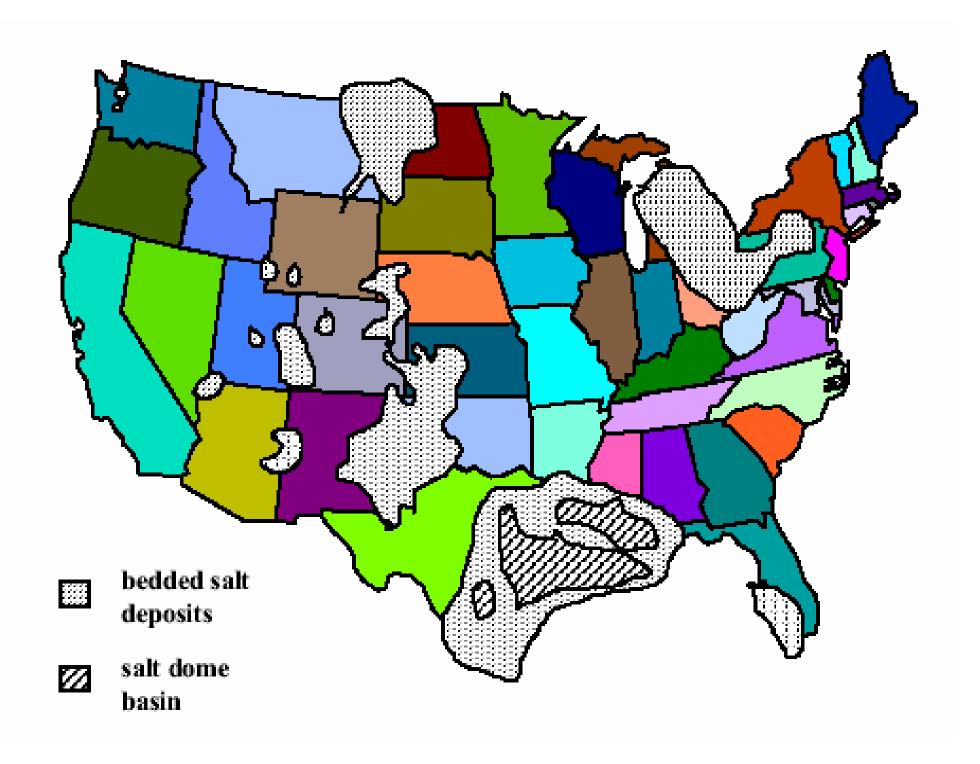




Wellhead, new Gaseous Hydrogen Storage Cavern

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





Solution-mined Salt Caverns assume

- "Clemens Terminal"
 - $-6.4 \text{ M ft}^3 = 580,000 \text{ m}^3 \text{ gross}$
 - 2,200 psi MAOP → 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: Total Installed Capital Cost 1,000 mile Pipeline "Firming" GH2 cavern storage

Windplant nameplate 2,000 MW

Wind generators	\$ 2,000	million
Electrolyzers	1,000	
Pipeline, 20"	1,100	
# storage caverns	[8]	
Caverns @ \$10M ea	80	
Cushion gas @ \$5M ea	40	
TOTAL	\$ 4.220	

Cavern storage: ~ 3 % of total capital cost

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

Windplant nameplate

2,000 MW

Wind generators	\$ 2,000 million
Electrolyzers	1,000
Pipeline, 20"	1,100
# storage caverns	[8]
Caverns @ \$50M ea	400
Cushion gas @ \$5M ea	<u>60</u>
TOTAL	\$ 4.560

Cavern storage: ~ 10 % 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**

• Ammonia (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

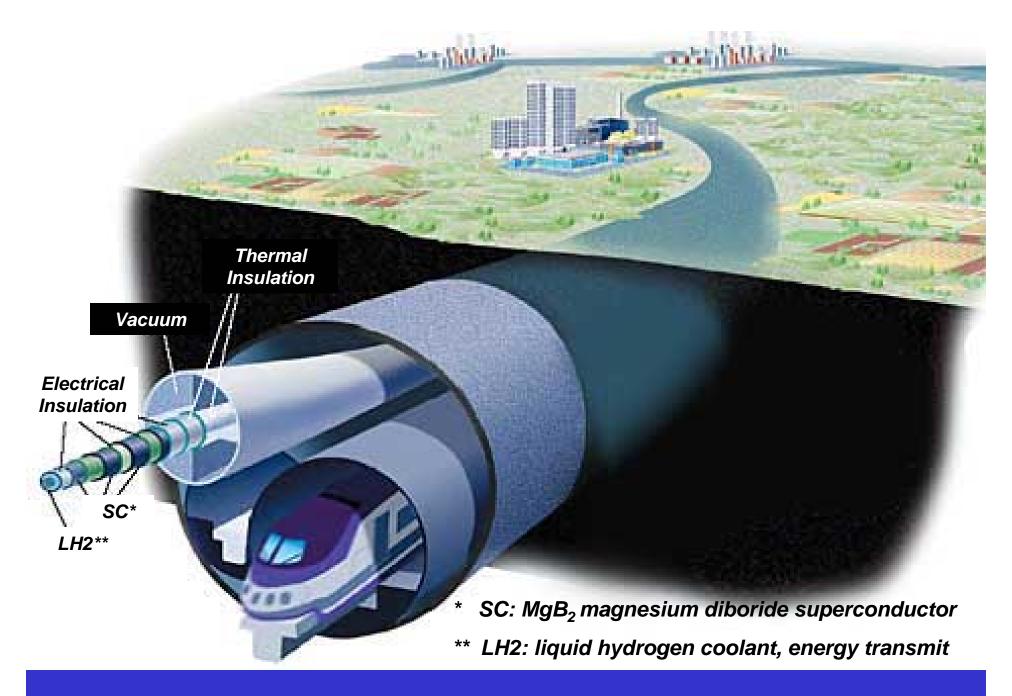
Total \$ 935 B

• NH3 tanks: ~ 5,000

Capital \$25 M each \$125 B

Other

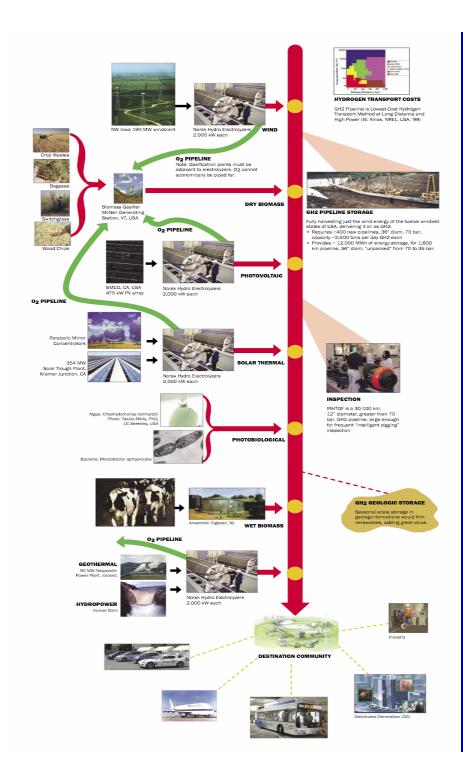
- EPRI "Energy Pipeline"
- Aluminum gallium
- Fischer Tropsch Liquids (FTL's)
- Hythane ™
- Nuclear nexus



Continental Supergrid – EPRI concept "Energy Pipeline"

Hypothesis:

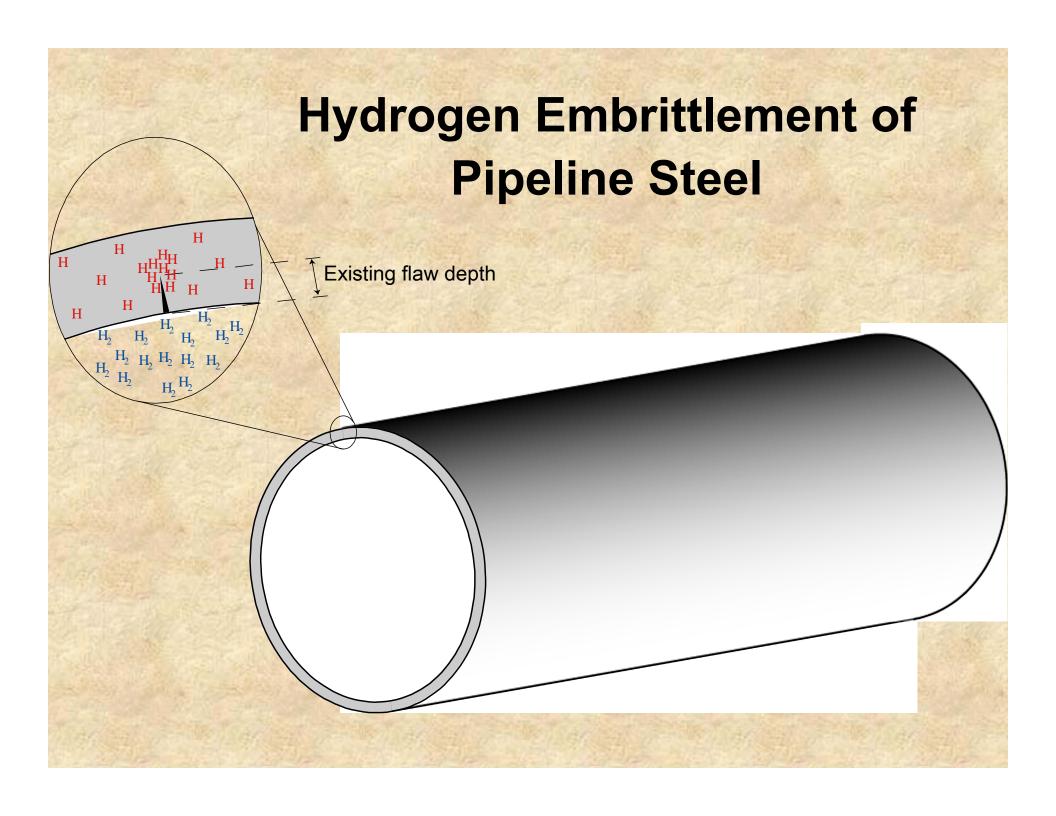
- Hydrogen's greatest value to humanity:
 - Not fuel for fuel cell cars
 - Means to gather, transmit, firm, deliver, use
 - Diverse, large-scale, stranded renewables
- Test: build pilot plants
 - Induce upstream R+D
 - Discover tech + econ feasibility
 - Assure public, business
 - Ready solutions: emergencies



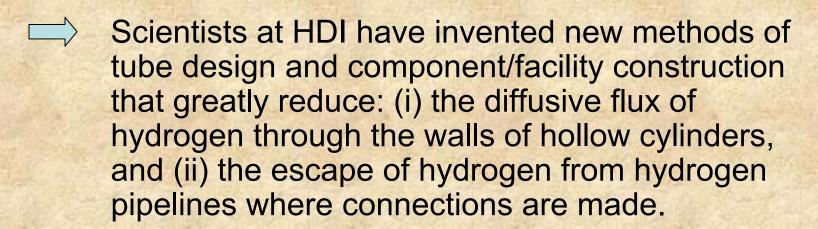
International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF) Pilot plant

Global opportunity: IPHE project





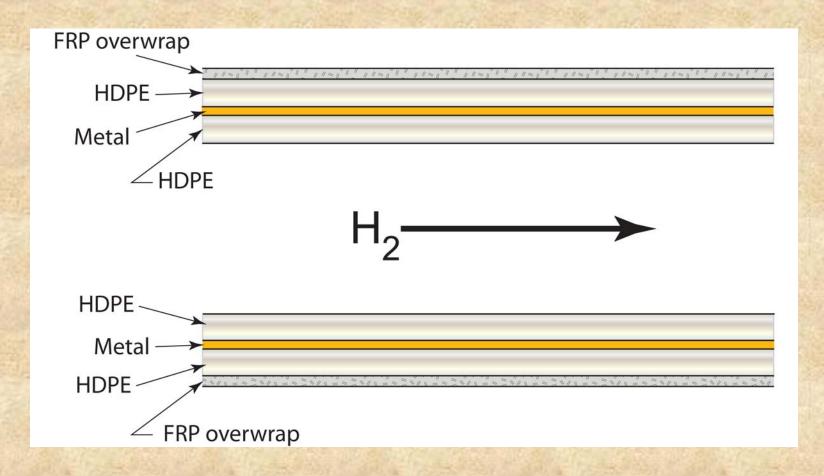
HDI Polymer/Metal Tube Technologies



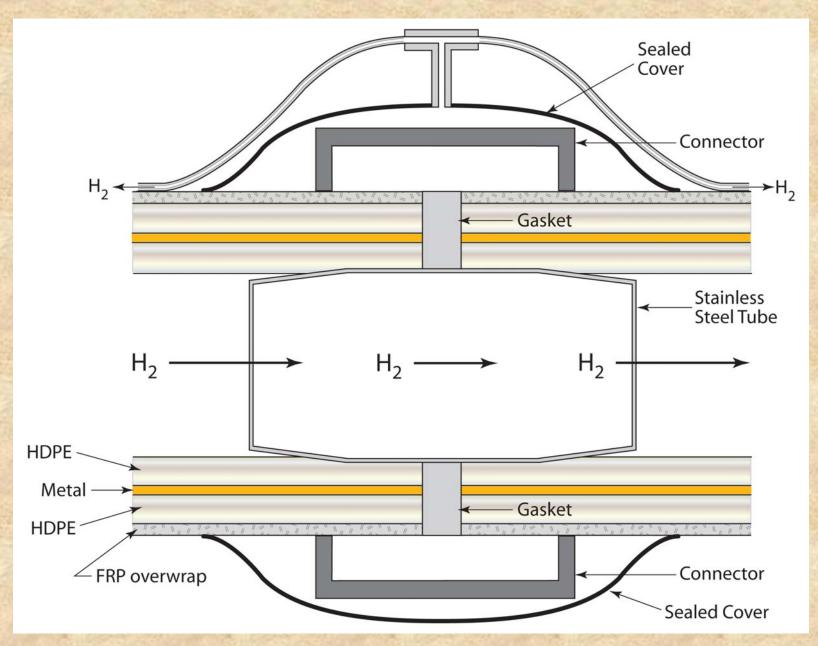
The techniques involve use of one or more layers of homogeneous or laminated polymeric material and a thin metal interlayer to create multiple equilibrium and kinetic barriers to hydrogen diffusion.

Hydrogen Discoveries, Inc. (HDI)

HDI Polymer/Metal Pipe Technology: Longitudinal Cross-Section

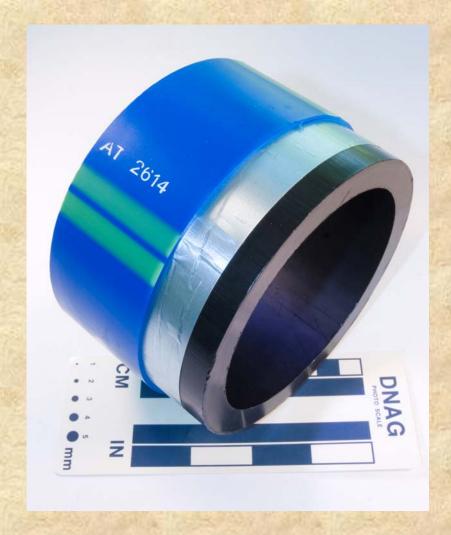


Hydrogen Discoveries, Inc. (HDI)



Hydrogen Discoveries, Inc. (HDI)

Seeing is believing!



A close-up photograph of a 3" long, 4" I.D. pipe specimen consisting of two layers of HDPE with a thin aluminum interlayer.

Hydrogen Discoveries, Inc. (HDI)





Anhydrous Ammonia (NH₃) for Transmission and Storage of Renewable Energy: Fertilizer and Fuel

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Facts About Ammonia (NH₃)

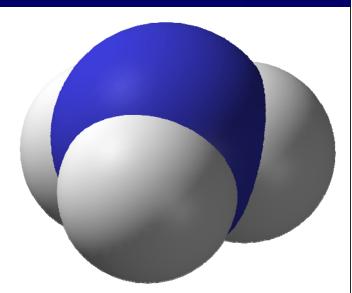


One of the most widely used chemicals worldwide

- > 100 million tons/year
- 80% used as fertilizer
- Refrigeration and cleaning
- Purification of water supplies
- Manufacture of plastics, dyes...

Easily stored as a liquid

- Compressed (~10 atm at 25°C)
- Refrigerated (-33°C at 1 atm)
- Strong odor, easy to detect leaks







Ammonia as a Fuel



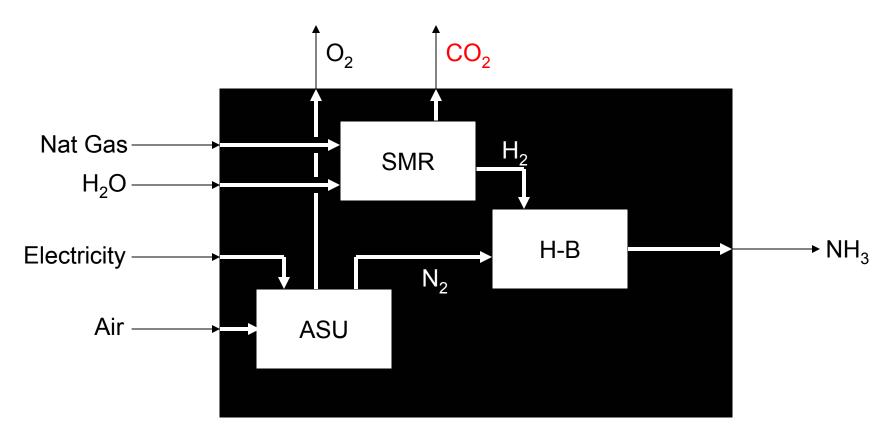
$2 \text{ NH}_3 \rightarrow 3 \text{ H}_2 + \text{ N}_2 \qquad \Delta \text{H}^\circ = 46 \text{ kJ/mol}$

- Very mild enthalpy of reforming, if H₂ is required
- NH₃ is typically stored and transported as a liquid
 - Power density is comparable to other liquid fuels
 - Vaporizes when throttled (no flash line required)
- Classified as non-flammable, non-explosive
- Suitable fuel for internal combustion engine
 - Spark ignition
 - High-compression diesel
- Suitable fuel for fuel cells
 - Cracked ammonia for PEMFC, AFC, PAFC
 - Direct ammonia for SOFC, PCFC, MCFC, MSAFC





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



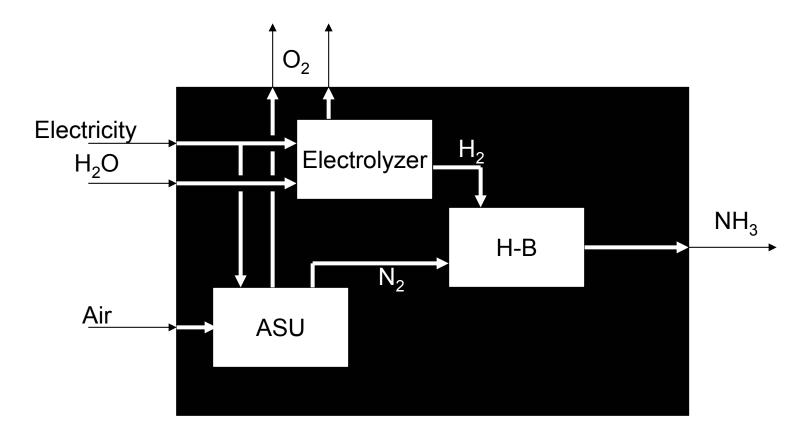


enewable Alternative: ectrolysis + Haber-Bosch



$$3 H_2O \rightarrow 3 H_2 + 3/2 O_2$$

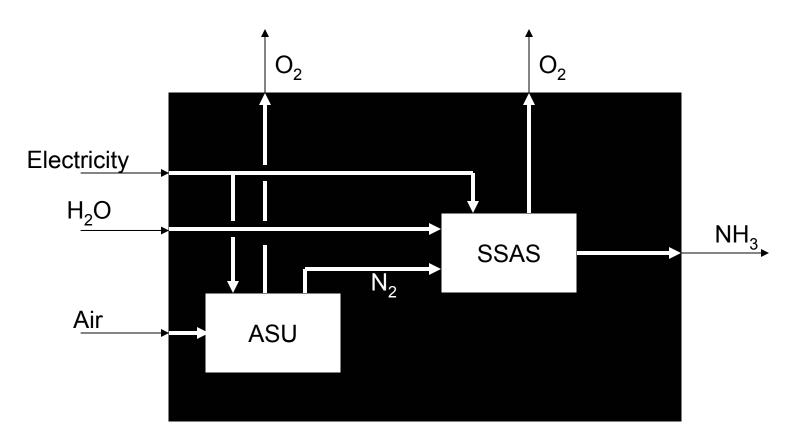
 $3 H_2 + N_2 \rightarrow 2 NH_3$



Alternative to Haber-Bosch: Solid State Ammonia Synthesis



$$6 H_2O + 2 N_2 \rightarrow 3 O_2 + 4 NH_3$$





NH₃ Transport: Pipelines



- Pipelines provide much of the NH₃ used in the Midwest
 - Local production: 47%
 - Pipeline: 33%
 - •River barge: 14%
 - Rail shipment: 6%
- Service is unique
 - Many local markets
 - High seasonal demand
- Pipeline construction: mild carbon steel

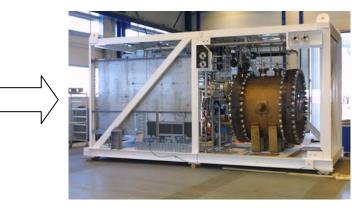




Wind-to-Ammonia Concept







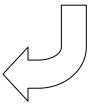










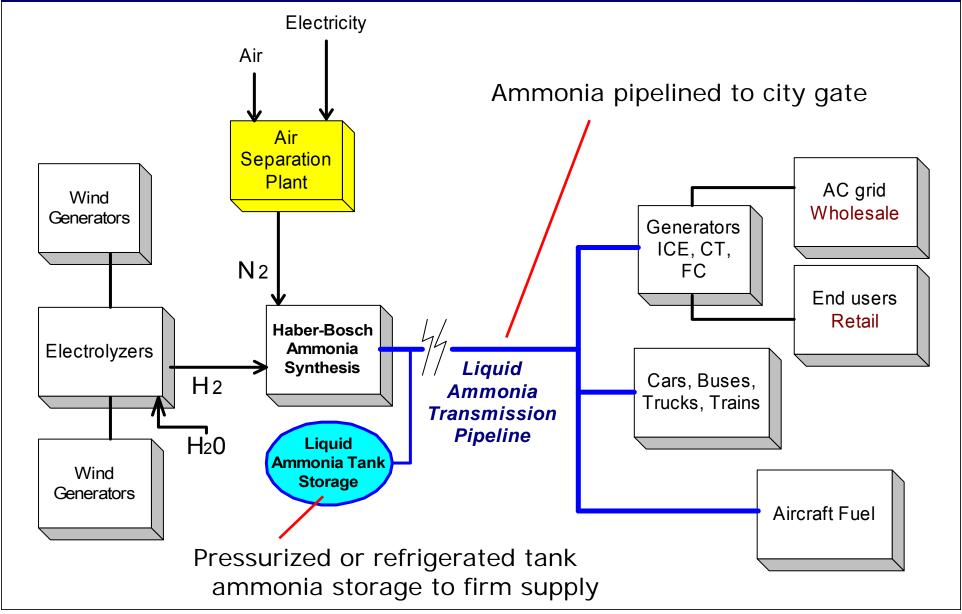


Only requirements for renewable NH₃: Air, Water, Electricity.



A Vision for Renewable Ammonia





'07 Senate Farm Bill

Sec. 9019 "Renewable Nitrogen Fertilizer"

- Research initiative
- "... identify key tech and econ barriers to producing commercial-scale quantities of nitrogen fertilizer from renewable energy sources."

Summary

- "Transmission" must include alternatives to electricity
 - Gaseous hydrogen, GH2
 - Liquid anhydrous ammonia, NH₃
 - Others
- "Run the World on Renewables" requires:
 - Annual-scale firming storage
 - Synergy among renewables
- Think energy systems

Transmission + Storage = System

- System optimize
- Long-term COE
- GW scale
- Diversity → Synergy → Minimum storage → Firm →
 Add value → COE

