



**Renewable Energy Bulk Storage for less  
than \$1.00 / kWh Capital Cost  
as Gaseous Hydrogen (GH<sub>2</sub>) and Liquid  
Anhydrous Ammonia (NH<sub>3</sub>)  
Carbon-free Fuels, with Transmission via  
Underground Pipelines**

**22<sup>nd</sup> World Energy Congress**

**14 October 2013**

**Daegu, Korea**

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Juneau, AK**

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**206-719-5554 cell**



**Mendenhall Glacier, Juneau, AK**

**June '71**



**Mendenhall Glacier, Juneau, AK**  
**10 October 10**



**Mendenhall Glacier, Juneau, AK  
10 October 10**

# MUST Run the World on Renewables – plus Nuclear ?

- Rapid climate change
- Ocean acidification
- Sea level rise
- Species extinctions



# MUST Run the World on Renewables – plus Nuclear ?

- Demand growth
- Water for energy
- War
- Depletion of Oil and Gas
- Only 200 years of Coal left
- Only Source of Income:
  - Sunshine
  - Tides
  - Spending our capital

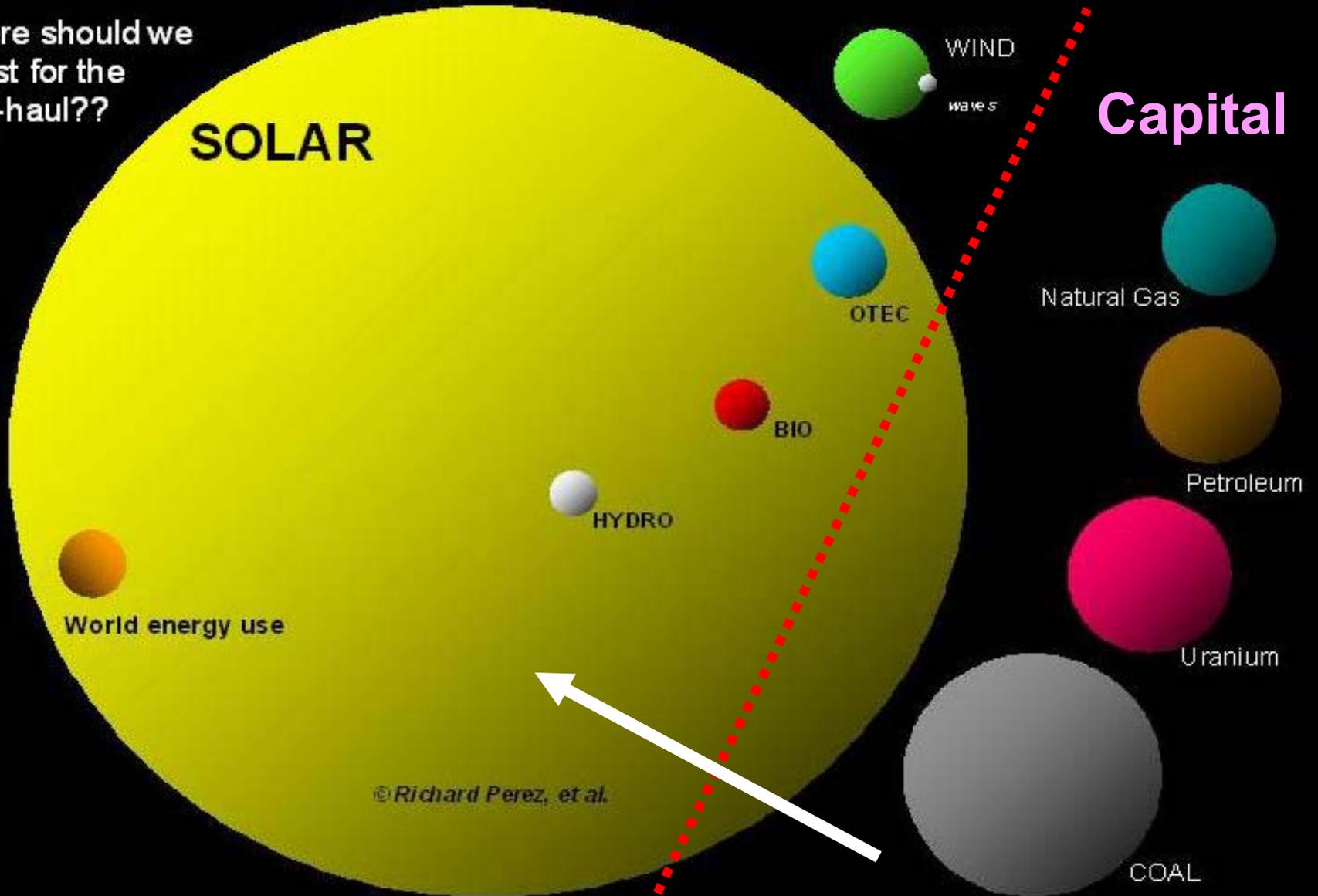


# Comparing the world's energy resources\*

Annual Income

Where should we invest for the long-haul??

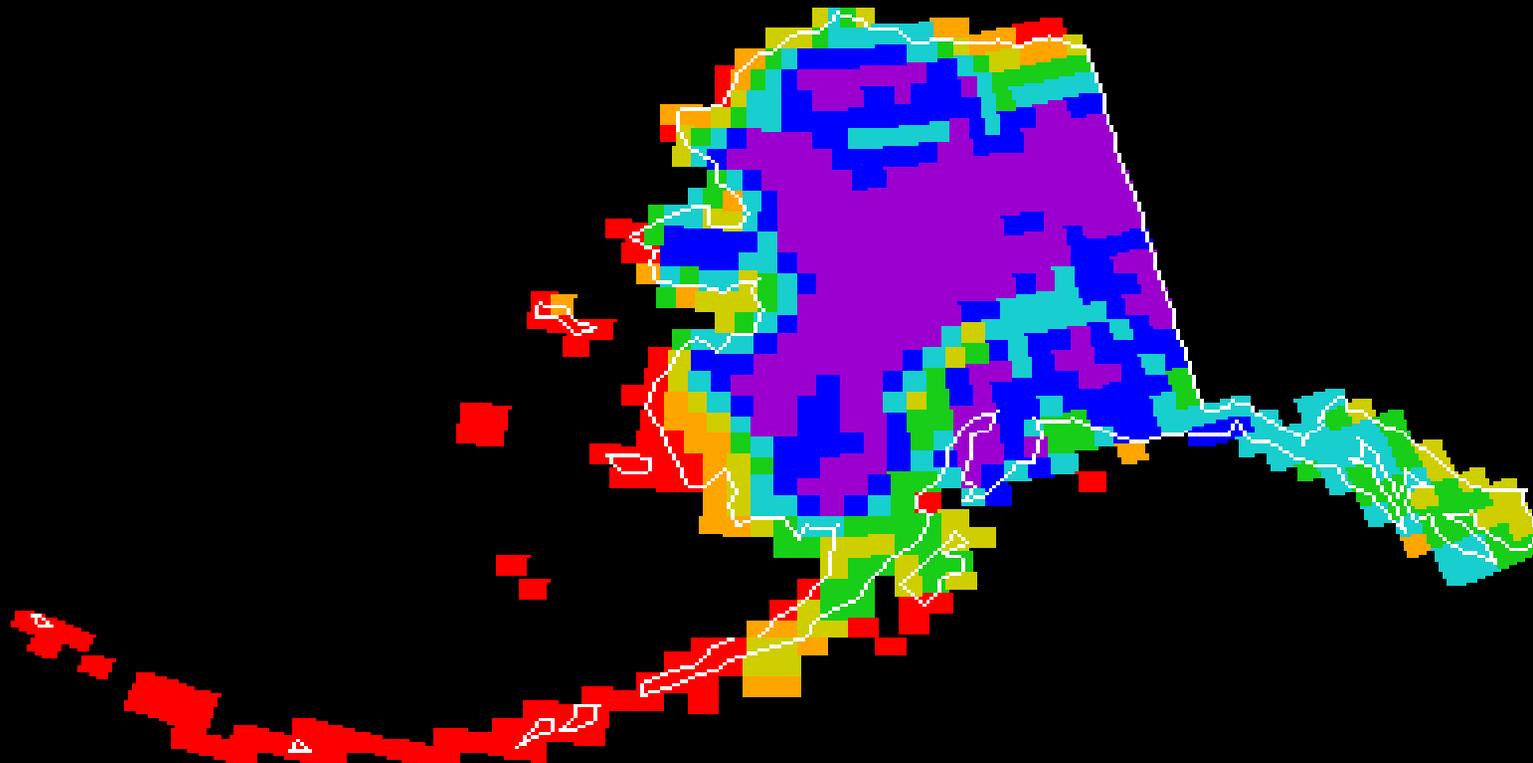
Capital



\*yearly potential is shown for the renewable energies. Total reserves are shown for the fossil and nuclear "use-them, lose-them" resources. World energy use is annual.



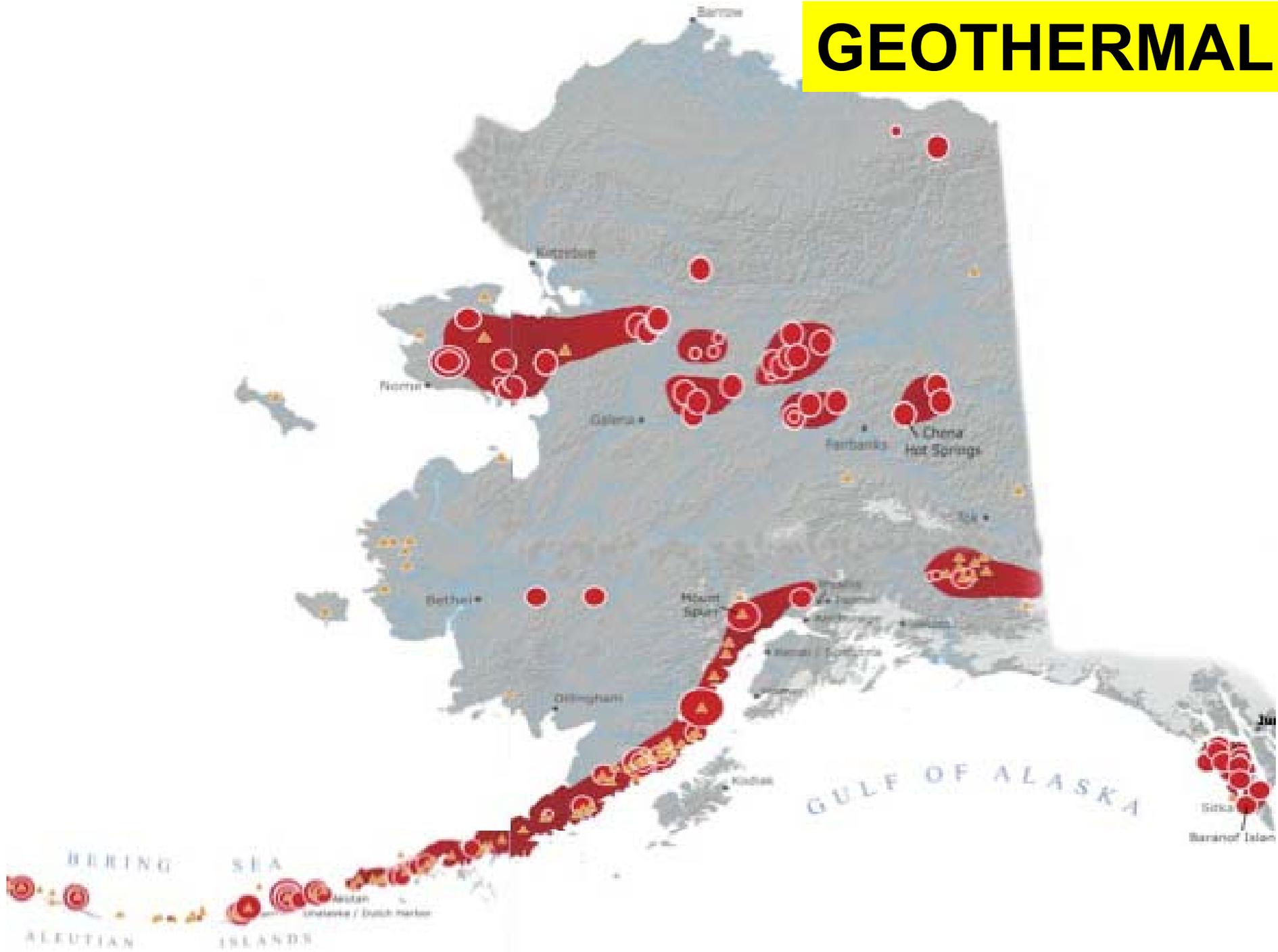
# Wind Power Class



Power Class	Speed	Power Density
1	0.0-5.6m/s	0-200W/m <sup>2</sup>
2	5.6-6.4m/s	200-300W/m <sup>2</sup>
3	6.4-7.0m/s	300-400W/m <sup>2</sup>
4	7.0-7.5m/s	400-500W/m <sup>2</sup>
5	7.5-8.0m/s	500-600W/m <sup>2</sup>
6	8.0-8.8m/s	500-800W/m <sup>2</sup>
7	>8.8m/s	>800W/m <sup>2</sup>

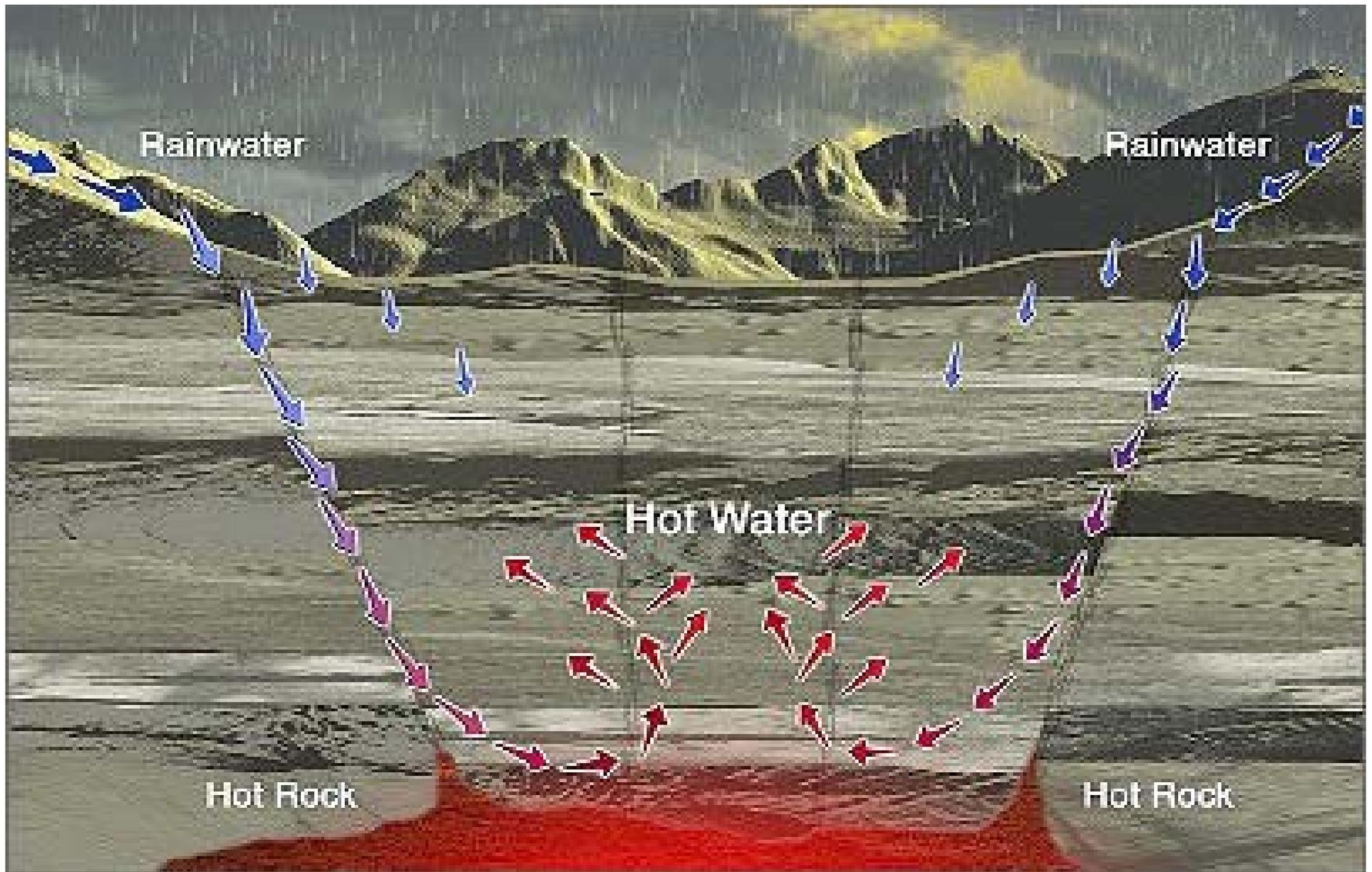


# GEO THERMAL





*Hydro*



**Geothermal: hot water, surface recharge**

# *Trouble with Renewables*

- **Diffuse, dispersed: gathering cost**
- **Richest are remote: “stranded”**
  - High intensity
  - Large geographic extent
- **Time-varying output:**
  - “Intermittent”
  - “Firming” integration + storage required
- **Distributed AND centralized**

# *Trouble with Renewables: Big Three*

1. Transmission and gathering
2. Storage: Annual-scale firming
3. Integration
  - Extant energy systems
  - Electricity grid
  - Fuels: CHP, transportation

# ***Trouble with Renewables: Electricity Transmission***

- **Grid nearly full: who pays?**
- **Integration**
  - **Continental energy system**
  - **Quality**
  - **Time-varying**
- **Costly “firming” storage: CAES, VRB, pump hydro**
- **Low capacity factor (CF) or curtailment**
- **Overhead vulnerable: God or man**
- **Underground: only HVDC, 6x cost**
- **Wide ROW**
- **NIMBY: delay + cost, site + ROW**

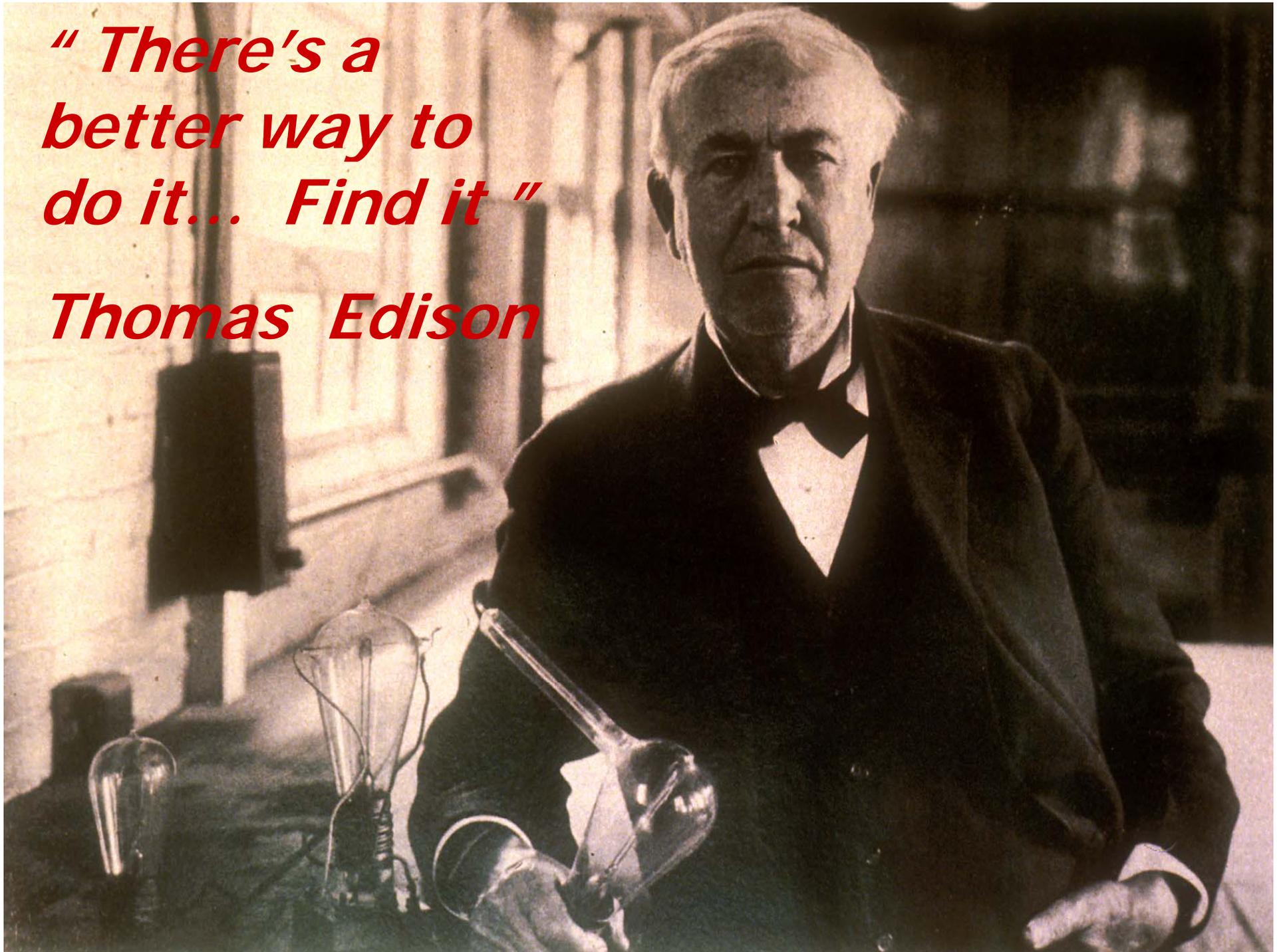
**Zion, IL**

**Near Zion nuclear plant, Oct 02**



*“ There’s a  
better way to  
do it... Find it ”*

*Thomas Edison*



**Sunlight from  
local star**

**Electricity**

**O<sub>2</sub>**

**Electricity**

**H<sub>2</sub>**

**Work**

**Electrolyzer**

**Fuel Cell**

PEM Electrolyzer  
 $2\text{H}_2\text{O} + \text{Energy} \rightarrow 2\text{H}_2 + \text{O}_2$

Item: 2010  
Solar Hydrogen System JuniorBasic  
www.h-tec.com

PEM Fuel Cell  
 $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O} + \text{Energy}$

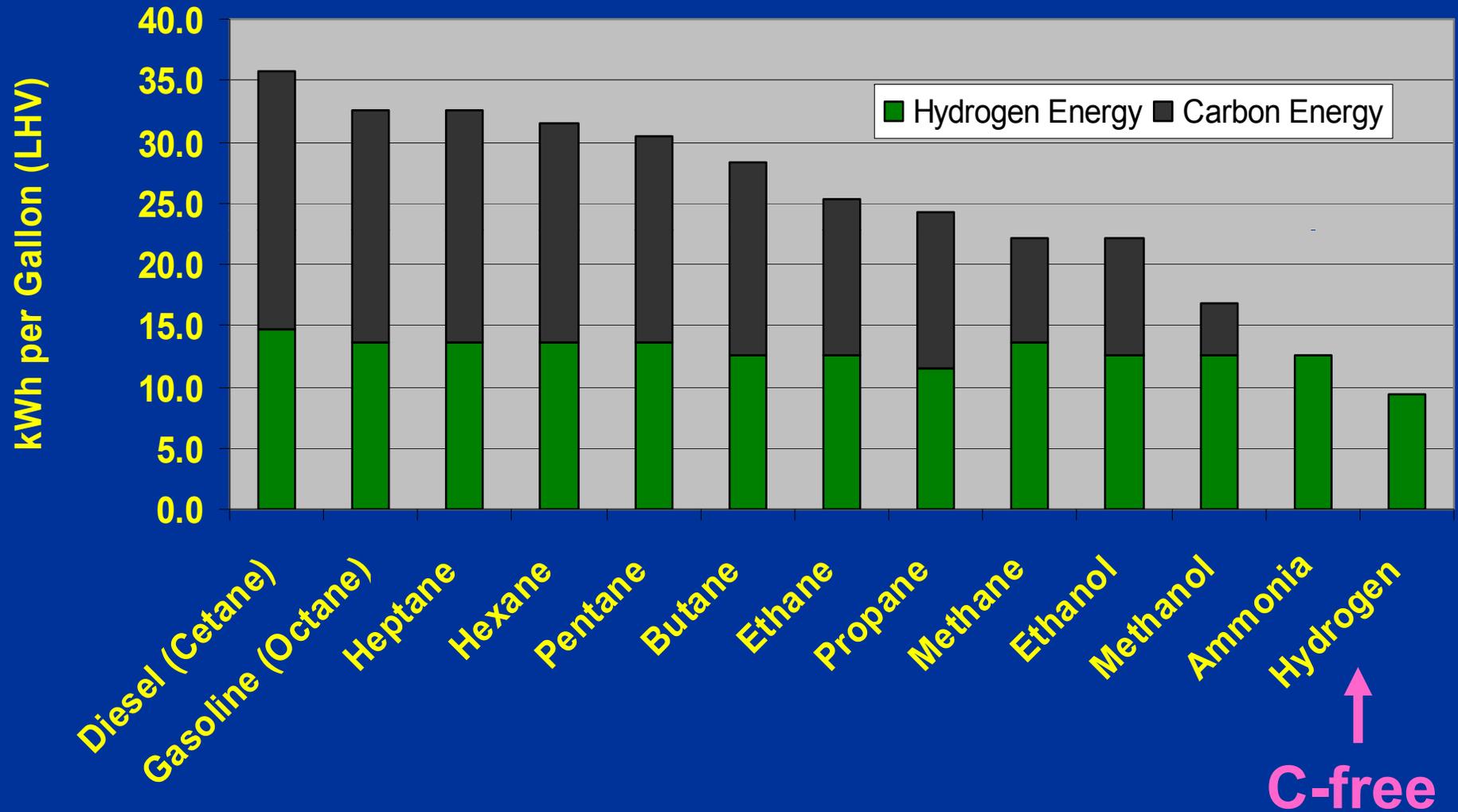


# **Solar Hydrogen Energy System**

# *Hydrogen and Ammonia Fuels*

- **Solve electricity's RE problems:**
  - **Transmission**
  - **Firming storage**
  - **Grid integration: time-varying output**
- **Carbon-free**
- **Underground pipelines**
- **Low-cost storage: < \$ 1.00 / kWh capital**
  - **Pipelines**
  - **GH2 salt caverns**
  - **NH3 tanks**

# Volumetric Energy Density of Fuels (Fuels in their Liquid State)

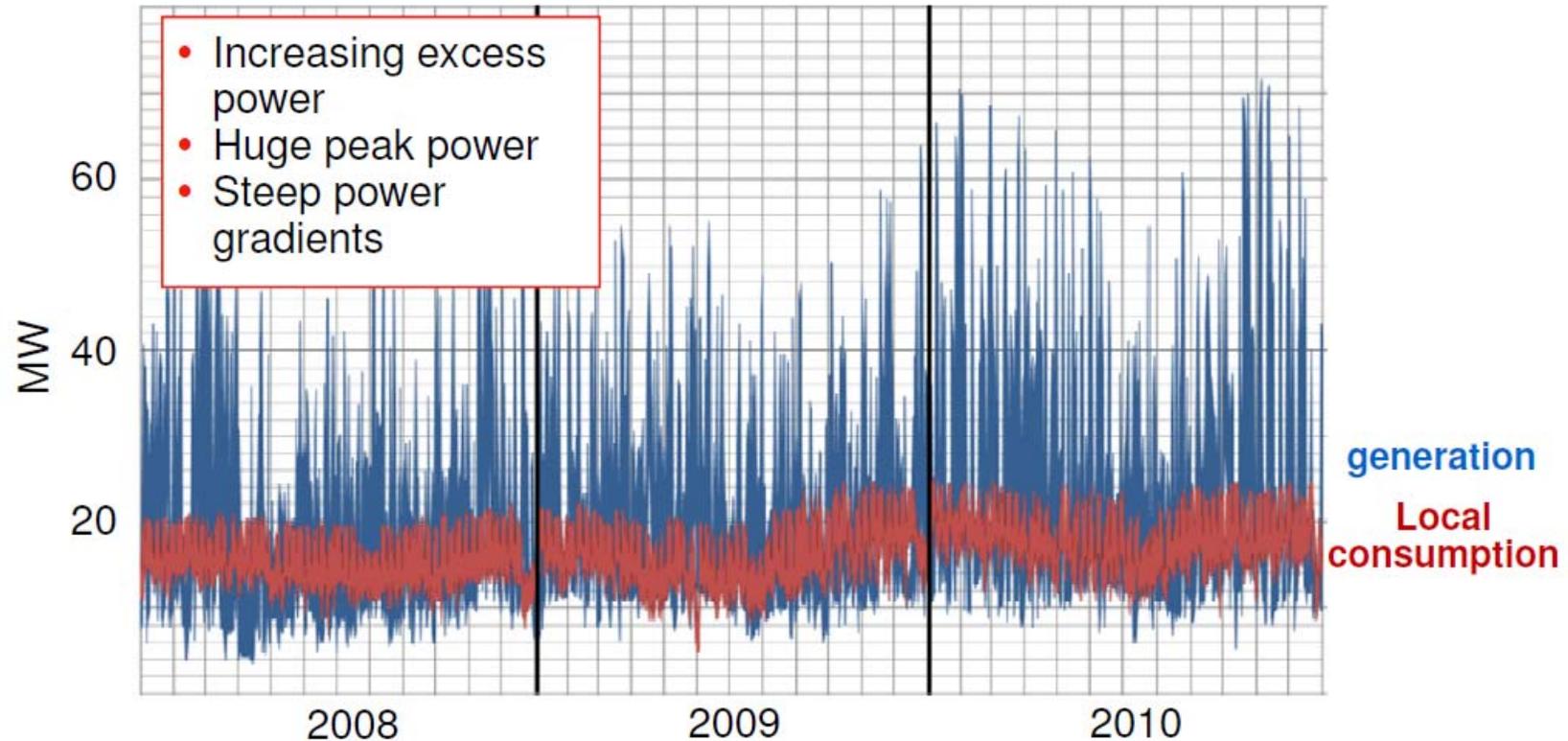


# *Hydrogen and Ammonia Fuels*

- Delivering fuels: distribution
- ICE, CT, Fuel cell
- CHP on-site
- Utility substation wholesale
- Transportation
  - Rail
  - Truck
  - Personal
- Emissions: H<sub>2</sub>O, N<sub>2</sub>

## Germany: window on the challenges of integrating high penetration of renewables

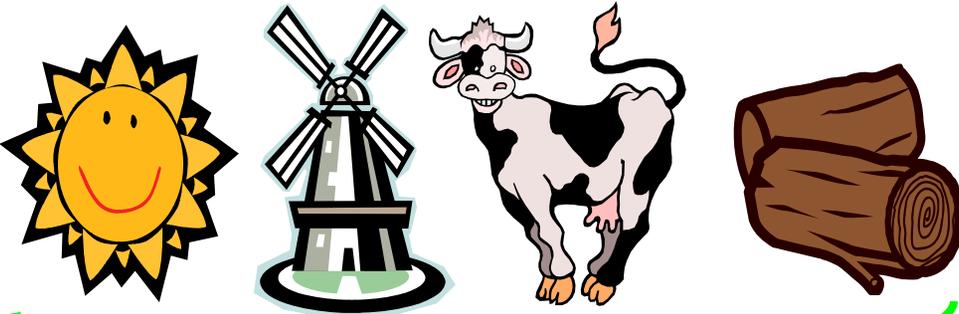
Falkenhagen Region in Northern Germany



Solution: Storage of excess wind power instead of curtailment.



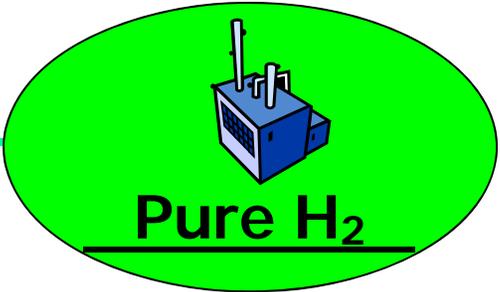
# The NATURALHY approach: EC, R+D



H<sub>2</sub>

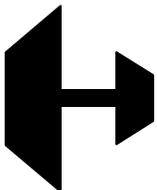
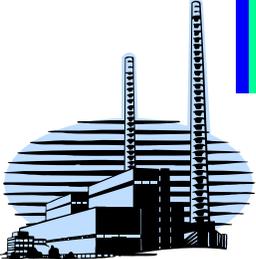


NG



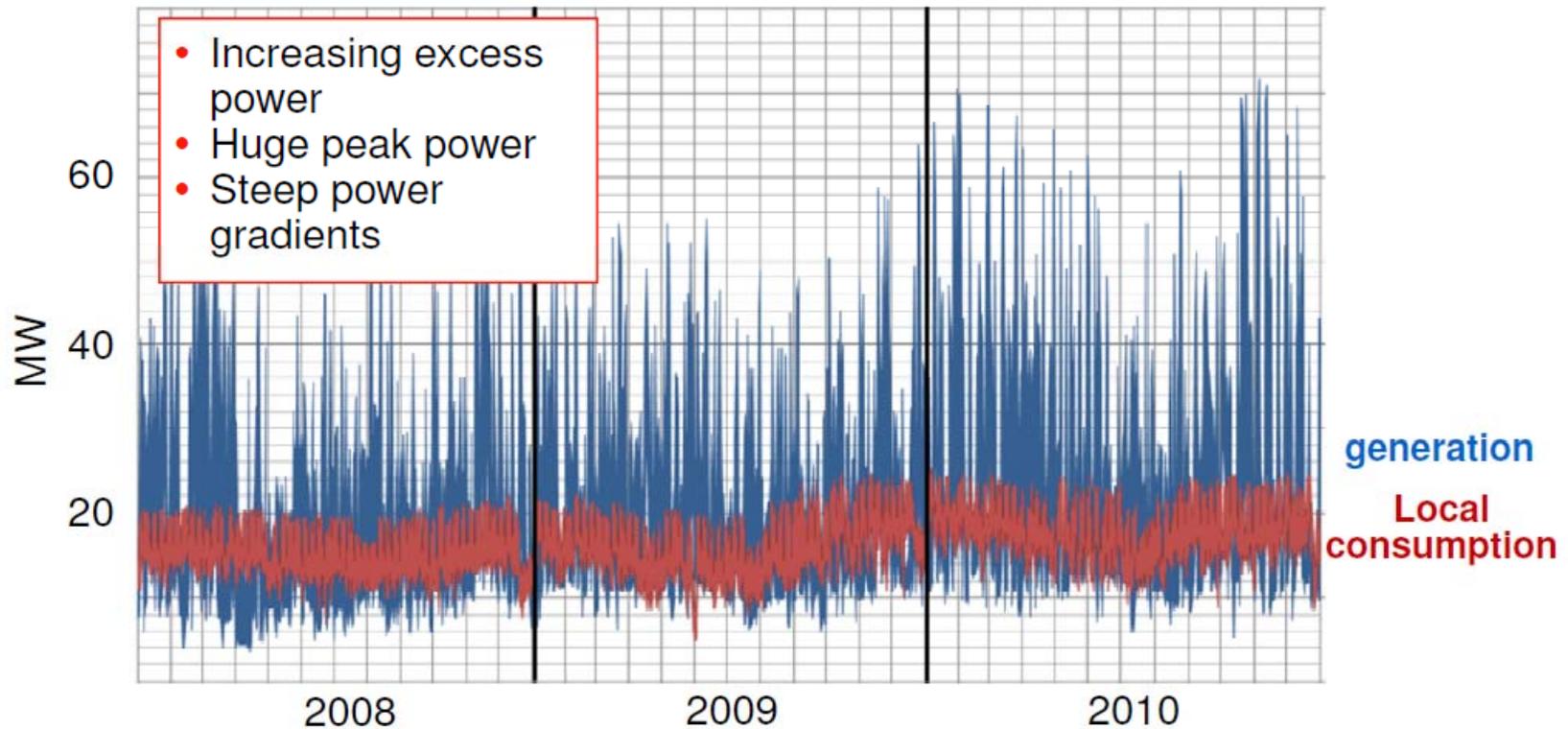
**NATURALHY:**

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



# Free Storage + Free Transmission in E.on Natural Gas Pipeline System

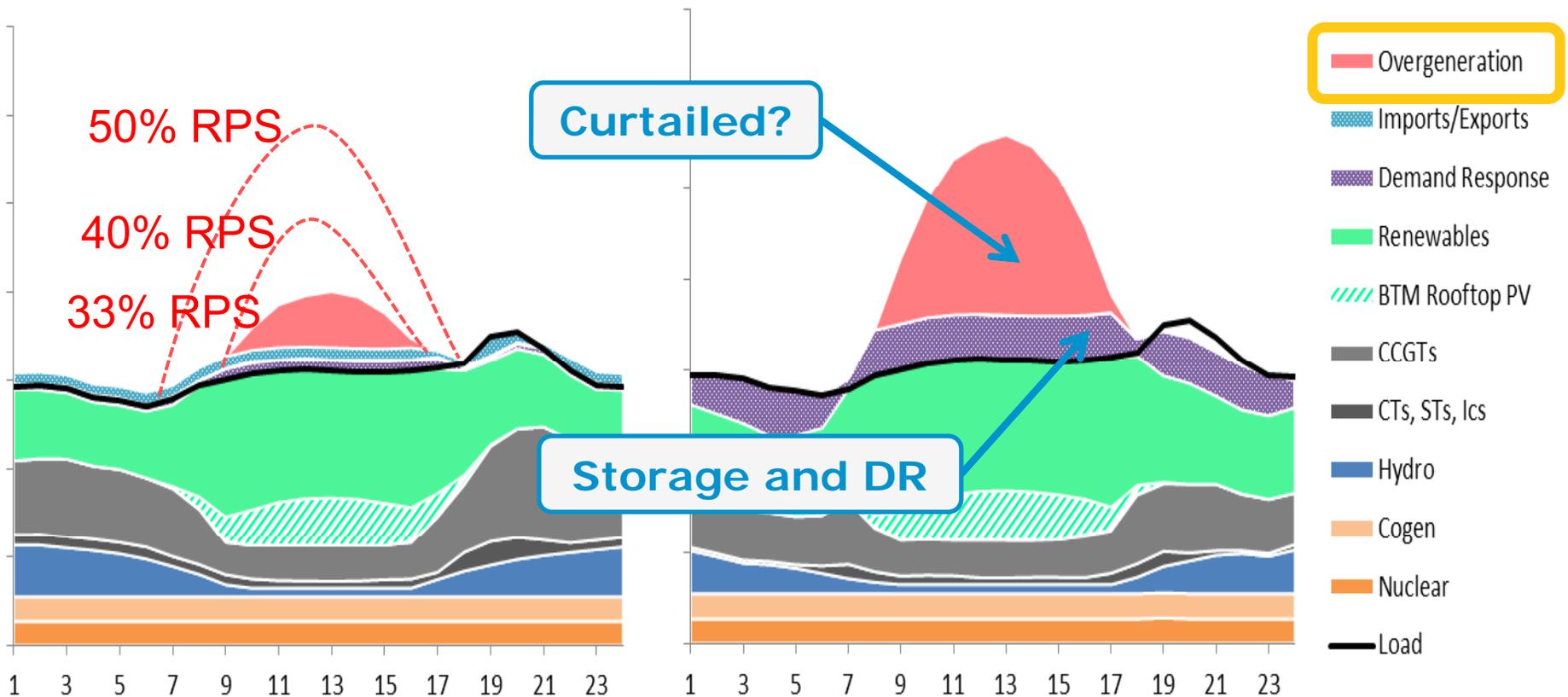
Falkenhagen Region in Northern Germany



Solution: Storage of excess wind power instead of curtailment.



# California's surplus renewable generation



Do Not Cite  
For Illustrative Purposes Only

Source: Adapted from + *Valuing Storage*, Eric Cutter, Energy + Environmental Economics – October 2013

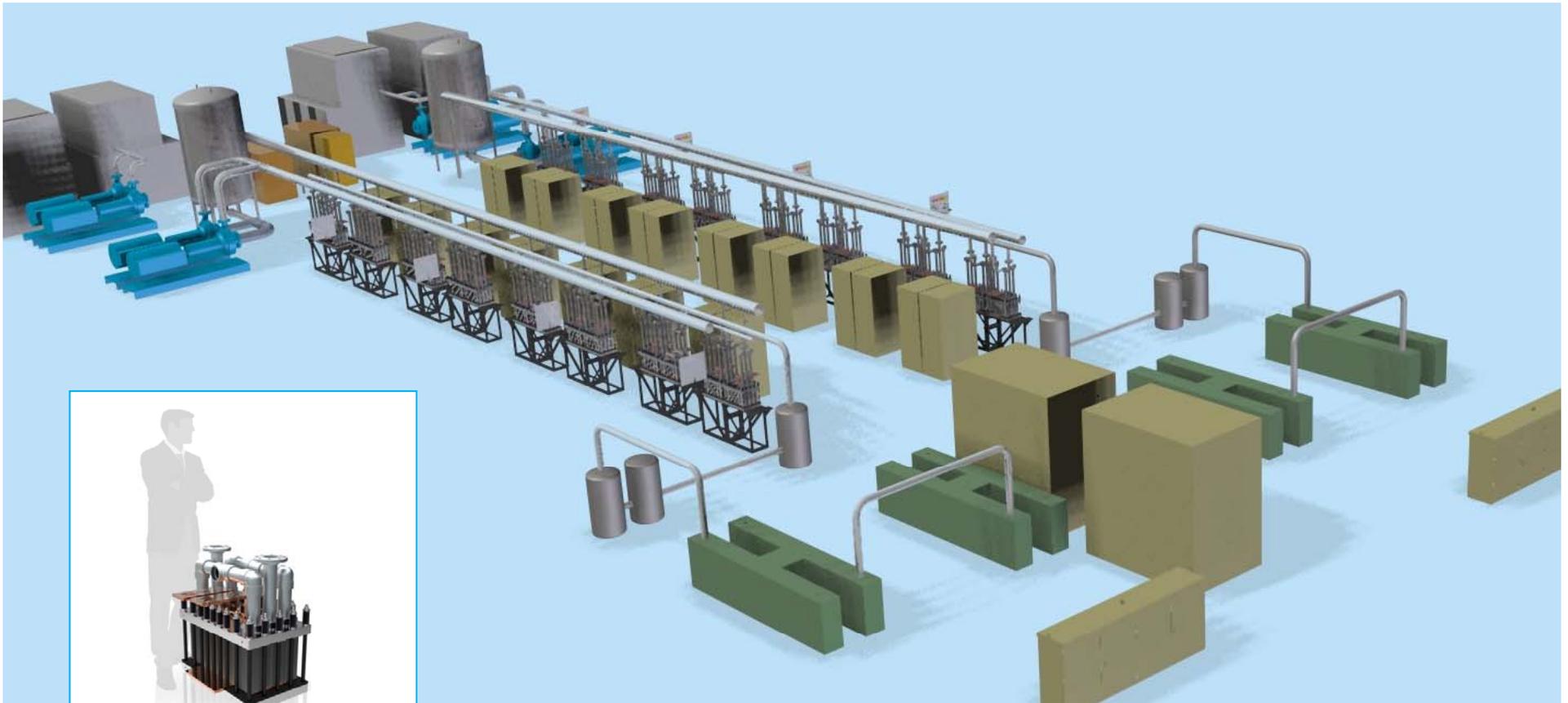
# E.ON first Power-to-Gas plant Injecting hydrogen into natural gas grid

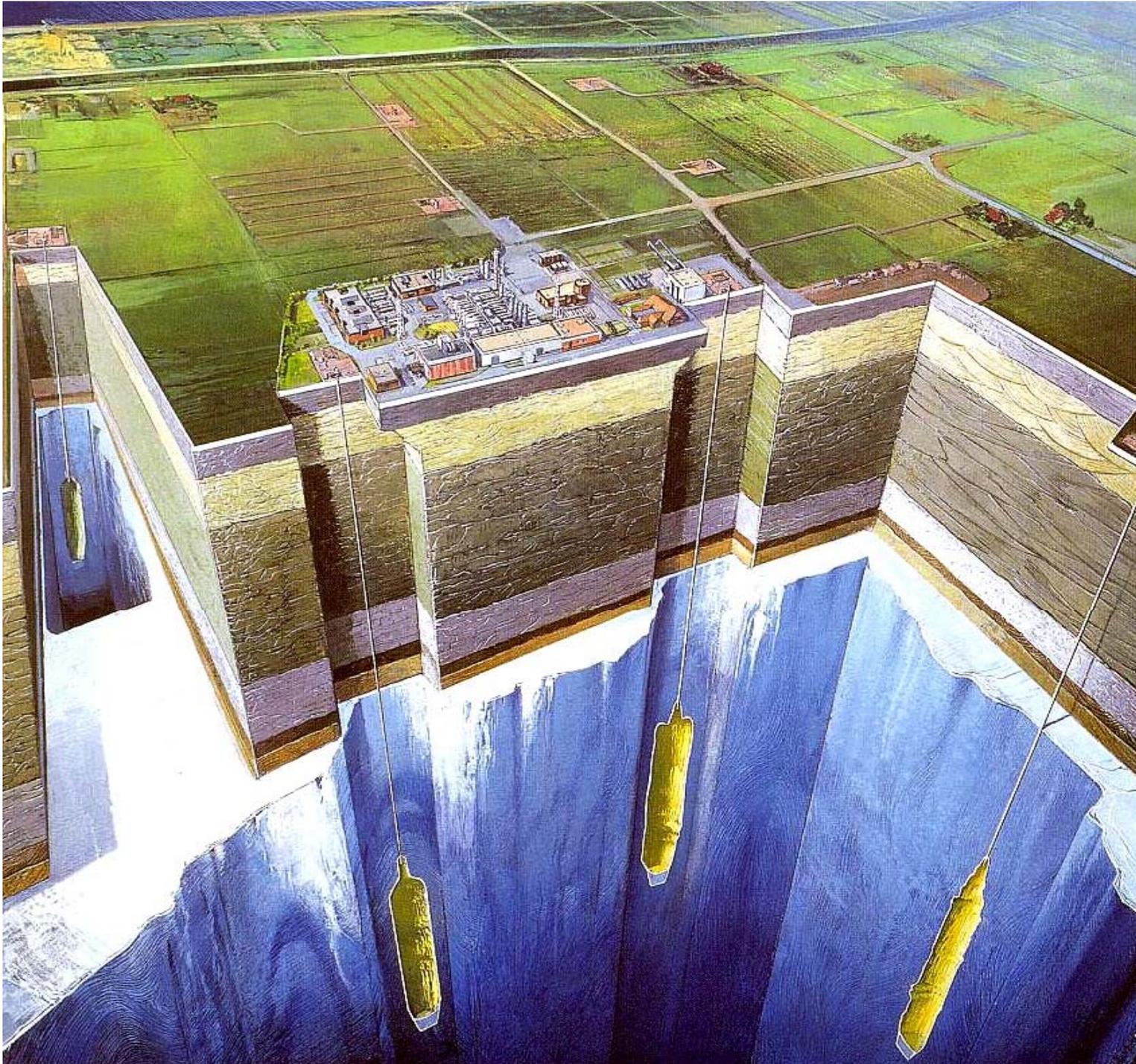
2MW Power-to-Gas Demonstration Plant in Falkenhagen, Germany



# Hydrogenics' compact 1 MW PEM electrolyser Increments up to 1,500 kg/day

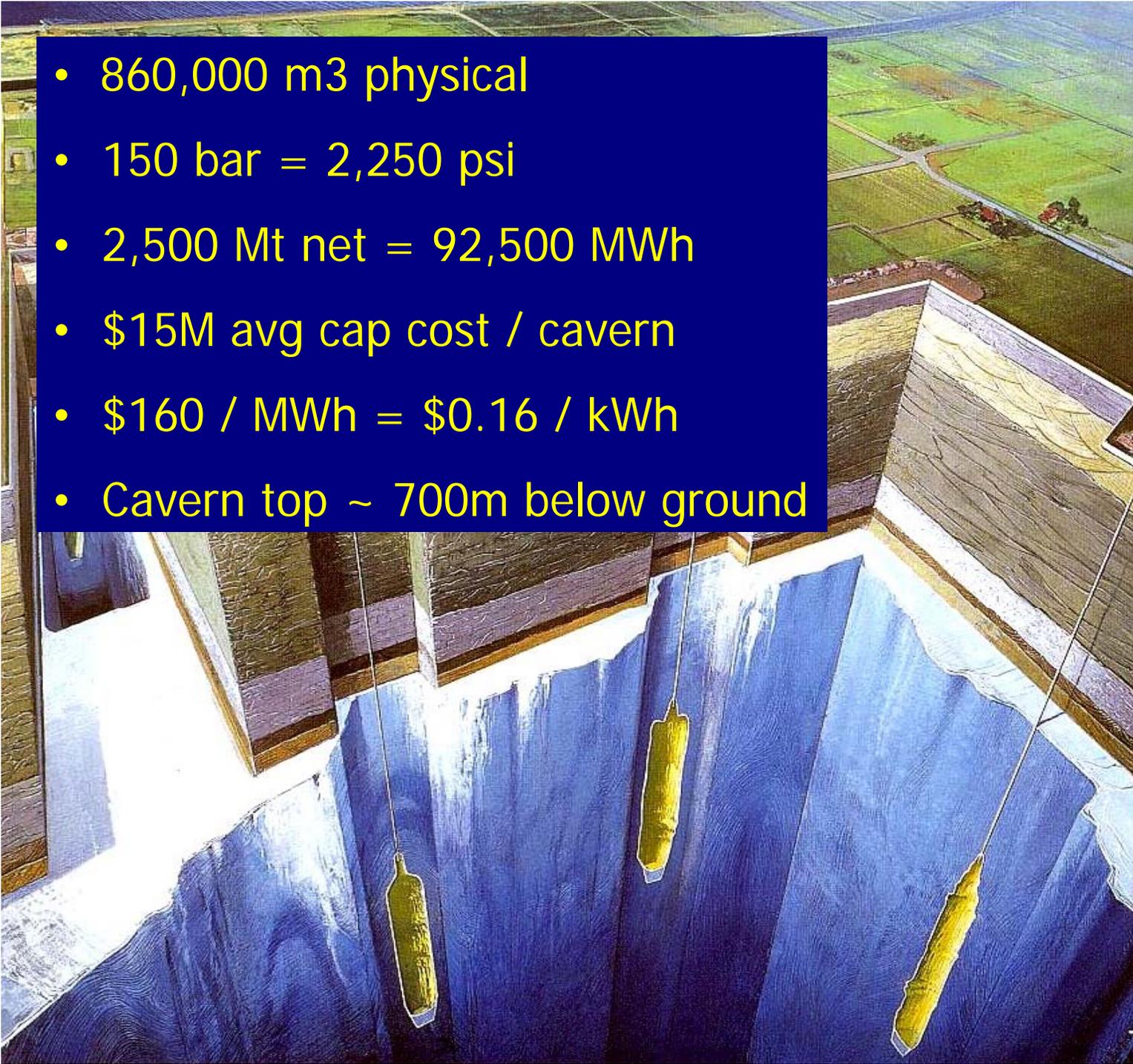
*Future Hydrogenics' PEM Electrolyser Configuration*





# Domal Salt Storage Caverns

PB ESS

- 
- 860,000 m<sup>3</sup> physical
  - 150 bar = 2,250 psi
  - 2,500 Mt net = 92,500 MWh
  - \$15M avg cap cost / cavern
  - \$160 / MWh = \$0.16 / kWh
  - Cavern top ~ 700m below ground

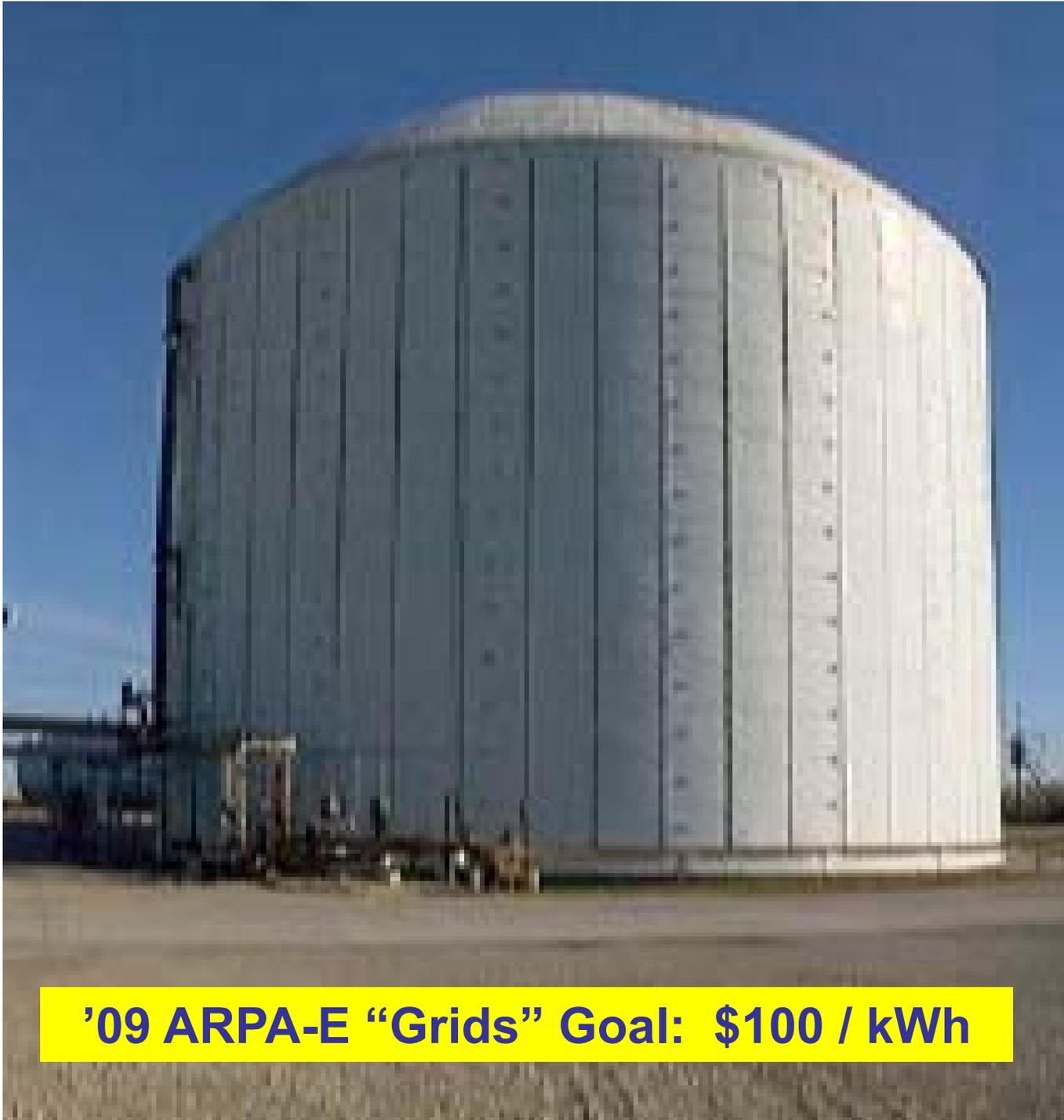
## Domal Salt Storage Caverns

Texas

“Clemens  
Terminal”  
Conoco  
Phillips  
20 years

Praxair  
'07

**PB ESS**



***“Atmospheric”  
Liquid  
Ammonia  
Storage Tank  
(corn belt)***

***30,000 Tons***

***190 GWh***

***\$ 15M turnkey***

***\$ 80 / MWh***

***\$ 0.08 / kWh***

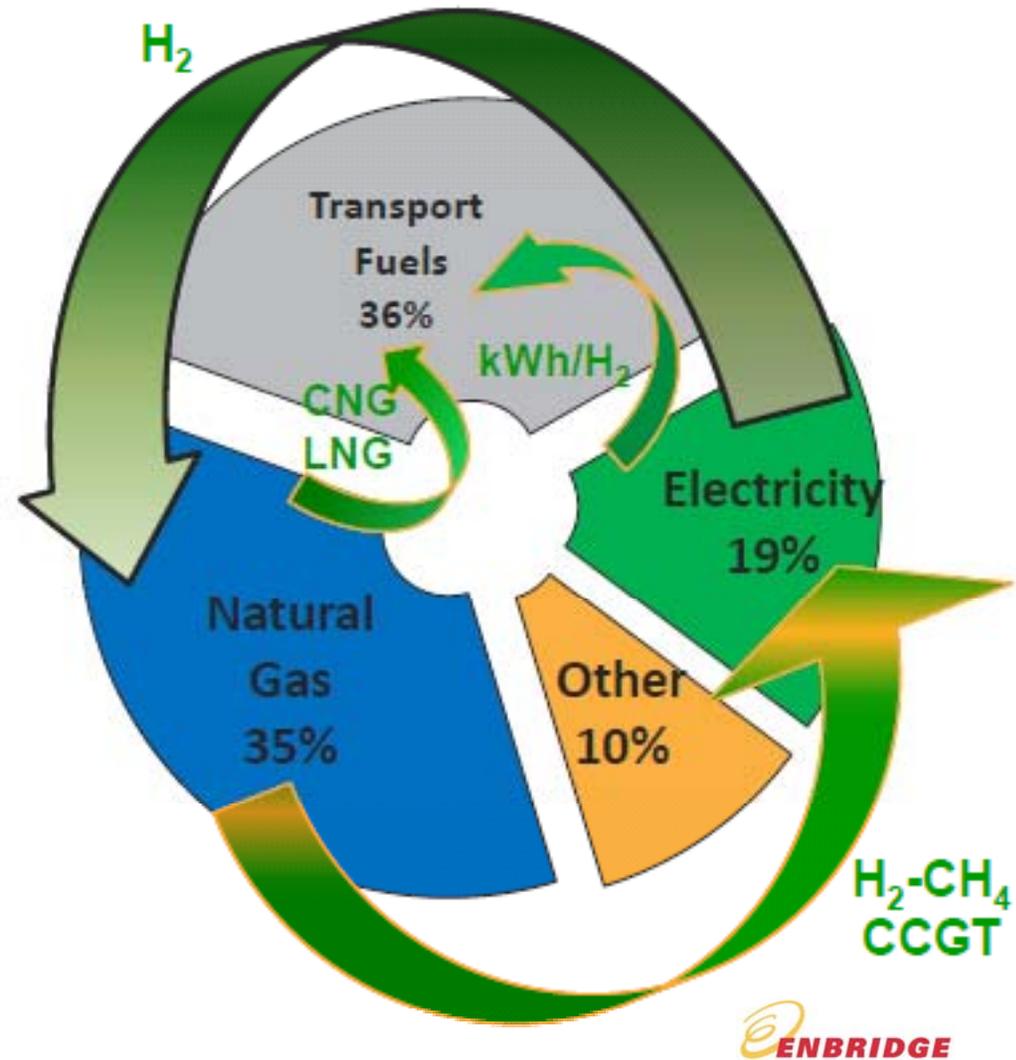
***-33 C***

***1 Atm***

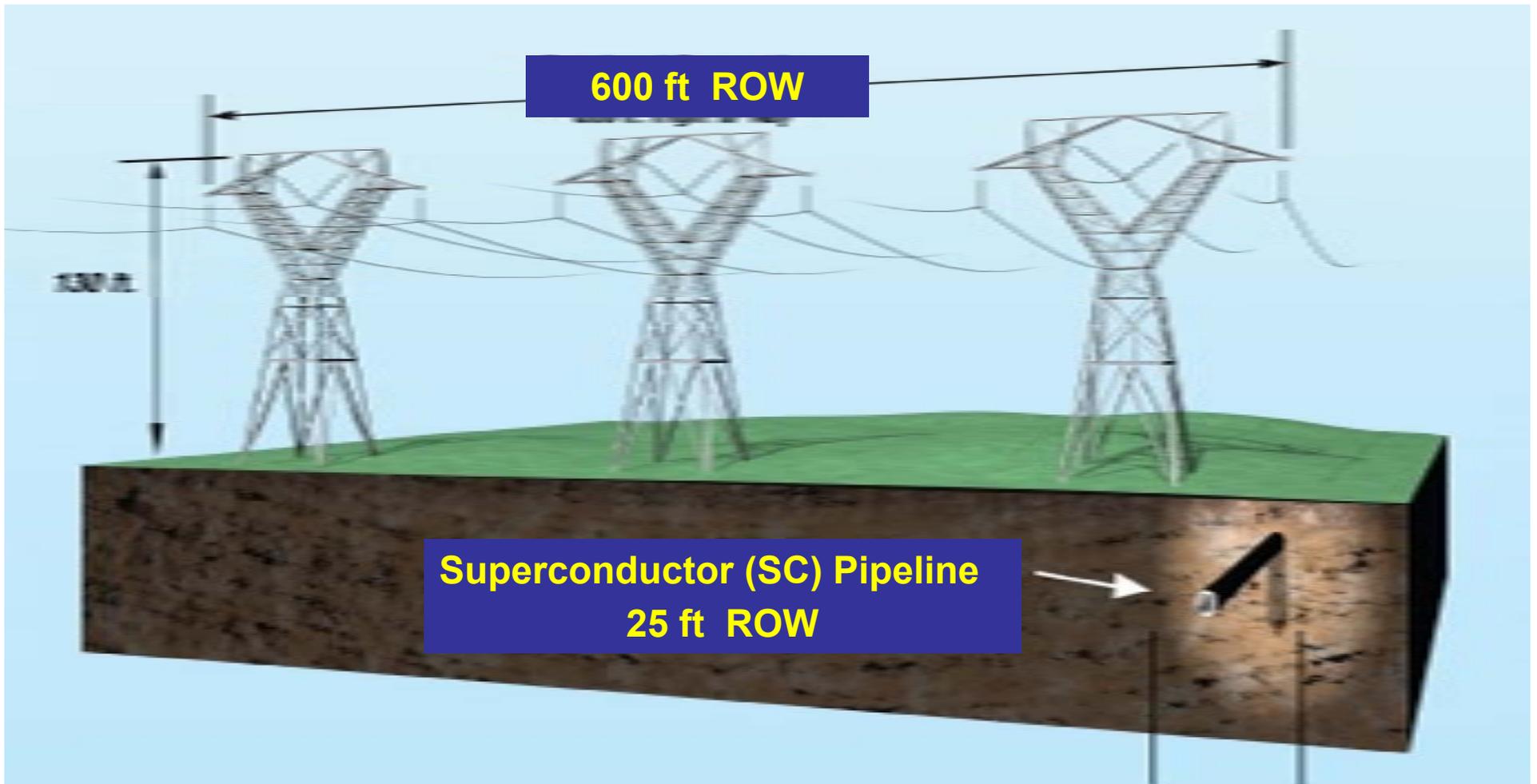
**'09 ARPA-E “Grids” Goal: \$100 / kWh**

## What if we broke down our silos

Integrative  
Thinking  
About  
Electricity  
and  
Energy



Source data: National Energy Board secondary energy demand forecast, Rethinking Energy Conservation in Ontario, May 2010 report



## Out of Sight, Out of Harm's Way

*10,000 MW alternatives: HVAC vs HVDC superconductor*

# ***“Firm” Energy Essential***

- **Every hour, every year**
- **Dispatchable**
- **Strategically: indigenous, secure**
- **Market price: worth more**
- **Bankable large projects**
- **Risk avoidance:**
  - **Rapid climate change**
  - **Economic chaos**

**Sunlight from  
local star**

**Electricity**

**O<sub>2</sub>**

**Electricity**

**H<sub>2</sub>**

**Work**

**Electrolyzer**

**Fuel Cell**

PEM Electrolyzer  
 $2\text{H}_2\text{O} + \text{Energy} \rightarrow 2\text{H}_2 + \text{O}_2$

Item: 2010  
Solar Hydrogen System JuniorBasic  
www.h-tec.com

PEM Fuel Cell  
 $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O} + \text{Energy}$



# **Solar Hydrogen Energy System**

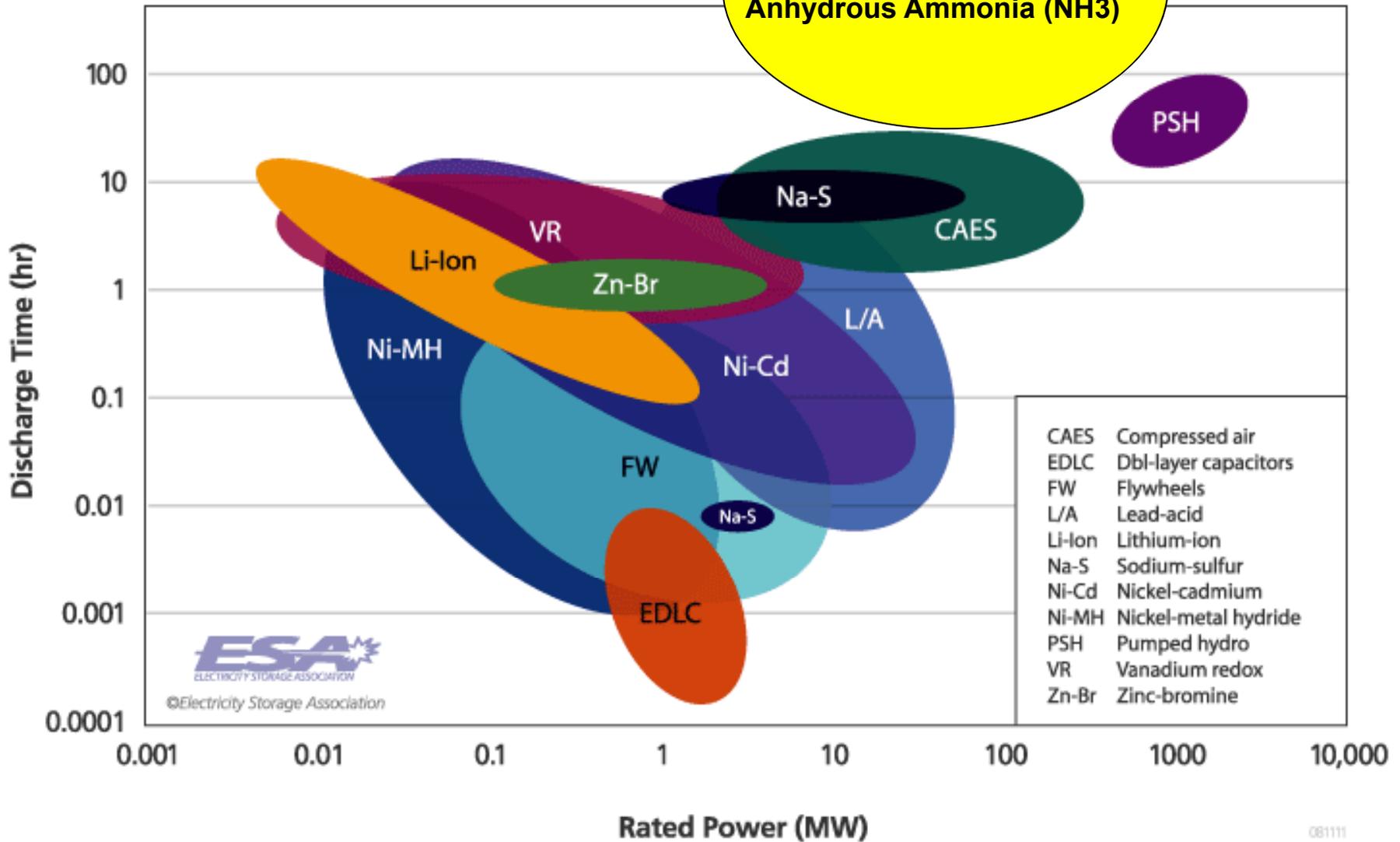
# ***Energy Storage System Characteristics***

## ***Hydrogen and Ammonia off the charts ?***

- ***Storage capacity (Mwh, scf, nM3, Mt, gallons .... )***
- ***Power (MW, scfm ....) In / Out rate***
- ***Costs***
  - ***Capital***
  - ***O&M***
- **Efficiency**
- **Response time**
- **Durability (cycling capacity)**
- **Reliability**
- **Autonomy**
- **Self-discharge**
- **Depth of discharge**
- **Adaptation to the generating source**
- **Mass and volume densities of energy**
- **Monitoring and control equipment**
- **Operational constraints**
- **Feasibility**
- **Environmental**

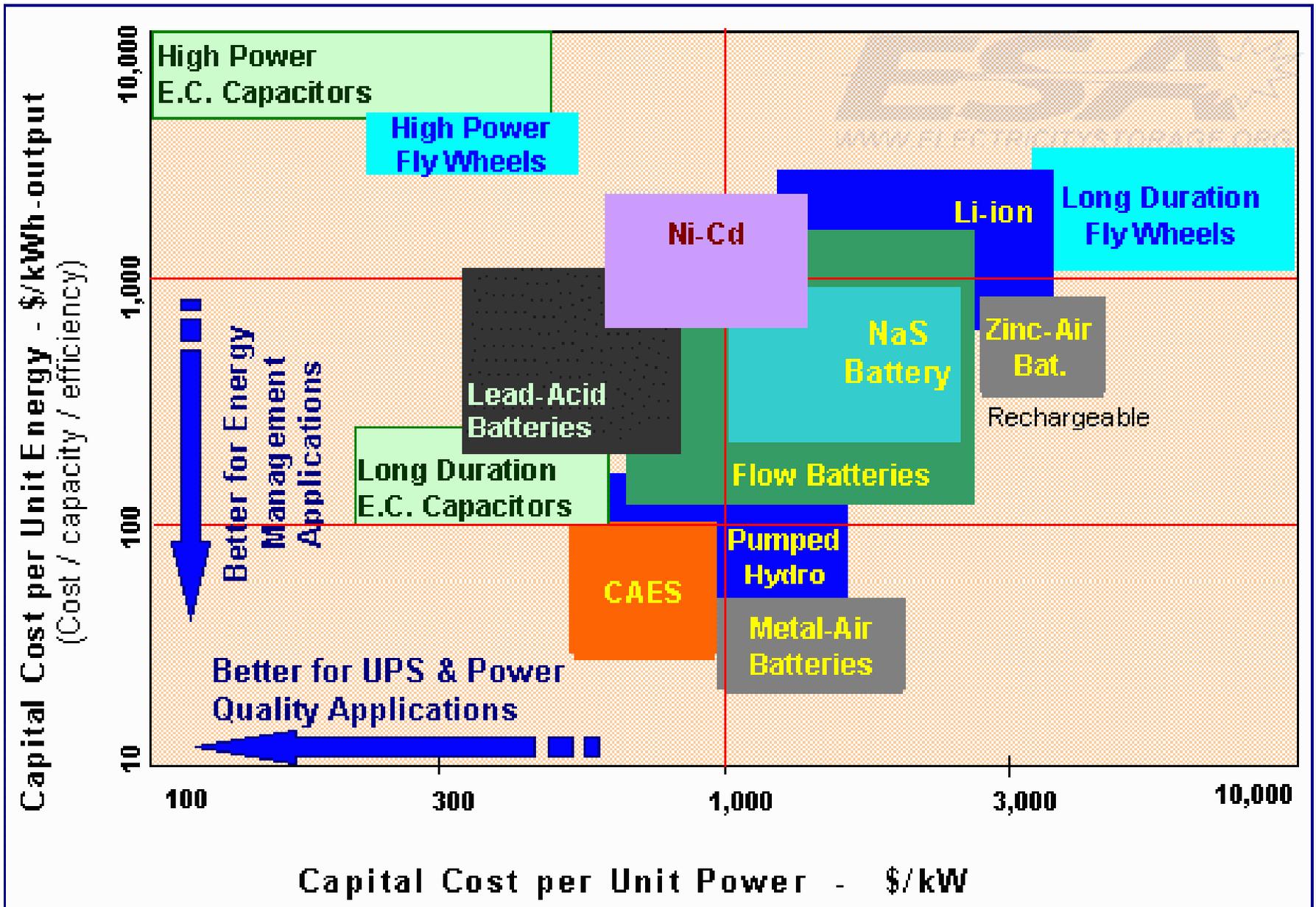
# System Ratings

Gaseous Hydrogen (GH<sub>2</sub>)  
Anhydrous Ammonia (NH<sub>3</sub>)



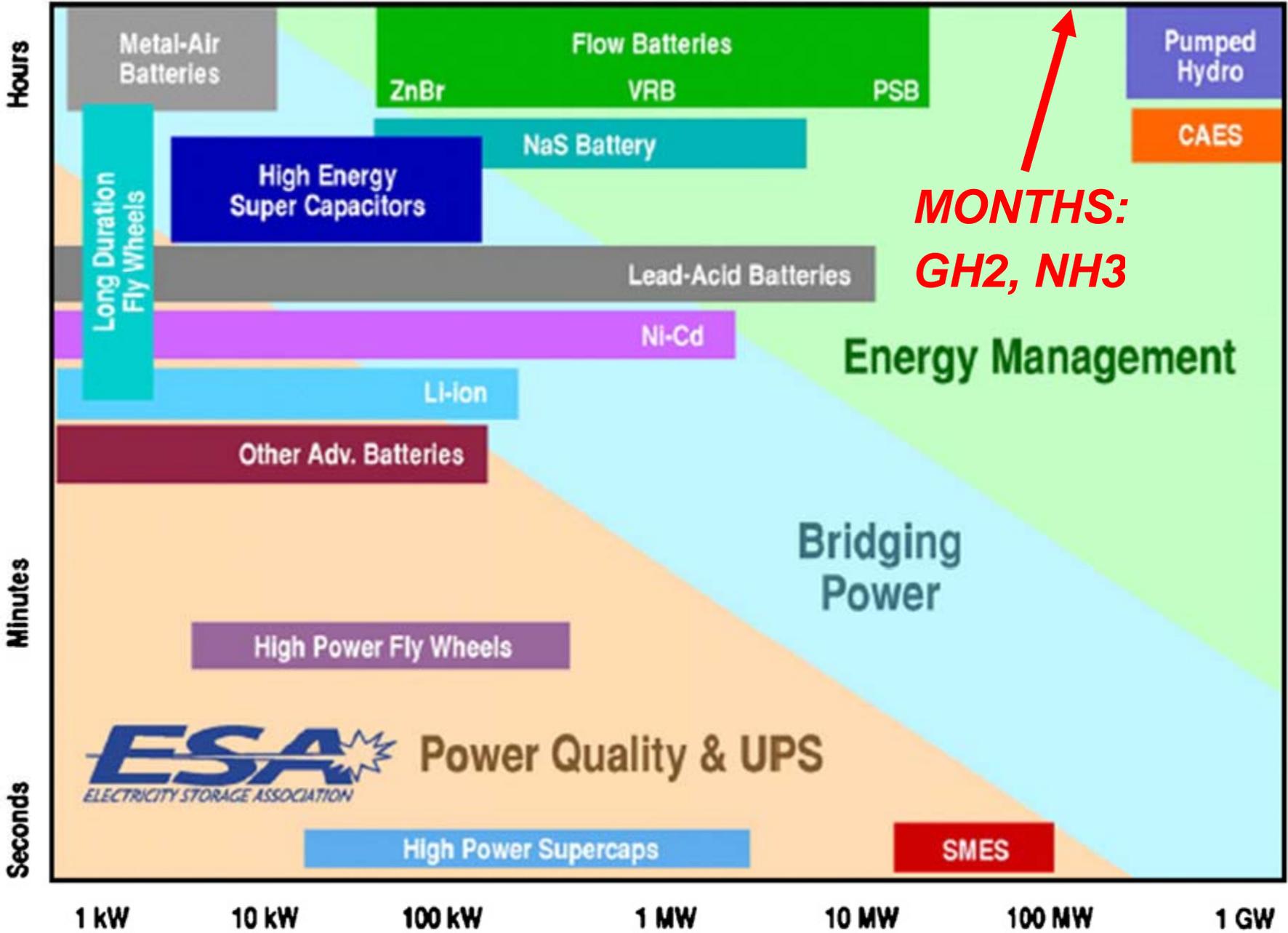
**ESA**  
ELECTRICITY STORAGE ASSOCIATION  
©Electricity Storage Association

CAES Compressed air  
EDLC Dbl-layer capacitors  
FW Flywheels  
L/A Lead-acid  
Li-Ion Lithium-ion  
Na-S Sodium-sulfur  
Ni-Cd Nickel-cadmium  
Ni-MH Nickel-metal hydride  
PSH Pumped hydro  
VR Vanadium redox  
Zn-Br Zinc-bromine



**GH2 and NH3**

Discharge Time



Power



**“ Americans can be  
counted on to  
always do the right  
thing –**

**but only after they  
have tried  
everything else ”**

**Winston Churchill**

The dog caught the car.

Dan Reicher

# ***Beyond “Smart Grid”***

- **Primarily DSM**
- **More vulnerable to cyberattack ?**
- **Adds no physical:**
  - **Transmission, gathering, distribution**
  - **Storage**
- **Next big thing; panacea**
- **Running the world on renewables ?**
- **Must think:**
  - **Beyond electricity**
  - **Complete energy systems**
  - **ALL energy: Hermann Scheer**

# ***“Transmission”***

- **Electrofuels**
- **Renewable-source electricity**
- **Underground pipelines**
- **Carbon-free fuels: hydrogen, ammonia**
- **Low-cost storage:**
  - \$ 0.10 – 0.20 / kWh capital**
- **CHP, transport, industrial**
- **GW scale**

# The Great Plains Wind Resource



# Exporting From 12 Windiest Great Plains States

Number of GH2 pipelines or HVDC electric lines necessary to export total wind resource

Capacity at 500 miles length

Capacity Factor (CF) = 30%

State	Annual Energy Production (TWh)	Nameplate Installed Capacity (MW)	Nameplate Installed Capacity (GW)	6 GW 36" GH2 Hydrogen Pipelines	\$ Billion Total Capital Cost	3 GW 500 KV HVDC Electric Lines	\$ Billion Total Capital Cost
Texas	6,528	1,901,530	1,902	317		634	
Kansas	3,647	952,371	952	159		317	
Nebraska	3,540	917,999	918	153		306	
South Dakota	3,412	882,412	882	147		294	
Montana	3,229	944,004	944	157		315	
North Dakota	2,984	770,196	770	128		257	
Iowa	2,026	570,714	571	95		190	
Wyoming	1,944	552,073	552	92		184	
Oklahoma	1,789	516,822	517	86		172	
Minnesota	1,679	489,271	489	82		163	
New Mexico	1,645	492,083	492	82		164	
Colorado	1,288	387,220	387	65		129	
<b>TOTALS</b>	<b>33,711</b>	<b>9,376,694</b>	<b>9,377</b>	<b>1,563</b>	<b>\$1,500</b>	<b>3,126</b>	<b>\$2,000</b>

Wind energy source: Archer, Jacobson 2003

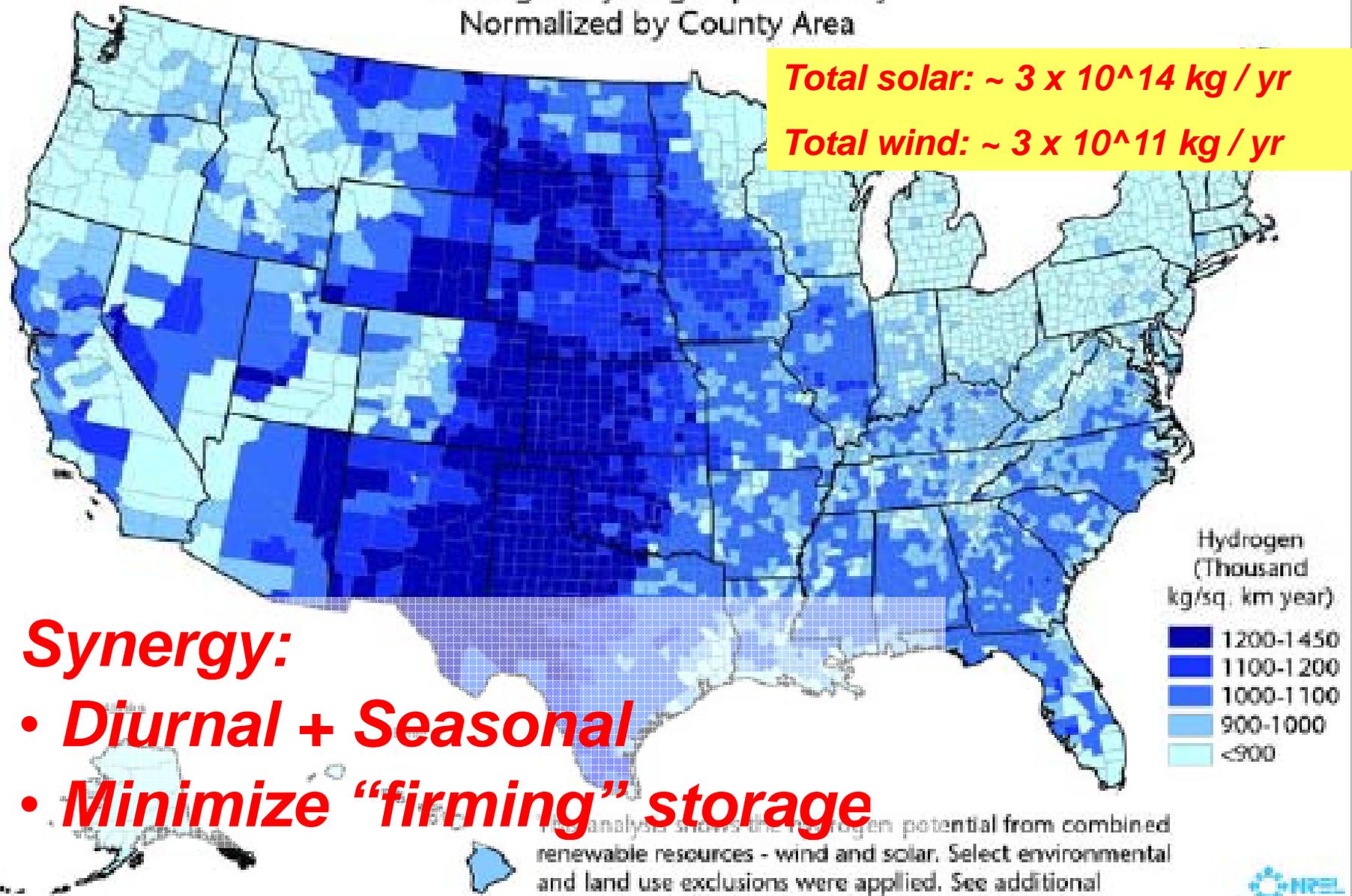
Figure 3

## Hydrogen Potential from Solar and Wind Resources

Total kg of Hydrogen per County  
Normalized by County Area

**Total solar:  $\sim 3 \times 10^{14}$  kg / yr**

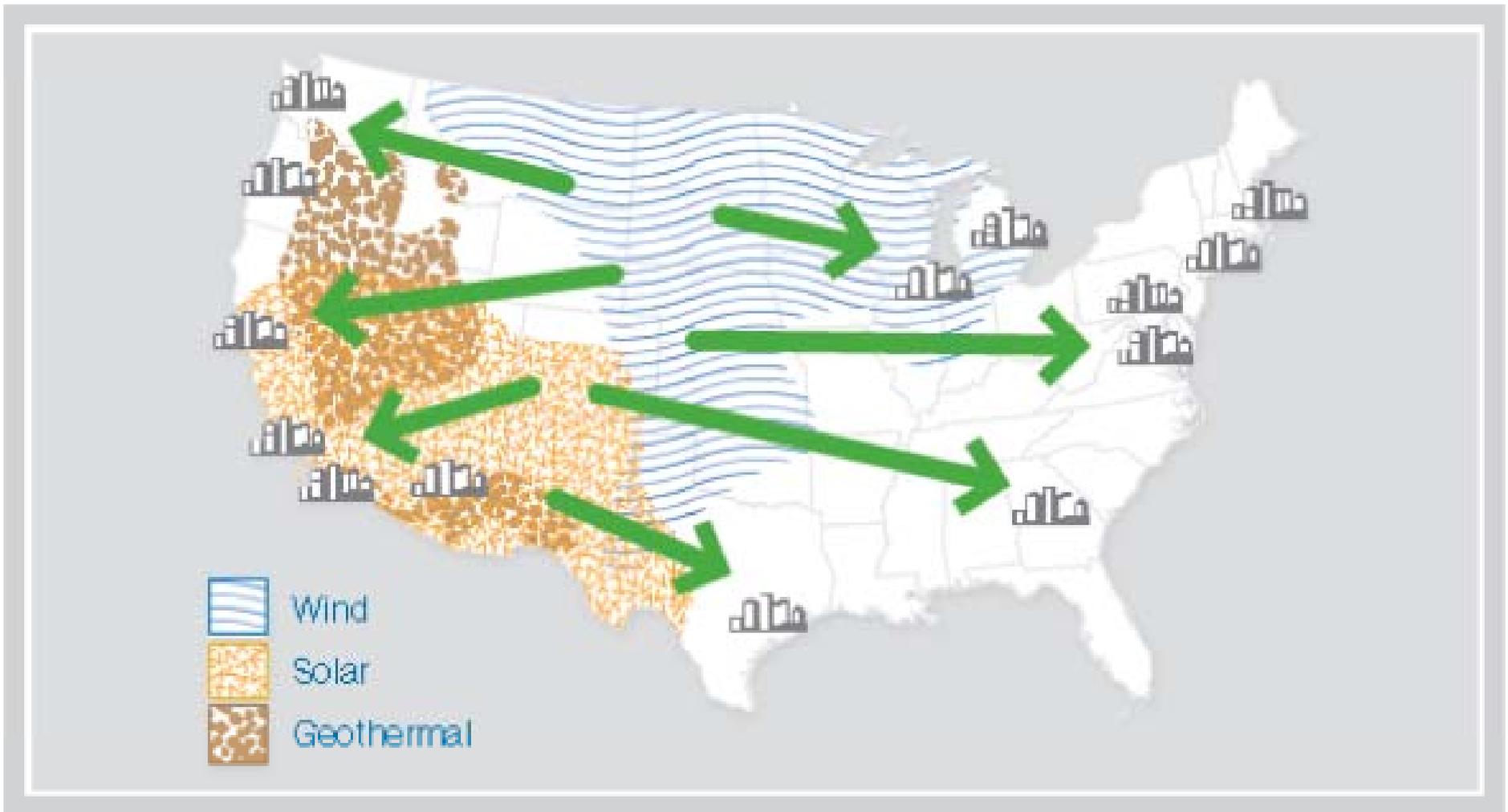
**Total wind:  $\sim 3 \times 10^{11}$  kg / yr**



### **Synergy:**

- **Diurnal + Seasonal**
- **Minimize “firming” storage**

This analysis shows the hydrogen potential from combined renewable resources - wind and solar. Select environmental and land use exclusions were applied. See additional documentation for more information.



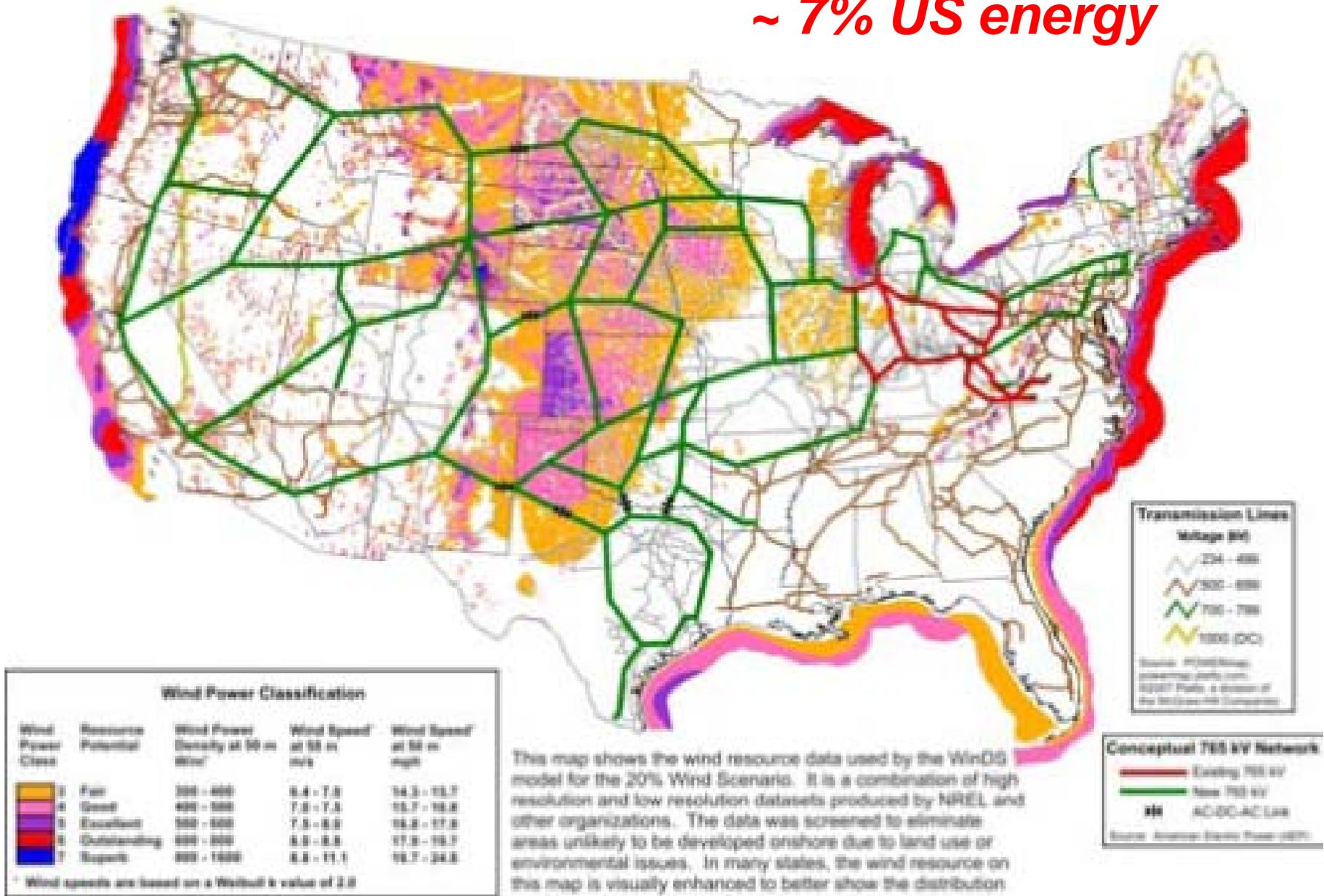
Source: AWEA and SEIA

**SEIA – AWEA      Feb 09**  
**“Green Power Superhighways:  
Building a Path to America’s Clean Energy Future”**



# AWEA: 20% Electricity from Wind by 2030

~ 7% US energy



# *Electricity Capital Cost per GW-mile*

	<u>KV</u>	<u>Capacity</u> <u>MW</u>	<u>\$M / GW-mile</u>
• SEIA:	765	5,000	1.3
	345	1,000	2.6
• AEP-AWEA	765	5,000	3.2
			<b>2.5</b>
			<b>Consensus ?</b>

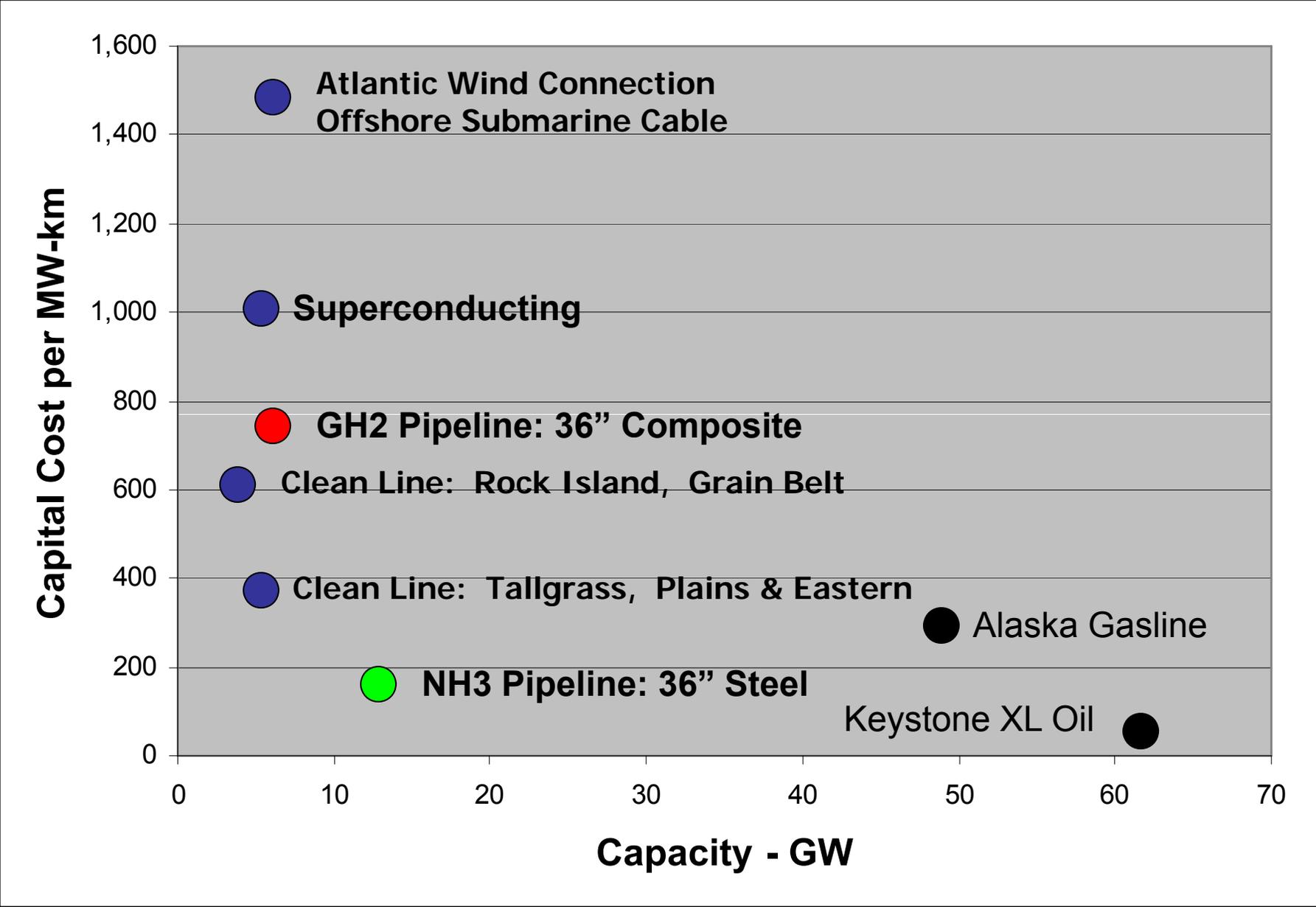


350 miles

5 GW

\$ 5B

1,750 GW-miles @ \$5,000M =  
\$2.8M / GW-mile



# ***Wind seasonality, Great Plains***

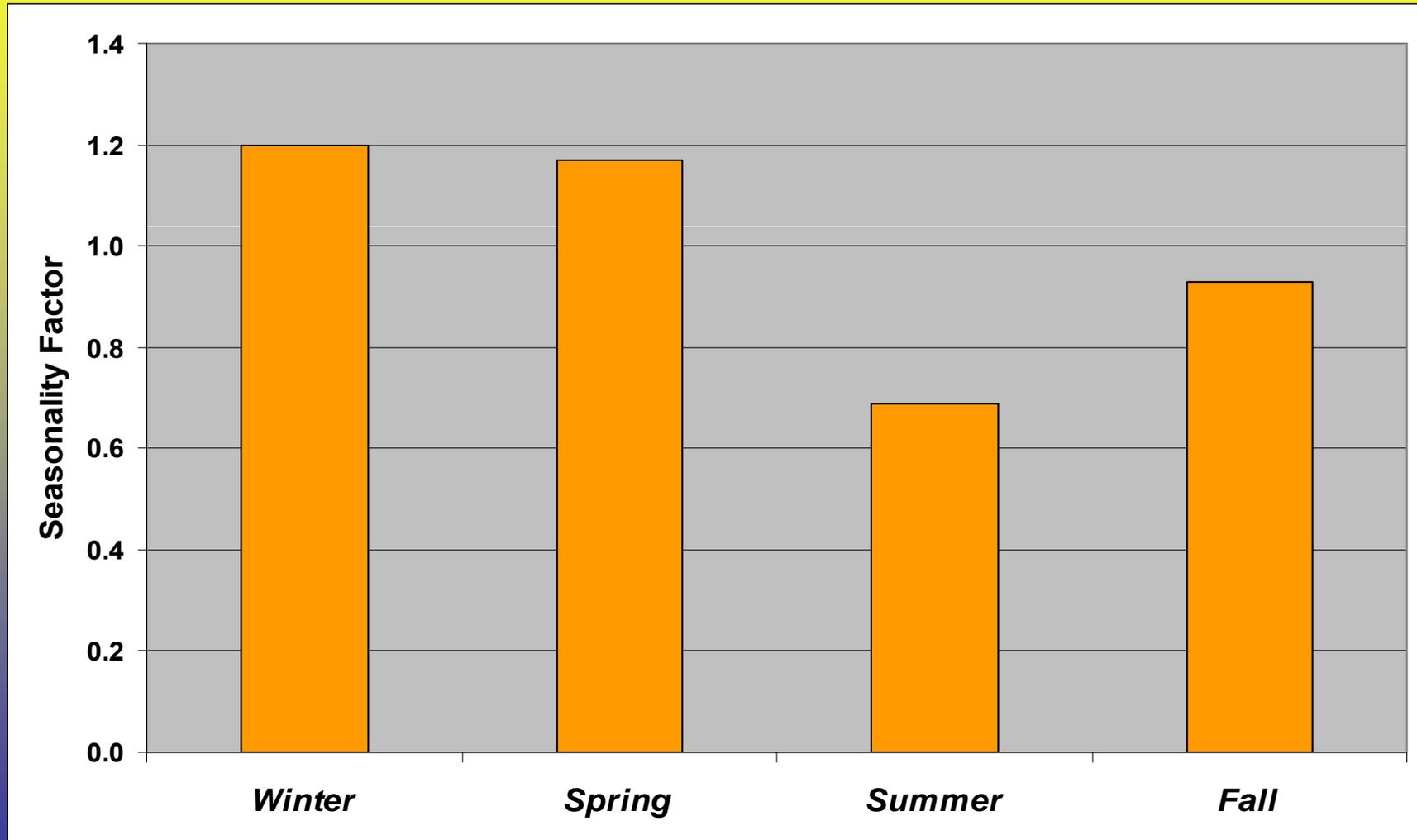
***Normalized to 1.0***

- **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***



# Wind Seasonality, Northern Great Plains

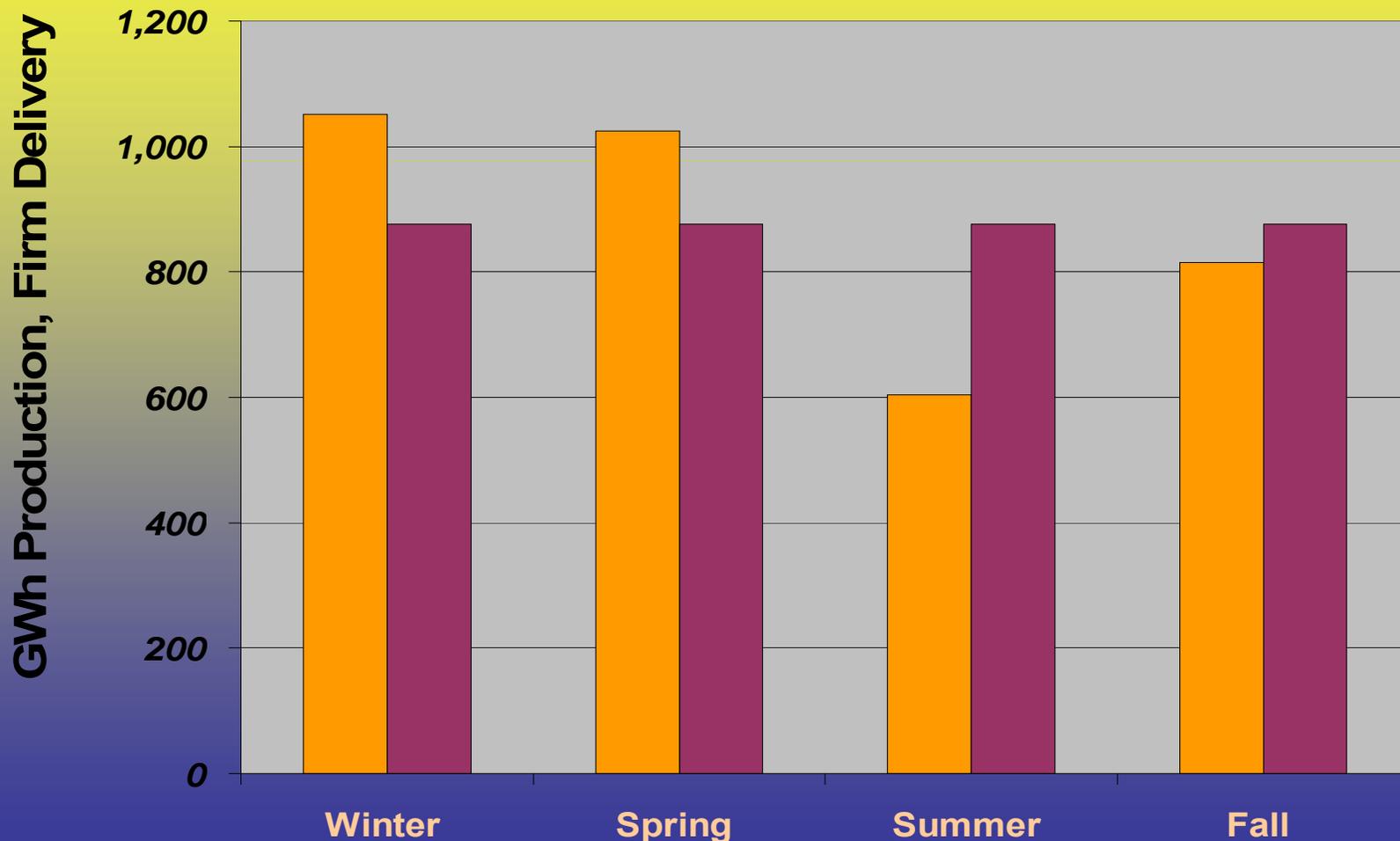
**1,000 MW windplant:**

**AEP = 3,500 GWh / yr**

**“Firm” goal = 875 GWh / season**

**Storage: 320 GWh per 1,000 MW wind**

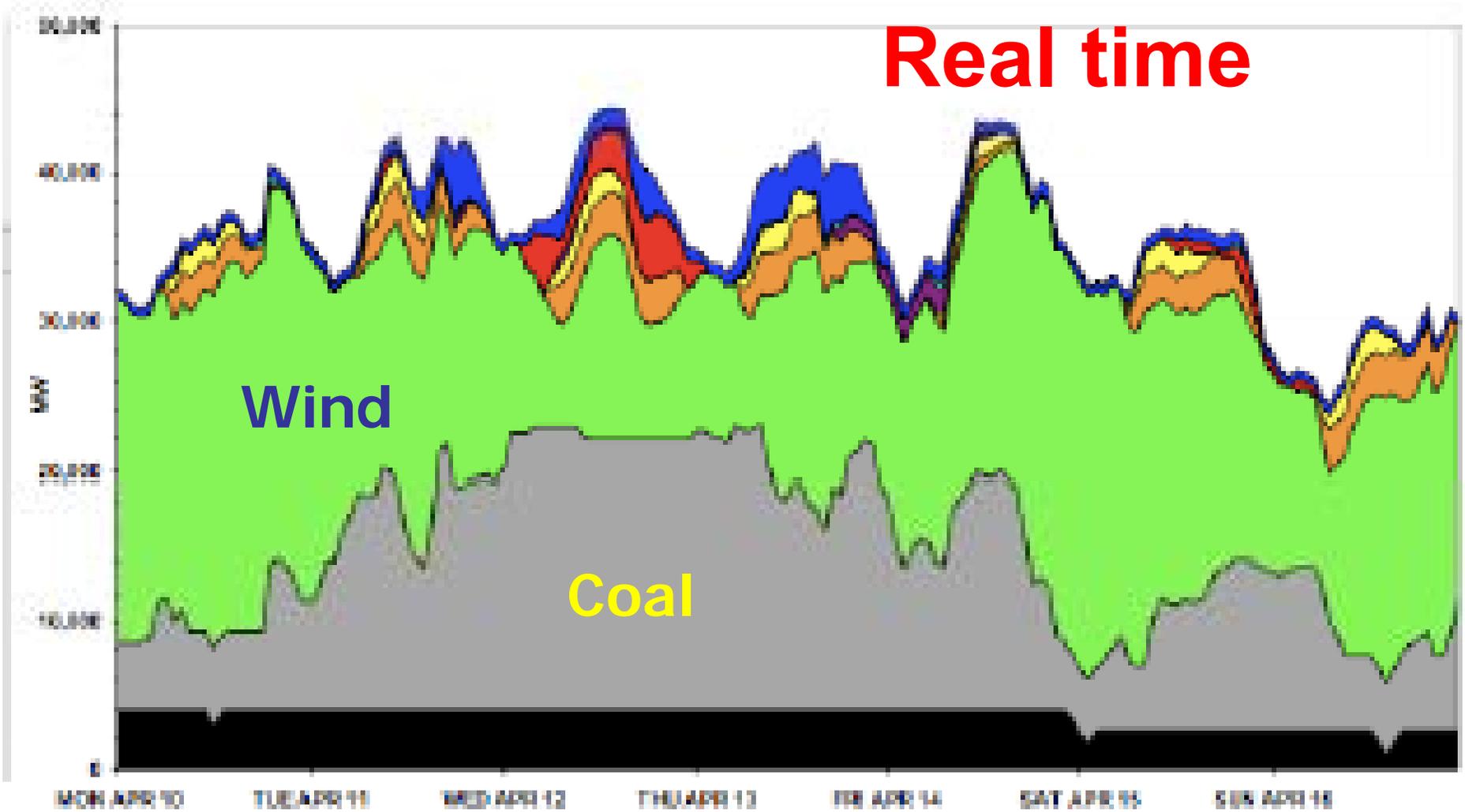
Source: NREL, D. Elliott



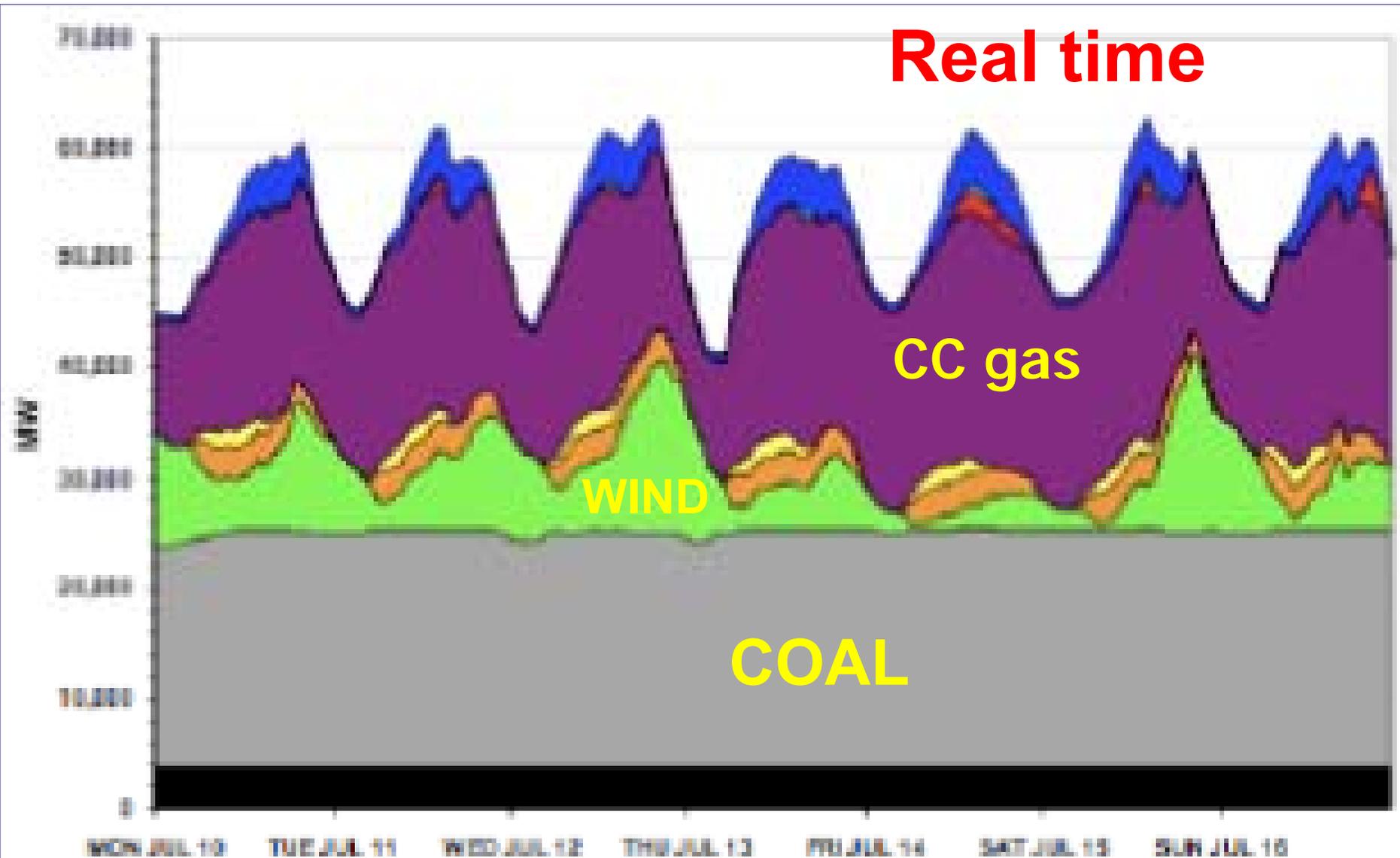
# ***320 GWh***

***Annual firming, 1,000 MW wind***

- **CAES (compressed air energy storage)**
  - **O&M: \$46 / MWh typical**
  - **Iowa: Power = 268 MW**
    - Energy capacity = 5,360 MWh**
    - Capital: 268 MW @\$800 / kW = \$214 M**
    - Storage @ \$40 / kWh = \$13 Billion**
    - Storage @ \$1 / kWh = \$325 Million**
- **VRB flow battery**
  - **O&M: 80% efficiency round-trip**
  - **Capital: \$500 / kWh = \$160 Billion**



**WWSIS: April week: ~30% RE**



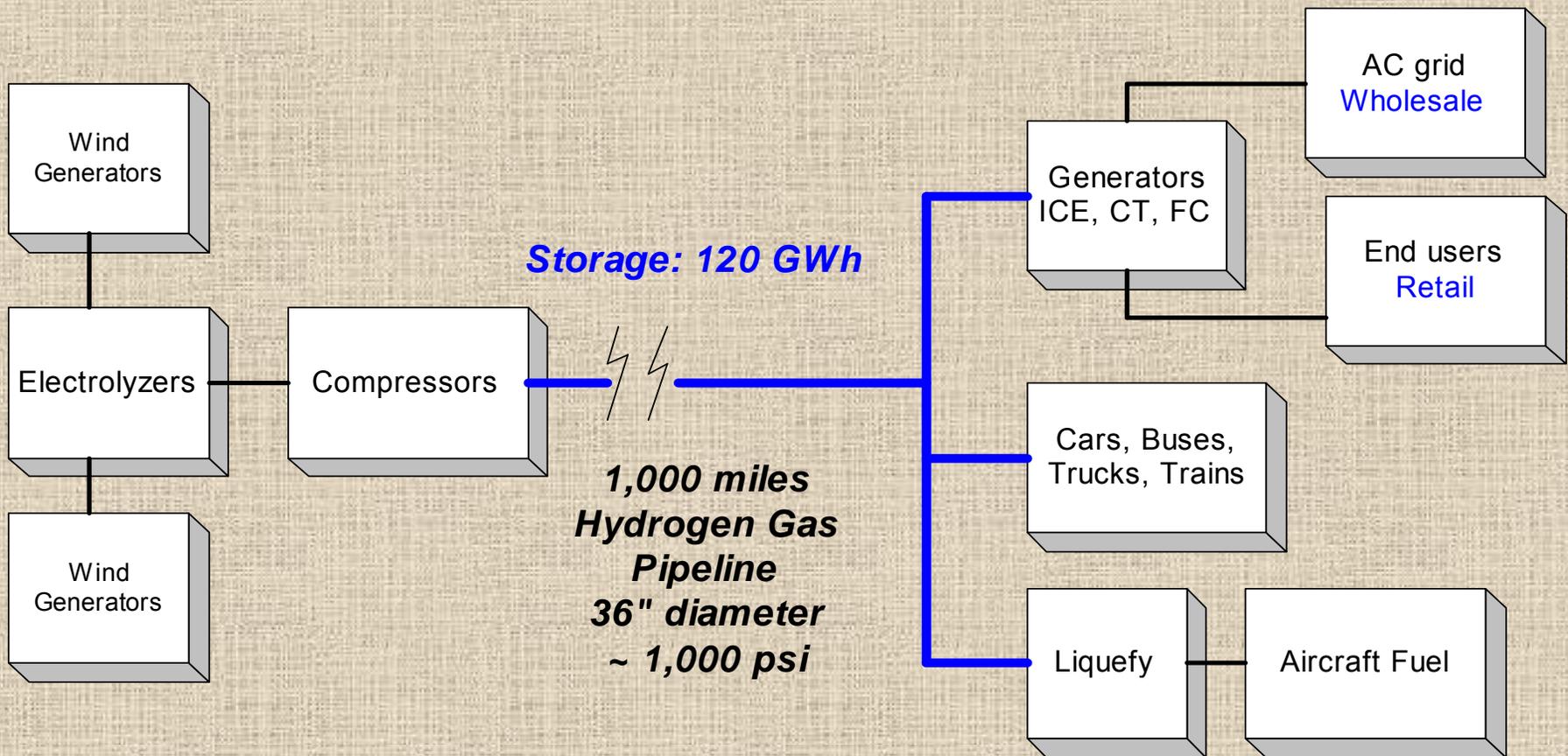
**WWSIS: July week: ~10% RE**

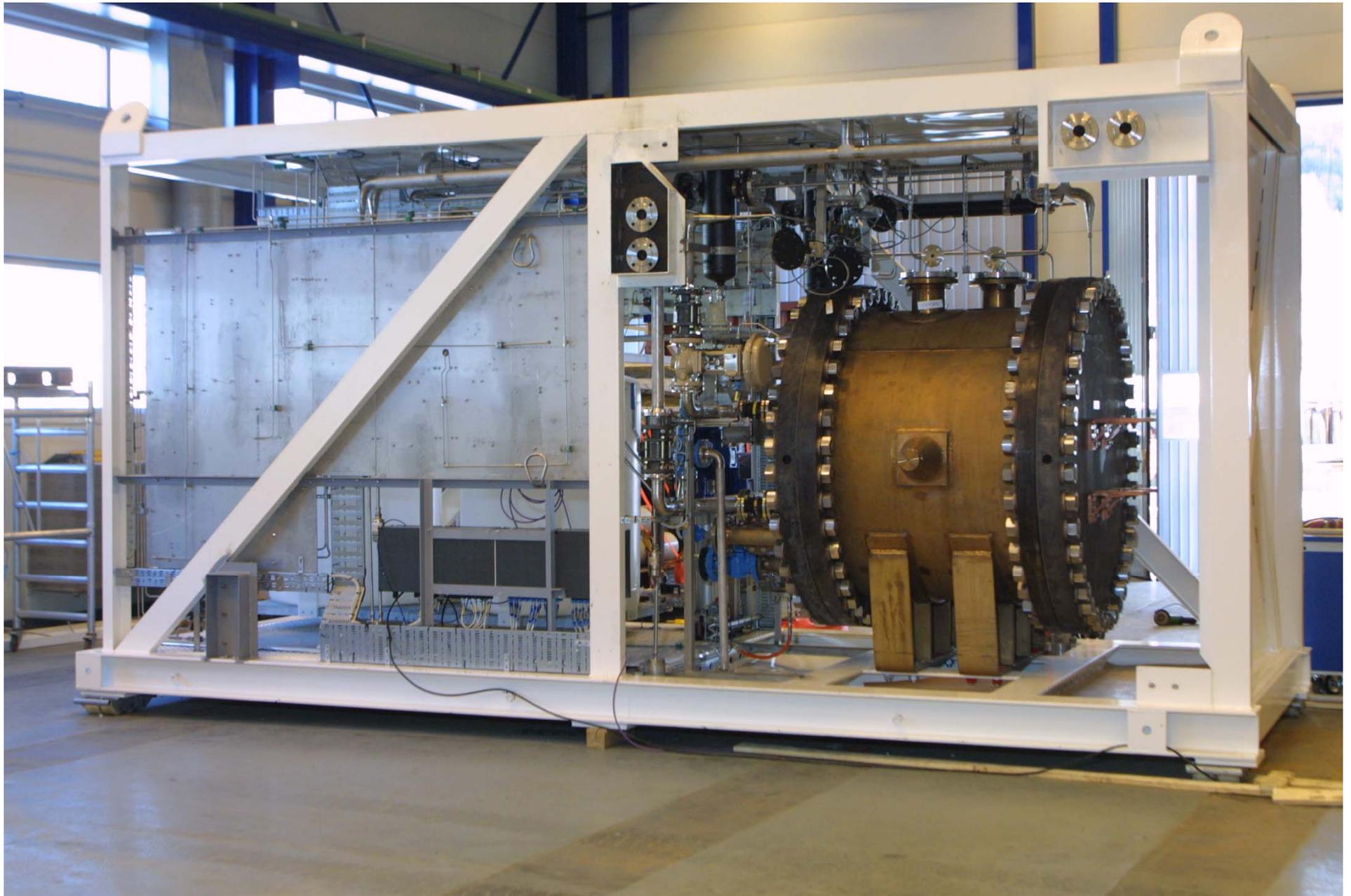
# *Why Hydrogen, Ammonia ?*

- **Transmission via underground pipeline**
  - Easier to site, permit
  - Lower NIMBY
  - Protected: acts of God and man
  - FERC interstate jurisdiction
  - High capacity: 5 - 10 GW
  - Lower capital cost / GW - mile
- **Affordable storage:**
  - Annual-scale firming
  - Dispatchable fuel supply
- **Zero-carbon fuels: RE**
- **Nascent markets: transport fuel, other**
- **Integration**
  - Continental energy system
  - Elec grid quality

# Hydrogen Transmission Scenario

- *Low-pressure electrolyzers*
- *“Pack” pipeline: ~ 120 GWh*



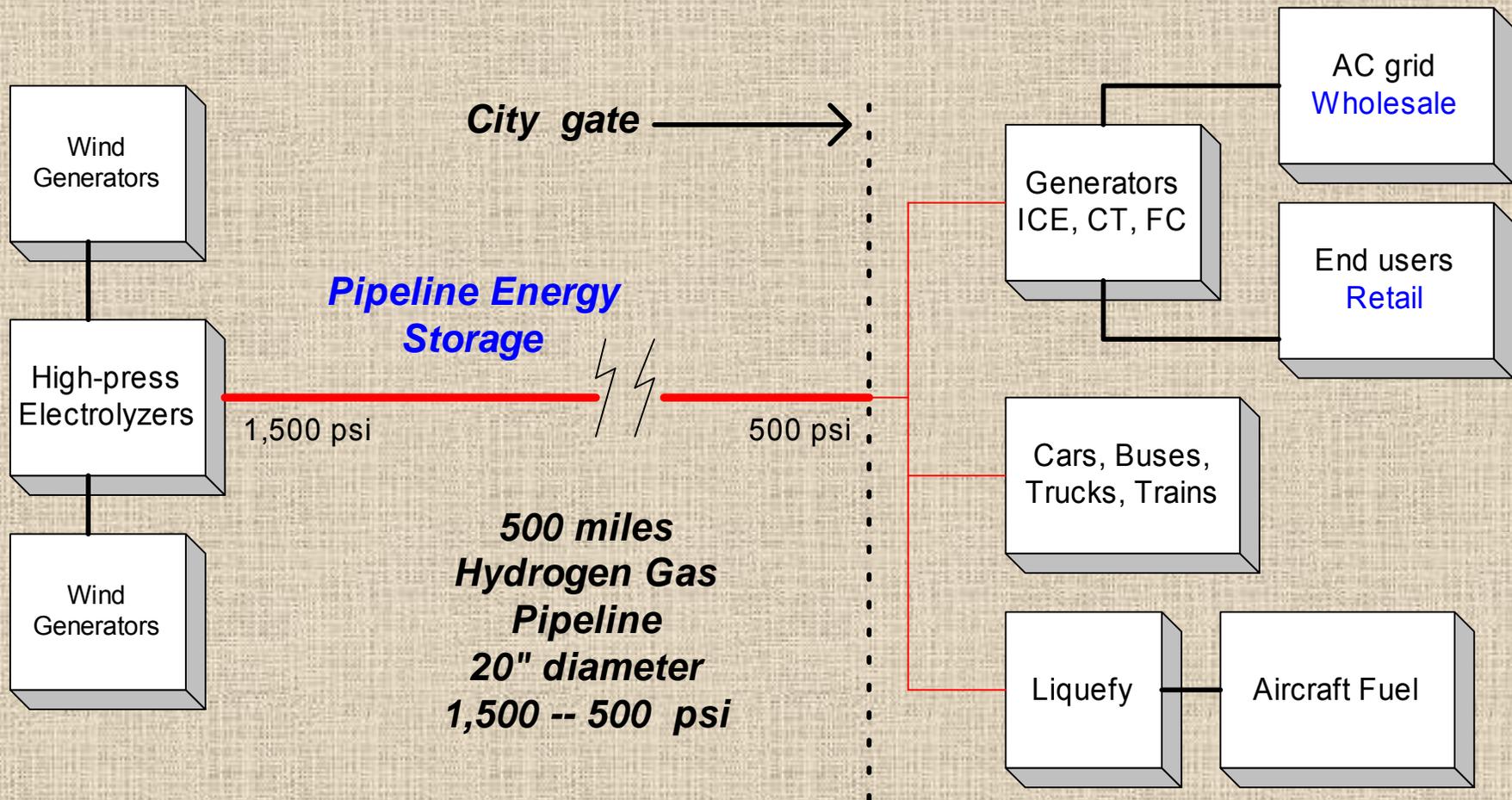


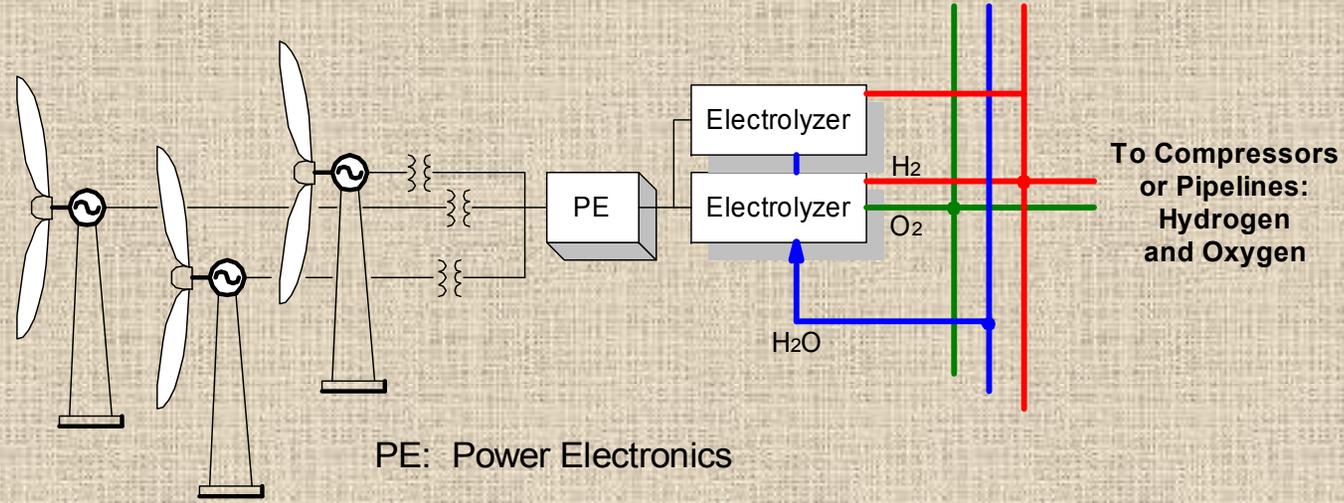
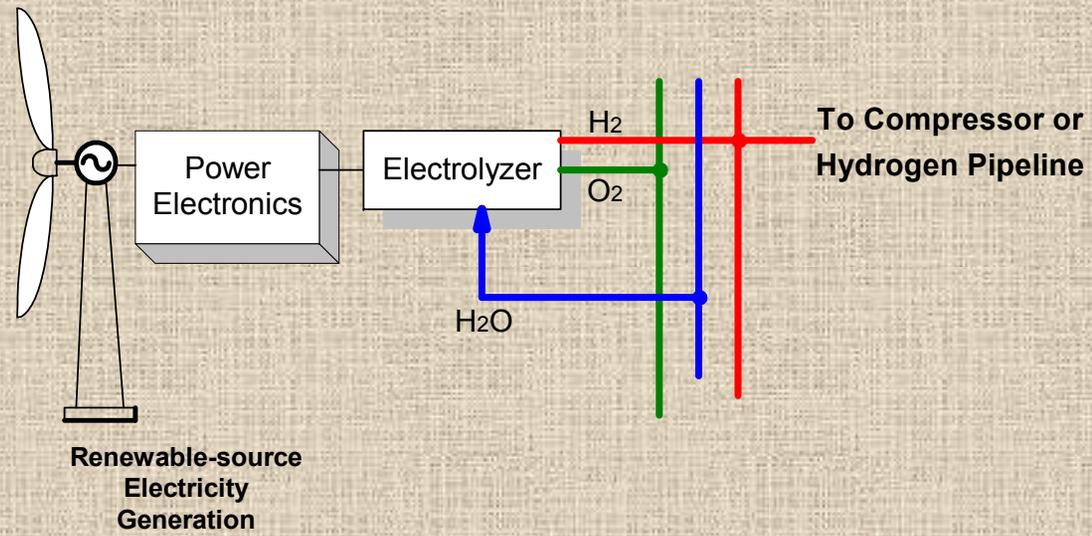
***Norsk Hydro electrolyzer, KOH type  
560 kW input, 130 Nm<sup>3</sup> / hour at 450 psi (30 bar)***

# Compressorless system: No geologic storage

## Transmission

## Distribution



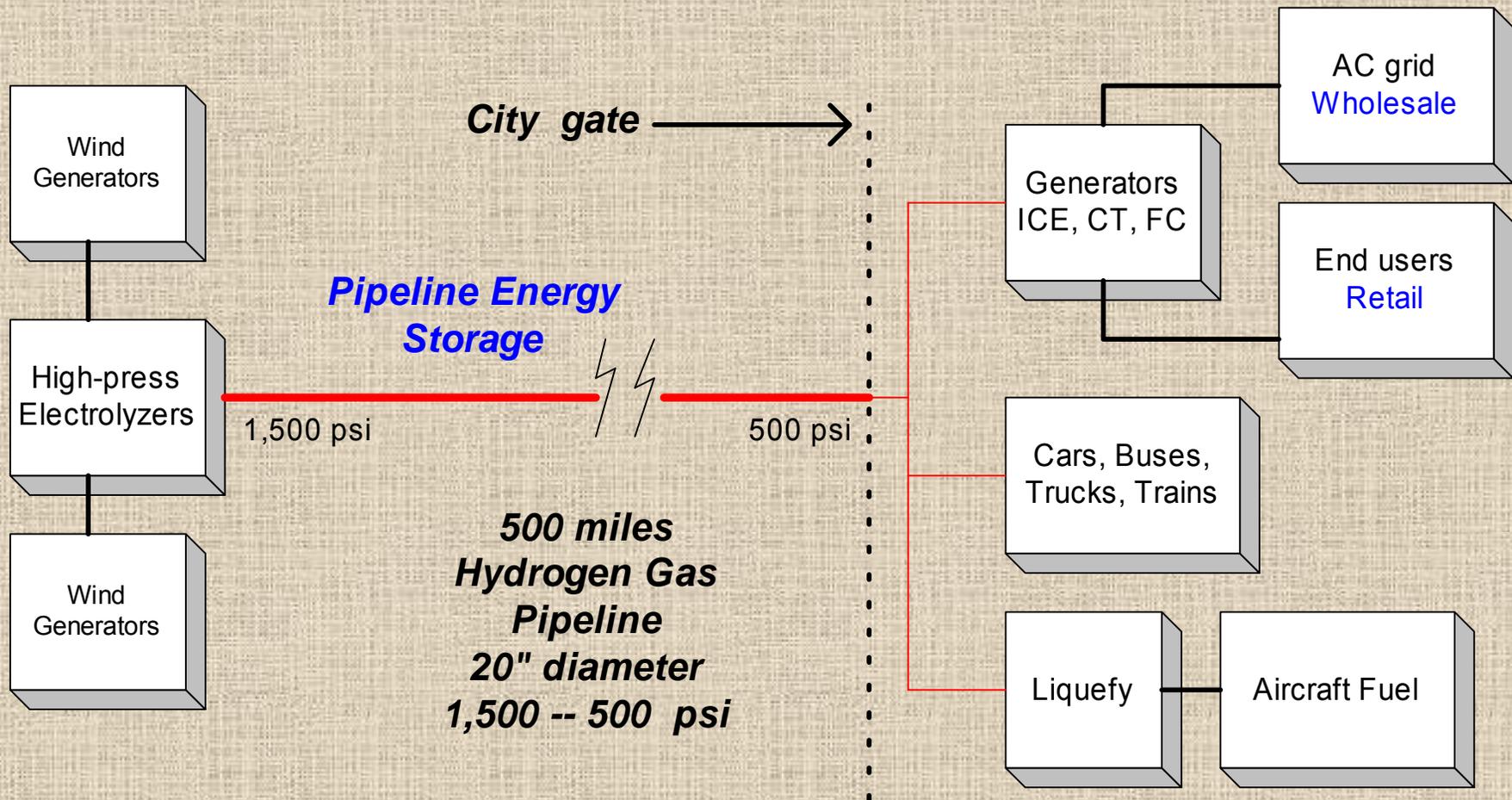


# Topology Options: H<sub>2</sub> and O<sub>2</sub> Production and Gathering from Renewable Energy Generation

# Compressorless system: No geologic storage

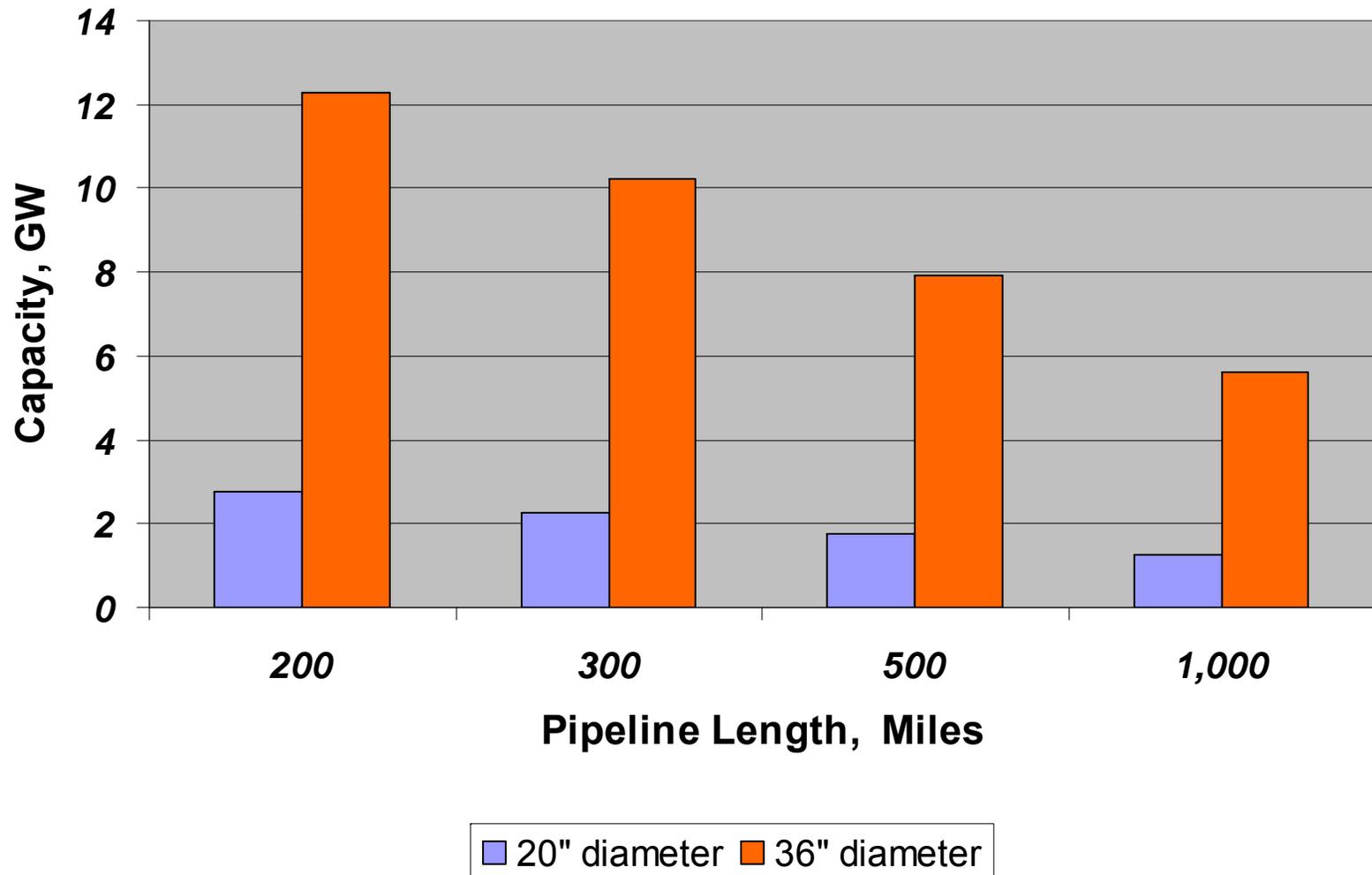
## Transmission

## Distribution

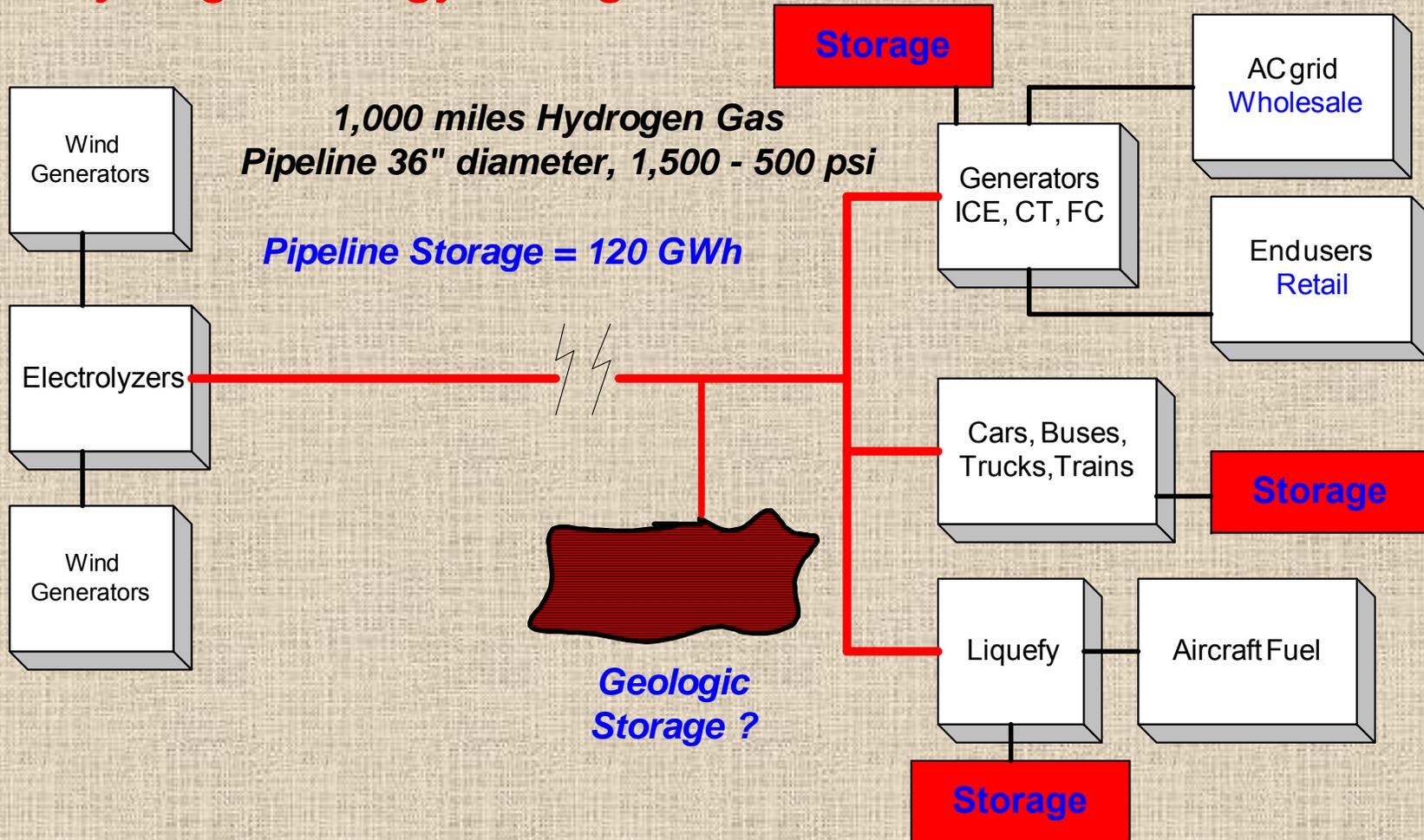


# Compressorless 20", 36" GH2 Pipeline Capacity

1,500 psi IN / 500 psi OUT



# Hydrogen Energy Storage



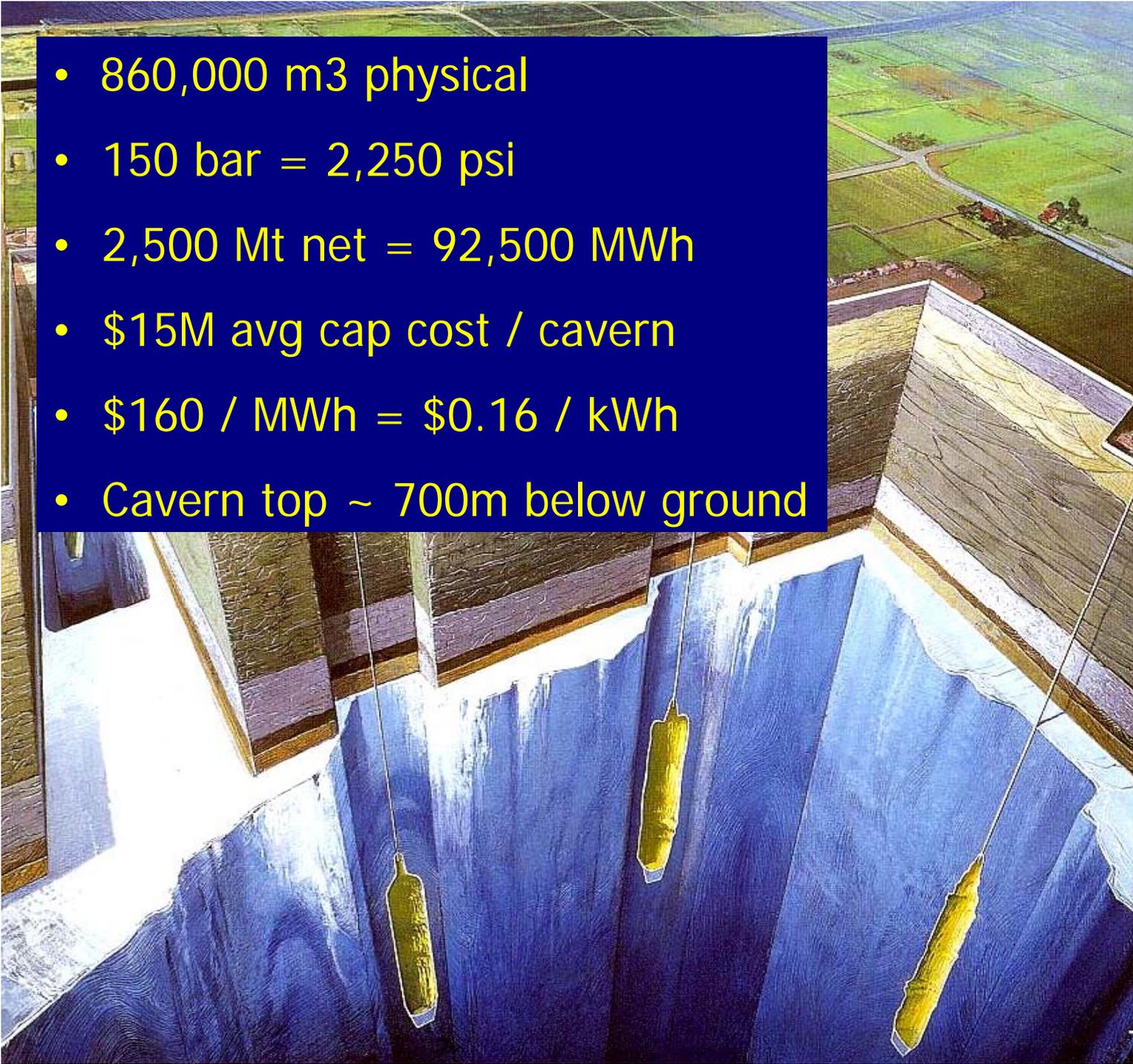
# Hydrogen Caverns in Texas

- Chevron-Phillips 25 years
- Praxair 6 years

Domal  
Salt  
Storage  
Caverns

PB ESS



- 
- 860,000 m<sup>3</sup> physical
  - 150 bar = 2,250 psi
  - 2,500 Mt net = 92,500 MWh
  - \$15M avg cap cost / cavern
  - \$160 / MWh = \$0.16 / kWh
  - Cavern top ~ 700m below ground

## Domal Salt Storage Caverns

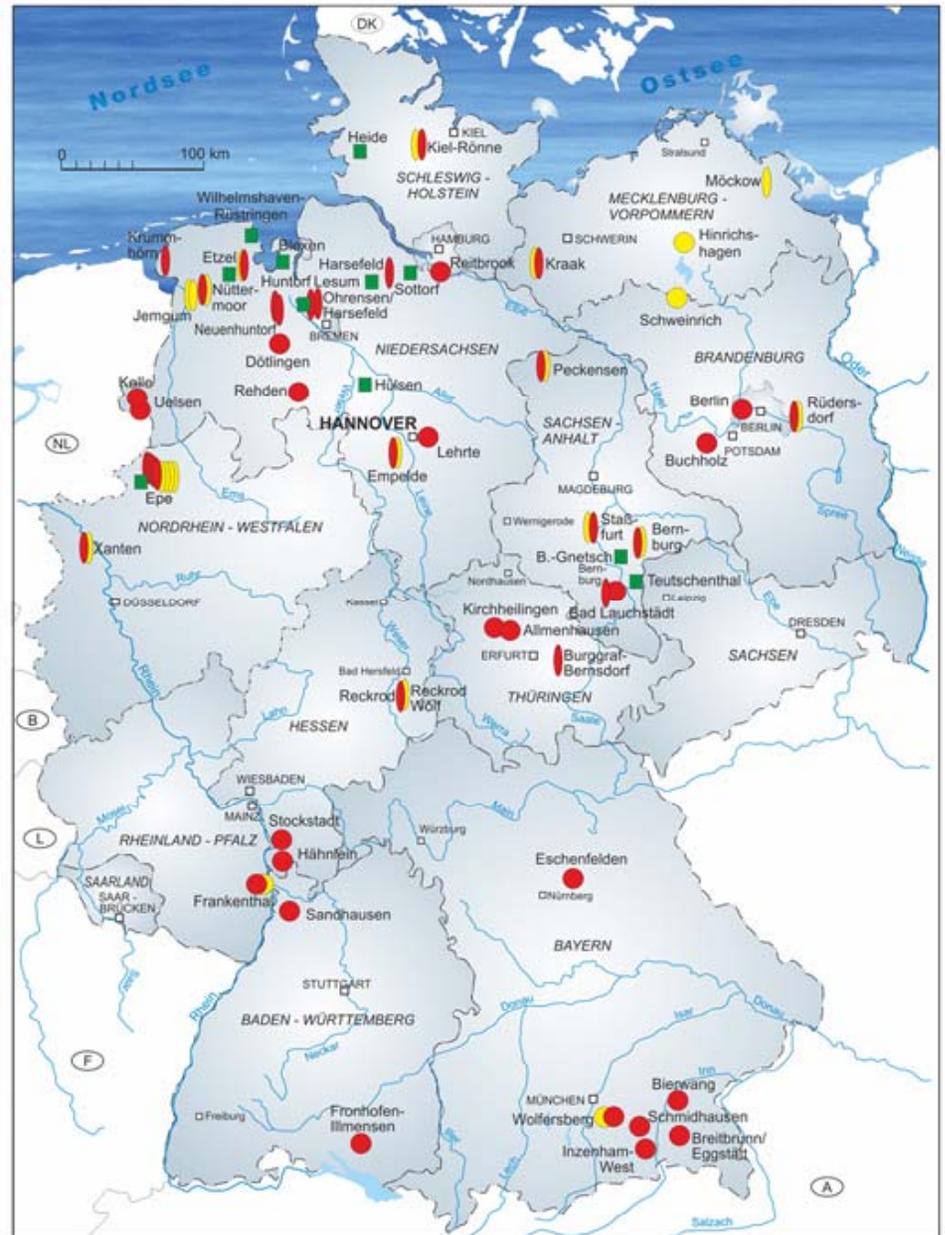
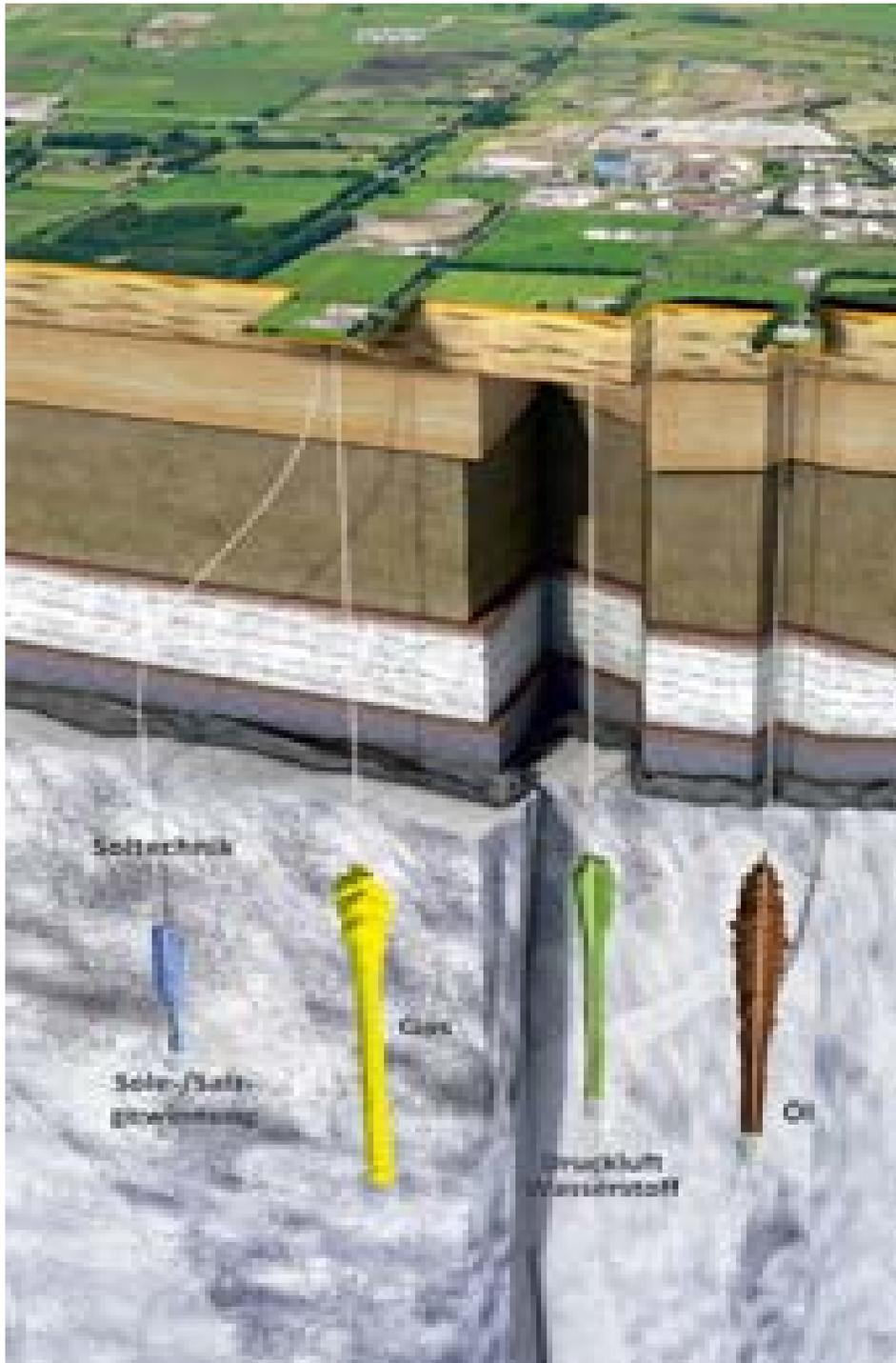
Texas

“Clemens  
Terminal”  
Conoco  
Phillips  
20 years

Praxair  
'07

PB ESS





**Erdgas**

Porenspeicher

● in Betrieb      ● in Planung oder Bau

Kavernenspeicher

● in Betrieb      ● in Planung oder Bau

**Rohöl, Mineralprodukte, Flüssiggas**

Kavernenspeicher

■ in Betrieb

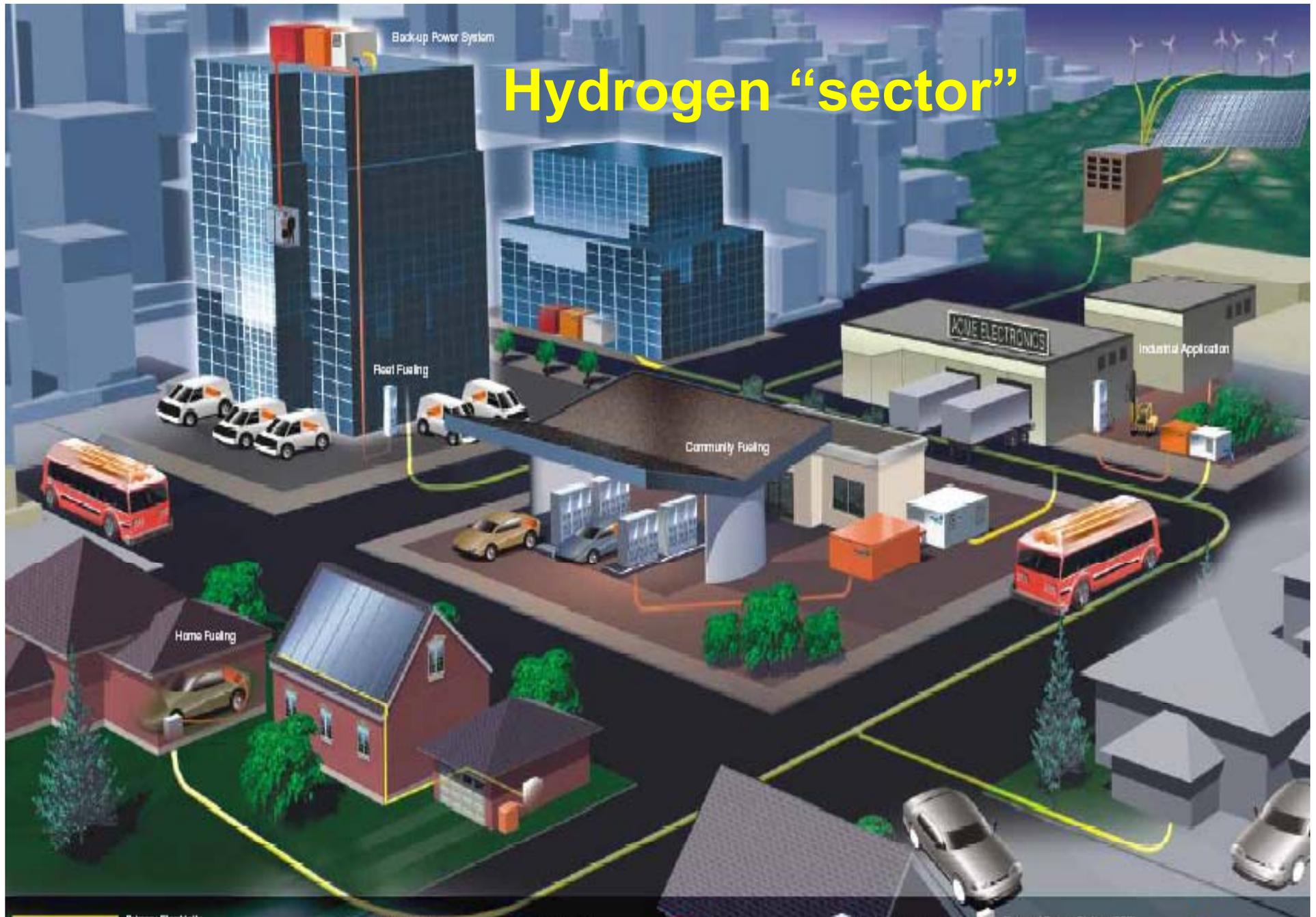
(Quelle: LBEG, 2010)

**Optimistic: Total Installed Capital Cost**  
**1,000 mile Pipeline**  
**“Firming” GH2 cavern storage**

Windplant size	<b>1,000 MW</b>	
		[million]
Wind generators	\$ 1,000	
Electrolyzers	500	
Pipeline, 20”	1,100	
# storage caverns	[4]	
Caverns @ \$10M ea		40
Cushion gas @ \$5M ea		20
TOTAL	\$ 2,660	

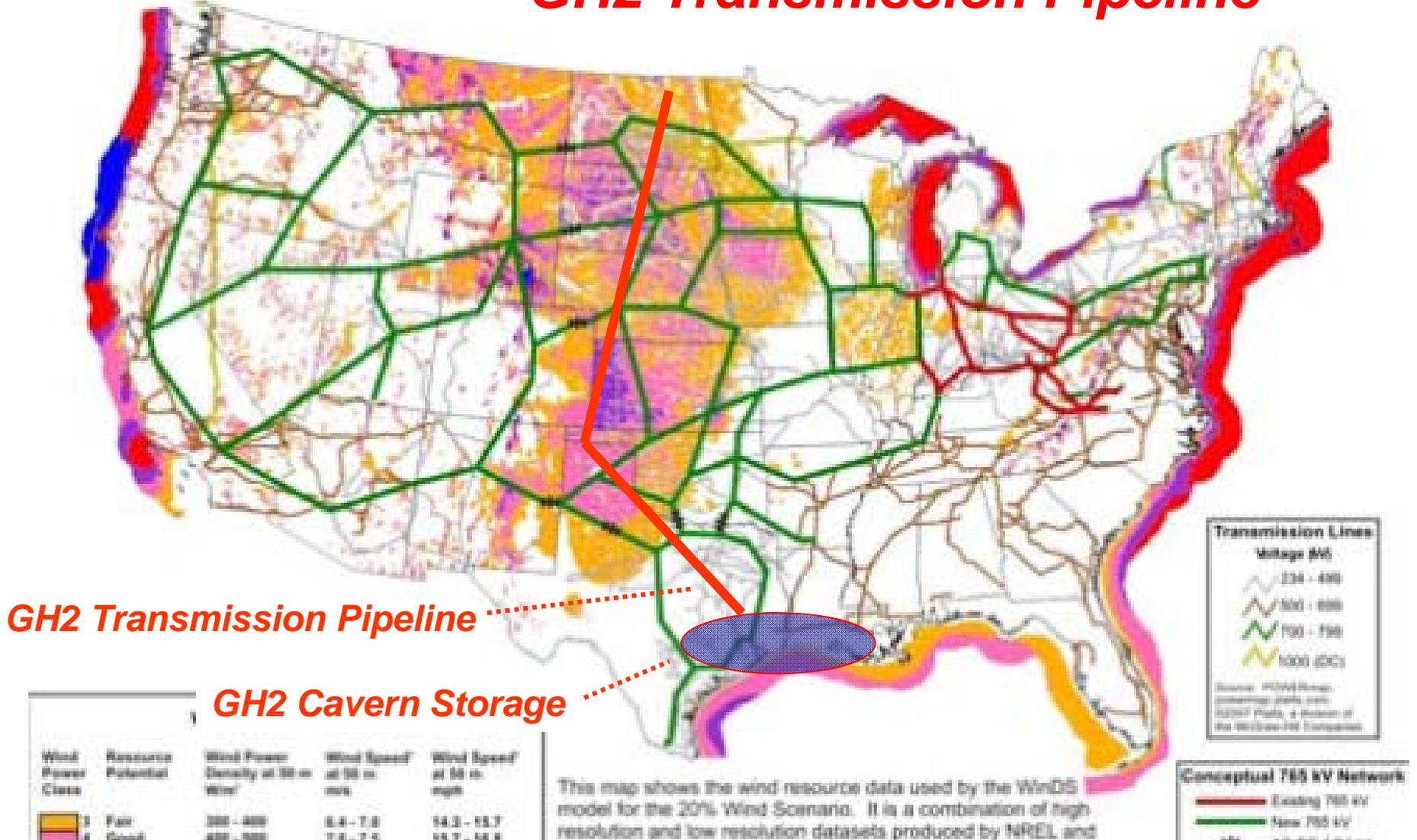
Cavern storage: ~ 3 % of total capital cost

# Hydrogen "sector"



Hydrogen "sector" of a benign, sustainable, equitable, global energy economy

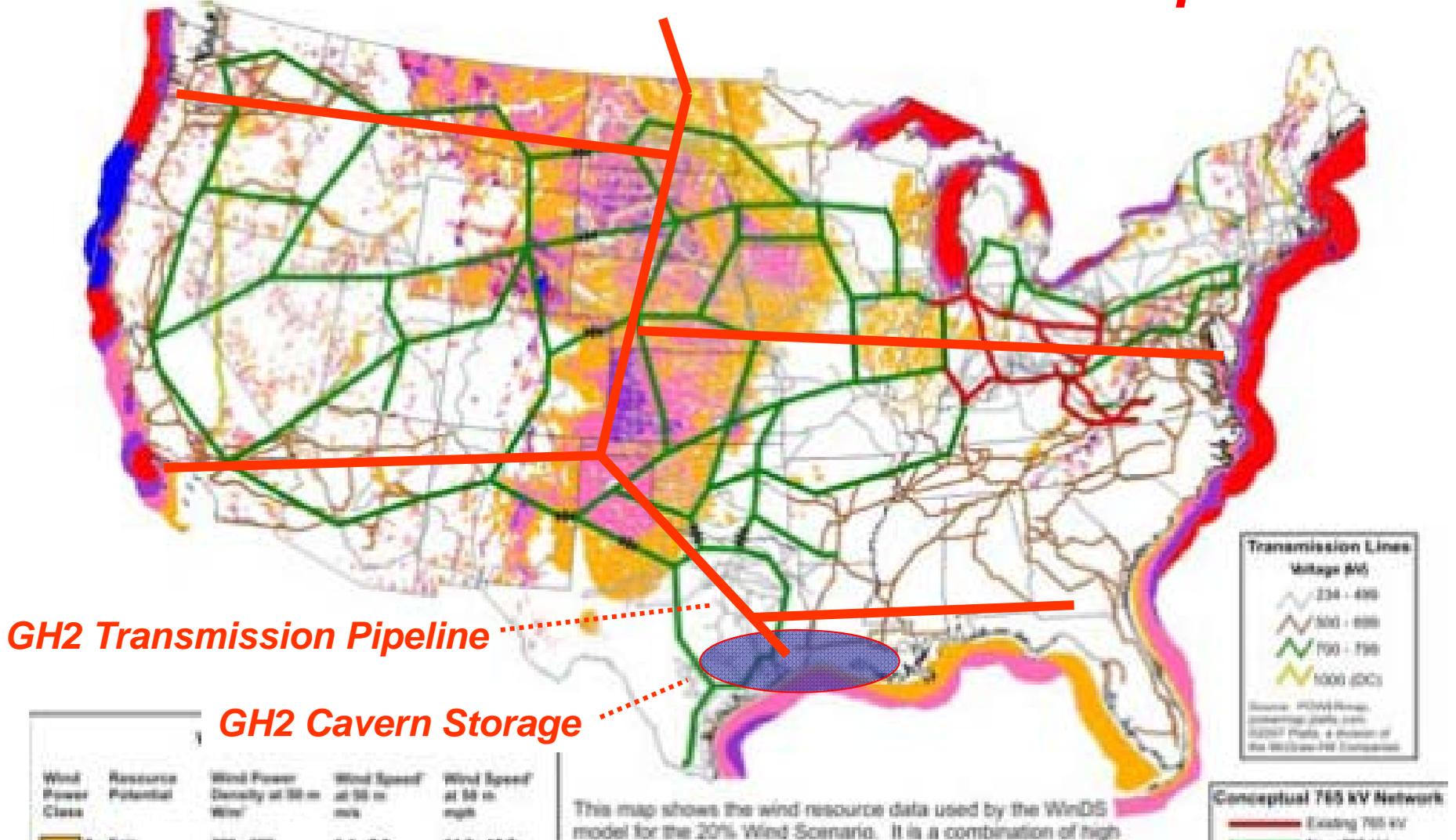
# GH2 Transmission Pipeline



**Wind Potential ~ 10,000 GW**

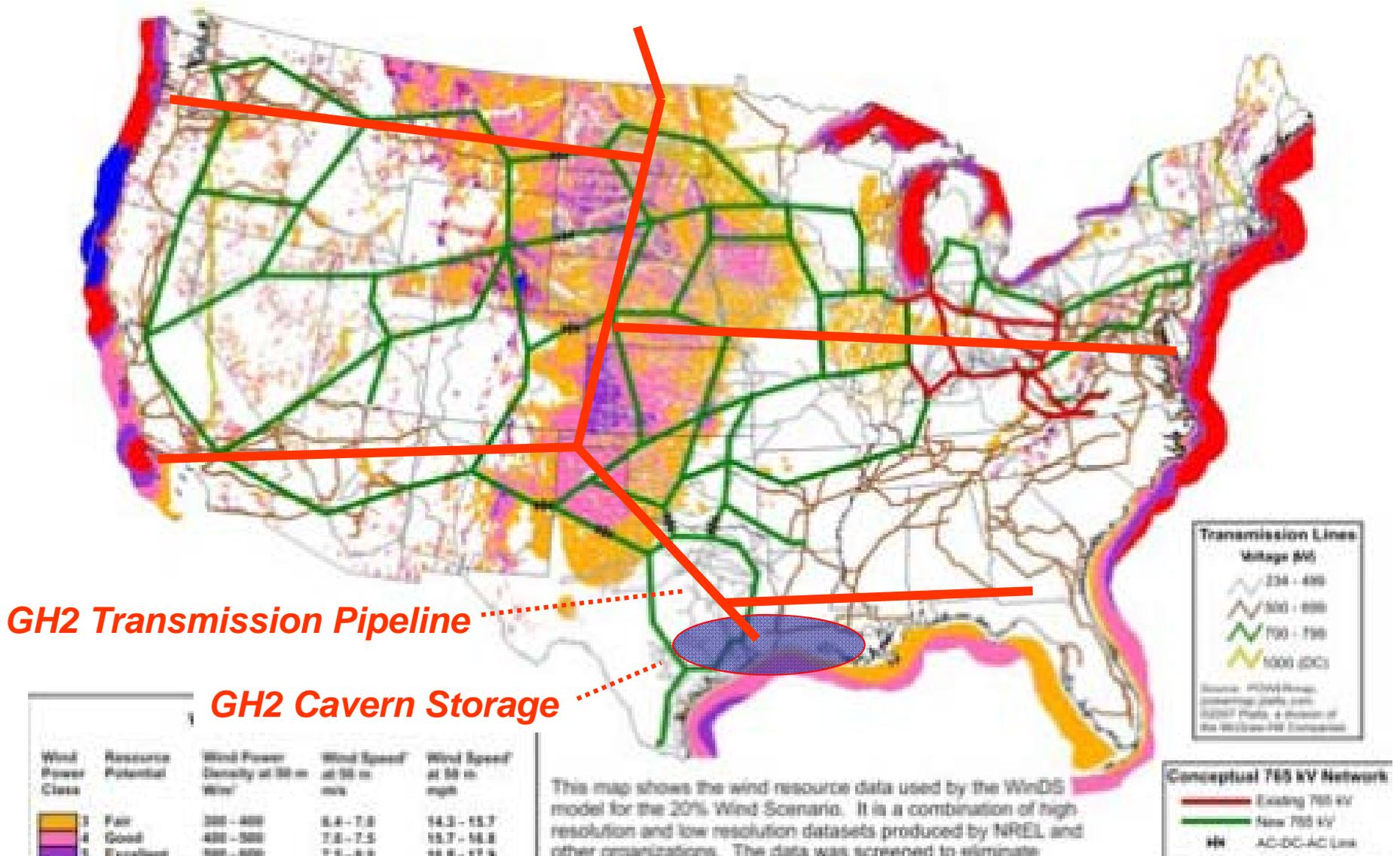
**12 Great Plains states**

# ***GH2 Transmission Pipeline***



***Wind Potential ~ 10,000 GW***  
***12 Great Plains states***

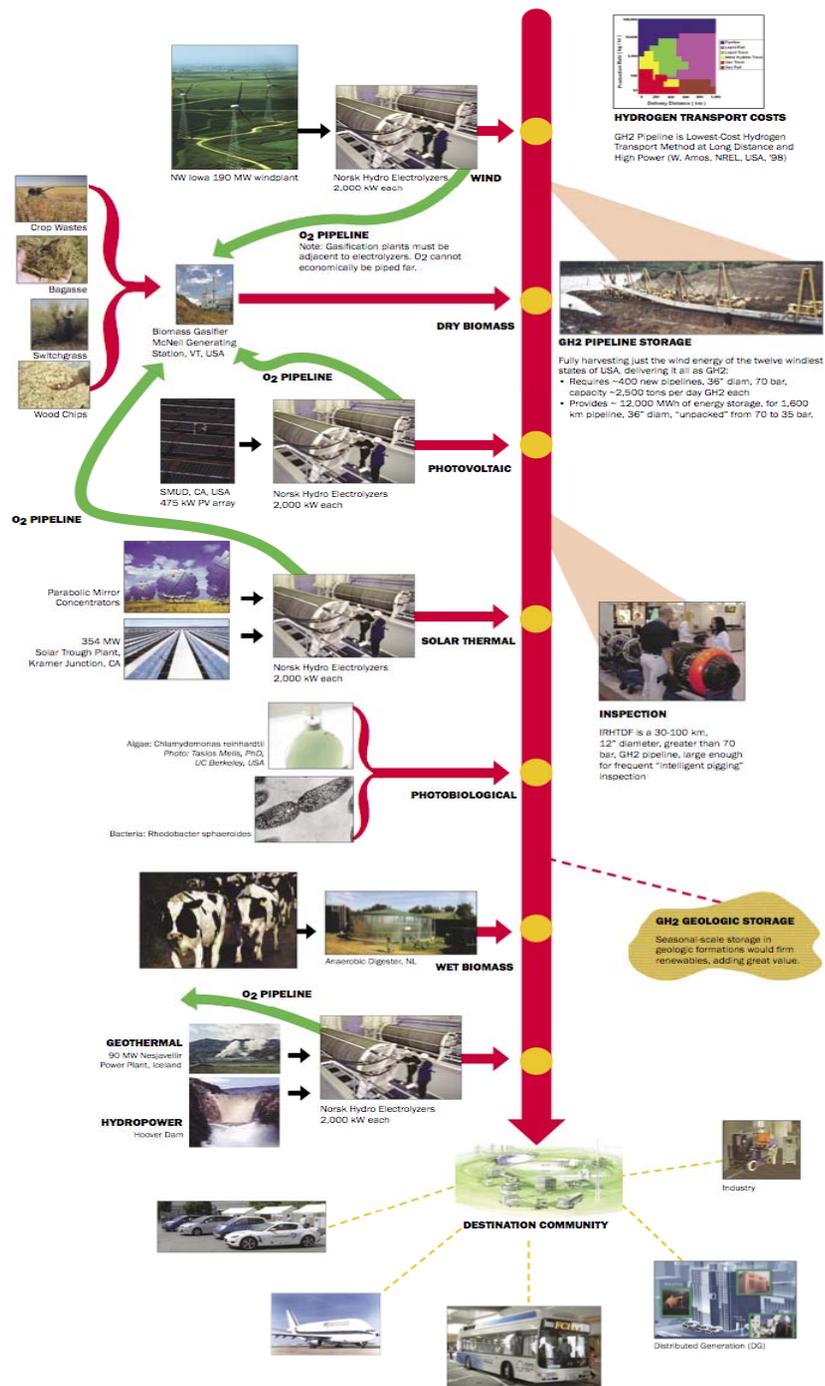
# AWEA 20% Wind Electricity by 2030



**Wind Potential ~ 10,000 GW**

## ***Pilot plant needed***

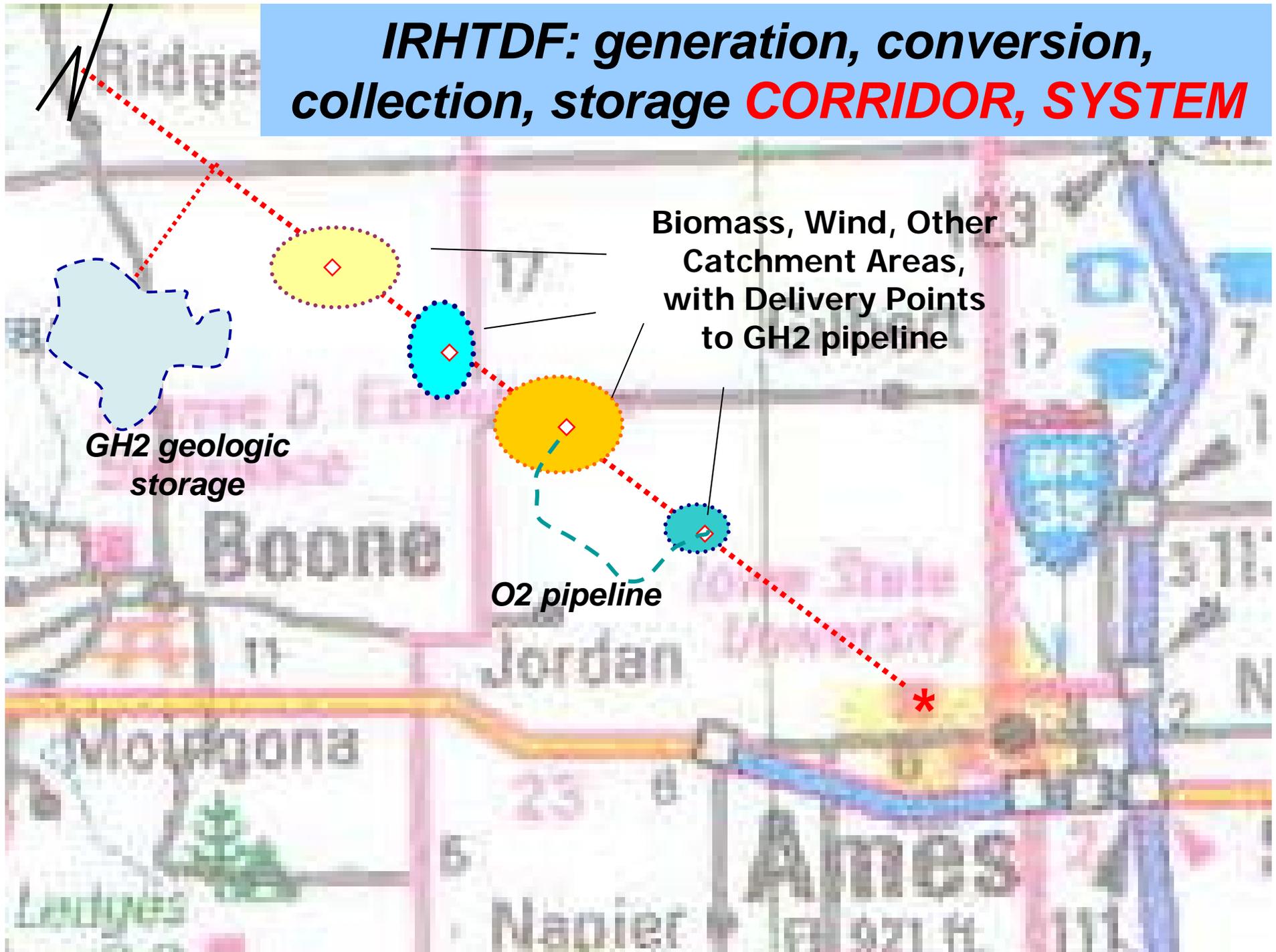
- **Every major new industrial process**
- **Renewables-source systems**
- **Diverse, large-scale, stranded**
- **US, Japan, Canada, IPHE → “ IRHTDF “**

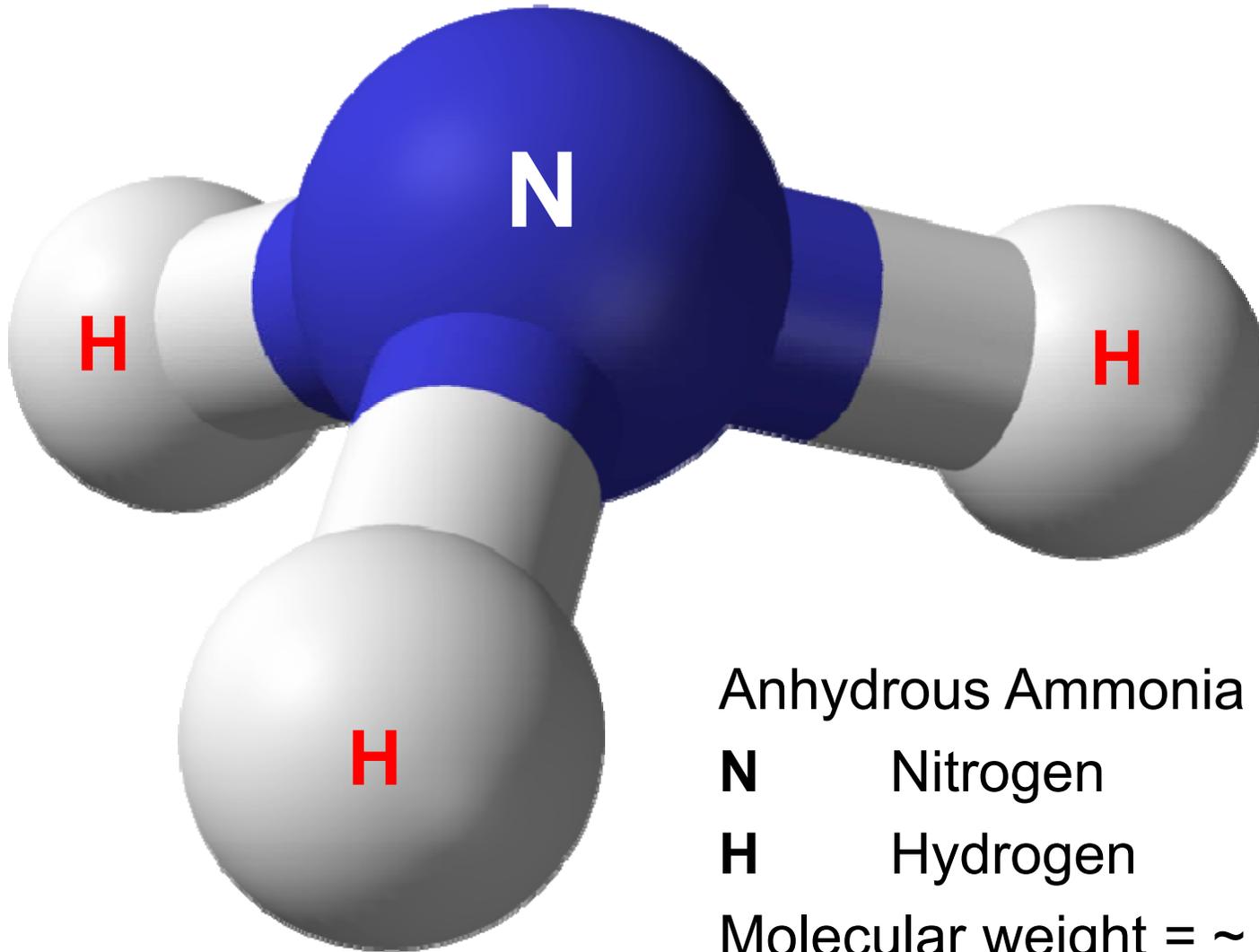


# Pilot-scale Hydrogen Pipeline System: Renewables

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

# IRHTDF: generation, conversion, collection, storage **CORRIDOR, SYSTEM**





Anhydrous Ammonia **NH<sub>3</sub>**

**N** Nitrogen

**H** Hydrogen

Molecular weight = ~ 17

18% **H** by weight: “other hydrogen”



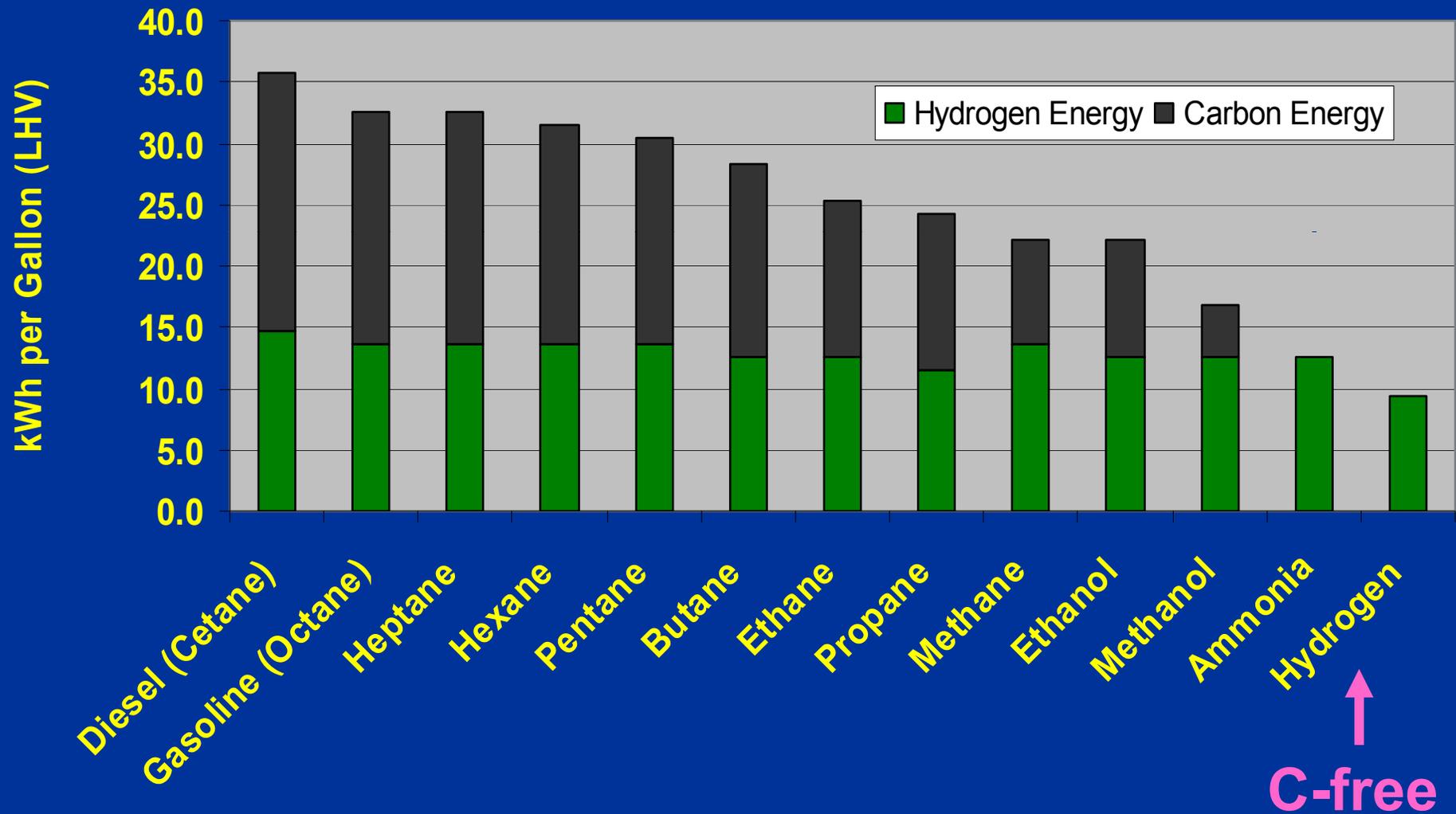
# *Why Ammonia ?*

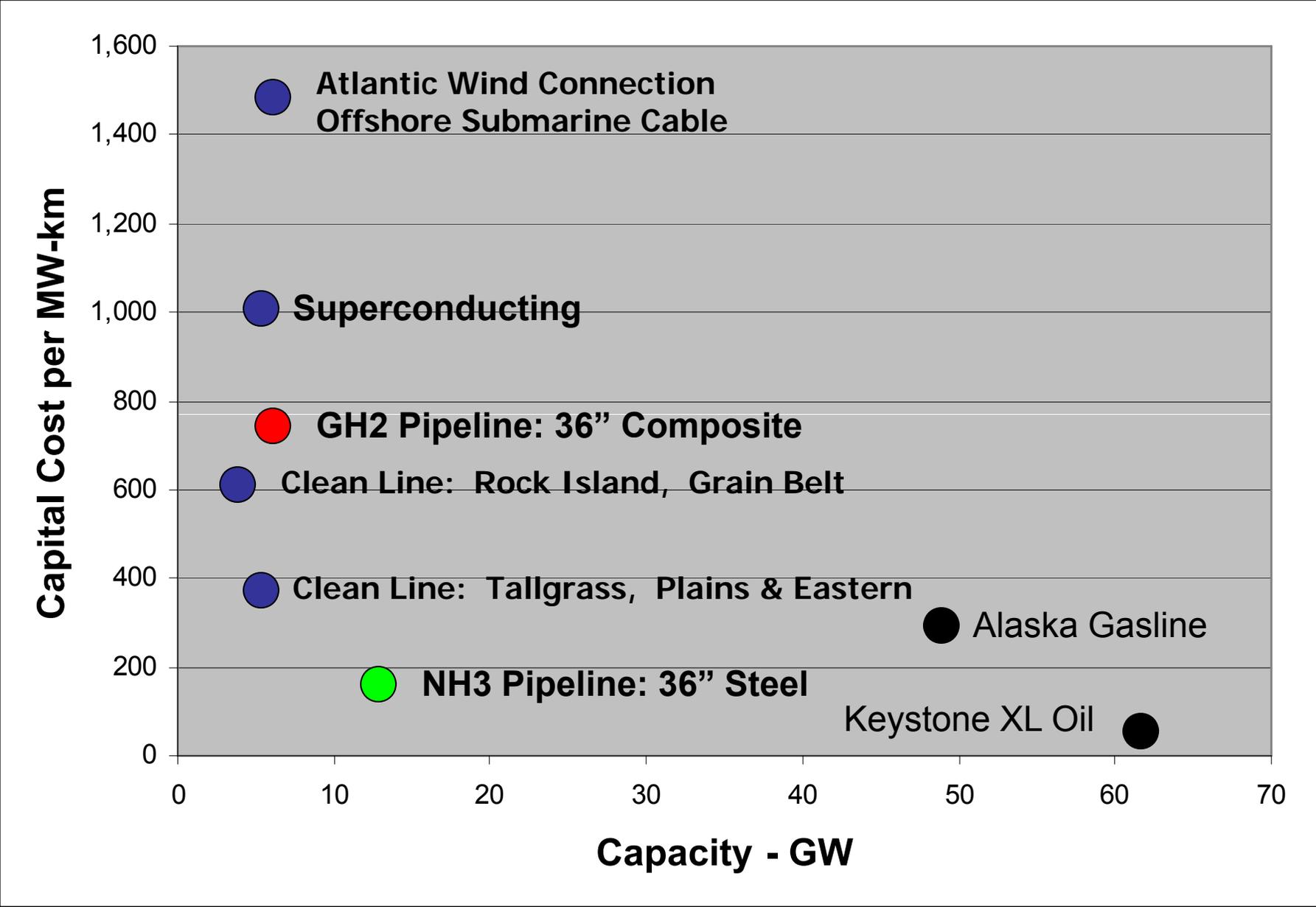
## *Fertilizer and Fuel*

Only liquid fuel embracing:

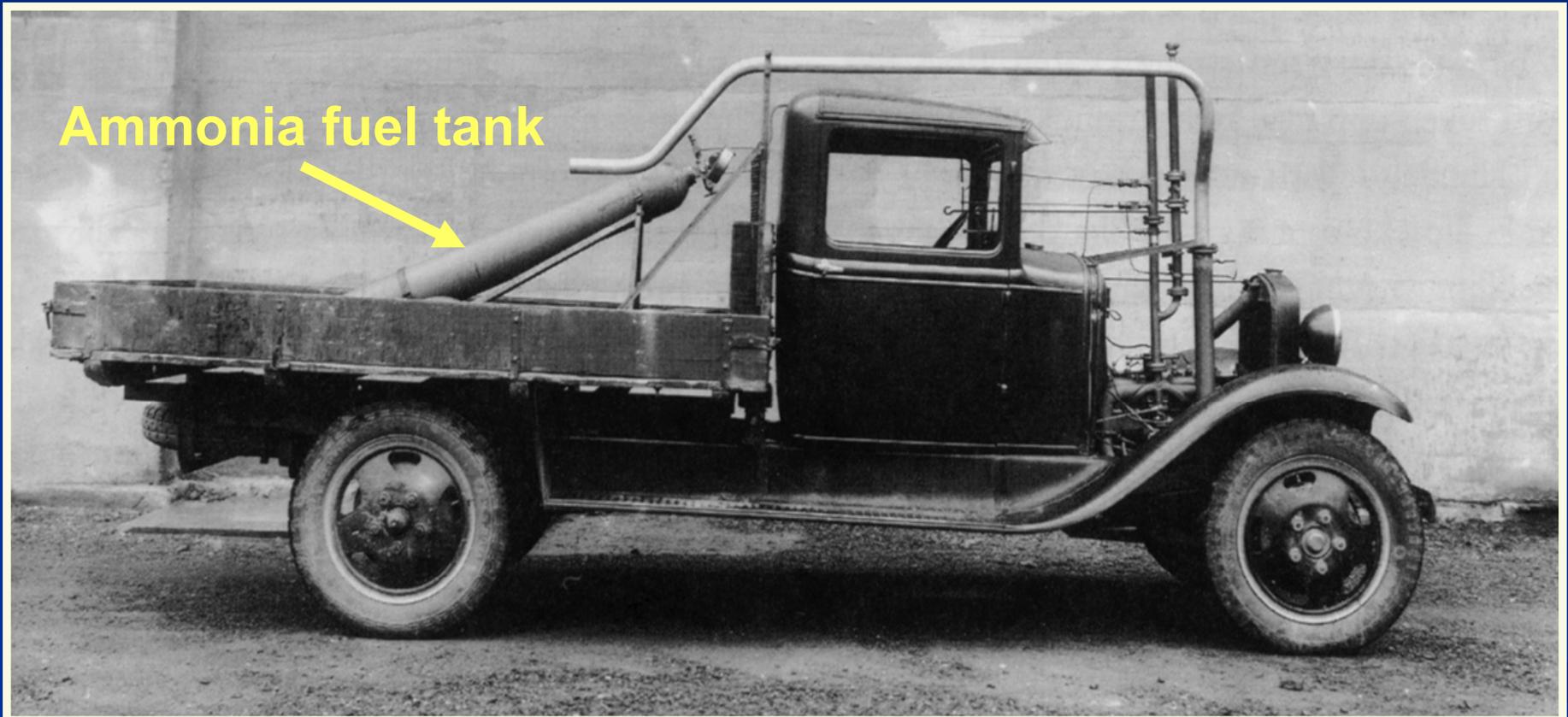
- Carbon-free: clean burn or conversion; no CO<sub>2</sub>
  - Excellent hydrogen carrier
  - Easily “cracked” to H<sub>2</sub>
- Reasonably high energy density
- Energy cycle inherently pollution free
  - Potentially all RE-source: elec + water + Nitrogen
  - Cost competitive with hydrocarbon fuels ?
- Decades of global use, infrastructure
  - Practical to handle, store, and transport
  - End-use in ICE, Combustion Turbine, fuel cell
  - Safety: self-odorizing; safety regs; hazard

# Volumetric Energy Density of Fuels (Fuels in their Liquid State)



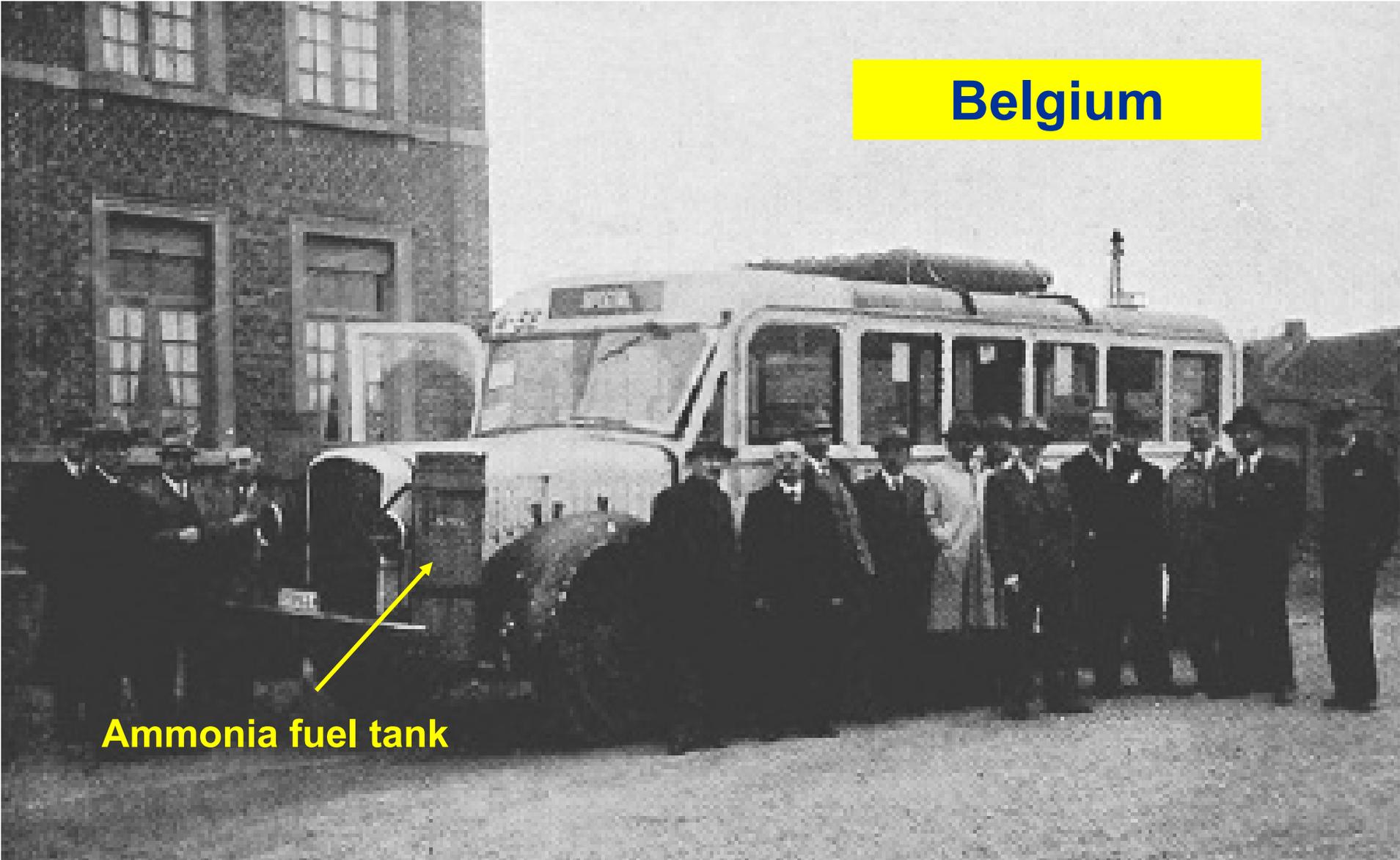


# *Ammonia fueled – Norway*



1933

**Belgium**



**Ammonia fuel tank**

**Ammonia Fueled Bus: Thousands of Problem-free Miles**

**1943**



**X-15 rocket plane: NH<sub>3</sub> + LOX fuel**

**Mach 6.7 on 3 Oct 67**

**199 missions**

**1959 - 68**



## University of Michigan

### Ammonia + Gasoline Powered

- Idle: gasoline
- Full power: 80% ammonia

Summer '07 Detroit → San Francisco

**2007**

**1,000 hours, ICE, 6 cyl, 100 hp  
75% ammonia, 25% propane**

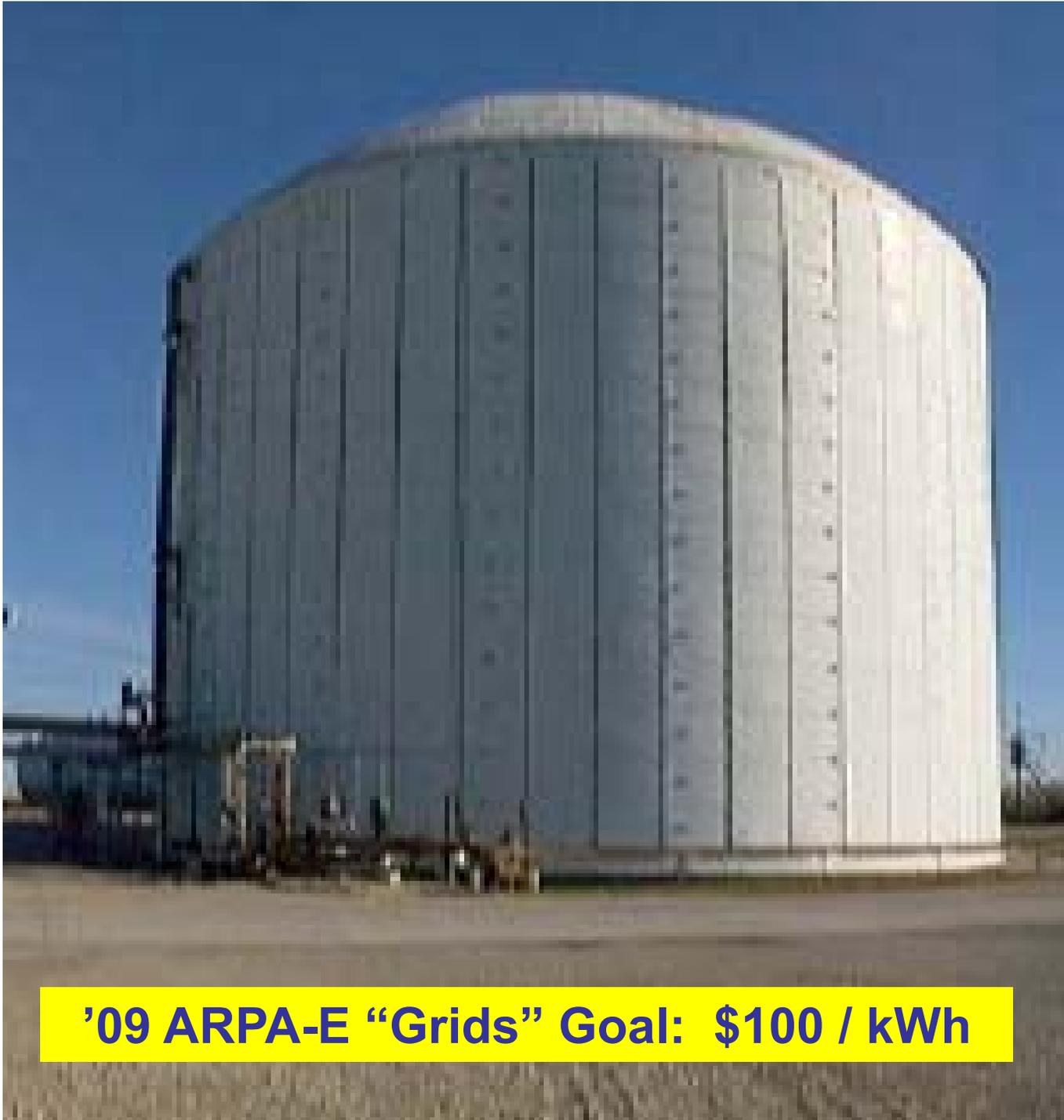


**Irrigation pump  
Central Valley, CA**

**2008**

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





***“Atmospheric”  
Liquid  
Ammonia  
Storage Tank  
(corn belt)***

***30,000 Tons***

***190 GWh***

***\$ 15M turnkey***

***\$ 80 / MWh***

***\$ 0.08 / kWh***

***-33 C***

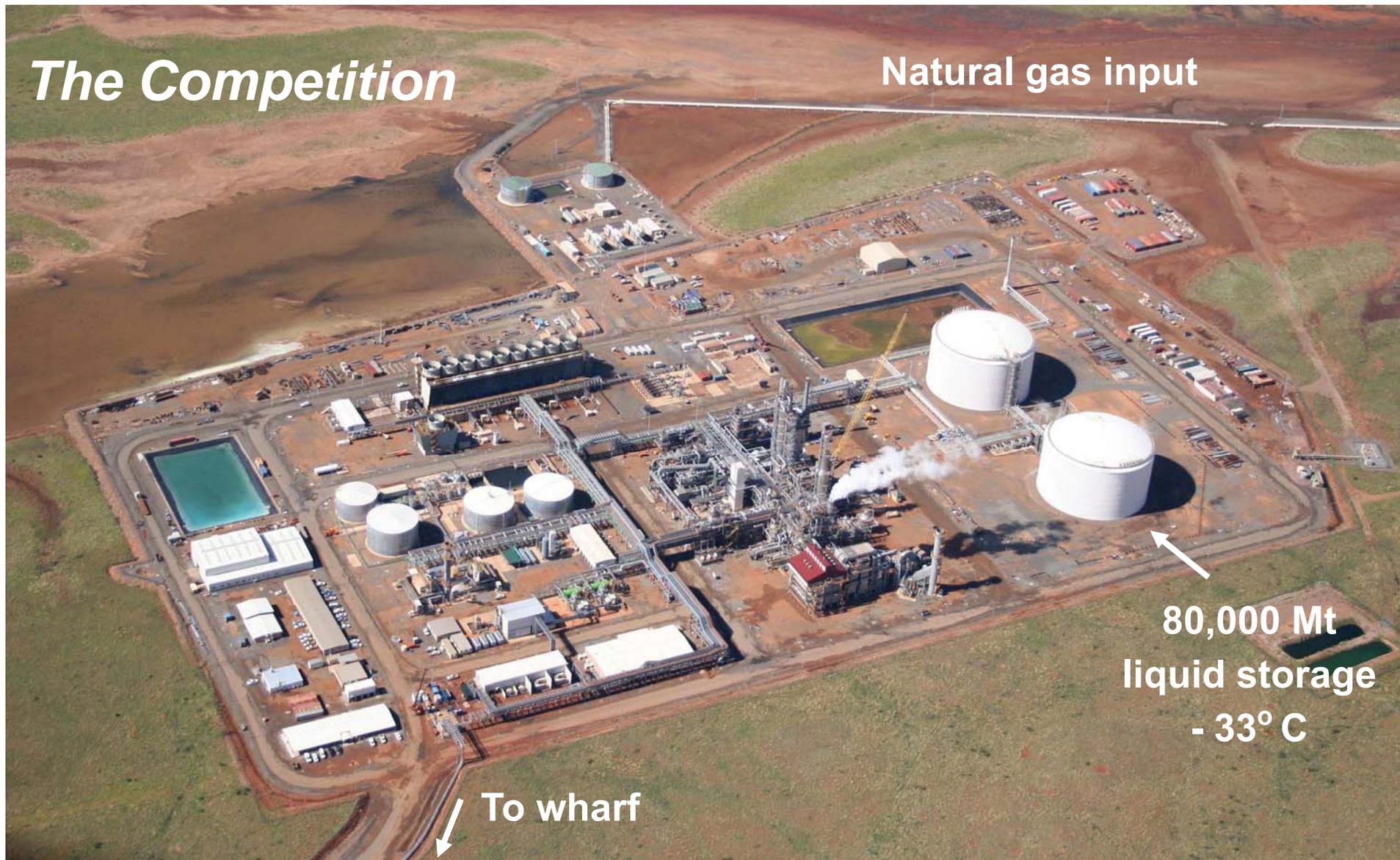
***1 Atm***

**'09 ARPA-E “Grids” Goal: \$100 / kWh**

**Ammonia Storage Terminal  
Mississippi River  
Winona, MN**



# *The Competition*



Natural gas input

80,000 Mt  
liquid storage  
- 33° C

To wharf

**Burrup Peninsula, NW Australia, Natural Gas to Ammonia Plant**  
**760,000 Mt / year**  
**\$US 650 million capital cost '06**



***95% Global  
Ammonia***

***Synthesis  
Plant***

***Natural Gas  
1 – 3,000 tpd***

***Haber-Bosch  
process***



Fritz Haber



## Haber-Bosch Process

1909 – 1913 BASF

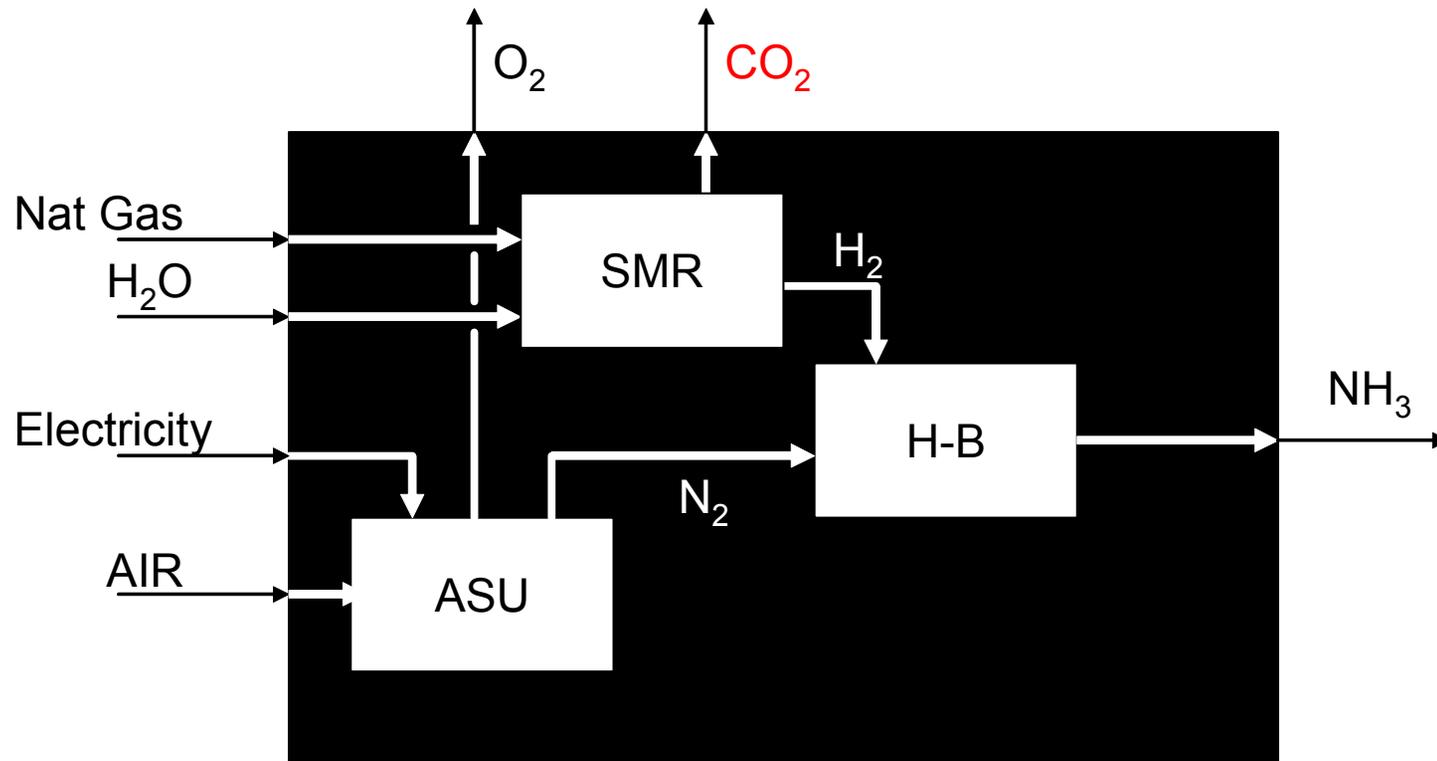
- $\text{NH}_3$  synthesis
- Coal gasification  $\rightarrow \text{H}_2$
- WW I explosives
- 40% humanity: N fertilizer

Haber-Bosch Reactor

1921

Ludwigshafen, Germany

# Inside the Black Box: Steam Reforming + Haber-Bosch (H-B)



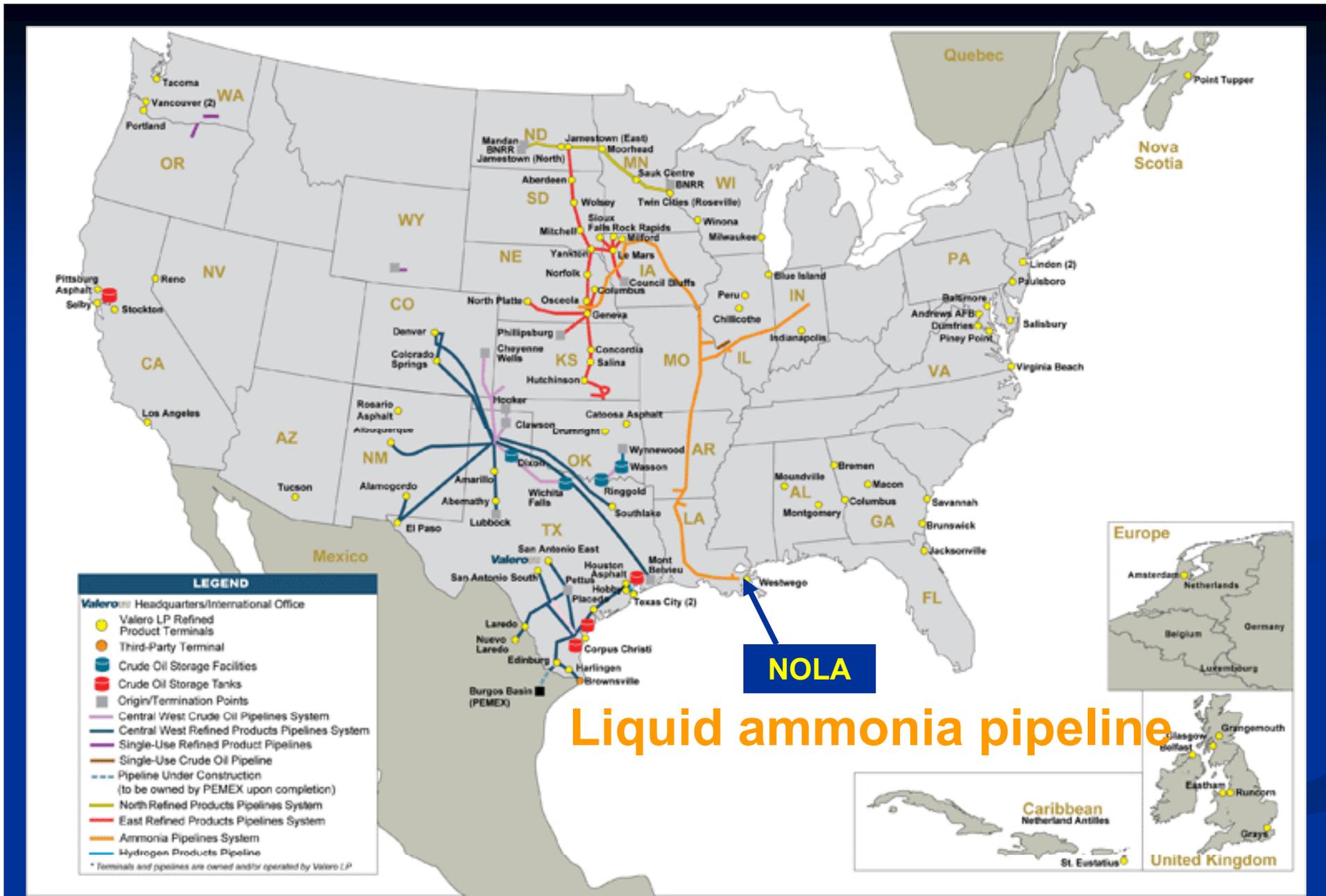
**Energy consumption ~33 MMBtu (9,500 kWh) per ton NH<sub>3</sub>**  
**Tons CO<sub>2</sub> per ton NH<sub>3</sub> = 1.8**



**Ammonia or LPG Tanker**  
**To 35,000 Mt**  
**Refrigerated**

# ***USA NH3 Infrastructure***

- USA imports ~60% of 14 MMt / year
- ~ 3,000 miles pipelines
  - ~ 250 psi liquid
  - Smaller diameter than NG or hydrogen
- ~ 4.5 MMt large “atmospheric” tank storage
- Mild steel construction
  - Low cost
  - No corrosion or embrittlement



Valero LP Operations

# Capital Cost per GW-mile

## Electricity :

	<u>KV</u>	<u>Capacity MW</u>	<u>\$M / GW-mile</u>
• SEIA:	765	5,000	1.3
	345	1,000	2.6
• AEP-AWEA	765	5,000	3.2
Consensus ?			2.5

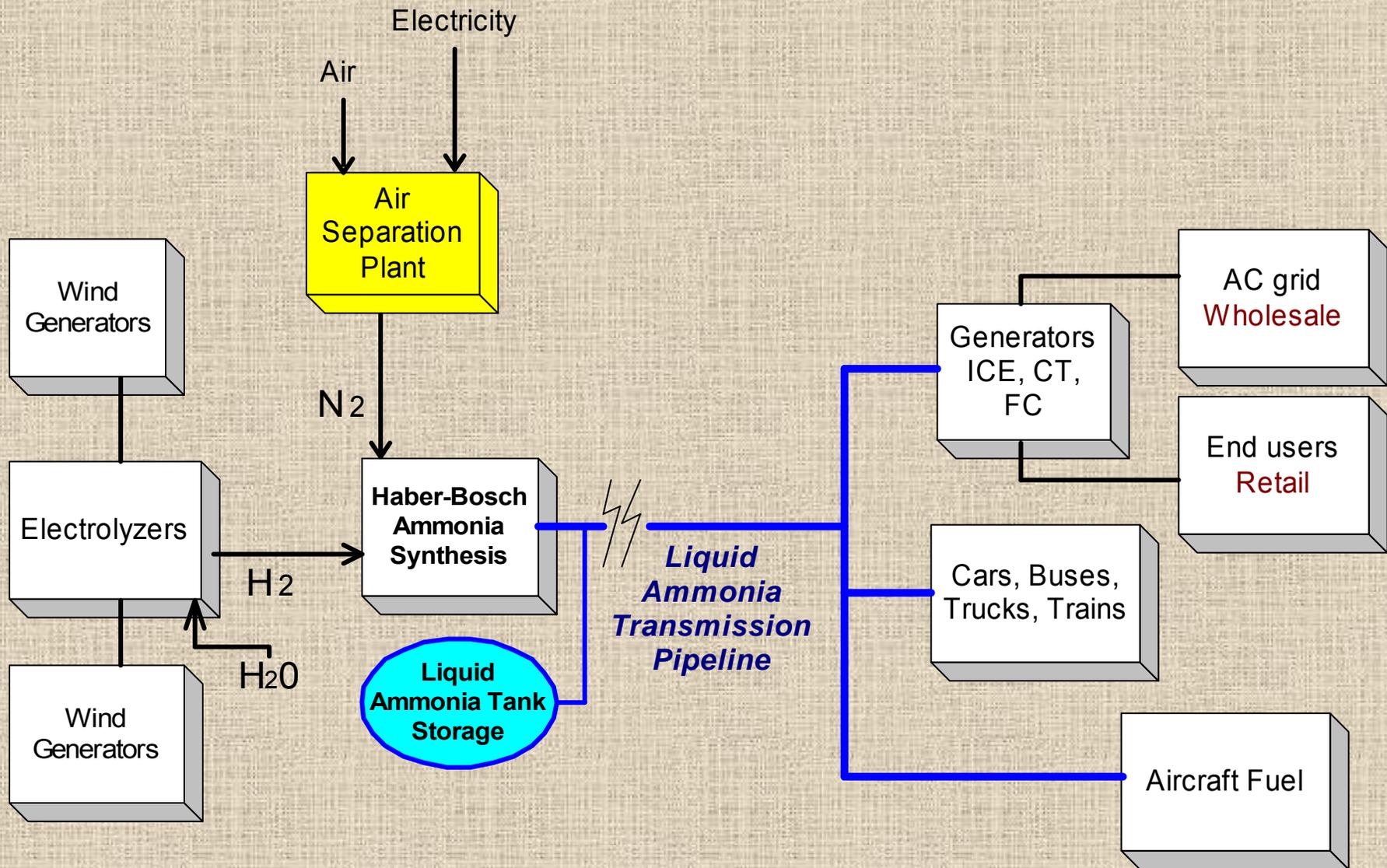
## Hydrogen pipeline:

36", 100 bar, 500 miles, no compress 0.3

## Ammonia pipeline:

10" , liquid, 500 miles, with pumping 0.2

# RE Ammonia Transmission + Storage Scenario

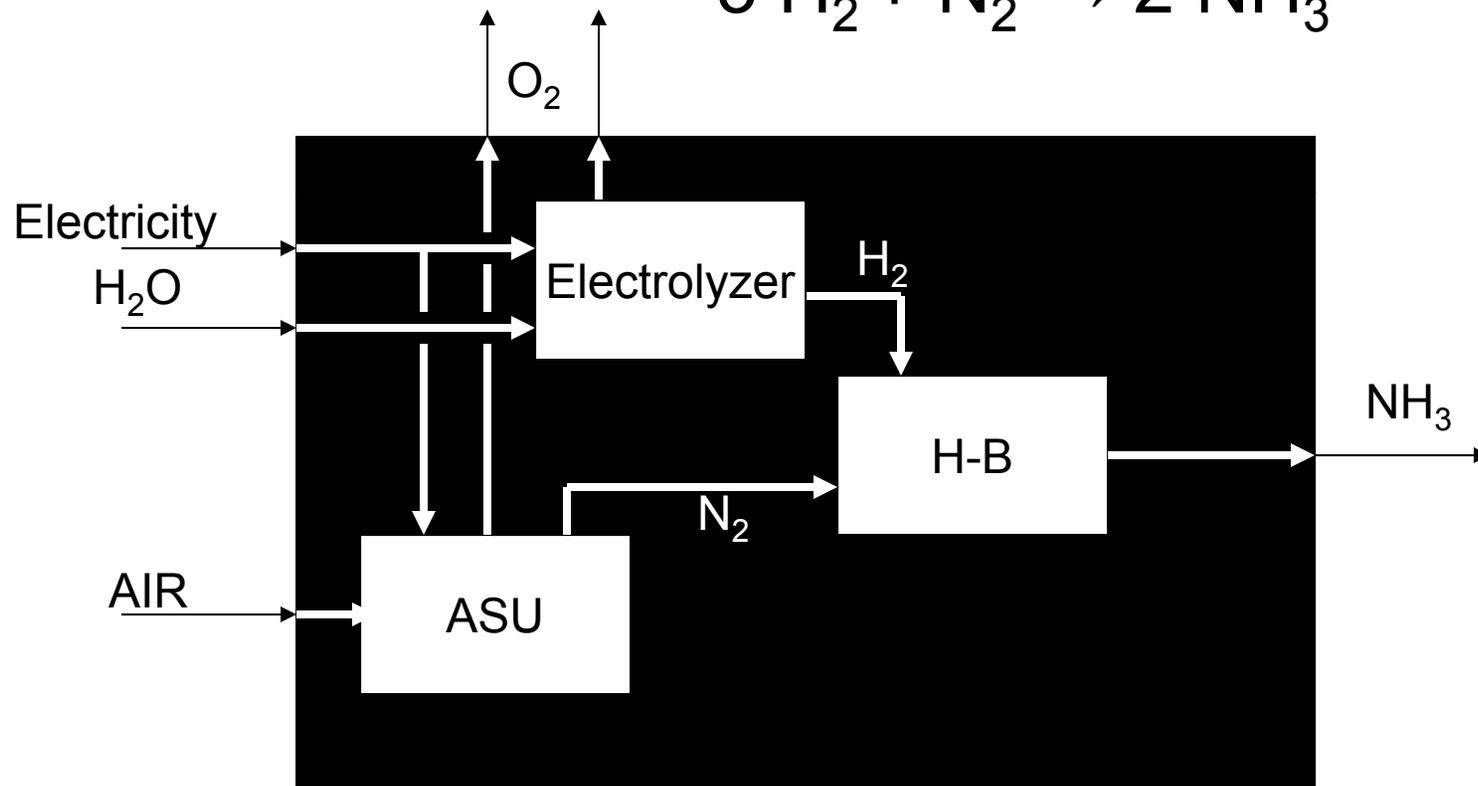
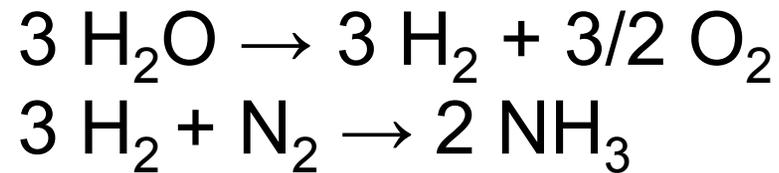


A photograph of a large industrial facility containing several massive electrolyzers. The electrolyzers are large, cylindrical units with a complex internal structure, mounted on a metal frame. In the background, there are several large white storage tanks and a network of pipes. Two workers in white hard hats and dark clothing are standing on a platform in the foreground, looking at a set of plans. The overall environment is clean and well-lit.

**Norsk Hydro  
Electrolyzers  
2 MW each**

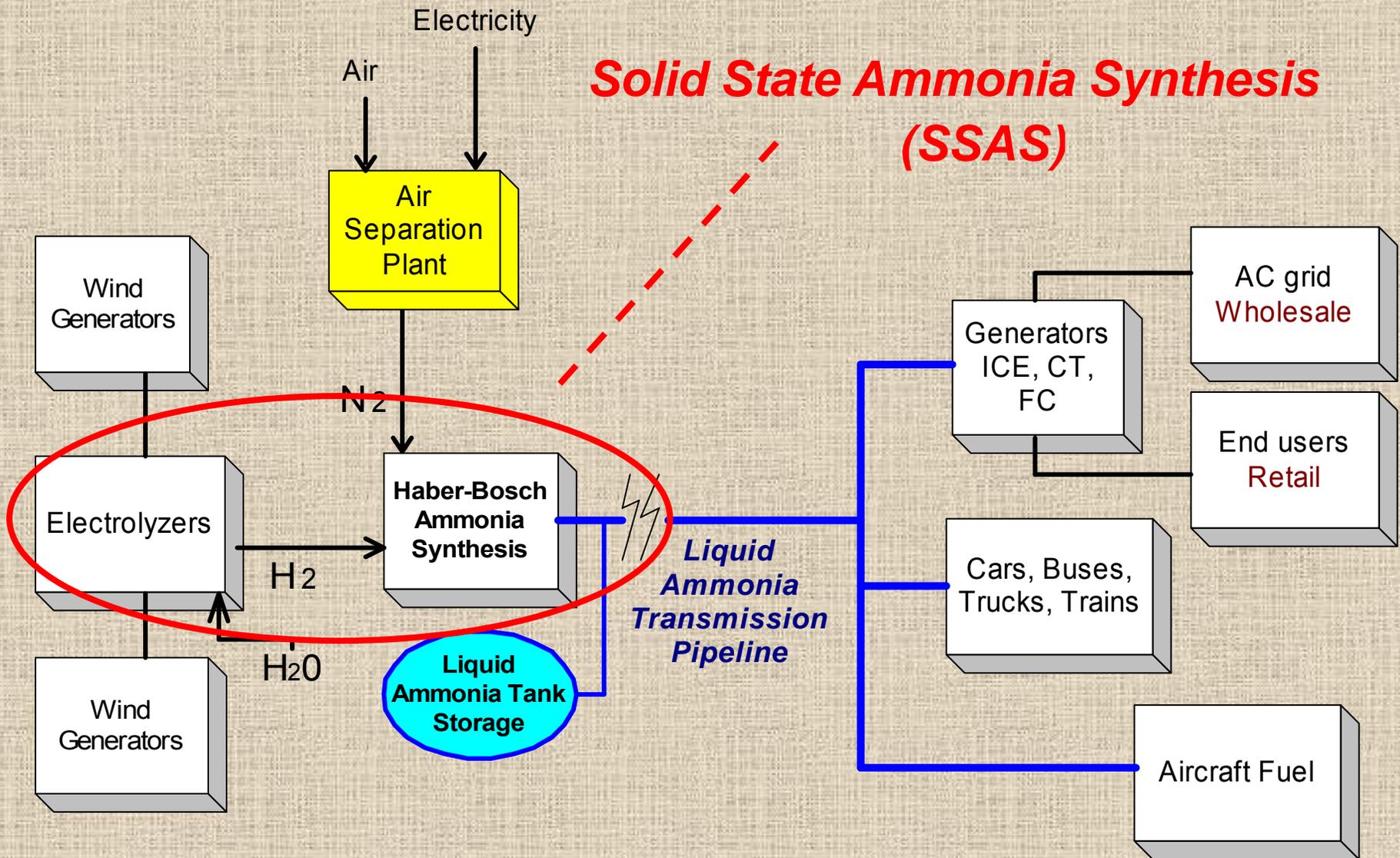
**Ammonia from  
hydrogen  
from zero-cost  
off-peak hydro**

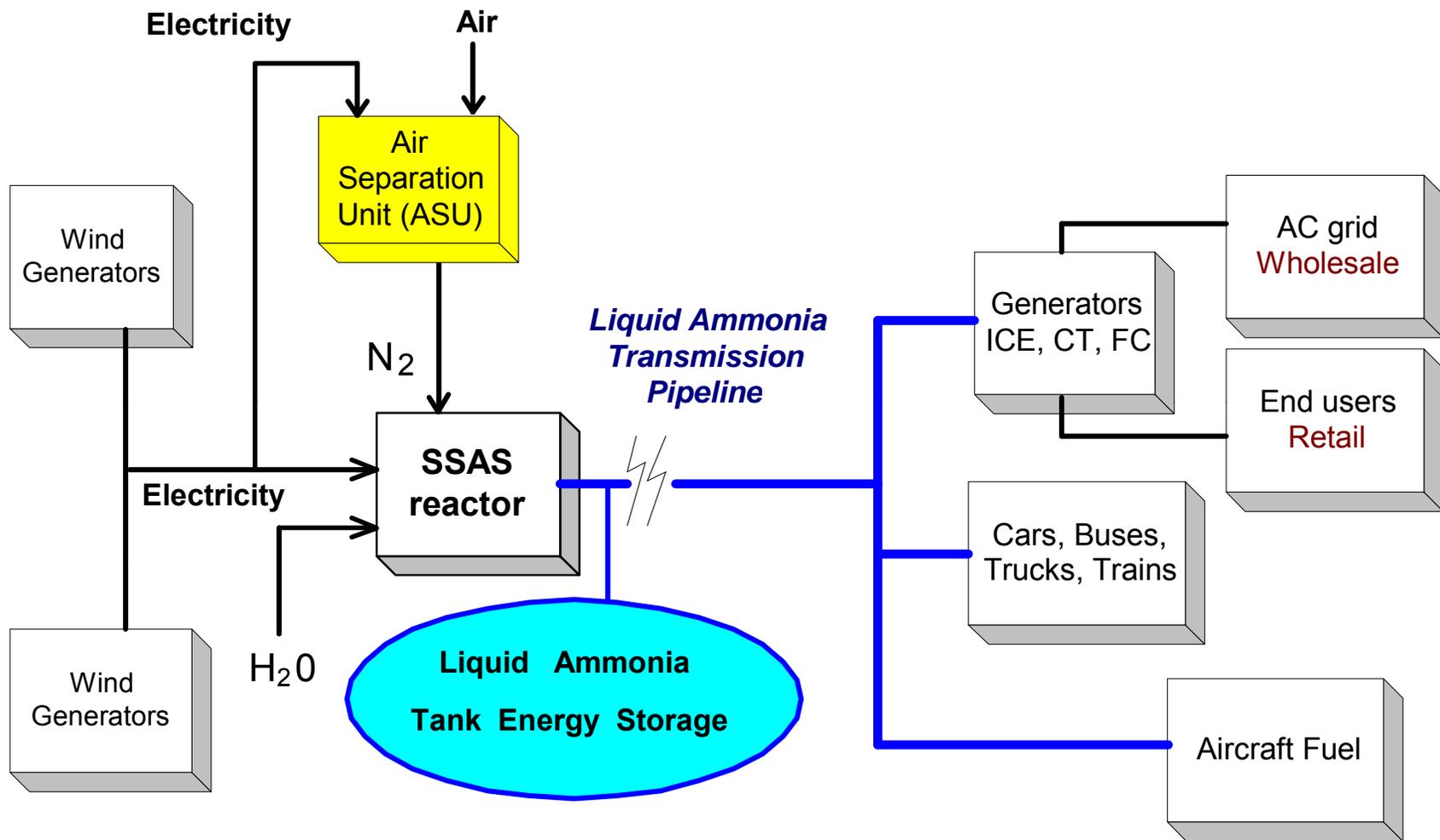
# Inside the Black Box: HB Plus Electrolysis



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

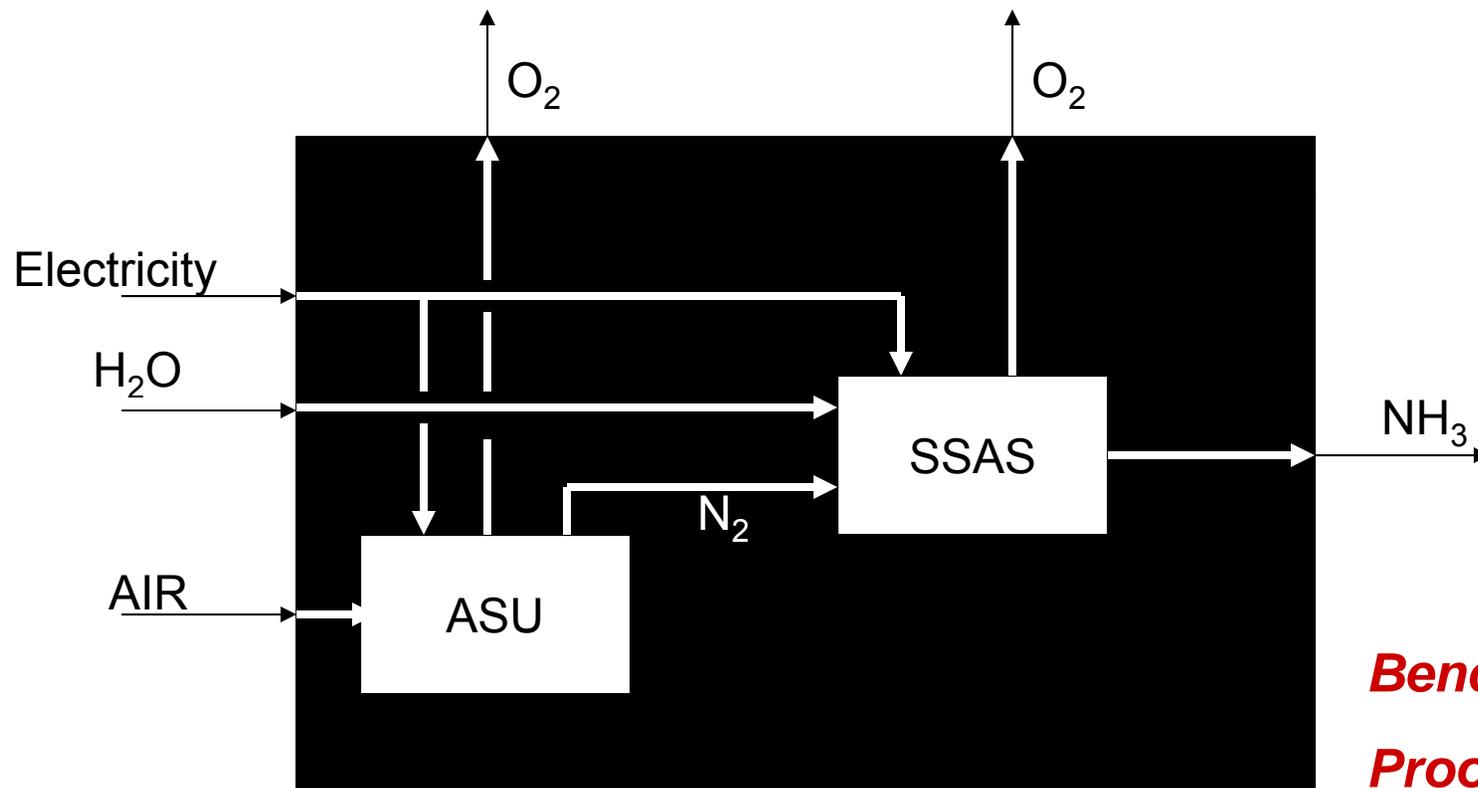
# RE Ammonia Transmission + Storage Scenario





# Solid State Ammonia Synthesis (SSAS)

# Inside the Black Box: Solid State Ammonia Synthesis

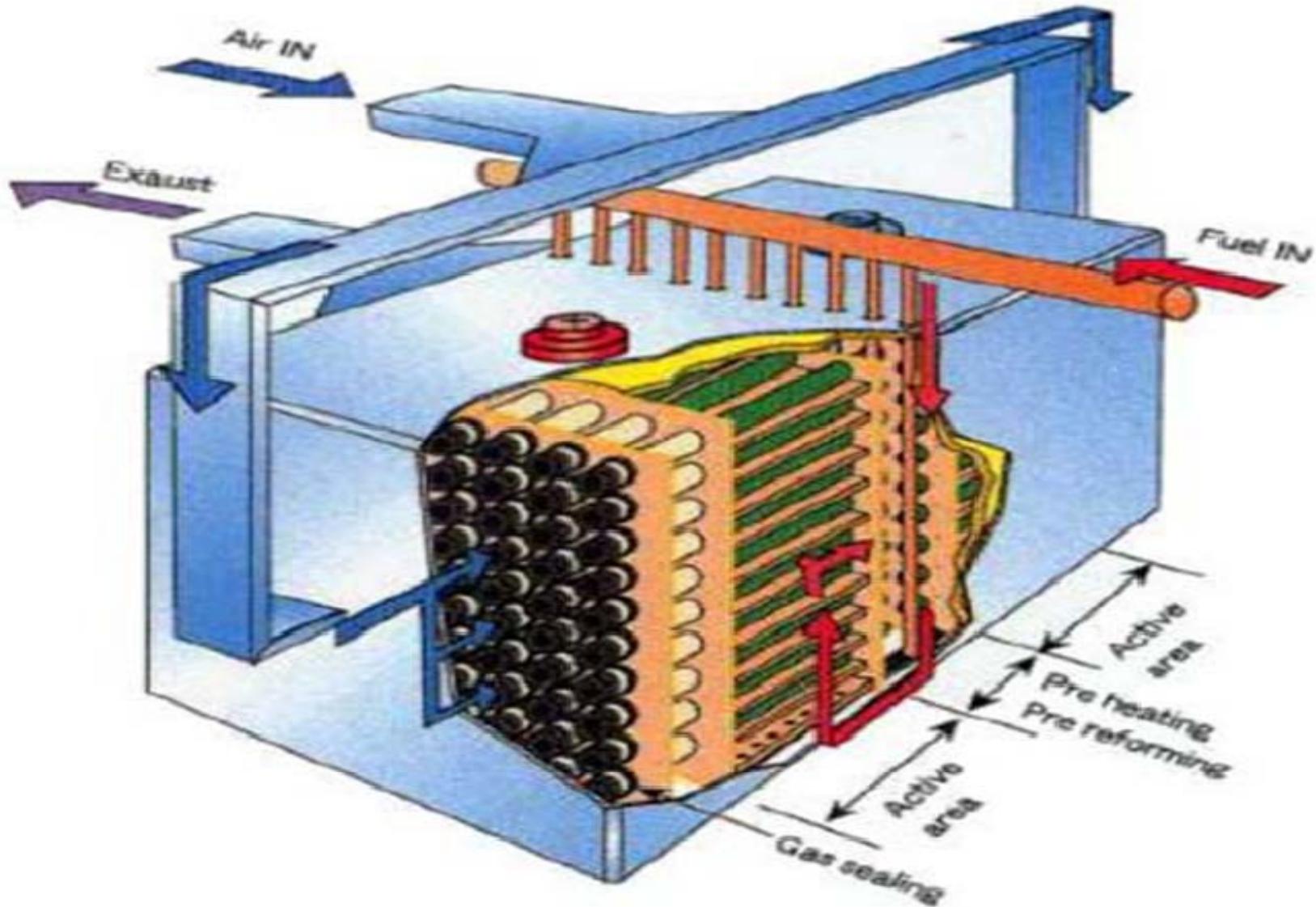


*Benchtop*  
*Proof-of-concept*

Energy consumption 7,000 – 8,000 kWh per ton NH<sub>3</sub>

# Solid State Ammonia Synthesis (SSAS)

## NHThree LLC patent

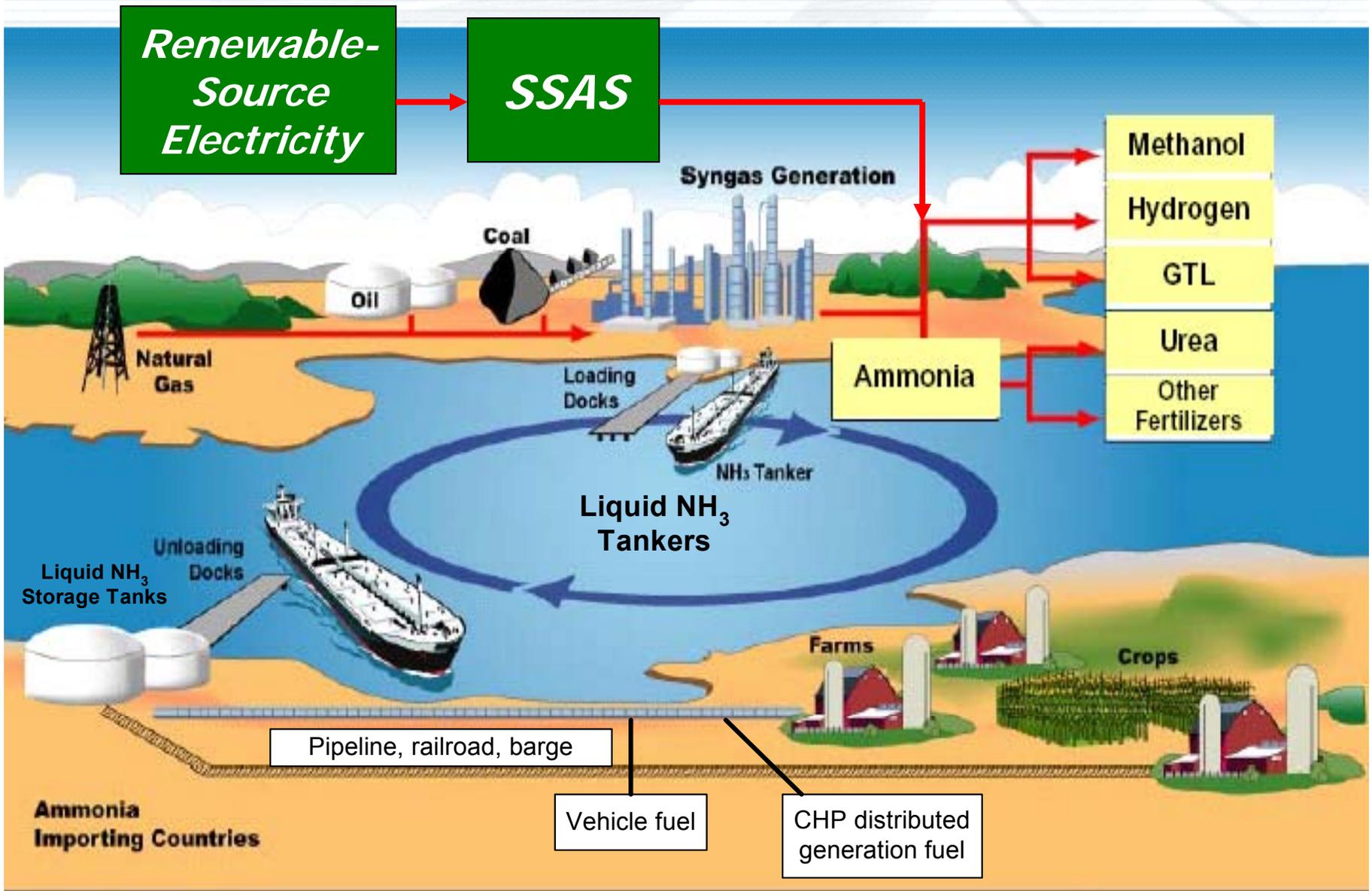


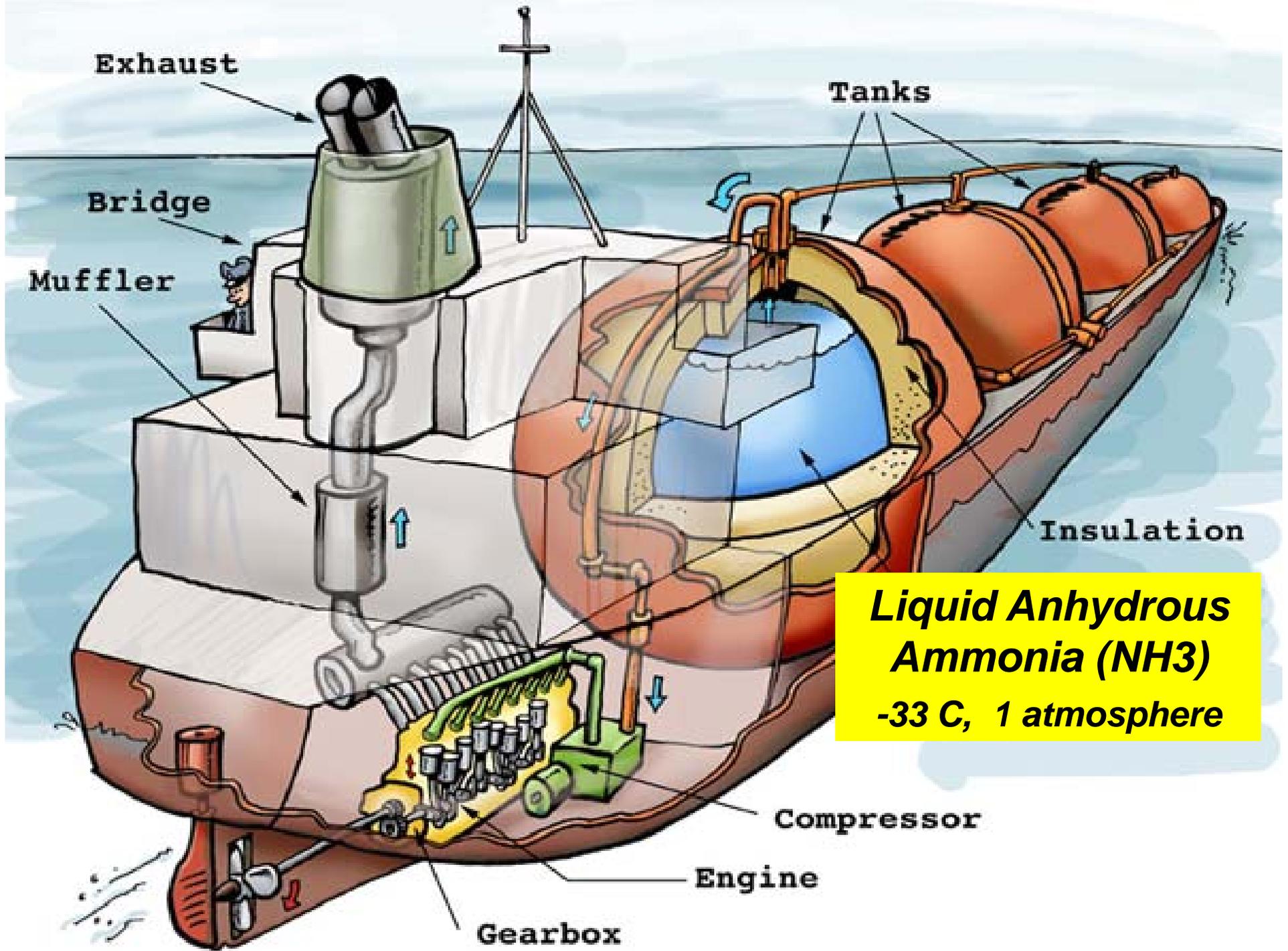
# *Wind – to – Ammonia Potential, NW Iowa*



***320,000 MWh storage***  
***Annual firming 1,000 MW wind***

- **Electricity**
  - **VRB (Vanadium Redox Battery)**
    - **O&M: 80% efficiency round-trip**
    - **Capital: \$500 / kWh = \$ 160 Billion**
  - **CAES (Compressed Air Energy Storage)**
    - **O&M: \$46 / MWh typical**
    - **Iowa Stored Energy Park:**
      - **Power = 268 MW**
      - **Energy capacity = 5,360 MWh**
      - **Capital: 268 MW @ \$ 1,450 / kW = \$ 390 M**
        - @ \$ 40 / kWh = \$ 13 Billion**
        - @ \$1 / kWh = \$ 325M**
- **GH2 (3 hydrogen caverns)                      Capital                      \$70 Million**
- **NH3 (2 ammonia tanks)                      Capital                      \$30 Million**





***Humanity's Goal:***  
***“Run World on Renewables”***

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

- **CANNOT with only  
electricity transmission**

# ***“Transmission”***

- **Beyond “Smart Grid”, GW scale**
- **Electrofuels**
- **Renewable-source electricity**
- **Underground pipelines**
- **Carbon-free fuels: hydrogen, ammonia**
- **Low-cost storage:**
  - \$ 0.10 – 0.20 / kWh capital**
- **CHP, transport, industrial**

# ***Beyond “Smart Grid”***

- **Primarily DSM**
- **More vulnerable to cyberattack ?**
- **Adds no physical:**
  - **Transmission, gathering, distribution**
  - **Storage**
- **Next big thing; panacea**
- **Running the world on renewables ?**
- **Must think:**
  - **Beyond electricity**
  - **Complete energy systems**

# MUST Run the World on Renewables – plus Nuclear ?

- Rapid climate change
- Ocean acidification
- Sea level rise
- Species extinctions



**Sunlight from  
local star**

**Electricity**

**O<sub>2</sub>**

**Electricity**

**H<sub>2</sub>**

**Work**

**Electrolyzer**

**Fuel Cell**

PEM Electrolyzer  
 $2\text{H}_2\text{O} + \text{Energy} \rightarrow 2\text{H}_2 + \text{O}_2$

Item: 2010  
Solar Hydrogen System JuniorBasic  
www.h-tec.com

PEM Fuel Cell  
 $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O} + \text{Energy}$



# **Solar Hydrogen Energy System**



**Renewable Energy Bulk Storage for less  
than \$1.00 / kWh Capital Cost  
as Gaseous Hydrogen (GH<sub>2</sub>) and Liquid  
Anhydrous Ammonia (NH<sub>3</sub>)  
Carbon-free Fuels, with Transmission via  
Underground Pipelines**

**Handouts + DVD's**

*22<sup>nd</sup> World Energy Congress*

*14 October 2013                      Daegu, Korea*

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The Leighty Foundation  
Juneau, AK*

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