Beyond Smart Grid: Alternatives for Transmission and Low-cost Firming Storage of Stranded Renewables as Hydrogen and Ammonia Fuels via Underground Pipelines

World Hydrogen Energy Conference
WHEC 2012, Toronto
3 - 8 June 12

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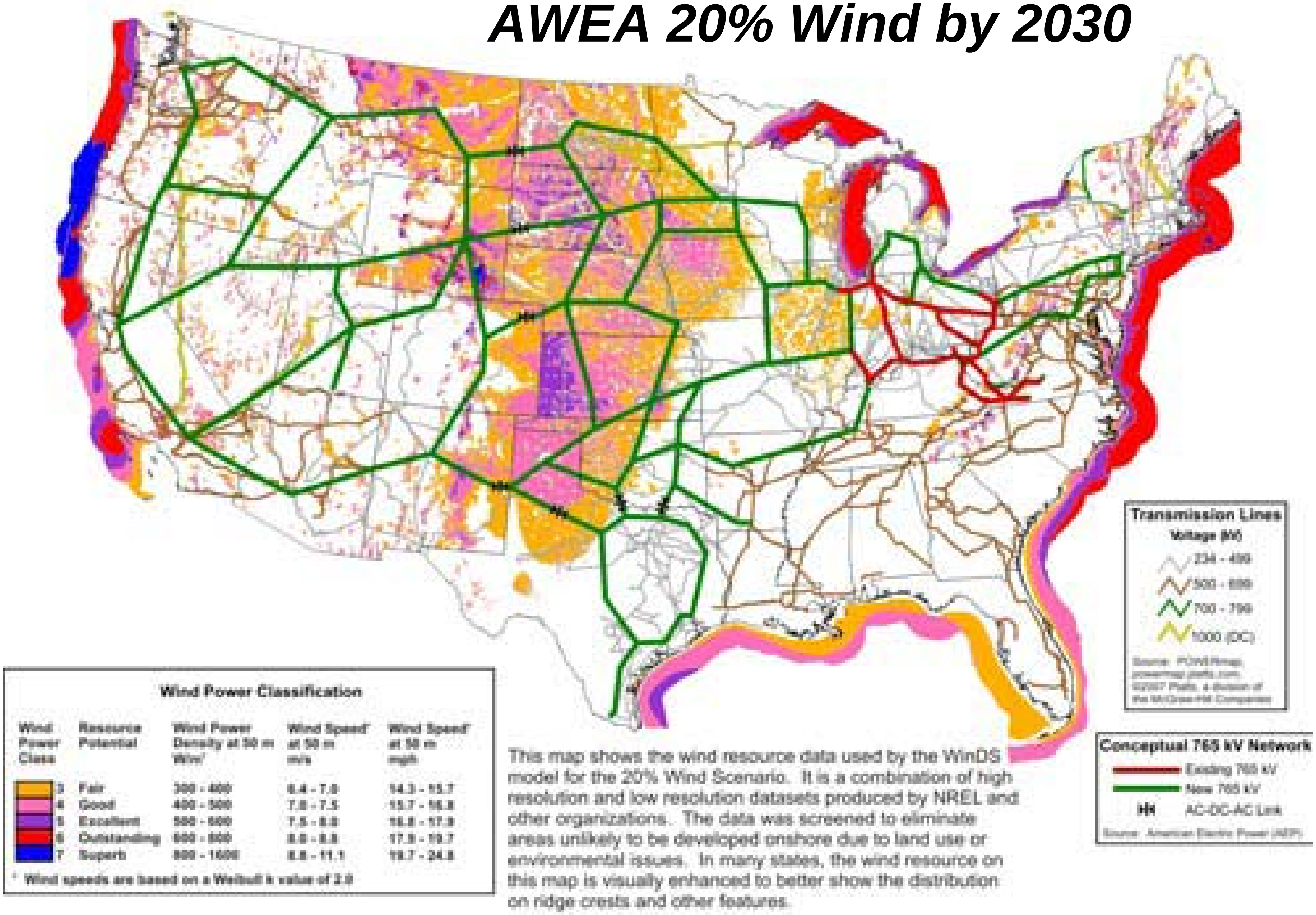
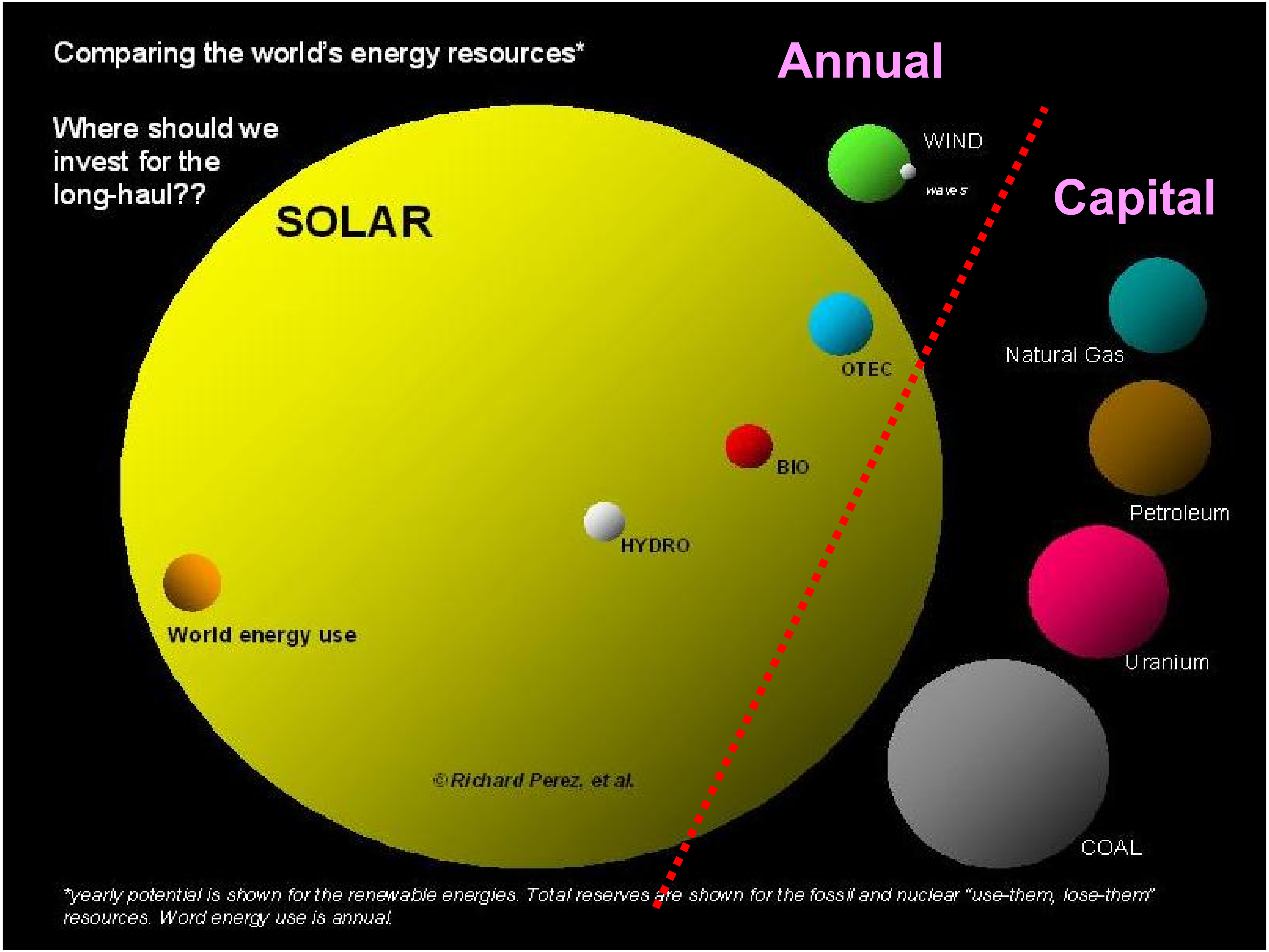
907-586-1426   206-719-5554 cell

AWEA 20% Wind by 2030



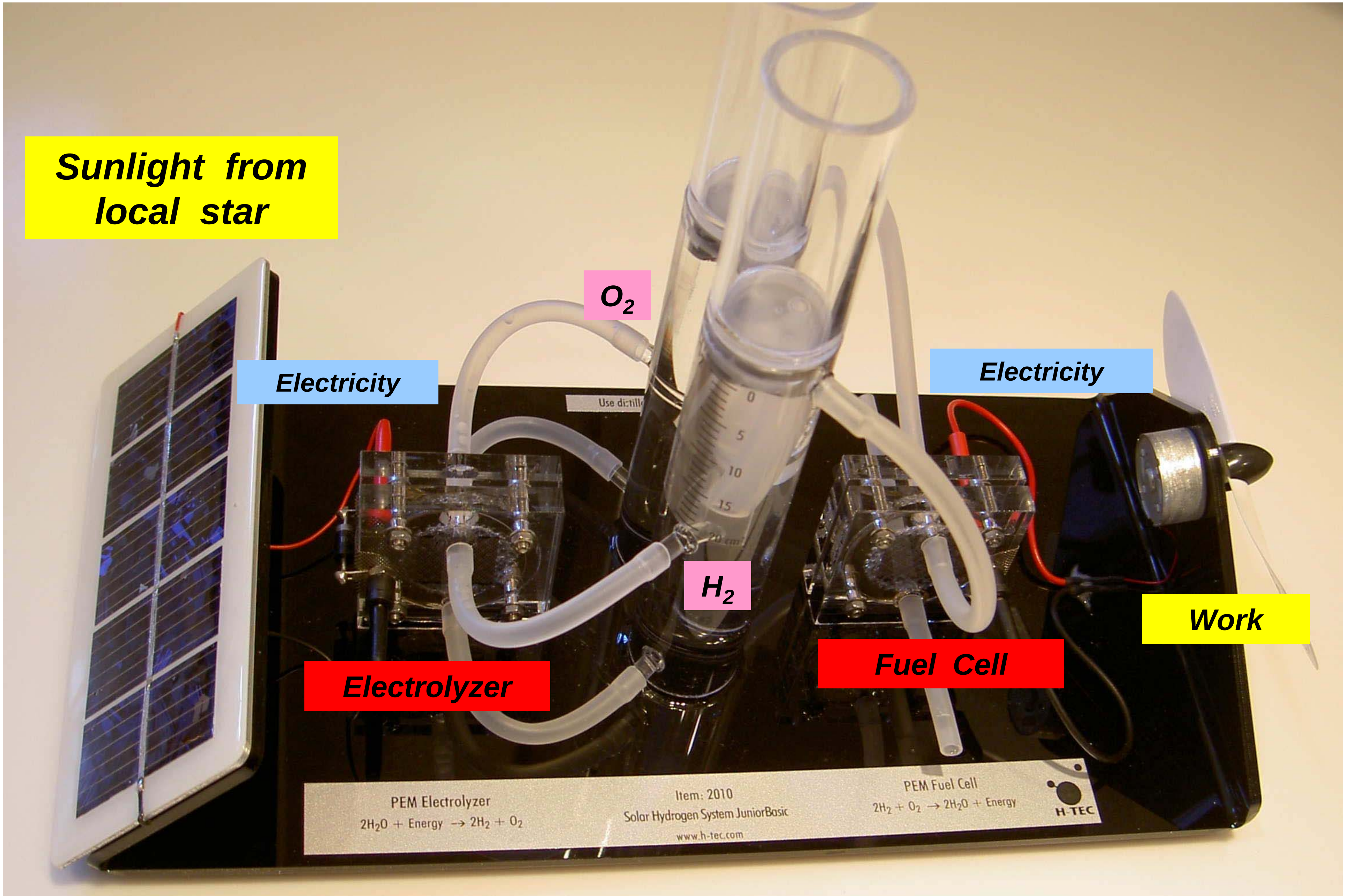
MUST Run the World on Renewables – plus Nuclear ?

- Climate Change
- Demand growth
- Water for energy
- War
- Depletion of Oil and Gas
- Only 200 years of Coal left
- Only Source of Income:
    - Sunshine
    - Tides
    - Meteor dust
- Spend our capital ?


Comparing the world's energy resources*
Annual
Where should we invest for the long-haul??
SOLAR
WIND
waves
Capital
Natural Gas
OTEC
BIO
Petroleum
HYDRO
World energy use
Uranium
© Richard Perez, et al.
COAL
*yearly potential is shown for the renewable energies. Total reserves are shown for the fossil and nuclear "use-them, lose-them" resources. Word energy use is annual.

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



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

Hydrogen and Ammonia Fuels

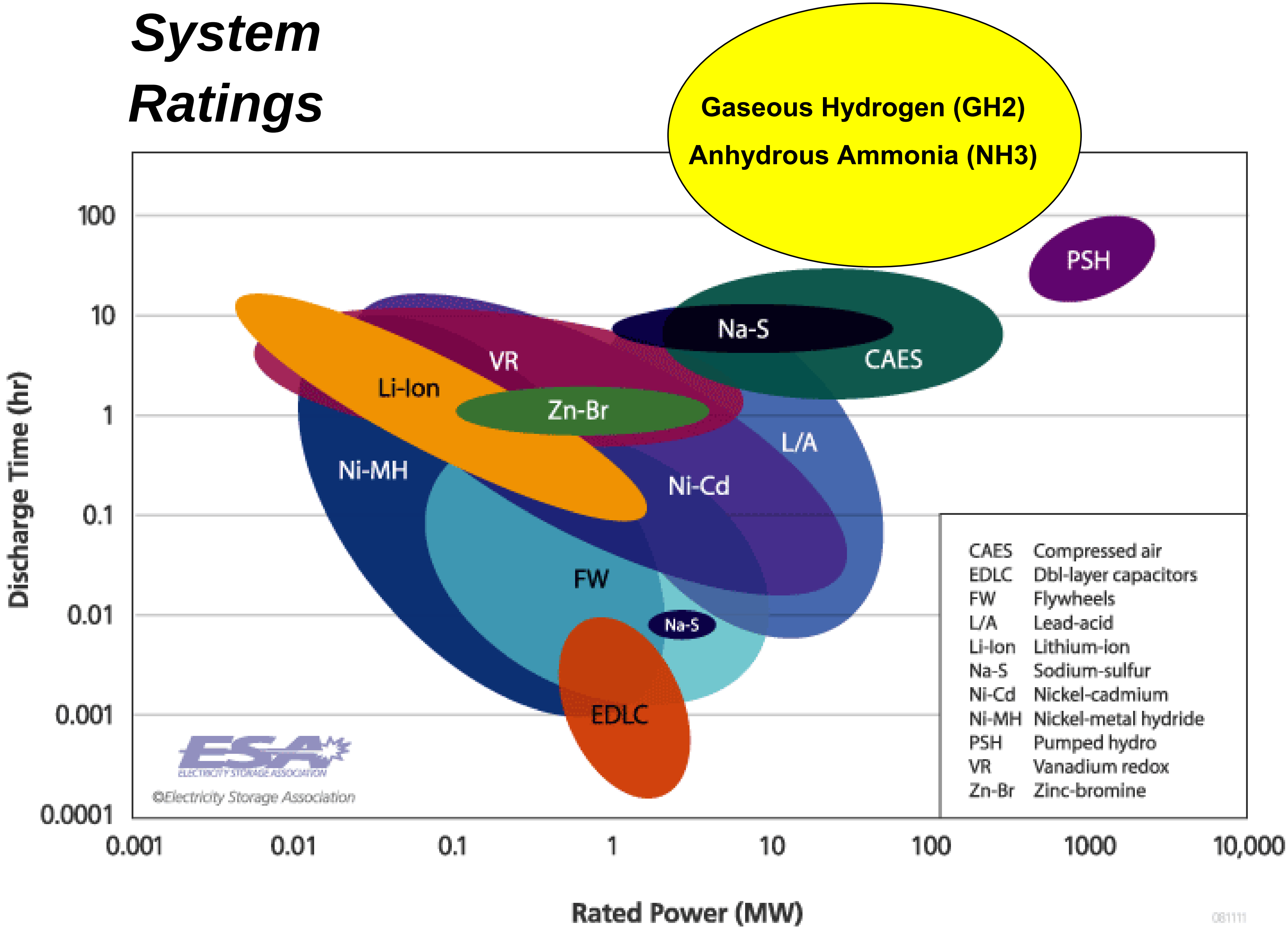
- Delivering fuels: distribution
- ICE, CT, Fuel cell
- CHP on-site: 90% fuel energy recover
- Utility substation wholesale
- Transportation
  - Rail
  - Truck
  - Personal
- Emissions: H_2O, N_2

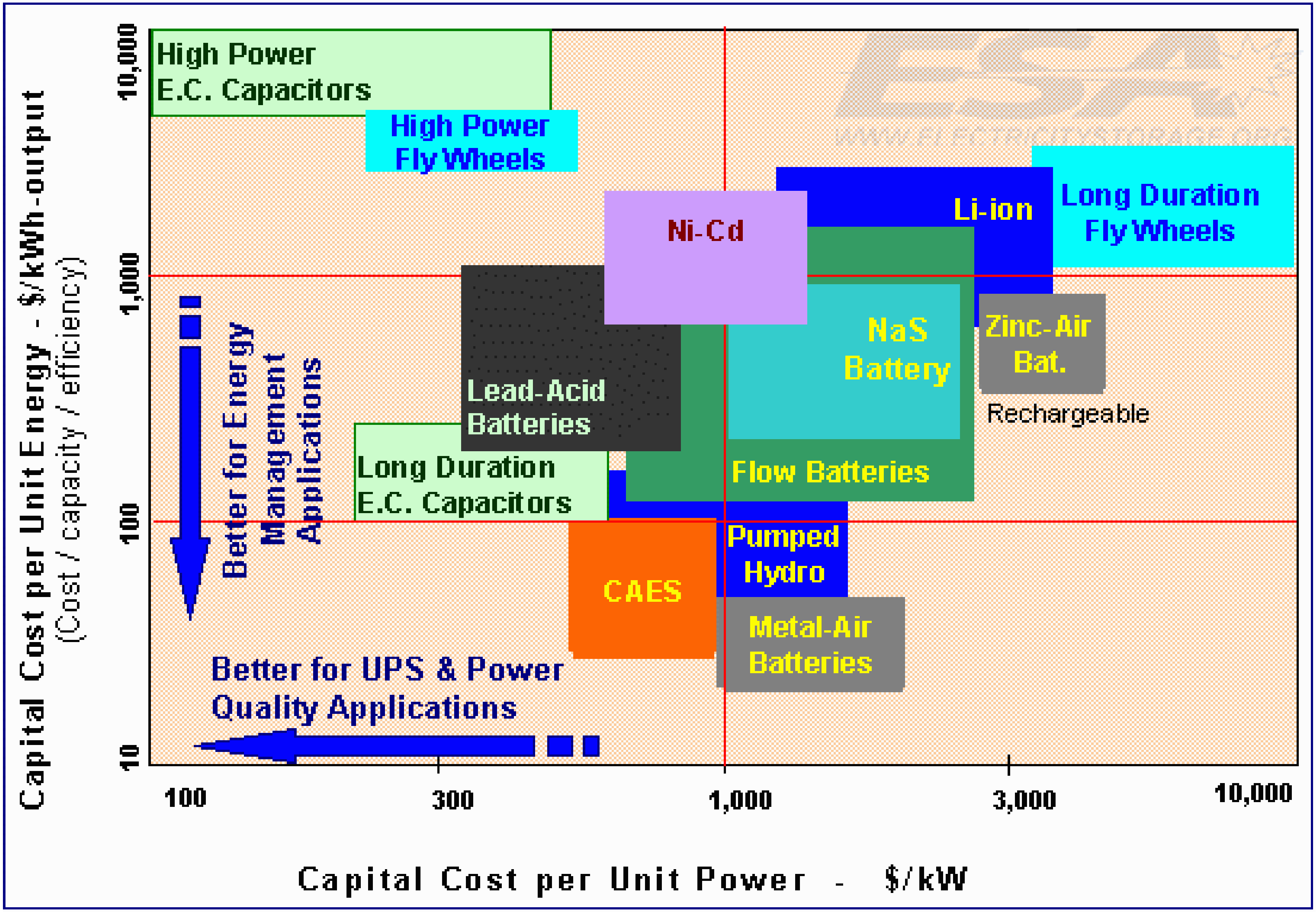
Annual Fresh Water for Energy

- ***USA today***
- ***All energy***

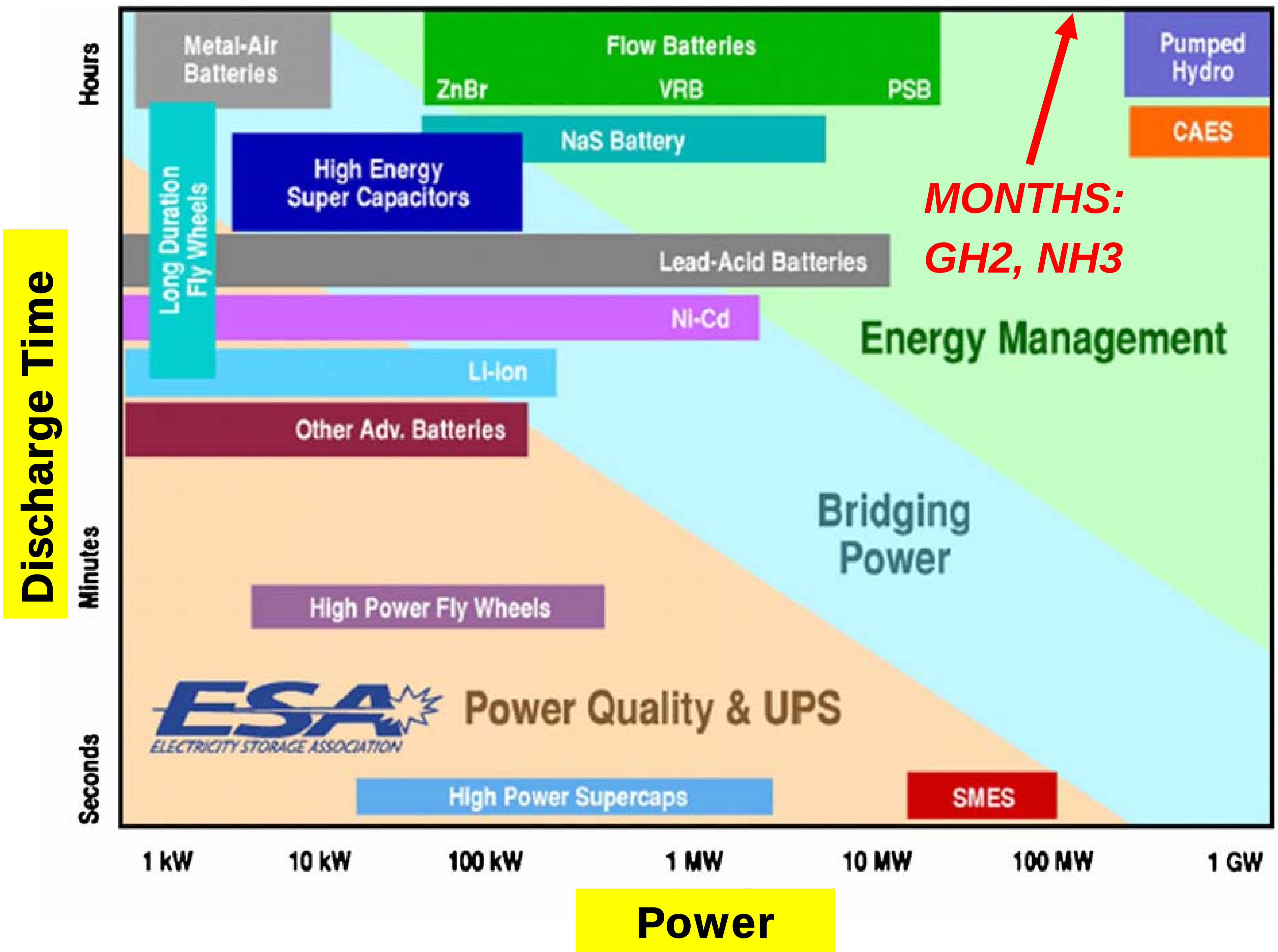
- **17,000 billion liters**
  - **"Withdrawn"**
  - **"Consumed"**
  - **Include all NG "fracking" ?**
- **If all via GH2 + NH3 feedstock:**
  - **Dissociated, disintegrated: $H_2O \rightarrow H_2 + O_2$**
  - **900 billion liters**

System Ratings




High Power
E.C. Capacitors
High Power
Fly Wheels
Ni-Cd
Li-ion
Long Duration
Fly Wheels
NaS
Battery
Zinc-Air
Bat.
Rechargeable
Lead-Acid
Batteries
Long Duration
E.C. Capacitors
Flow Batteries
Pumped
Hydro
CAES
Metal-Air
Batteries
Better for Energy
Management
Applications
Better for UPS & Power
Quality Applications
Capital Cost per Unit Energy - $/kWh-output
(Cost / capacity / efficiency)
10,000
1,000
100
10
100
300
1,000
3,000
10,000
Capital Cost per Unit Power - $/kW

GH2 and NH3


Discharge Time
Hours
Minutes
Seconds
Metal-Air Batteries
Flow Batteries
ZnBr
VRB
PSB
Pumped Hydro
CAES
NaS Battery
High Energy Super Capacitors
Long Duration Fly Wheels
MONTHS: GH2, NH3
Lead-Acid Batteries
Ni-Cd
Energy Management
Li-ion
Other Adv. Batteries
Bridging Power
High Power Fly Wheels
ESA
ELECTRICITY STORAGE ASSOCIATION
Power Quality & UPS
High Power Supercaps
SMES
1 kW
10 kW
100 kW
1 MW
10 MW
100 MW
1 GW
Power

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

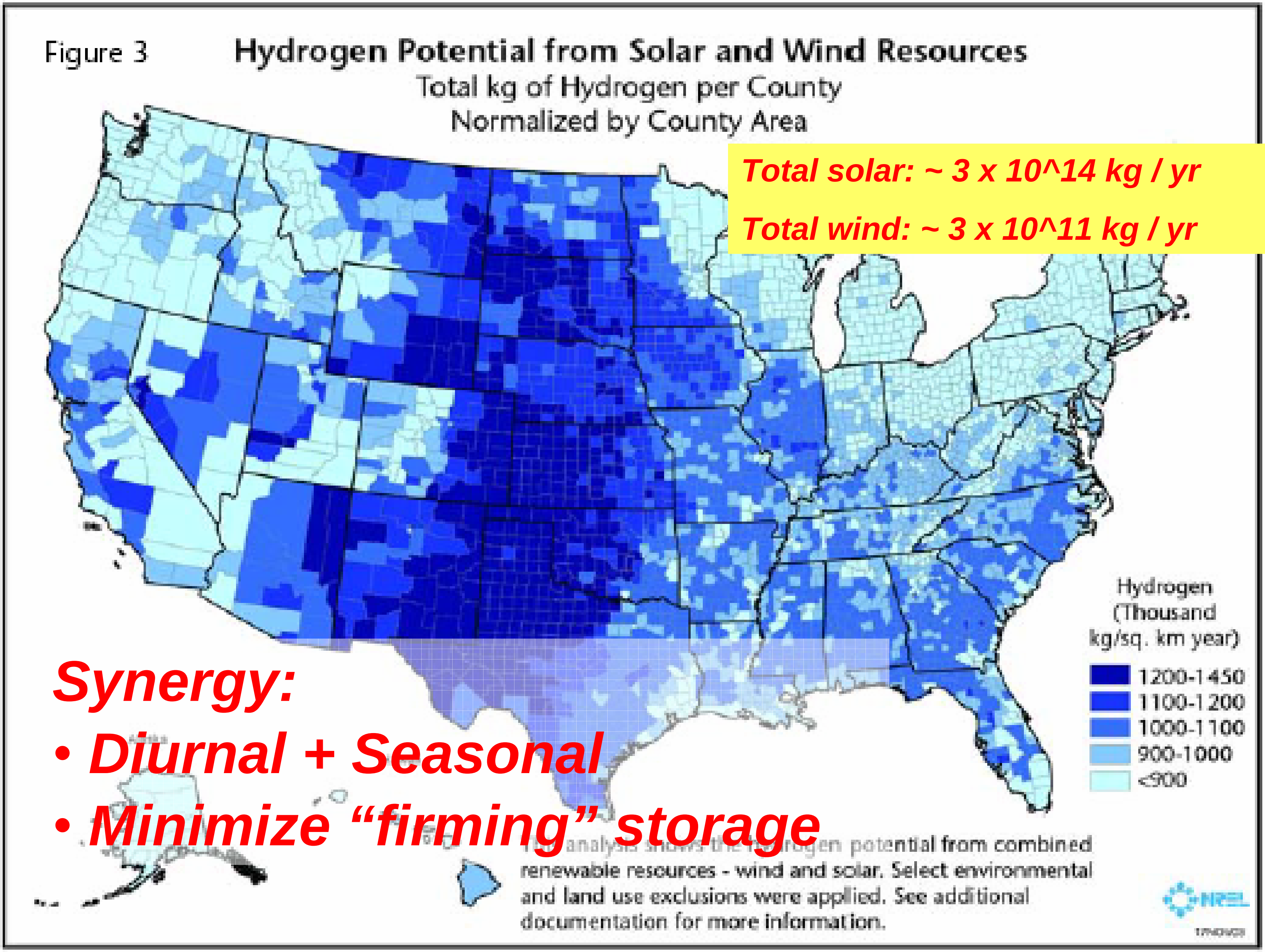
Capacity at 500 miles length **Capacity Factor (CF) = 30%**

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	
TOTALS	33,711	9,376,694	9,377	1,563	$1,500	3,126	$2,000

Wind energy source: Archer, Jacobson 2003

Total solar: ~ 3 x 10^14 kg / yr

Total wind: ~ 3 x 10^11 kg / yr



Synergy:

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

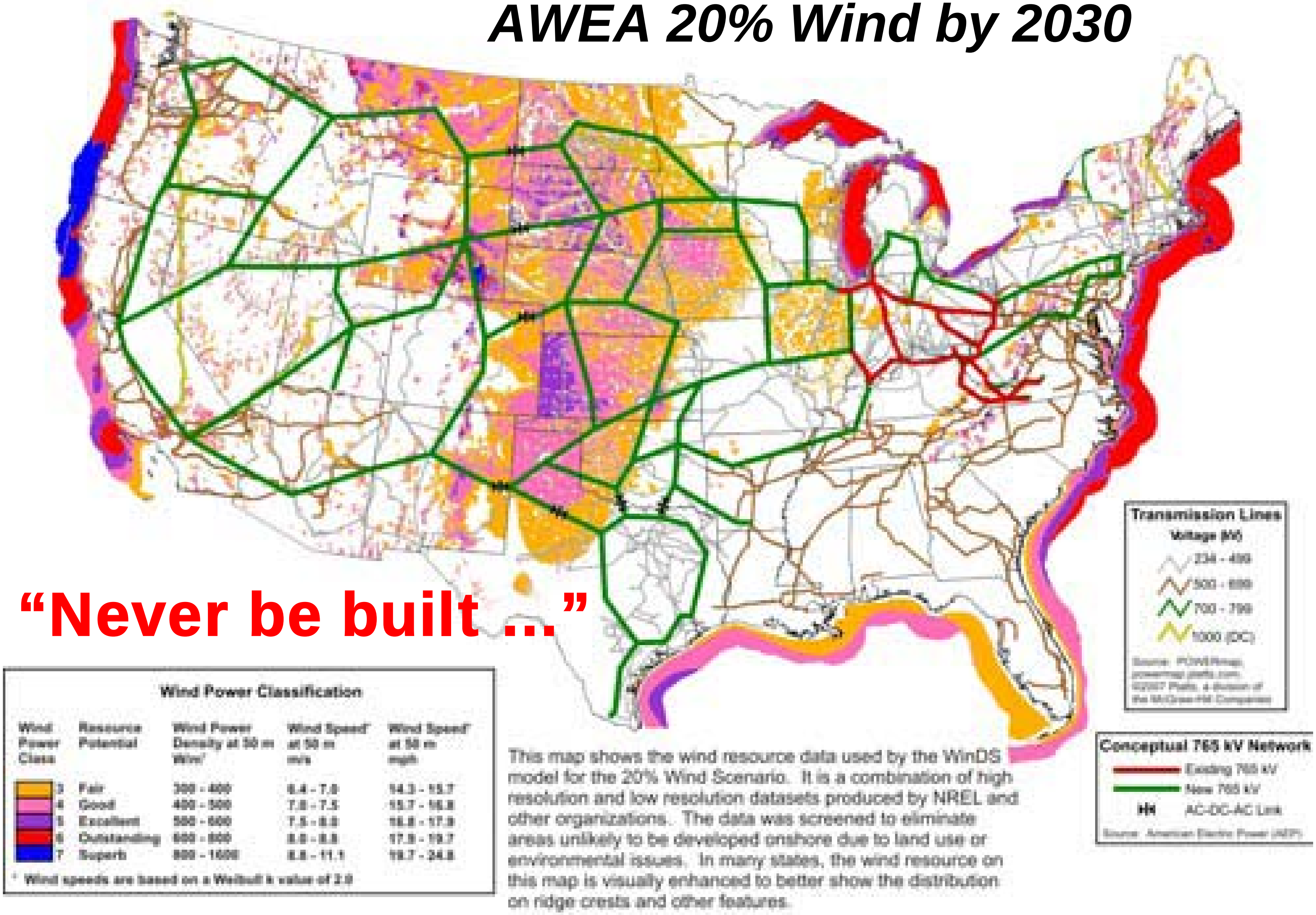
Major Electricity Transmission Studies

• EWITS-NREL	225 - 330	GW
• WWSIS-NREL	30	GW
• Brattle Group	24	GW
• SEIA-AWEA	300	GW
• JCSP	745	GW
• AEP-AWEA	350	GW
• Frontier + Transwest	115	GW
• ICFI Wyoming	12	GW
Total	**~ 1,500**	**GW**

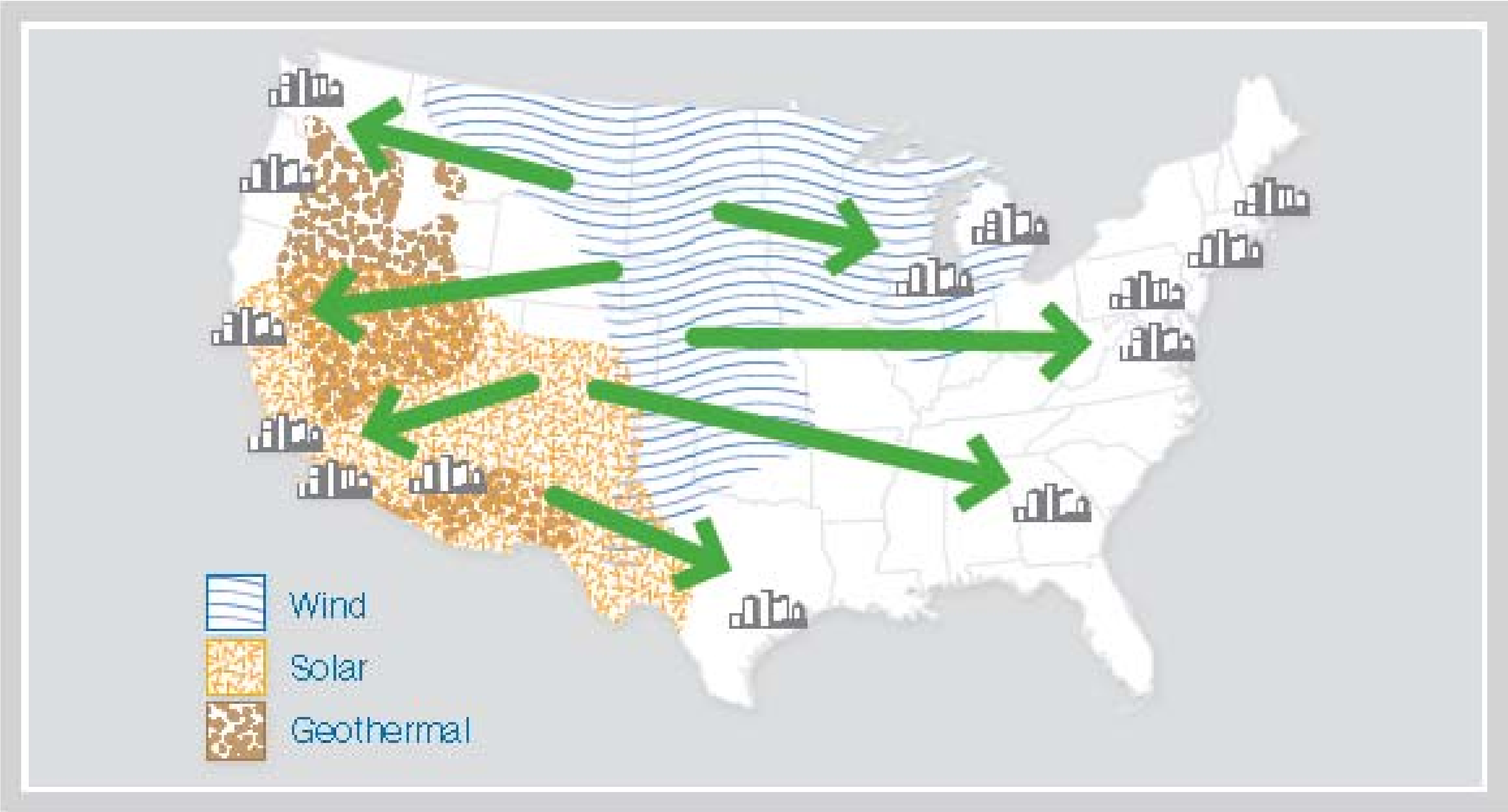
Great Plains Potential: 10,000 GW wind, nameplate
3,000,000 GW solar, nameplate

Total USA energy @ 33% CF: ~ 3,460 GW
@ 5 GW / 765 kv AC line: ~ 700 new lines

AWEA 20% Wind by 2030



"Never be built ..."

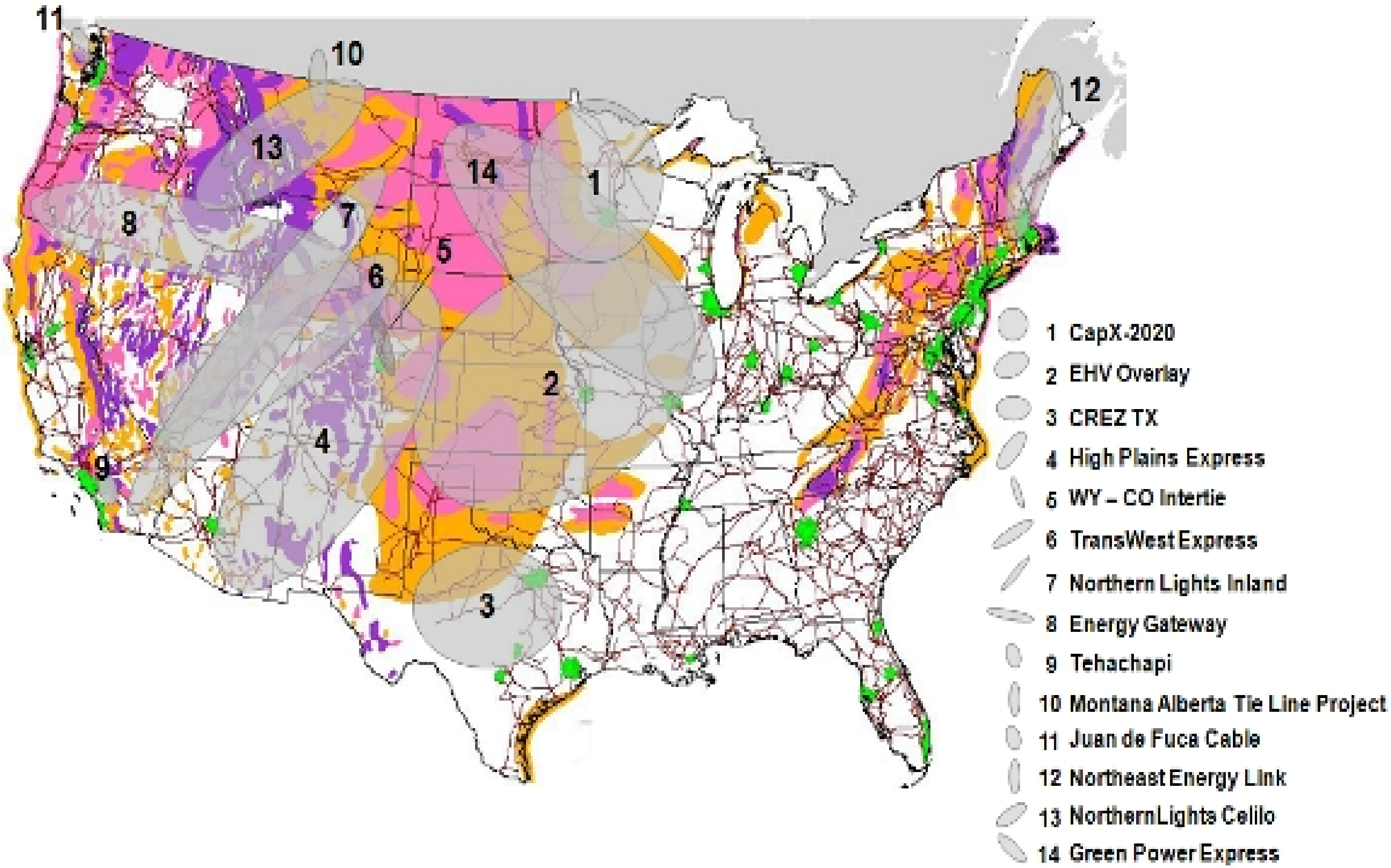


Source: AWEA and SEIA

SEIA – AWEA Feb 09

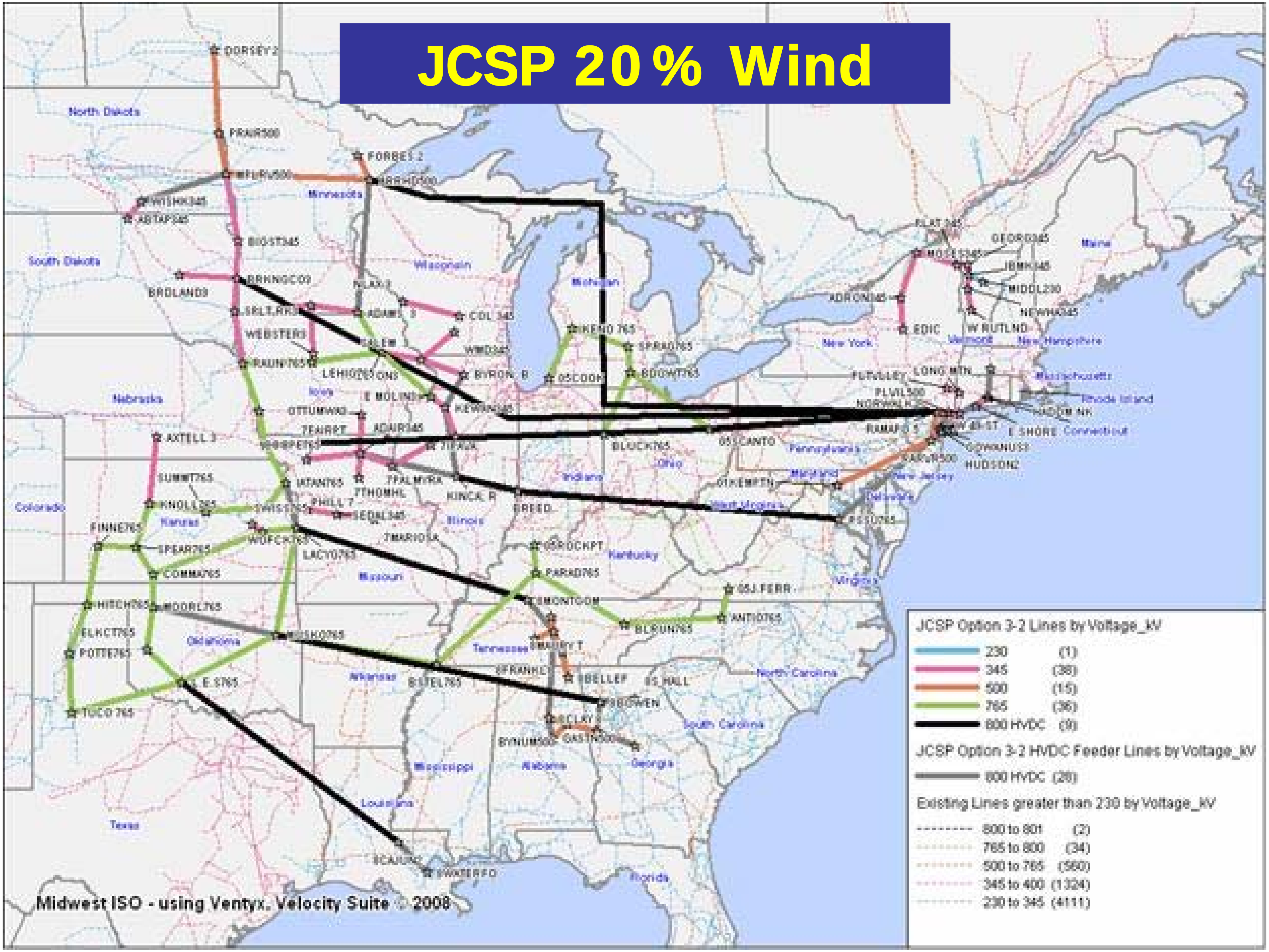
“Green Power Superhighways:

Building a Path to America’s Clean Energy Future”



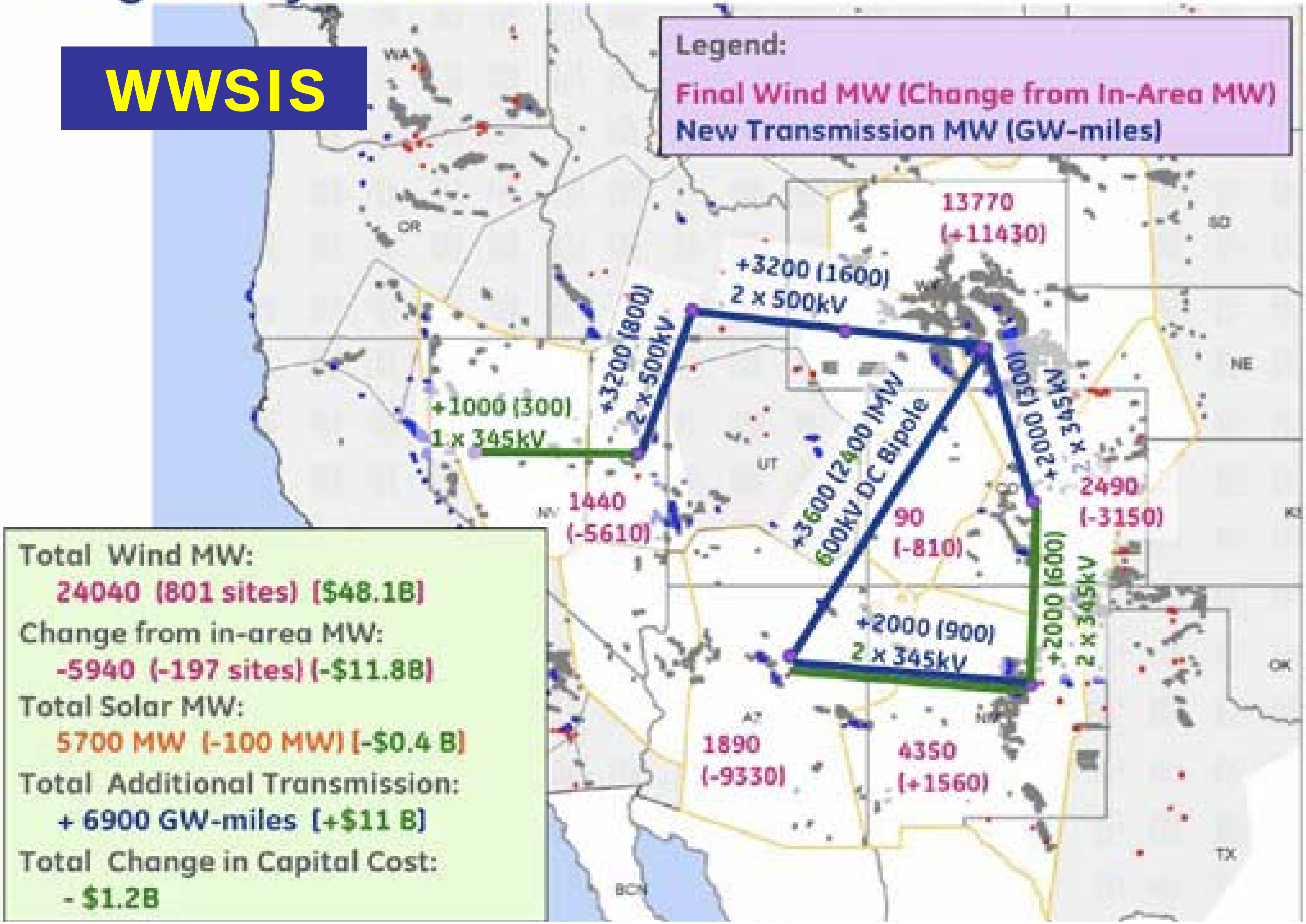
Emerging Energy Research LLC

JCSP 20 % Wind

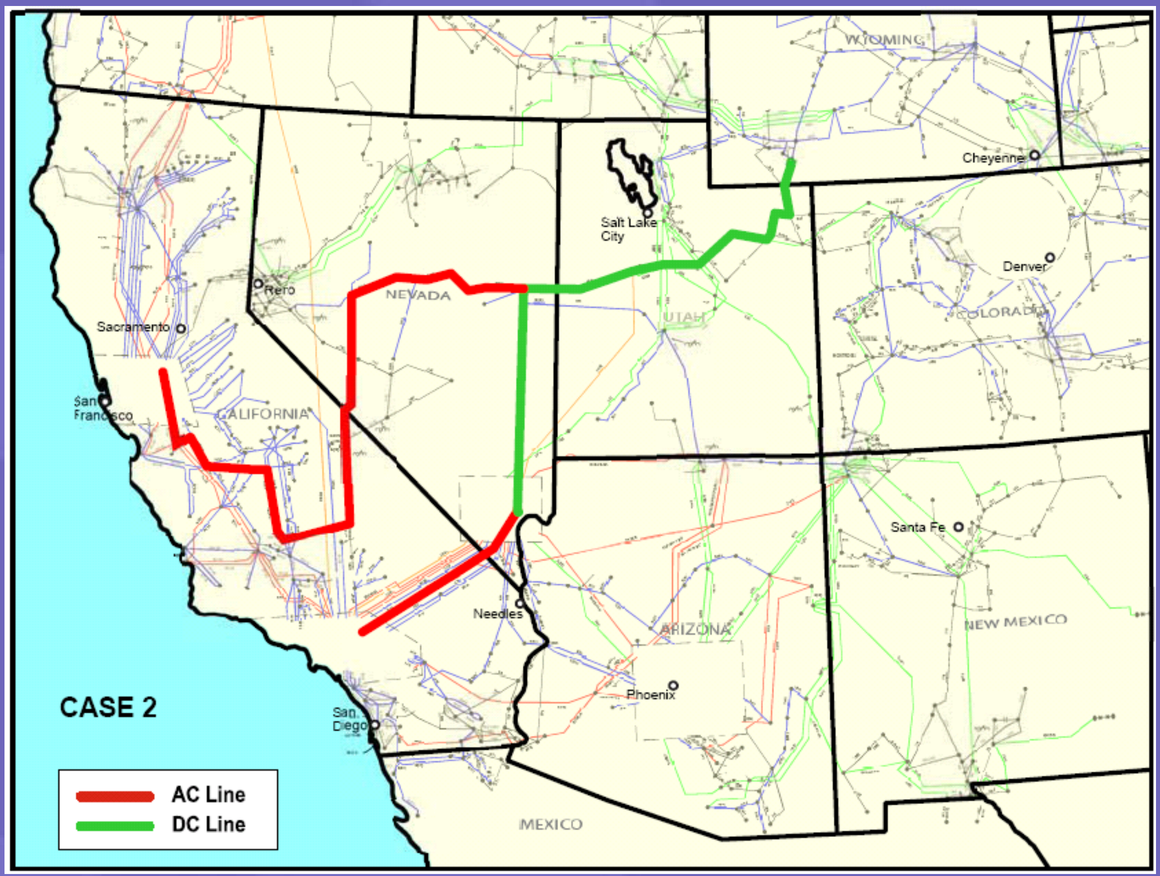


JCSP Option 3-2 Lines by Voltage_kV
230 (1)
345 (38)
500 (15)
765 (36)
800 HVDC (9)
JCSP Option 3-2 HVDC Feeder Lines by Voltage_kV
800 HVDC (28)
Existing Lines greater than 230 by Voltage_kV
800 to 801 (2)
765 to 800 (34)
500 to 765 (560)
345 to 400 (1324)
230 to 345 (4111)
North Dakota
South Dakota
Minnesota
Wisconsin
Michigan
Iowa
Nebraska
Colorado
Kansas
Illinois
Indiana
Ohio
Missouri
Kentucky
Oklahoma
Arkansas
Tennessee
Texas
Mississippi
Alabama
Georgia
Louisiana
Florida
North Carolina
South Carolina
Virginia
West Virginia
Pennsylvania
New York
New Jersey
Maryland
Delaware
Vermont
New Hampshire
Maine
Massachusetts
Rhode Island
Connecticut
Midwest ISO - using Ventyx, Velocity Suite © 2008

Mega Project Scenario



Frontier Line

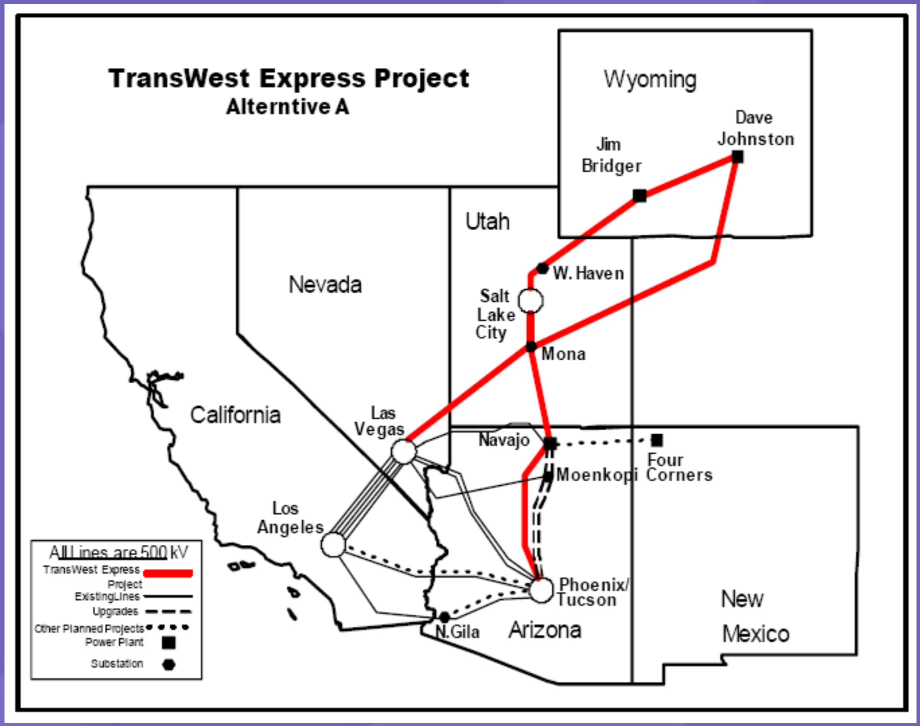


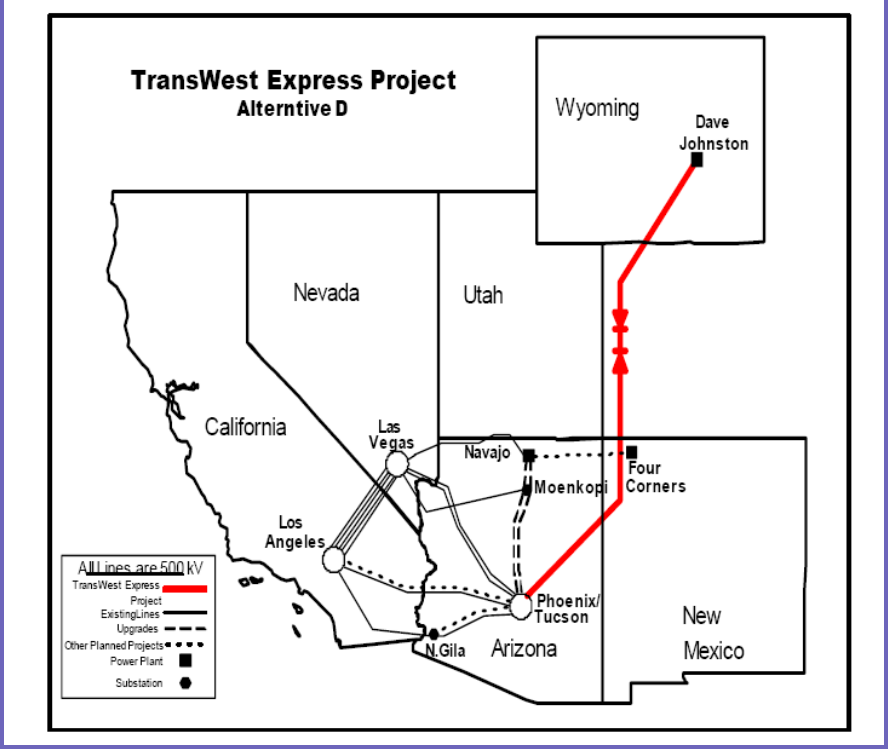
Example pathway by California Energy Commission, *Wyoming-California Corridor Transmission Expansion Study*, Global Energy Decisions, June 2006, CEC-700-2006-008.

- Proposed transmission corridor to interconnect Wyoming, Utah, Nevada, California and possibly other states
- MOU signed on April 4, 2005

TransWest Express

Several alternatives proposed, including:





Statement of Robert Smith on behalf of Arizona Public Service Company and the TransWest Express Project before the House Subcommittee on Water and Power and the House Subcommittee on Forests and Forest Health, June 27, 2006.

NOTE: Approximate relationship based on Surge Impedance Loading (i.e. reactive power balance point) 345 kV single circuit tower lines with two conductors per phase compared to 765 kV single circuit lines with six conductors per phase.

Transmission Voltage (kV)	Cost per Mile ($/mile)	Capacity (MW)	Cost per Unit of Capacity ($/MW-mile)
230	$2.077 million	500	$5,460
345	$2.539 million	967	$2,850
500	$4.328 million	2040	$1,450
765	$6.578 million	5000	$1,320

(Sources: Edison Foundation[12], AEP[13])

SEIA – AWEA Feb 09

“Green Power Superhighways:
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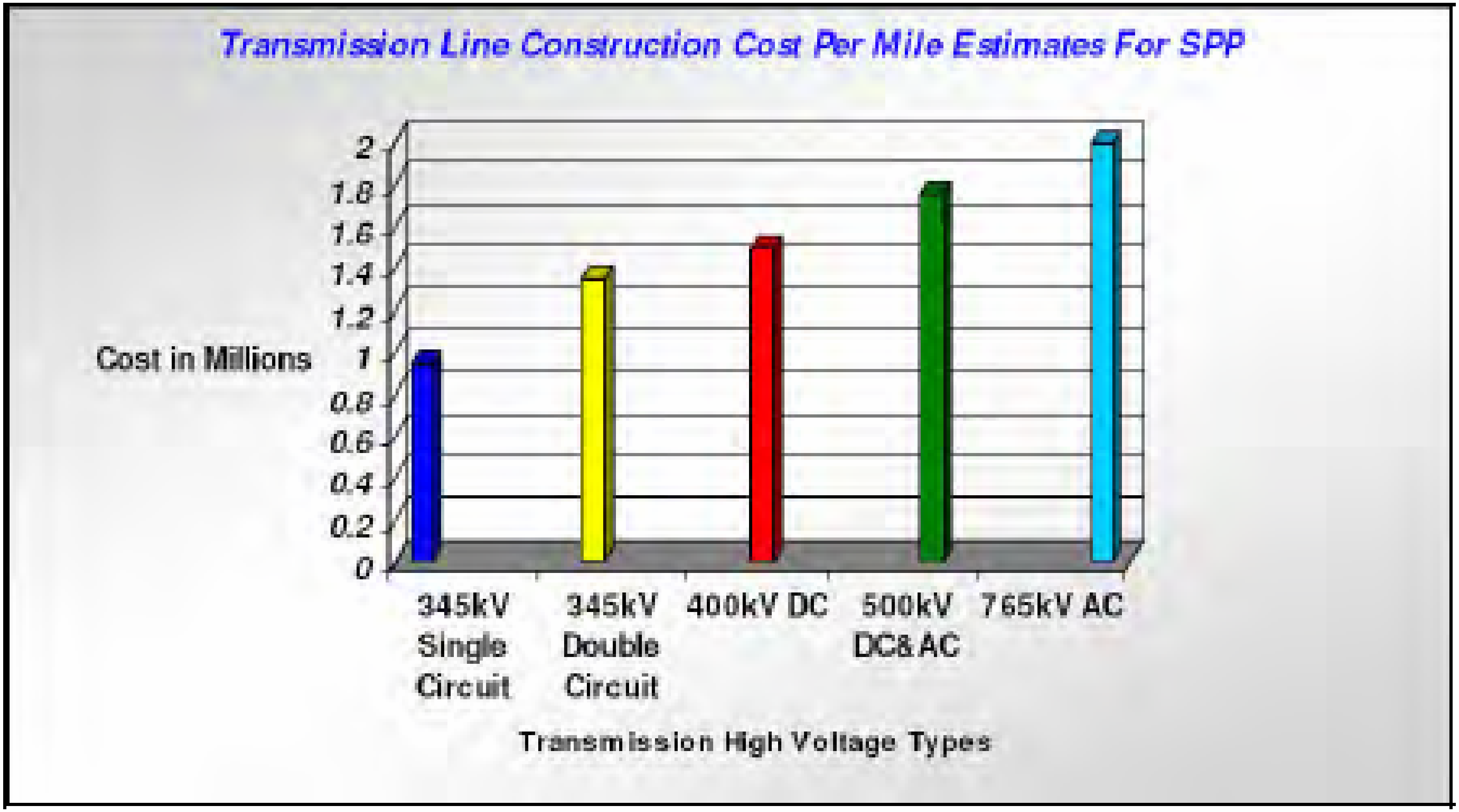


Transmission Line Construction Cost

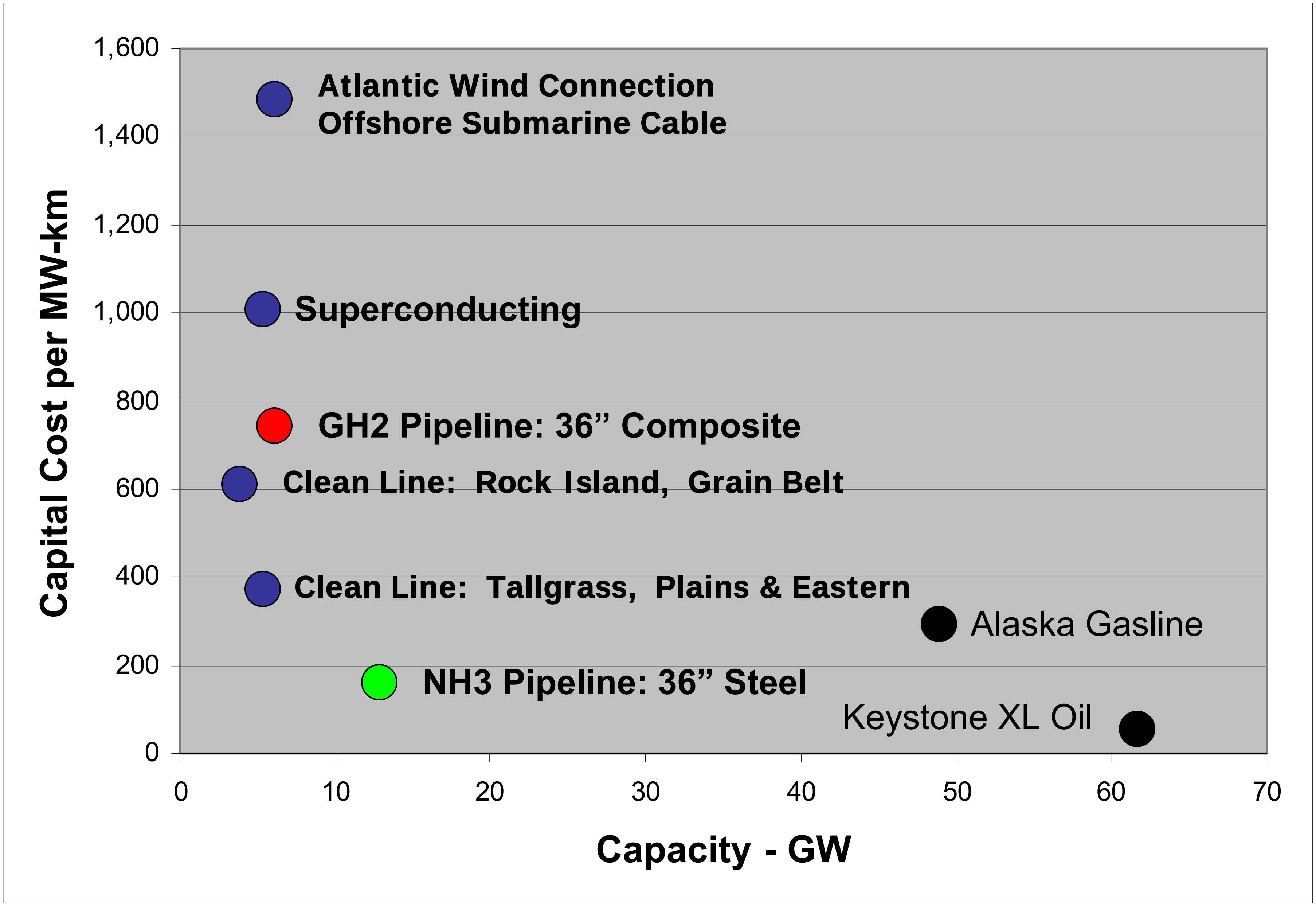
$ million per Mile

Southwest Power Pool '07

Electricity Capital Cost per GW-mile

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


Atlantic
Wind Connection
The Atlantic Wind Connection transmission backbone would connect 6,000 MW of wind turbine capacity, built on the broad, windy spaces of the mid-Atlantic continental shelf, to population centers and transmission nodes on land.



Atlantic Wind Connection
Offshore Submarine Cable
Superconducting
GH2 Pipeline: 36" Composite
Clean Line: Rock Island, Grain Belt
Clean Line: Tallgrass, Plains & Eastern
Alaska Gasline
NH3 Pipeline: 36" Steel
Keystone XL Oil
Capital Cost per MW-km
Capacity - GW
0
200
400
600
800
1,000
1,200
1,400
1,600
0
10
20
30
40
50
60
70

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

but only after they have tried everything else ”

Winston Churchill

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

“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

GW-scale Transmission + Storage Options

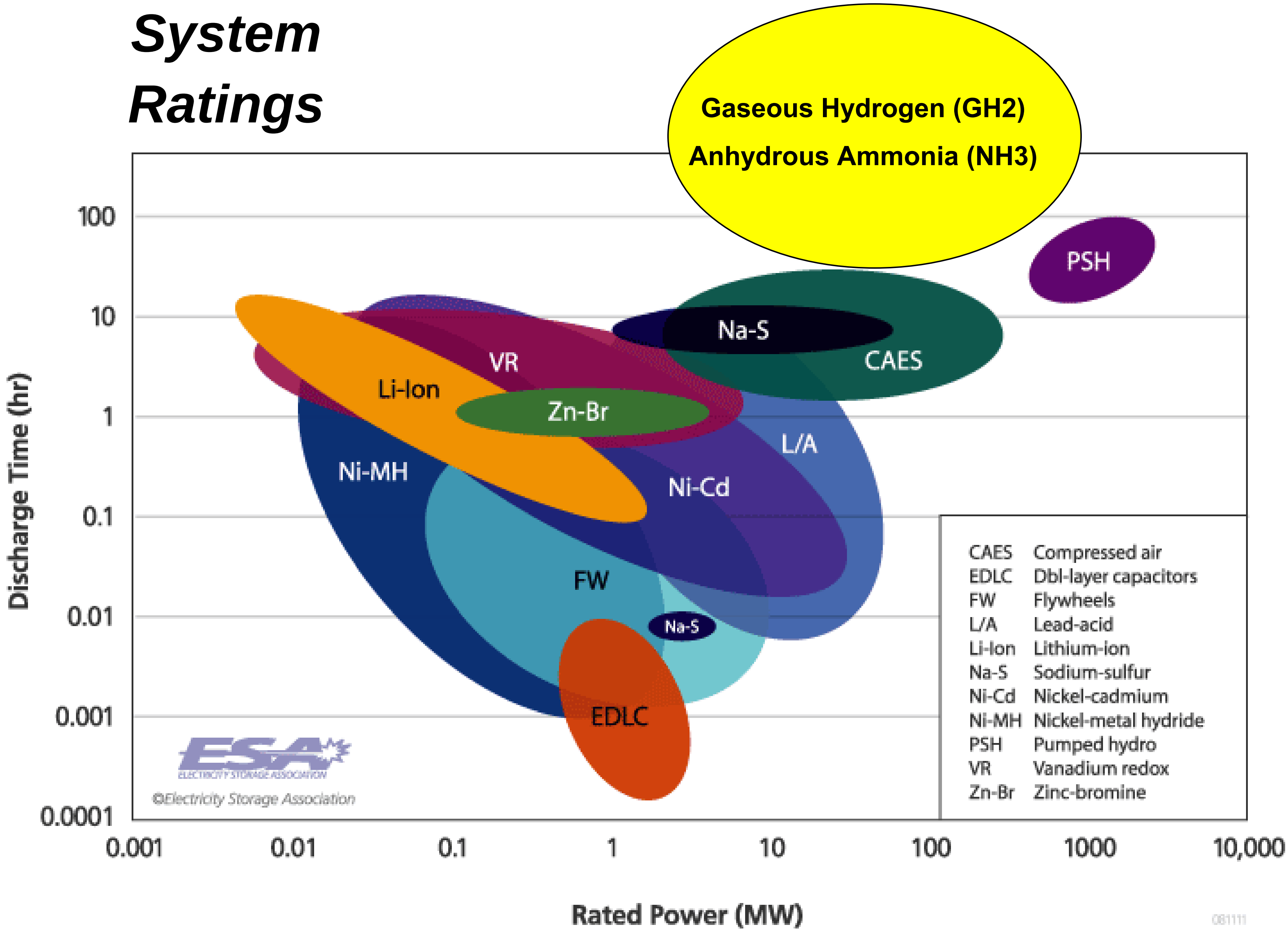
- **Electricity: HVAC, HVDC**
  - **CAES compressed air energy storage**
  - **Vanadium Redox battery (VRB Power Systems)**
  - **Sodium-sulfur battery**
  - **PHEV, BEV (distributed)**
- **Gaseous Hydrogen (GH2)**
  - **Pipeline**
  - **Geologic: salt caverns (man-made)**
  - **Geologic: natural formations ? *Terra incognita***
- **Liquid Hydrogen (LH2)**
  - **Pipeline, truck, rail car, ship**
  - **1/3 energy to liquefy Ammonia (NH3) liquid**
  - **Tank, refrigerated, 10K – 60K ton**
  - **Truck, rail car, ship**
- **Liquid anhydrous ammonia (NH3)**
  - **Pipelines**
  - **Tanks**
- **Liquid synthetic HC's – zero net C**
  - **Pipeline**
  - **Tank, truck, rail car, ship**
  - **Geologic: salt caverns (man made)**
- **"Energy Pipeline", EPRI: LH2 in pipeline, SC LVDC electric**
- **Chemicals**
  - **Hydrides**
  - **Al – Ga ← → Alumina**

Energy Storage System Characteristics

Hydrogen and Ammonia off the charts

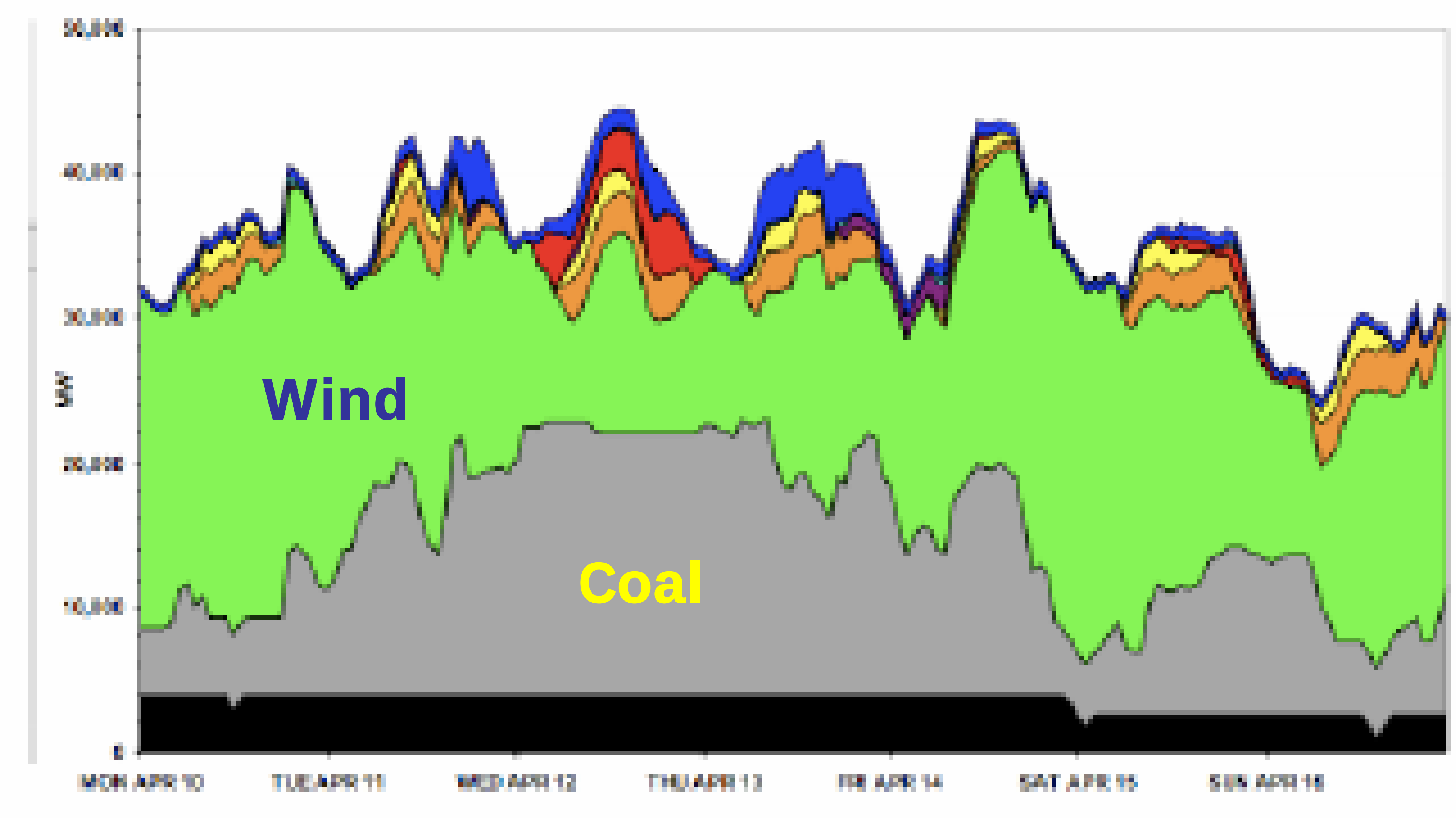
- ***Storage capacity (Mwh, scf, nM3, Mt, gallons ….)***
- ***Power (MW, scfm ….)   In / Out rate***
- ***Costs***
  - ***Capital***
  - ***O&M***
  - ***Conversion losses***
- **Efficiency**
- **Response time**
- **Durability (cycling capacity)**
- **Reliability**
- **Autonomy**
- **Self-discharge**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

System Ratings

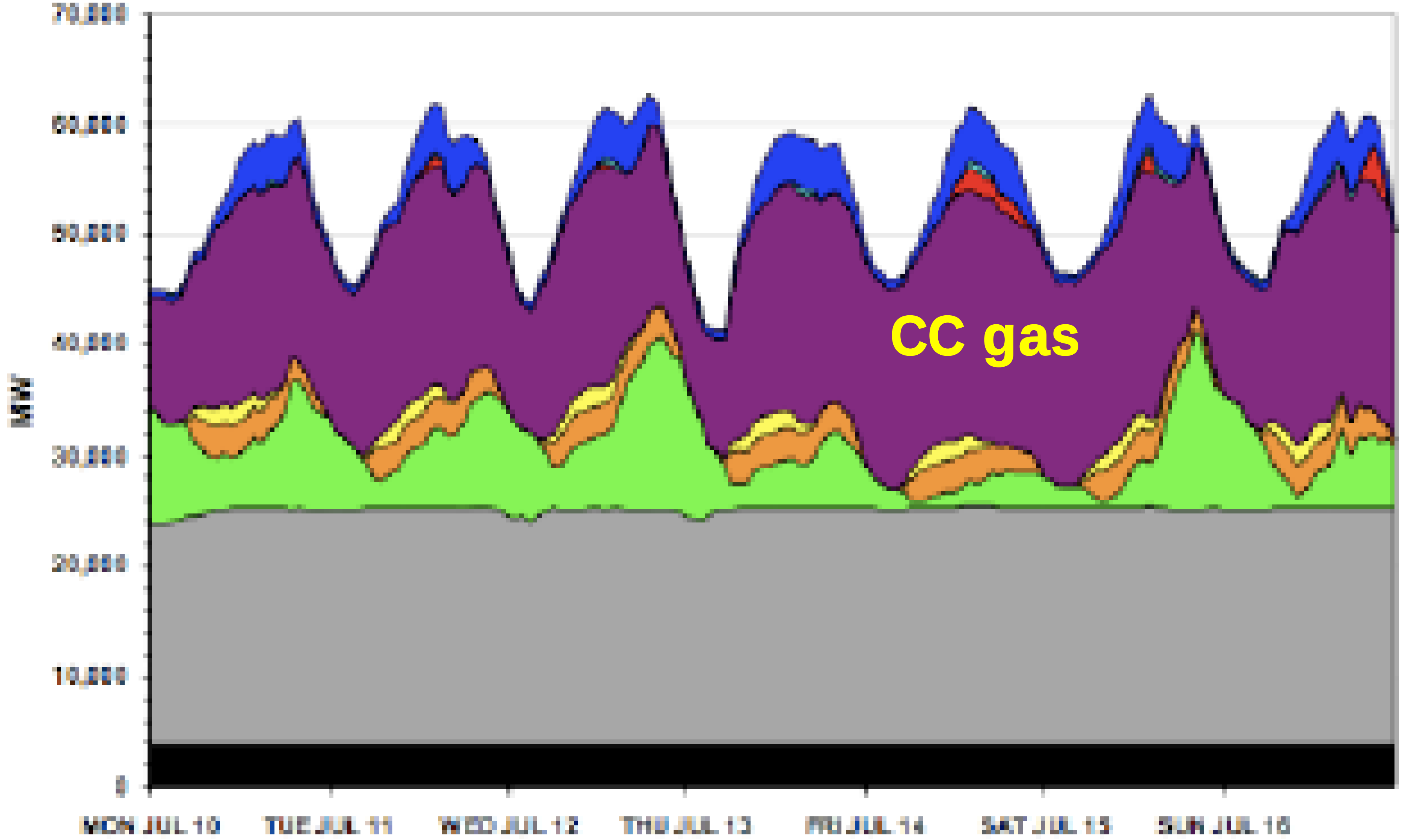


Trouble with Renewables: Electricity Transmission

- Grid nearly full
  - New must pay for transmission
  - Costly: AC or DC
- Integration
  - Continental energy system
  - Quality
  - Generation O+M: fatigue, wear, low efficiency
- Low capacity factor (CF) or curtailment
- Costly “firming” storage: CAES, VRB
- Overhead vulnerable: God or man
- Underground: Only HVDC, 6x cost
- FERC no interstate jurisdiction
- Wide ROW
- NIMBY: site, ROW delay + cost



WWSIS: April week: ~30% RE



WWSIS: July week: ~10% RE

Wind seasonality, Great Plains

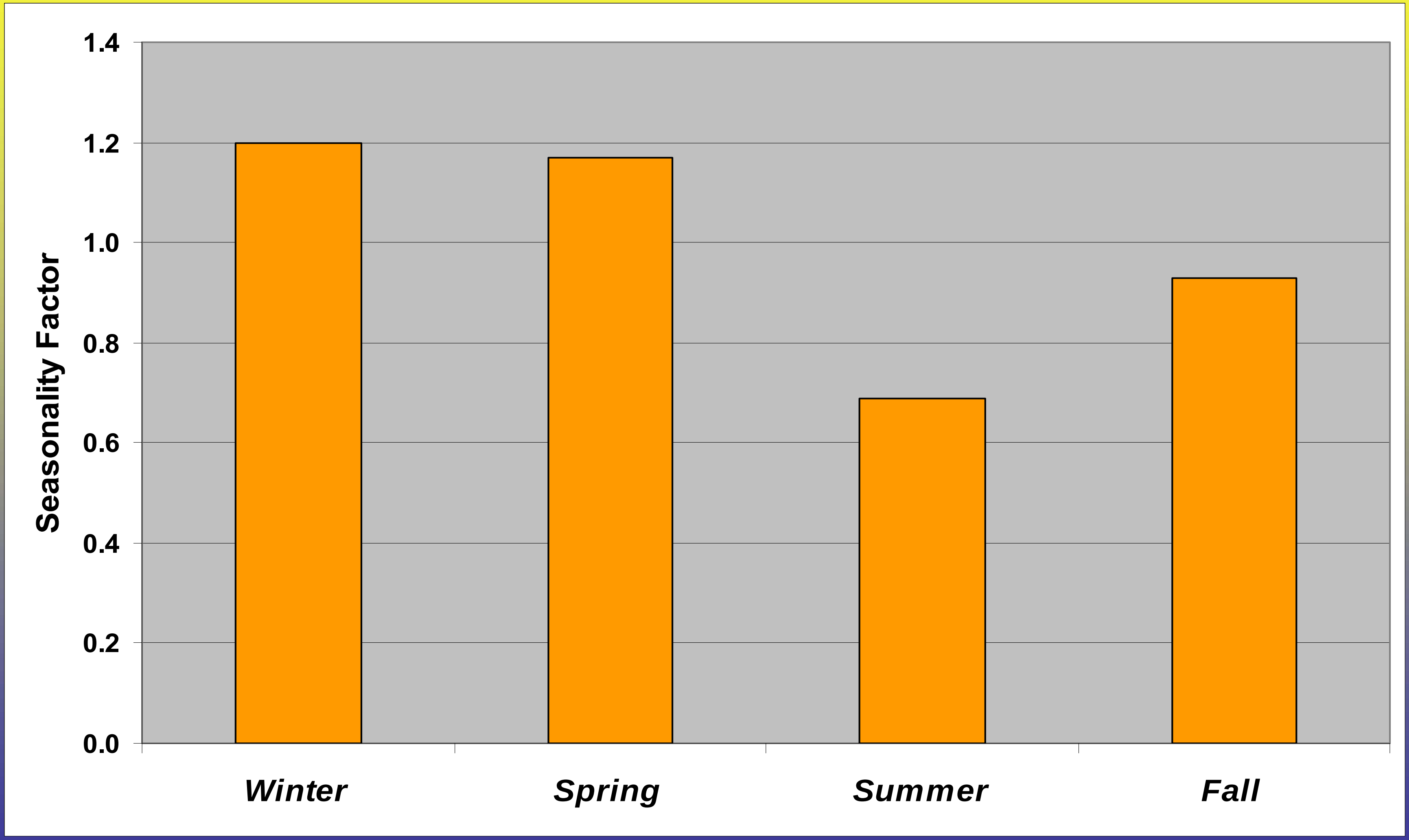
Normalized to 1.0

• **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



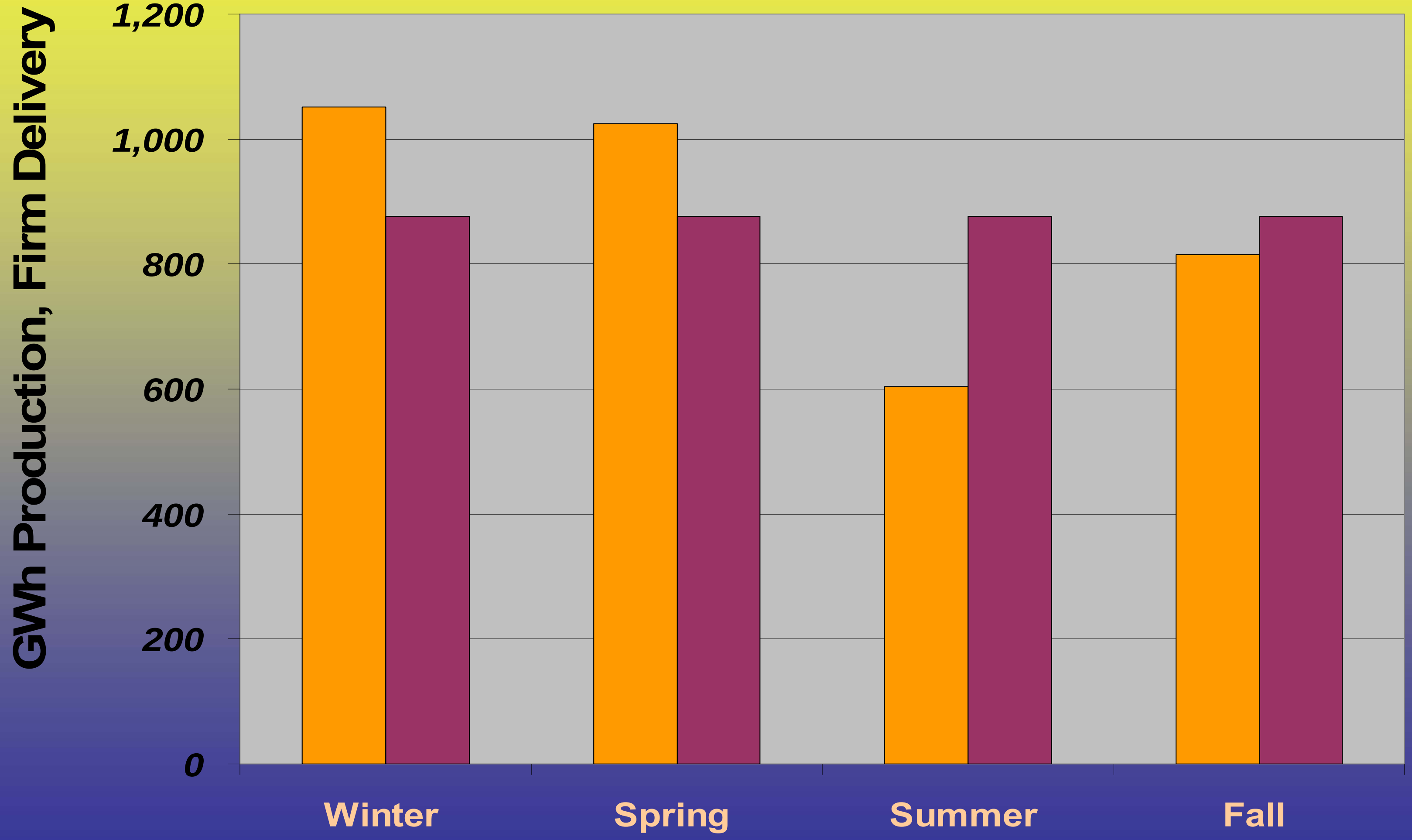
Wind Seasonality, Northern Great Plains

1,000 MW windplant: AEP = 3,500 GWh / yr

"Firm" goal = 875 GWh / season

Storage: 320 GWh per 1,000 MW wind

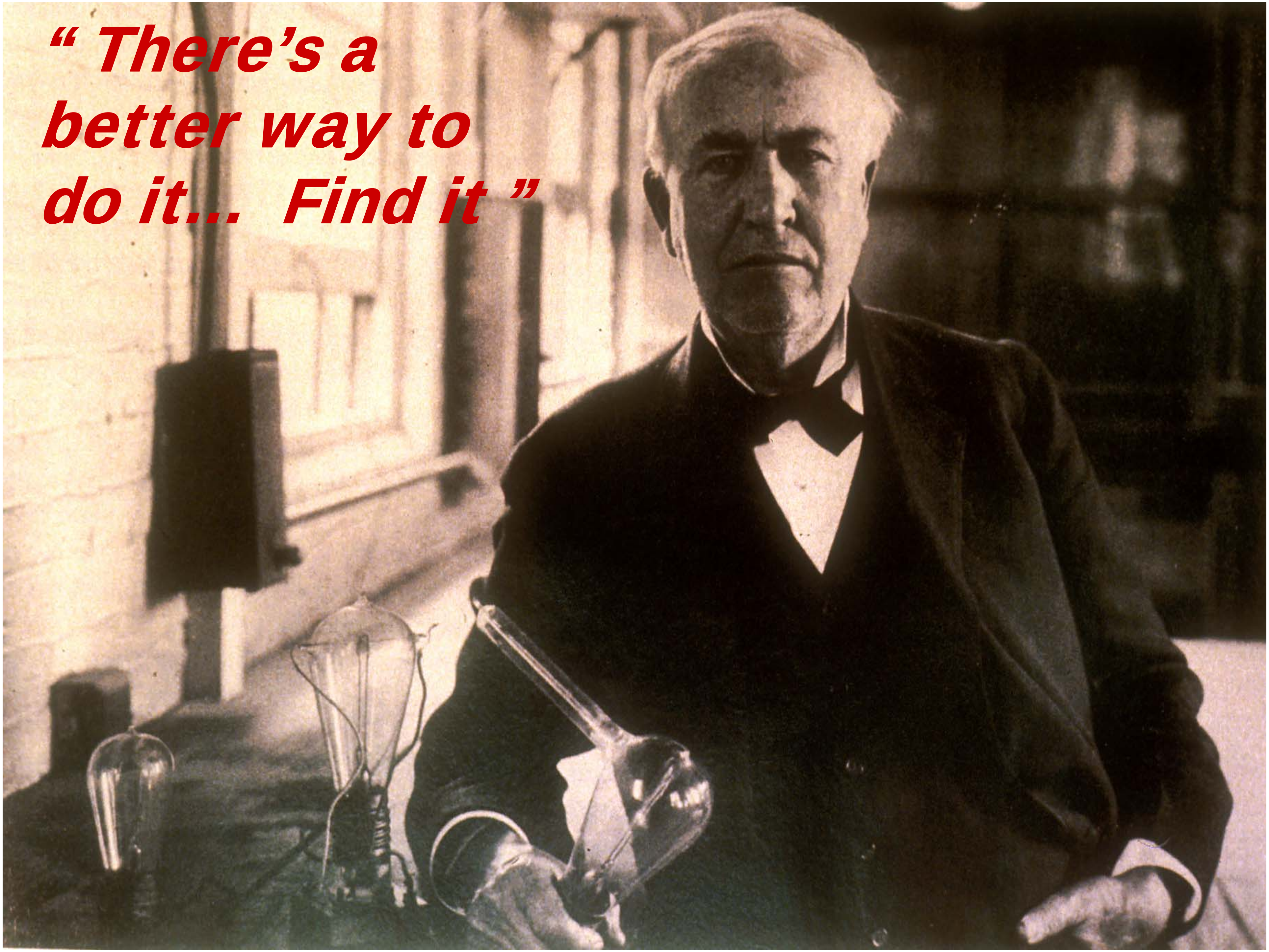
Source: NREL, D. Elliott



320 GWh

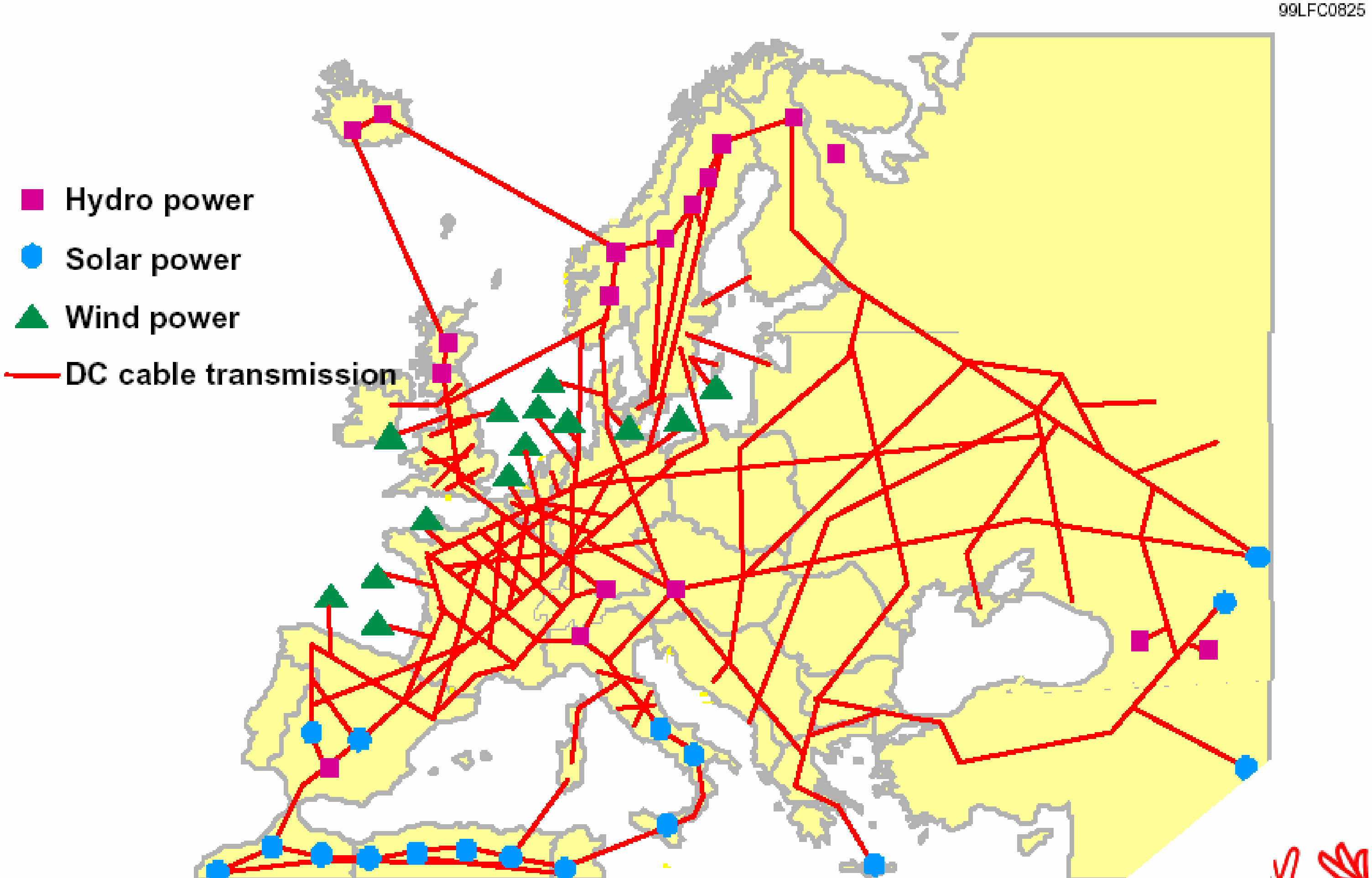
Annual firming, 1,000 MW wind

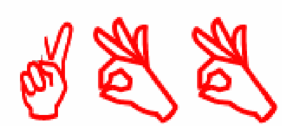
- **CAES (compressed air energy storage)**
  - **O&M: $46 / MWh typical**
  - **Iowa: Power = 268 MW**
    Energy capacity = 5,360 MWh
    Capital: 268 MW @$800 / kW = $214 M
    Storage @ $40 / kWh = $13 Billion
    Storage @ $1 / kWh = $325 Million
- **VRB flow battery**
  - **O&M: 80% efficiency round-trip**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

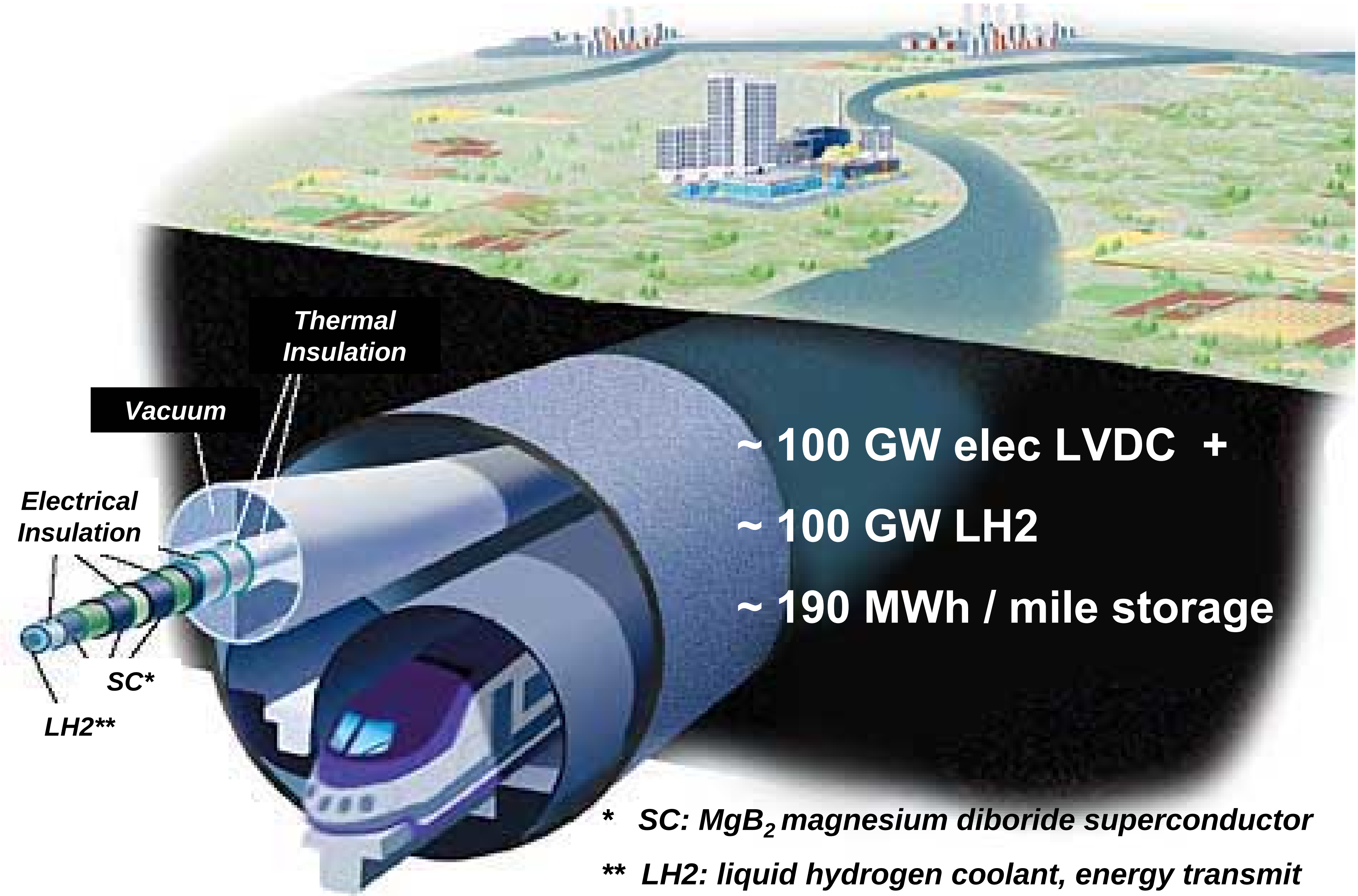

" There's a
better way to
do it... Find it "

Vision: Remote renewable energy sources

connected to loads by DC grid



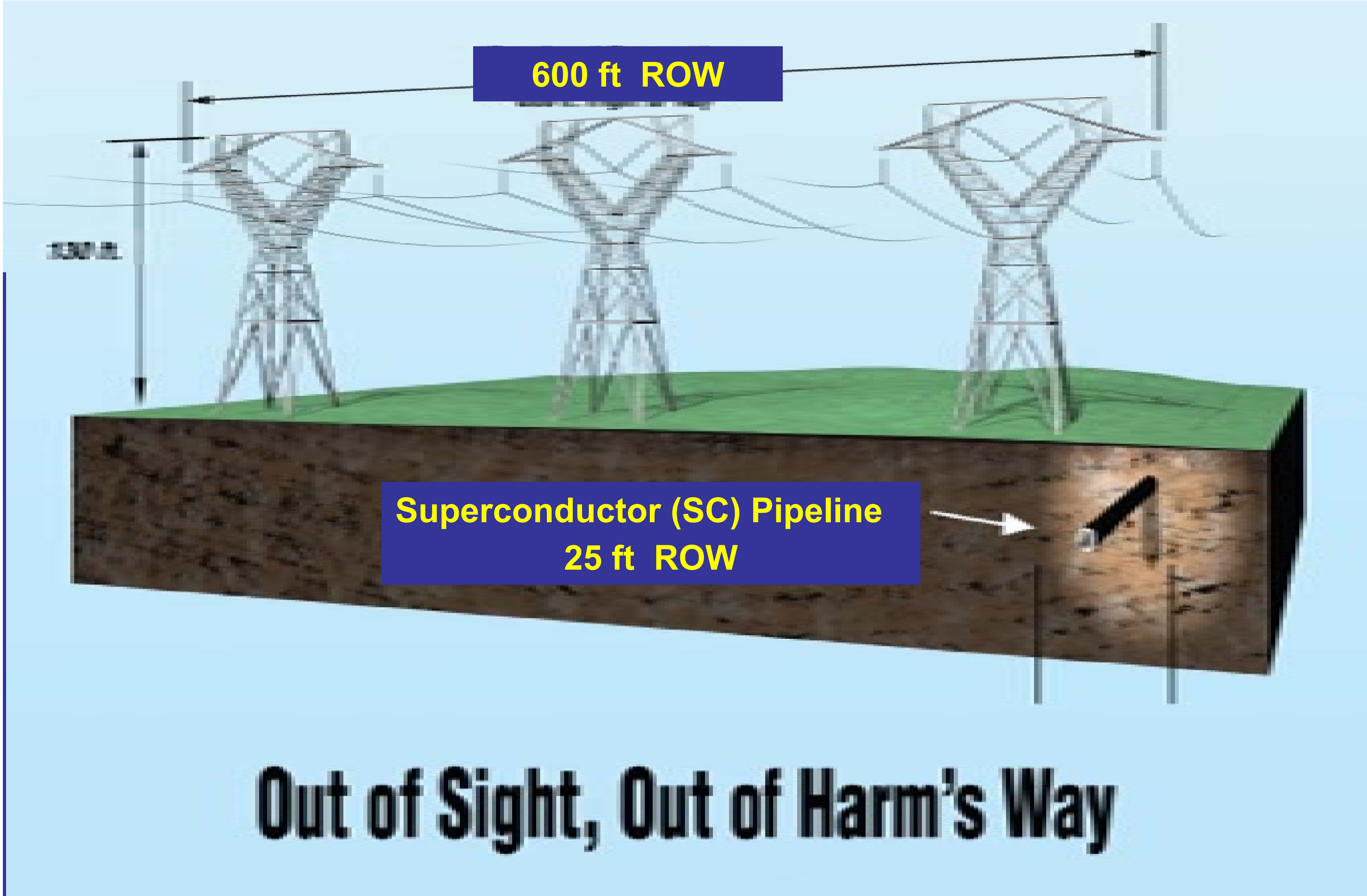




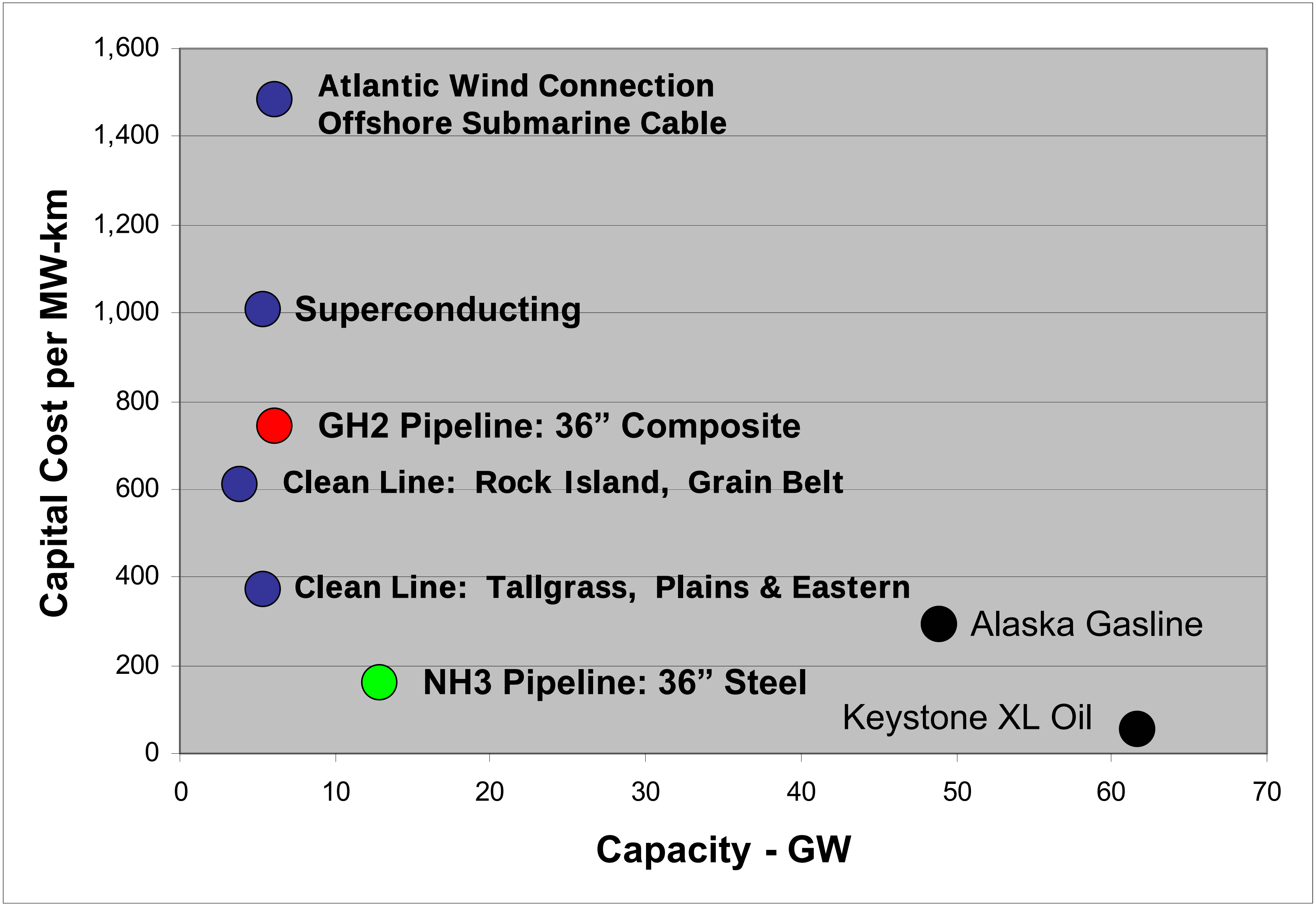
* SC: MgB_2 magnesium diboride superconductor

** LH2: liquid hydrogen coolant, energy transmit

Continental Supergrid – EPRI concept "Energy Pipeline"



10,000 MW alternatives: HVAC vs HVDC superconductor


Capital Cost per MW-km
1,600
1,400
1,200
1,000
800
600
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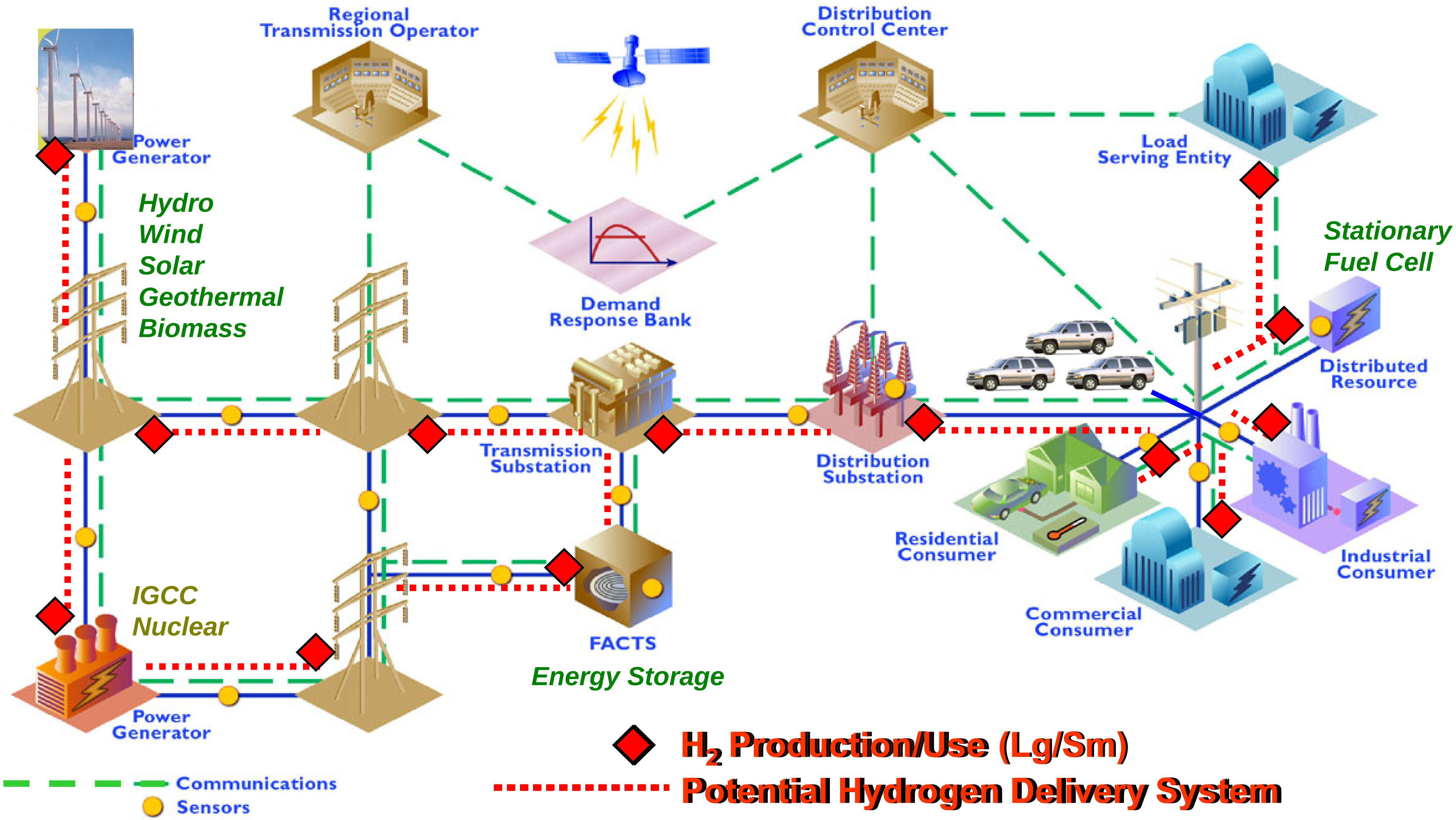
200
0
Atlantic Wind Connection
Offshore Submarine Cable
Superconducting
GH2 Pipeline: 36" Composite
Clean Line: Rock Island, Grain Belt
Clean Line: Tallgrass, Plains & Eastern
Alaska Gasline
NH3 Pipeline: 36" Steel
Keystone XL Oil
0
10
20
30
40
50
60
70
Capacity - GW

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
  - Elec grid generation O+M: fatigue, wear, efficiency

Energy System of the Future



Frank Novachek, Director Corporate Planning

Xcel Energy

EPRI

Hydrogen Utility Group (HUG)

SOUTHERN COMPANY
Energy to Serve Your World®

Sempra Energy®

SOUTHERN CALIFORNIA EDISON®
An EDISON INTERNATIONAL® Company

BC hydro

DTE Energy®

KEPCO
KOREA ELECTRIC POWER CORPORATION

Entergy.
ENTERGY NUCLEAR

SMUD
SACRAMENTO MUNICIPAL UTILITY DISTRICT
The Power To Do More.®

APS®

New York Power Authority

City of Fort Collins Utilities

CONNEXUS® ENERGY
Your Community Energy Partner

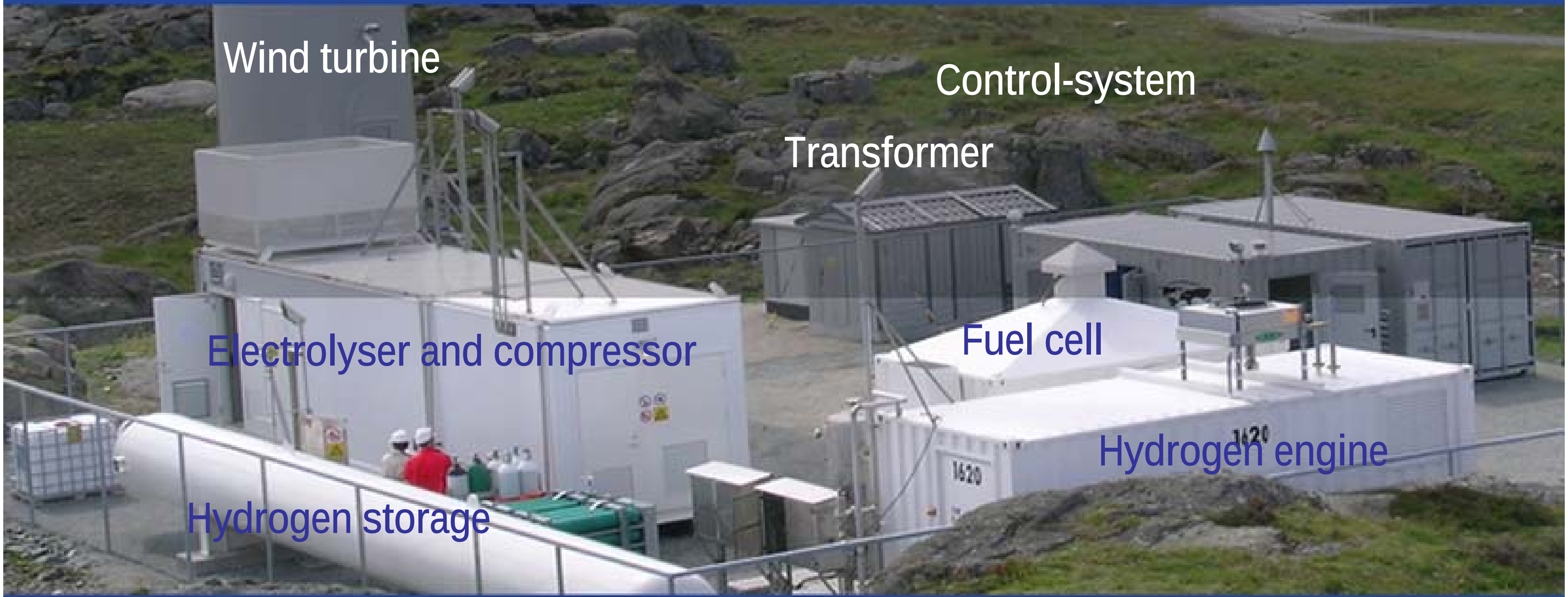
Xcel Energy®

Nebraska Public Power District
Always there when you need us

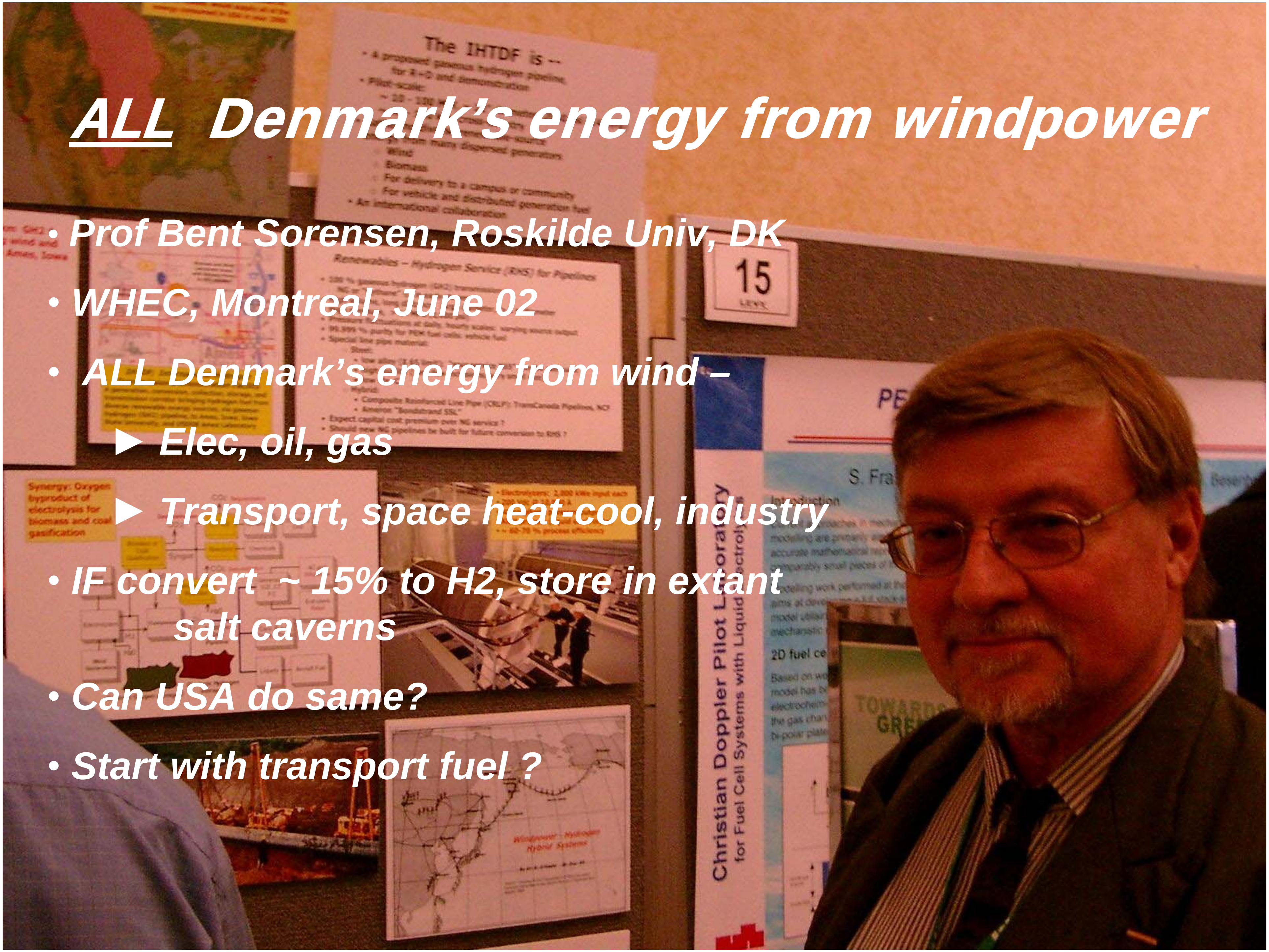
Utsira Island, Norway

The wind – hydrogen plant at Utsira

A vision becoming reality



HYDRO

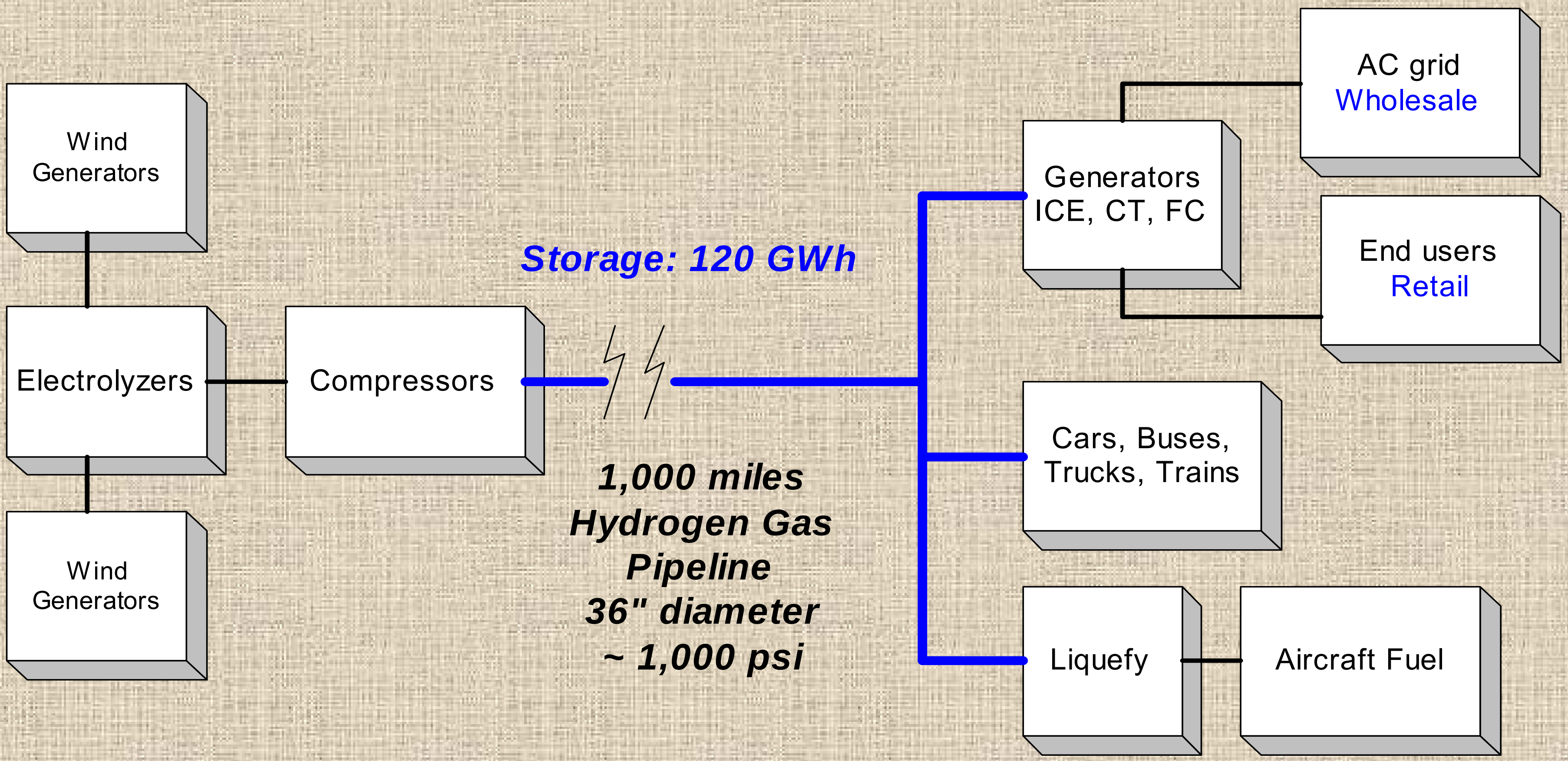


ALL *Denmark's energy from windpower*

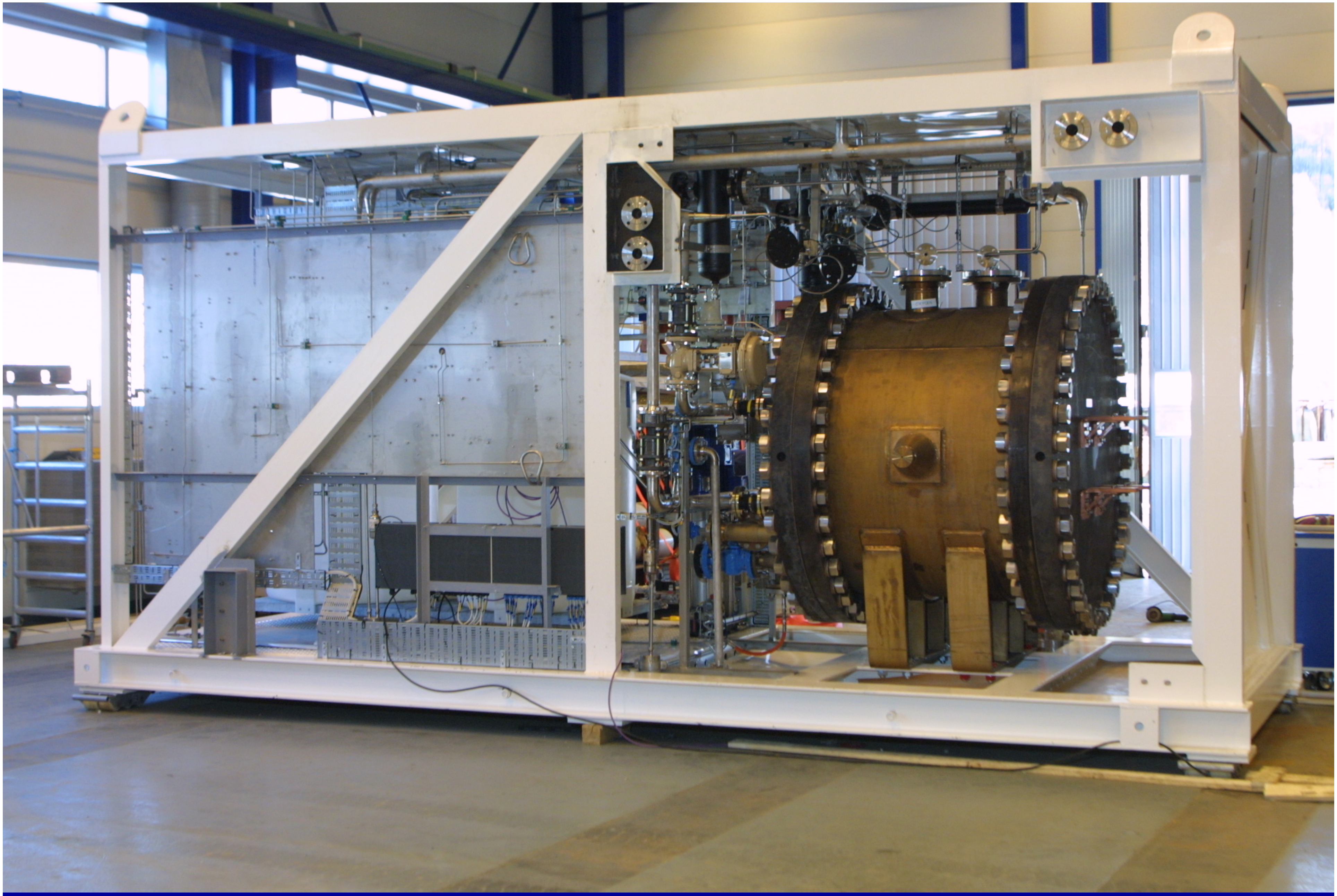
- *Prof Bent Sorensen, Roskilde Univ, DK*
- *WHEC, Montreal, June 02*
- *ALL Denmark's energy from wind –*
  - ► *Elec, oil, gas*
  - ► *Transport, space heat-cool, industry*
- *IF convert ~ 15% to H2, store in extant salt caverns*
- *Can USA do same?*
- *Start with transport fuel ?*

Hydrogen Transmission Scenario

- *Low-pressure electrolyzers*
- *"Pack" pipeline: ~ 120 GWh*



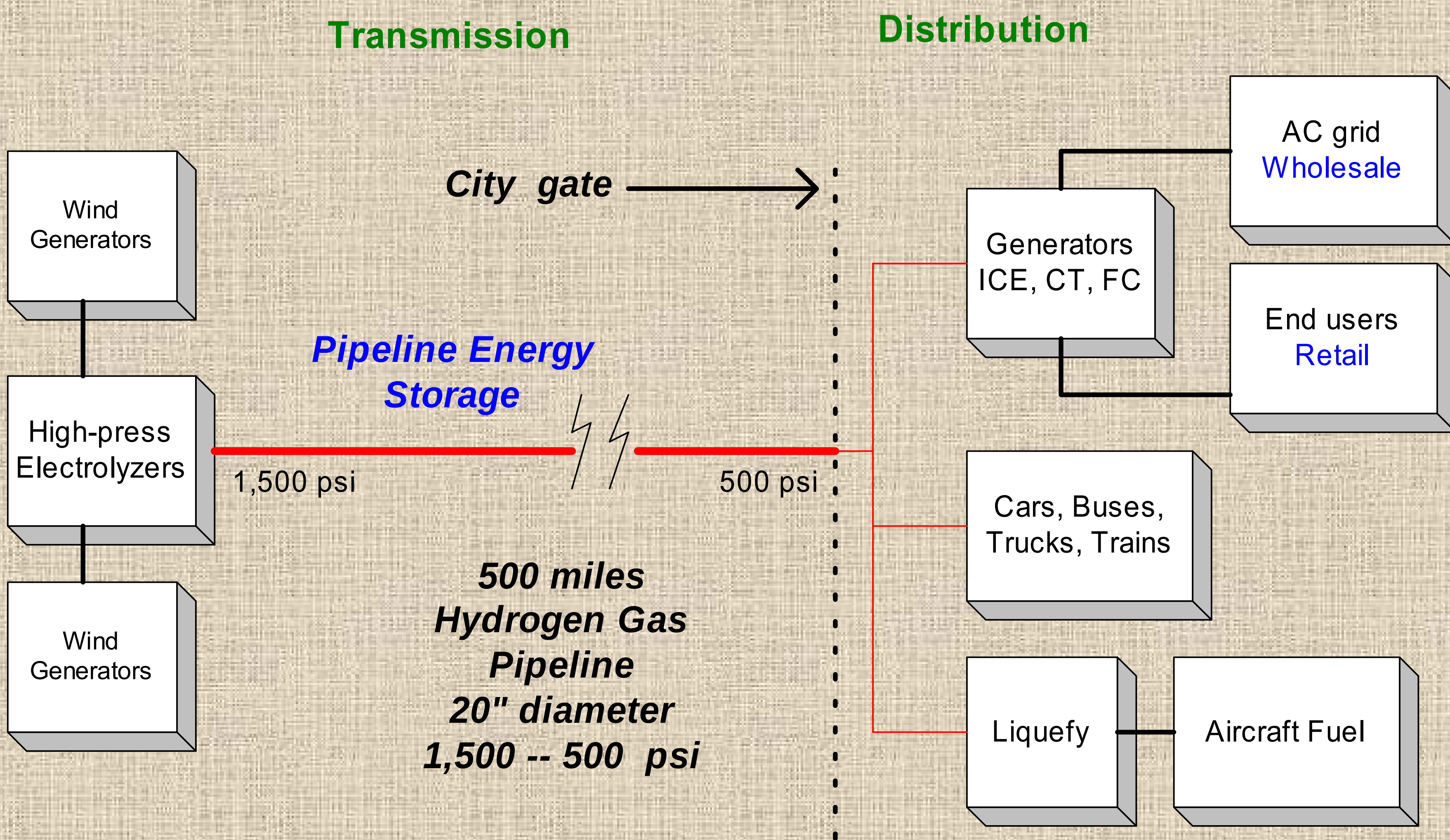
Norsk Hydro Electrolyzers 2 MW each

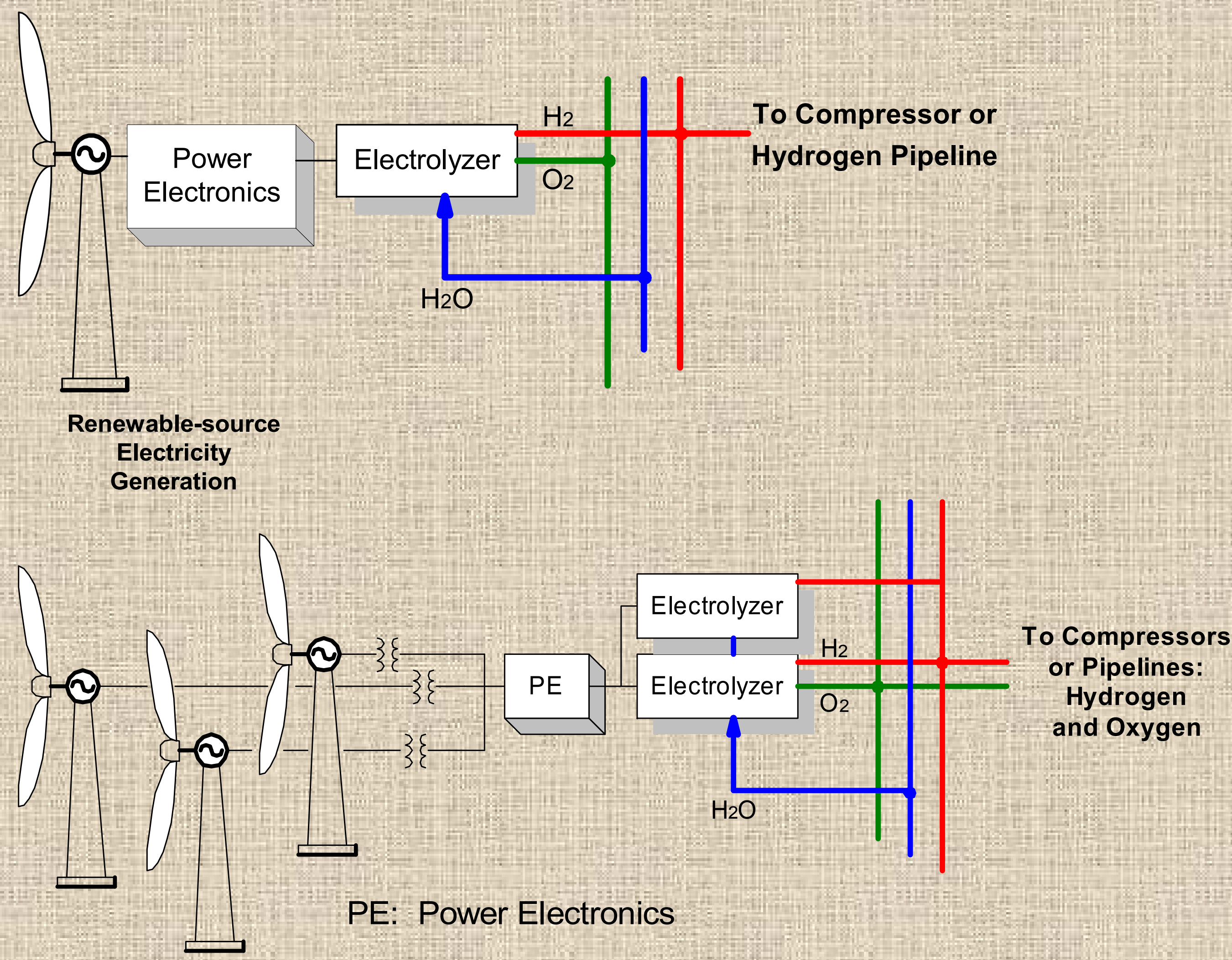


Norsk Hydro electrolyzer, KOH type

560 kW input, 130 Nm3 / hour at 450 psi (30 bar)

Compressorless system: No geologic storage

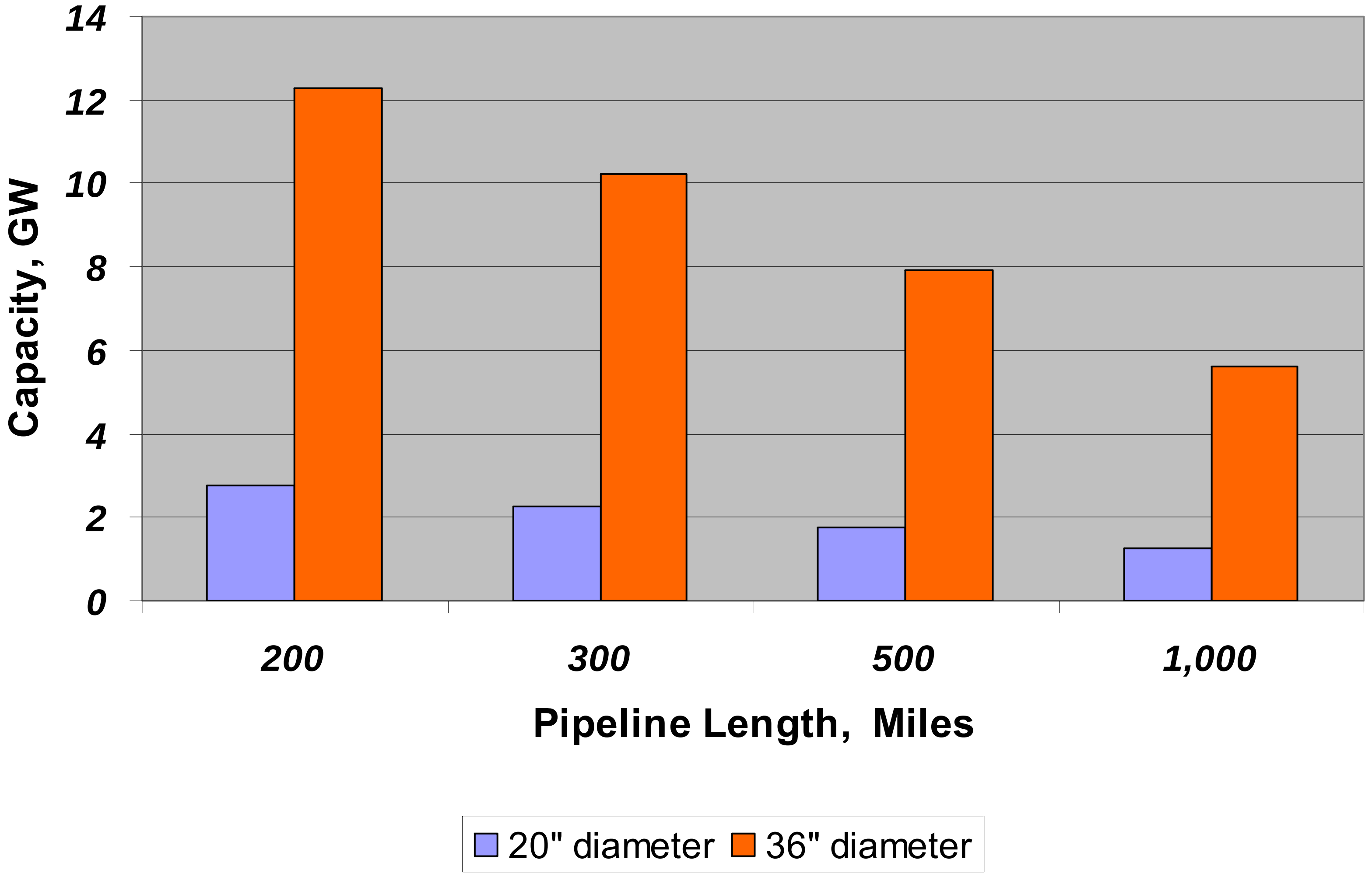




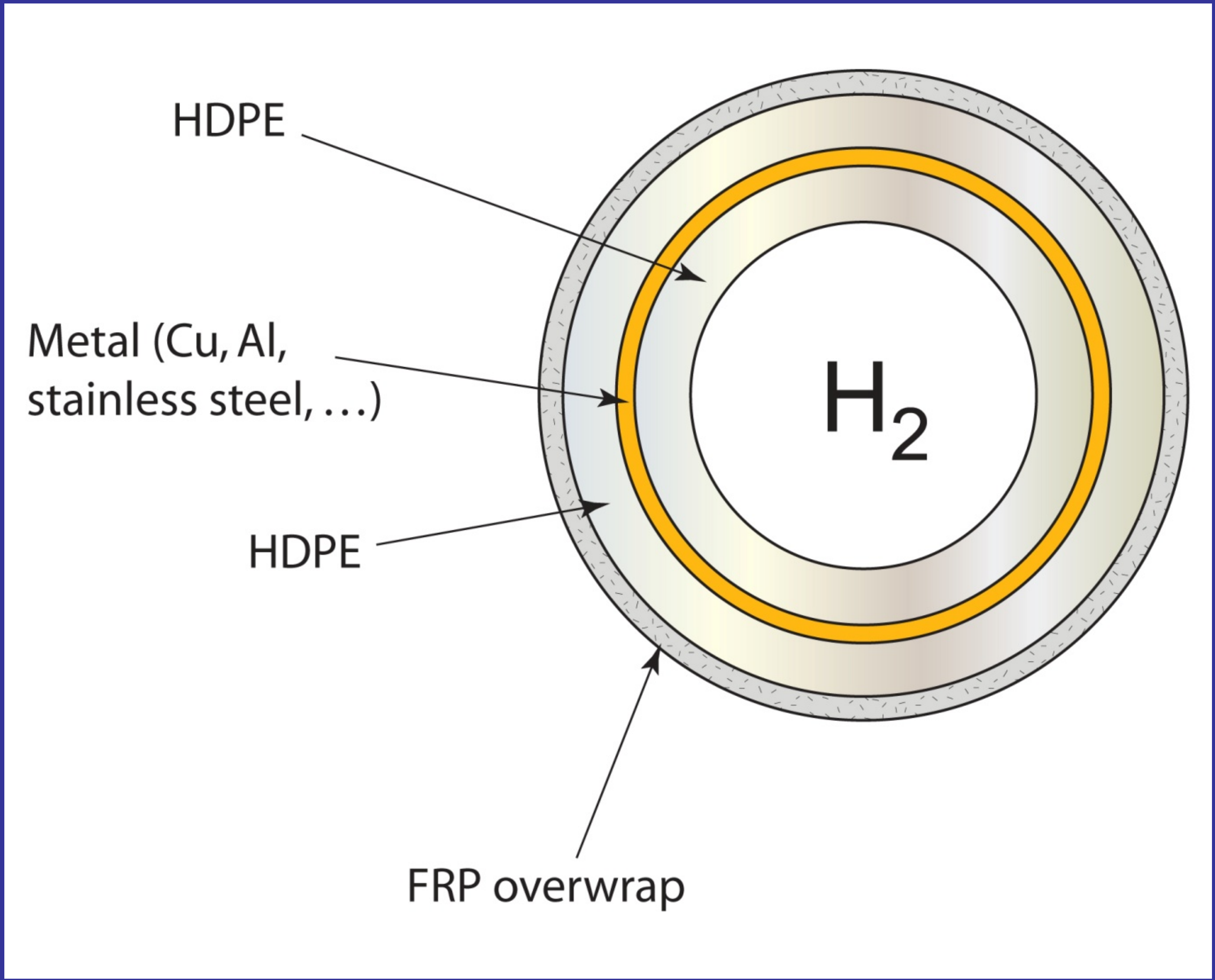
Topology Options: H_2 and O_2 Production and Gathering from Renewable Energy Generation

Compressorless 20", 36" GH2 Pipeline Capacity

1,500 psi IN / 500 psi OUT



Gaseous Hydrogen (GH2)
36" diam, 500 miles
No compression
8,000 MW



Polymer-metal linepipe avoids hydrogen embrittlement

Capital Cost per GW-mile

***Electricity* :**

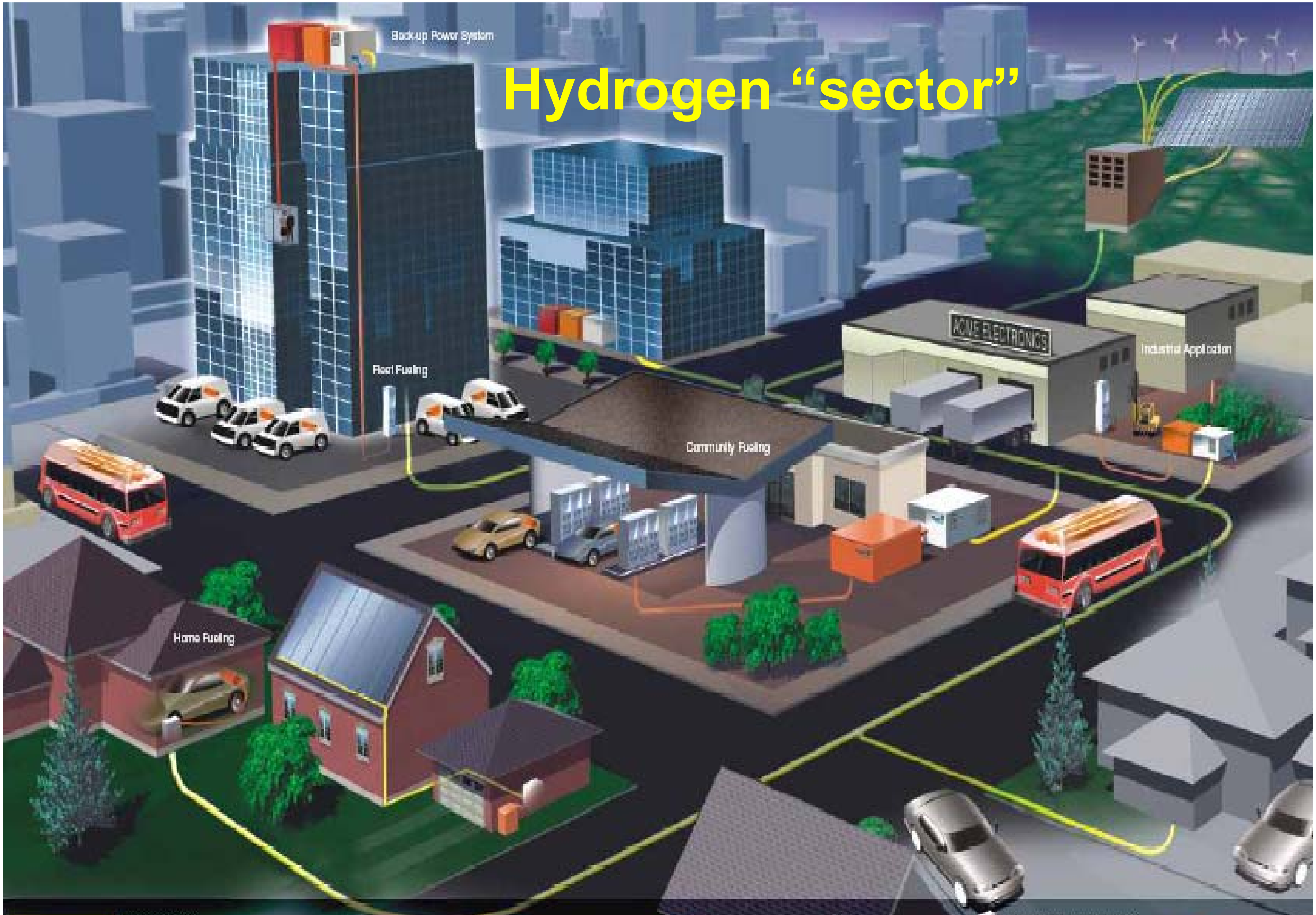
	KV	Capacity MW	$M / GW-mile
• SEIA:	765	5,000	1.3
	345	1,000	2.6
• AEP-AWEA	765	5,000	3.2
Consensus ?			2.5

Hydrogen pipeline:

36”, 100 bar, 500 mi, no compress 0.3

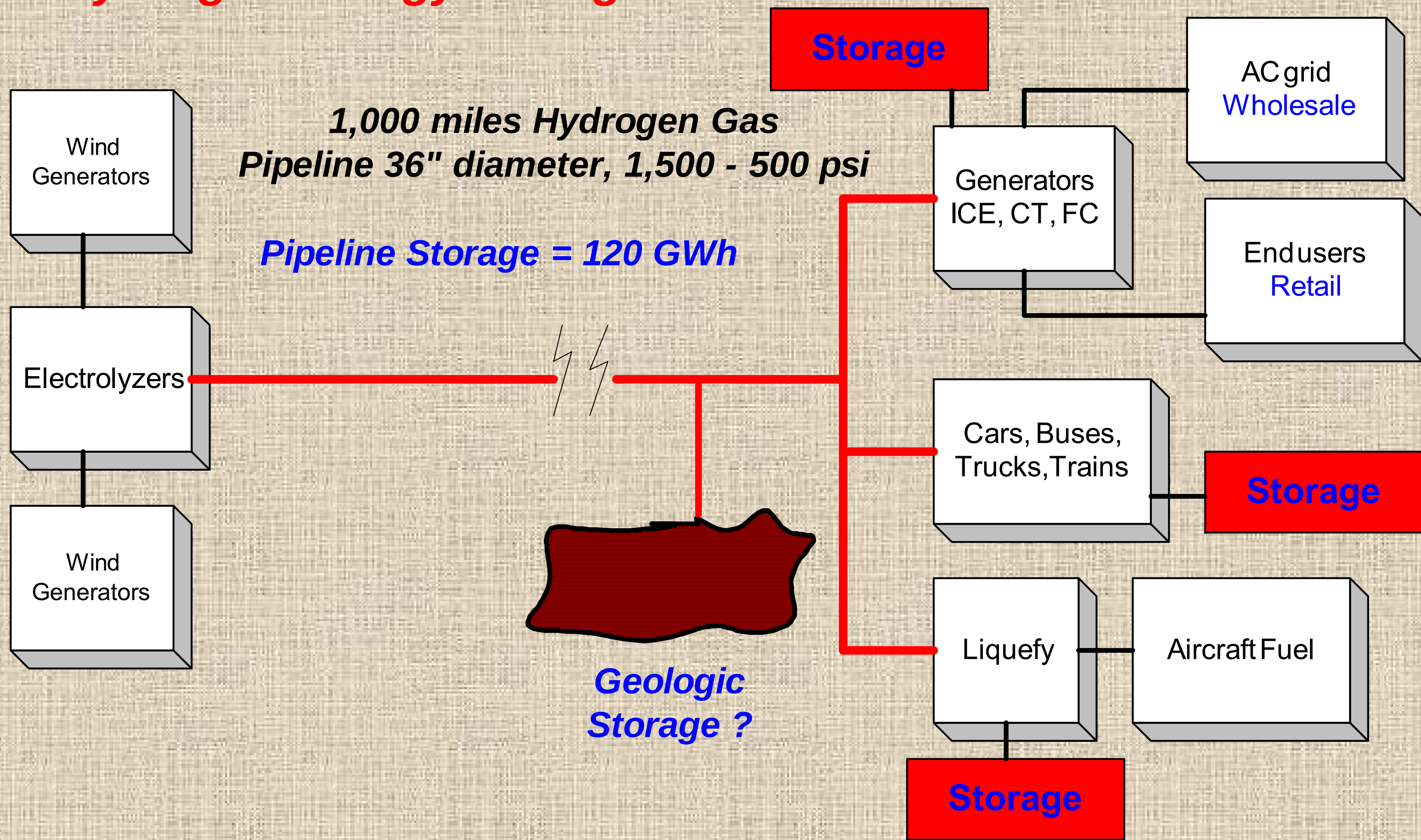
(100 bar = 1,500 psi)

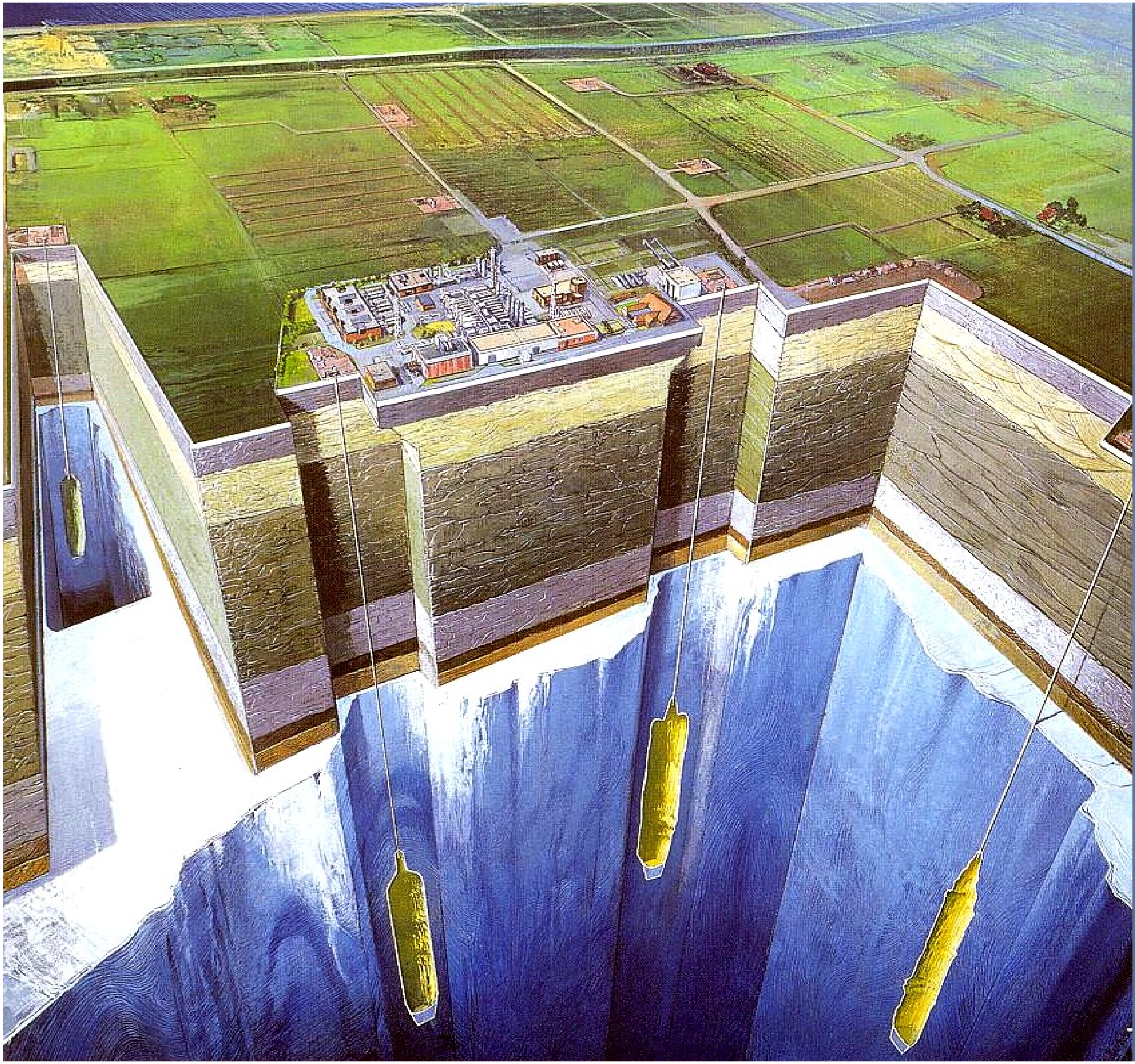
Hydrogen "sector"



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

Hydrogen Energy Storage



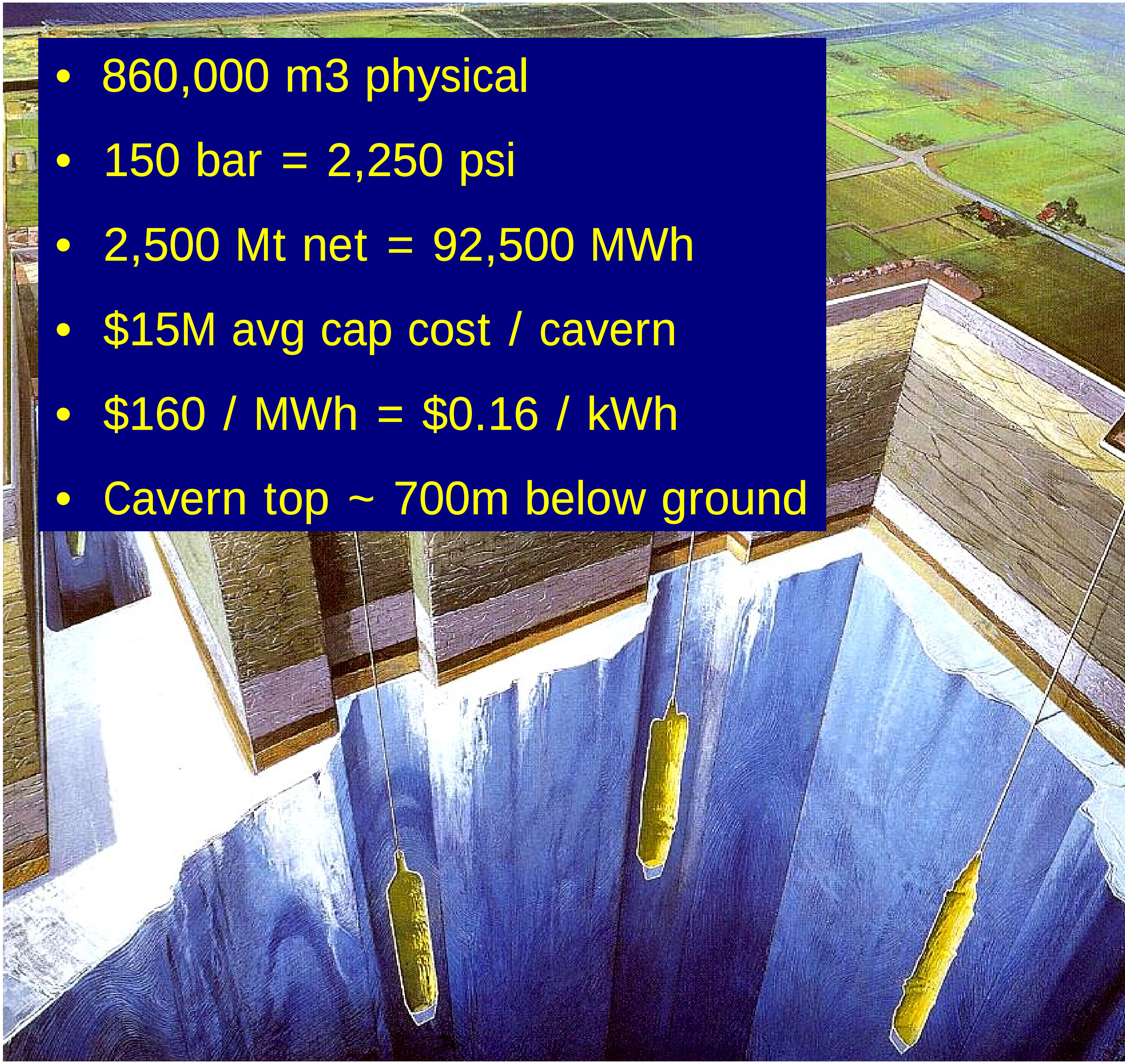


Domal Salt Storage Caverns

PB ESS

Domal Salt Storage Caverns

- 860,000 m3 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

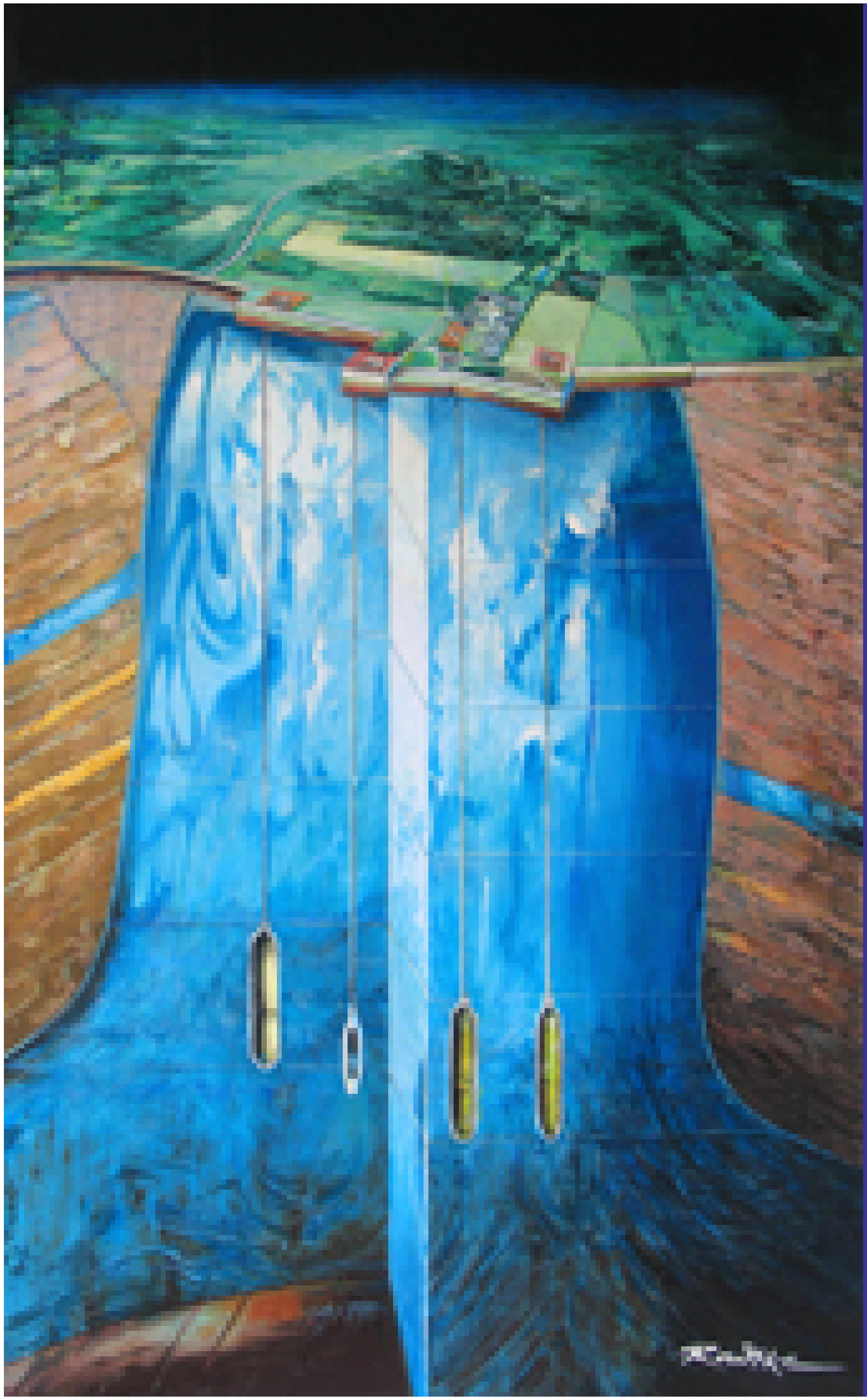


Texas

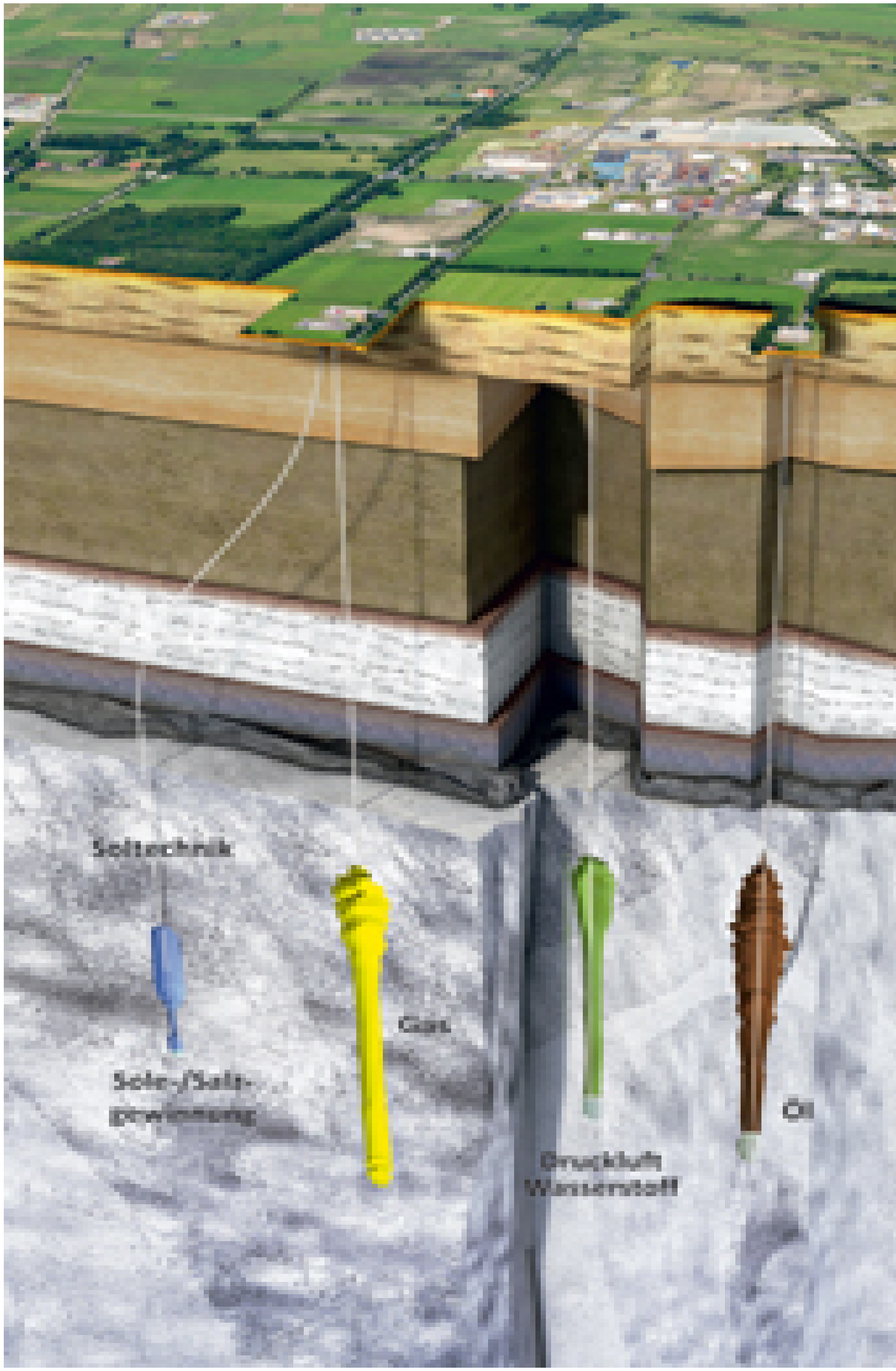
“Clemens Terminal” Conoco Phillips 20 years

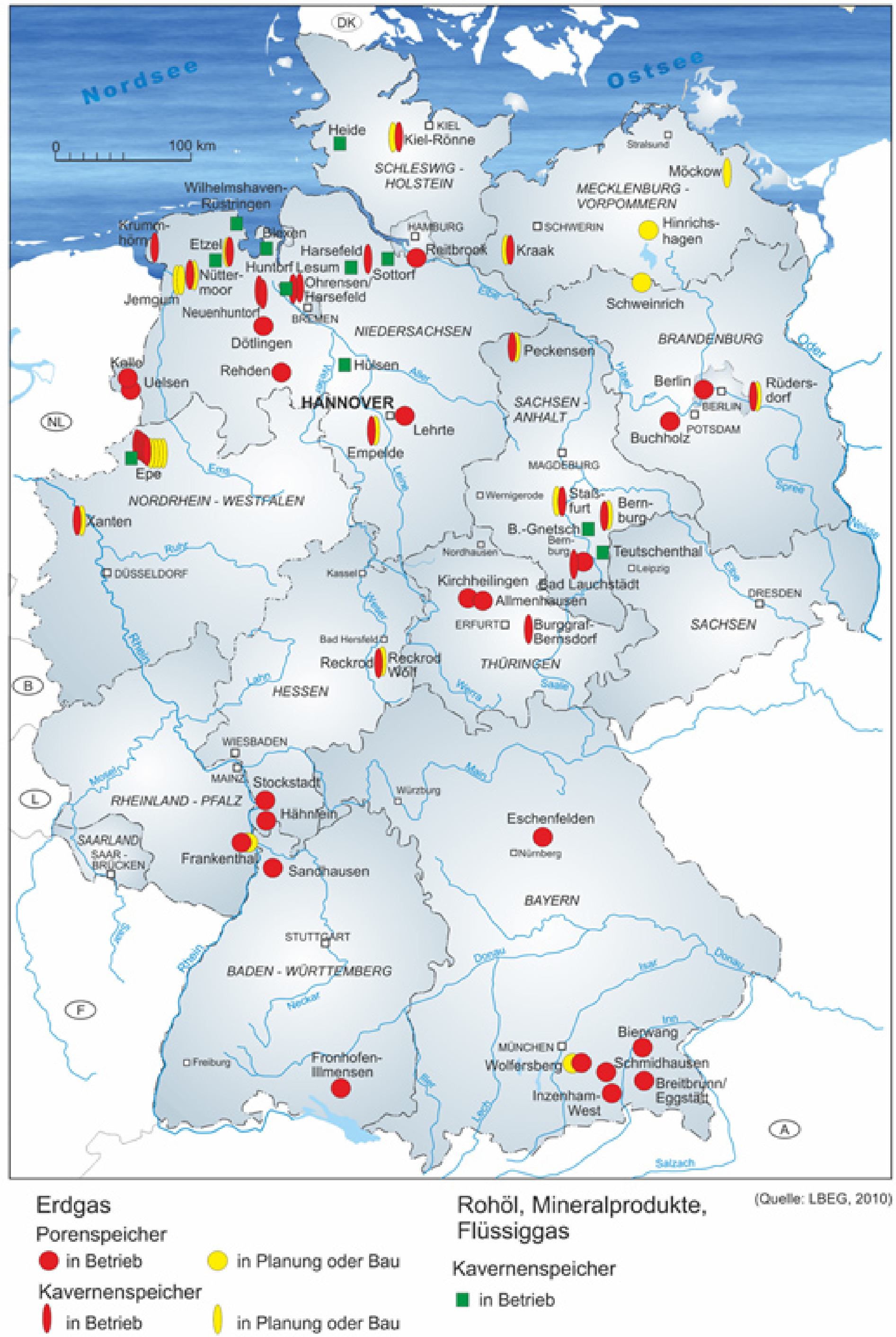
Praxair ‘07

Multiple Gaseous Hydrogen Storage Caverns in Domal Salt

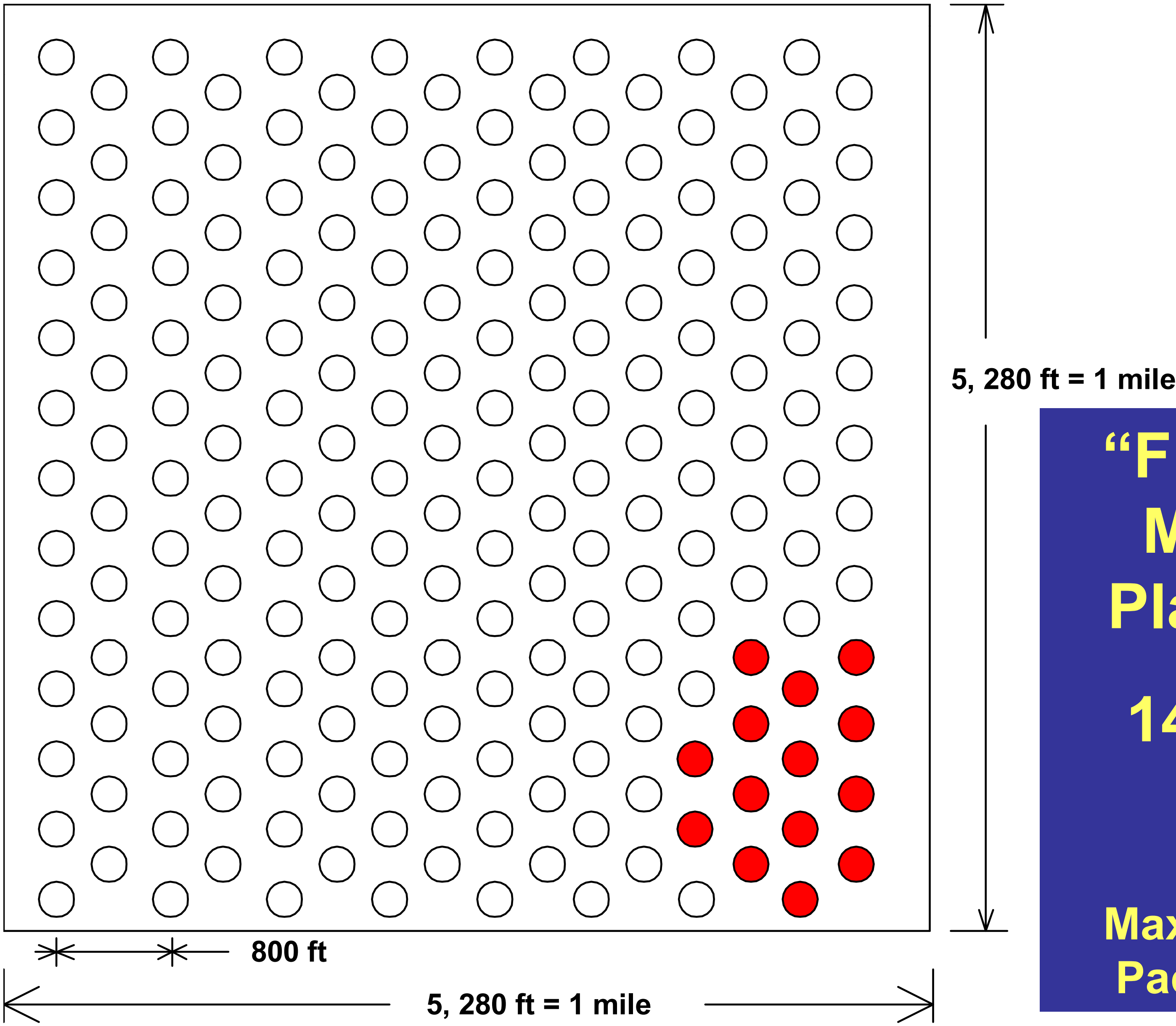


Multiple Gaseous Hydrogen Storage Caverns in Domal Salt


Soltechnik
Gas
Sole-/Salzgewinnung
Druckluft
Wasserstoff
Öl


Nordsee
Ostsee
DK
NL
B
L
F
A
0
100 km
Heide
Kiel-Rönne
KIEL
SCHLESWIG - HOLSTEIN
MECKLENBURG - VORPOMMERN
Stralsund
Möckow
Wilhelmshaven-Rüstringen
Krummhörn
Etzel
Bleixen
Nüttermoor
Jemgum
Huntorf
Neuenhuntorf
Harsefeld
Lesum
Ohrensen/Harsefeld
Reitbrook
Sottorf
HAMBURG
SCHWERIN
Kraak
Hinrichshagen
Schweinrich
BREMEN
NIEDERSACHSEN
Dötlingen
Peckensen
BRANDENBURG
Kalle
Uelsen
Rehden
Hülsen
HANNOVER
Lehrte
Empelde
SACHSEN - ANHALT
Berlin
BERLIN
Rüdersdorf
POTSDAM
Buchholz
Epe
MAGDEBURG
Wernigerode
Staßfurt
Bernburg
B.-Gnetsch
Teutschenthal
NORDRHEIN - WESTFALEN
Xanten
Nordhausen
Leipzig
DÜSSELDORF
Kassel
Kirchheilingen
Bad Lauchstädt
Allmenhausen
DRESDEN
ERFURT
Burggraf-Bernsdorf
SACHSEN
Bad Hersfeld
Reckrod
Reckrod Wolf
THÜRINGEN
HESSEN
WIESBADEN
MAINZ
Stockstadt
RHEINLAND - PFALZ
Hähnlein
Würzburg
Eschenfelden
SAARLAND
SAARBRÜCKEN
Frankenthal
Sandhausen
Nürnberg
BAYERN
STUTTGART
BADEN - WÜRTTEMBERG
MÜNCHEN
Bierwang
Wolfersberg
Schmidhausen
Freiburg
Fronhofen-Illmensen
Inzenham-West
Breitbrunn/Eggstätt
Elbe
Oder
Weser
Ems
Rhein
Ruhr
Main
Donau
Neckar
Mosel
Lahn
Werra
Saale
Spree
Havel
Aller
Leine
Isar
Inn
Iller
Lech
Salzach
Neiße
(Quelle: LBEG, 2010)
Erdgas
Porenspeicher
in Betrieb
in Planung oder Bau
Kavernenspeicher
in Betrieb
in Planung oder Bau
Rohöl, Mineralprodukte, Flüssiggas
Kavernenspeicher
in Betrieb

Renewable-source GH2 geologic storage potential.
Candidate formations for manmade, solution-mined,
salt caverns



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

"Firm" 4,000 MW Great Plains wind

14 caverns

Maximum Cavern Packing Density

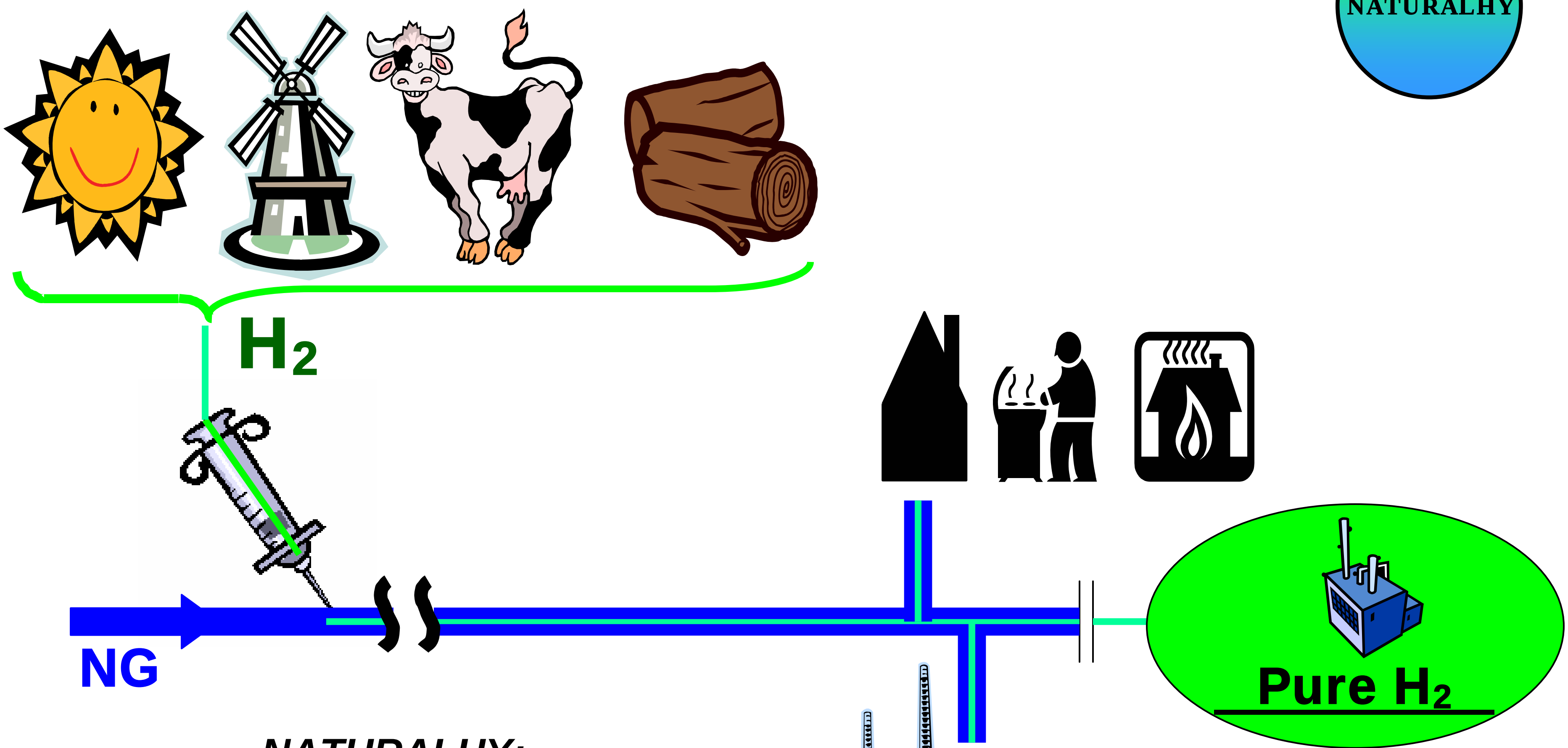
Optimistic: *Total Installed Capital Cost*
1,000 mile Pipeline
"Firming" GH2 cavern storage

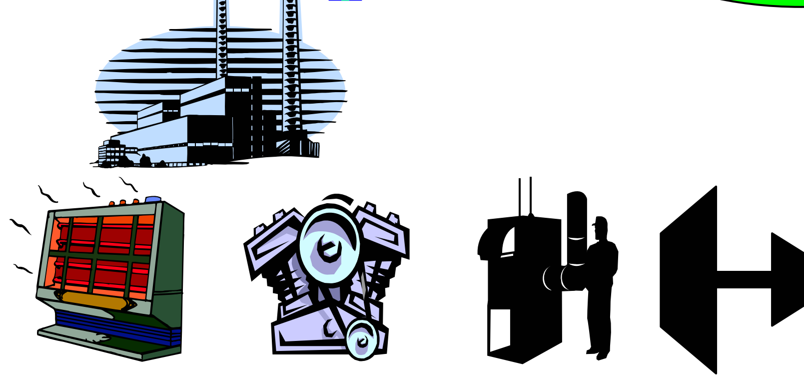
Windplant size **1,000 MW**

	[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

The NATURALHY approach: EC, R+D





NATURALHY:

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

Prepared by
O. Florisson
Gasunie

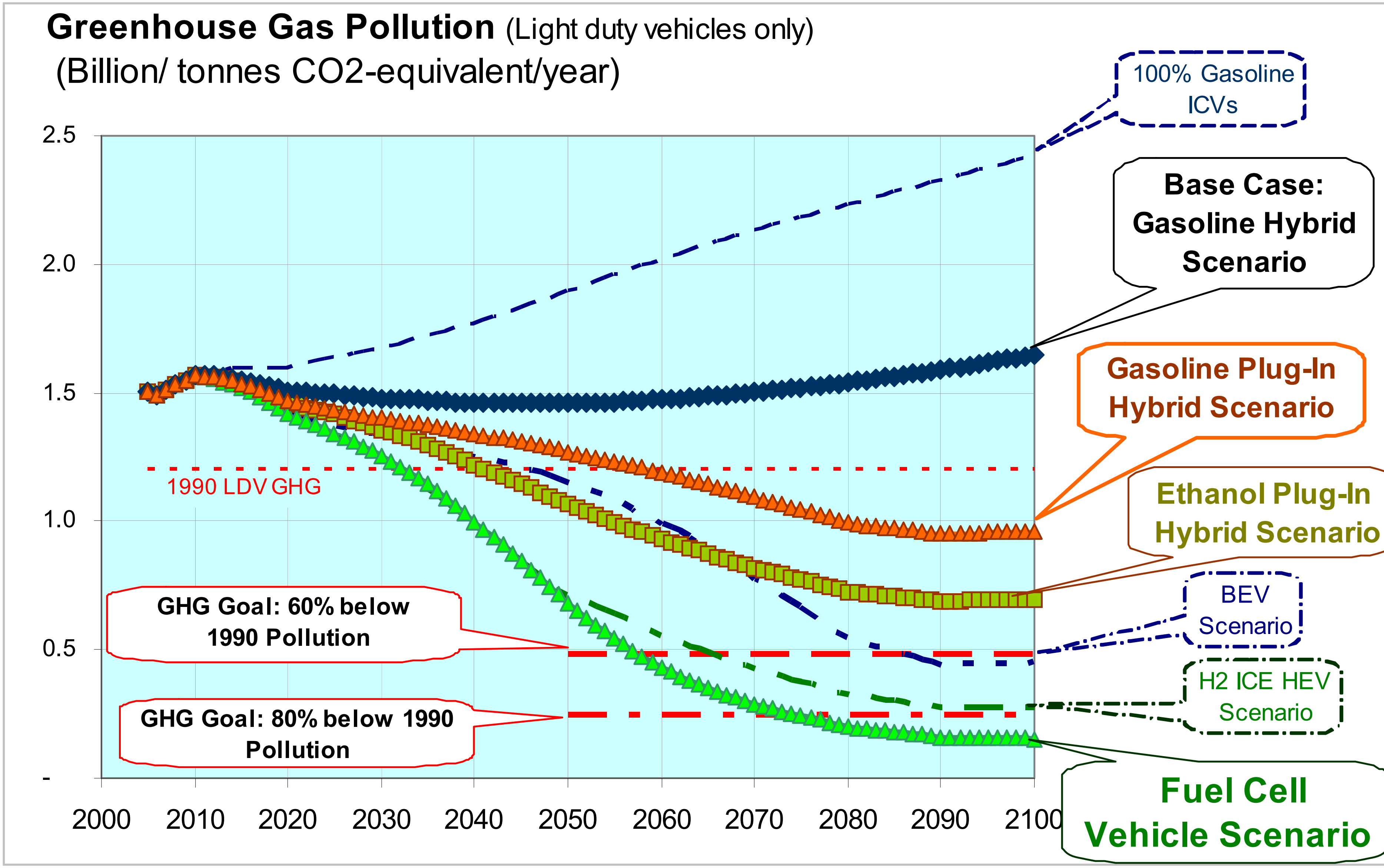

www.qtww.com
Hydrogen - fueled
2005 Prius
ICE Hybrid

Carmakers Commit to Hydrogen Fuel Cell Cars ?

- **9 Sept 09** "Letter of Understanding"
- Carmakers:

Daimler	Ford
GM/Opel	Honda
Hyundai/Kia	Renault
Nissan	Toyota

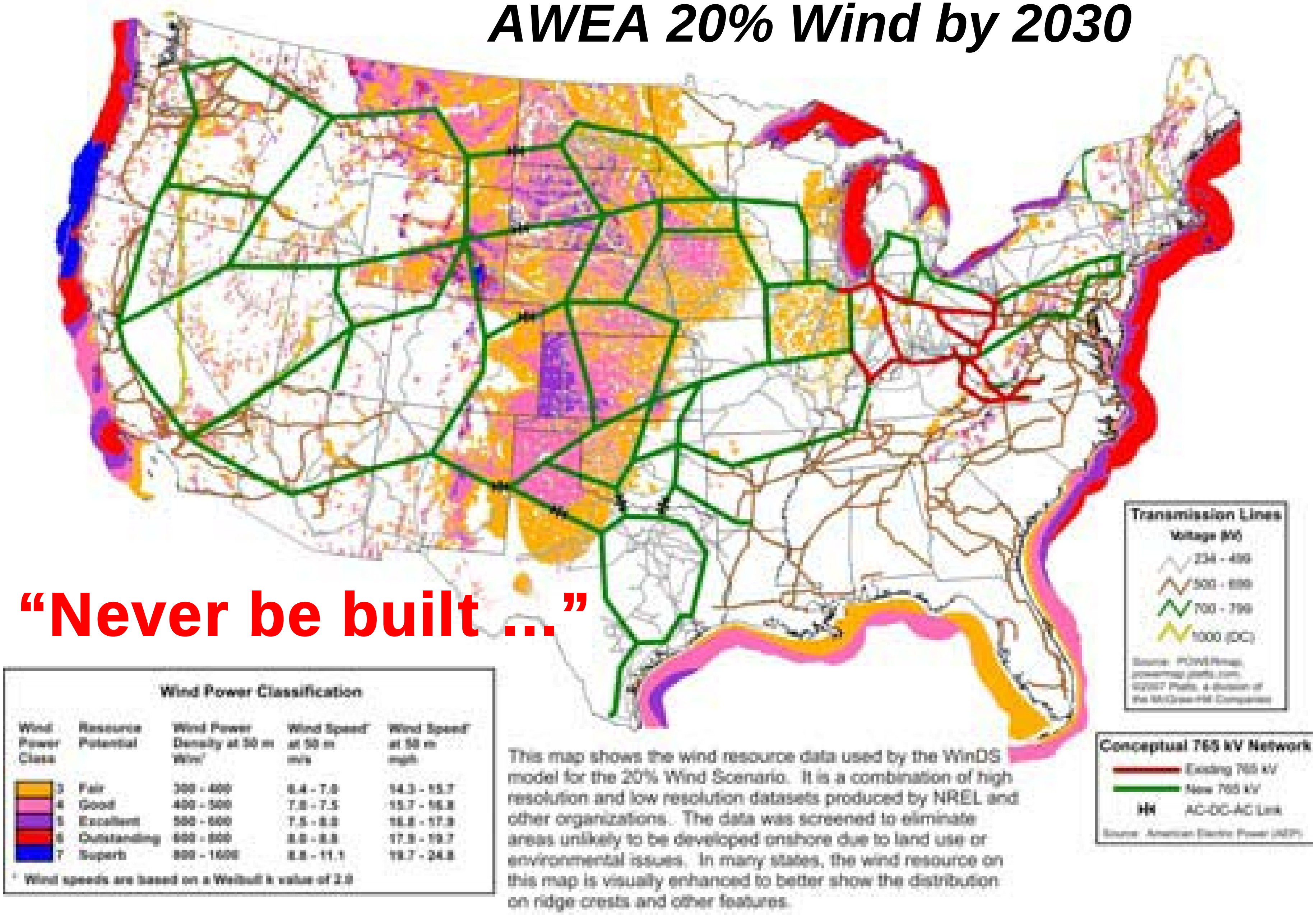
- Serial production **~ 2015**: "… quite significant number" of electric vehicles powered by fuel cells
- Vague; lobbying for fed FCV funds restore ?
- Will need H2 fuel: "… hydrogen infrastructure has to be built up with sufficient density …"


Greenhouse Gas Pollution (Light duty vehicles only)
(Billion/ tonnes CO2-equivalent/year)
2.5
2.0
1.5
1.0
0.5
-
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
1990 LDV GHG
100% Gasoline ICVs
Base Case: Gasoline Hybrid Scenario
Gasoline Plug-In Hybrid Scenario
Ethanol Plug-In Hybrid Scenario
BEV Scenario
H2 ICE HEV Scenario
Fuel Cell Vehicle Scenario
GHG Goal: 60% below 1990 Pollution
GHG Goal: 80% below 1990 Pollution

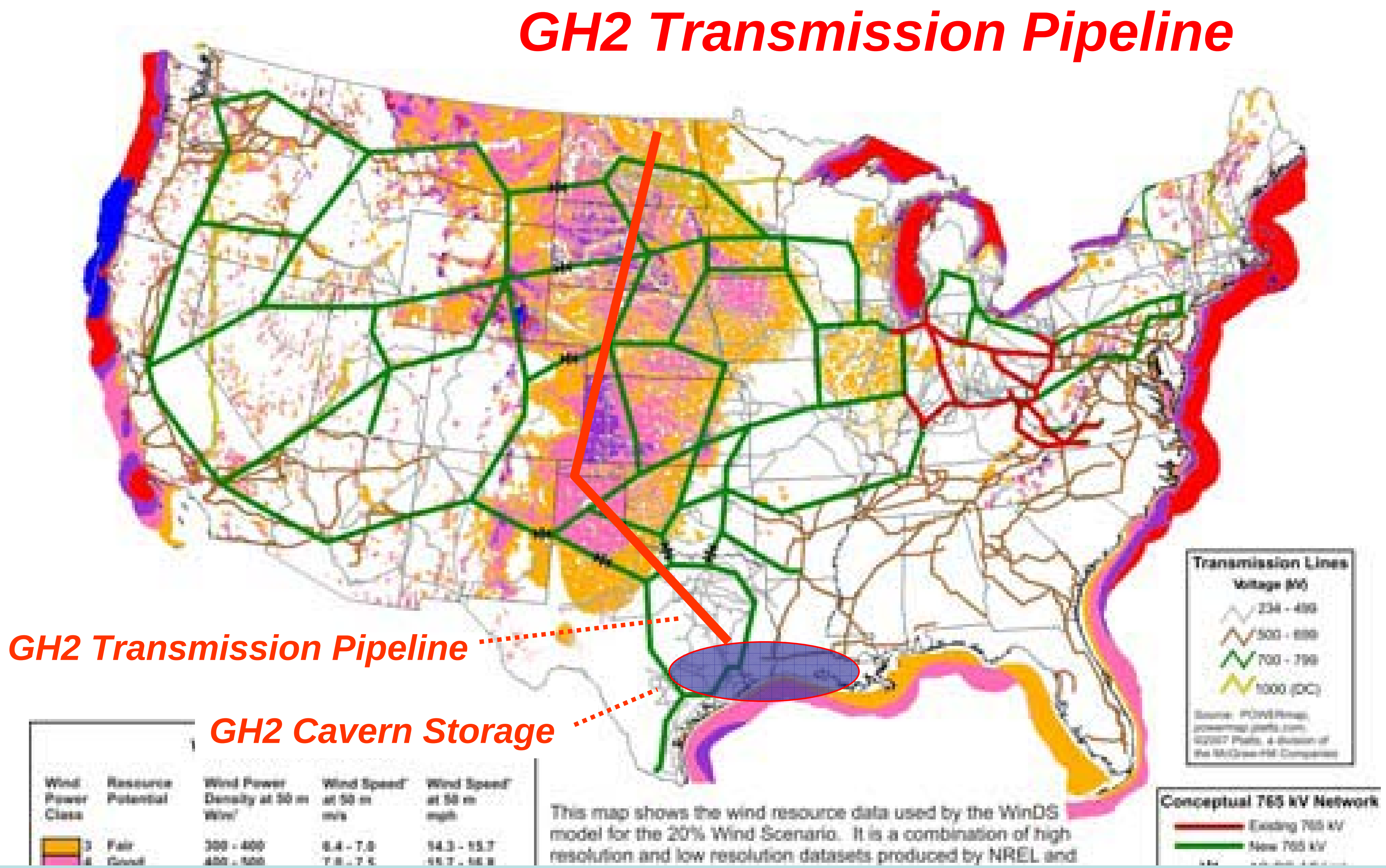
CA: 20% of "cars" hydrogen fueled by 2030

- 20% of 45M vehicles = 9M
- @ 78 mpg = 78 miles / kg H2
- 12,000 miles / year = 150 kg H2 / year
- 1,800 M kg H2 / year = 1.65 MMt H2 fuel
- @ 50 kWh / kg at windplant gate:
  - 82,500 GWh / year
  - @ 40% CF = 23,000 MW nameplate wind
  - Requires 3 GH2 pipelines, 36", 500 miles long
  - PLUS @ 4 caverns / GW = 92 storage caverns, to firm the supply at annual scale

AWEA 20% Wind by 2030

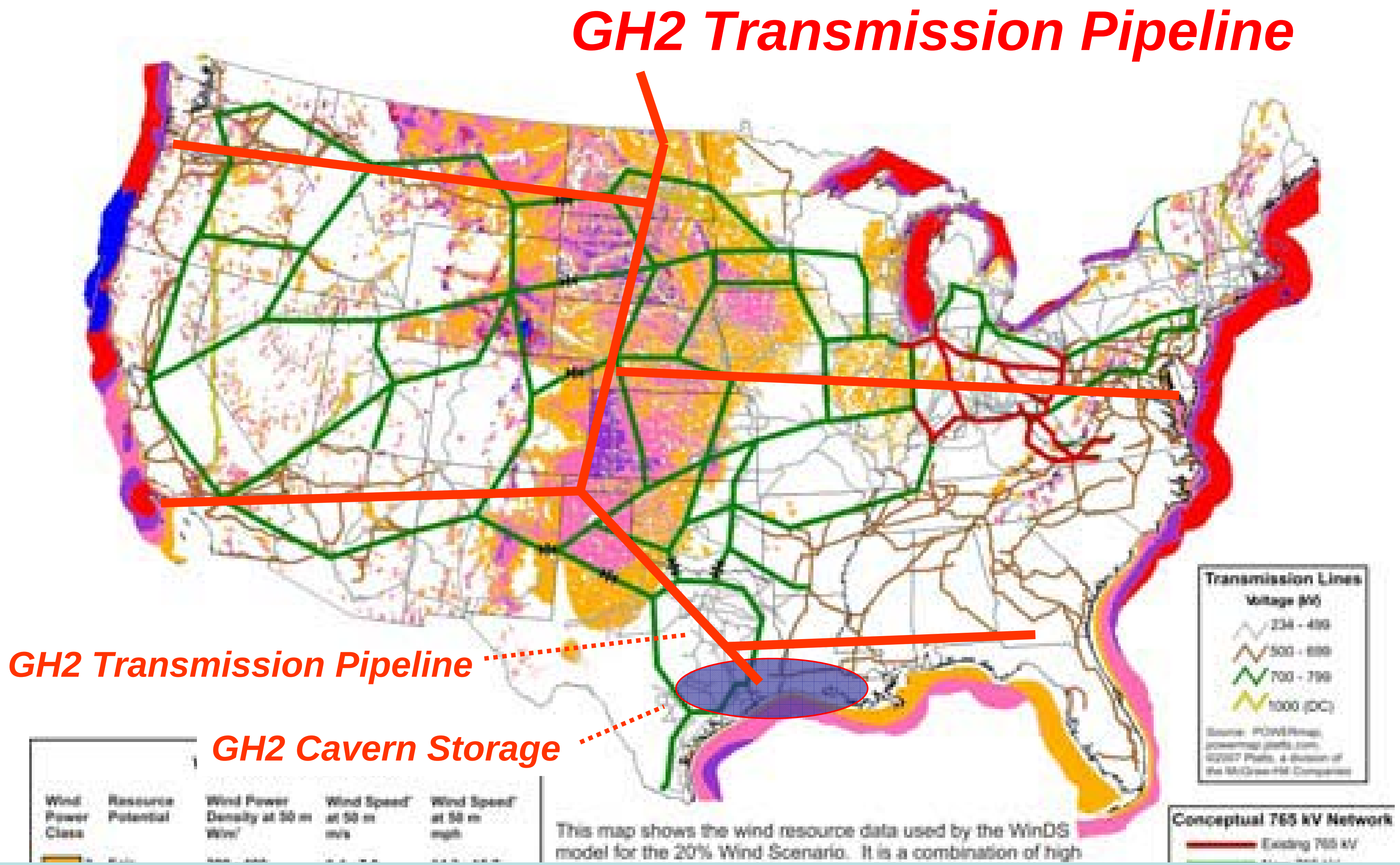


“Never be built ...”



Wind Potential ~ 10,000 GW

12 Great Plains states

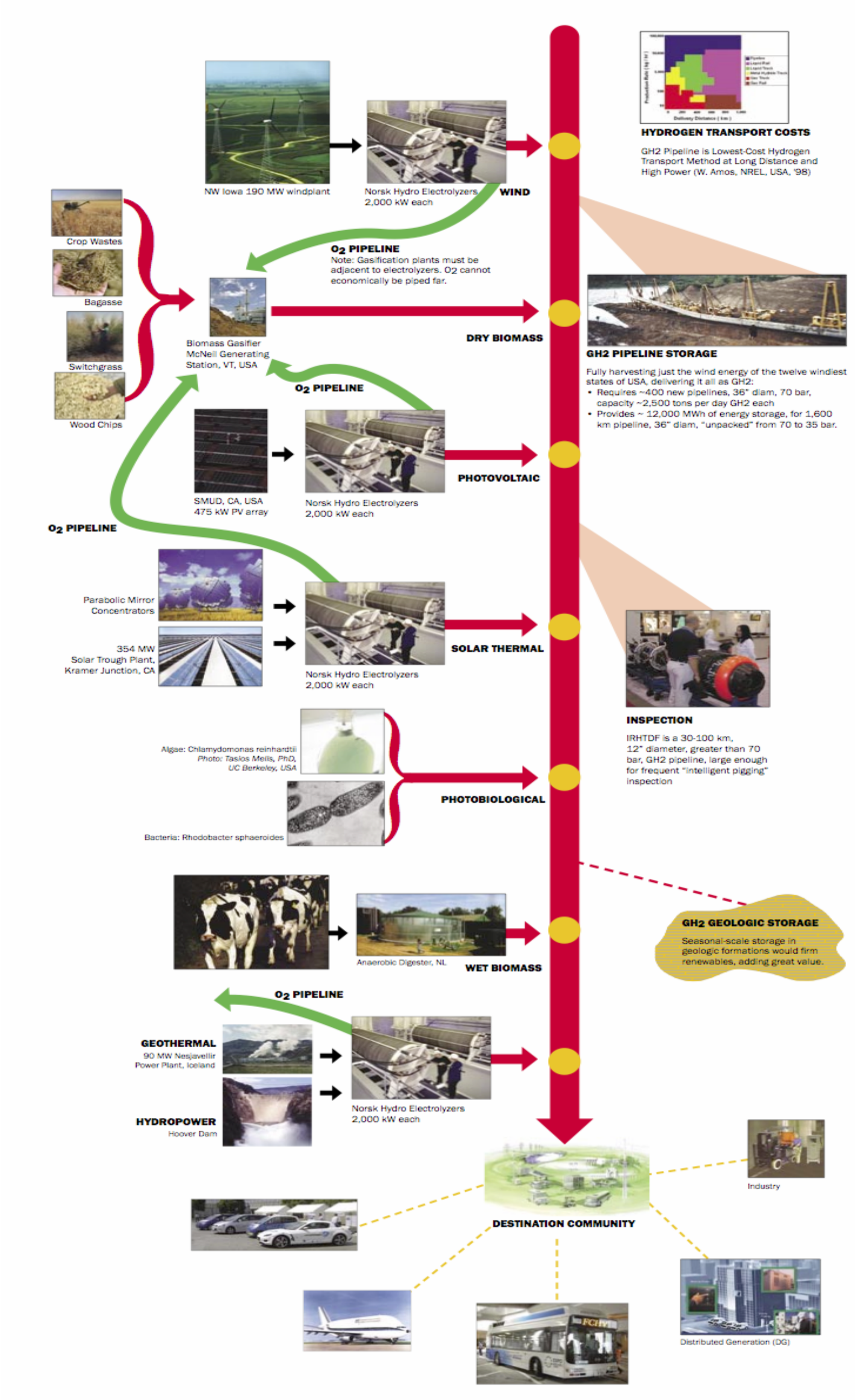


Wind Potential ~ 10,000 GW

12 Great Plains states

Pilot plant needed

- **Every major new industrial process**
- **Renewables-source systems**
- **Diverse, large-scale, stranded**
- **IPHE → " IRHTDF "**

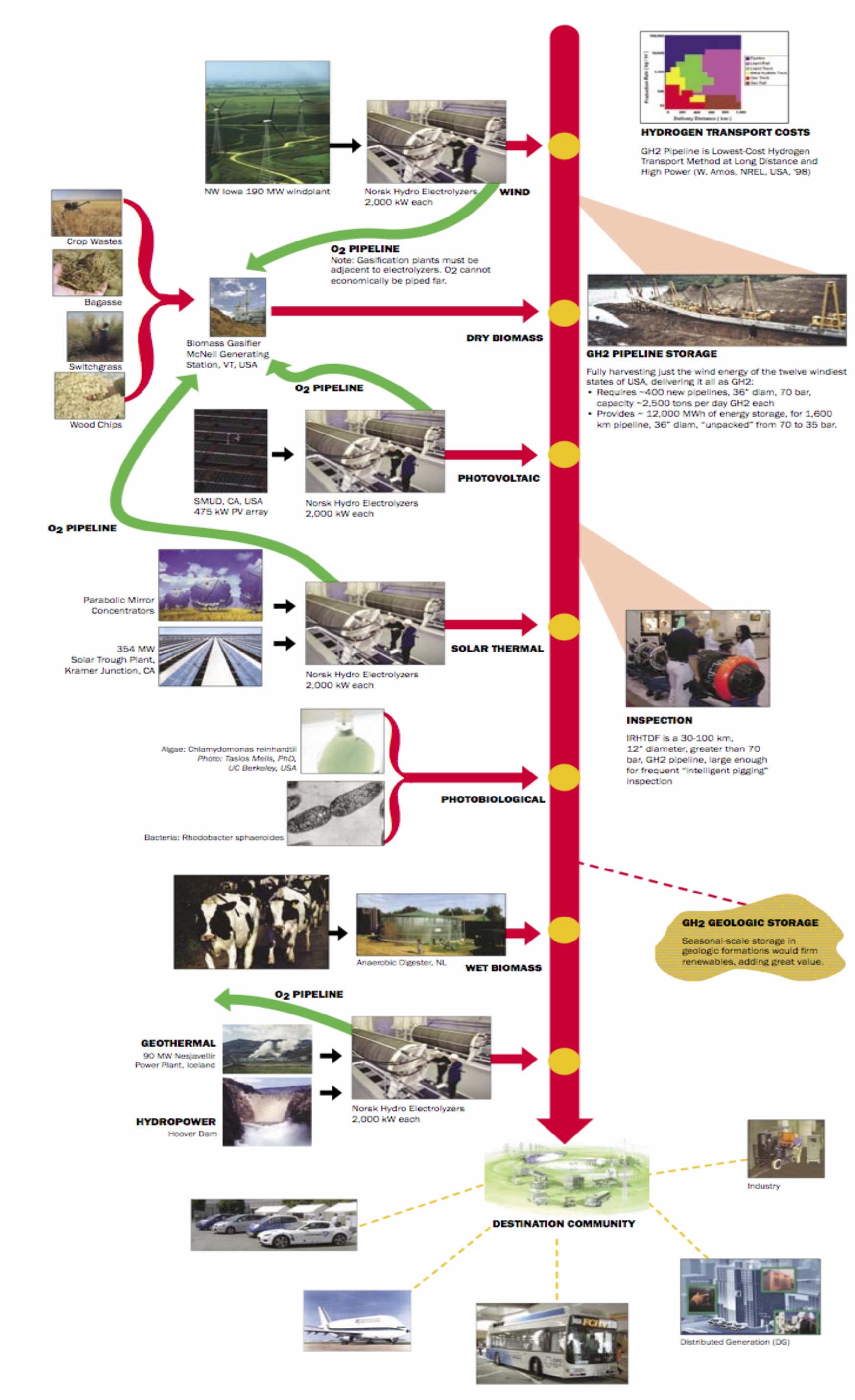


International Renewable Hydrogen Transmission Demonstration Facility

(IRHTDF)

Pilot plant

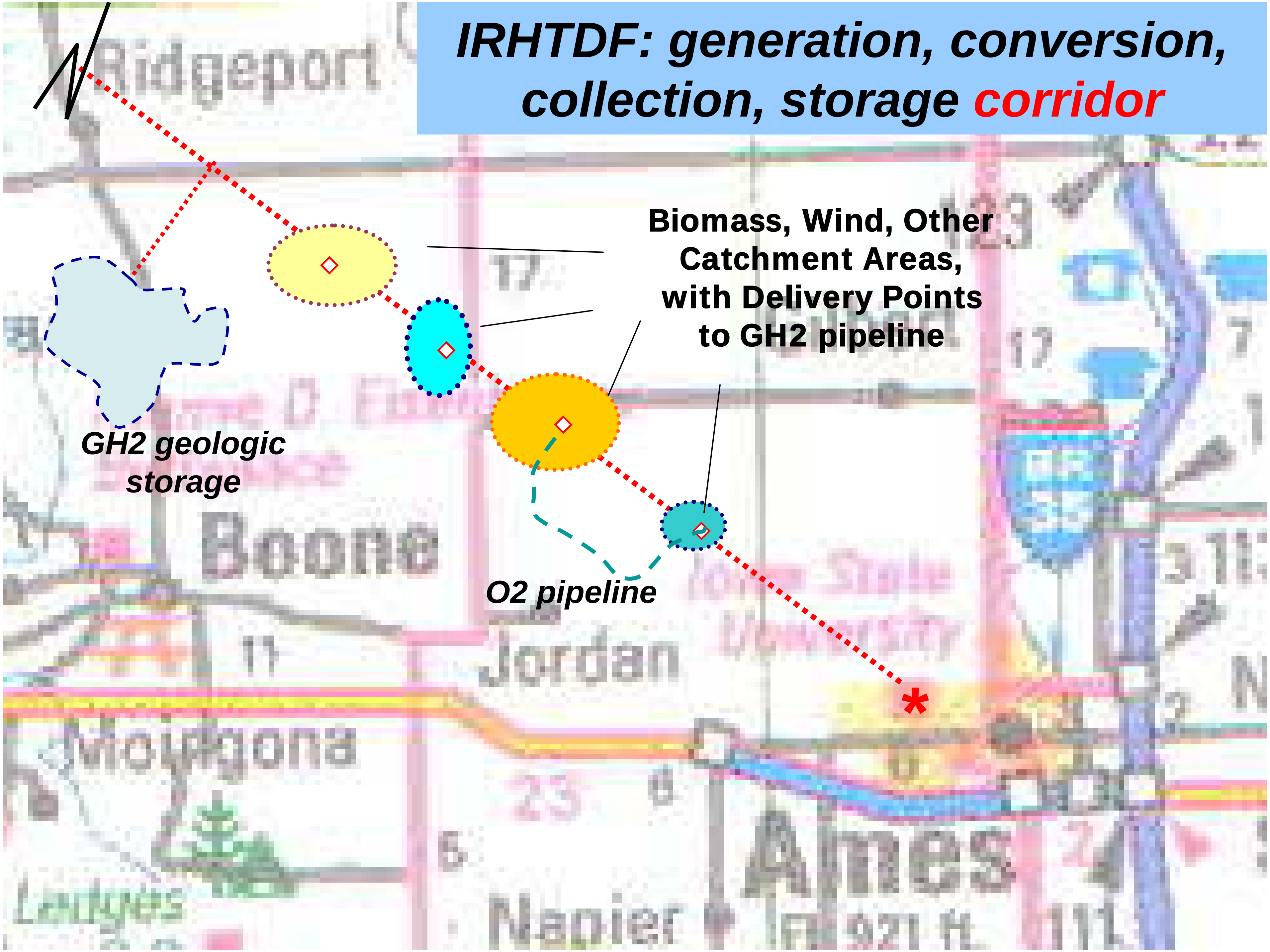
Global opportunity: IPHE project

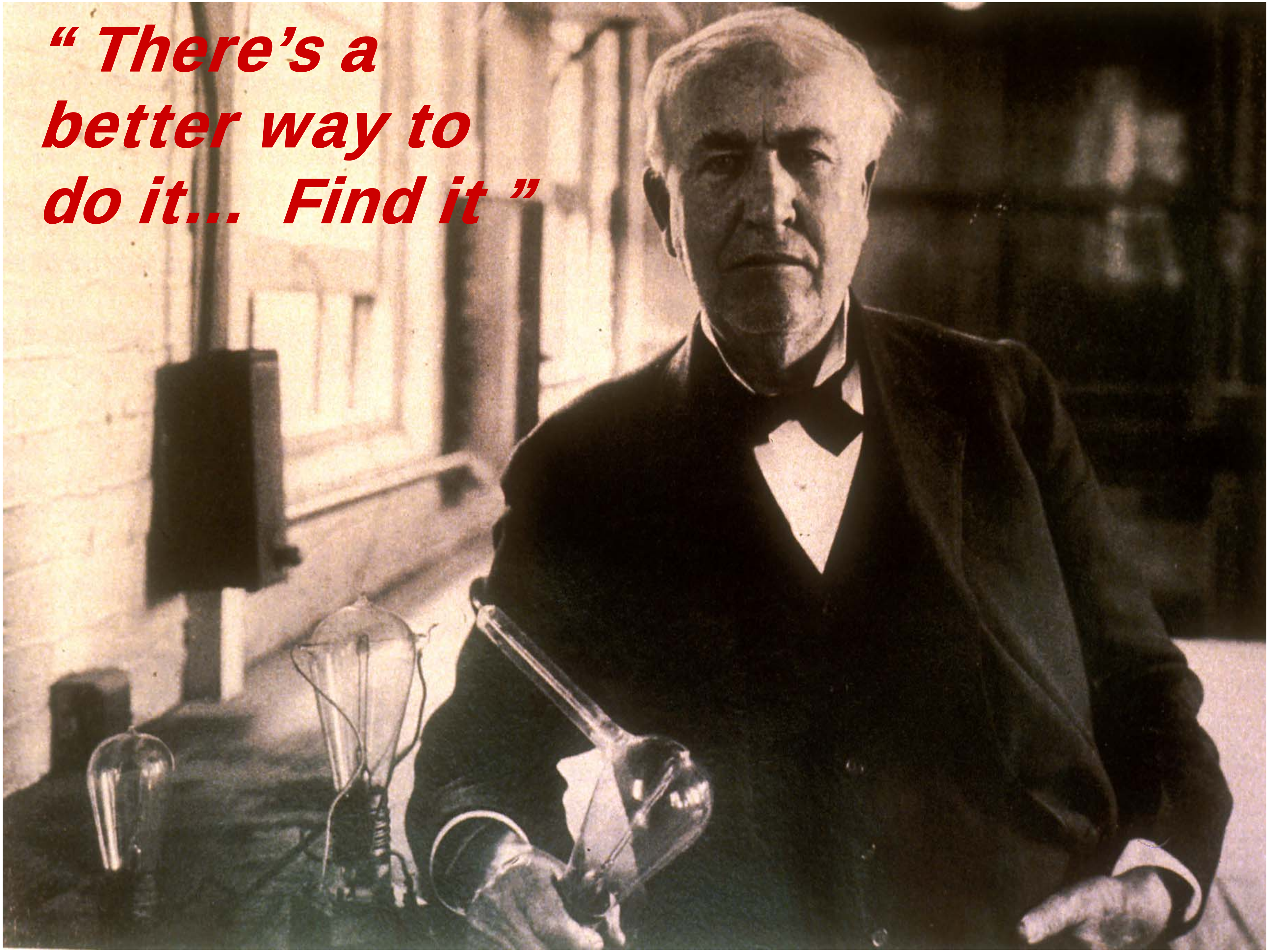


Pilot-scale Hydrogen Pipeline System: Renewables

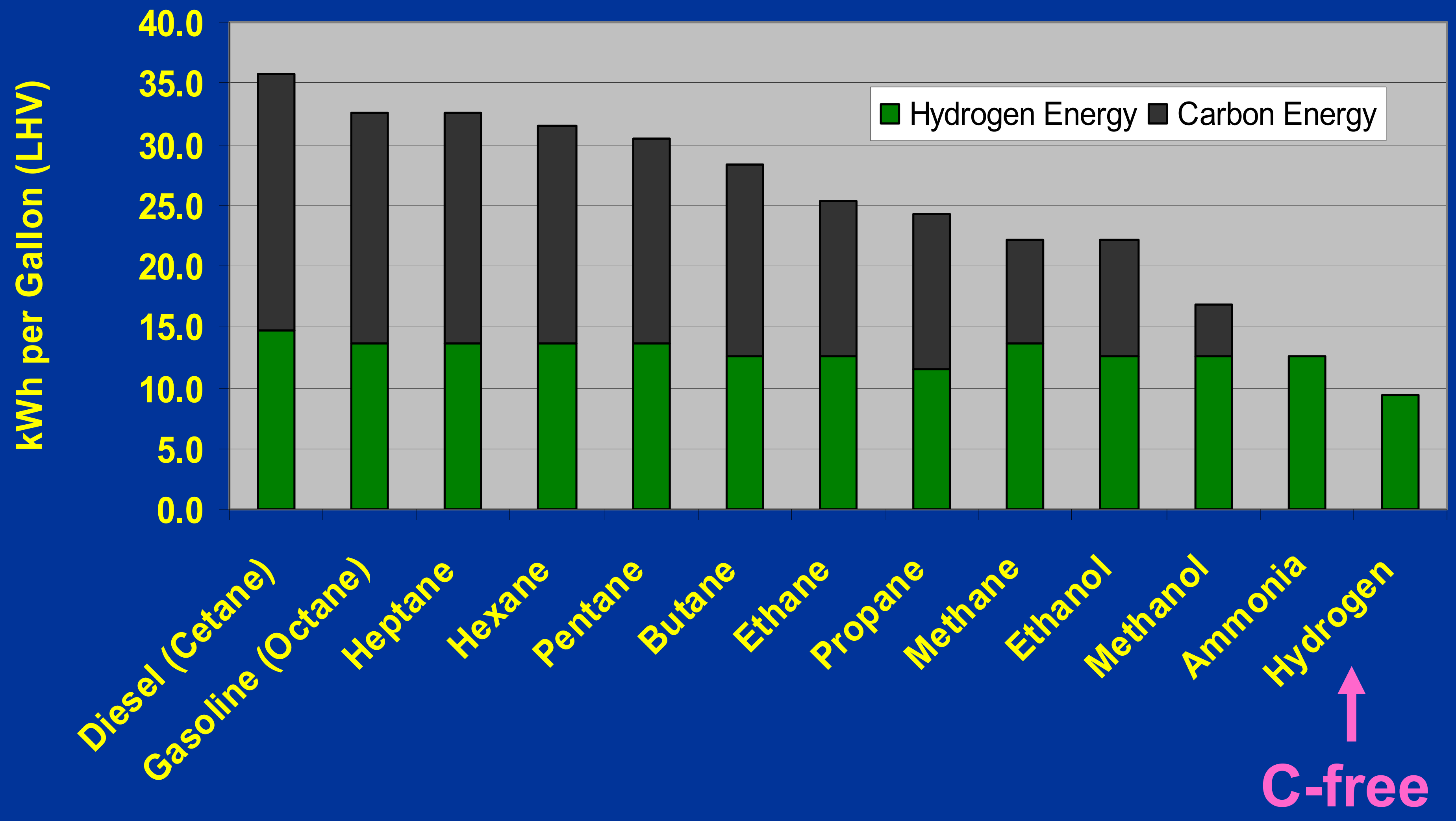
- ***Diverse***
- ***Dispersed, diffuse***
- ***Large-scale***
- ***Stranded***
  - ***Remote***
  - ***No transmission***

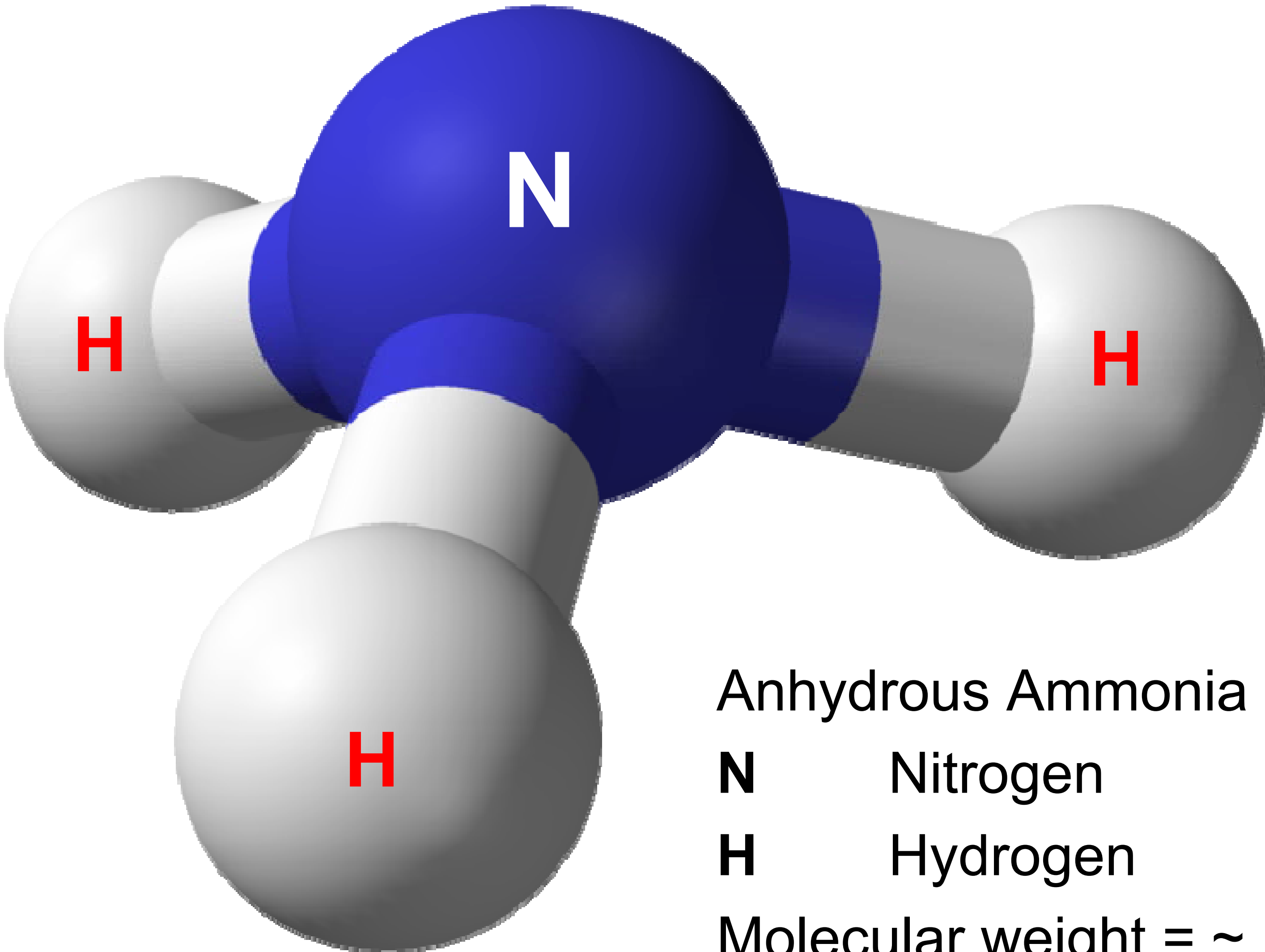
IRHTDF: generation, conversion, collection, storage corridor




" There's a
better way to
do it… Find it "

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





Anhydrous Ammonia **NH_3**

N Nitrogen

H Hydrogen

Molecular weight = ~ 17

18% **H** by weight: “other hydrogen”

$NH_3 + O_2 = N_2 + H_2O$

Why Ammonia ?

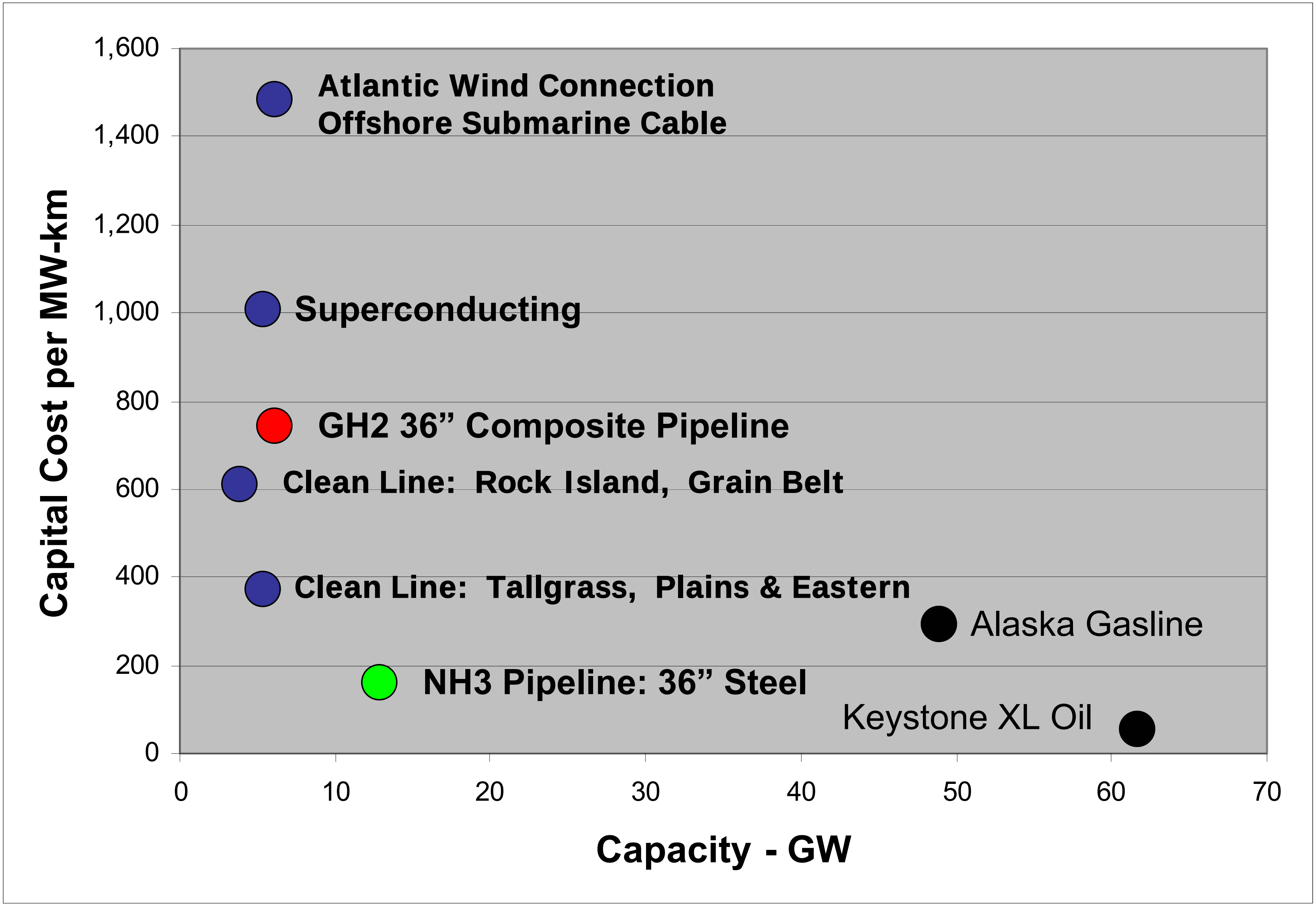
Fertilizer <u>and</u> Fuel

Only liquid fuel embracing:

- Carbon-free: clean burn or conversion; no CO_2
  - Excellent hydrogen carrier
  - Easily "cracked" to H_2
- 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

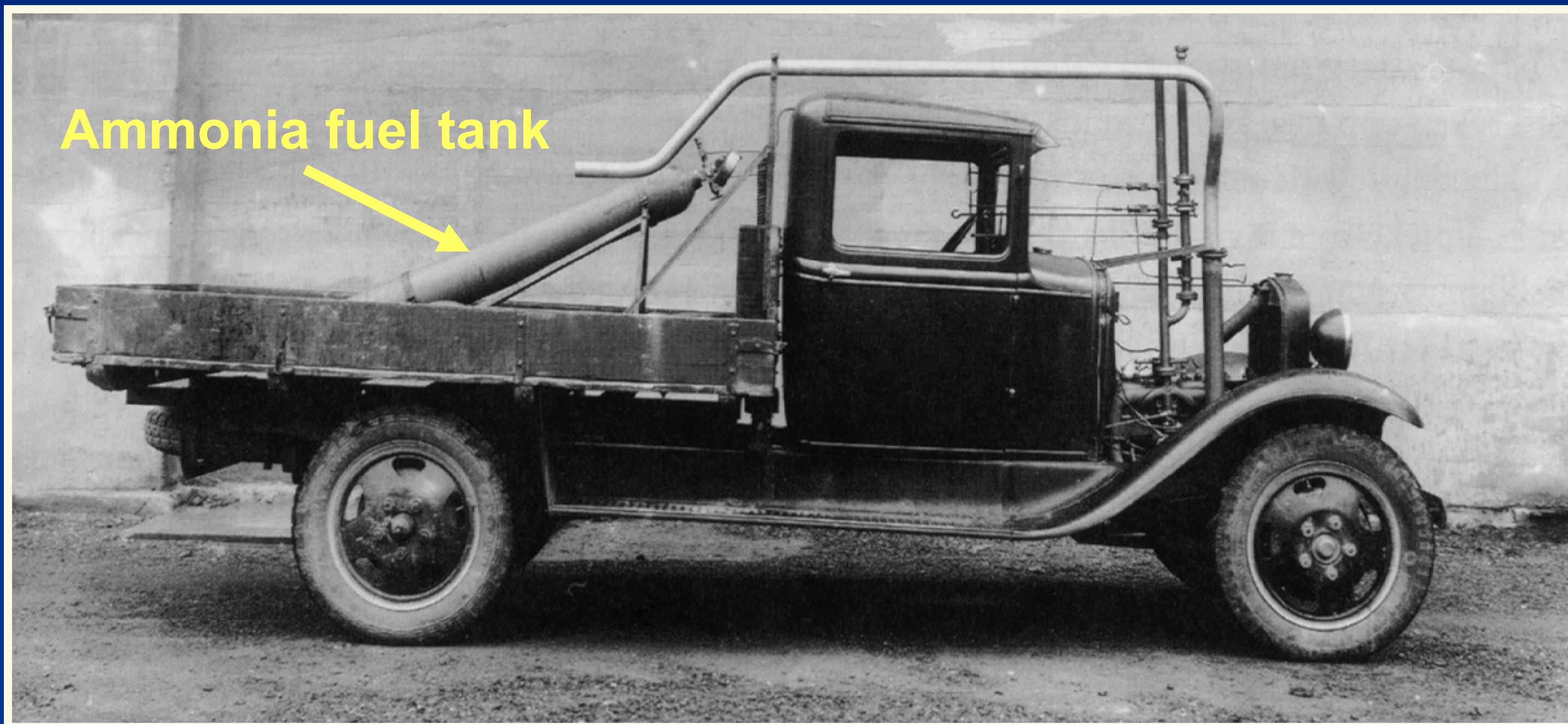
Ammonia Fuel Uses

1. Internal Combustion Engine (ICE)
   - Diesel: NH_3 gas mixed with intake air
   - Spark-ignition: 70%+ NH_3 plus gasoline, ethanol, propane, NG, hydrogen
   - NOx ~ ¼ gasoline engines
2. Combustion Turbines
3. Direct Ammonia Fuel Cells:
   - Combined heat + power (CHP)
   - No NOx
4. Reform ("crack") to liberate hydrogen for fuel cells: $2NH_3 \rightarrow 3H_2 + N_2$

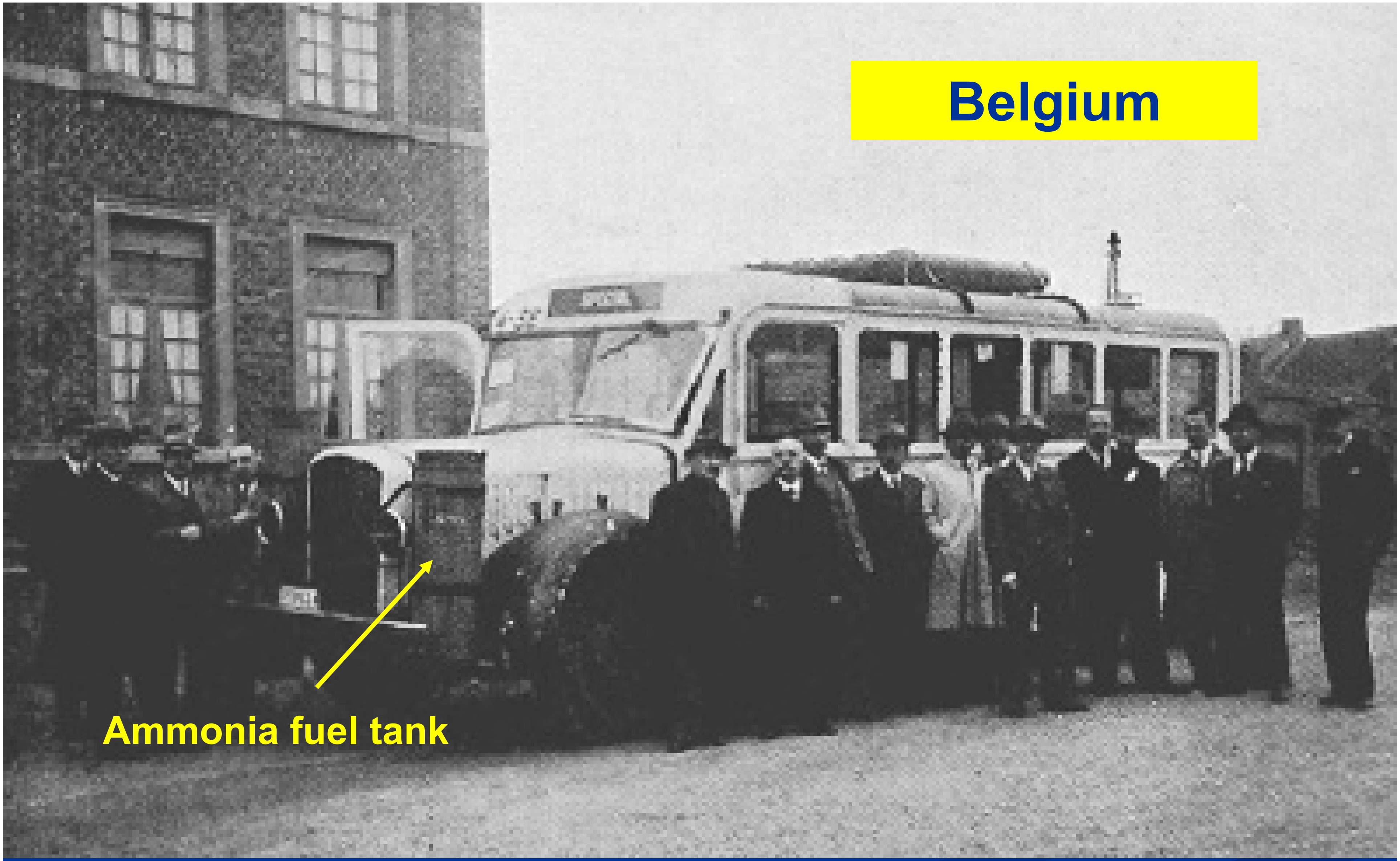


Capital Cost per MW-km
1,600
1,400
1,200
1,000
800
600
400
200
0
Atlantic Wind Connection
Offshore Submarine Cable
Superconducting
GH2 36" Composite Pipeline
Clean Line: Rock Island, Grain Belt
Clean Line: Tallgrass, Plains & Eastern
Alaska Gasline
NH3 Pipeline: 36" Steel
Keystone XL Oil
0
10
20
30
40
50
60
70
Capacity - GW

Ammonia fueled – Norway



1933



Ammonia Fueled Bus: Thousands of Problem-free Miles

1943

X-15 rocket plane: NH3 + LOX fuel

Mach 6.7 on 3 Oct 67

199 missions

1959 - 68

University of Michigan

Ammonia + Gasoline Powered

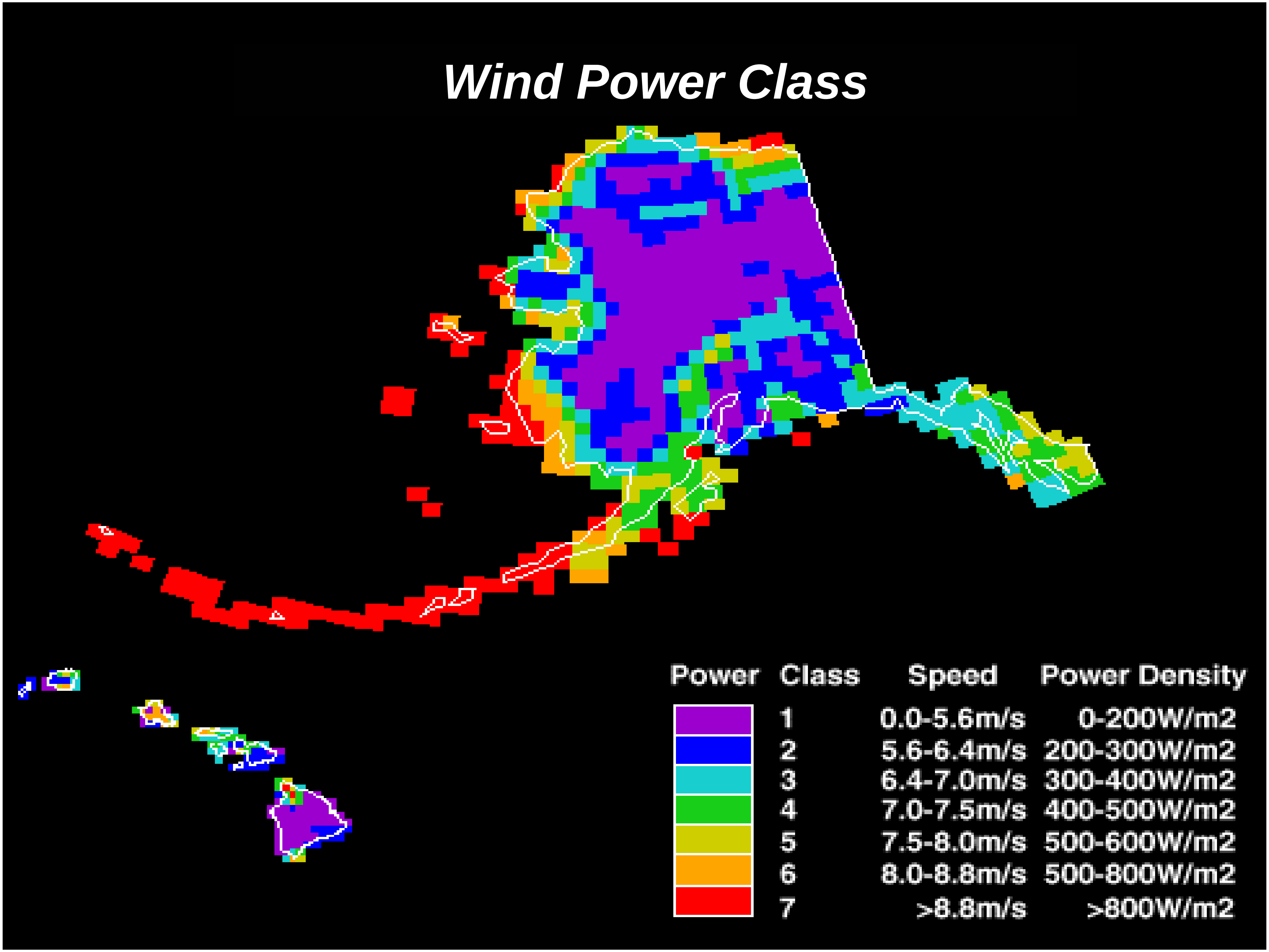
- Idle: gasoline
- Full power: 80% ammonia

Summer ’07 Detroit → San Francisco

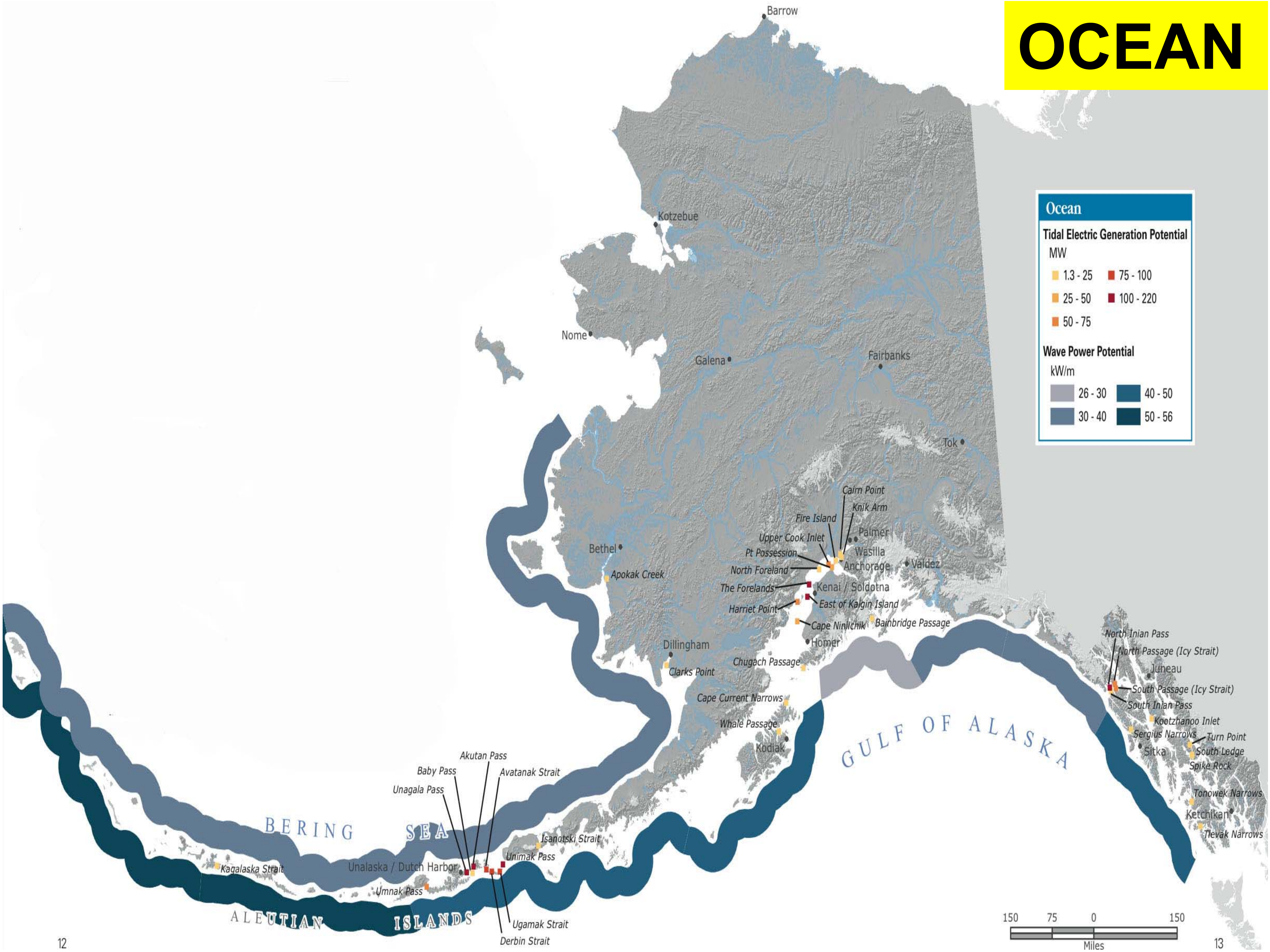
2007

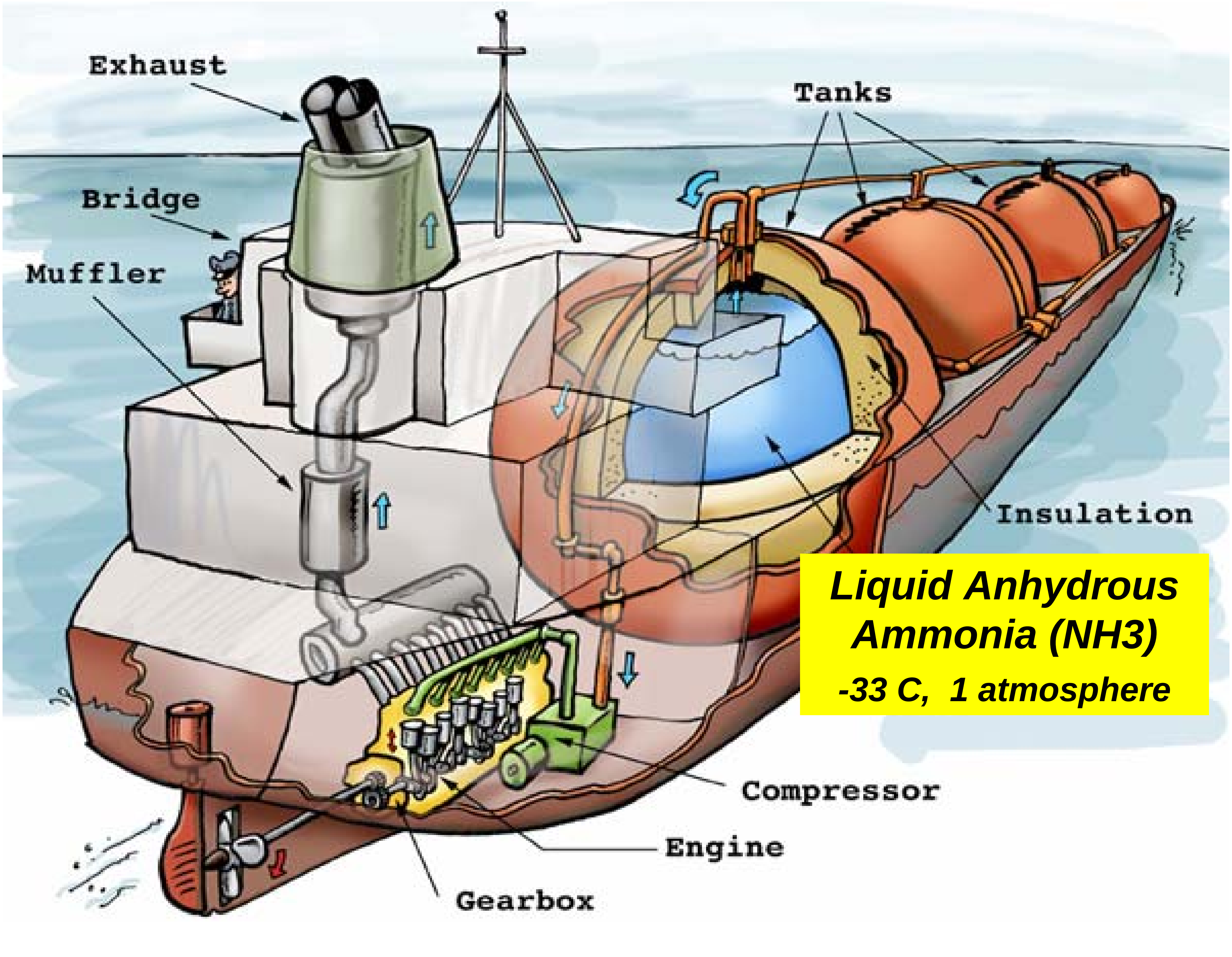
1,000 hours, ICE, 6 cyl, 100 hp
75% ammonia, 25% propane

NH_3 Ag Fertilizer Tanks, Wind Generators, NW Iowa


Wind Power Class
Power Class
Speed
Power Density
1 0.0-5.6m/s 0-200W/m2
2 5.6-6.4m/s 200-300W/m2
3 6.4-7.0m/s 300-400W/m2
4 7.0-7.5m/s 400-500W/m2
5 7.5-8.0m/s 500-600W/m2
6 8.0-8.8m/s 500-800W/m2
7 >8.8m/s >800W/m2

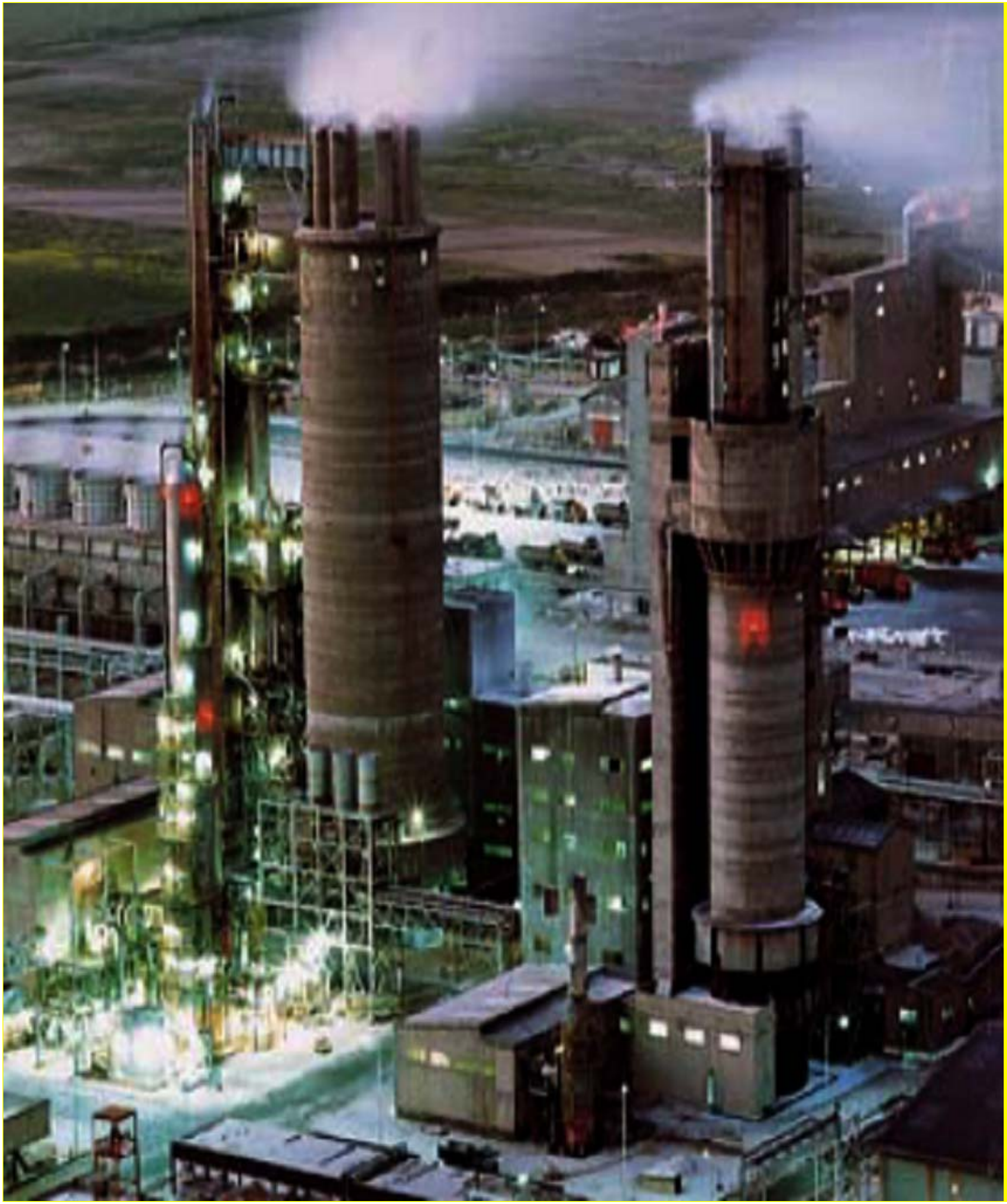
OCEAN


Ocean
Tidal Electric Generation Potential
MW
1.3 - 25
25 - 50
50 - 75
75 - 100
100 - 220
Wave Power Potential
kW/m
26 - 30
30 - 40
40 - 50
50 - 56
Barrow
Kotzebue
Nome
Galena
Fairbanks
Tok
Bethel
Apokak Creek
Dillingham
Clarks Point
Cairn Point
Knik Arm
Fire Island
Upper Cook Inlet
Pt Possession
North Foreland
The Forelands
Harriet Point
Palmer
Wasilla
Anchorage
Valdez
Kenai / Soldotna
East of Kalgin Island
Cape Ninilchik
Bainbridge Passage
Homer
Chugach Passage
Cape Current Narrows
Whale Passage
Kodiak
GULF OF ALASKA
BERING SEA
ALEUTIAN ISLANDS
Akutan Pass
Baby Pass
Avatanak Strait
Unagala Pass
Isanotski Strait
Unimak Pass
Unalaska / Dutch Harbor
Kagalaska Strait
Umnak Pass
Ugamak Strait
Derbin Strait
North Inian Pass
North Passage (Icy Strait)
Juneau
South Passage (Icy Strait)
South Inian Pass
Kootzhanoo Inlet
Sergius Narrows
Turn Point
Sitka
South Ledge
Spike Rock
Tonowek Narrows
Ketchikan
Tlevak Narrows
150 75 0 150
Miles



Liquid Anhydrous Ammonia (NH_3)

-33 C, 1 atmosphere



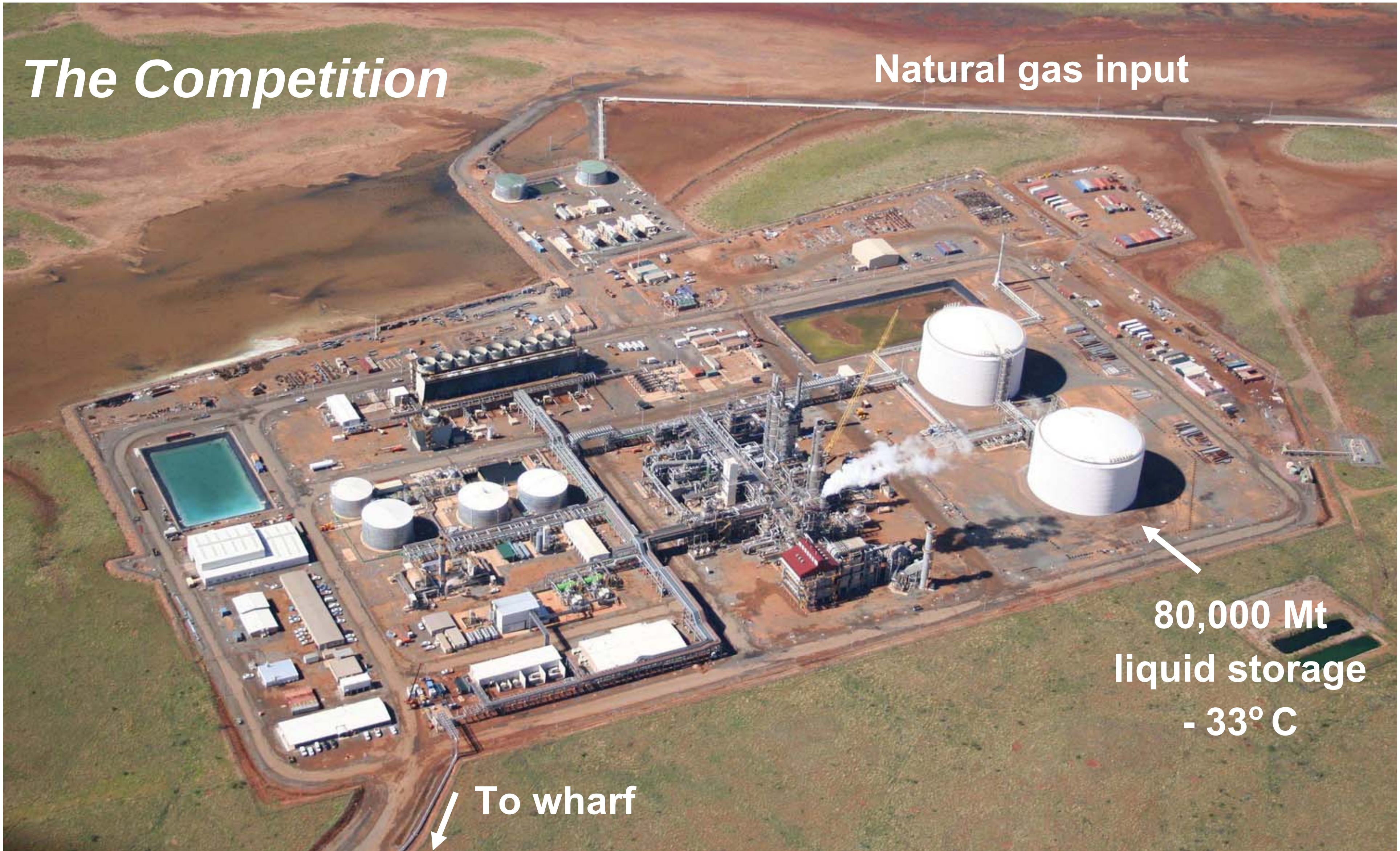
95% Global Ammonia ~140 MMtpy

Synthesis Plant

Natural Gas

1 – 3,000 tpd

Haber-Bosch process



Burrup Peninsula, NW Australia, Natural Gas to Ammonia Plant

760,000 Mt / year

$US 650 million capital cost ‘06

Fritz Haber

Carl Bosch

Haber-Bosch Process

1909 – 1913 BASF

- NH_3 synthesis
- Coal gasification → H2
- WW I explosives
- 40% humanity: N fertilizer

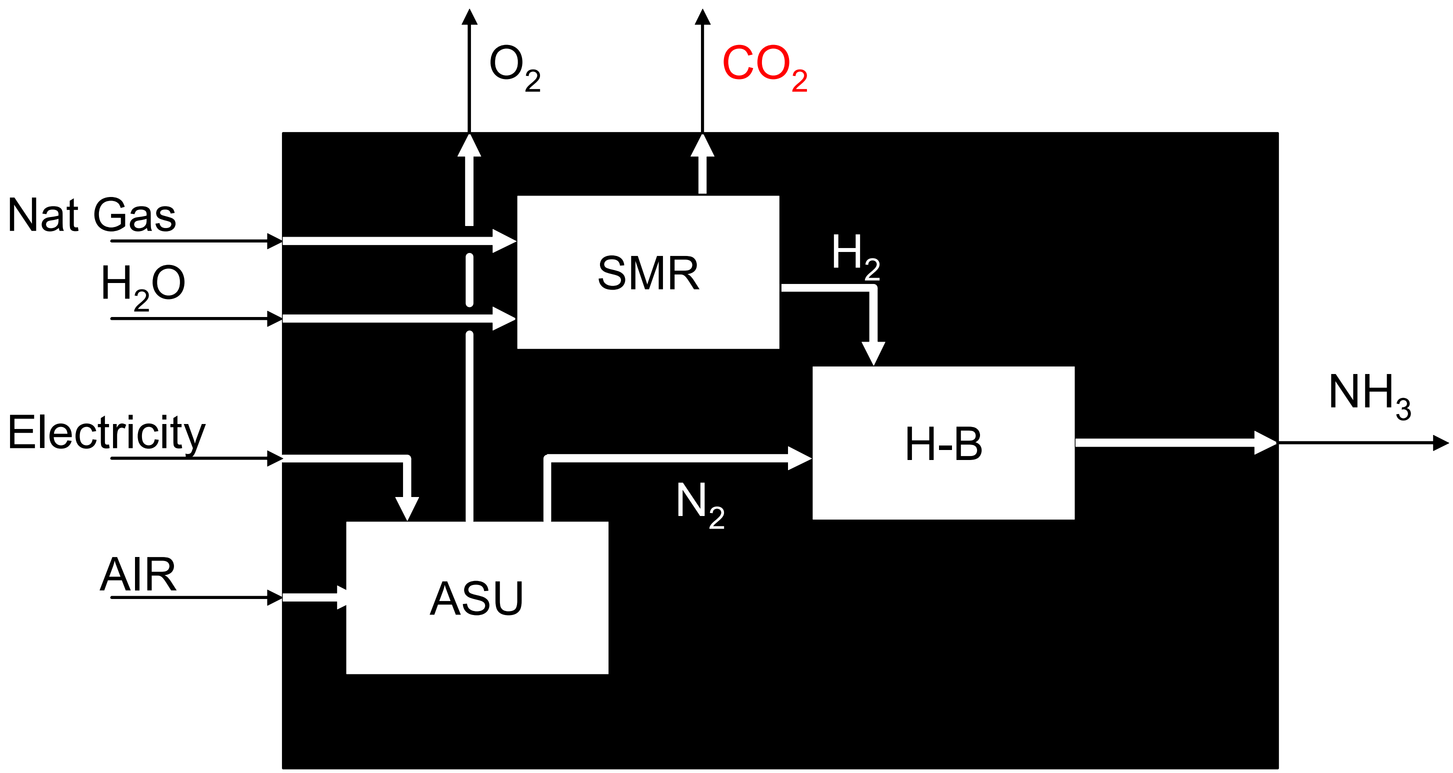
Haber-Bosch Reactor

1921

Ludwigshafen, Germany

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

$$3\ CH_4 + 6\ H_2O + 4\ N_2 \rightarrow 3\ CO_2 + 8\ NH_3$$



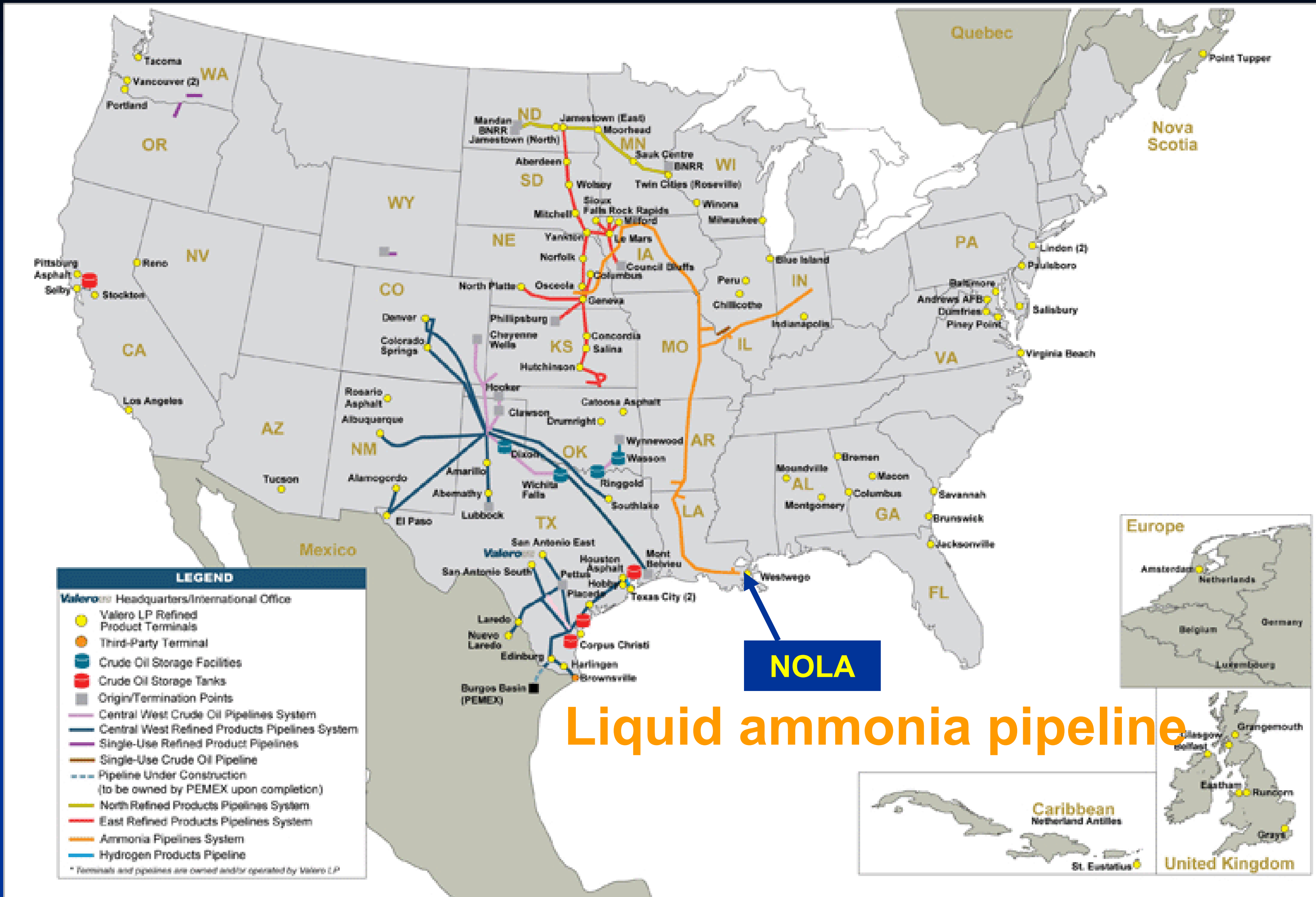
Energy consumption ~33 MMBtu (9,500 kWh) per ton NH_3
Tons CO_2 per ton NH_3 = 1.8

Ammonia Tanker
Burrup Peninsula
Western Australia

Ammonia or LPG Tanker

To 35,000 Mt

Refrigerated



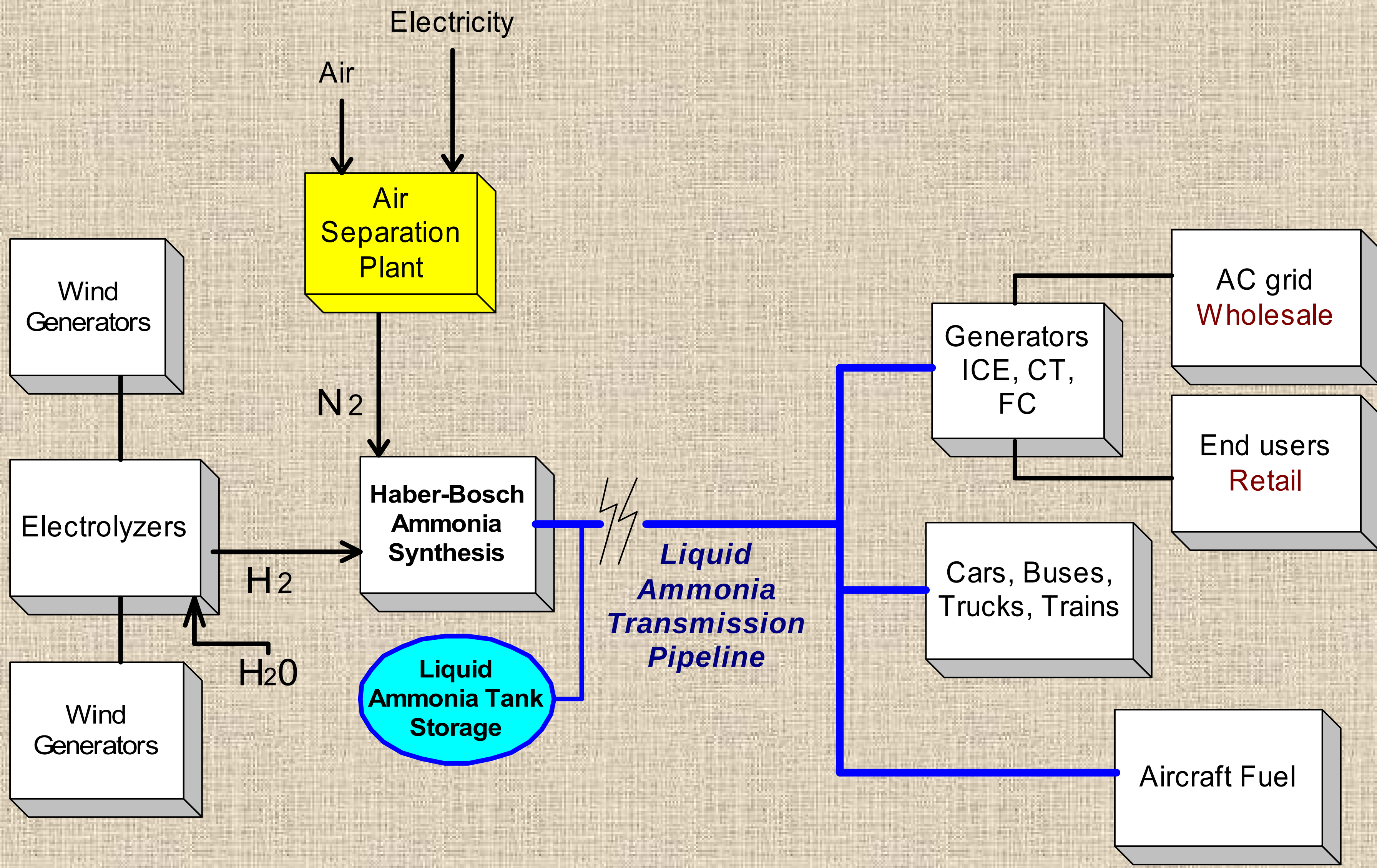
Valero LP Operations

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

Ammonia Storage Terminal
Mississippi River
Winona, MN

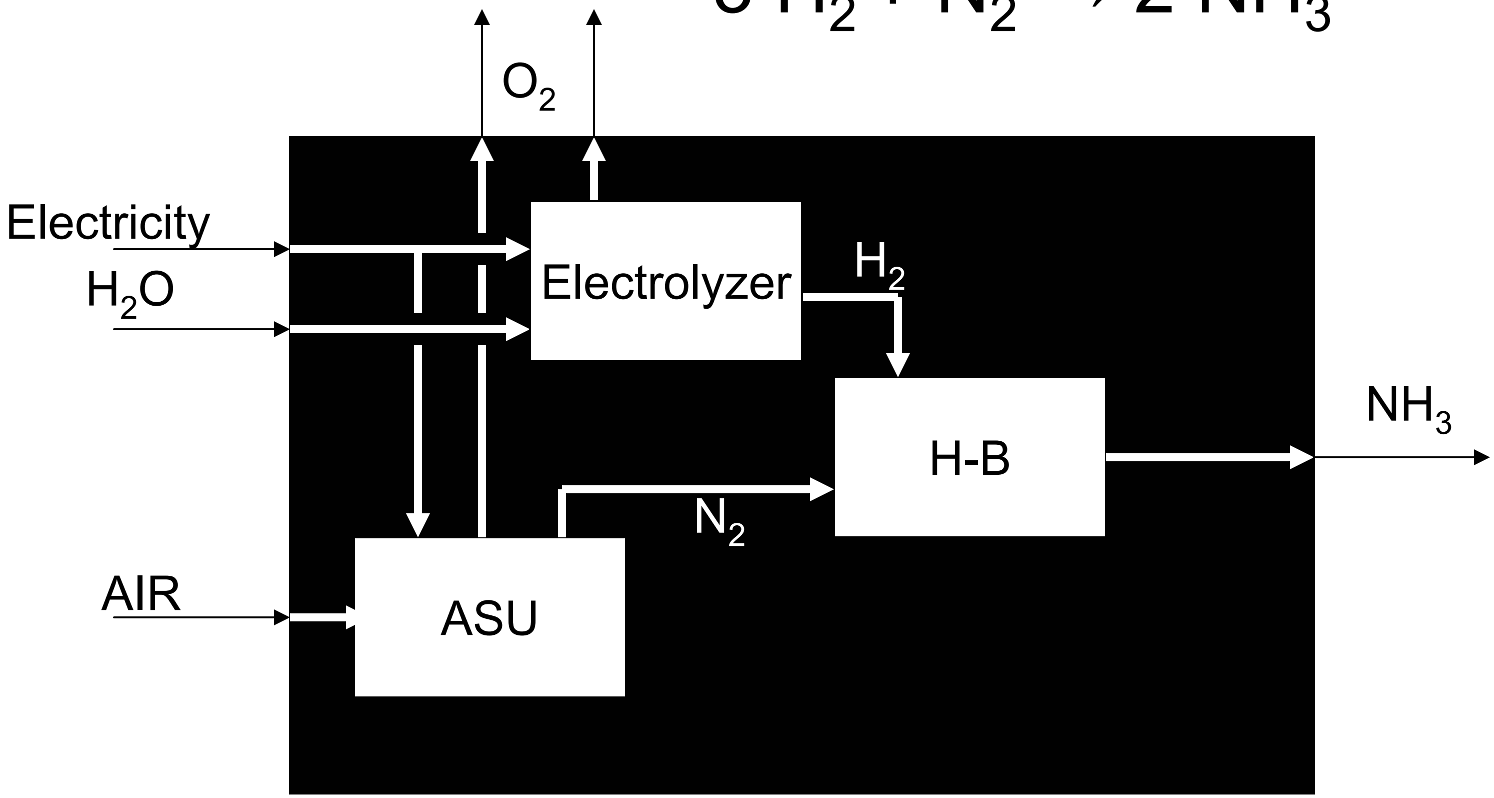
RE Ammonia Transmission + Storage Scenario



Wind – to – Ammonia Potential, NW Iowa

Inside the Black Box: HB Plus Electrolysis

$$3\ H_2O \rightarrow 3\ H_2 + 3/2\ O_2$$
$$3\ H_2 + N_2 \rightarrow 2\ NH_3$$



Energy consumption ~12,000 kWh per ton NH_3

10” NH_3 liquid pipeline cost

- Industry sources, all costs:
  - $750 – 900 K per mile, 10”,
    “uncongested area”
  - $250K per mile “small diameter”
- 1,000 mile pipeline @ 10” = $ 400M
- Capacity 2 GW
- Capital cost = $200K / GW-mile

Capital Cost per GW-mile

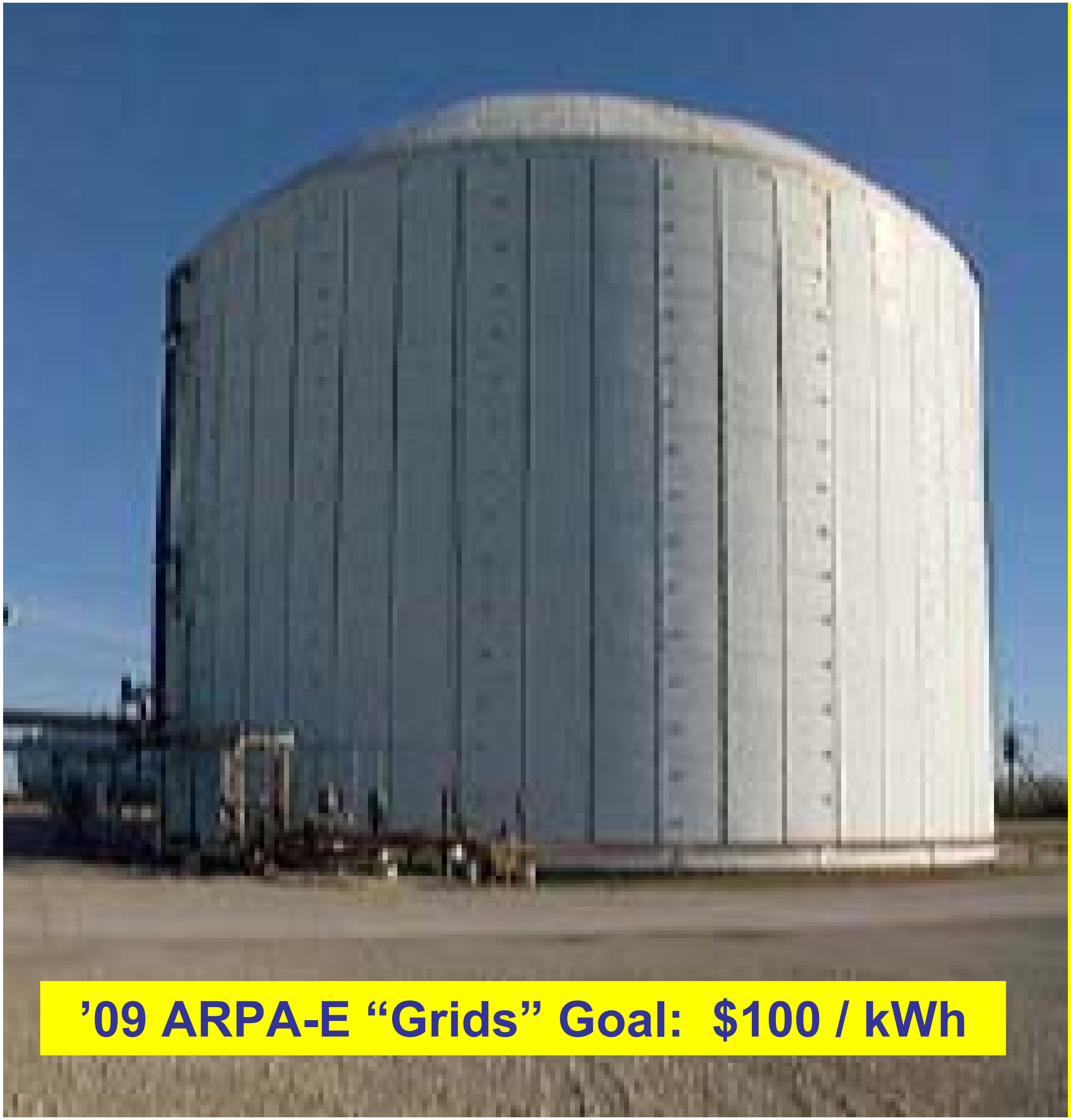
	KV	Capacity MW	$M / GW-mile
Electricity **:**			
• **SEIA:**	**765**	**5,000**	**1.3**
	345	**1,000**	**2.6**
• **AEP-AWEA**	**765**	**5,000**	**3.2**
Consensus ?			**2.5**

Hydrogen pipeline:

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

Ammonia pipeline:

10” , liquid, 500 miles, with pumping 0.2



’09 ARPA-E “Grids” Goal: $100 / kWh

“Atmospheric” Liquid Ammonia Storage Tank (corn belt)

30,000 Tons

190 GWh

$ 15M turnkey

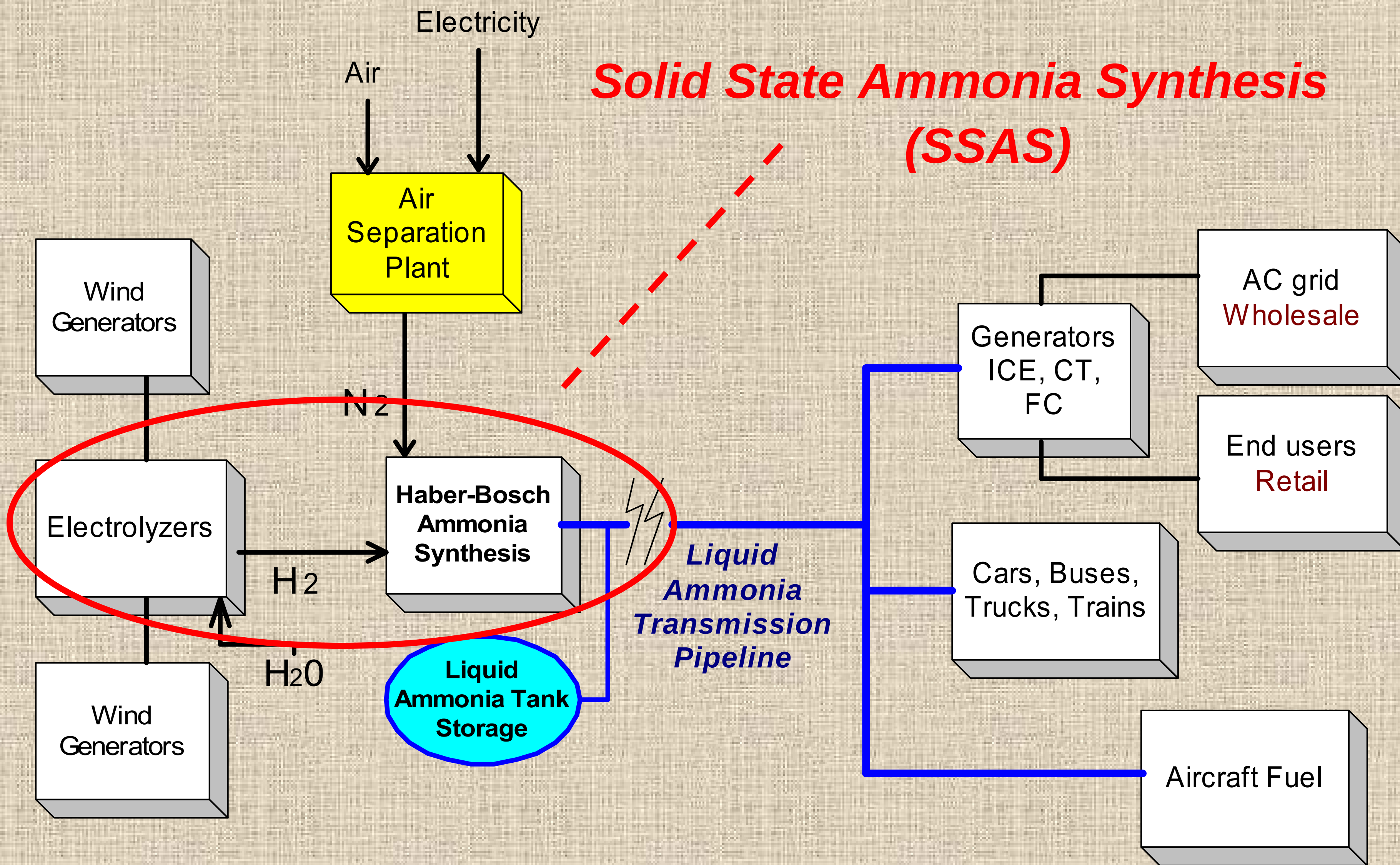
$ 80 / MWh

$ 0.08 / kWh

-33 C

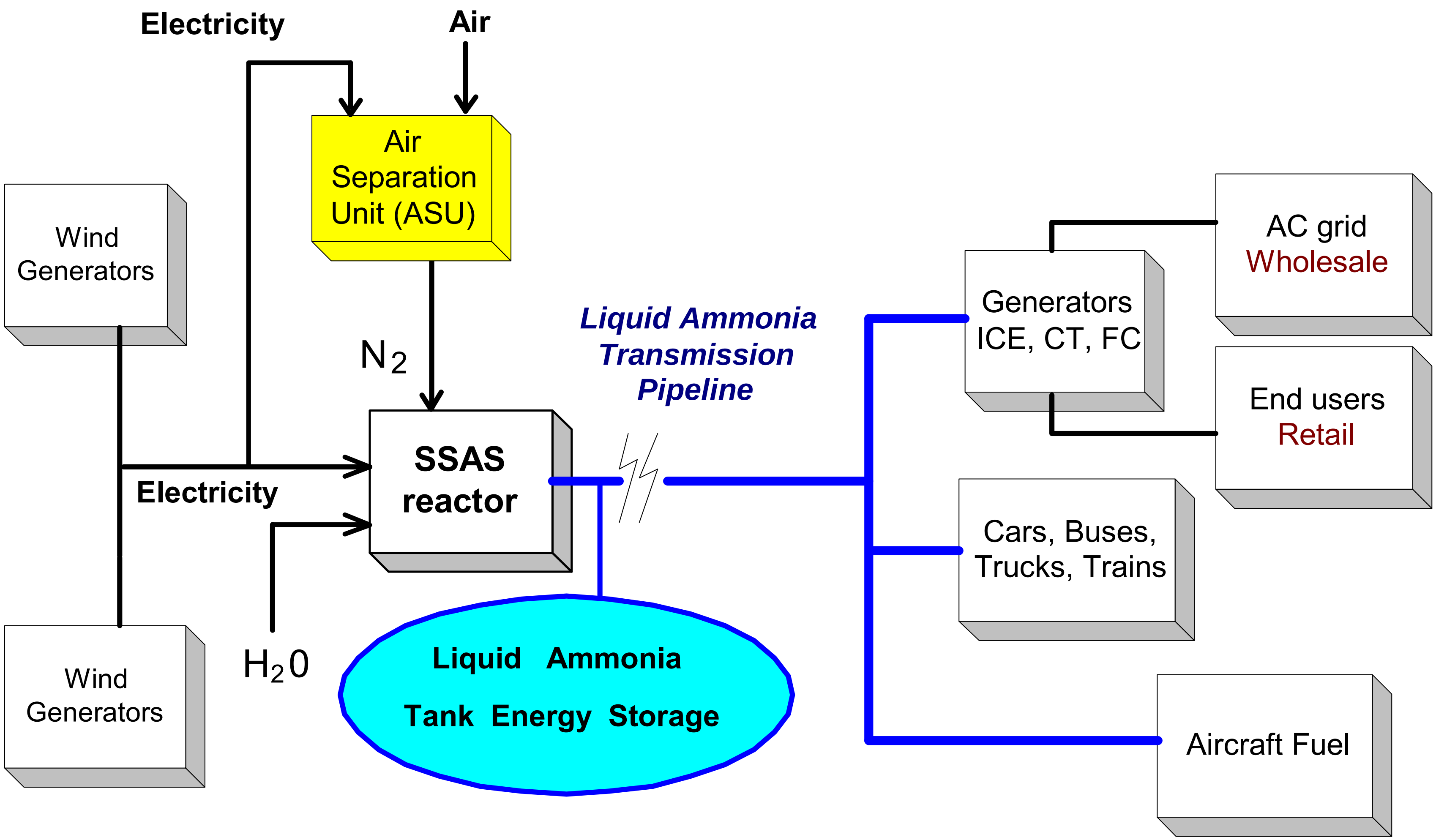
1 Atm

RE Ammonia Transmission + Storage Scenario



Why SSAS ?

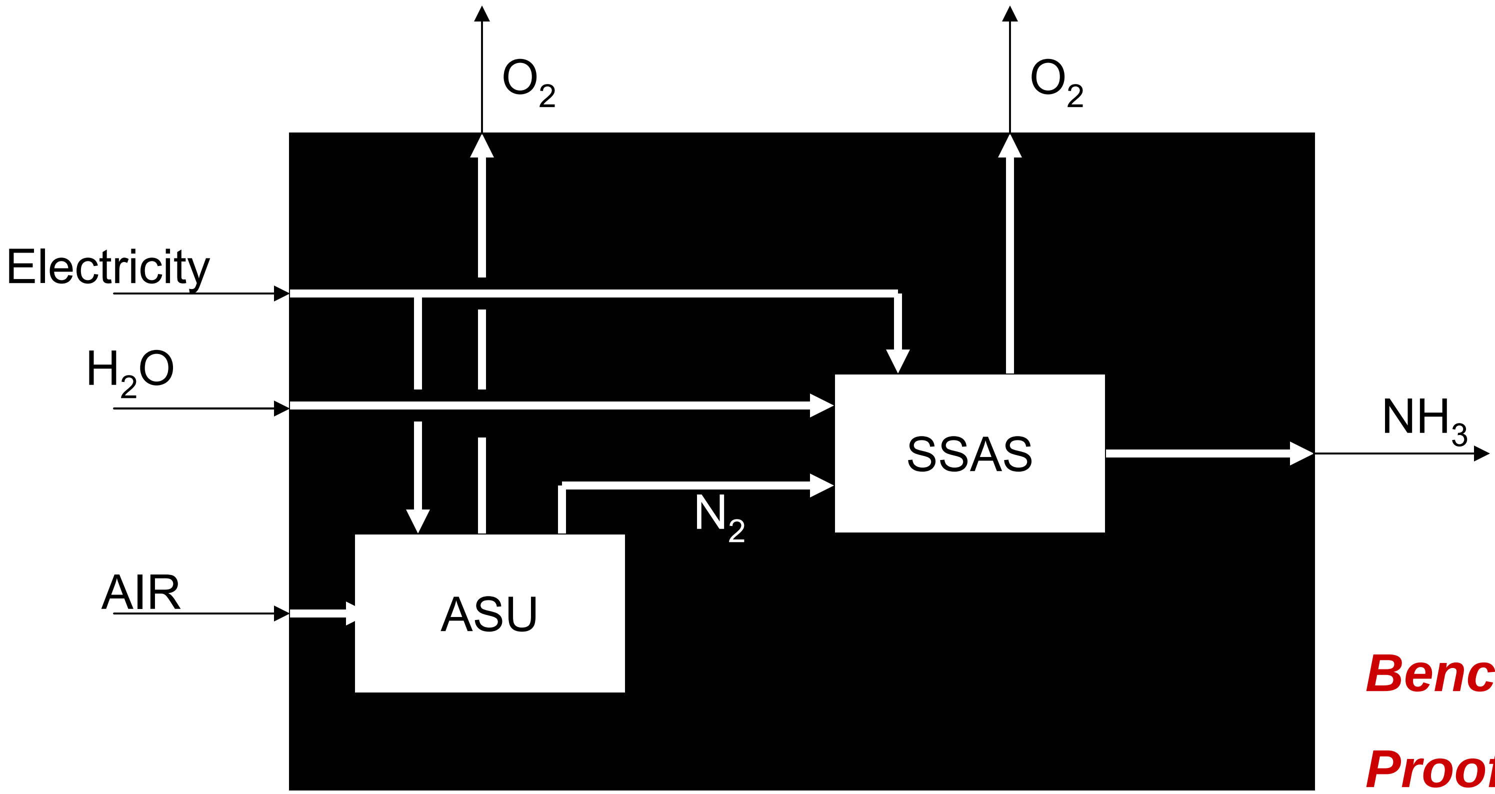
- Electrolysis + Haber-Bosch too costly
  - From RE electricity
  - Capital components at low capacity factor (CF)
  - Energy conversion losses
- Proton conducting ceramics (PCC) now
- Solid oxide fuel cell (SOFC) success
- Need stranded RE transmission
- Need RE storage



Solid State Ammonia Synthesis (SSAS)

Inside the Black Box: Solid State Ammonia Synthesis

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

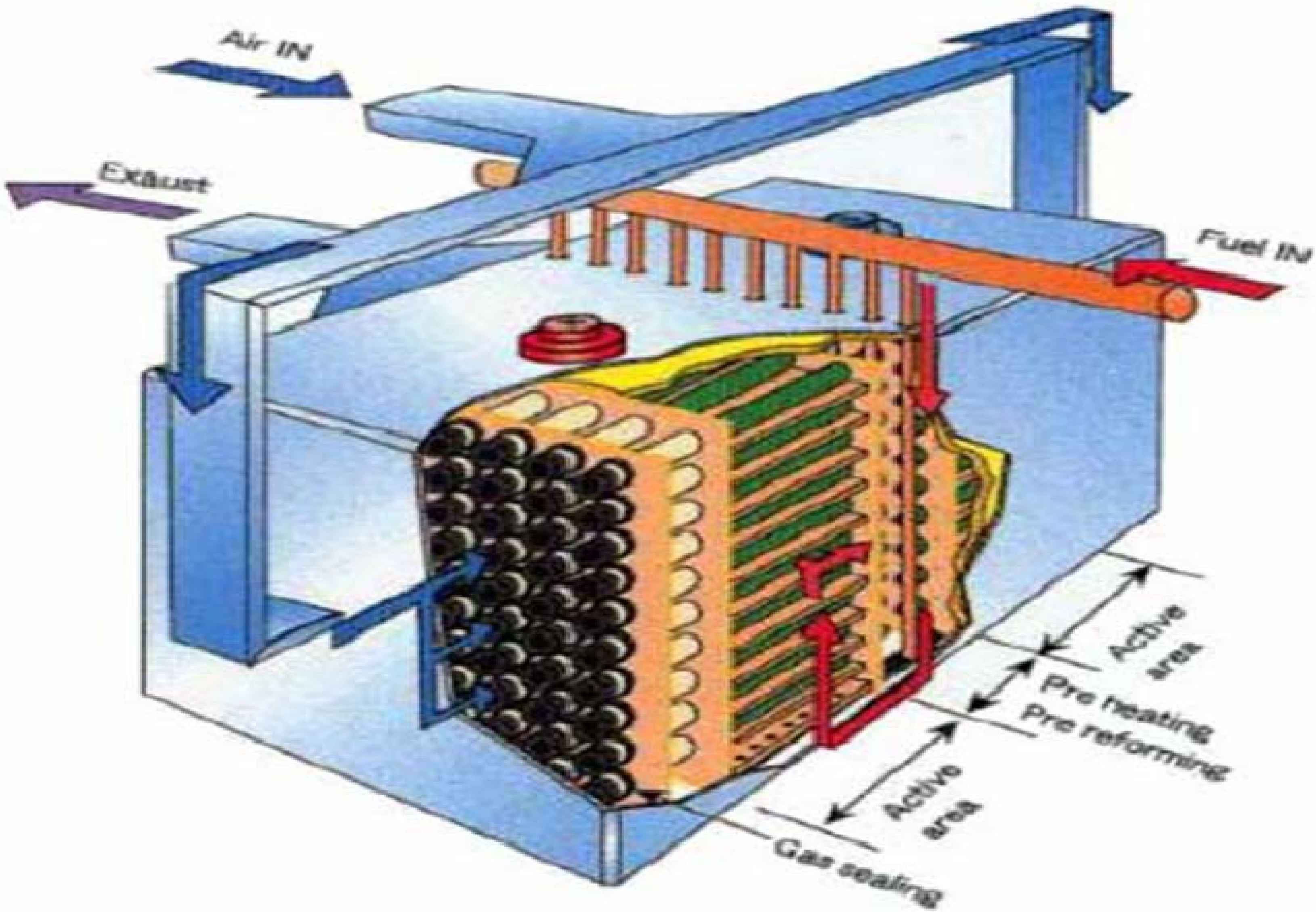


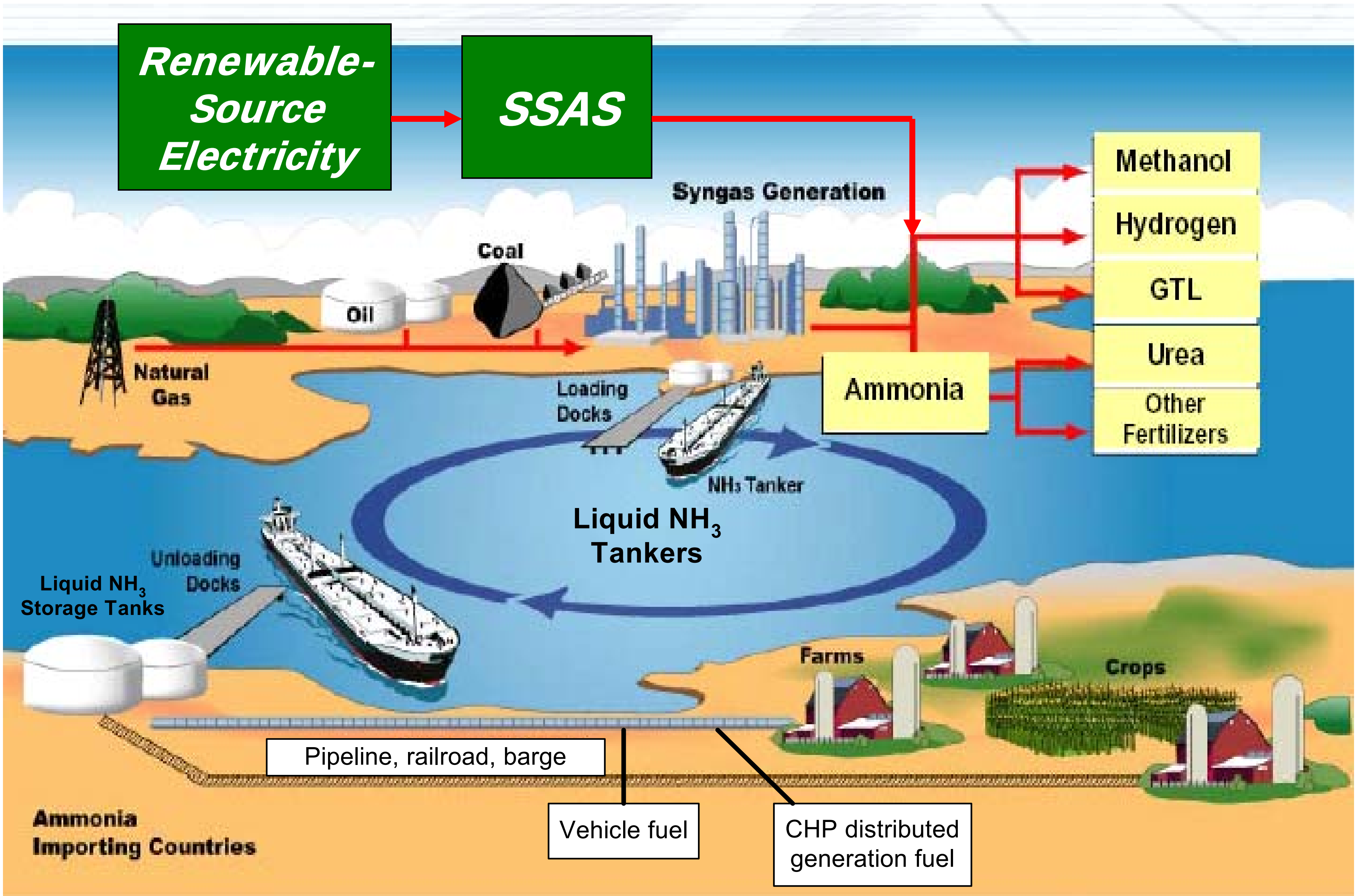
Benchtop

Proof-of-concept

Energy consumption 7,000 – 8,000 kWh per ton NH_3

Solid State Ammonia Synthesis (SSAS)
NHThree LLC patent





KBR

Energy and Chemicals

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**

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

but only after they have tried everything else ”

Winston Churchill

Humanity's Goal

A global, sustainable,

benign-source, equitable,

energy economy

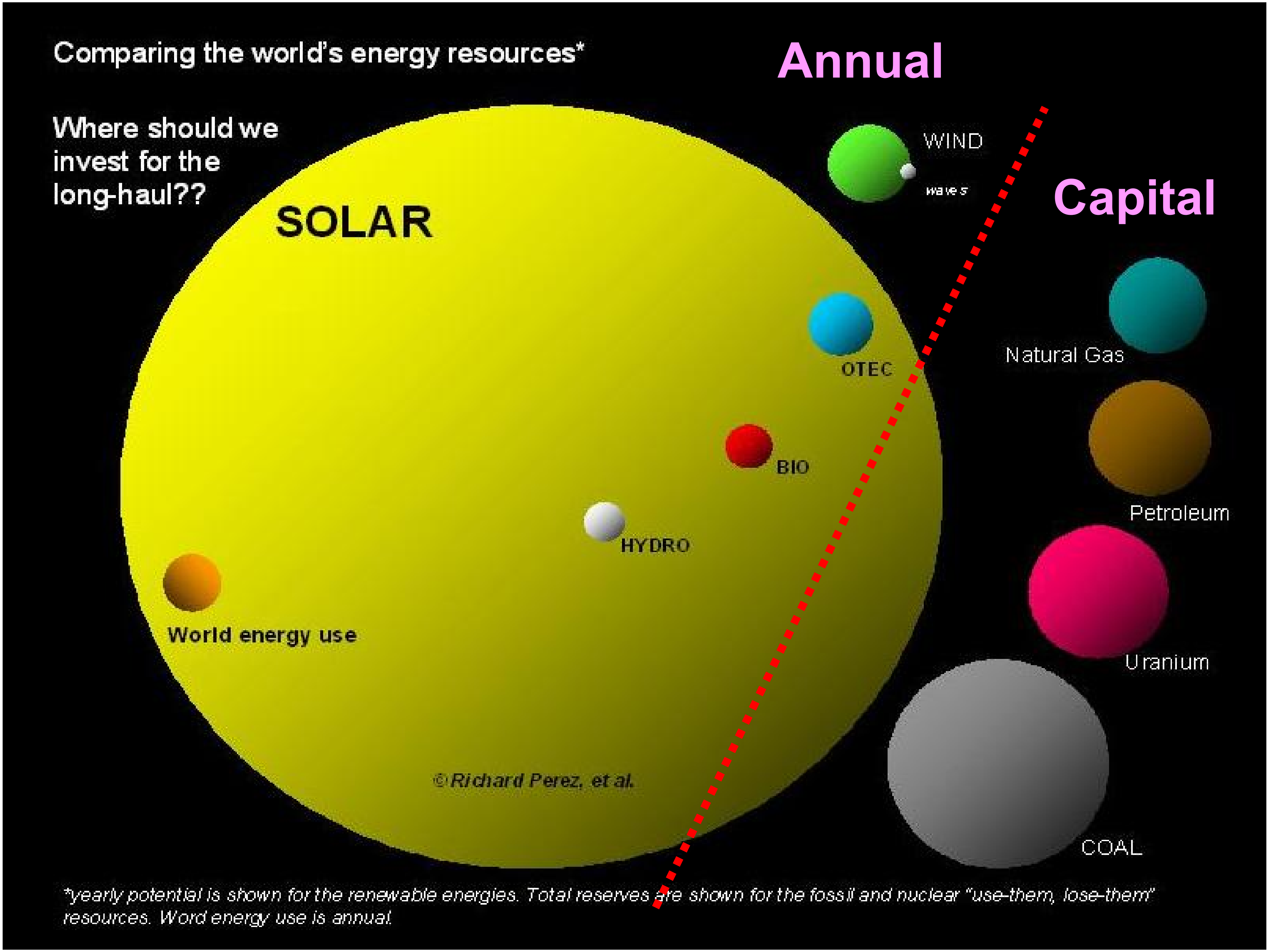
- **CANNOT with only electricity transmission**
- **"Transmission" must include GH2, NH3, other**

MUST Run the World on Renewables – plus Nuclear ?

- Global
- Indigenous
- Firm: available
- C-free
- Benign
- Abundant
- Affordable
- Equitable
- Perpetual:
  - solar
  - geothermal
  - tidal

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


Comparing the world's energy resources*
Annual
Where should we invest for the long-haul??
SOLAR
WIND
waves
Capital
Natural Gas
OTEC
Petroleum
BIO
HYDRO
World energy use
Uranium
© Richard Perez, et al.
COAL
*yearly potential is shown for the renewable energies. Total reserves are shown for the fossil and nuclear "use-them, lose-them" resources. Word energy use is annual.

Beyond Smart Grid: Alternatives for Transmission and Low-cost Firming Storage of Stranded Renewables as Hydrogen and Ammonia Fuels via Underground Pipelines

World Hydrogen Energy Conference
WHEC 2012, Toronto
3 - 8 June 12

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Mendenhall Glacier, Juneau, AK

June ‘71

Mendenhall Glacier, Juneau, AK
10 October 10

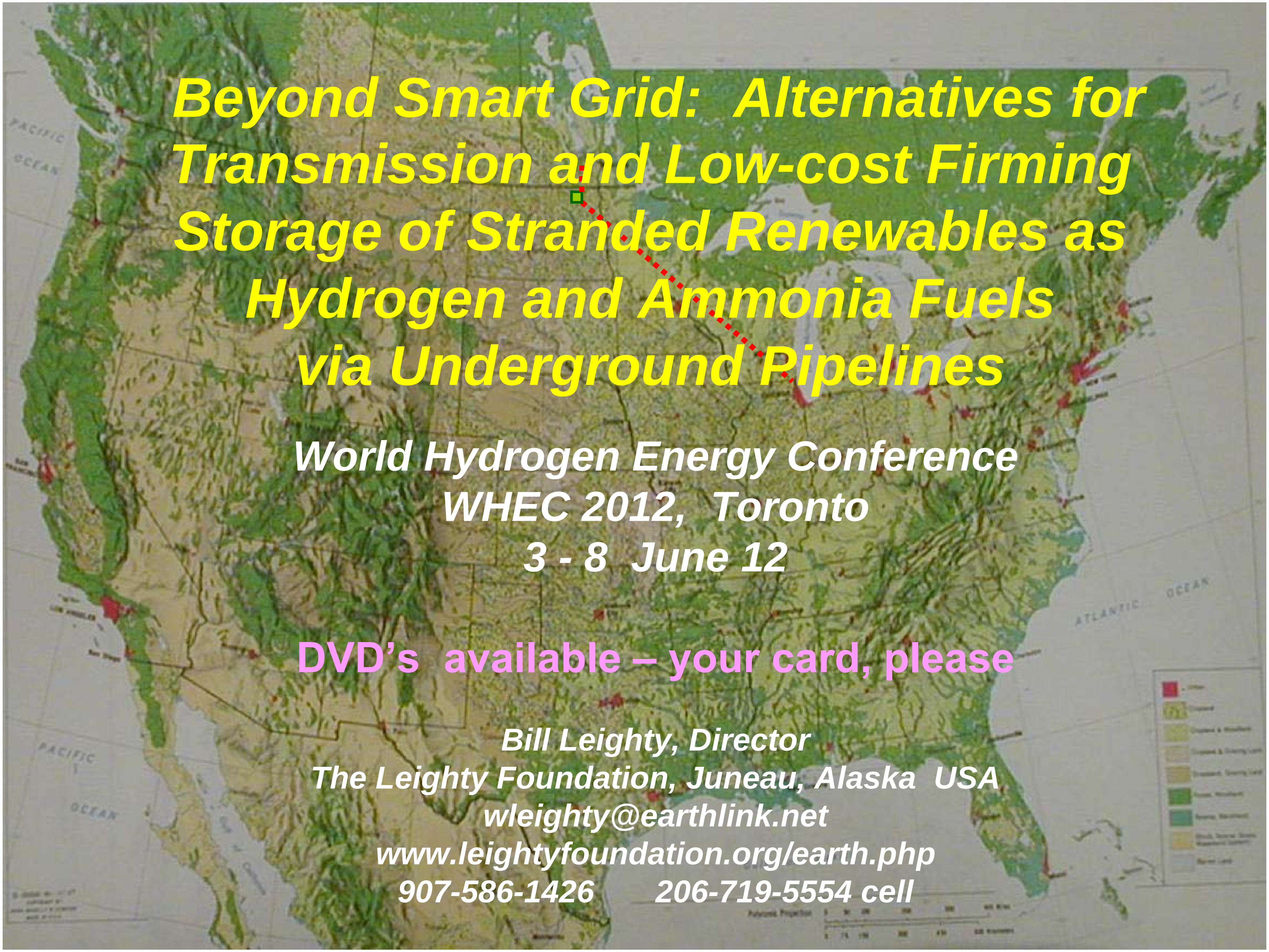
Mendenhall Glacier, Juneau, AK
10 October 10

Spruce bark beetle kill, Alaska

“Drunken Trees” on thawing permafrost

Shishmaref, Alaska

Winter storms coastal erosion



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DVD's available – your card, please

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End of Presentation

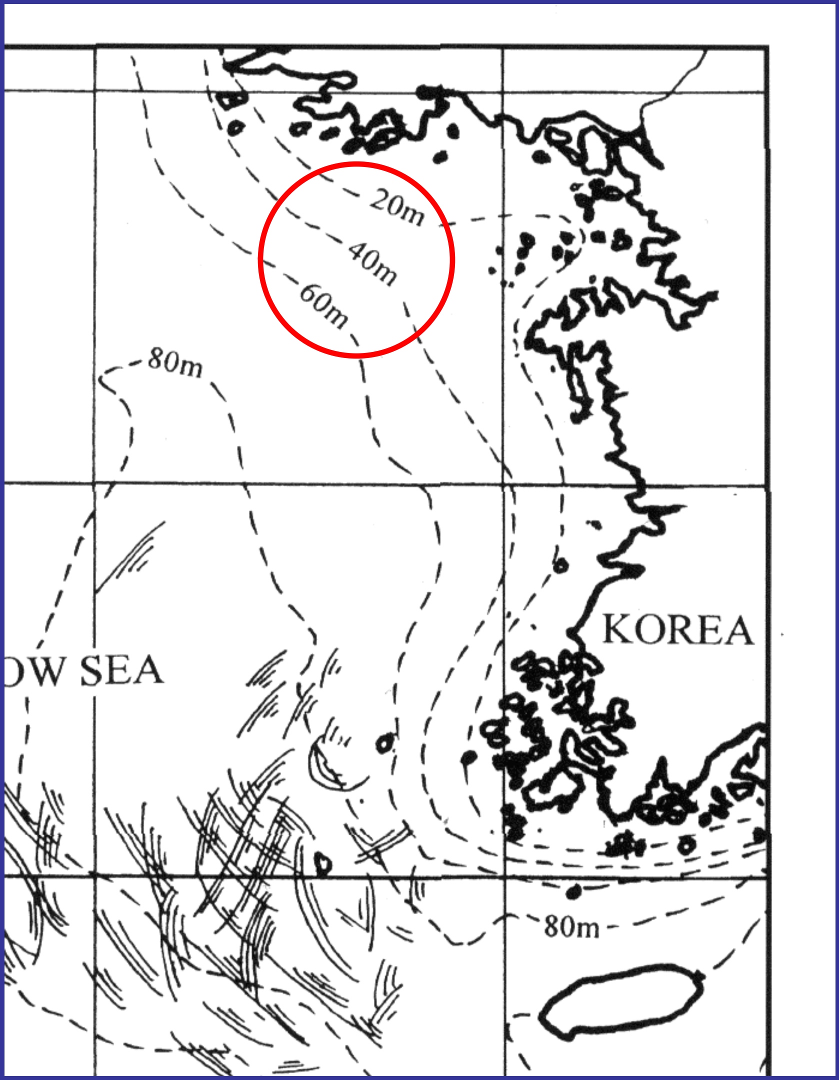
The following slides are supplementary

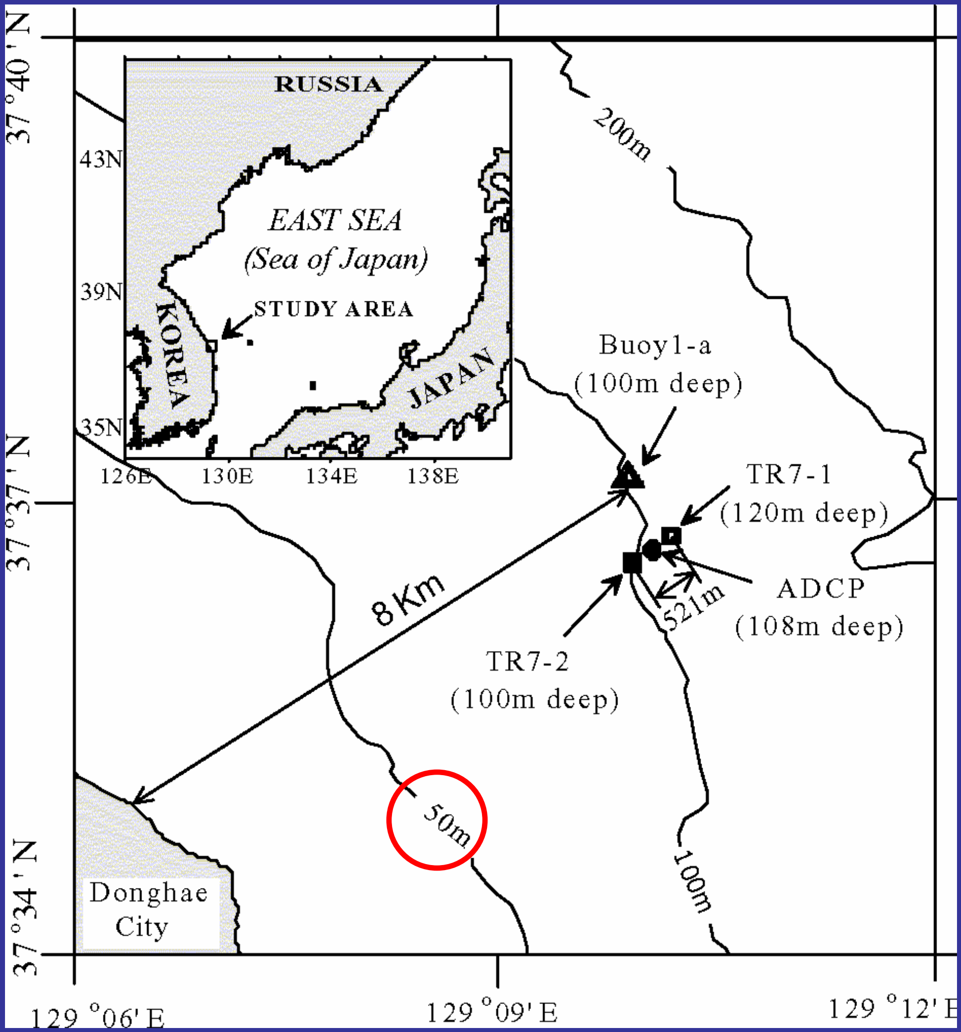
Humanity's Goal

A global, sustainable,

benign-source, equitable,

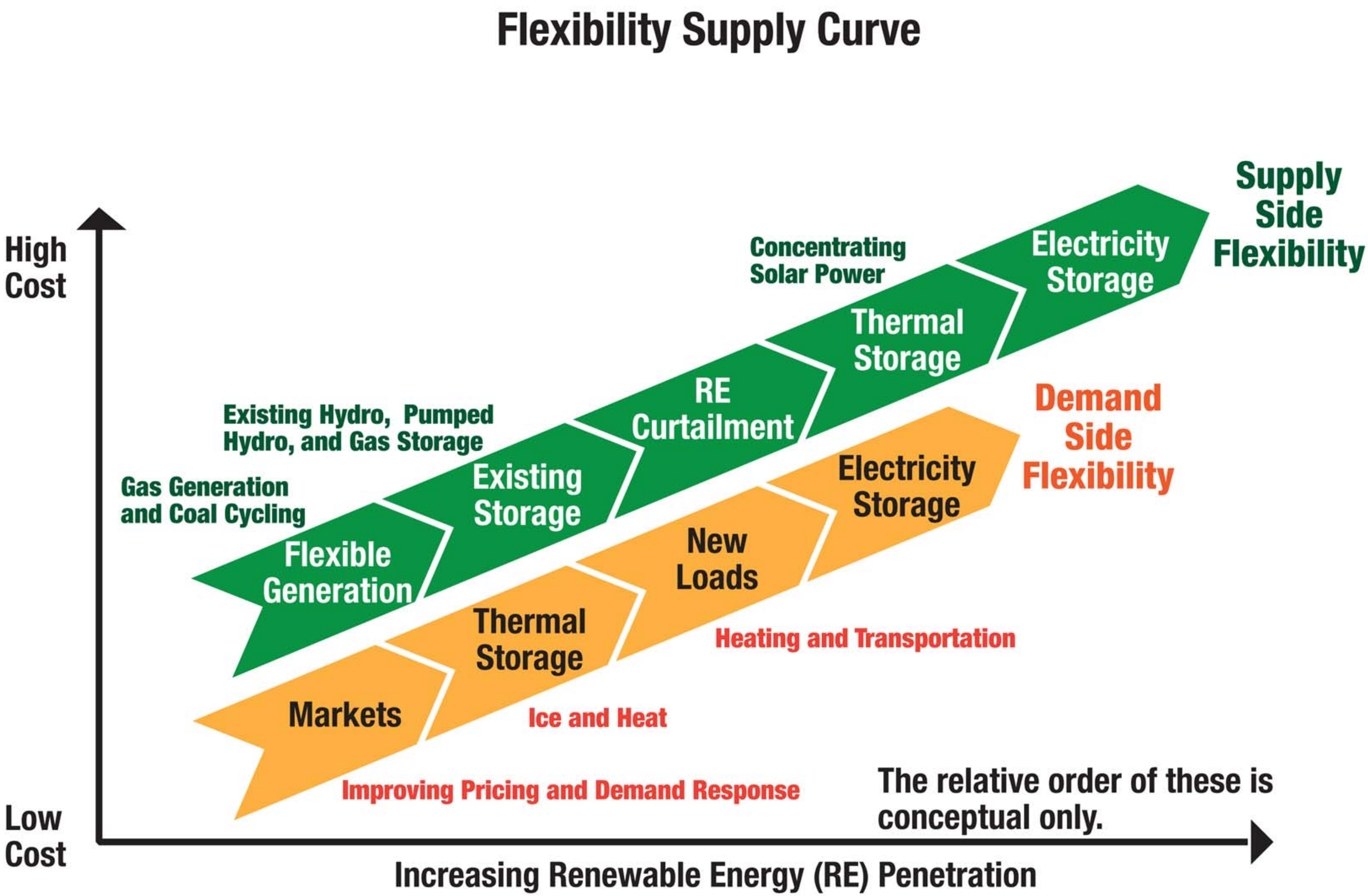
energy economy


20m
40m
60m
80m
KOREA
OW SEA
80m


37°40'N
37°37'N
37°34'N
129°06'E
129°09'E
129°12'E
RUSSIA
EAST SEA
(Sea of Japan)
STUDY AREA
KOREA
JAPAN
43N
39N
35N
126E
130E
134E
138E
200m
Buoy1-a
(100m deep)
TR7-1
(120m deep)
ADCP
(108m deep)
521m
TR7-2
(100m deep)
8 Km
50m
100m
Donghae
City

Opportunities

- Collaboration
  - International: "Run world on renewables"
  - RE systems: sources to end uses, firm and dispatchable
  - USA lead ? Korea ?
  - R&D
  - Demonstrations & pilot plants
- Solid State Ammonia Synthesis (SSAS)
  - RE electricity + water + $N_2 \rightarrow NH_3$
  - Proof-of-concept pilot plant
  - Technical + economic promise?
  - Several processes ?
    - NHThree LLC patented PCC
    - Hydrogen Engine Center lithium
    - Other ?
- End use: stationary, transportation, fertilizer
- Commercialization

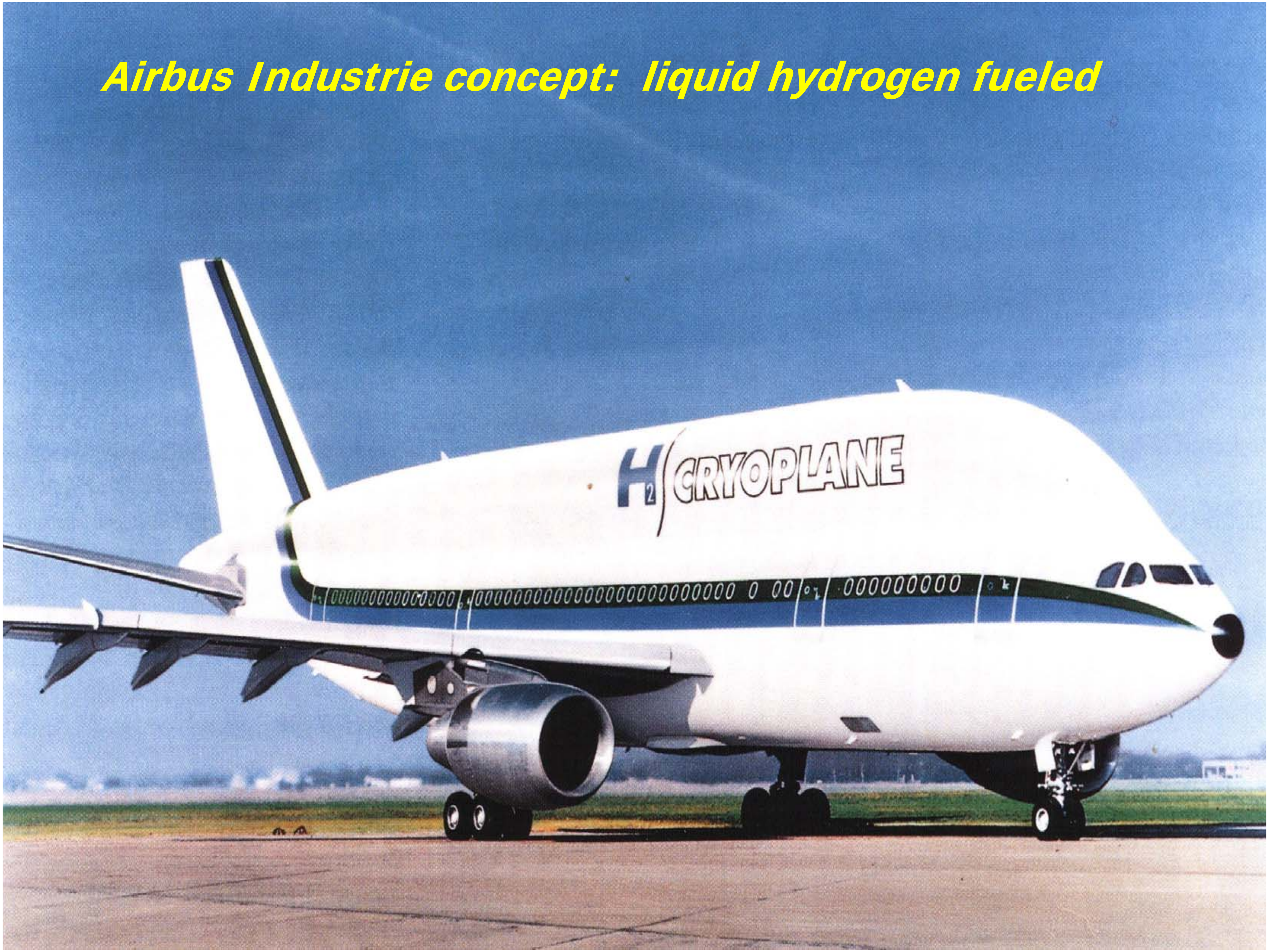


NREL: Systems Integration

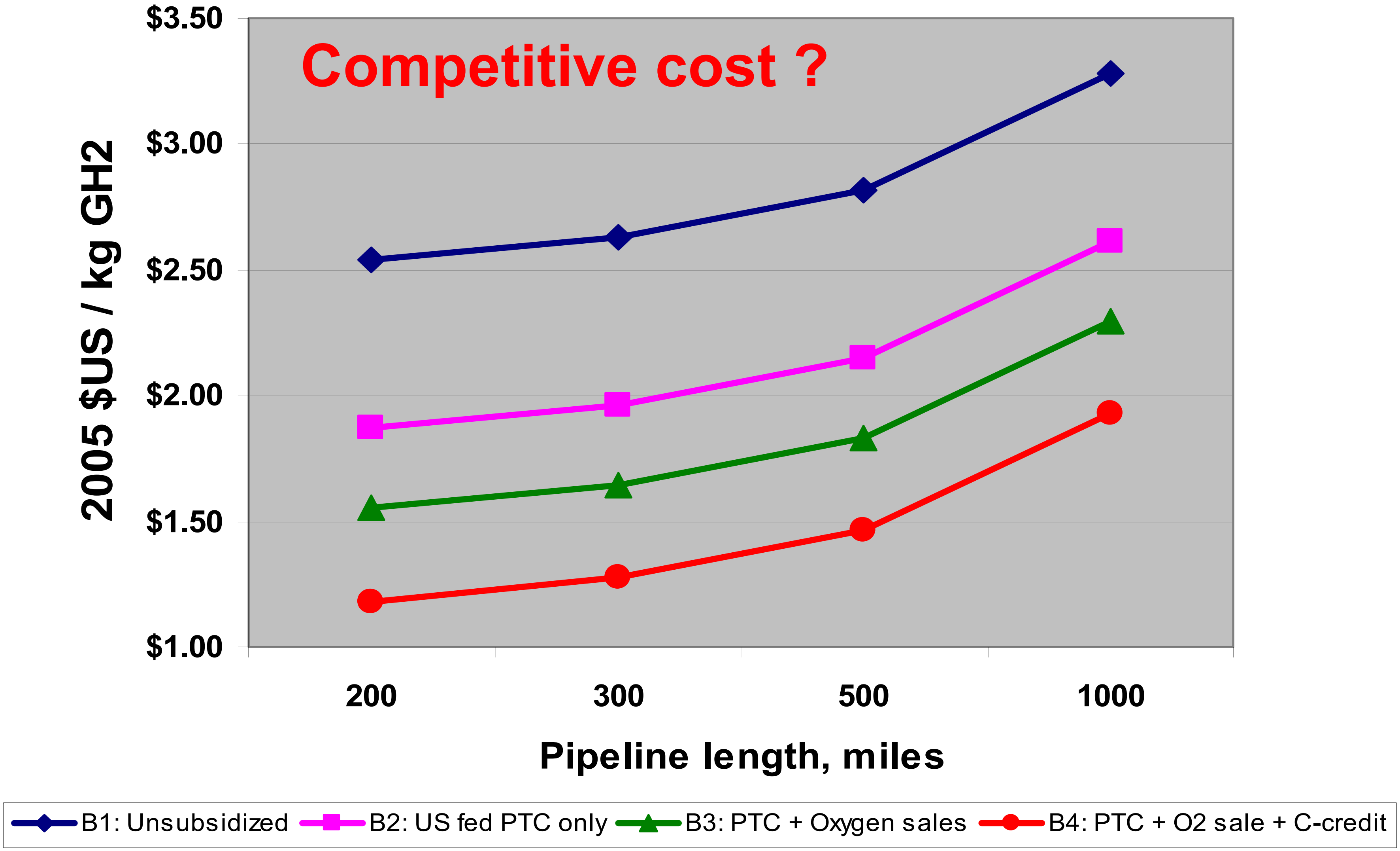
Jan '09 Transmission Backlog

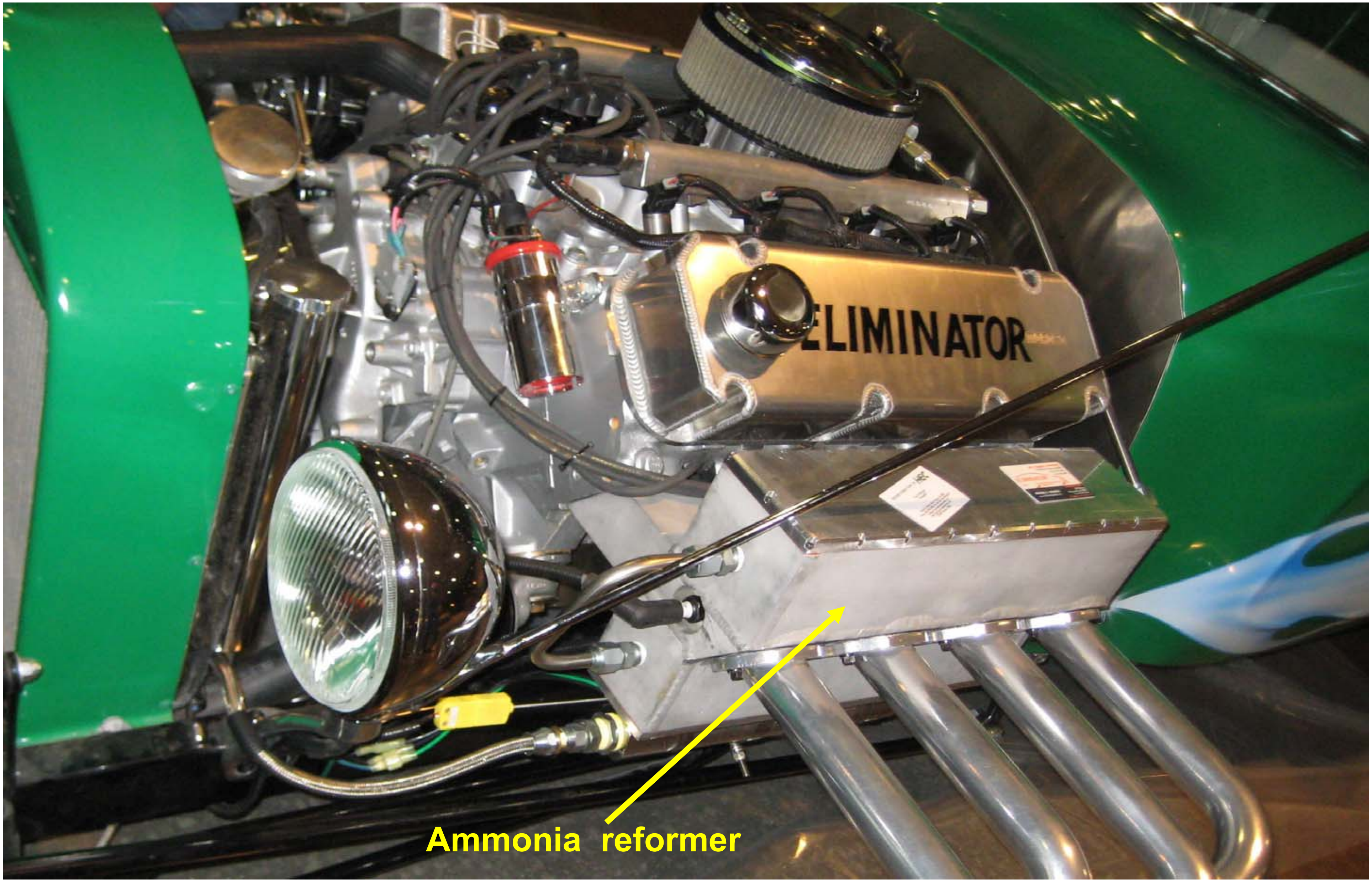
• **California:**	**13 GW wind**
	30 GW solar
• **Upper Midwest**	**70 GW wind**
• **Lower Midwest**	**40 GW wind**
• **Great Lakes + Mid Atlantic**	**40 GW wind**
• **Texas**	**50 GW wind**
Total	**243 GW**
Potential Great Plains Wind	**3,000 GW**

Airbus Industrie concept: liquid hydrogen fueled



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





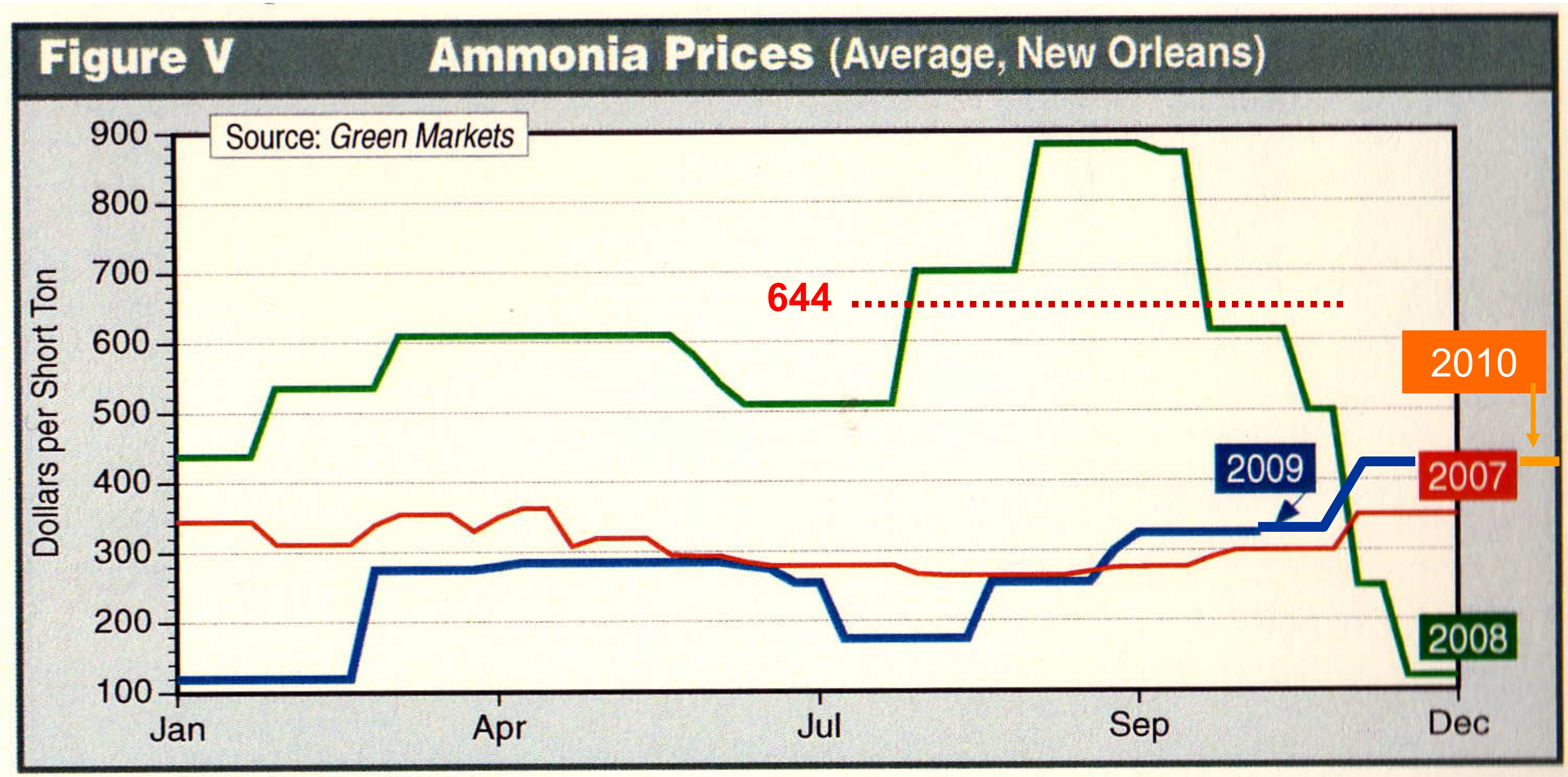
Oct '09 Ammonia Fueled V-8 with Hydrogen Injection: Reformed from NH_3

Hydrogen Engine Center, Algona, IA

2009

Norsk Hydro Electrolyzers 2 MW each

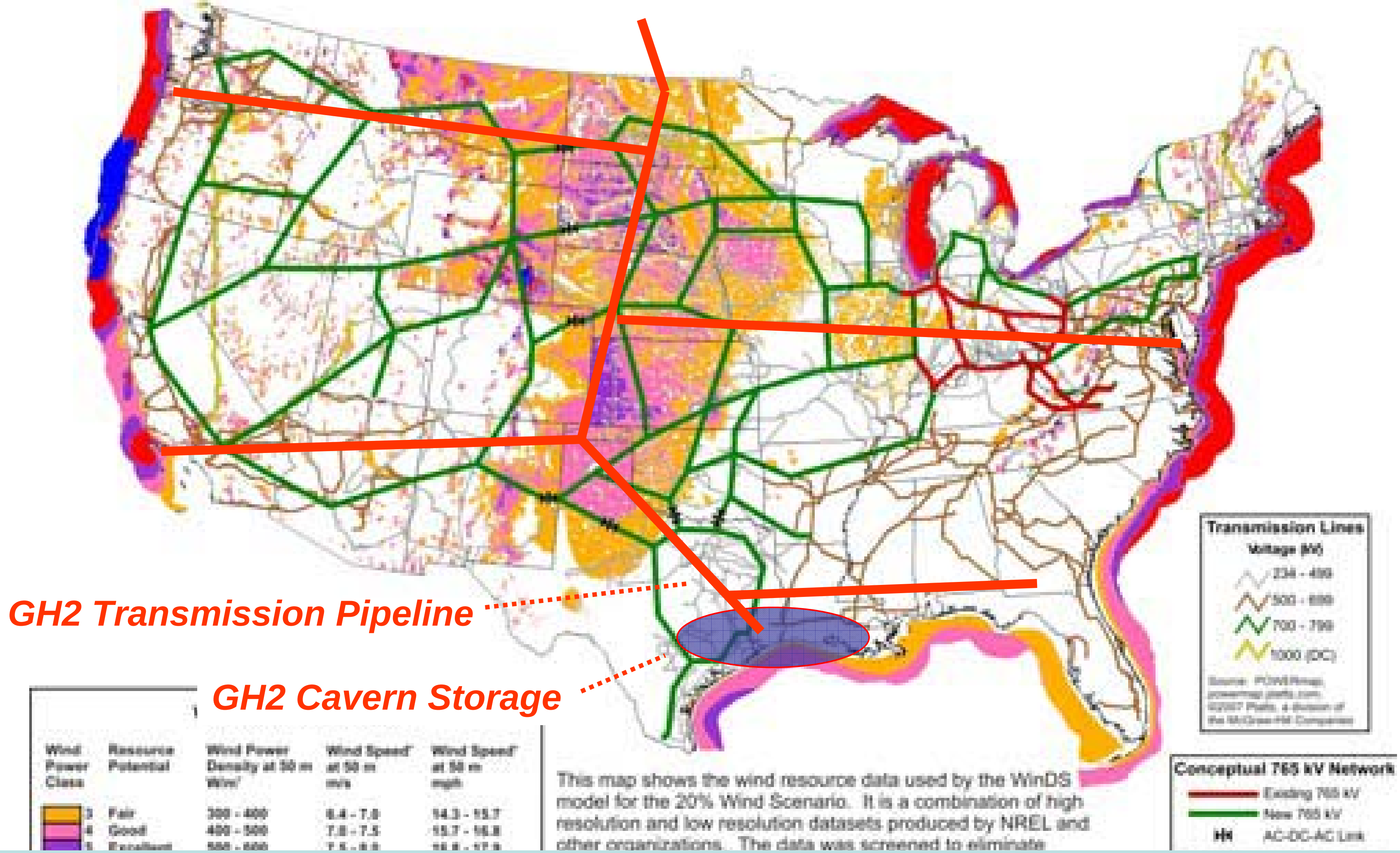
Ammonia from hydrogen from zero-cost off-peak hydro



Anhydrous Ammonia (NH3) wholesale price,

NOLA (New Orleans, LA)

AWEA 20% Wind Electricity by 2030



Wind Potential ~ 10,000 GW

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
Iowa	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

Stanford wind energy study: 2003

- Underestimated: PNNL '91, NREL
- 80 m hub height
- 1.3 – 1.7 m / s faster windspeed
- IF transmission network:
  steady, reliable, abundant supply

"Spatial and temporal distributions of U.S. winds and wind power at 80 m derived from measurements"

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