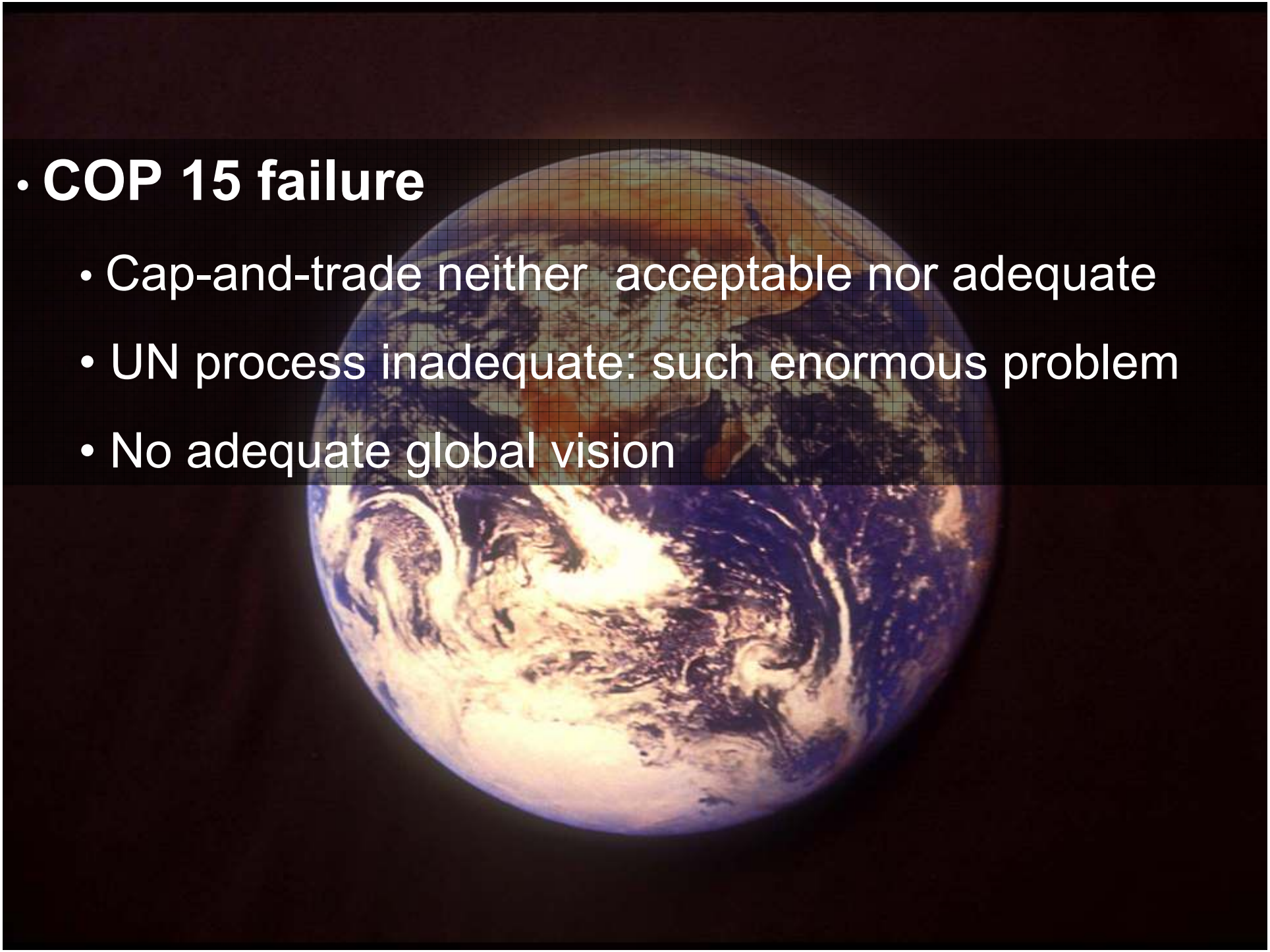
Transmission and Annual-scale Firming Storage Alternatives to Electricity: Gaseous Hydrogen and Anhydrous Ammonia via Underground Pipeline

EUEC
2 Feb 10, Phoenix

Bill Leighty, Director
The Leighty Foundation
Juneau, AK
wleighty@earthlink.net
907-586-1426 206-719-5554 cell



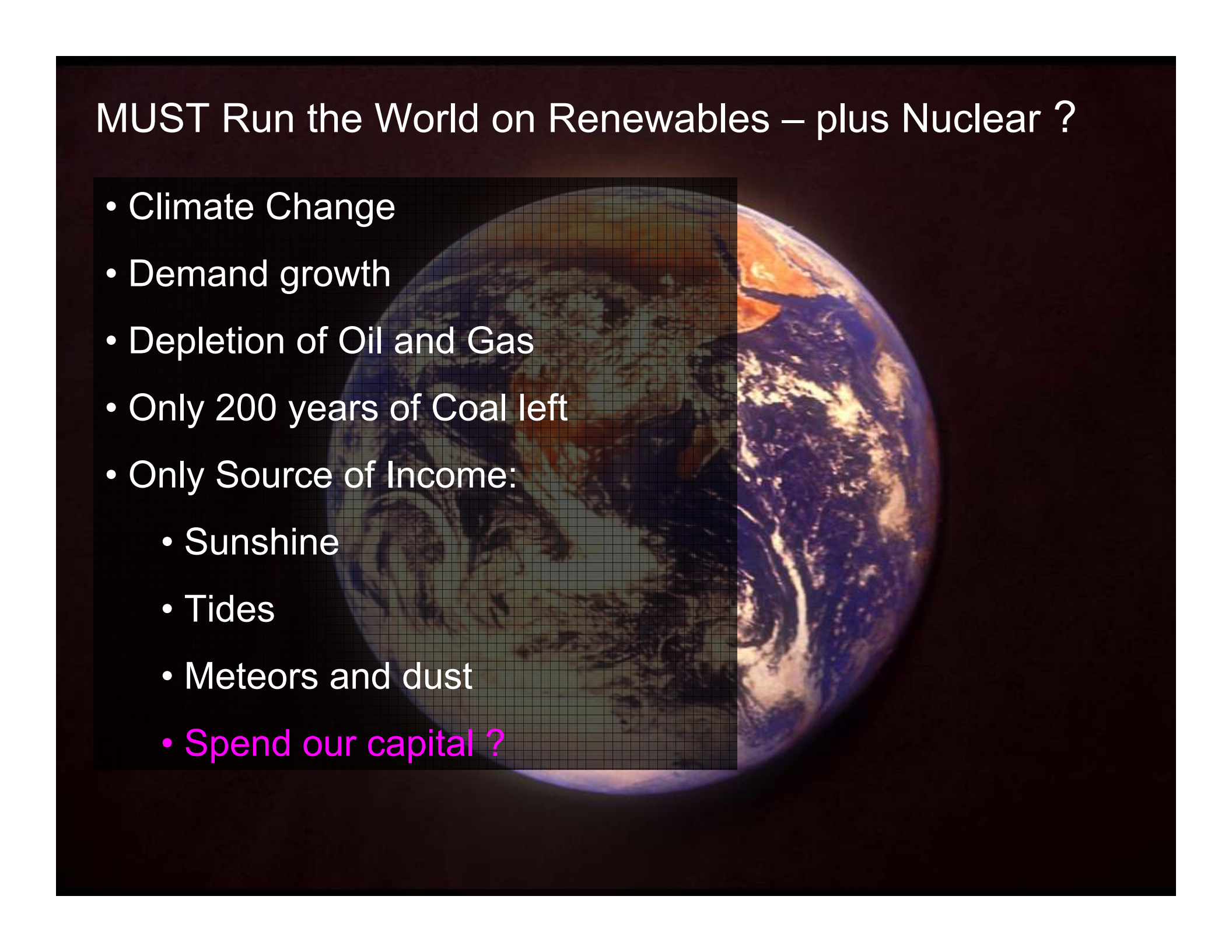
- **COP 15 failure**
  - Cap-and-trade neither acceptable nor adequate
  - UN process inadequate: such enormous problem
  - No adequate global vision

Humanity's Goal ?

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

Rapid Climate Change (GCC)
Global Warming (GW)

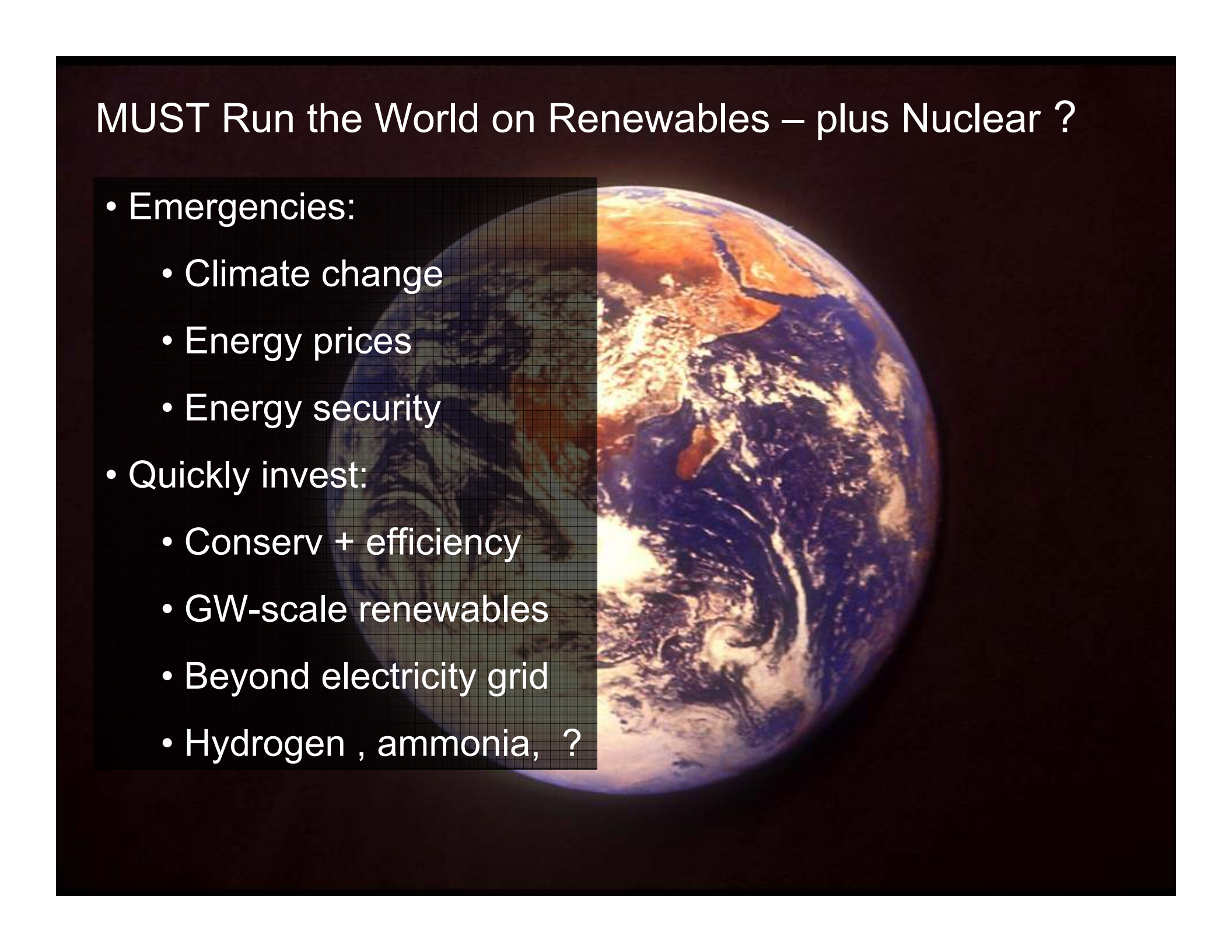
MUST Run the World on Renewables – plus Nuclear ?



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

MUST Run the World on Renewables – plus Nuclear ?

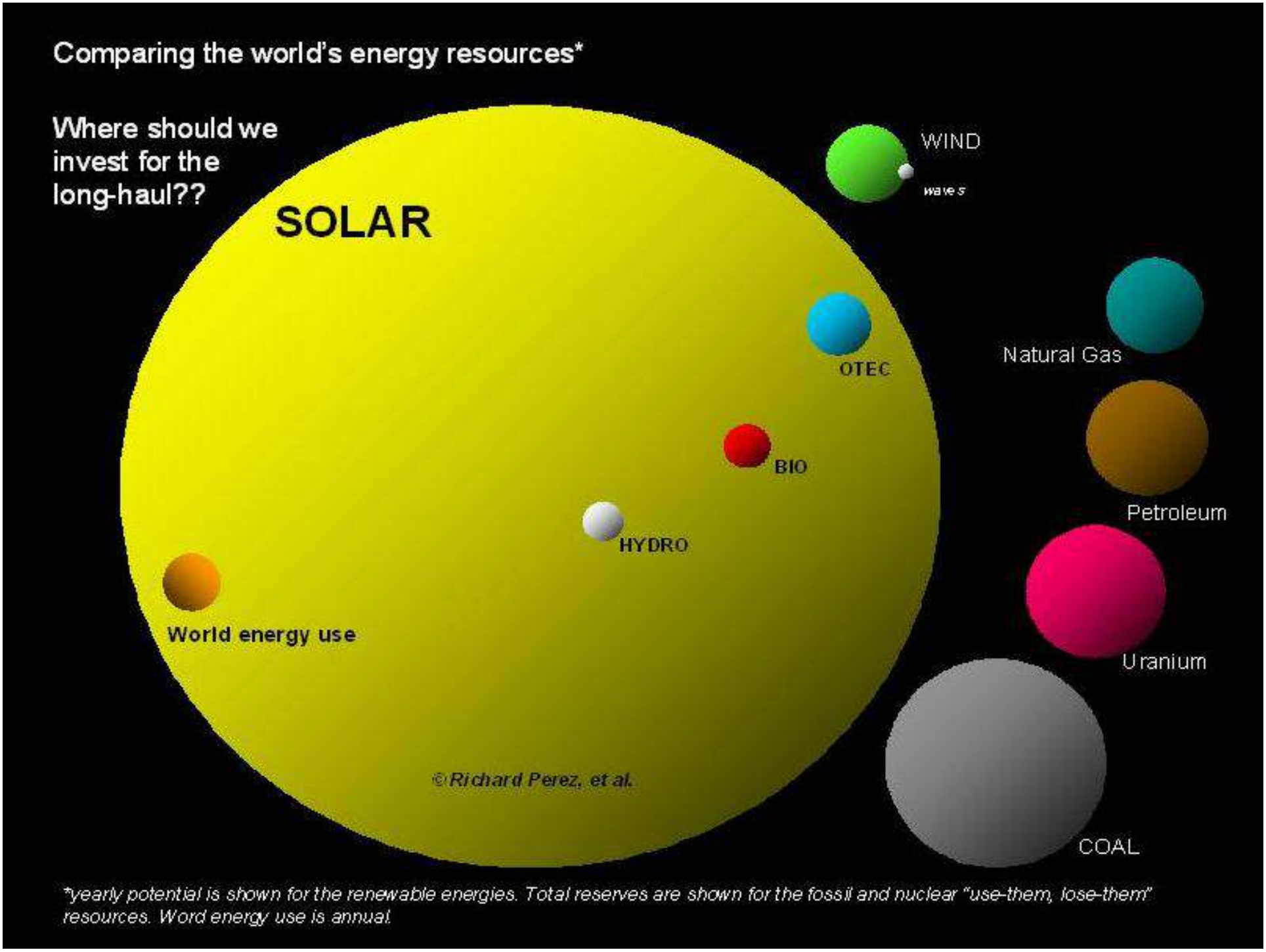
- Emergencies:
  - Climate change
  - Energy prices
  - Energy security
- Quickly invest:
  - Conserv + efficiency
  - GW-scale renewables
  - Beyond electricity grid
  - Hydrogen , ammonia, ?




WE'RE HERE:
385.92 ppm
WE NEED TO GET BELOW:
350 ppm
www.350.org
CO_2 in the Atmosphere

MUST Run the World on Renewables – plus Nuclear ?

- Global
- Indigenous
- Firm: available
- C-free
- Benign
- Abundant
- Affordable
- Equitable
- Perpetual:
  - Solar
  - Geothermal
  - Tidal


Comparing the world's energy resources*
Where should we invest for the long-haul??
SOLAR
WIND
waves
OTEC
BIO
HYDRO
World energy use
Natural Gas
Petroleum
Uranium
COAL
© Richard Perez, et al.
*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.


The Great Plains Wind Resource
PACIFIC OCEAN
ATLANTIC OCEAN
Gulf of Mexico

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

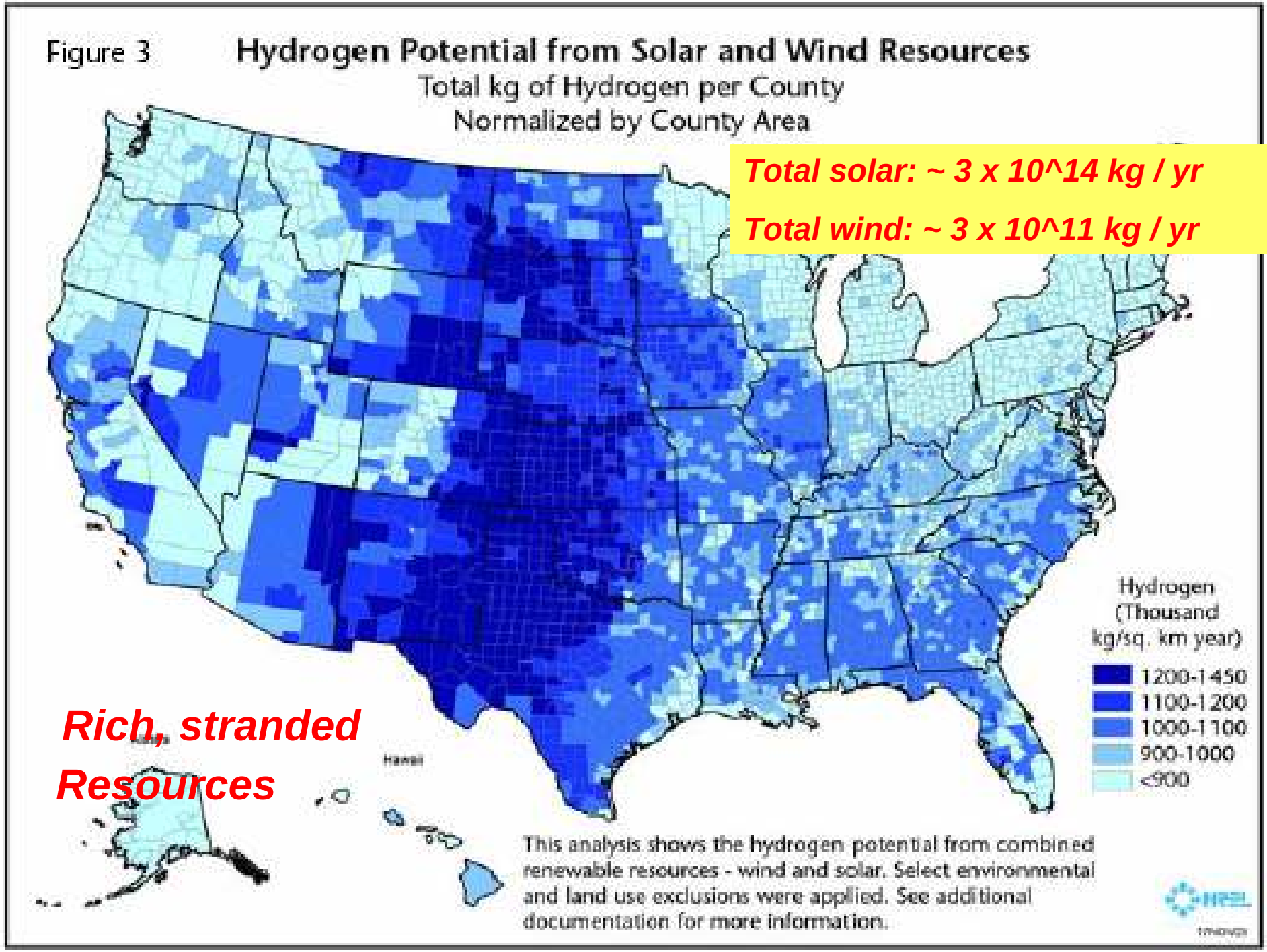
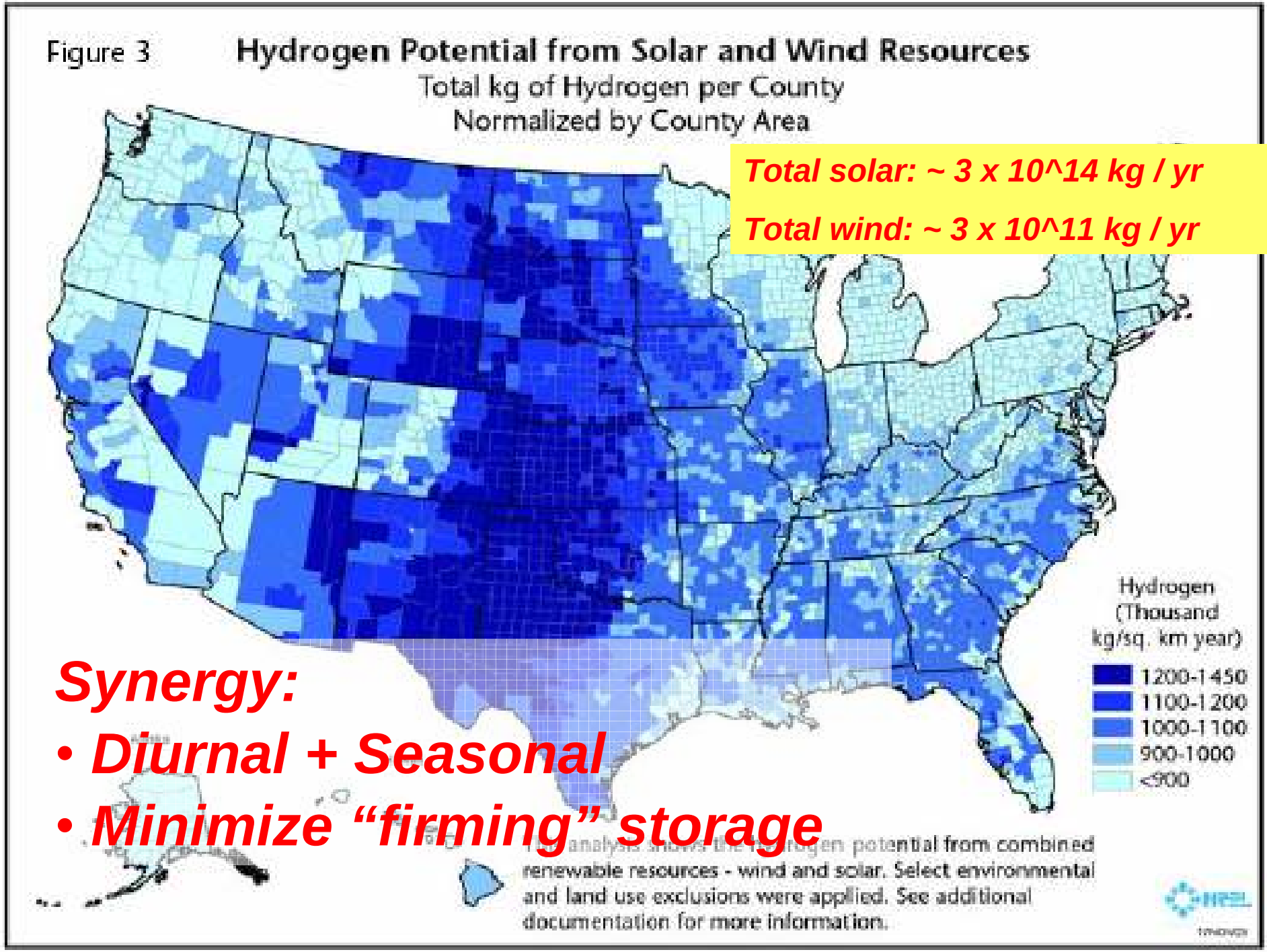


Figure 3
Hydrogen Potential from Solar and Wind Resources
Total kg of Hydrogen per County
Normalized by County Area
Total solar: ~ 3 x 10^14 kg / yr
Total wind: ~ 3 x 10^11 kg / yr
Rich, stranded Resources
Hydrogen (Thousand kg/sq. km year)
1200-1450
1100-1200
1000-1100
900-1000
<900
Hawaii
This analysis 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.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Hydrogen (Thousand kg/sq. km year)
1200-1450
1100-1200
1000-1100
900-1000
<900
Synergy:
• Diurnal + Seasonal
• Minimize "firming" storage
renewable resources - wind and solar. Select environmental and land use exclusions were applied. See additional documentation for more information.

Jan '09 Transmission Backlog

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

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

but only after they have tried everything else ”

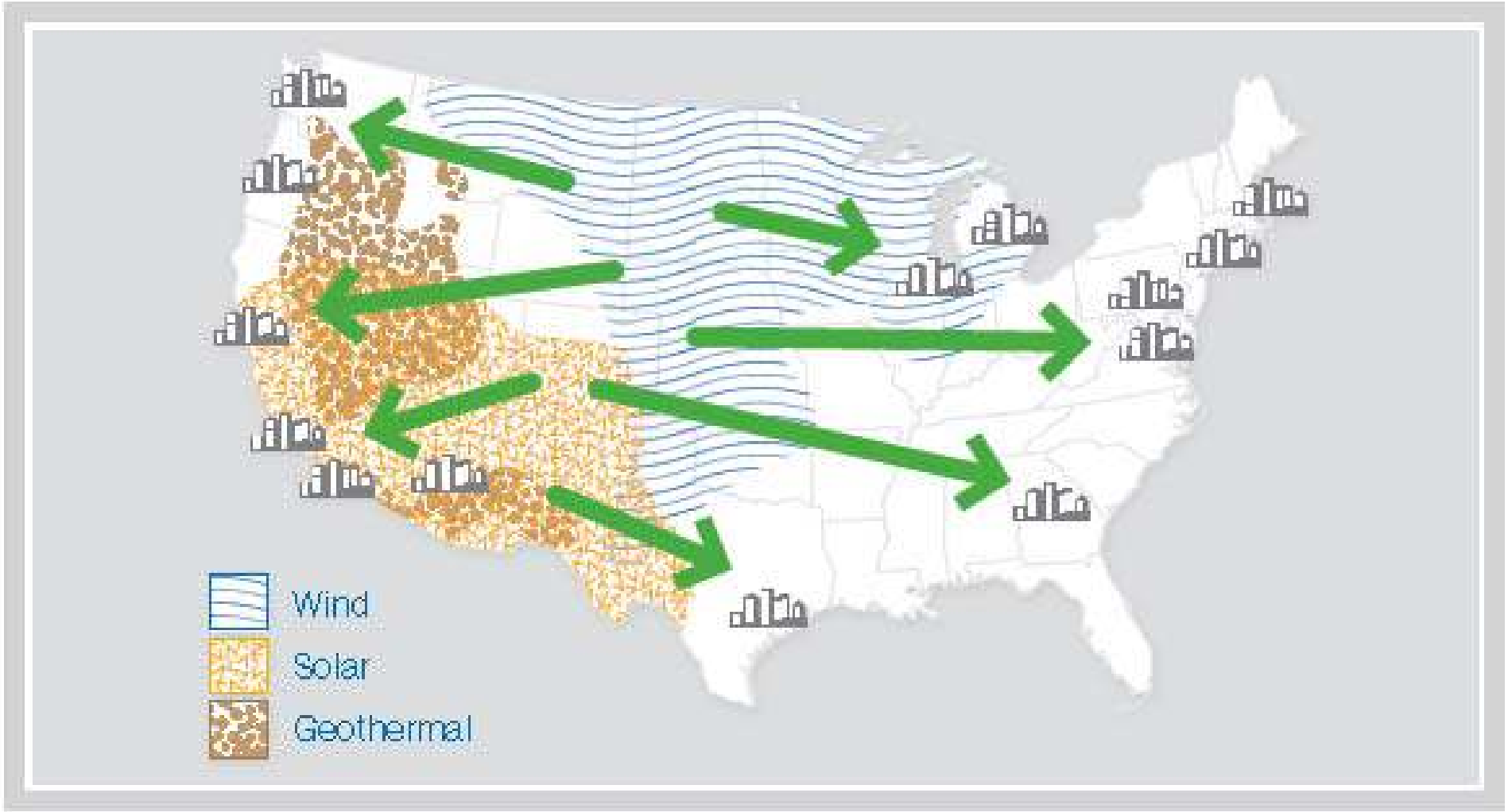
Winston Churchill

The dog caught the car.

Dan Reicher

Major Electricity Transmission Studies

- **EWITS-NREL** **‘09**
- **WWSIS-NREL** **‘09**
- **Brattle Group** **‘09**
- **SEIA-AWEA** **‘09**
- **JCSP** **‘08**
- **AEP-AWEA** **‘07**
- **Frontier Line** **‘07**
- **Transwest Express** **‘07**

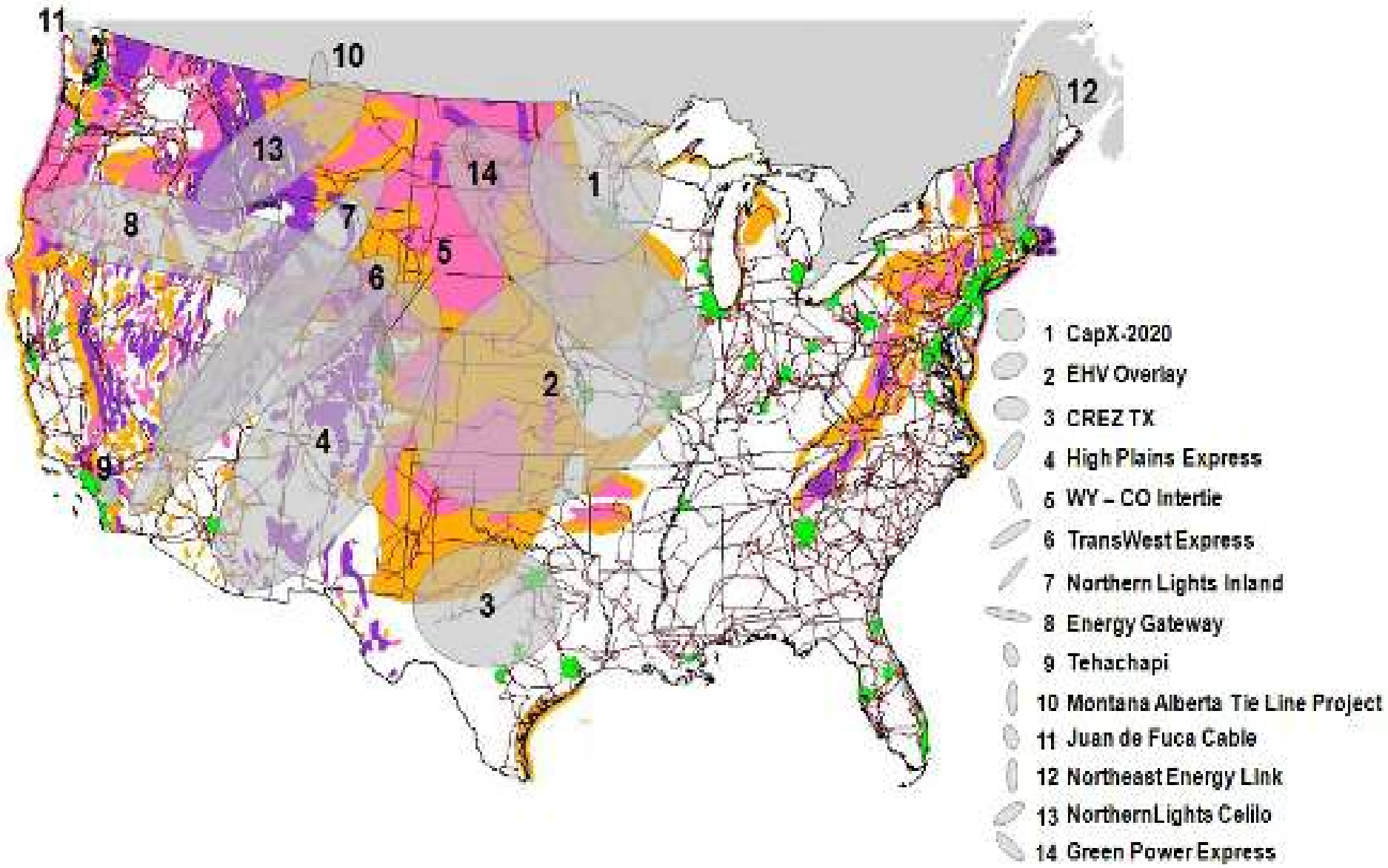


Source: AWEA and SEIA

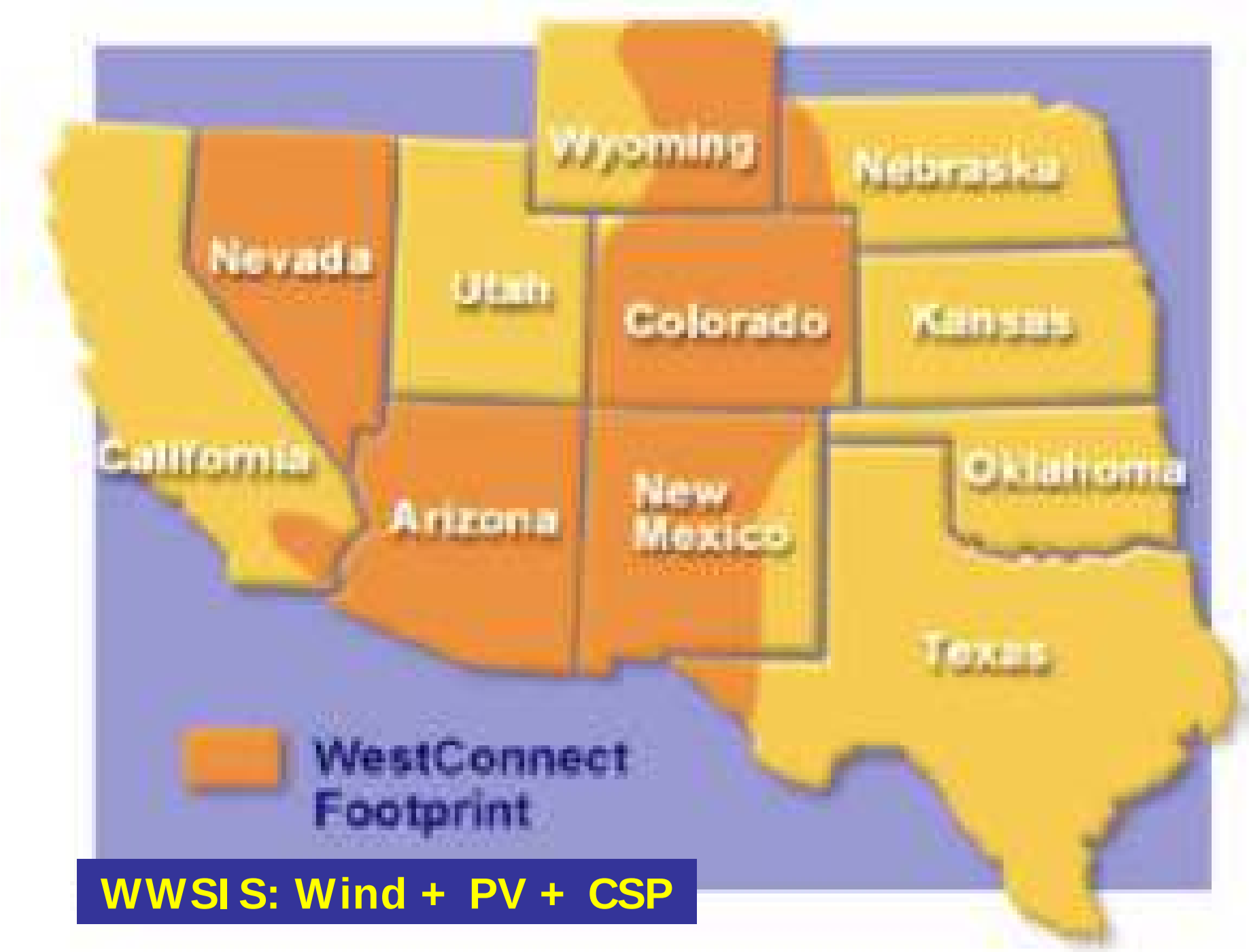
SEIA – AWEA Feb 09

"Green Power Superhighways:

Building a Path to America's Clean Energy Future"

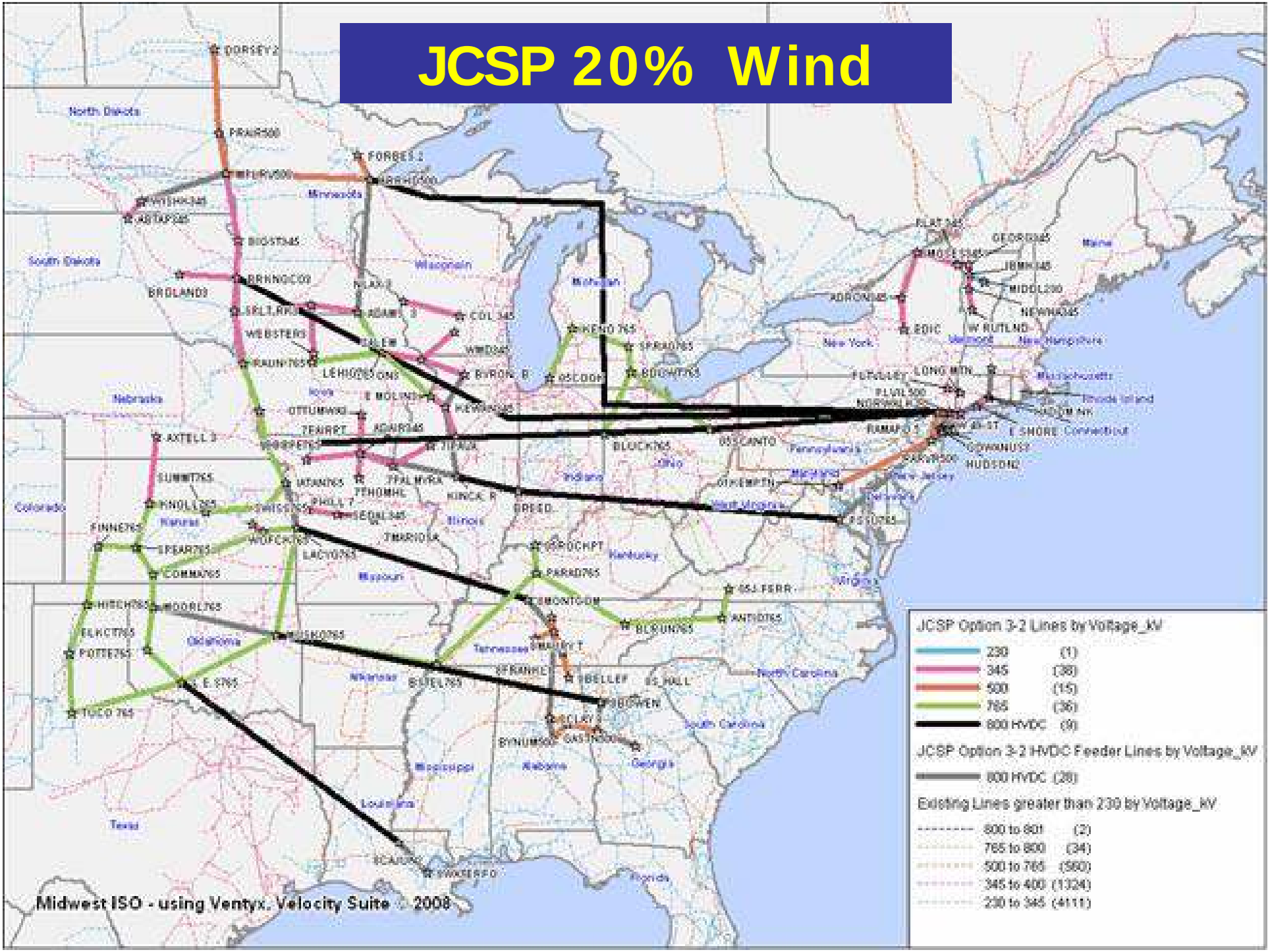


Emerging Energy Research LLC



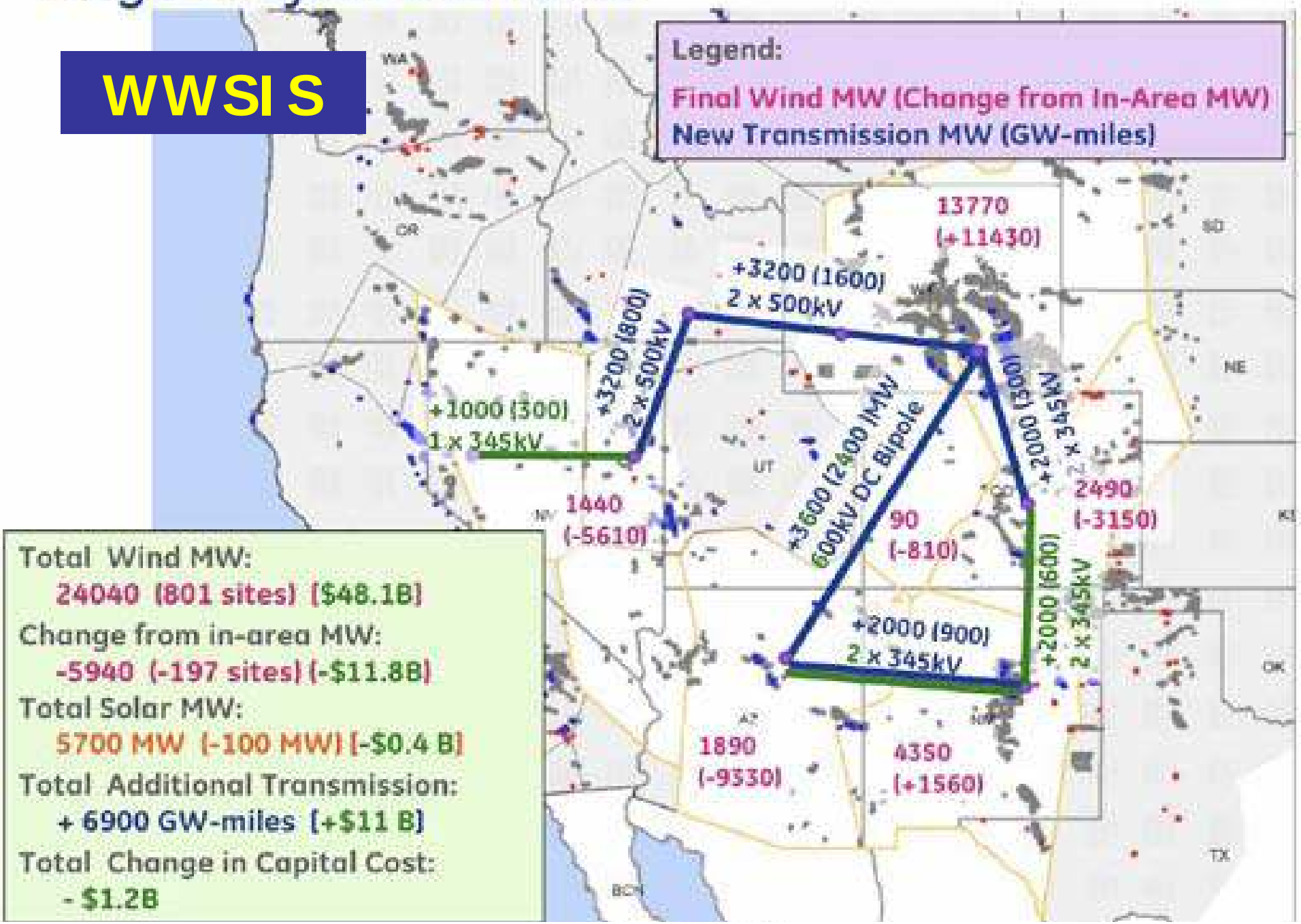
WWSIS: Wind + PV + CSP

JCSP 20% Wind

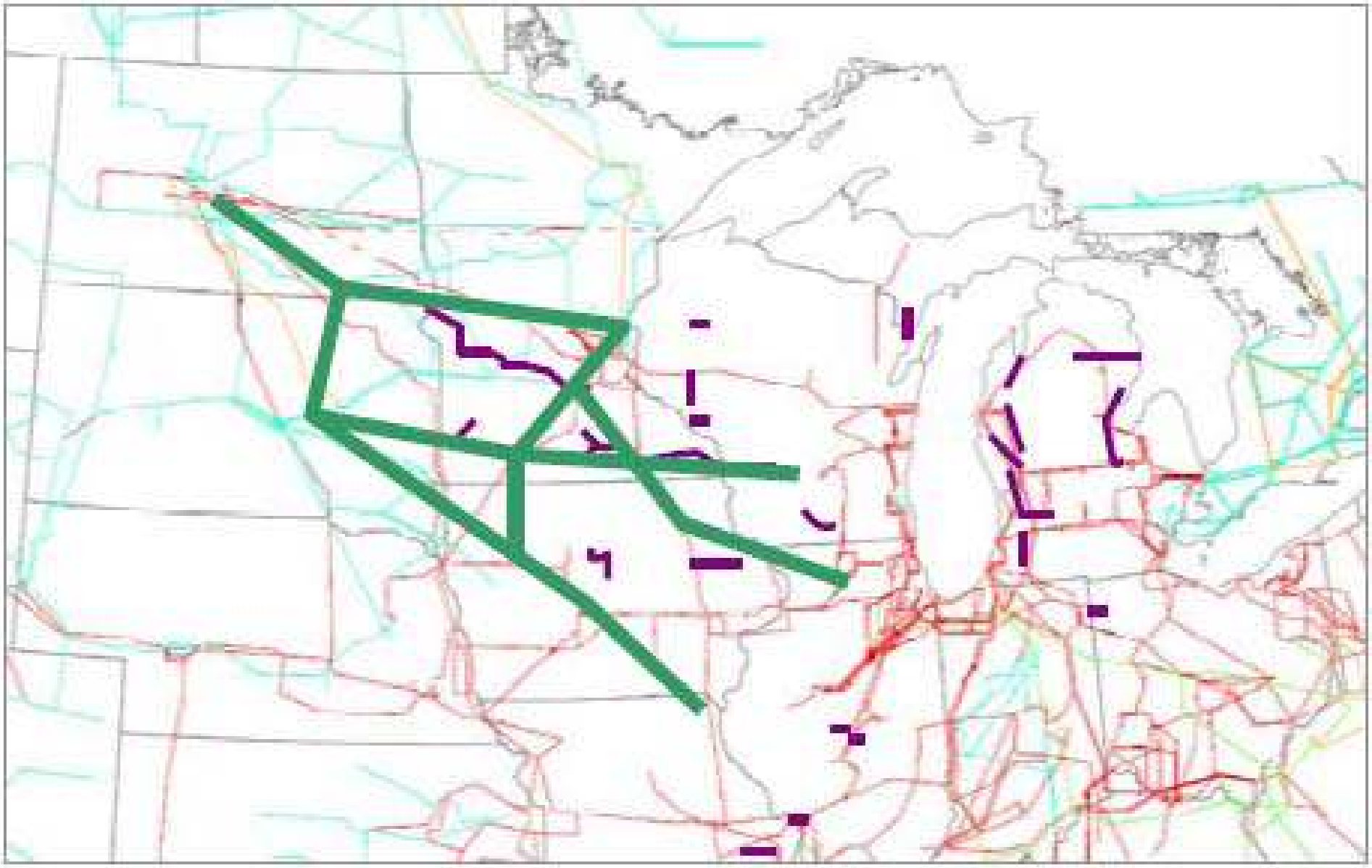

JCSP Option 3-2 Lines by Voltage_kV
230 (1)
345 (38)
500 (15)
765 (36)
800 HVDC (9)
JCSP Option 3-2 HVDC Feeder Lines by Voltage_kV
800 HVDC (28)
Existing Lines greater than 230 by Voltage_kV
800 to 801 (2)
765 to 800 (34)
500 to 765 (560)
345 to 400 (1324)
230 to 345 (4111)
Midwest ISO - using Ventyx, Velocity Suite © 2008

Mega Project Scenario

WWSIS

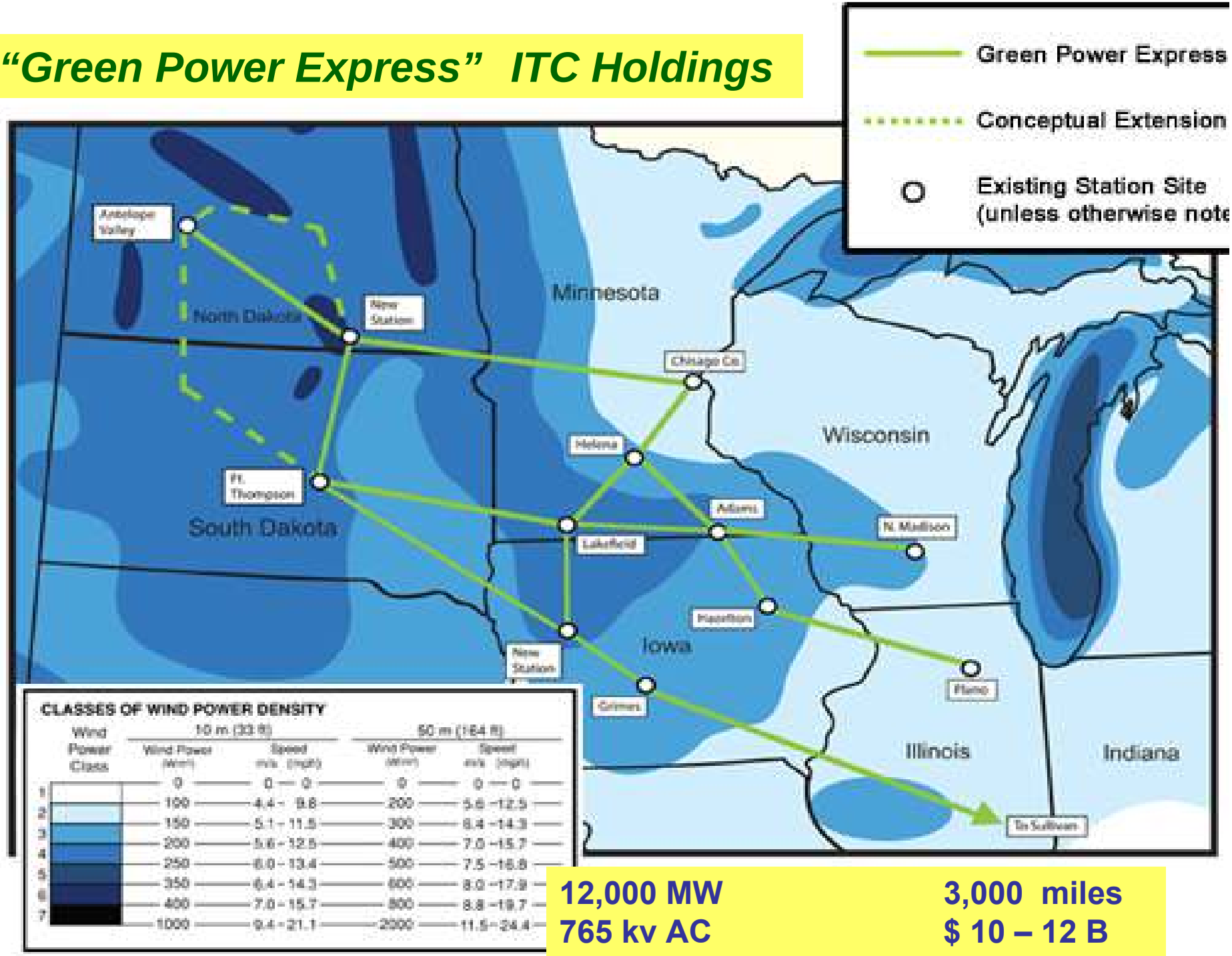


Total Wind MW:
24040 (801 sites) ($48.1B)
Change from in-area MW:
-5940 (-197 sites) (-$11.8B)
Total Solar MW:
5700 MW (-100 MW) (-$0.4 B)
Total Additional Transmission:
+ 6900 GW-miles (+$11 B)
Total Change in Capital Cost:
- $1.2B



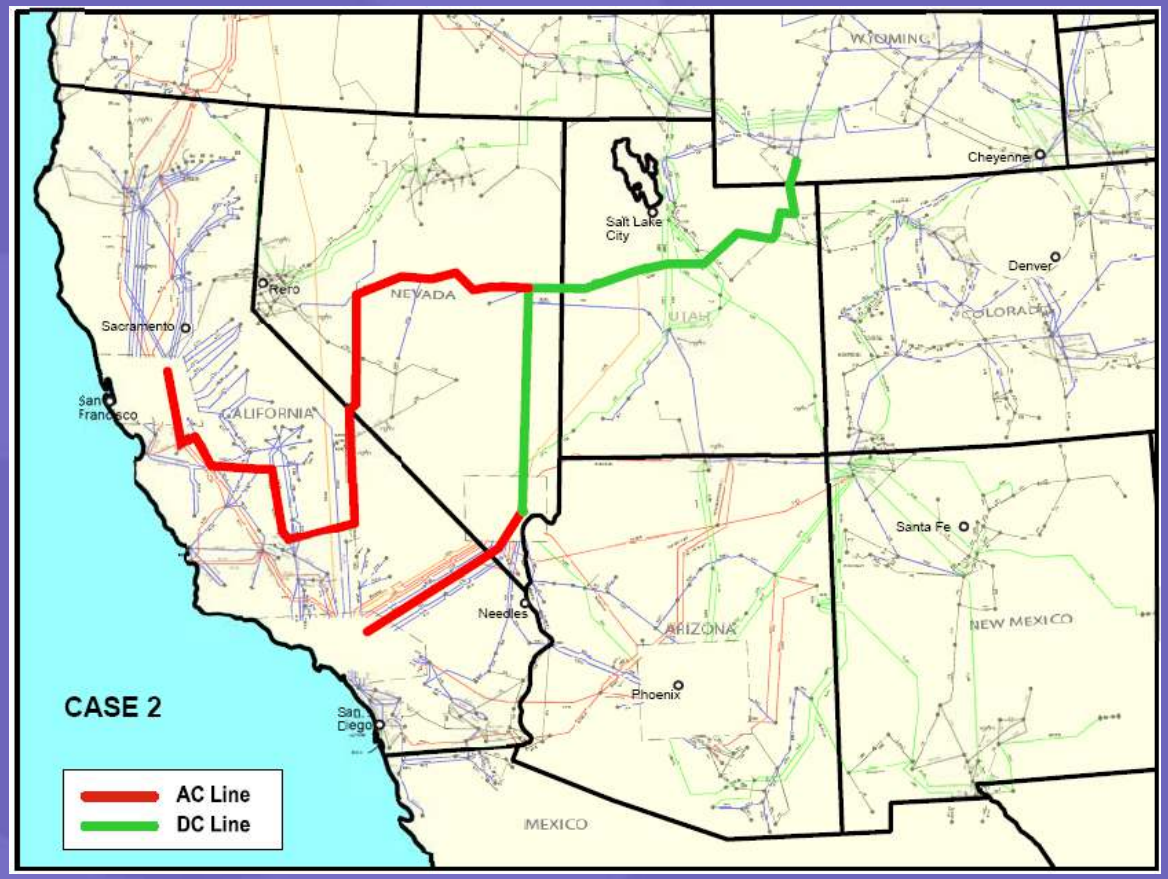
Brattle Group

"Green Power Express" ITC Holdings



12,000 MW **3,000 miles**
765 kv AC **$ 10 – 12 B**

Frontier Line

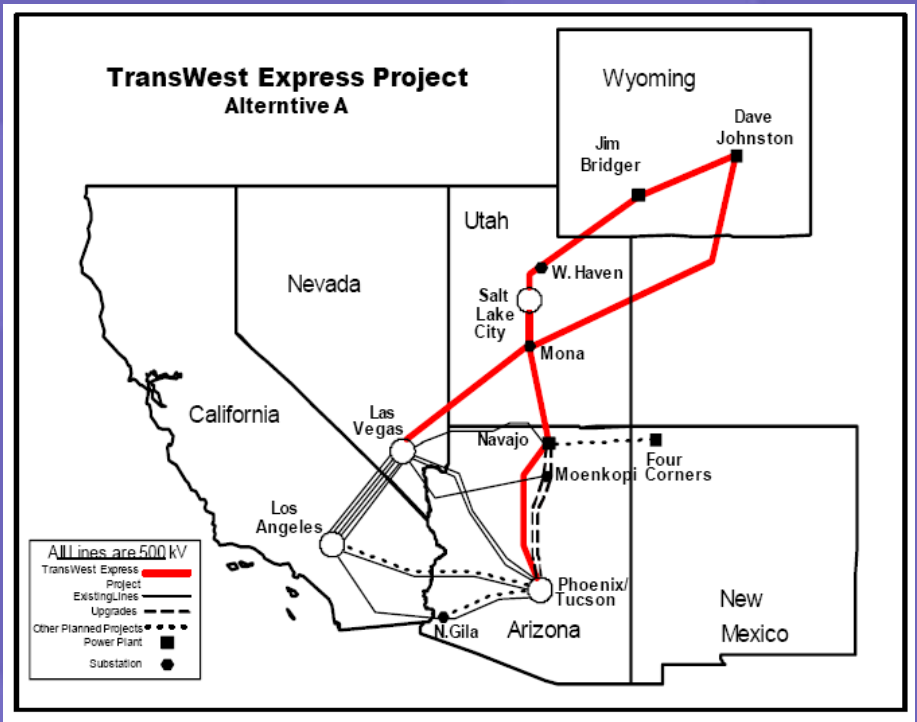


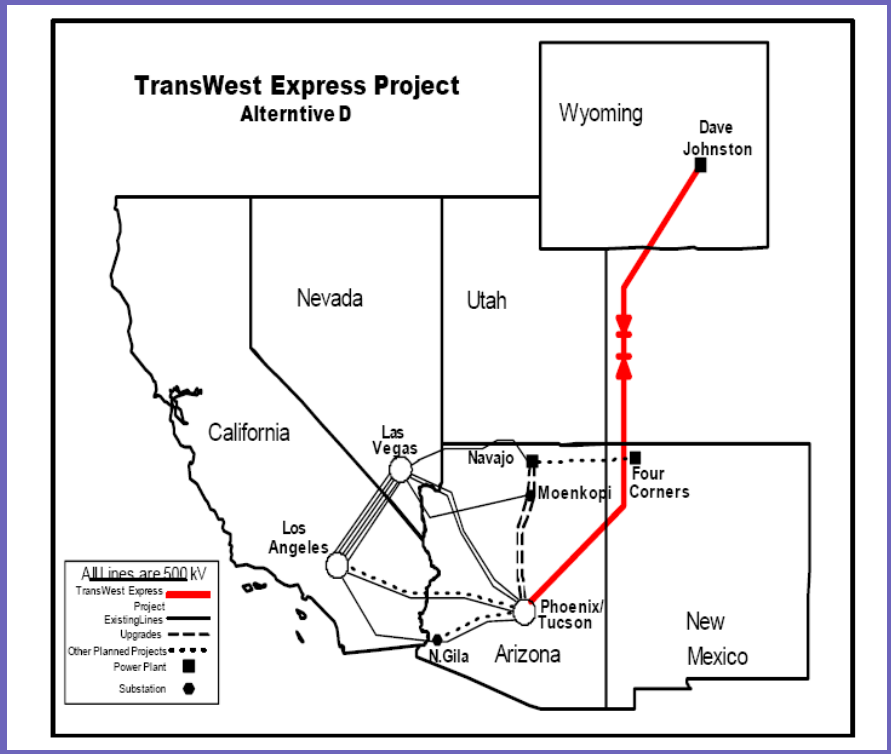
Example pathway by California Energy Commission, *Wyoming-California Corridor Transmission Expansion Study,* Global Energy Decisions, June 2006, CEC-700-2006-008.

- 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:
Building a Path to America's Clean Energy Future"

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
Total	**~ 1,000**	**GW**

Great Plains Potential: 3,000 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

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 ?			2.5

GW-scale Transmission + Storage Options

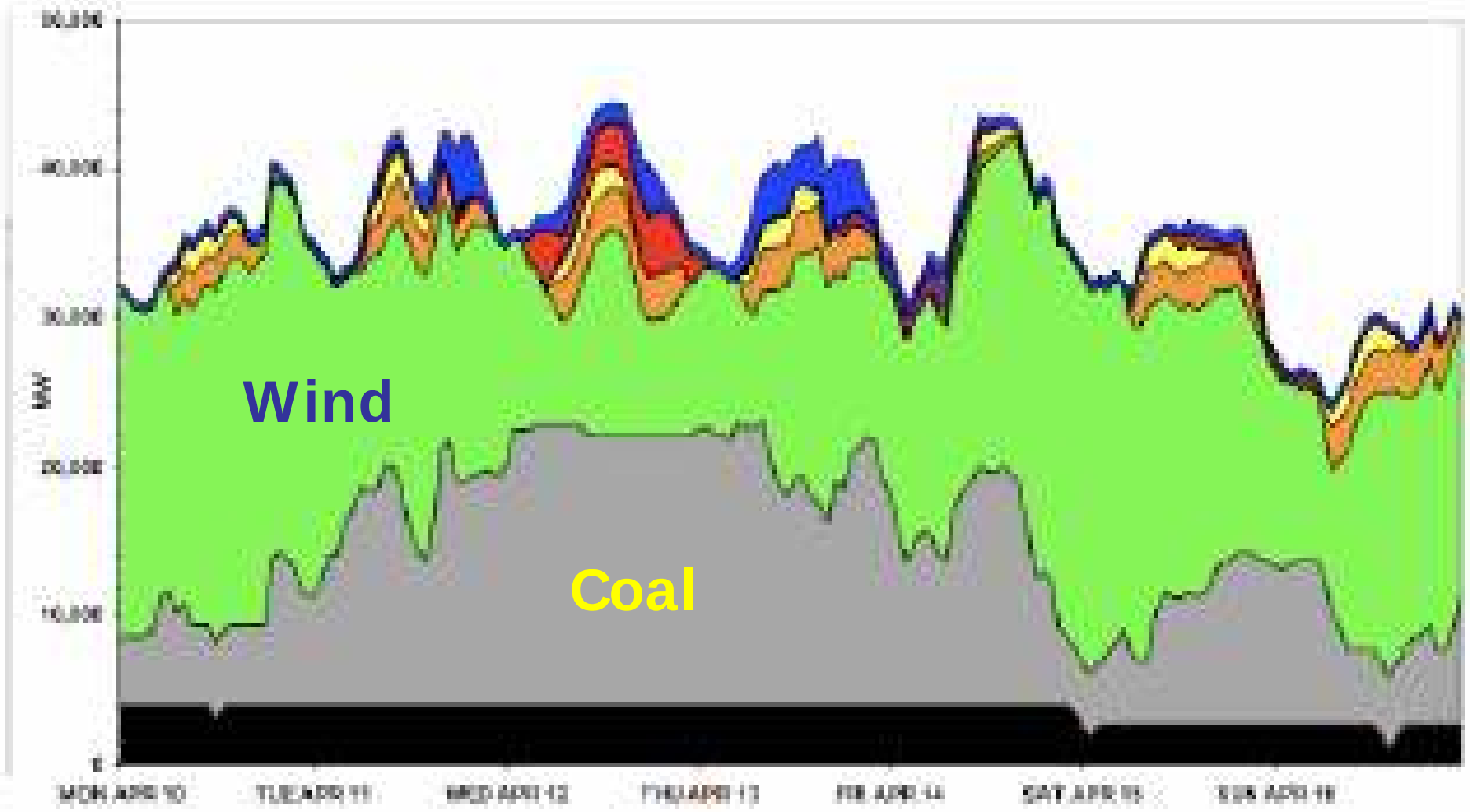
- **Electricity: HVAC, HVDC**
  - **CAES compressed air energy storage**
  - **Vanadium Redox battery (VRB Power Systems)**
  - **Sodium-sulfur battery**
  - **PHEV (distributed)**
- **Gaseous Hydrogen (GH2)**
  - **Pipeline**
  - **Geologic: salt caverns (man-made)**
  - **Geologic: natural formations ? *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**

Trouble with Renewables

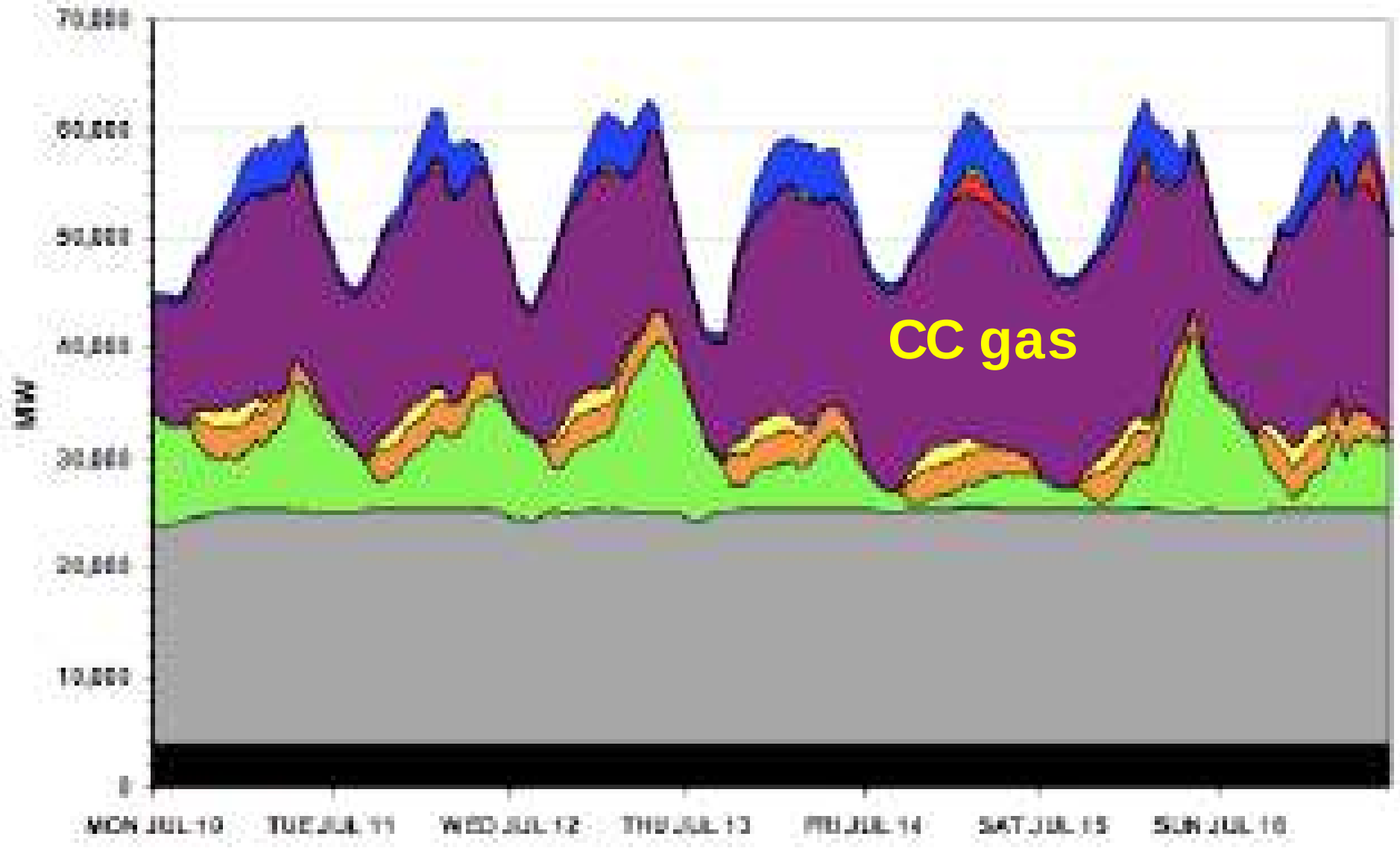
- Diffuse, dispersed: gathering cost
- Richest are remote: “stranded”
- Time-varying output:
  - “intermittent”
  - “firming” integration + storage required
- Transmission:
  - low capacity factor (CF) or curtailment
  - NIMBY
- Distributed or centralized ?

Trouble with Renewables - Electricity Transmission

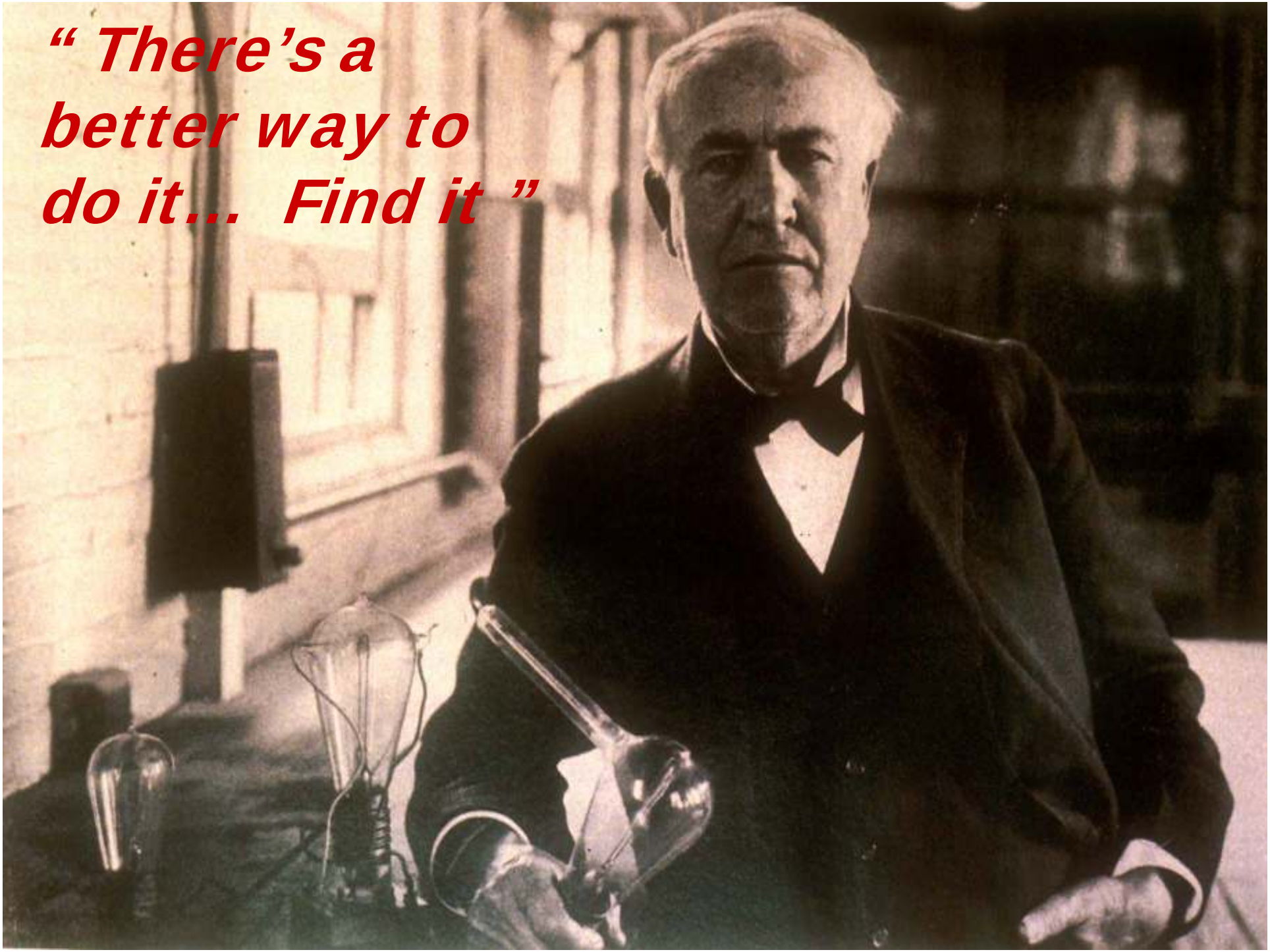
- **Grid nearly full**
  - **New wind must pay for transmission**
  - **Costly: AC or DC**
- **NIMBY**
- **Low CF or curtailment**
- **Costly “firming” storage: CAES, VRB**
- **Overhead towers vulnerable: God or man**
- **Underground: Only HVDC**
- **FERC no interstate jurisdiction**



WWSIS: April week: 30% RE



WWSIS: July week: 30% RE


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

Wind seasonality, Great Plains

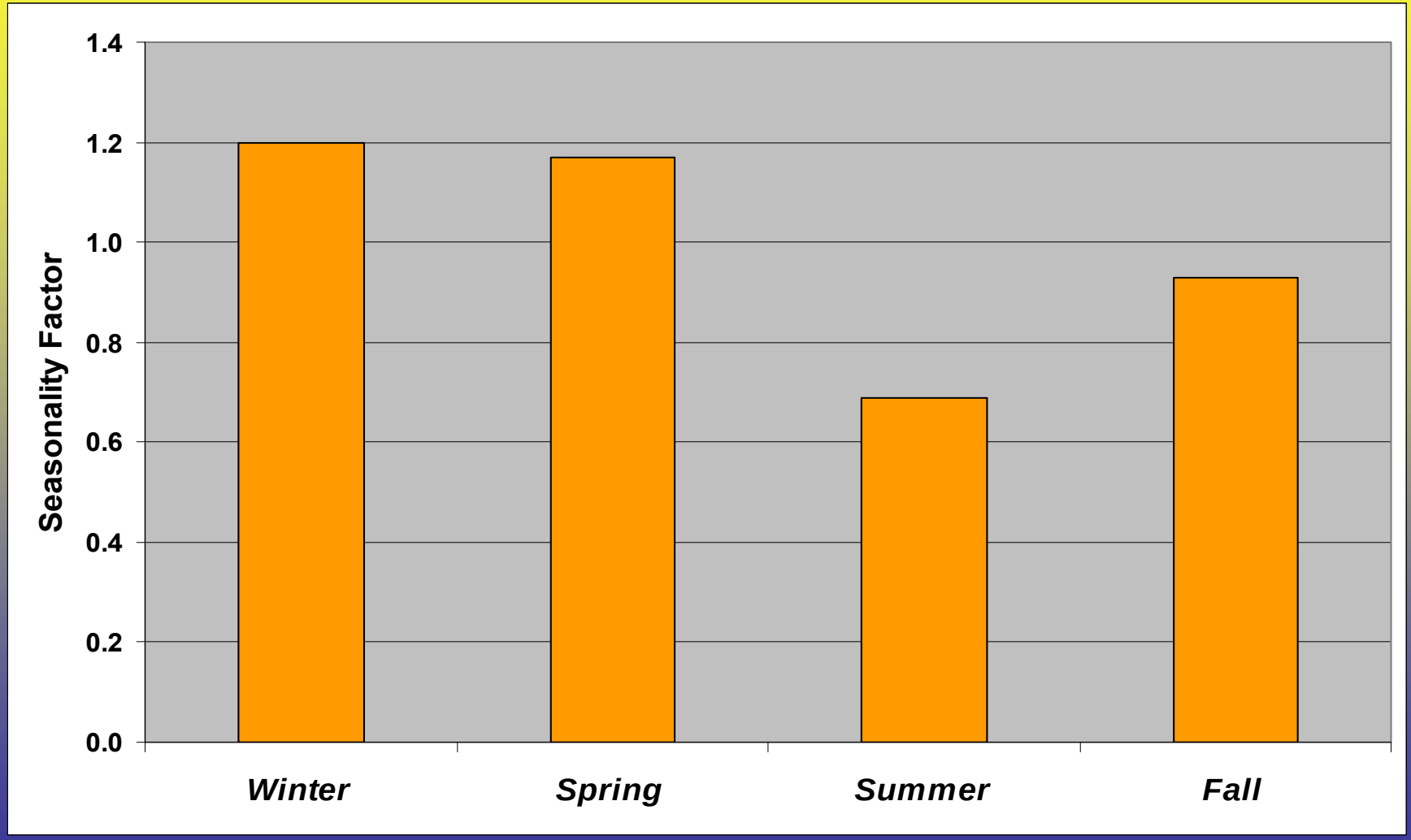
Normalized to 1.0

- **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



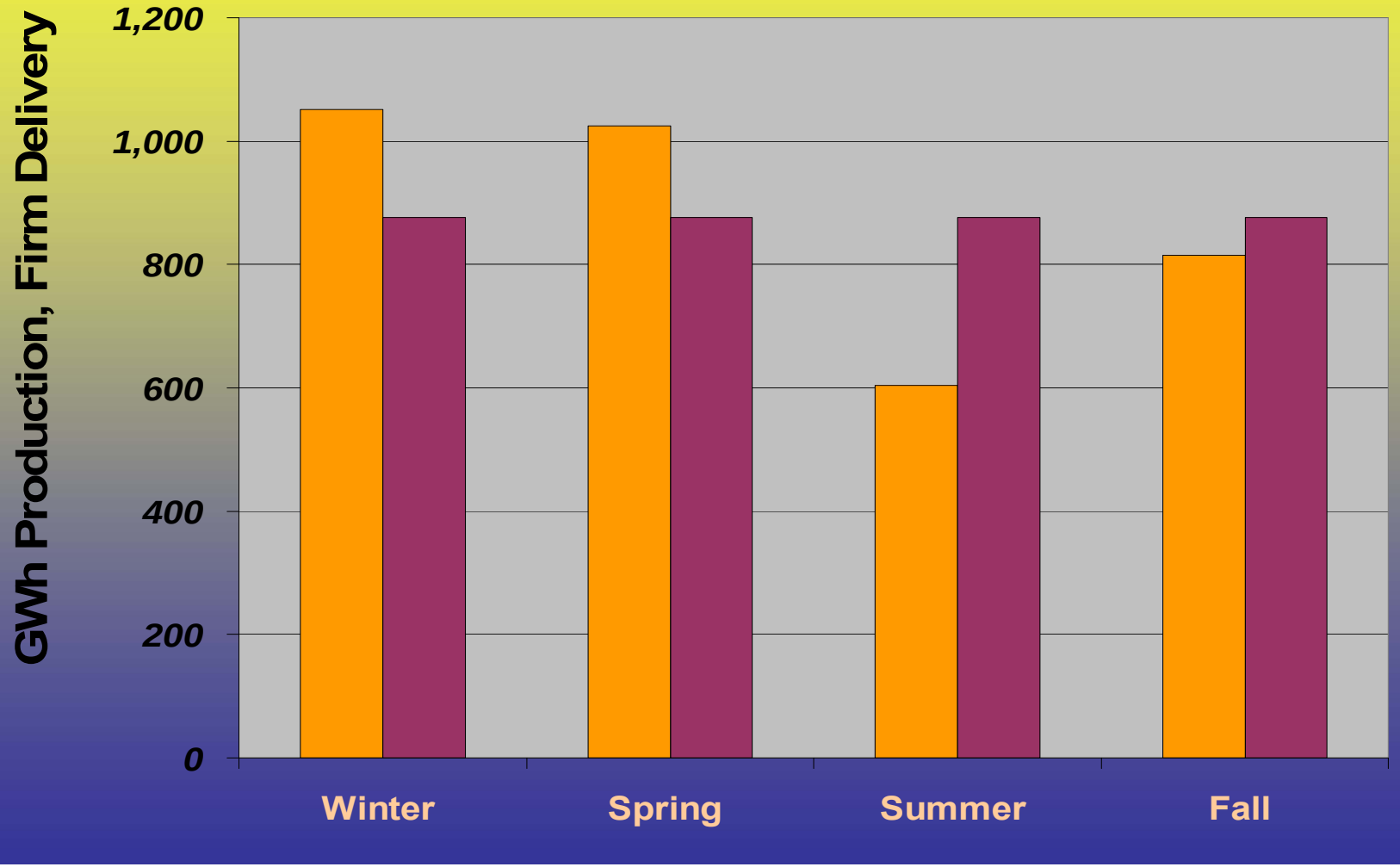
Wind Seasonality, Northern Great Plains

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



320,000 MWh

Annual firming, 1,000 MW wind

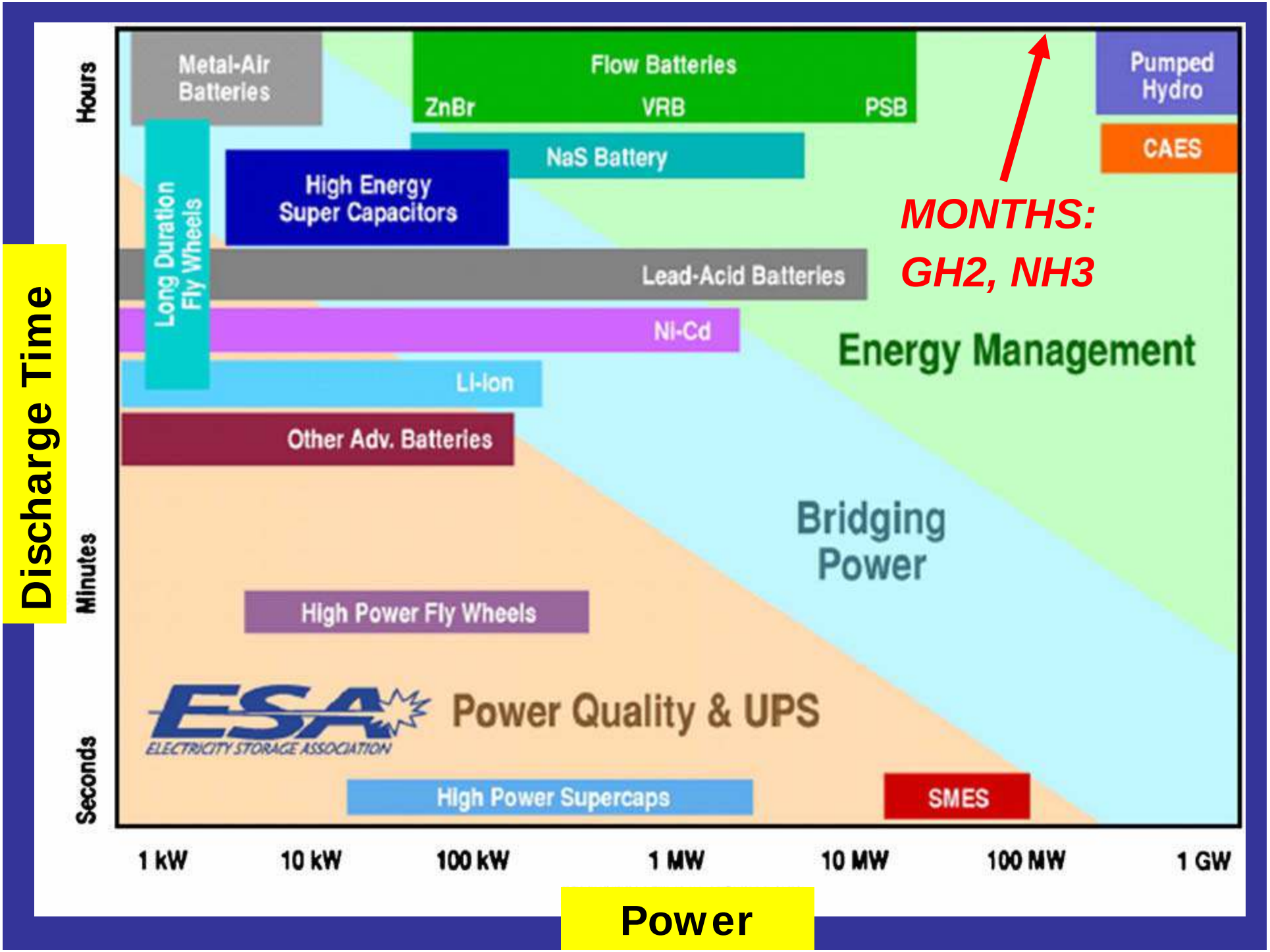
- **CAES (compressed air energy storage)**
  - **O&M: $46 / MWh typical**
  - **Iowa: Power = 268 MW**
    Energy capacity = 5,360 MWh
    Capital: 268 MW @$800 / kW = $214 M
    @ $40 / kWh = $13 Billion
    @ $1 / kWh = $325 Million
- **VRB flow battery**
  - **O&M: 80% efficiency round-trip**
  -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

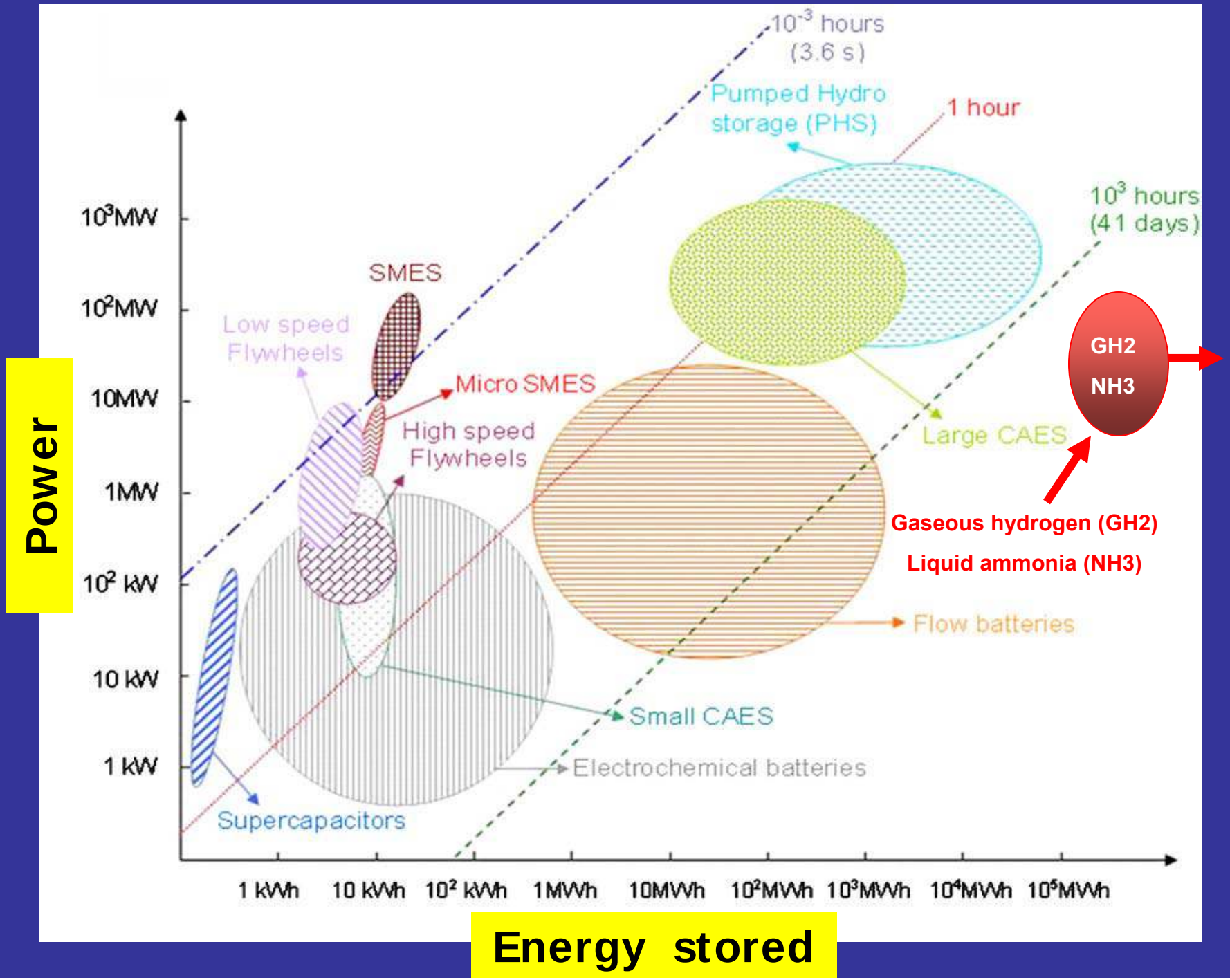
"Firm" energy worth more

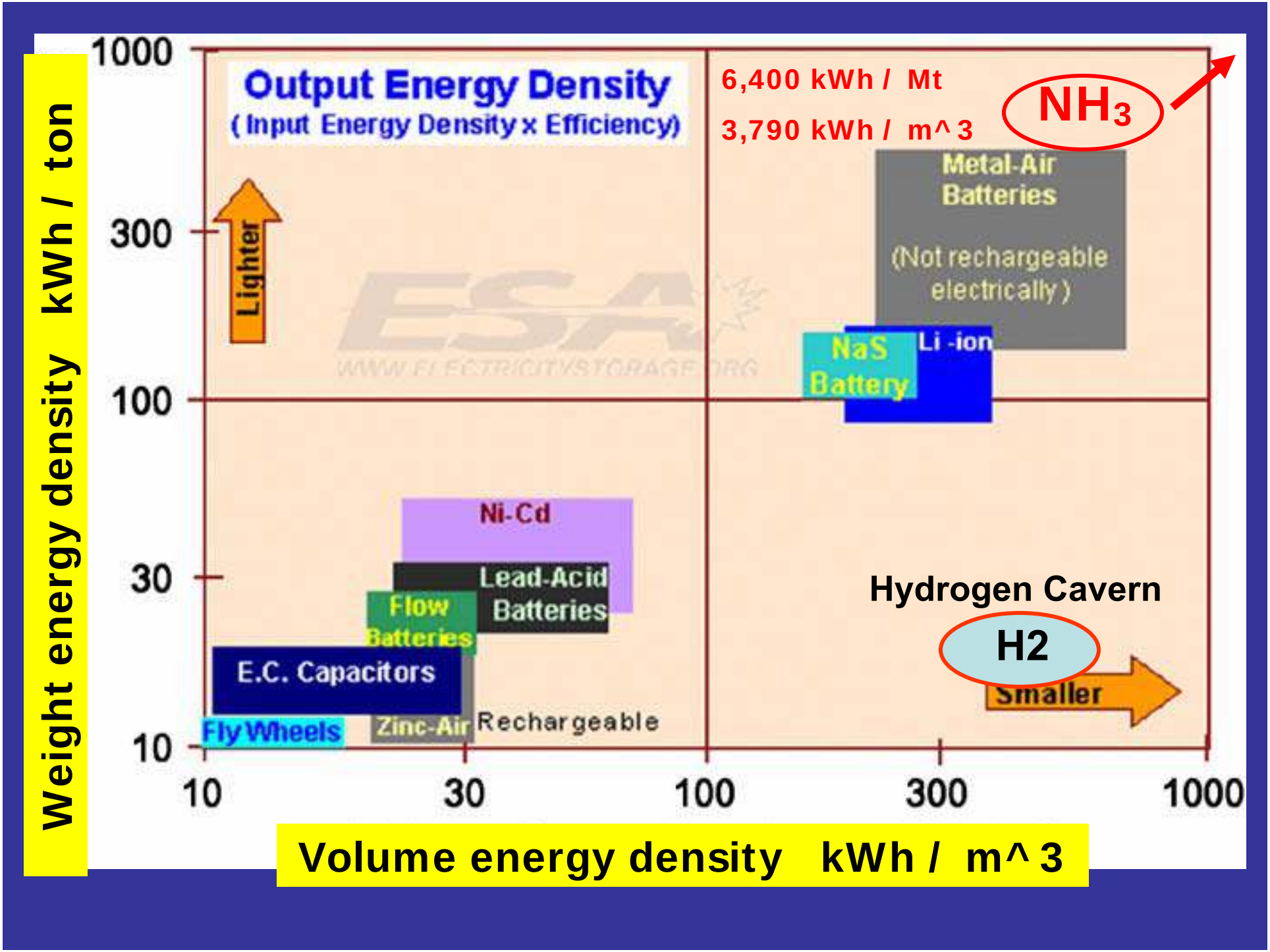
- **Essential**
- **Every hour, every year**
- **Strategic: indigenous, secure**
- **Dispatchable**
- **Market price**
- **Bankable large projects**
- **Risk avoidance: rapid climate change**
- **C-taxes acceptable: RE**

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**

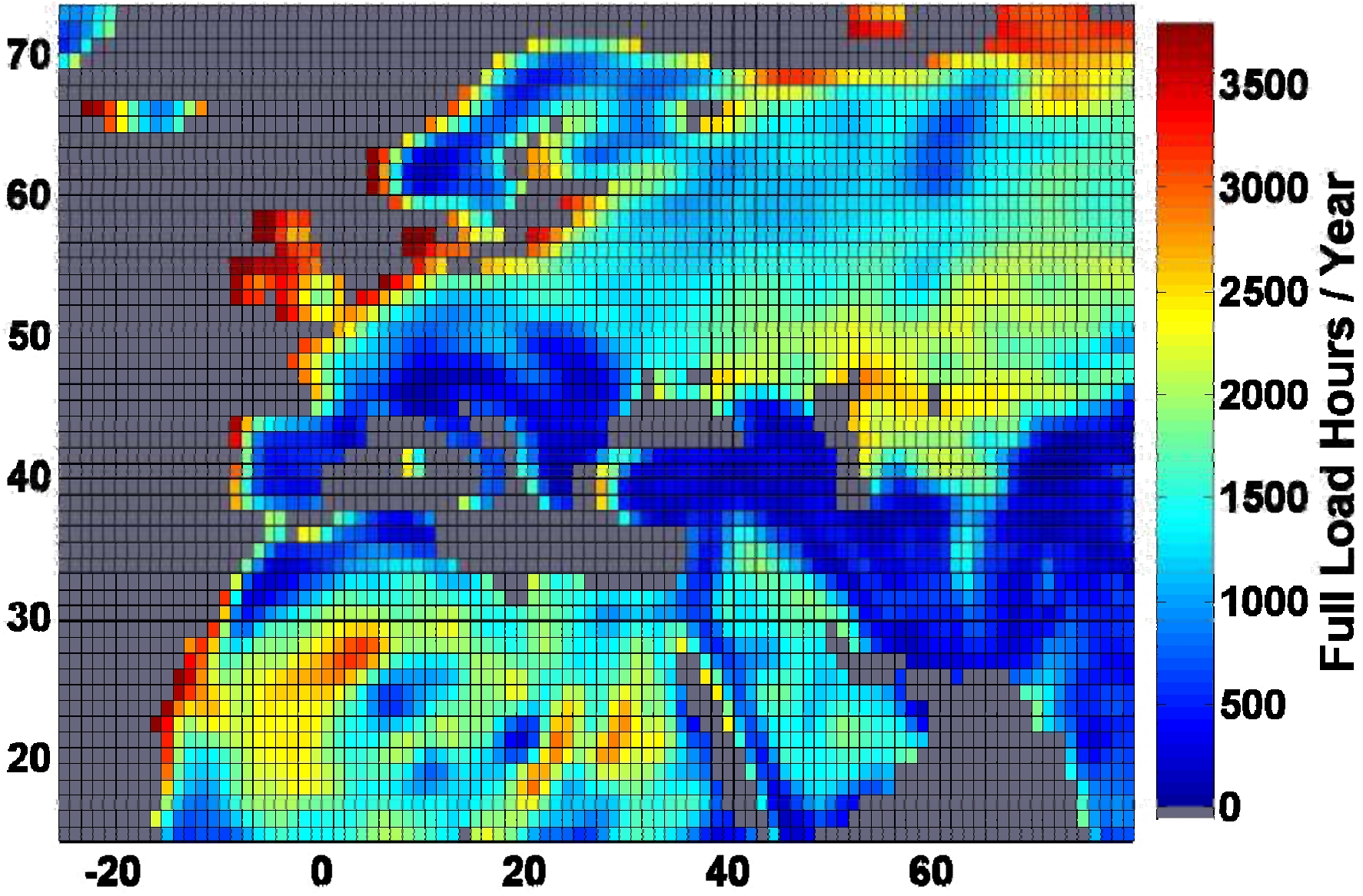

Discharge Time
Hours
Minutes
Seconds
Metal-Air Batteries
Flow Batteries
ZnBr
VRB
PSB
Pumped Hydro
CAES
NaS Battery
High Energy Super Capacitors
Long Duration Fly Wheels
MONTHS:
GH2, NH3
Lead-Acid Batteries
Ni-Cd
Energy Management
LI-ion
Other Adv. Batteries
Bridging Power
High Power Fly Wheels
ESA
ELECTRICITY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


Power
10^{-3} hours
(3.6 s)
Pumped Hydro
storage (PHS)
1 hour
10^{3} hours
(41 days)
10^{3}MW
10^{2}MW
10MW
1MW
10^{2} kW
10 kW
1 kW
SMES
Low speed
Flywheels
Micro SMES
High speed
Flywheels
Large CAES
GH2
NH3
Gaseous hydrogen (GH2)
Liquid ammonia (NH3)
Flow batteries
Small CAES
Electrochemical batteries
Supercapacitors
1 kWh
10 kWh
10^{2} kWh
1MWh
10MWh
10^{2}MWh
10^{3}MWh
10^{4}MWh
10^{5}MWh
Energy stored


Weight energy density kWh / ton
1000
300
100
30
10
Output Energy Density
(Input Energy Density x Efficiency)
6,400 kWh / Mt
3,790 kWh / m^3
NH3
Lighter
Metal-Air Batteries
(Not rechargeable electrically)
NaS Battery
Li -ion
Ni-Cd
Lead-Acid Batteries
Flow Batteries
E.C. Capacitors
Fly Wheels
Zinc-Air
Rechargeable
Hydrogen Cavern
H2
Smaller
10
30
100
300
1000
Volume energy density kWh / m^3

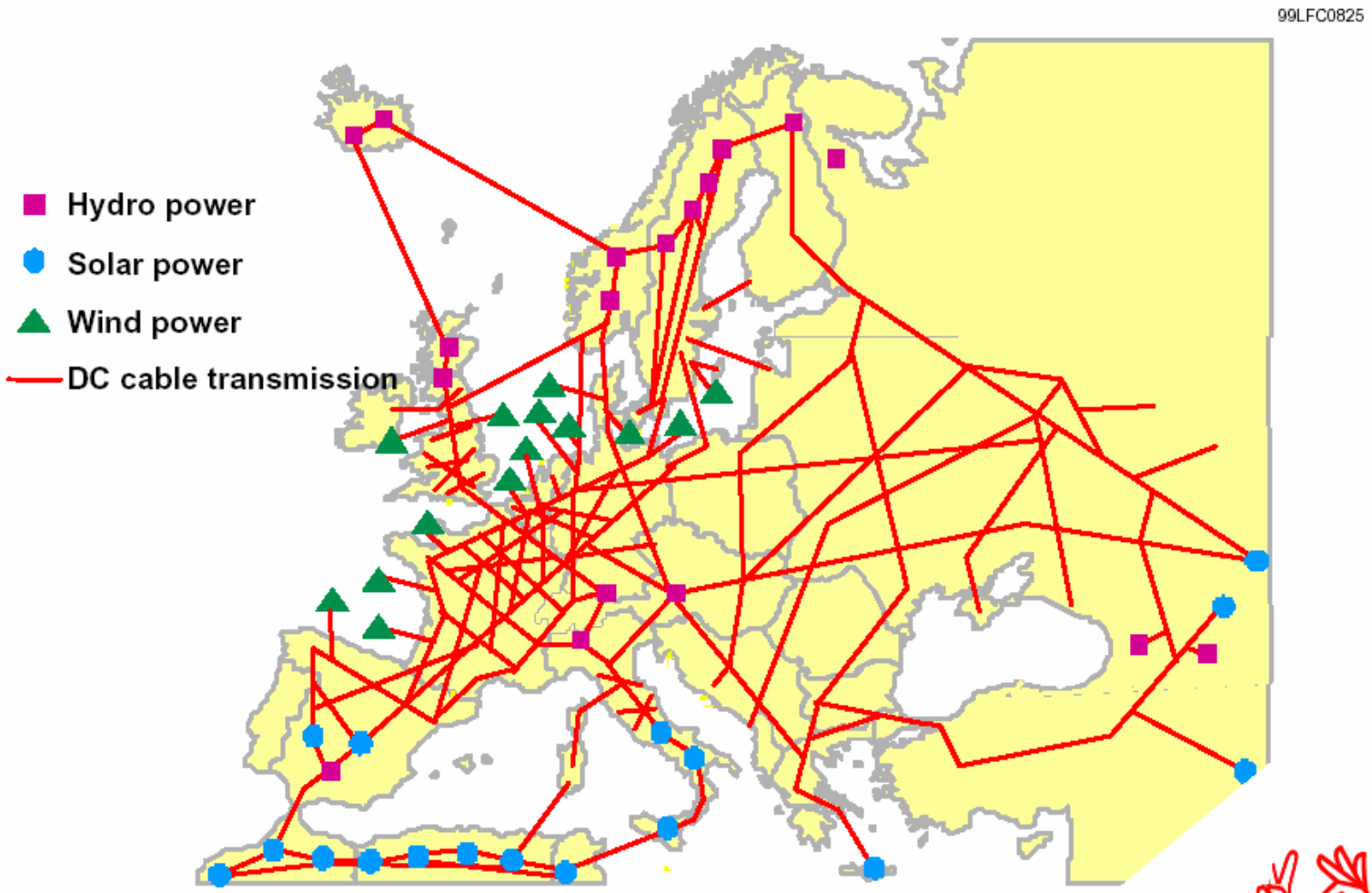
ABB, ISET Kassel "Huge Catchment Area"

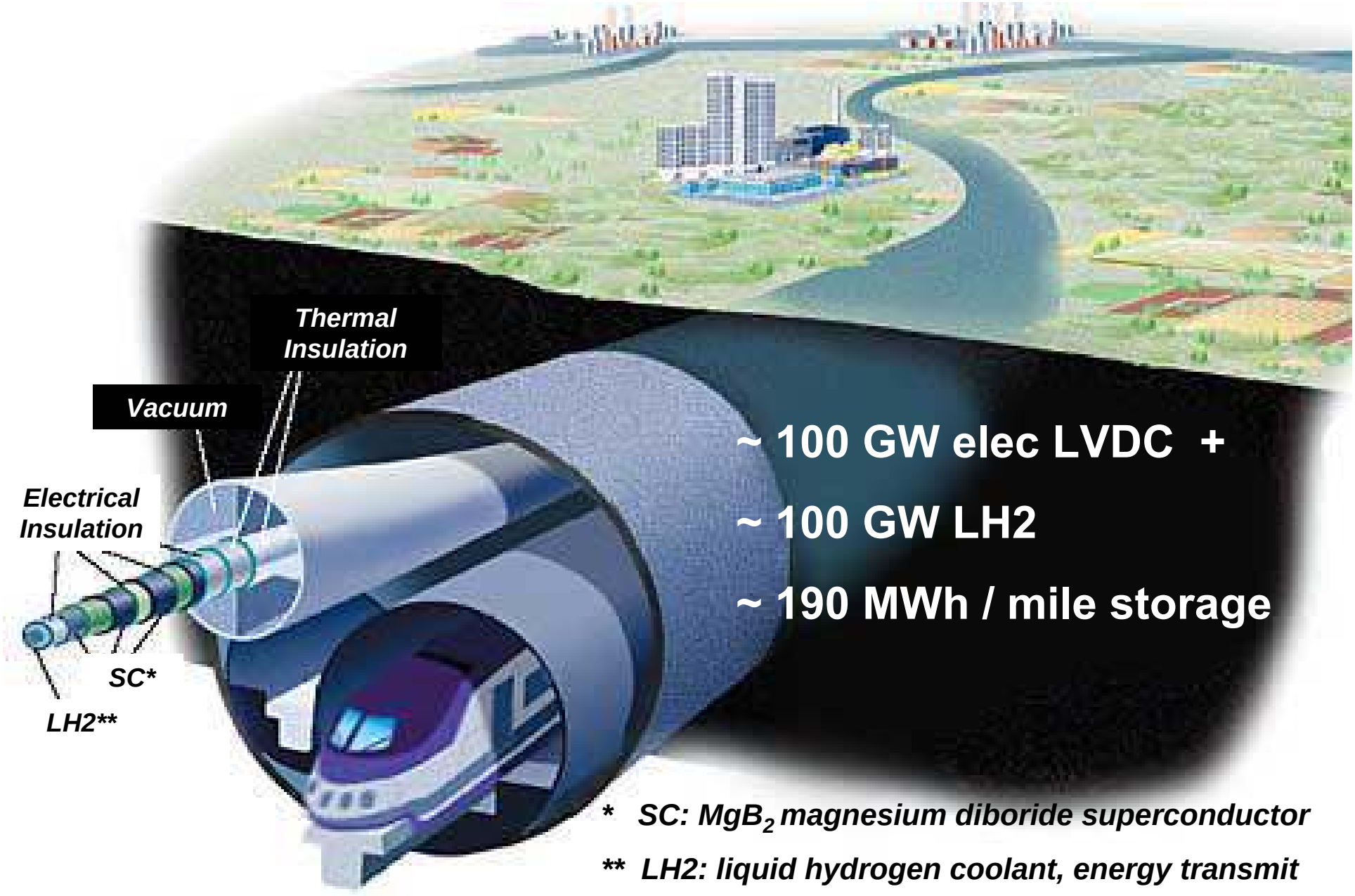
Wind – Electricity only: almost "Firm" ***Windpower 01***



Vision: Remote renewable energy sources

connected to loads by DC grid



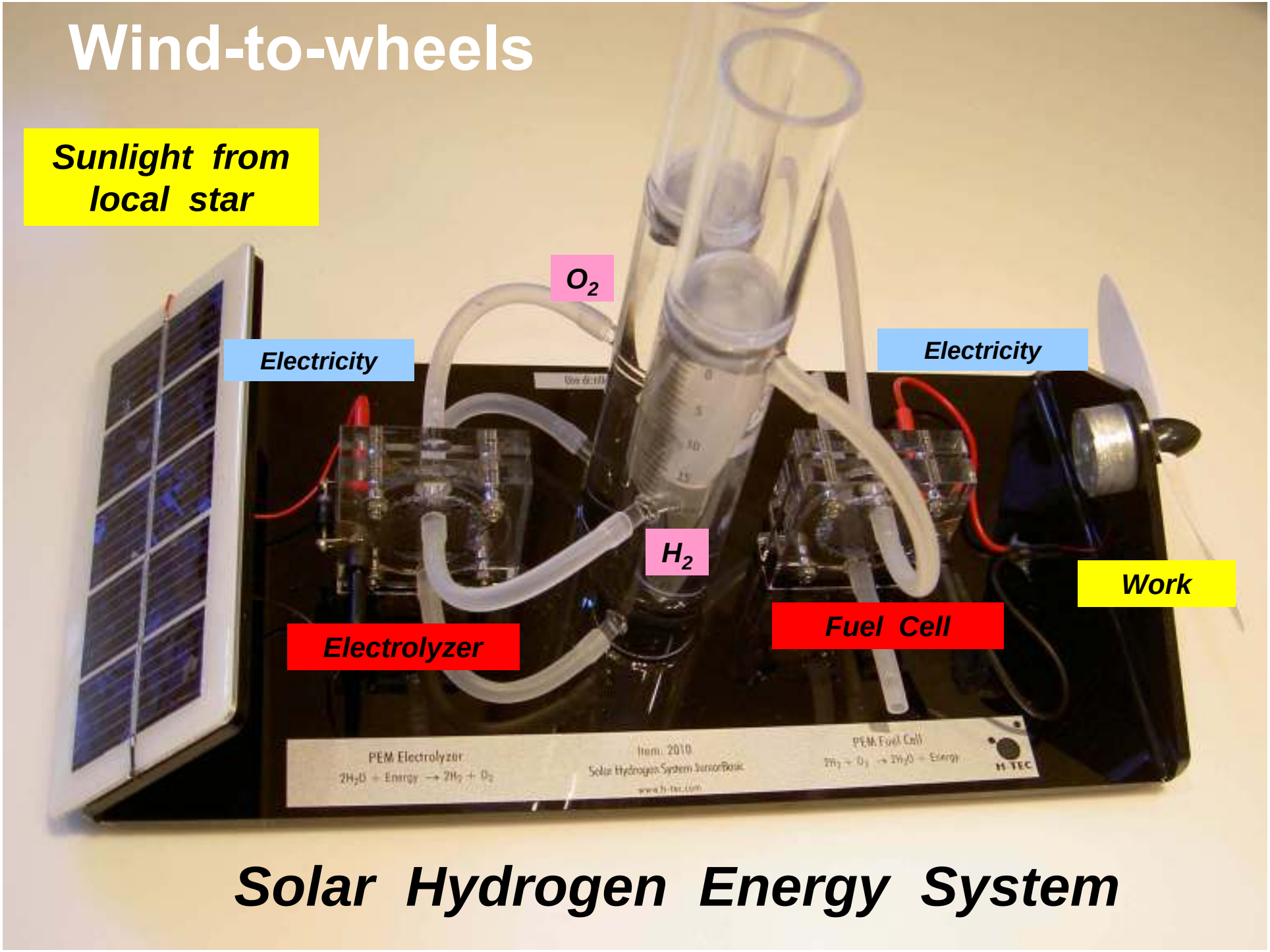


* SC: MgB_2 magnesium diboride superconductor

** LH2: liquid hydrogen coolant, energy transmit

Continental Supergrid – EPRI concept "Energy Pipeline"

Wind-to-wheels



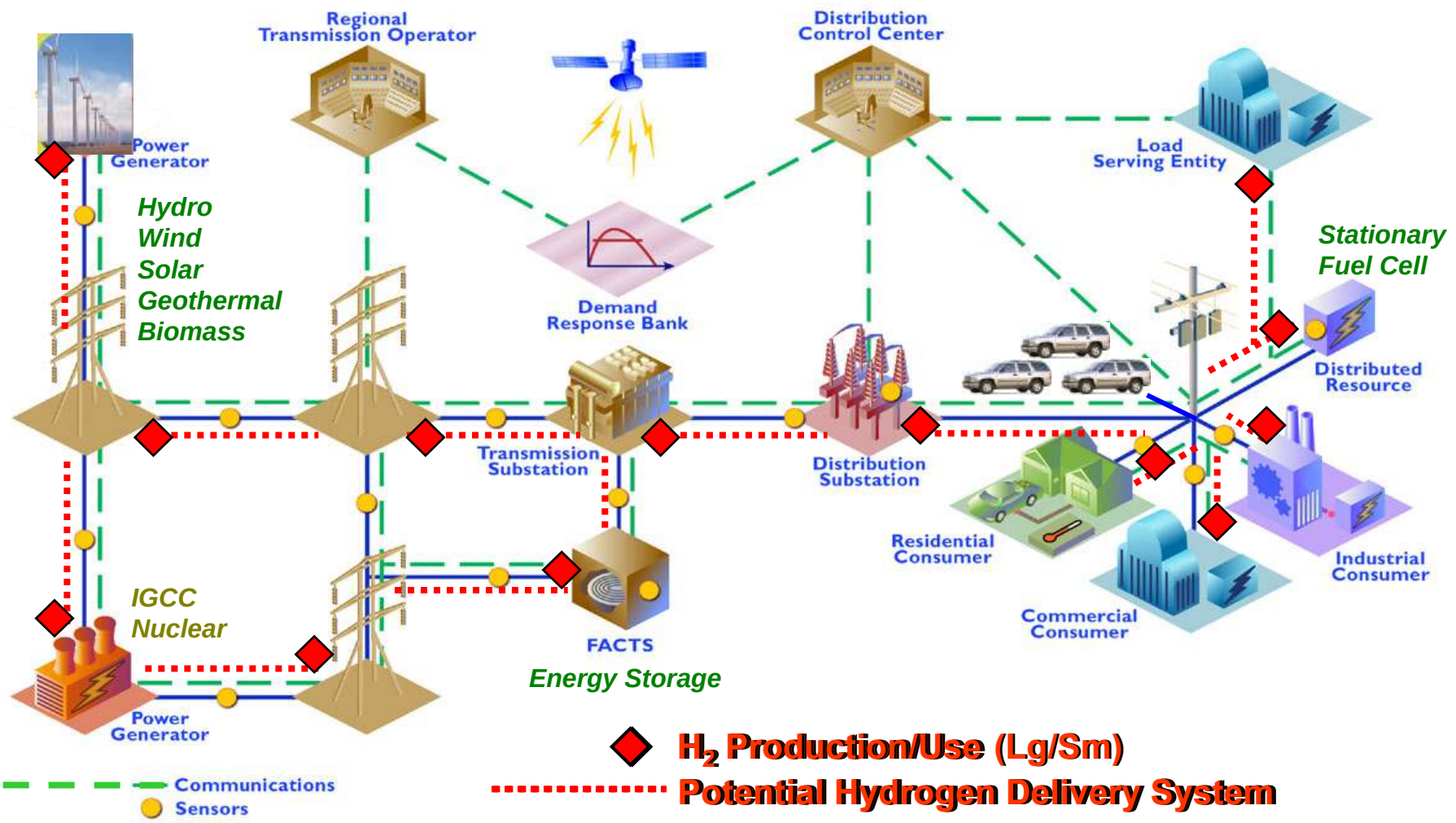
Solar Hydrogen Energy System

Hydrogen Fuel Cell

Proton Exchange Membrane (PEM) type

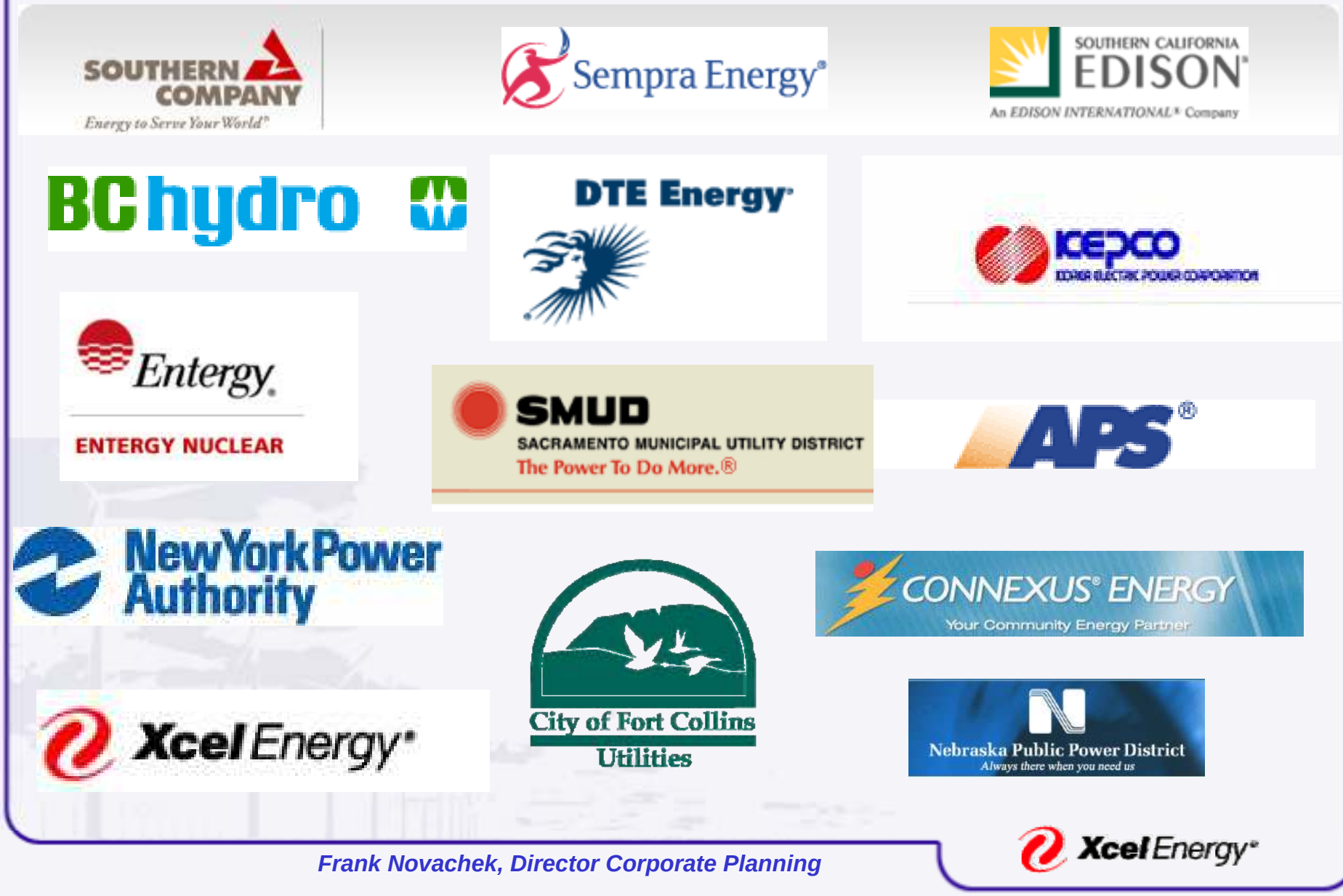
Hydrogen (H2) combines with Oxygen (O2) to make electricity + heat + water (H2O)

Energy System of the Future



Frank Novachek, Director Corporate Planning

Hydrogen Utility Group (HUG)



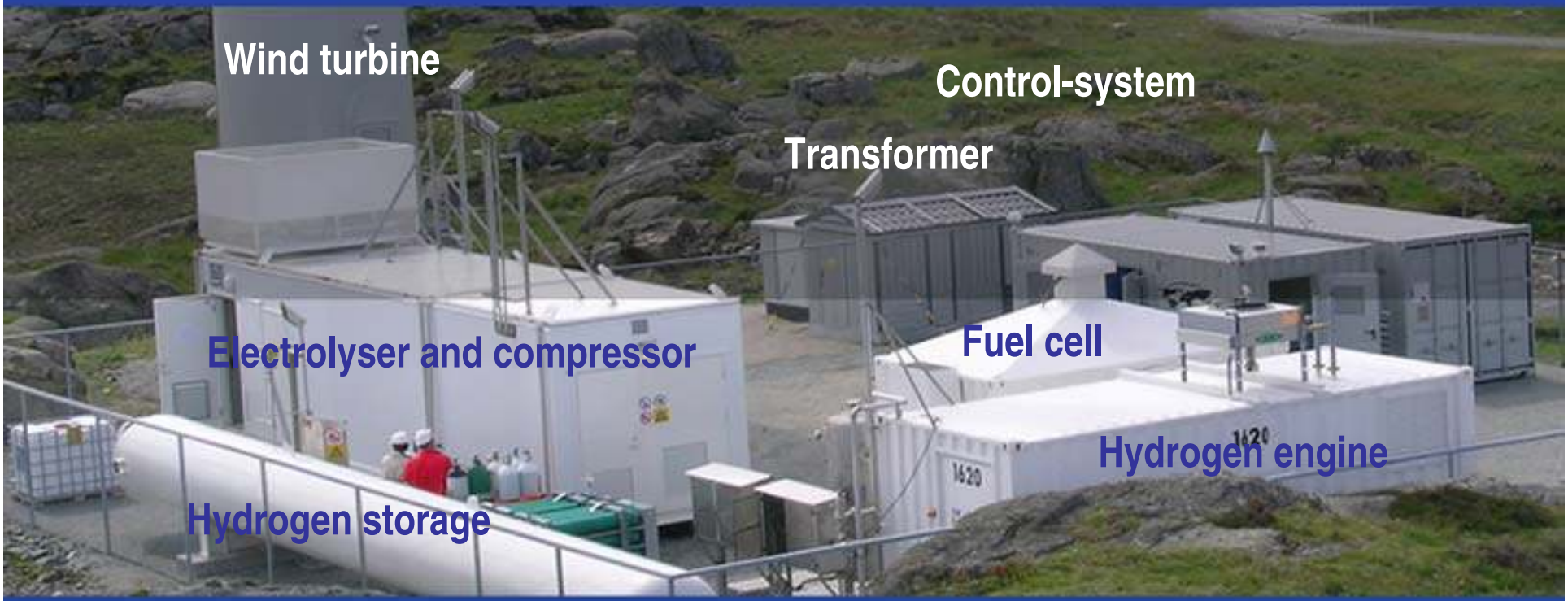
Frank Novachek, Director Corporate Planning

Xcel Energy®

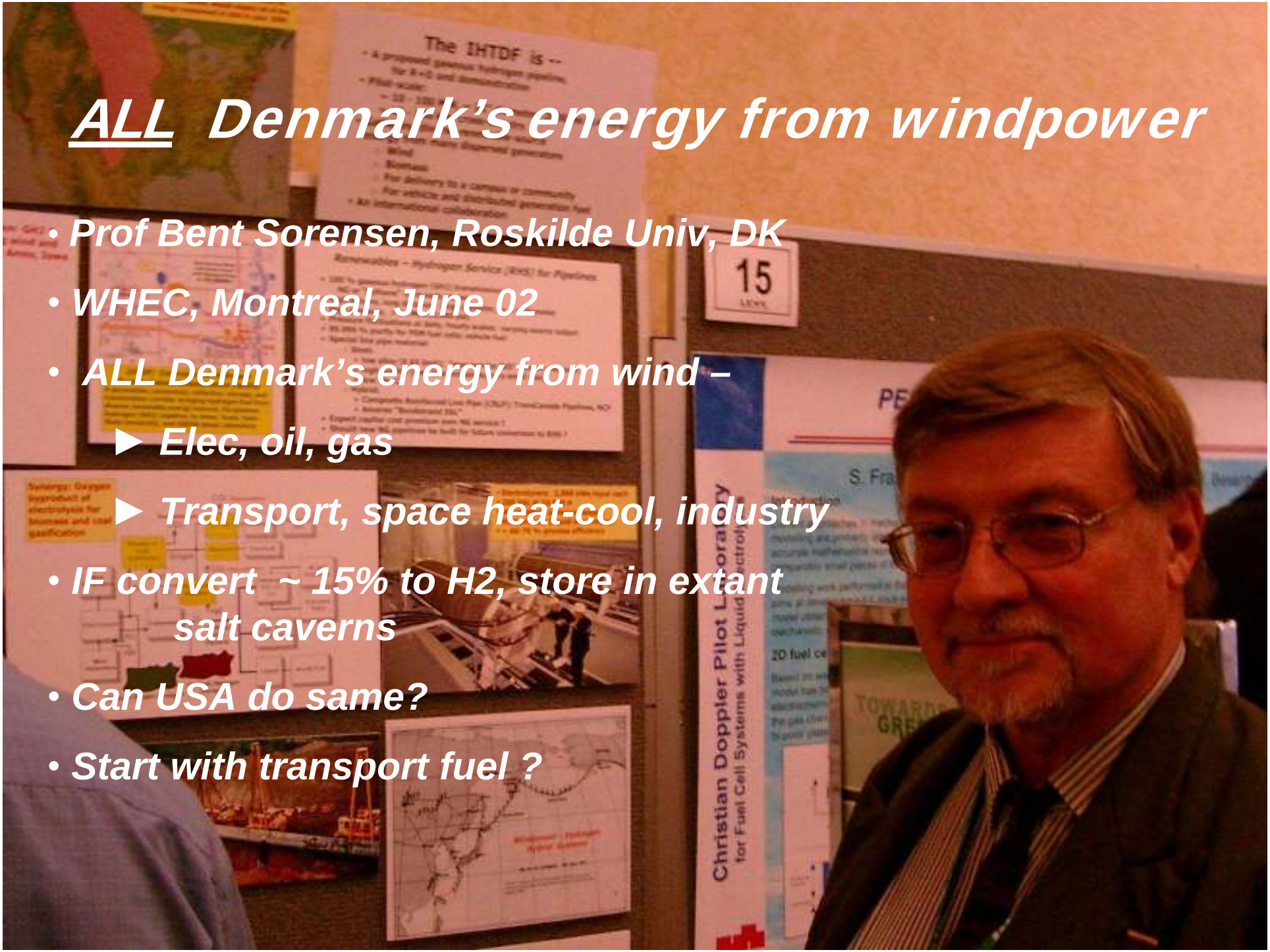
Utsira Island, Norway

The wind – hydrogen plant at Utsira

A vision becoming reality

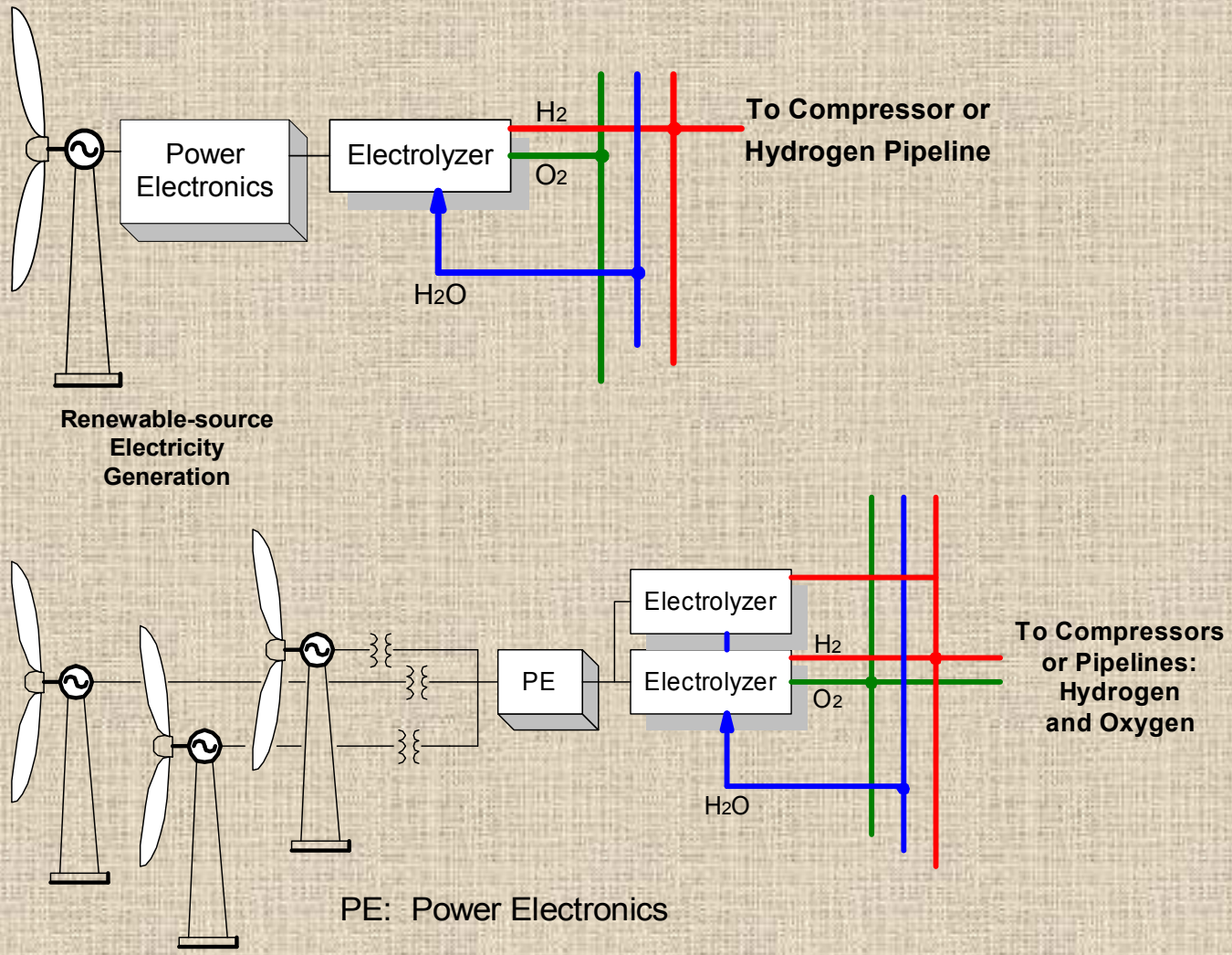


HYDRO



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 ?

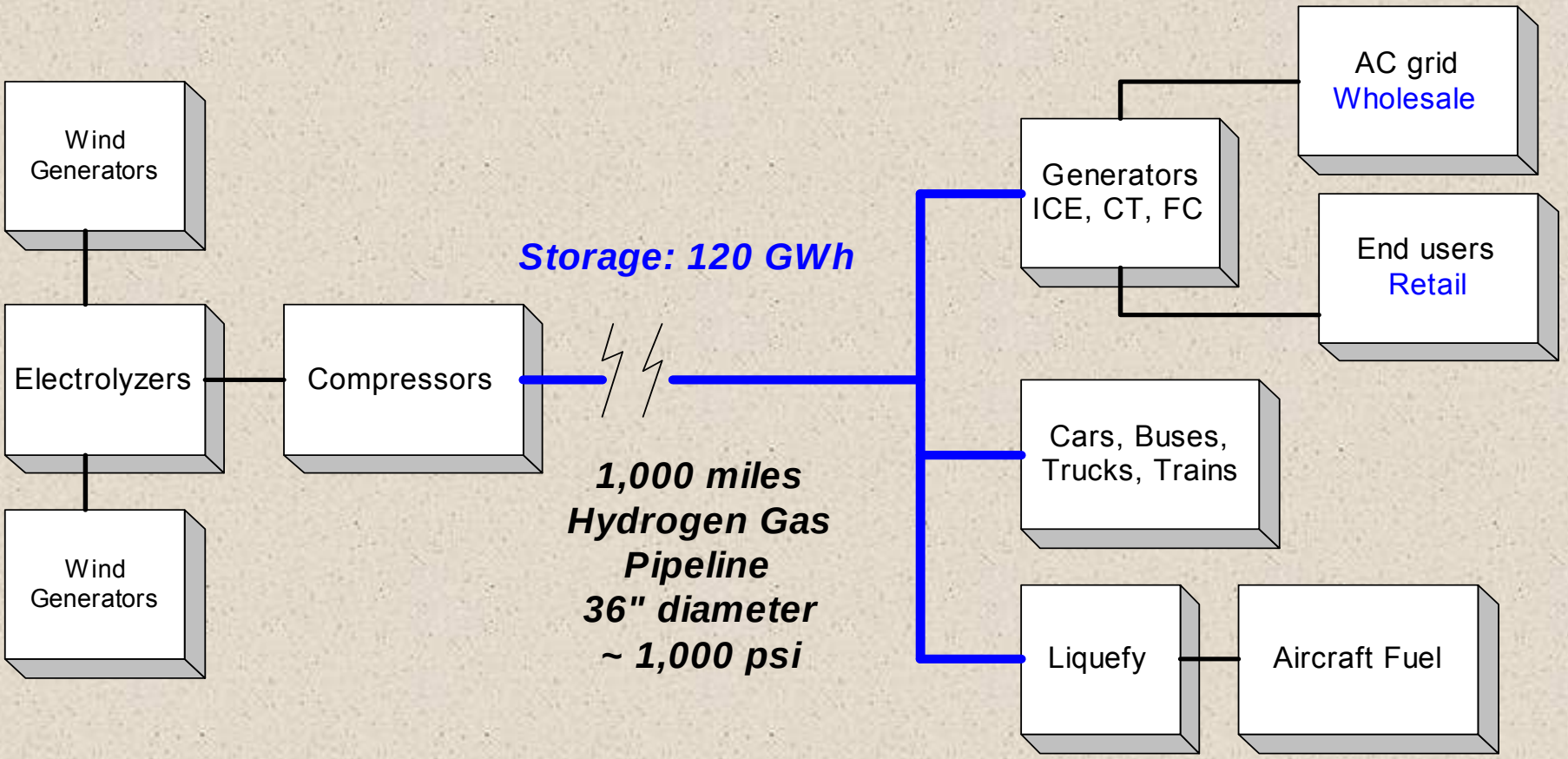


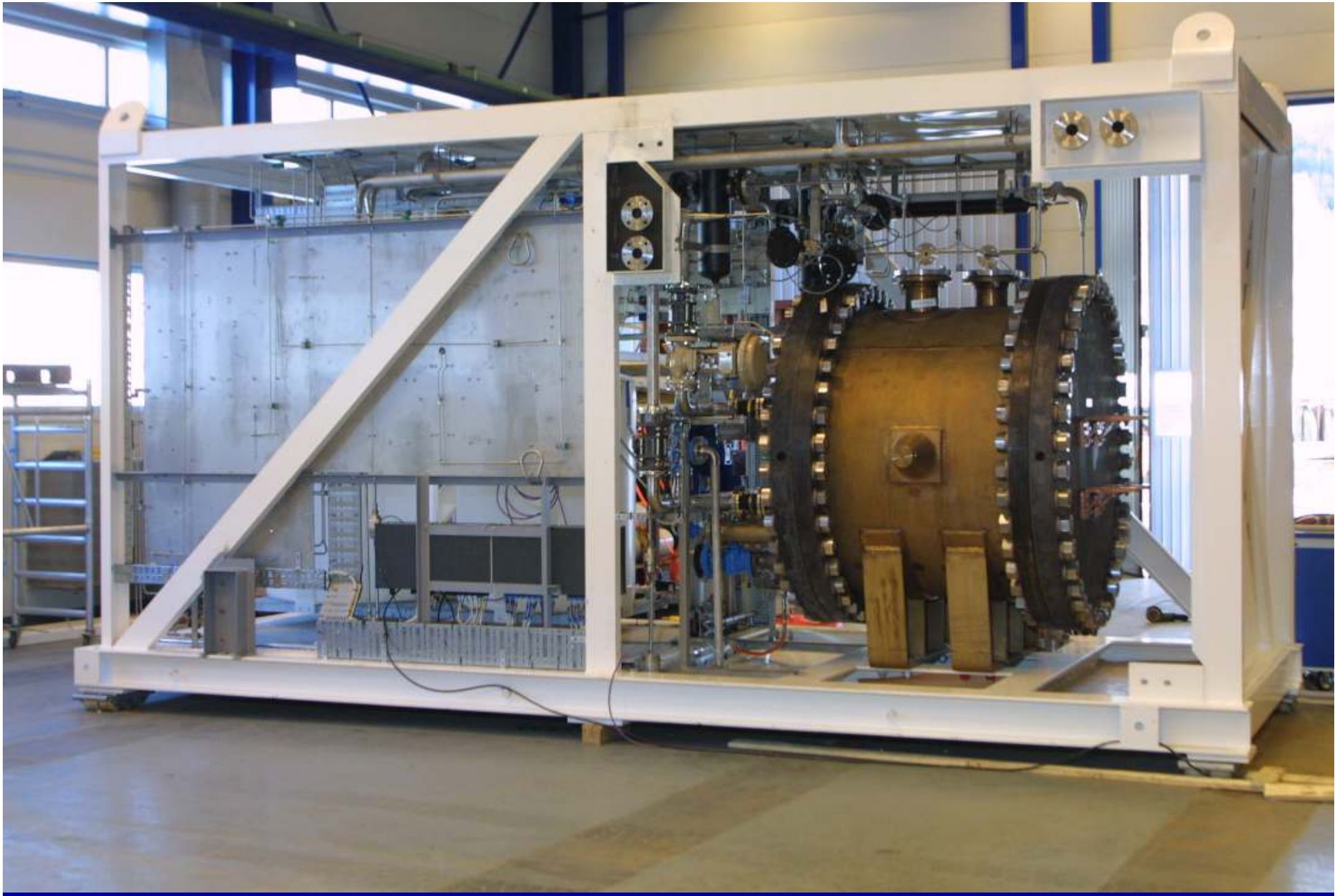
Topology Options: H_2 and O_2 Production and Gathering from Renewable Energy Generation


Norsk Hydro
Electrolyzers
2 MW each

Hydrogen Transmission Scenario

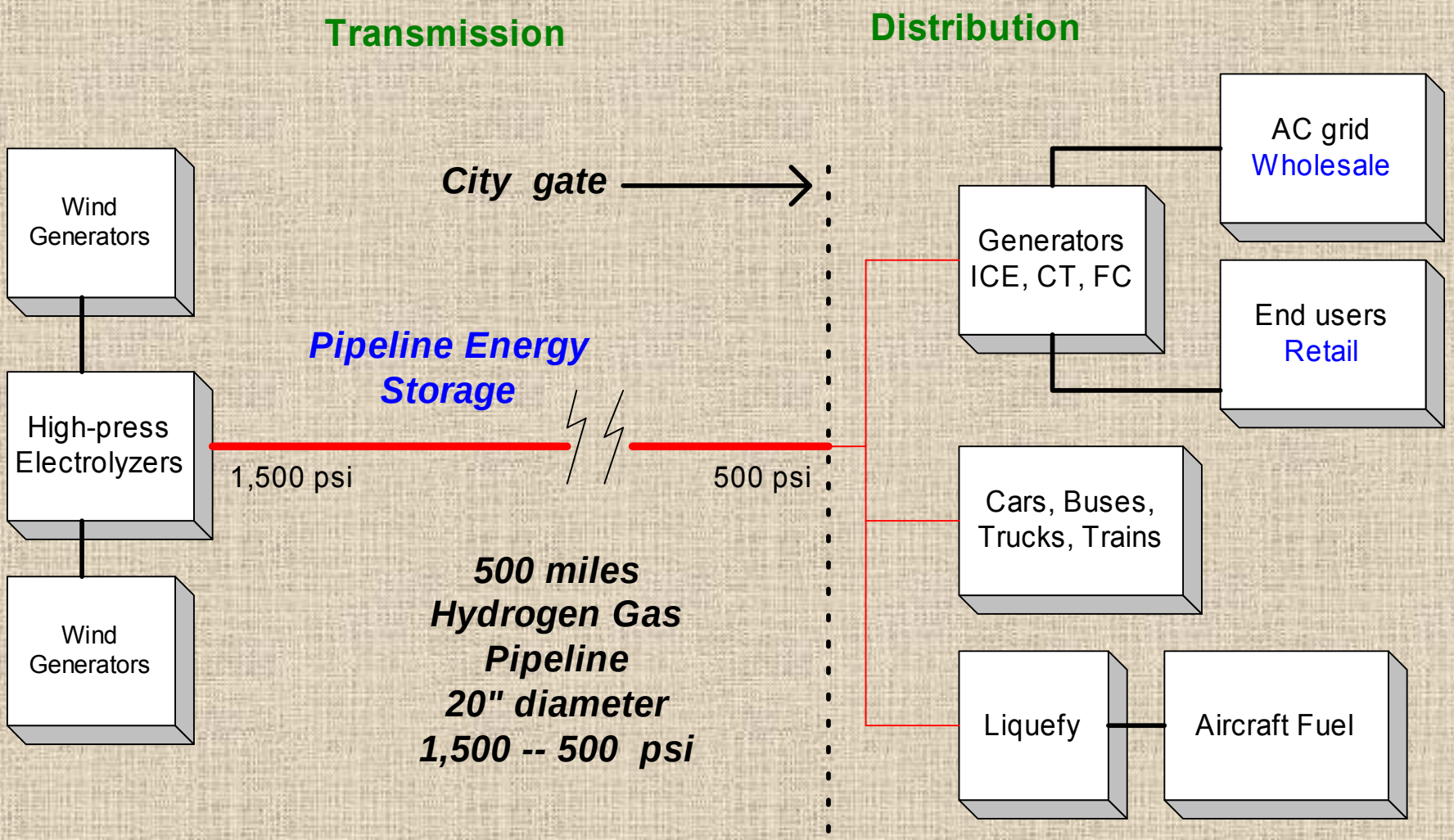
- *Low-pressure electrolyzers*
- *"Pack" pipeline: ~ 120 GWh*





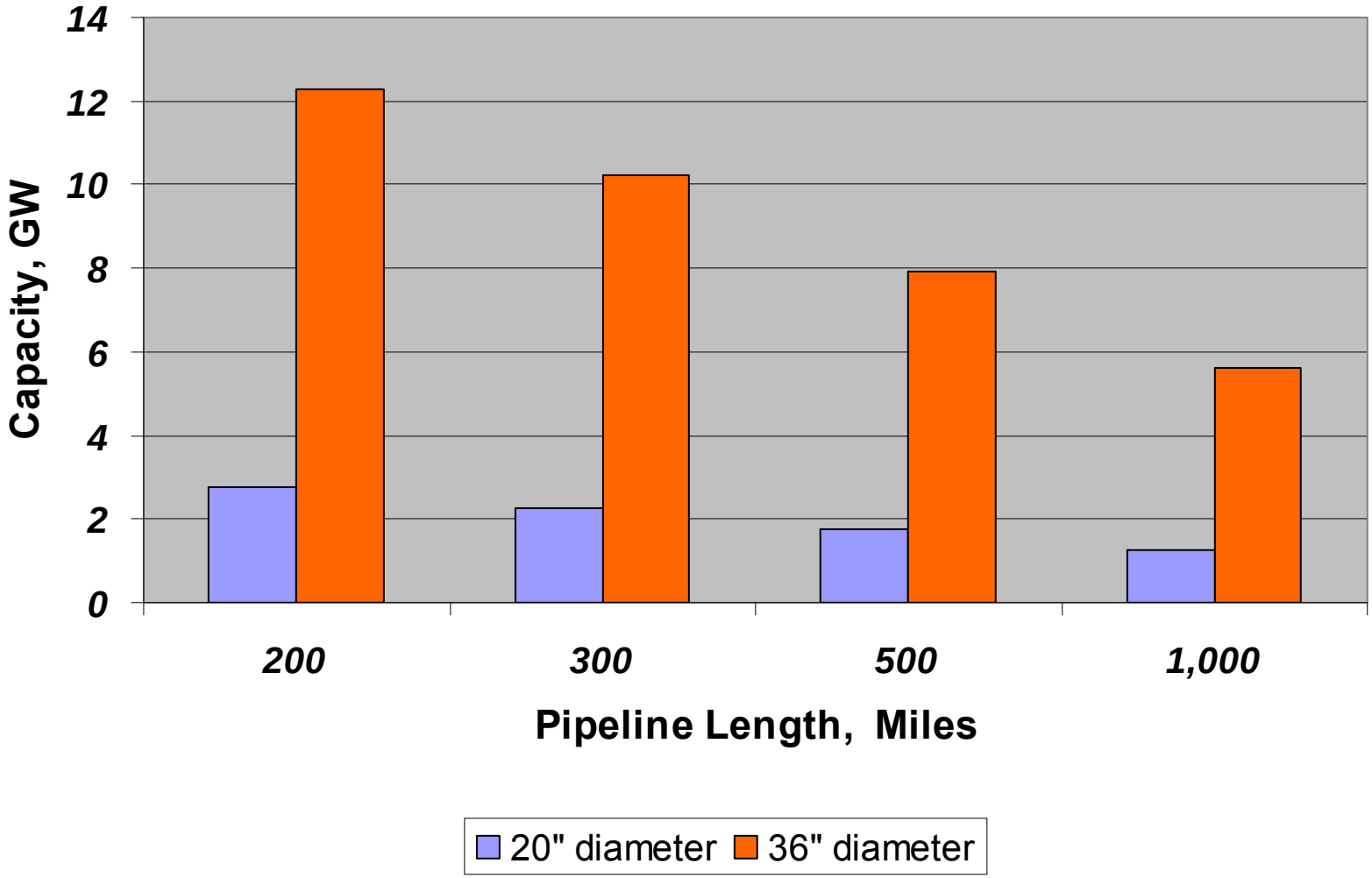
Norsk Hydro electrolyzer, KOH type
560 kW input, 130 Nm3 / hour at 450 psi (30 bar)

Compressorless system: No geologic storage



Compressorless 20”, 36” GH2 Pipeline Capacity

1,500 psi IN / 500 psi OUT



Capital Cost per GW-mile

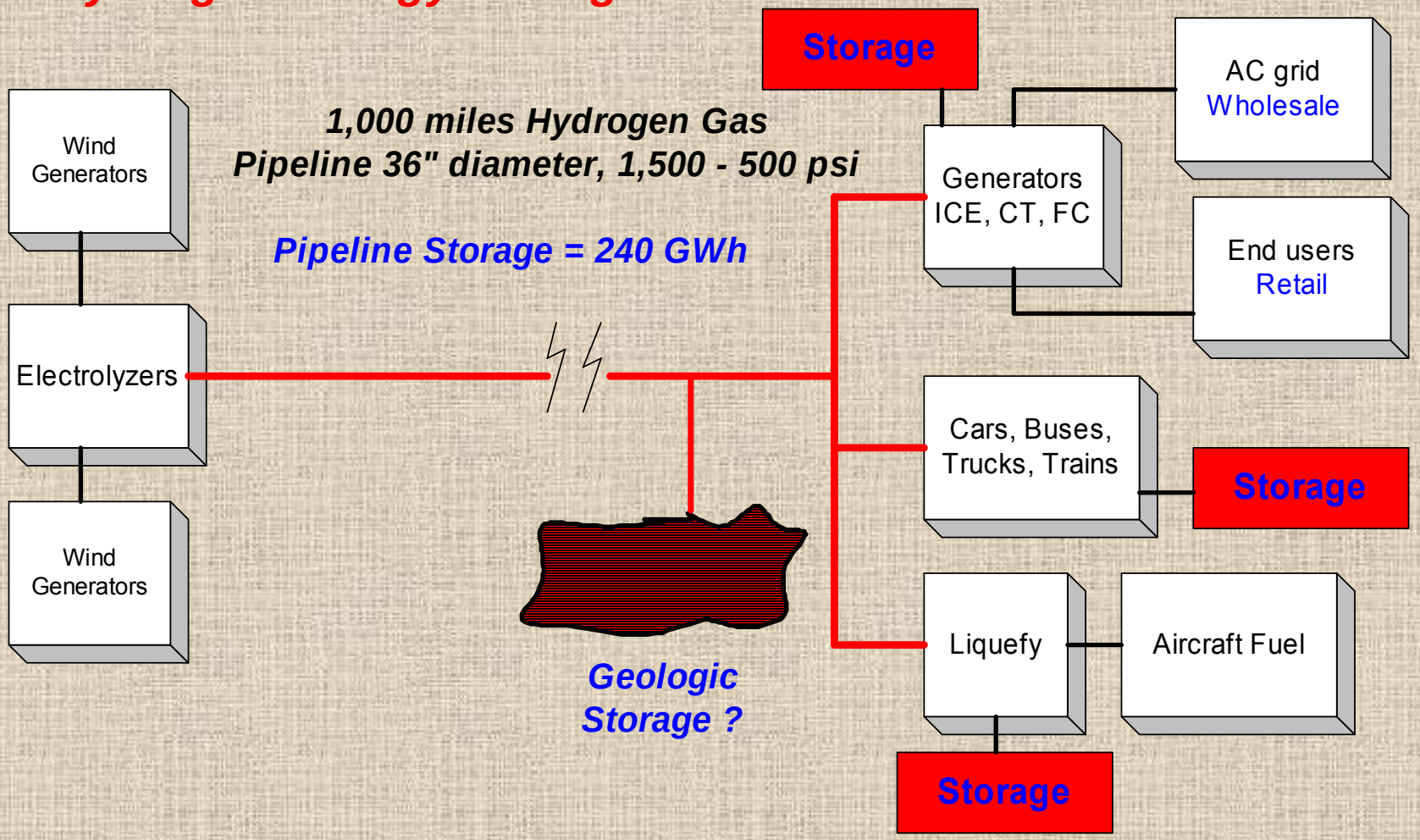
Electricity :	KV	Capacity MW	$M / MW-mile
• SEIA:	765	5,000	1.3
	345	1,000	2.6
• AEP-AWEA	765	5,000	3.2
Consensus ?			2.5

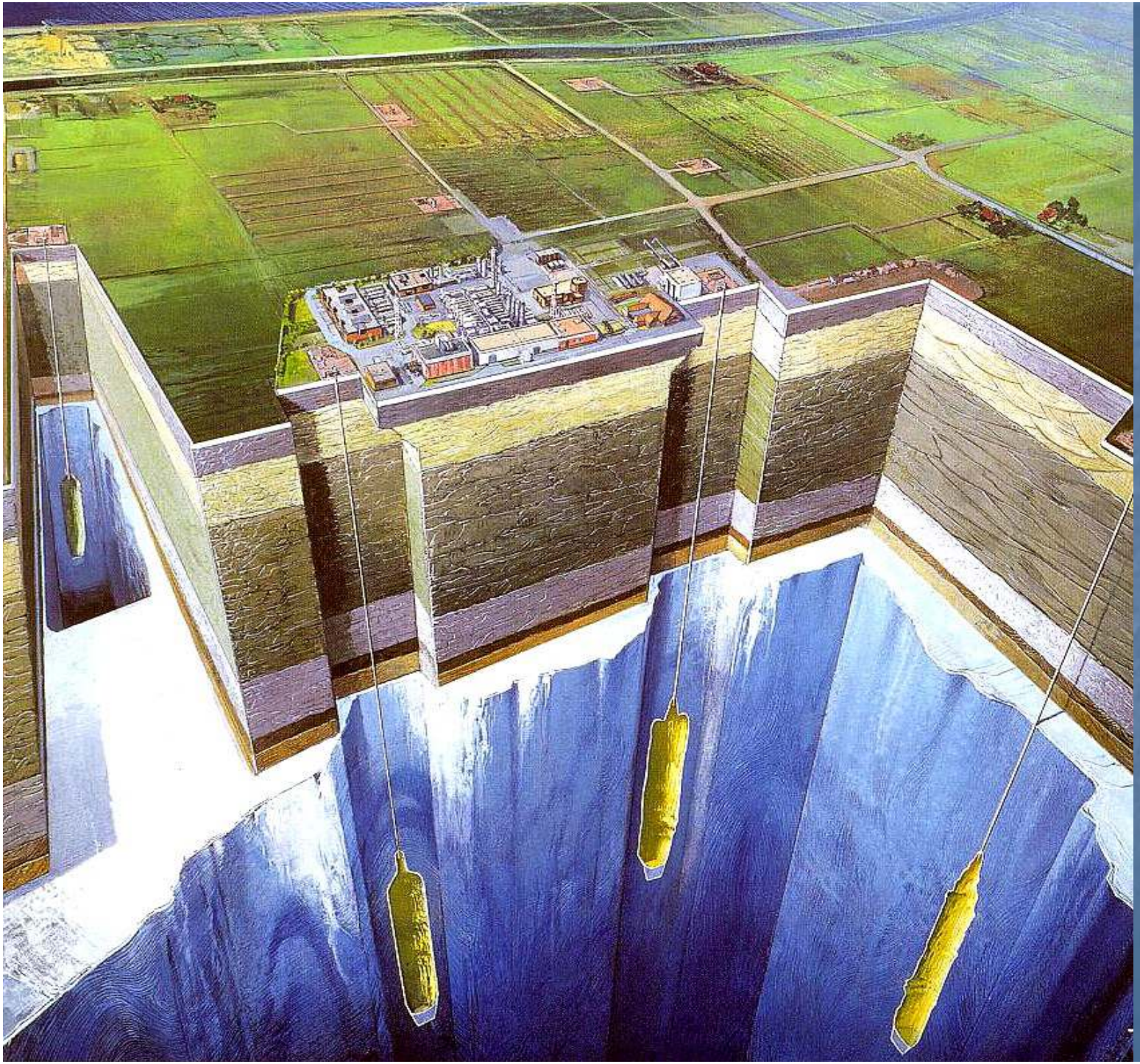
Hydrogen pipeline:

36”, 100 bar, 500 mi, no compress 0.3

(100 bar = 1,500 psi)

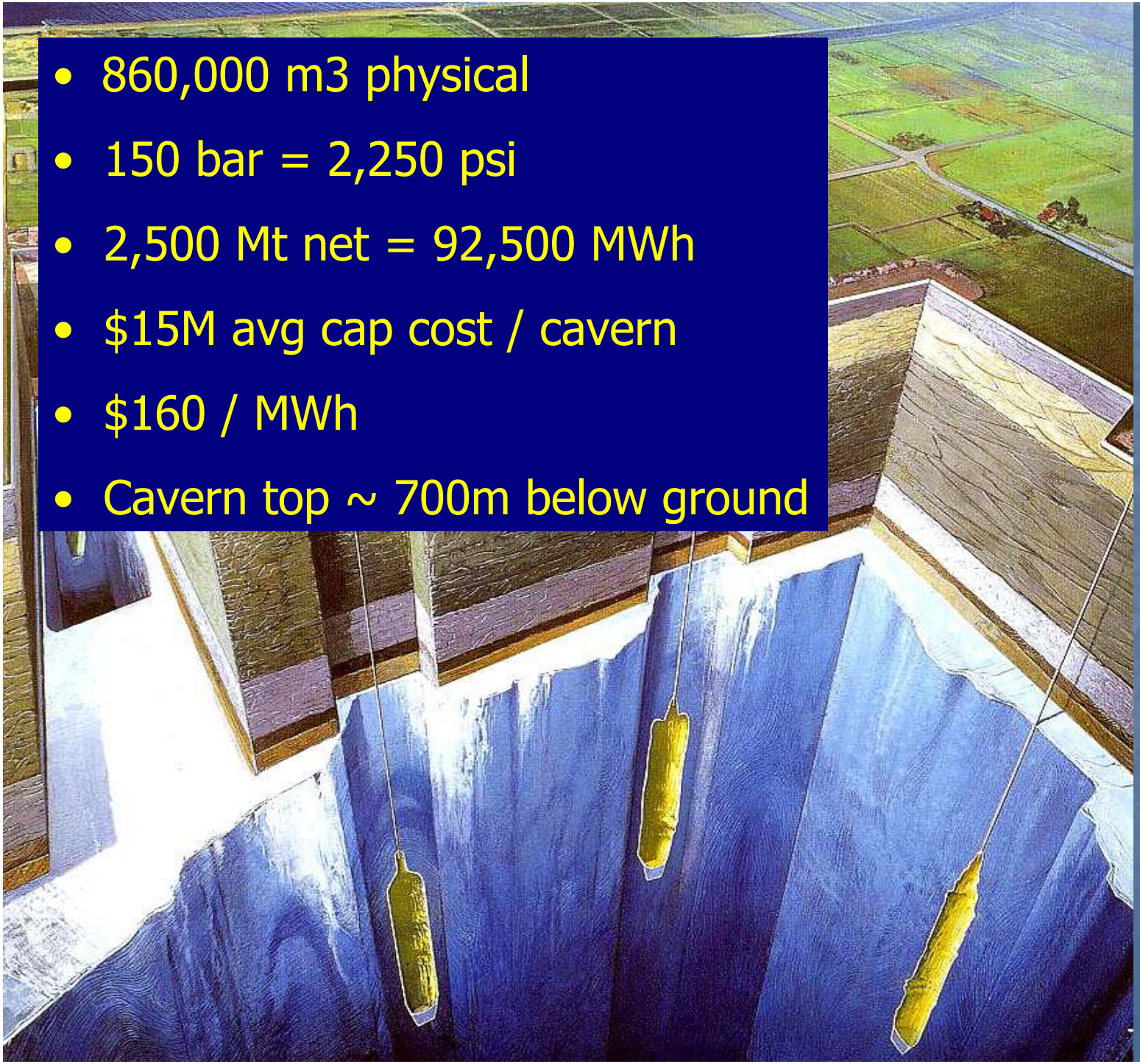
Hydrogen Energy Storage





Domal Salt Storage Caverns

PB ESS



- 860,000 m3 physical
- 150 bar = 2,250 psi
- 2,500 Mt net = 92,500 MWh
- $15M avg cap cost / cavern
- $160 / MWh
- Cavern top ~ 700m below ground

Domal Salt Storage Caverns

Texas

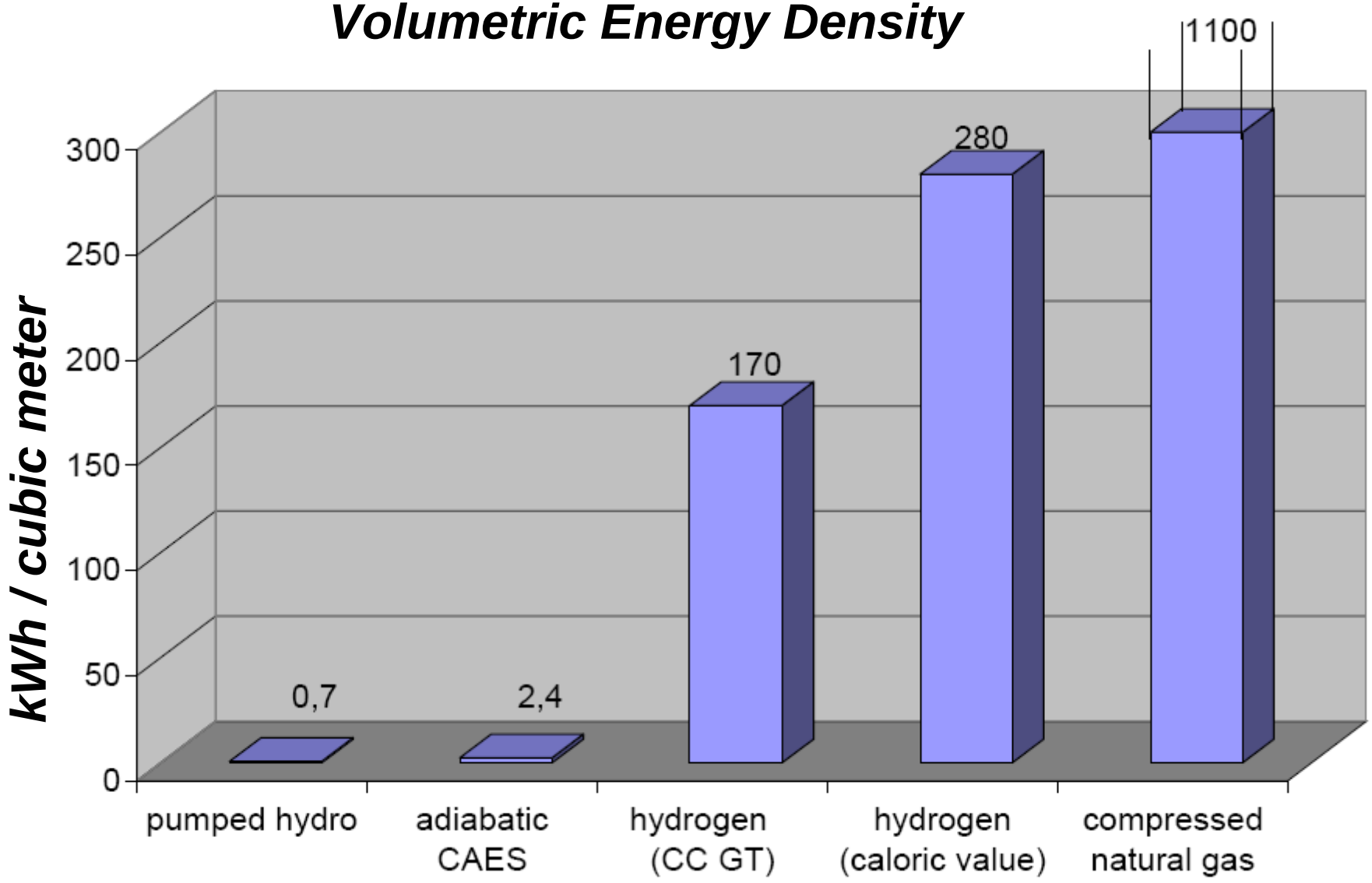
“Clemens Terminal” Conoco Phillips 20 years

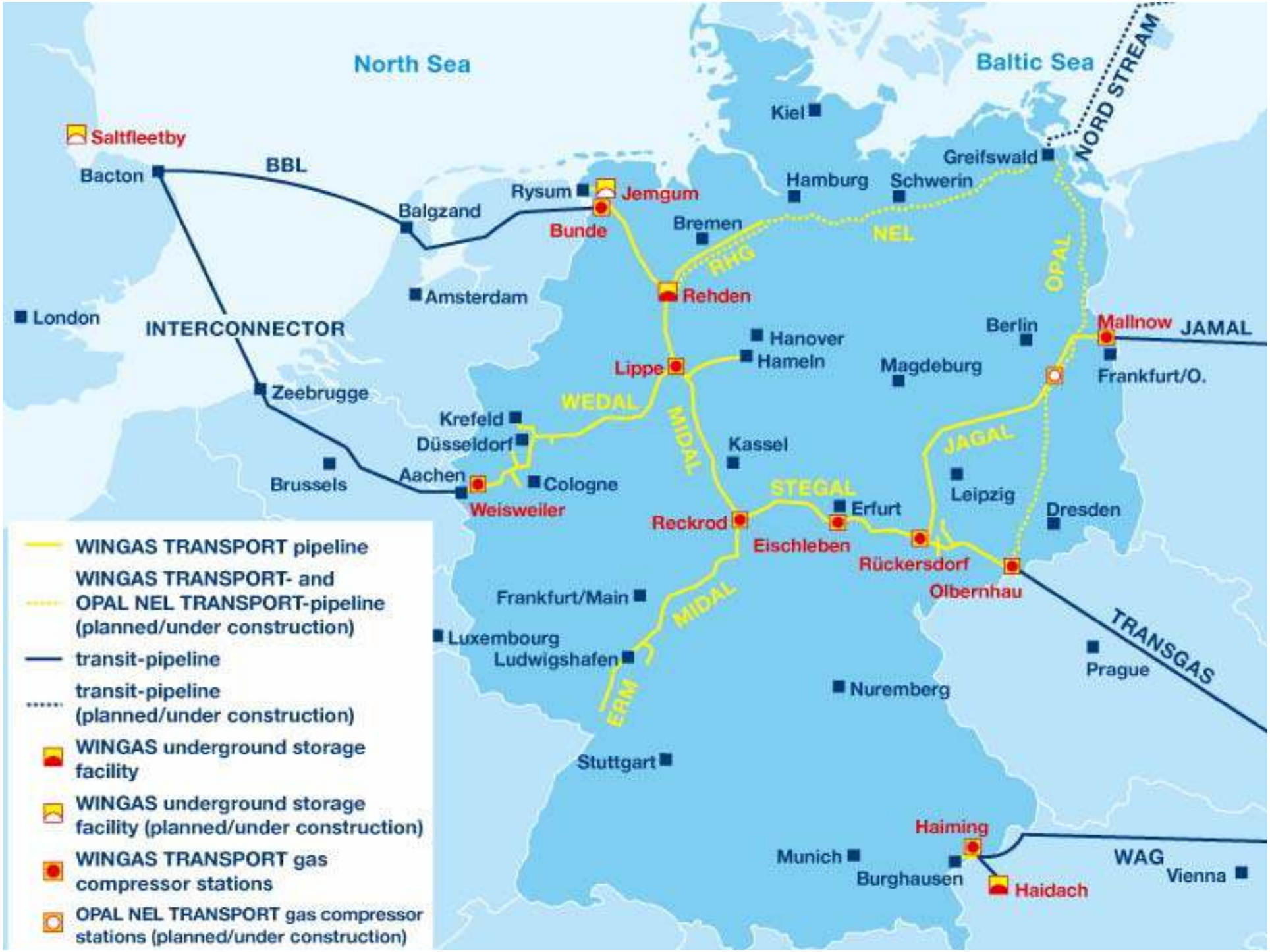
Praxair ‘07

PB ESS

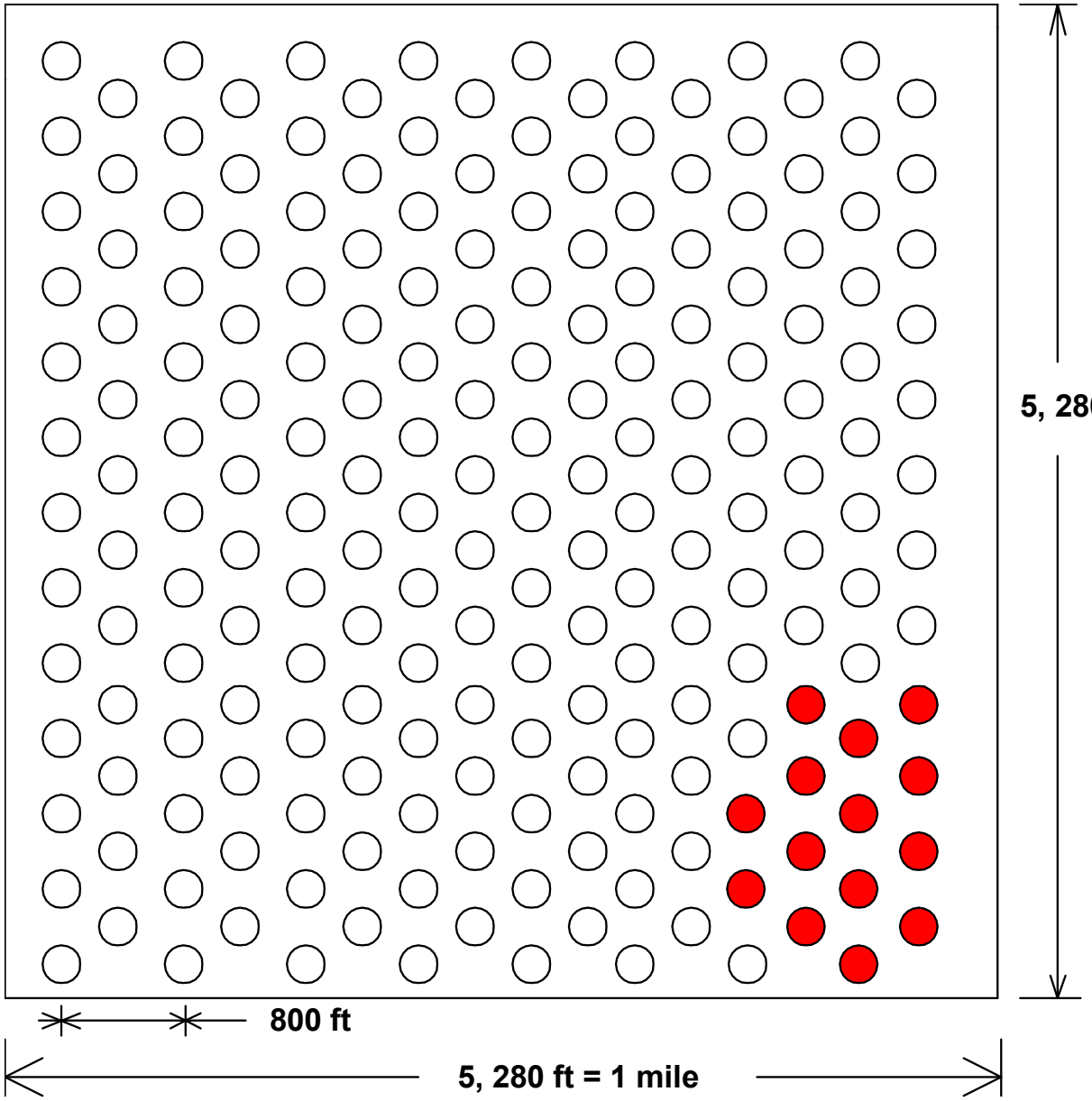
Germany Wind Industry

Volumetric Energy Density




North Sea
Baltic Sea
NORD STREAM
Kiel
Saltfleetby
Bacton
BBL
Greifswald
Hamburg
Schwerin
Rysum
Jemgum
Balgzand
Bunde
Bremen
NEL
OPAL
RHG
Rehden
Amsterdam
London
INTERCONNECTOR
Berlin
Mallnow
JAMAL
Hanover
Hameln
Lippe
Magdeburg
Frankfurt/O.
Zeebrugge
WEDAL
MIDAL
Krefeld
Düsseldorf
Kassel
JAGAL
Brussels
Aachen
Cologne
STEGAL
Leipzig
Weisweiler
Erfurt
Dresden
Reckrod
Eischleben
Rückersdorf
Olbernhau
Frankfurt/Main
MIDAL
TRANSGAS
Luxembourg
Ludwigshafen
Prague
ERM
Nuremberg
Stuttgart
Haiming
Munich
WAG
Burghausen
Vienna
Haidach
WINGAS TRANSPORT pipeline
WINGAS TRANSPORT- and OPAL NEL TRANSPORT-pipeline (planned/under construction)
transit-pipeline
transit-pipeline (planned/under construction)
WINGAS underground storage facility
WINGAS underground storage facility (planned/under construction)
WINGAS TRANSPORT gas compressor stations
OPAL NEL TRANSPORT gas compressor stations (planned/under construction)

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



“Firm” 4,000 MW Great Plains wind

14 caverns

Maximum Cavern Packing Density

(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.

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


Hydrogen “sector”
Back-up Power System
Fleet Fueling
Community Fueling
Home Fueling
Industrial Application
Hydrogen “sector” of a benign, sustainable, equitable, global energy economy

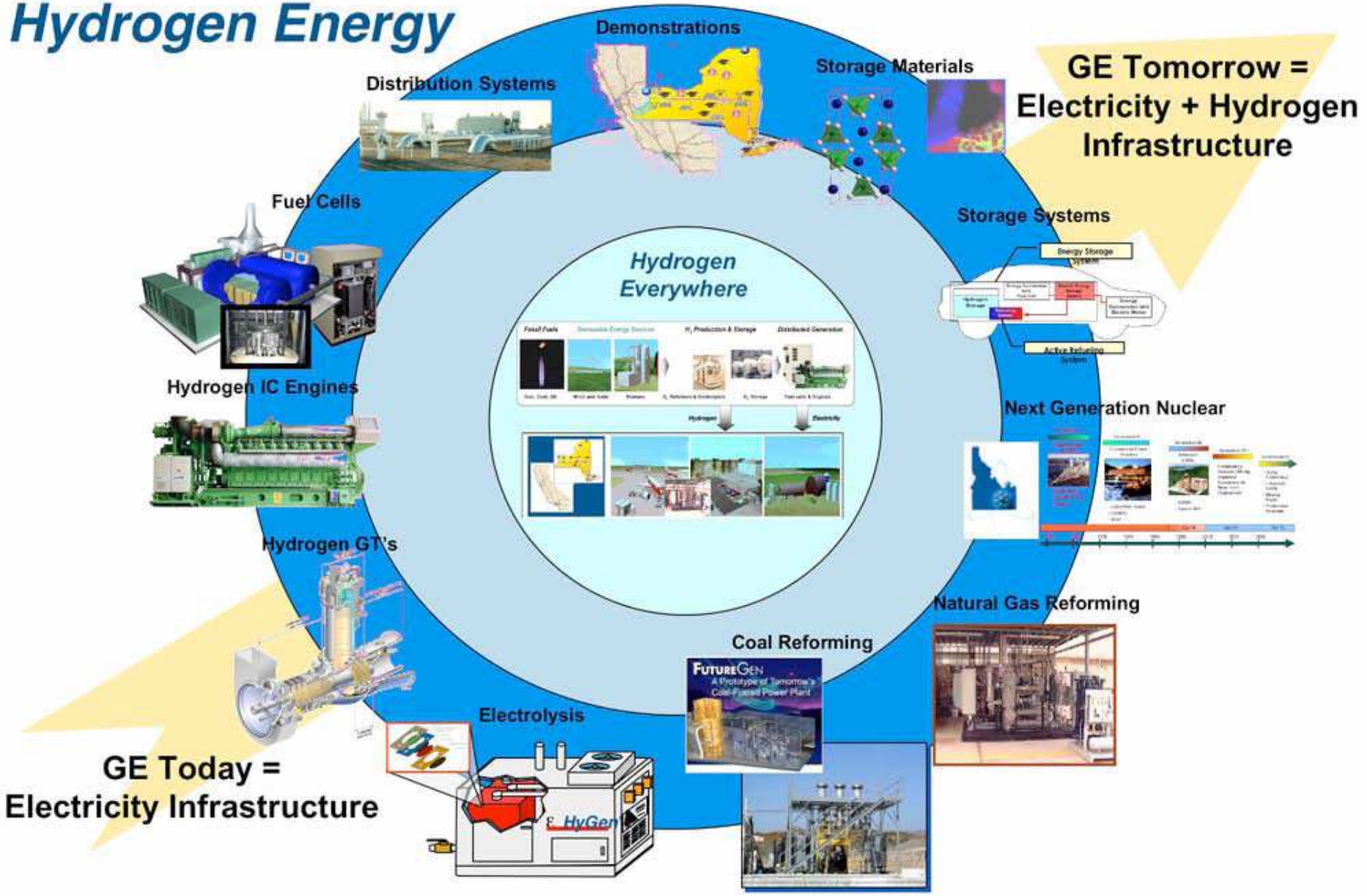
"Hydrogen and electricity become the primary currencies in the future energy economy"

Utility electrolysis vision

- MW-scale utility electrolyzers
- Affordable capital investment:
  Total system cost considerations
- Off-peak, wholesale electricity: Operated by utility
- Distributed, substation level operation
- Tightly integrated with electrical grid

Dan Smith
GE Global Research, 2004

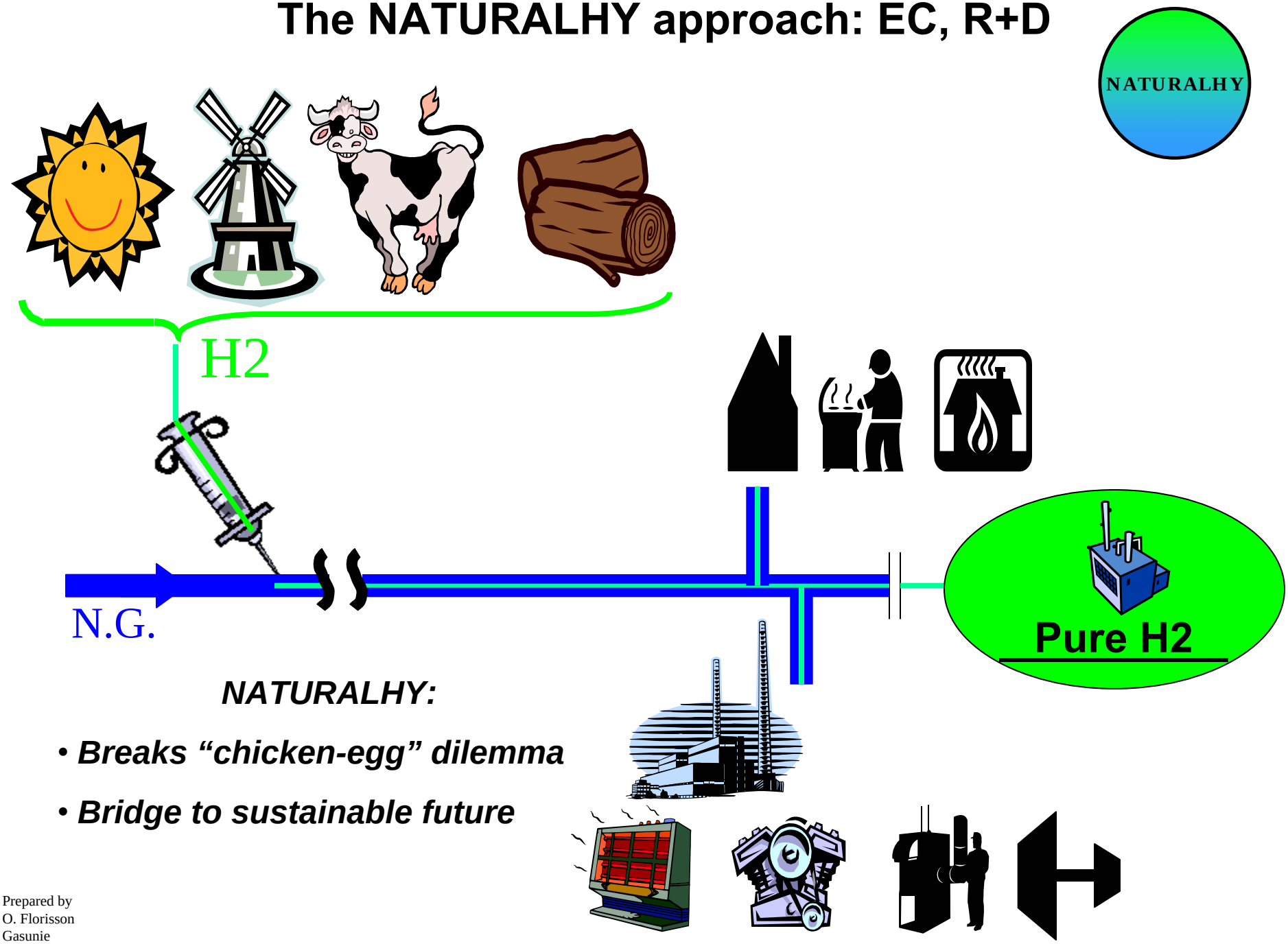
Hydrogen Energy



"Hydricity"

- **Nexus of electricity + hydrogen: twin currencies**
- **GH2, NH_3 for annual-scale "firming" storage**
- **Long-term:**
  - **Clear: energy currencies**
  - **Fuzzy: sources**
- **Climate Change: drive *transition***
- **Wood → coal → oil → natural gas → *elec, GH2, NH3***
- **Conversion costs:**
  - **Capital**
  - **O&M**
  - **Energy losses:**
    - **50 – 70% round-trip efficiency**
    - **CHP → 100%**

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 …"

Carmakers' letter Oct 09: FCV's production 2015, Need H_2 fuel !

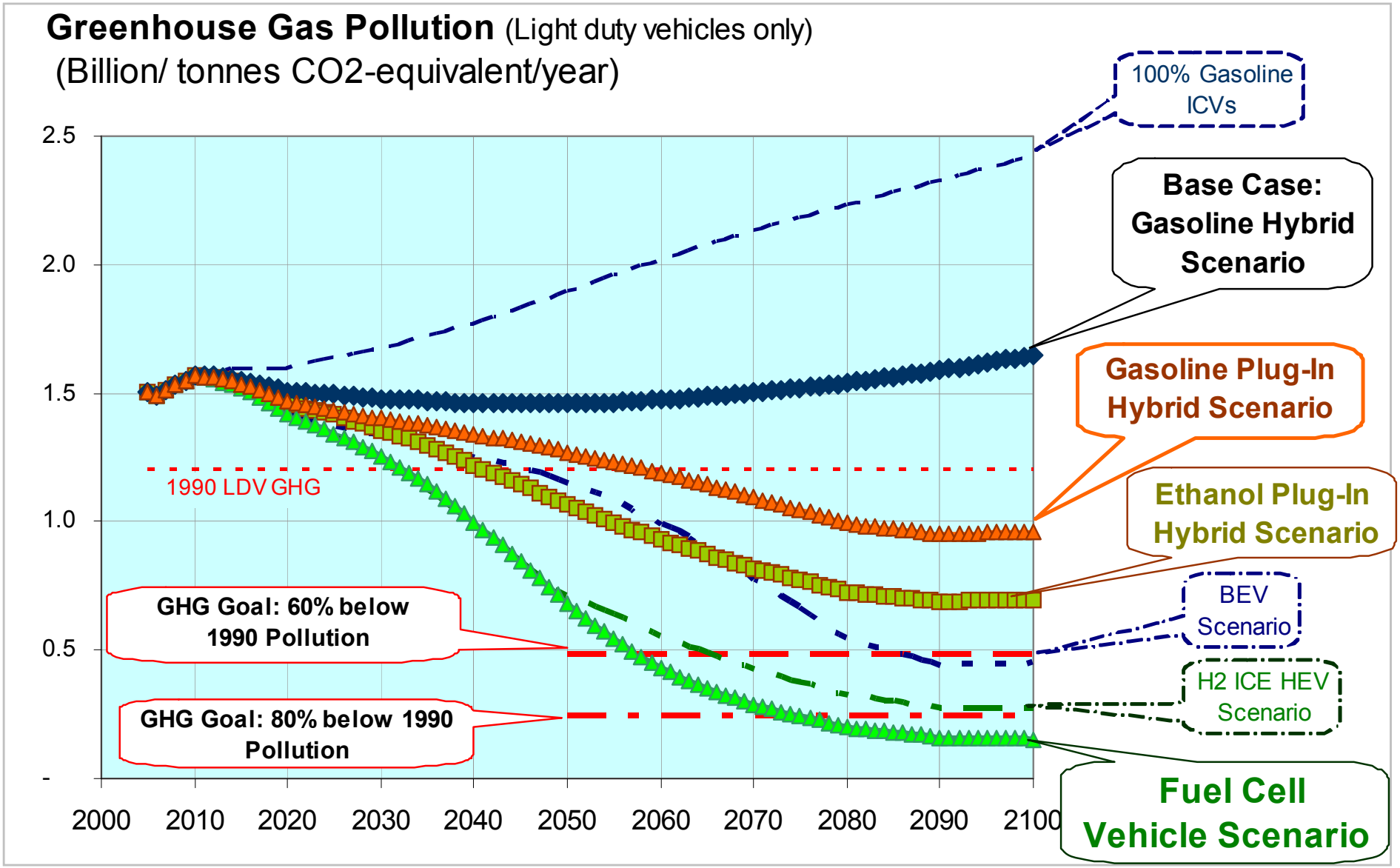
Hydrogen Fuel Cell Hybrid Electric Vehicle: HFCHEV

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

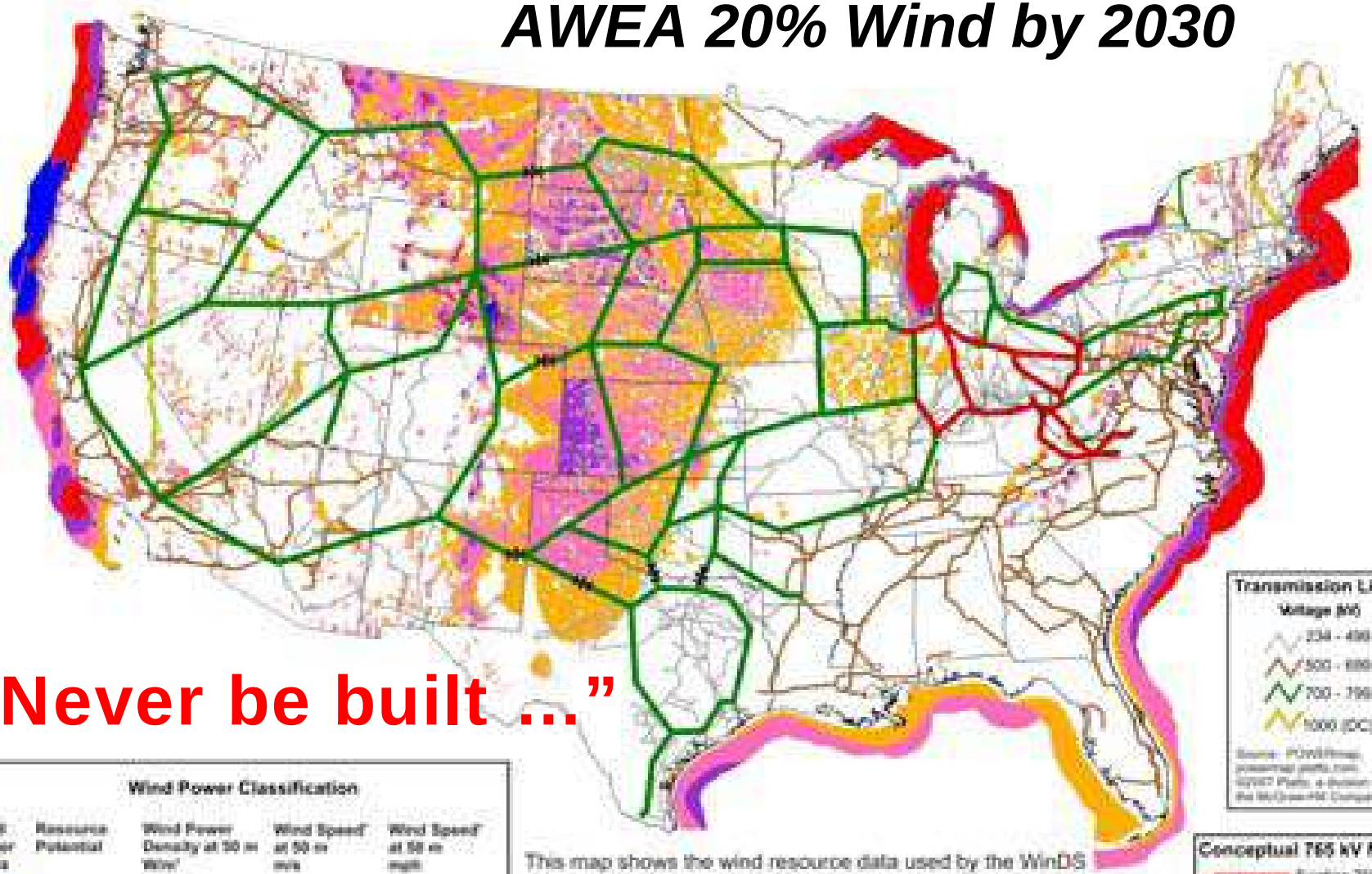
- **20% of 45M vehicles = 9M**
- **@ 78 mpg = 78 miles / kg H2**

- **12,000 miles / year = 150 kg H2 / year**

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


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

AWEA 20% Wind by 2030



"Never be built …"

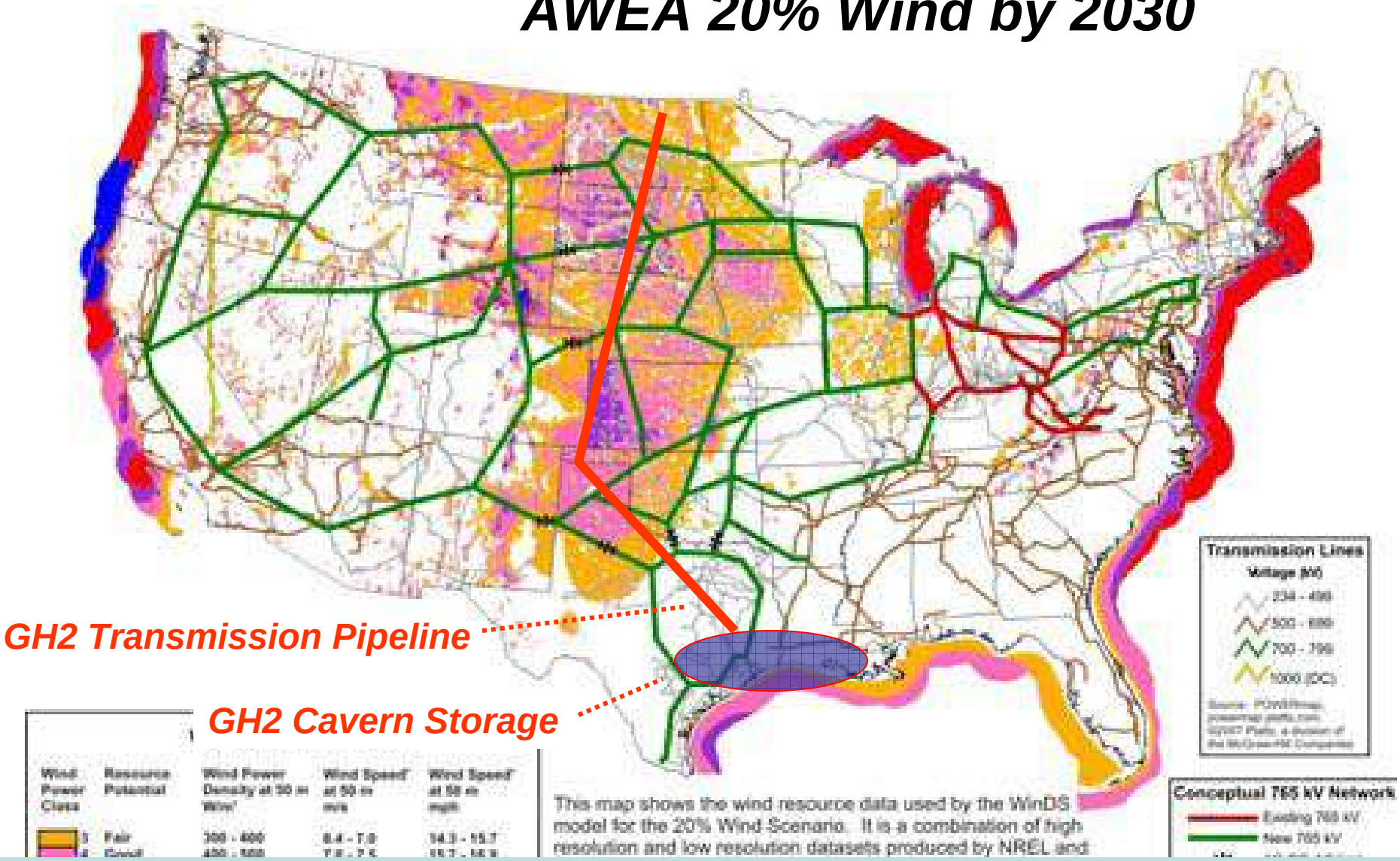
Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed* at 50 m m/s	Wind Speed* at 50 m mph
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
7	Superb	800 - 1600	8.8 - 11.1	19.7 - 24.8

* Wind speeds are based on a Weibull k value of 2.0

This map shows the wind resource data used by the WinDS model for the 20% Wind Scenario. It is a combination of high resolution and low resolution datasets produced by NREL and other organizations. The data was screened to eliminate areas unlikely to be developed onshore due to land use or environmental issues. In many states, the wind resource on this map is visually enhanced to better show the distribution on ridge crests and other features.

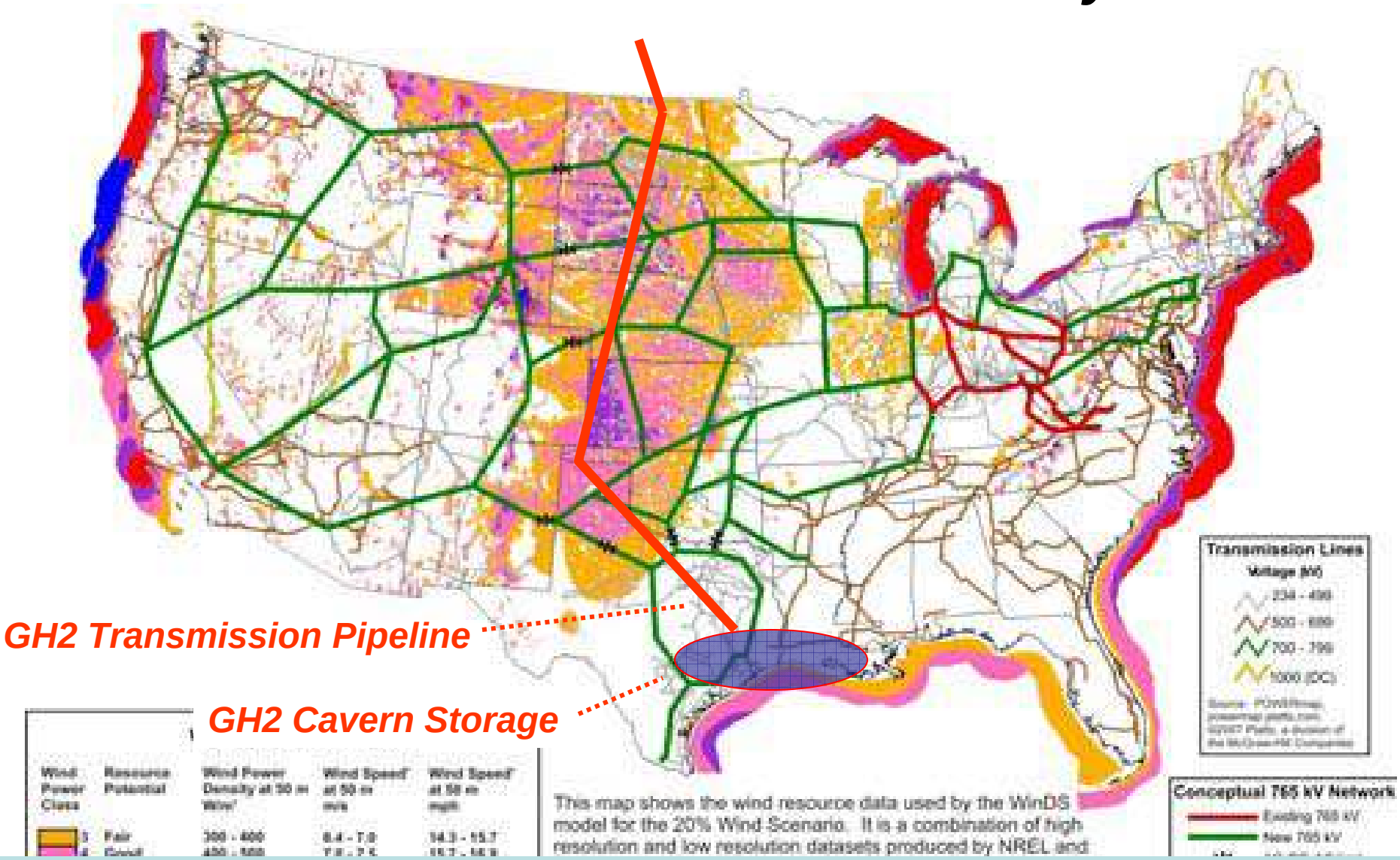
AWEA 20% Wind by 2030



Wind Potential ~= 3,000 GW

12 Great Plains states

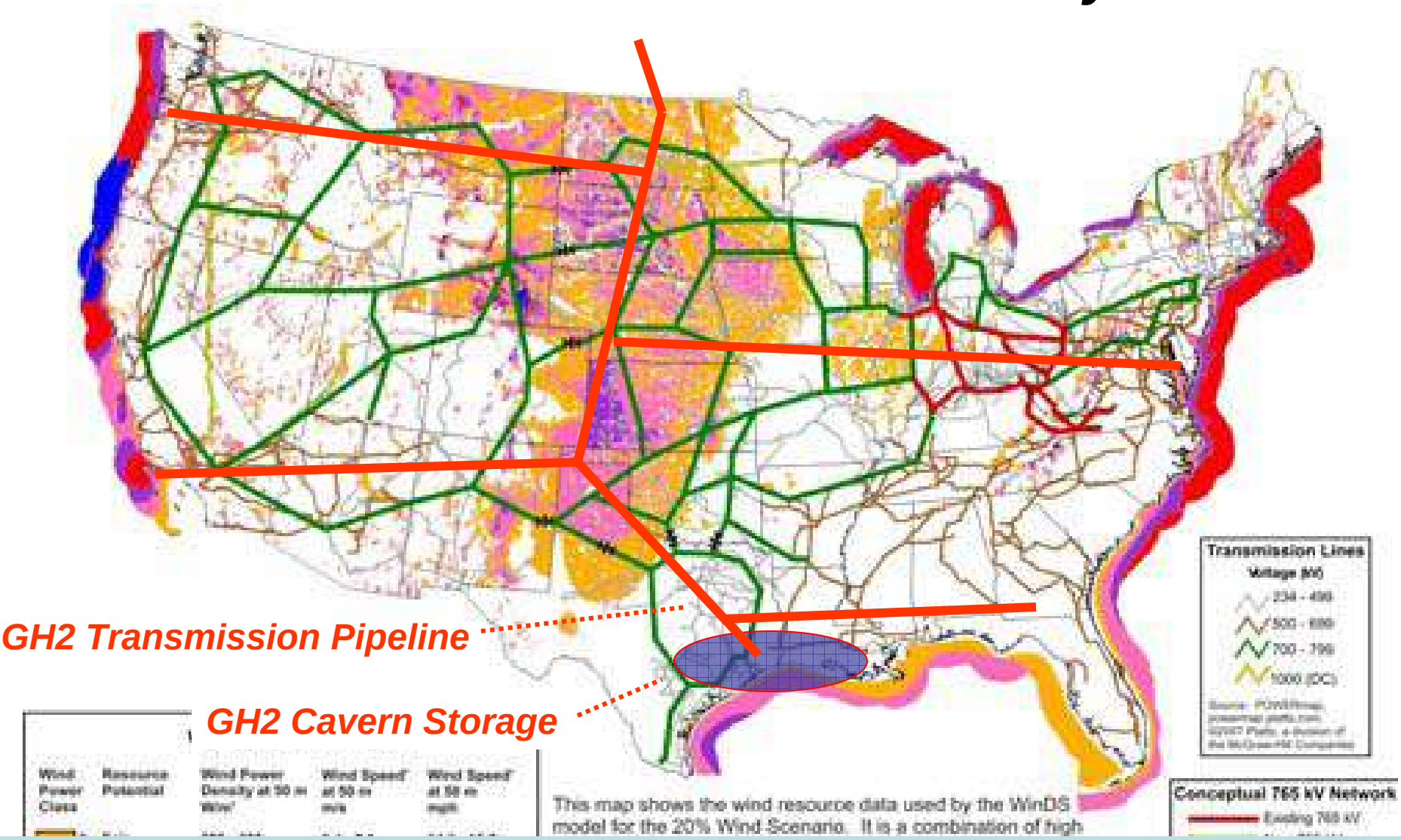
AWEA 20% Wind by 2030



Wind Potential ~= 3,000 GW

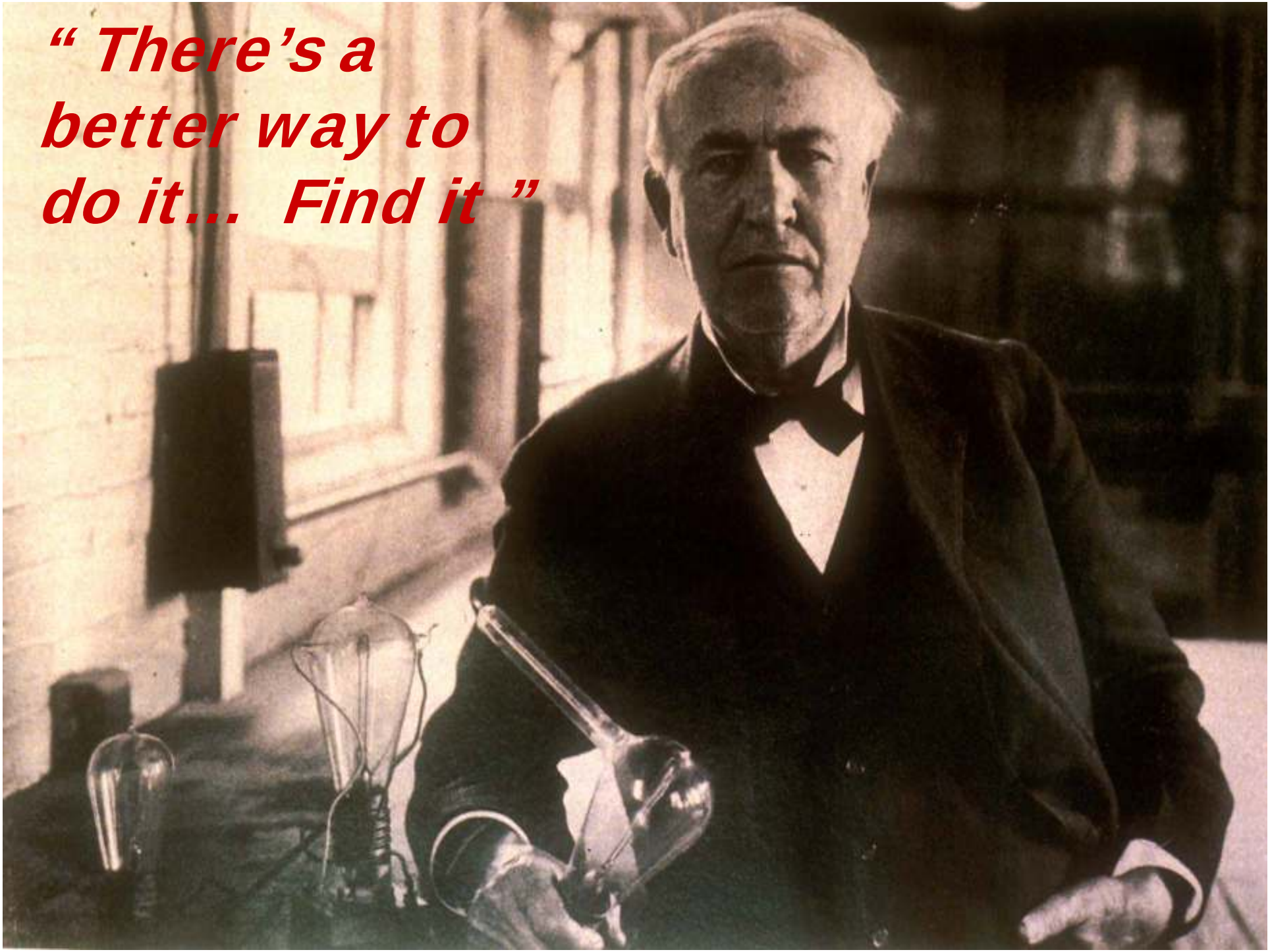
12 Great Plains states

AWEA 20% Wind by 2030



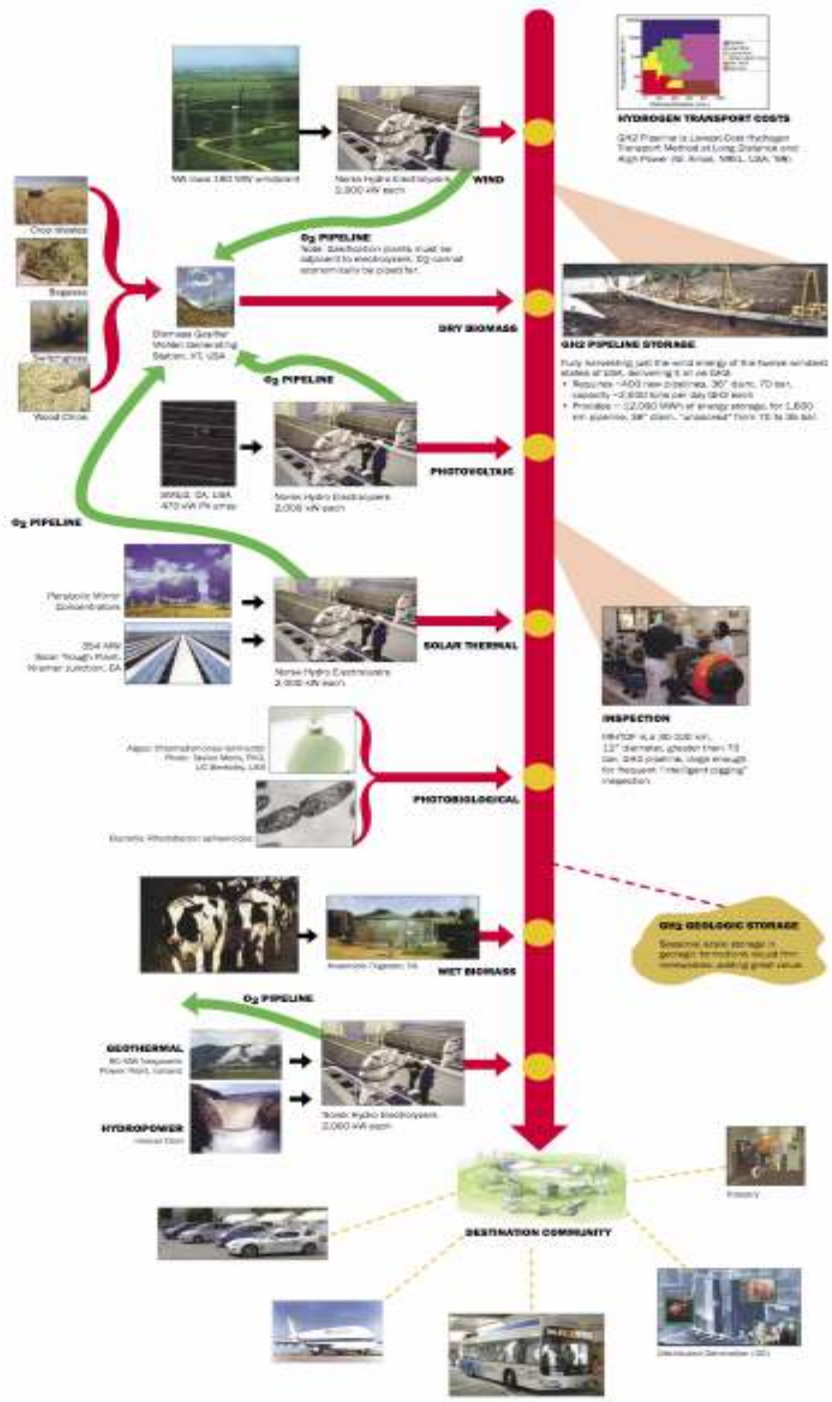
Wind Potential ~= 3,000 GW

12 Great Plains states


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

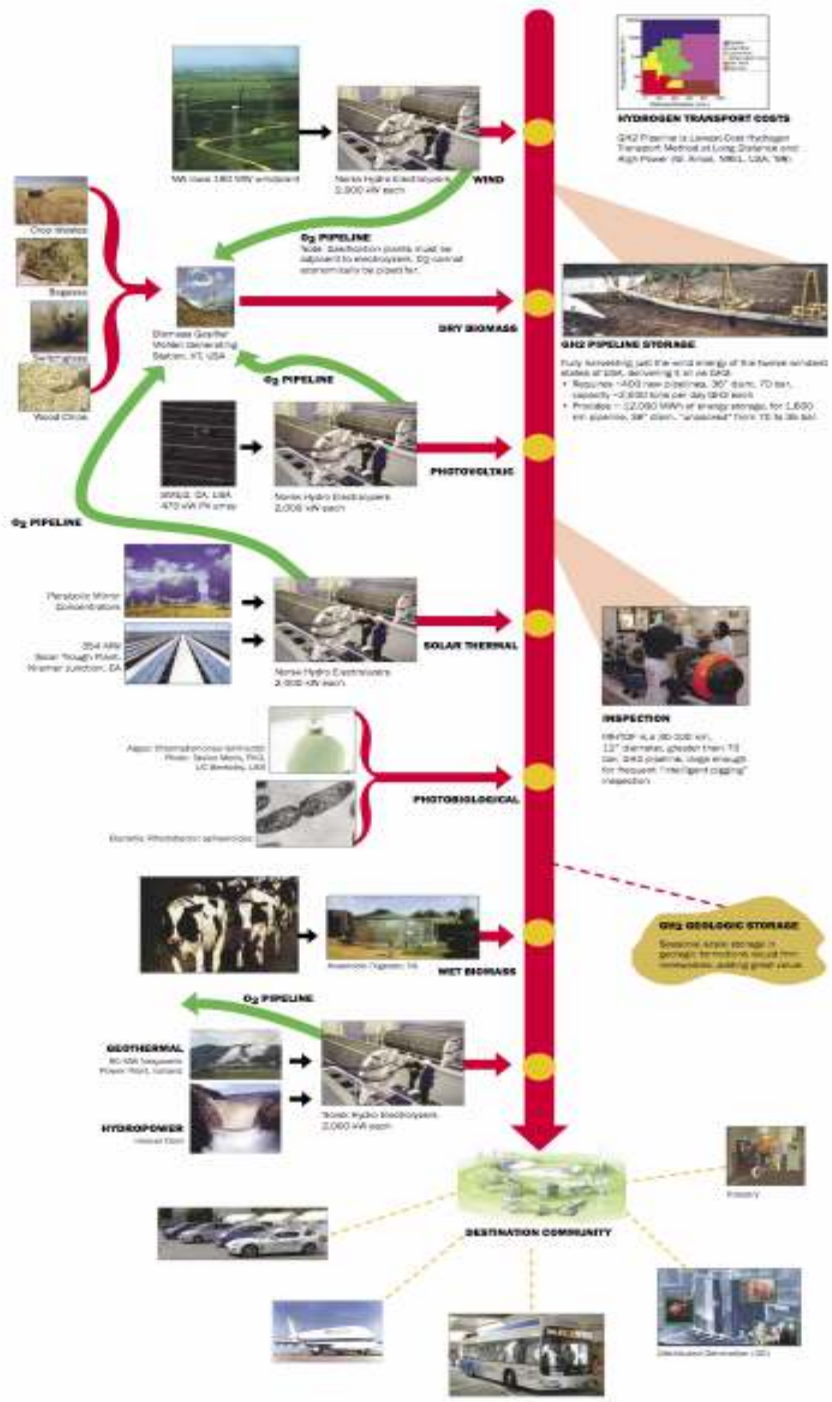
Pilot plant needed

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



Pilot-scale Hydrogen Pipeline System: Renewables

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



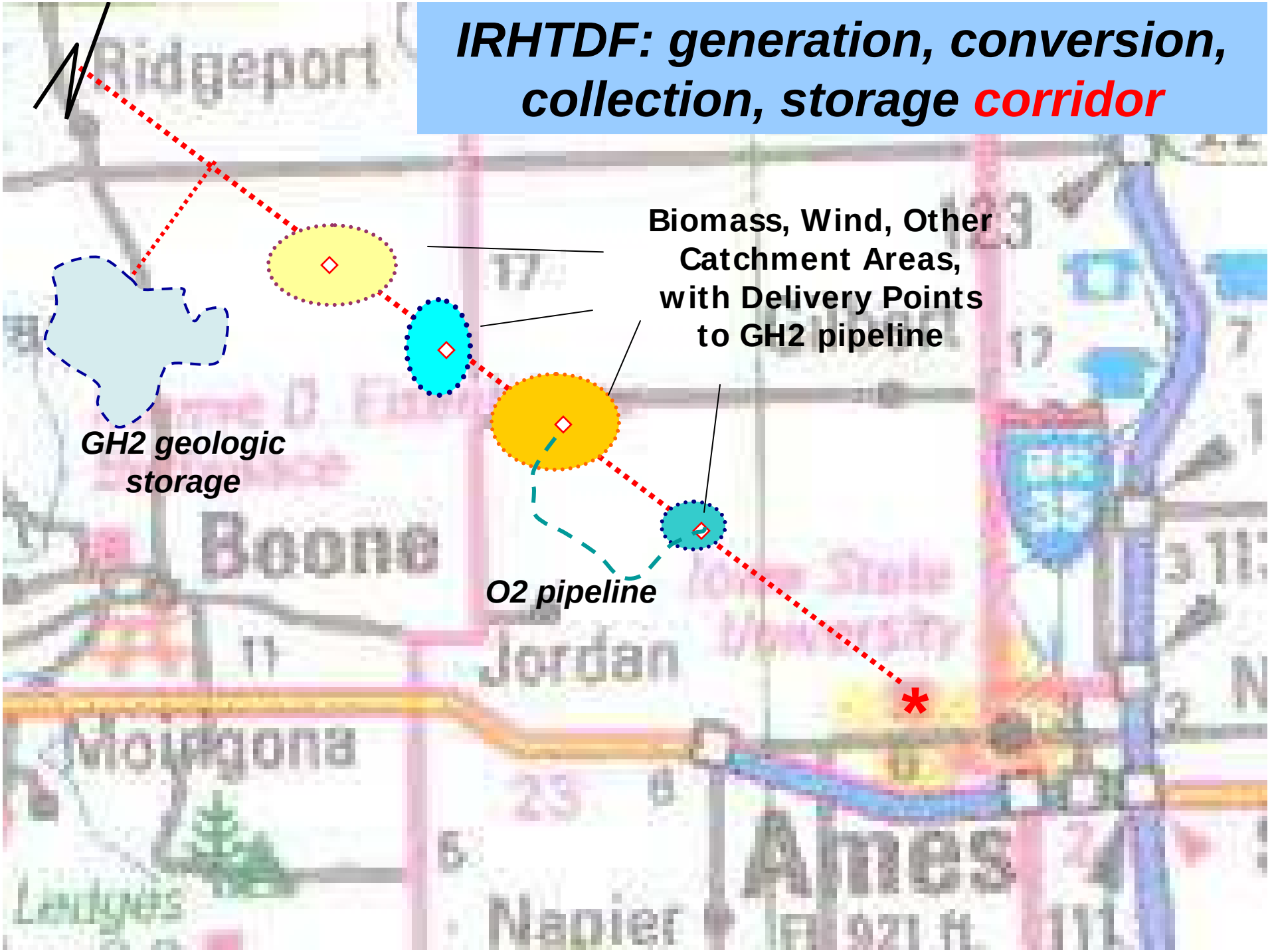
International Renewable Hydrogen Transmission Demonstration Facility

(IRHTDF)

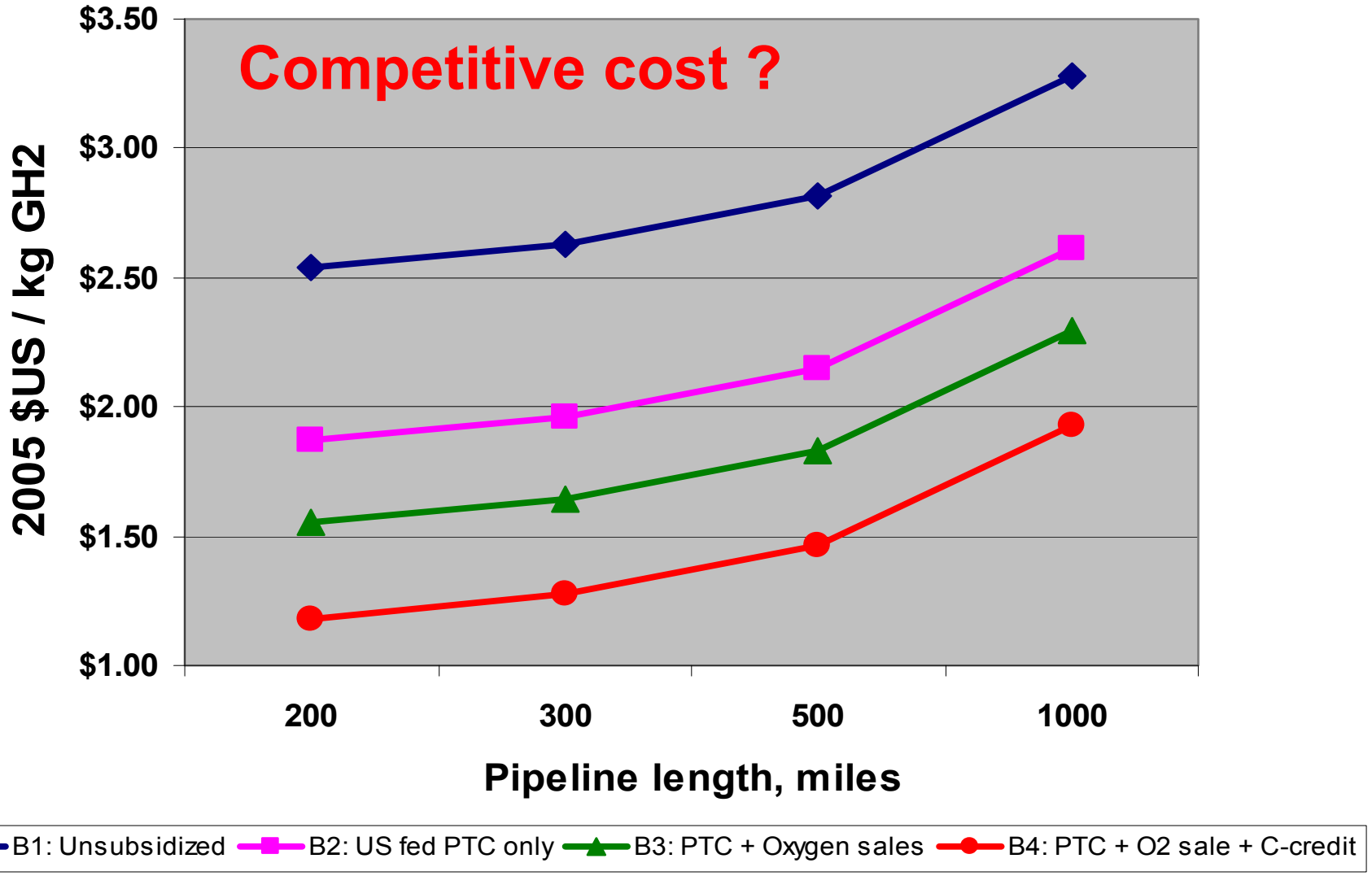
Pilot plant

Global opportunity: IPHE project

IRHTDF: generation, conversion, collection, storage corridor



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



Anhydrous Ammonia, NH_3 Fertilizer → Fuel

Business case:

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

"Ammonia Nation ?"

Anhydrous ammonia (NH3)

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

Why Ammonia ?

Only liquid fuel embracing:

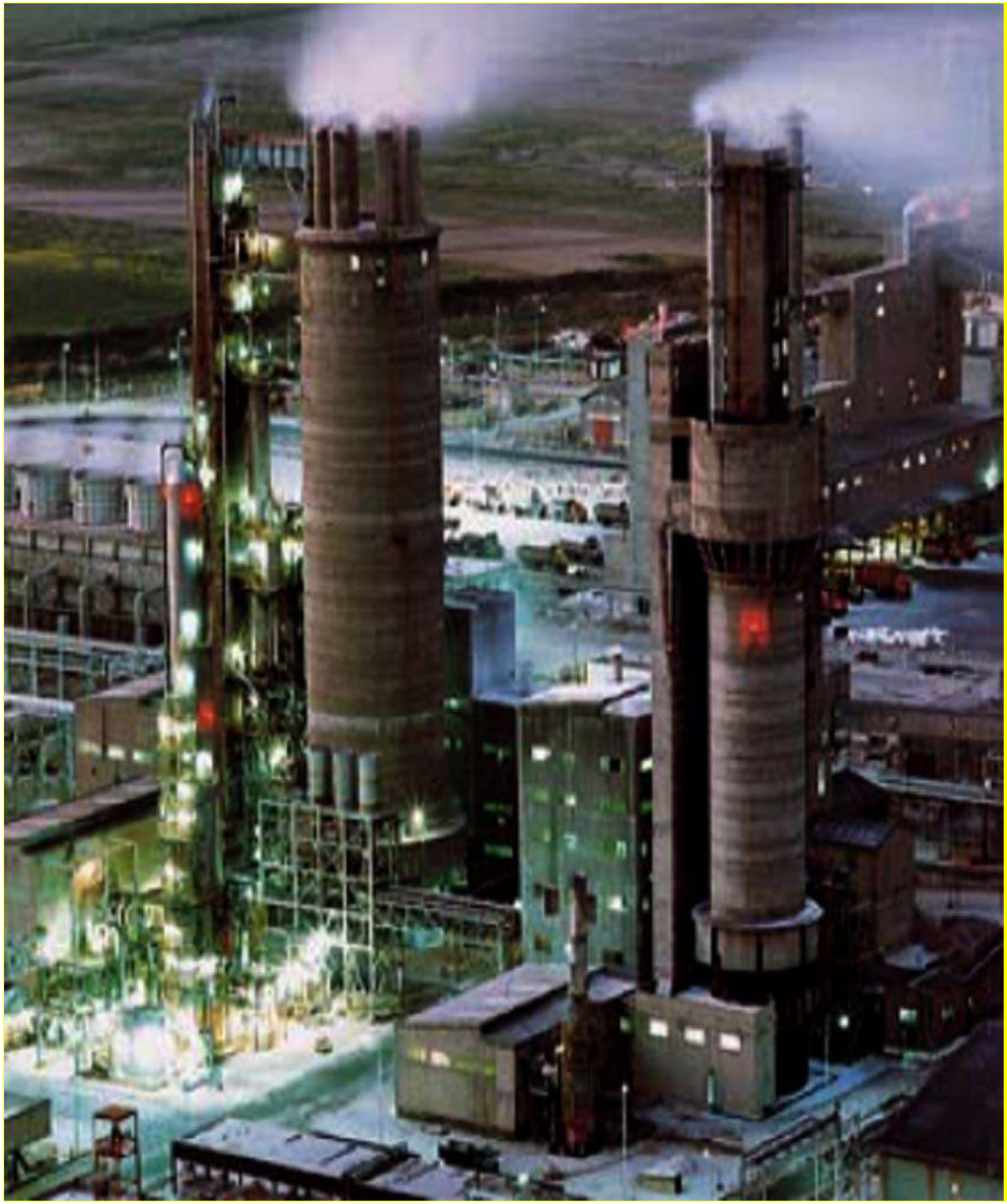
- Potentially all RE-source
- Cost competitive with HC fuels
- Carbon-free
- Energy cycle inherently pollution free
- Reasonably high energy density
- Practical to handle, store, and transport
- End-use in ICE, CT, fuel cell
- Self-odorizing safety
- "The other hydrogen"

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

Hydrogen Engine Center, Algona, IA

1,000 hours, ICE, 6 cyl, 100 hp

75% ammonia, 25% propane



Ammonia
(NH_3)
Synthesis
Plant

Natural Gas

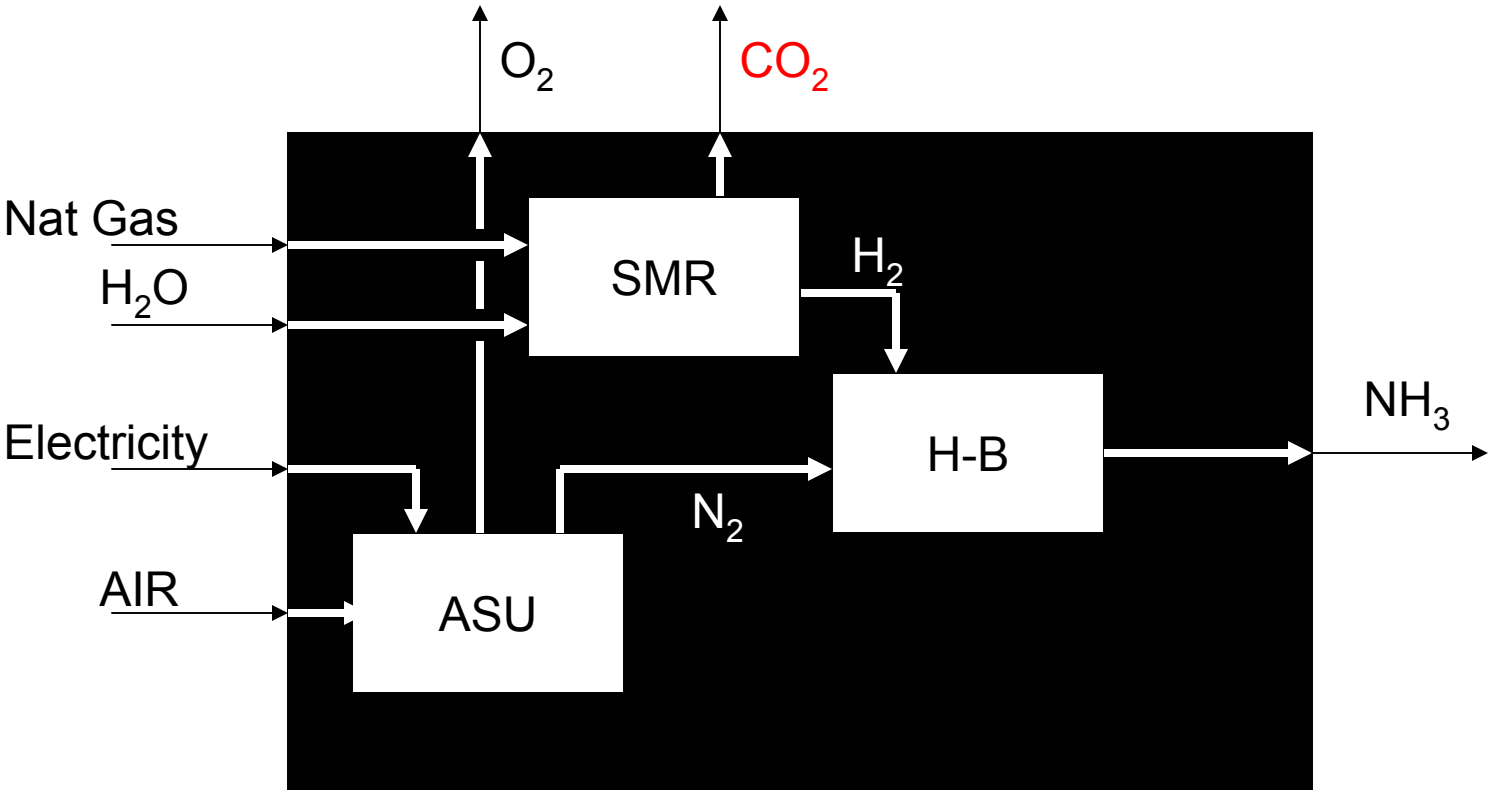
Feed

1 – 3,000 tpd

Haber-Bosch
“Synloop”

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

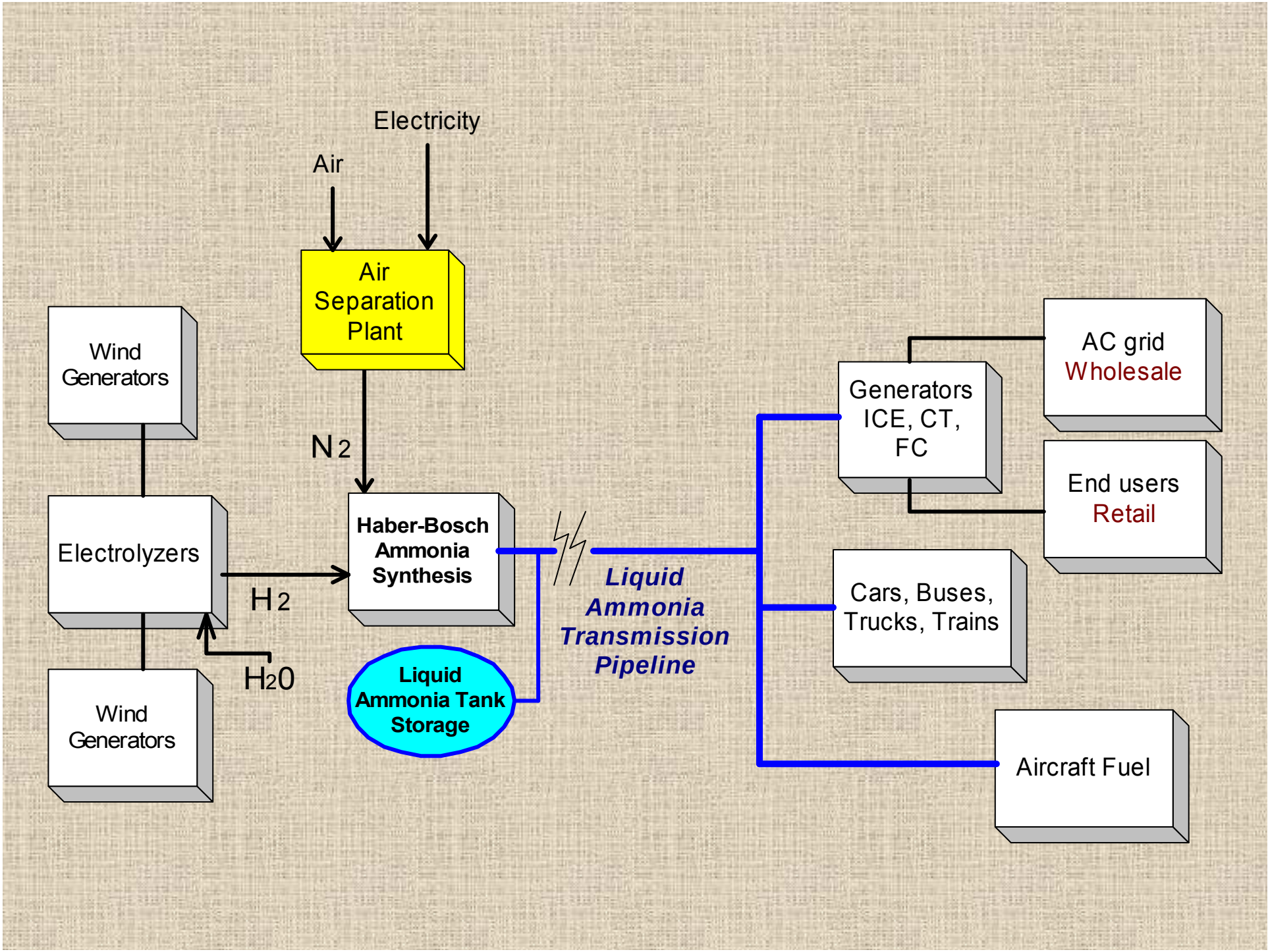
$$3\ CH_4 + 6\ H_2O + 4\ N_2 \rightarrow 3\ CO_2 + 8\ NH_3$$



Energy consumption ~33 MBtu (9500 kWh) per ton NH_3

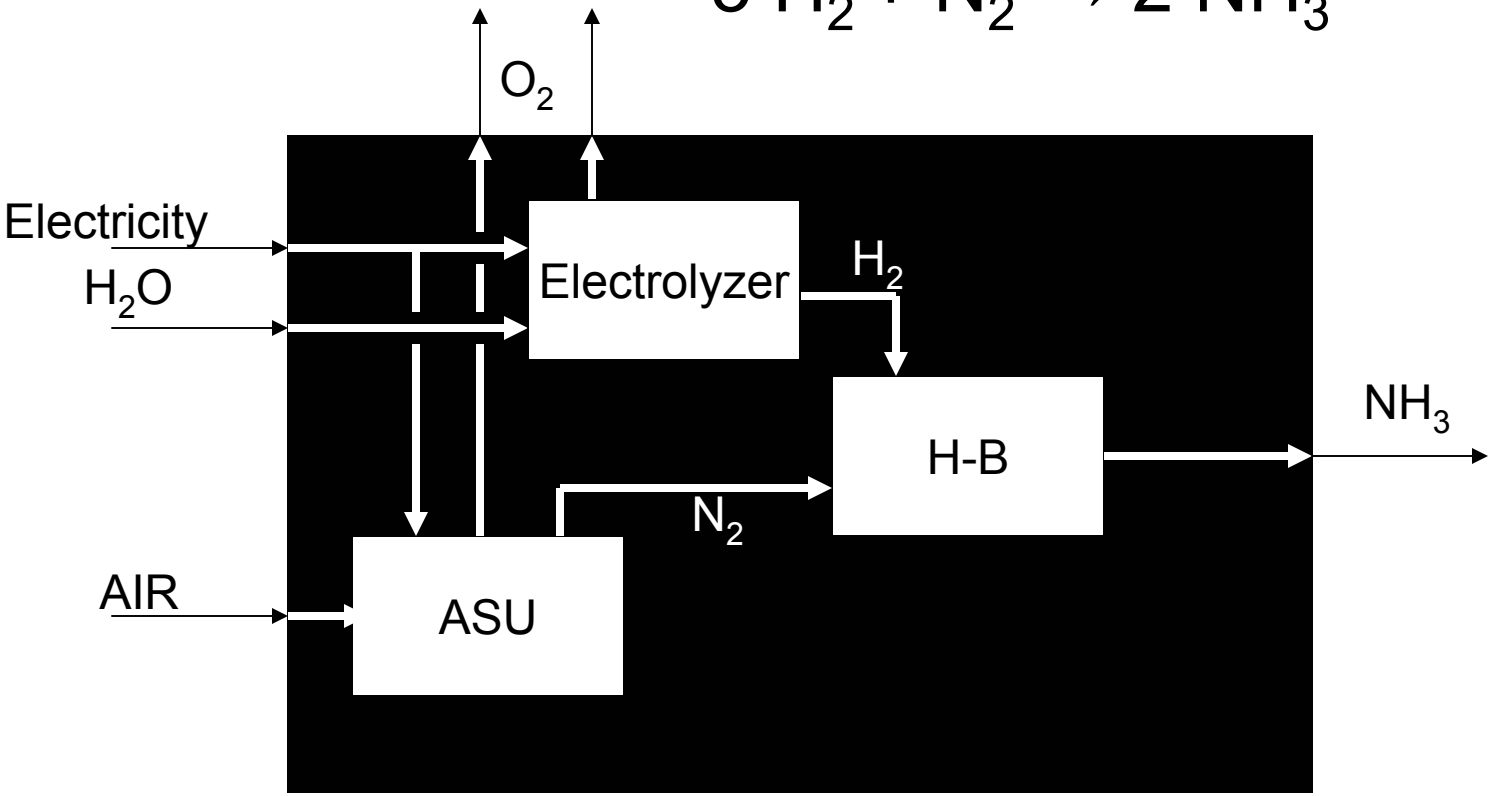
NH_3 Ag Fertilizer Tanks, Wind Generators, NW Iowa

- 500 and 1,000 gallon sizes
- Cost @ 1,000 gal = ~$ 10K
- Owned by Co-ops


Electricity
Air
Air Separation Plant
Wind Generators
N2
Electrolyzers
Haber-Bosch Ammonia Synthesis
H2
H20
Wind Generators
Liquid Ammonia Tank Storage
Liquid Ammonia Transmission Pipeline
Generators ICE, CT, FC
AC grid Wholesale
End users Retail
Cars, Buses, Trucks, Trains
Aircraft Fuel

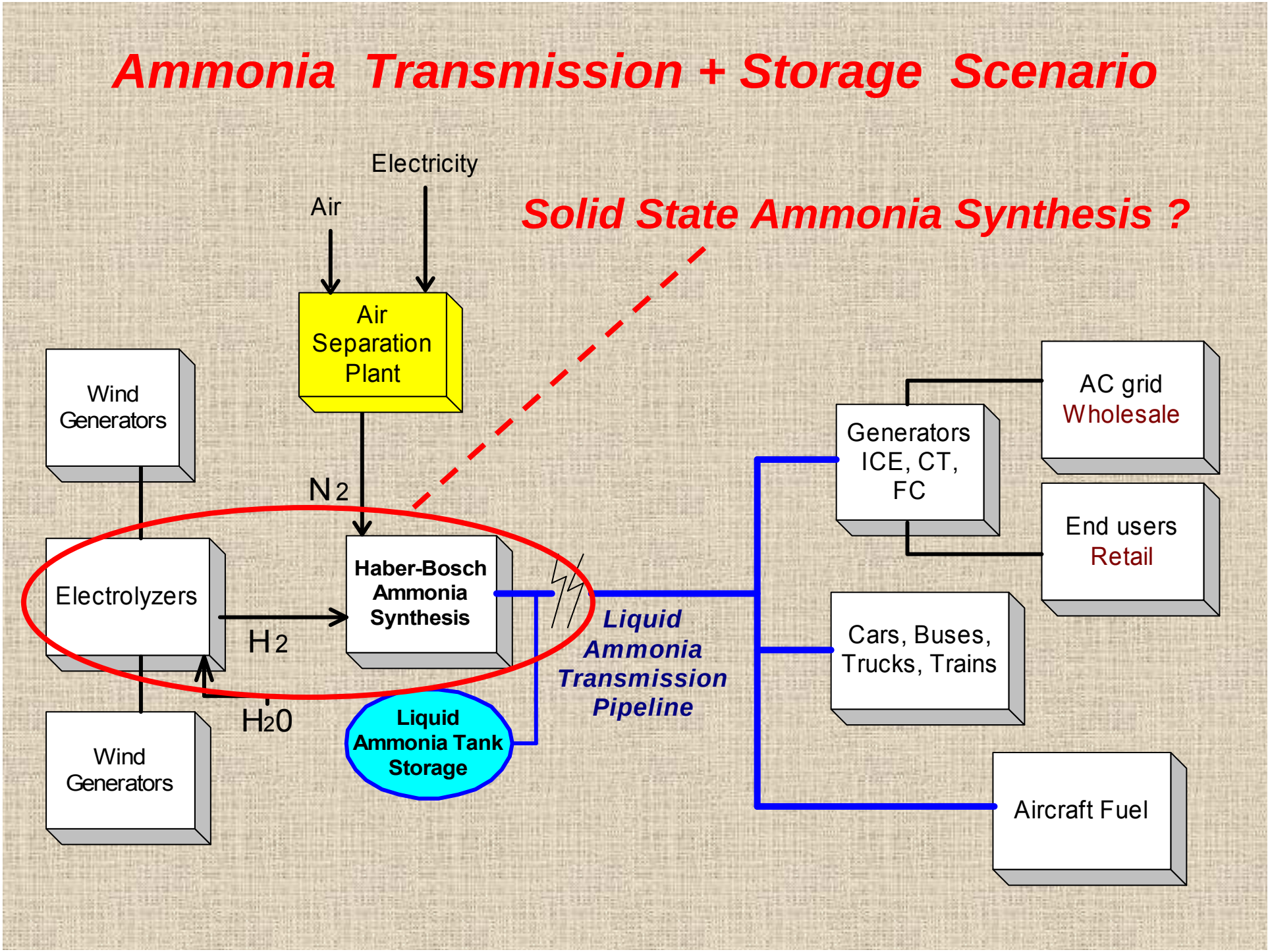
Inside the Black Box: HB Plus Electrolysis

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



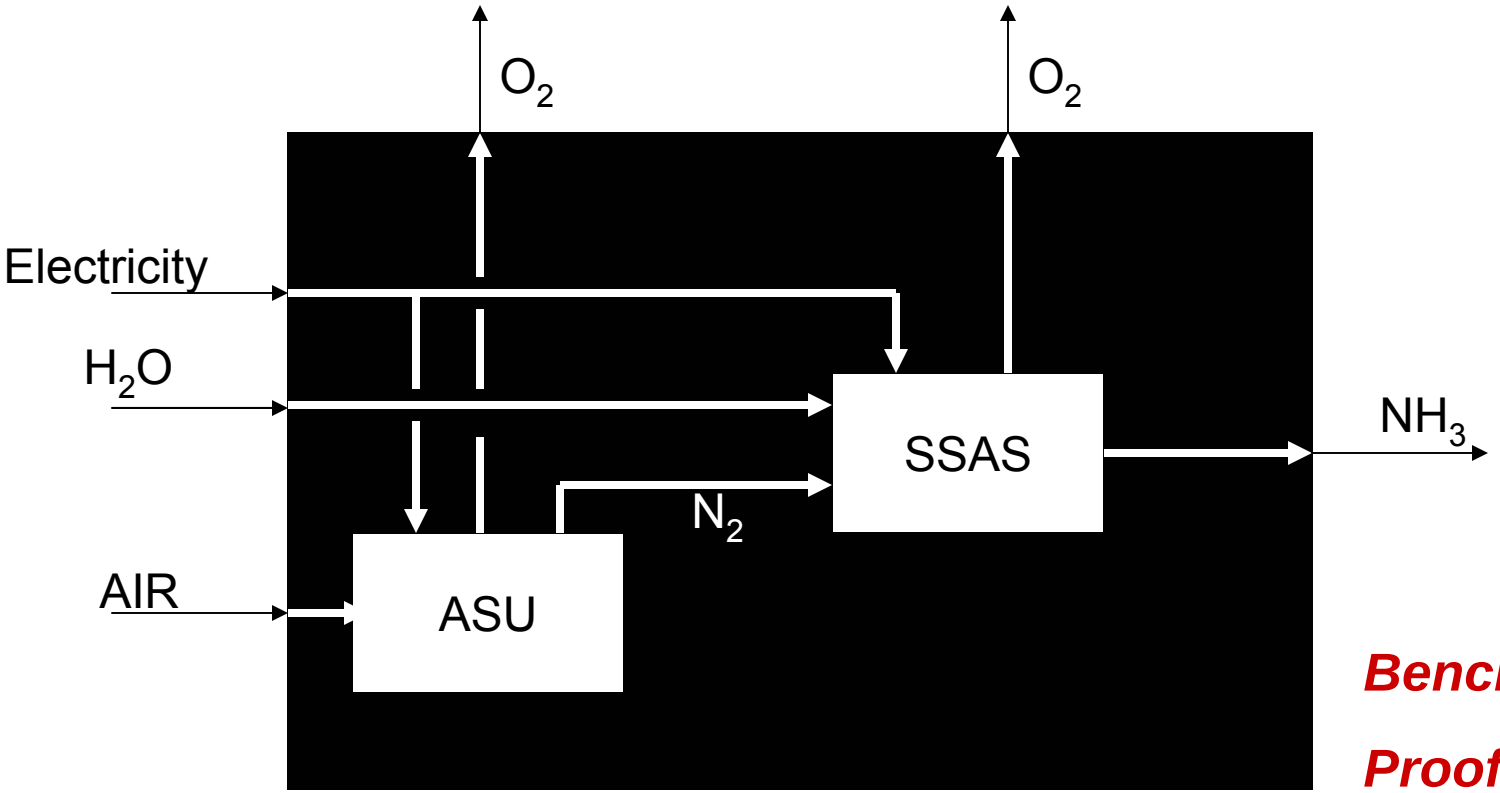
Energy consumption ~12,000 kWh per ton NH_3

Ammonia Transmission + Storage Scenario



Inside the Black Box: Solid State Ammonia Synthesis

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

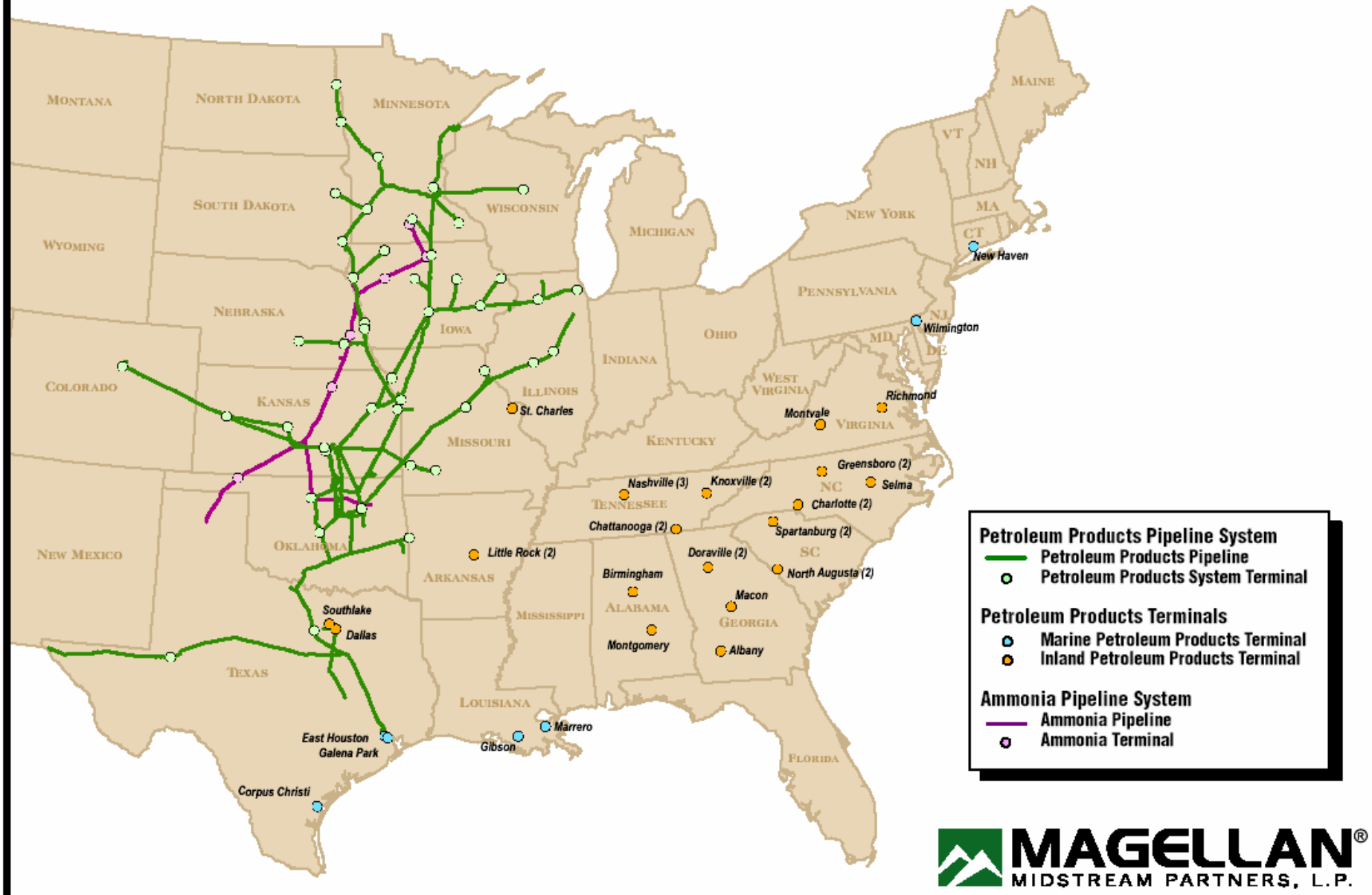


Benchtop

Proof-of-concept

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

Asset Portfolio



MAGELLAN®
MIDSTREAM PARTNERS, L.P.

Valero LP Operations

"Atmospheric" Liquid Ammonia Storage Tank (corn belt)

30,000 Tons

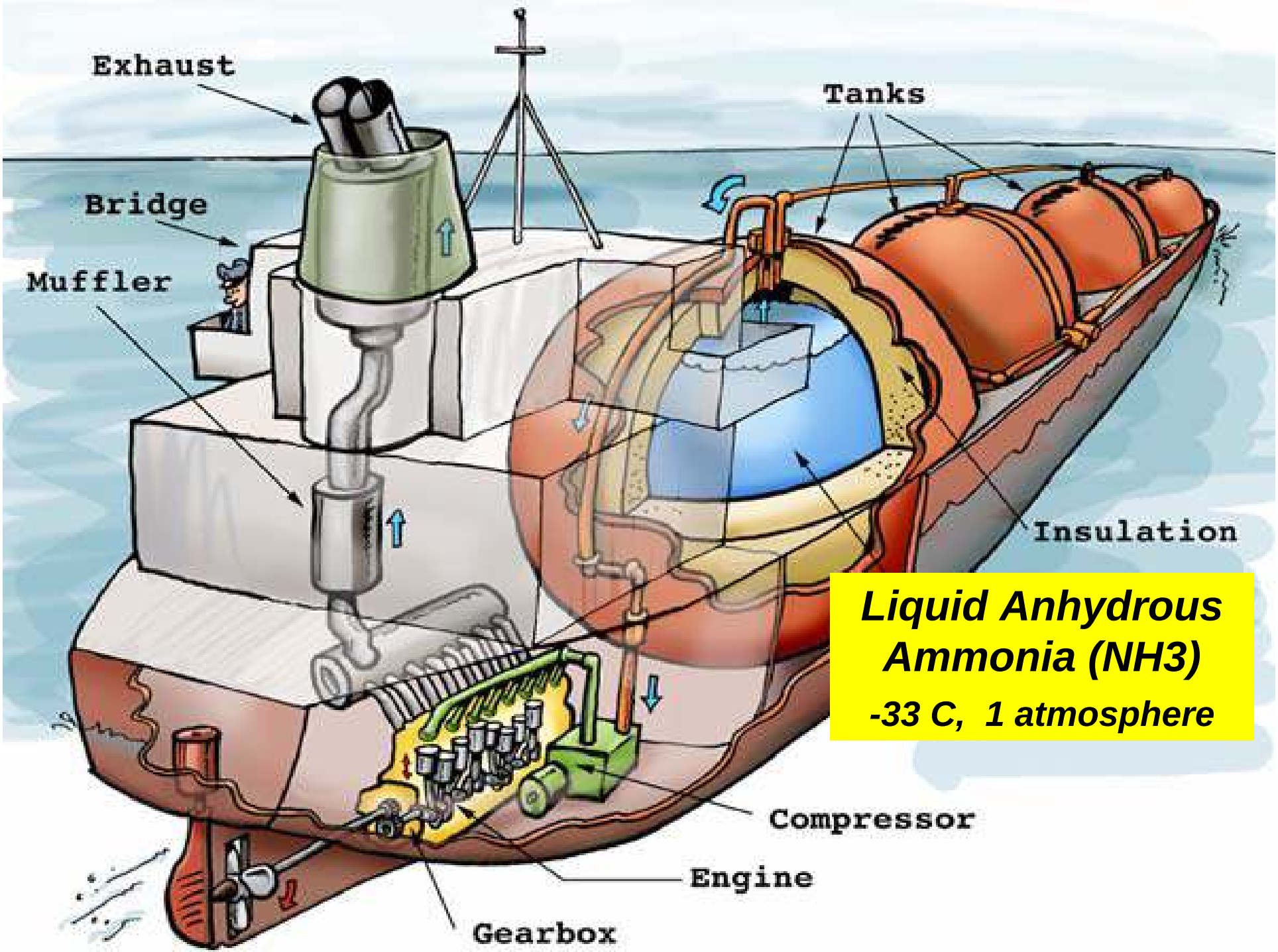
190 GWh

$15M turnkey

$77 / MWh

-33 C

1 Atm


Exhaust
Tanks
Bridge
Muffler
Insulation
Liquid Anhydrous Ammonia (NH3)
-33 C, 1 atmosphere
Compressor
Engine
Gearbox

Capital Cost per GW-mile

Electricity :	KV	Capacity MW	$M / MW-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 miles, no compress 0.3

Ammonia pipeline:

10” , liquid, 500 miles, with pumping 0.2

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

The dog caught the car.

Dan Reicher

Jon Wellinghof

FERC* Chairman

About new coal + nuclear plants:

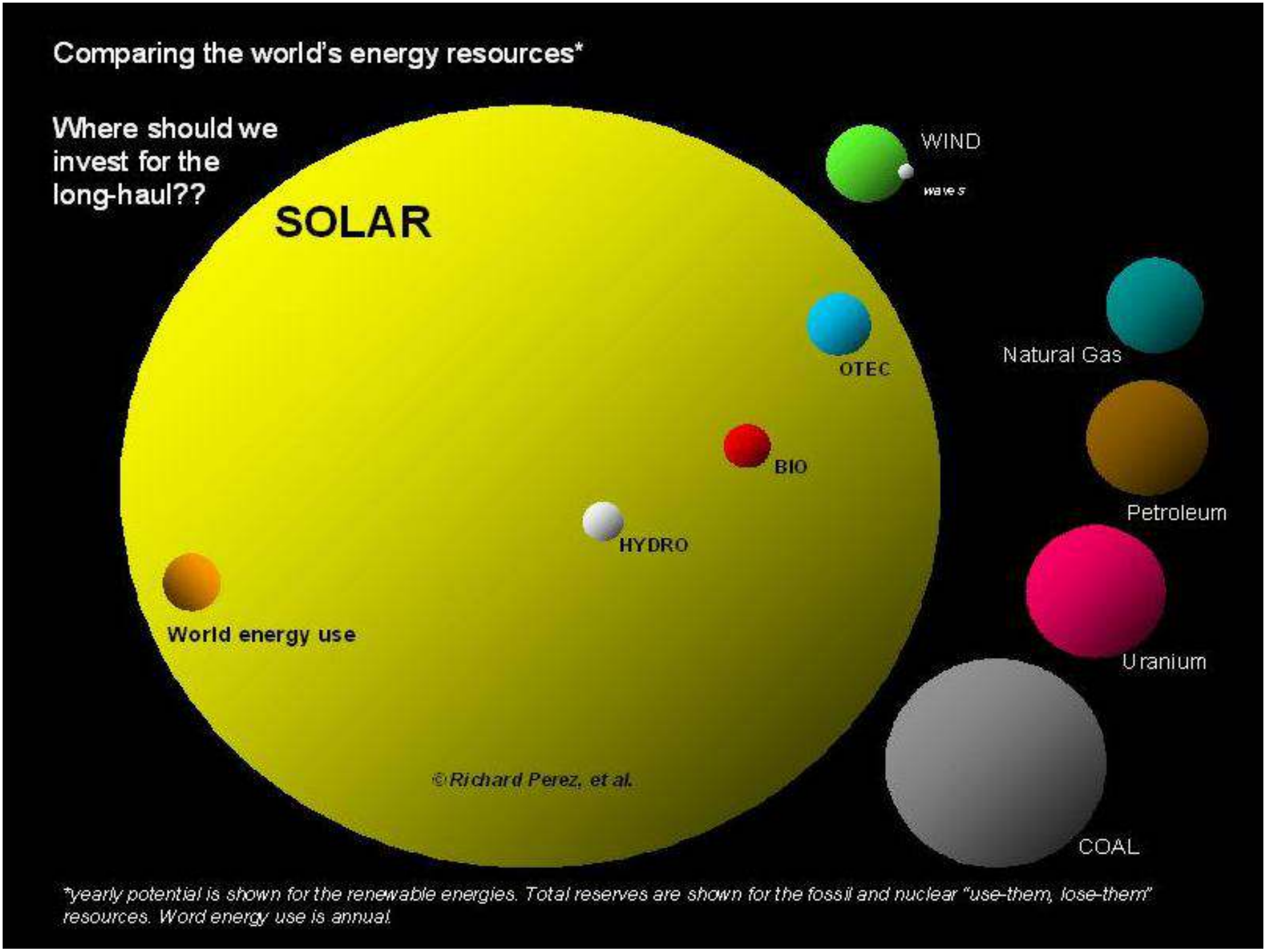
“ We may not need any, ever ”

NY Times, 22 Apr 09

*** FERC = Federal Energy Regulatory Commission**

MUST Run the World on Renewables – plus Nuclear ?

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


Comparing the world's energy resources*
Where should we invest for the long-haul??
SOLAR
WIND
waves
OTEC
BIO
HYDRO
World energy use
Natural Gas
Petroleum
Uranium
COAL
© Richard Perez, et al.
*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.

Humanity's Goal ?

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

Can't with only electricity transmission

Transmission and Annual-scale Firming Storage Alternatives to Electricity: Gaseous Hydrogen and Anhydrous Ammonia via Underground Pipeline

DVD's + handouts: Your card

EUEC
2 Feb 10, Phoenix

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