Alternatives to Electricity for Transmission and Annual-scale Firming Storage for Diverse Renewable Energy Resources: Hydrogen and Ammonia Fuels

ASME Power
14 July 10, Chicago

Bill Leighty, Director
The Leighty Foundation
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907-586-1426 206-719-5554 cell

COP 15 Failure

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

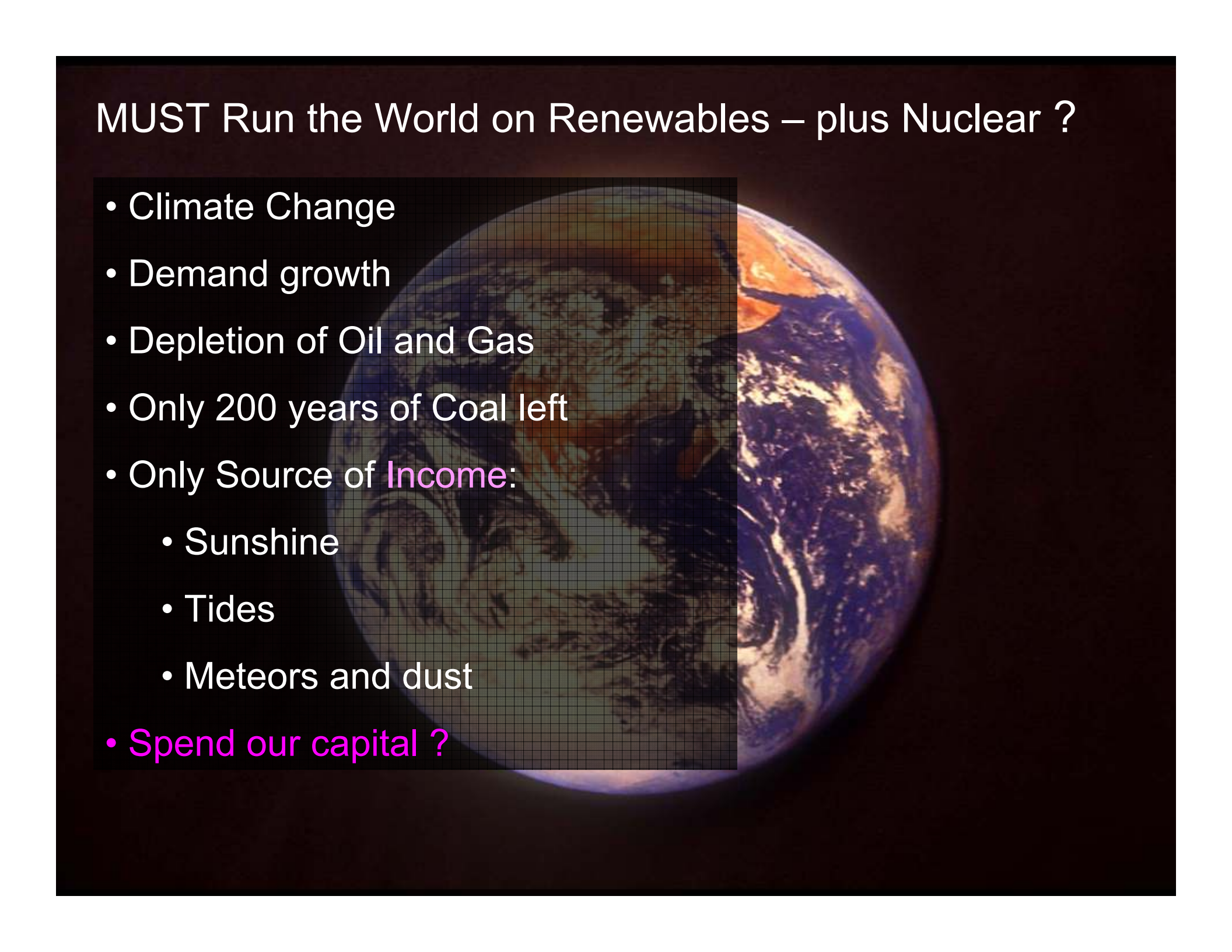
BP Gulf Tragedy

- Spending capital
- External costs

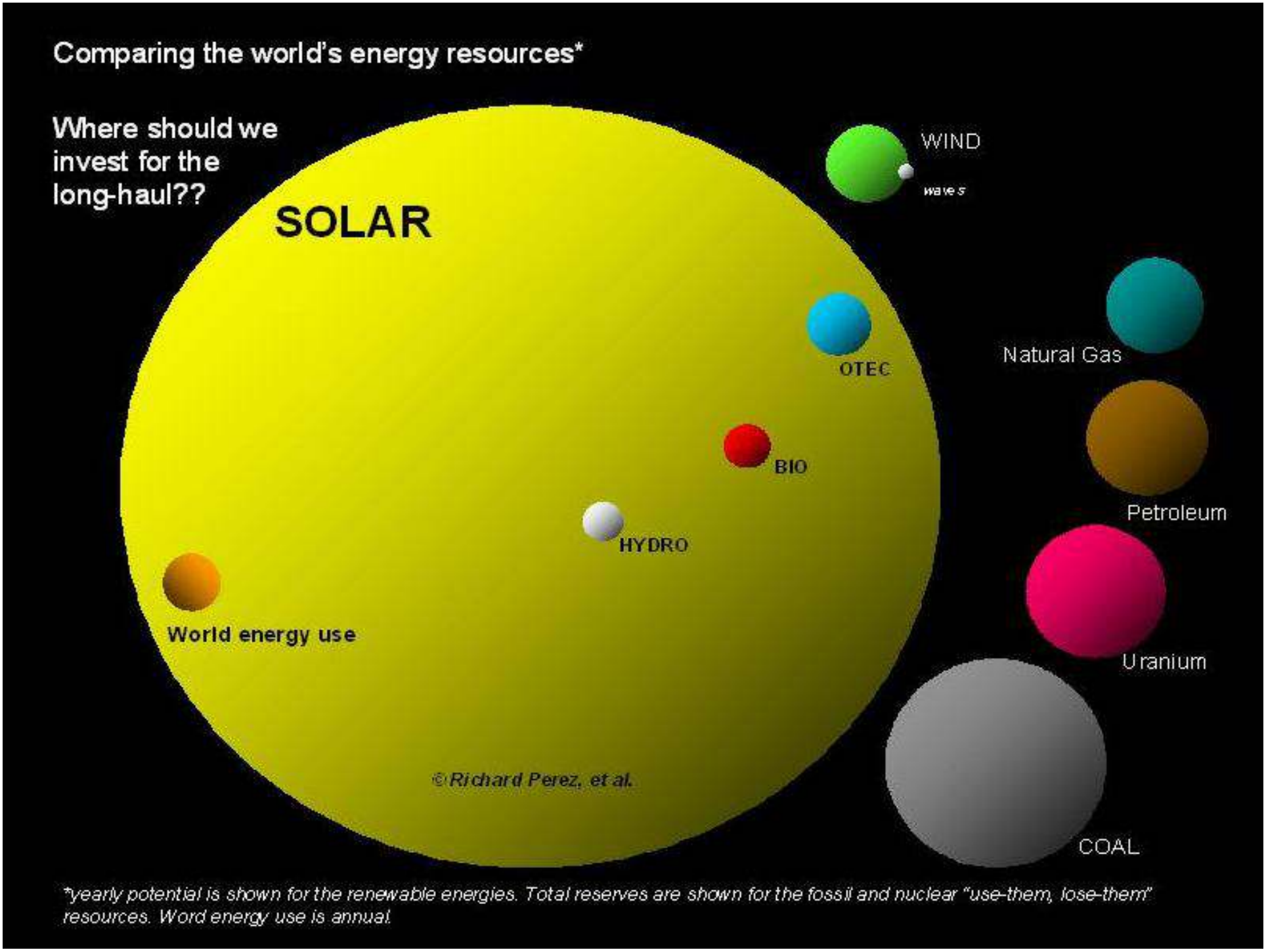
Humanity's Goal

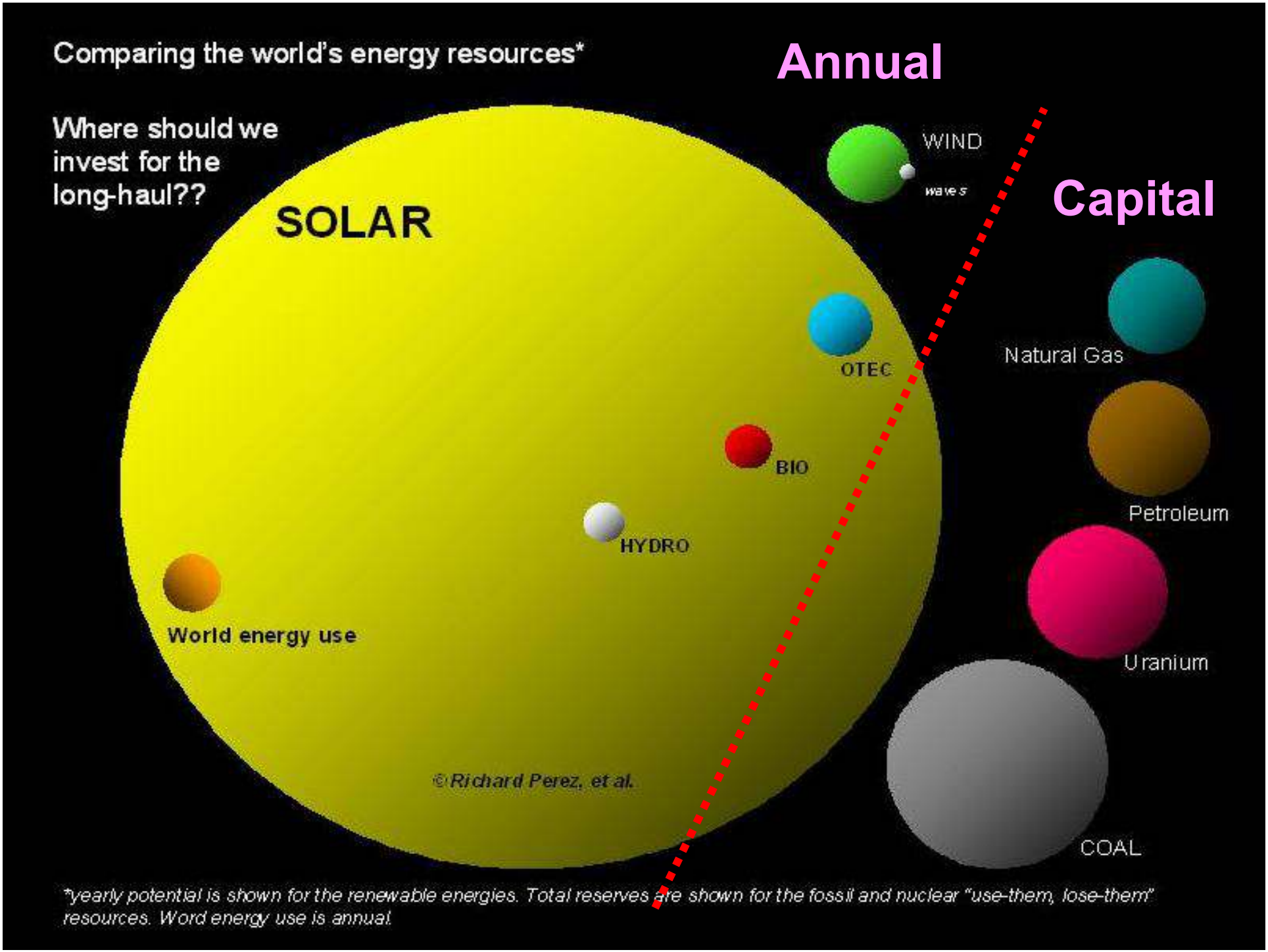
A global, sustainable, benign-source, equitable, energy economy

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 ?


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.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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

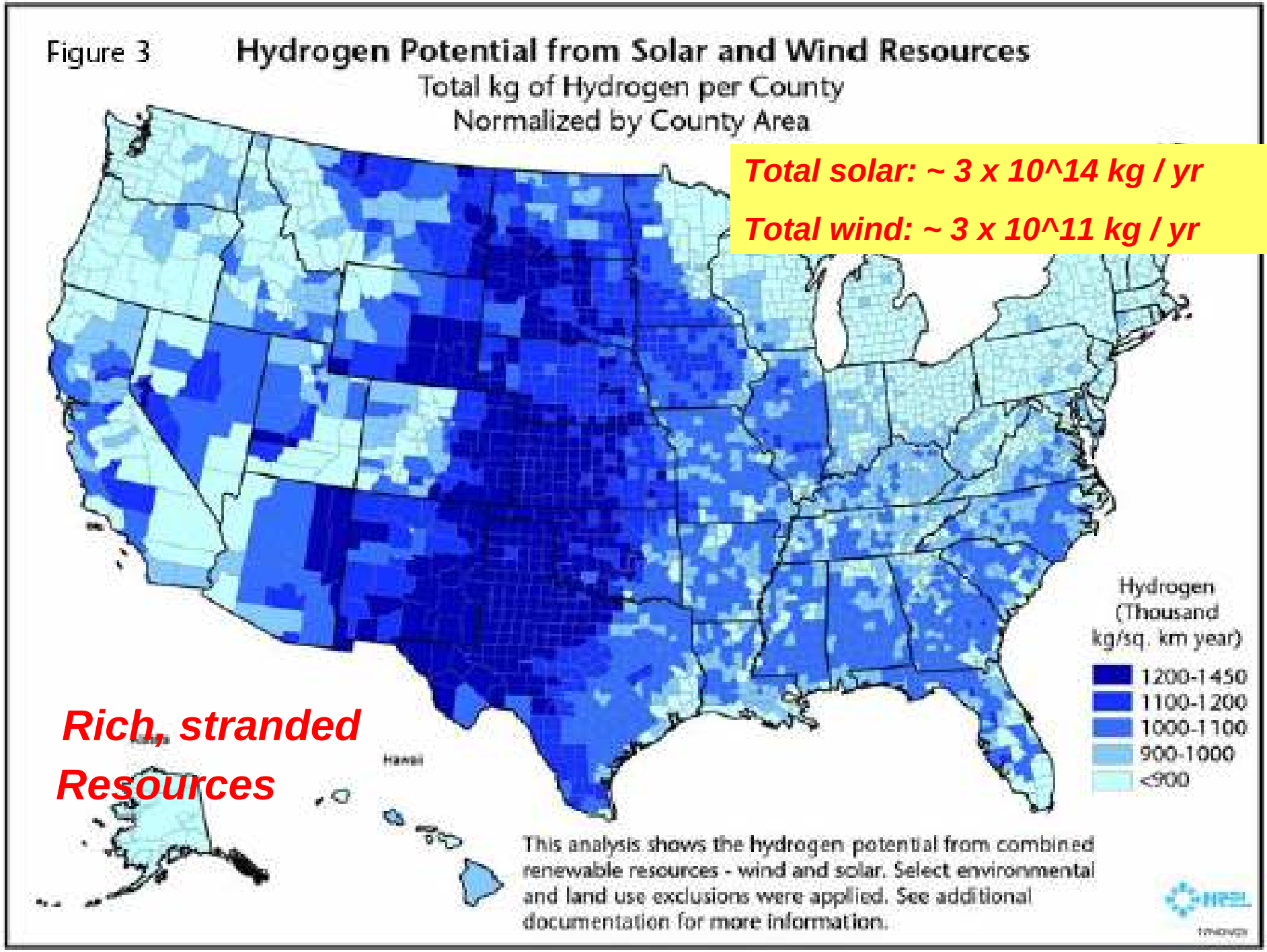
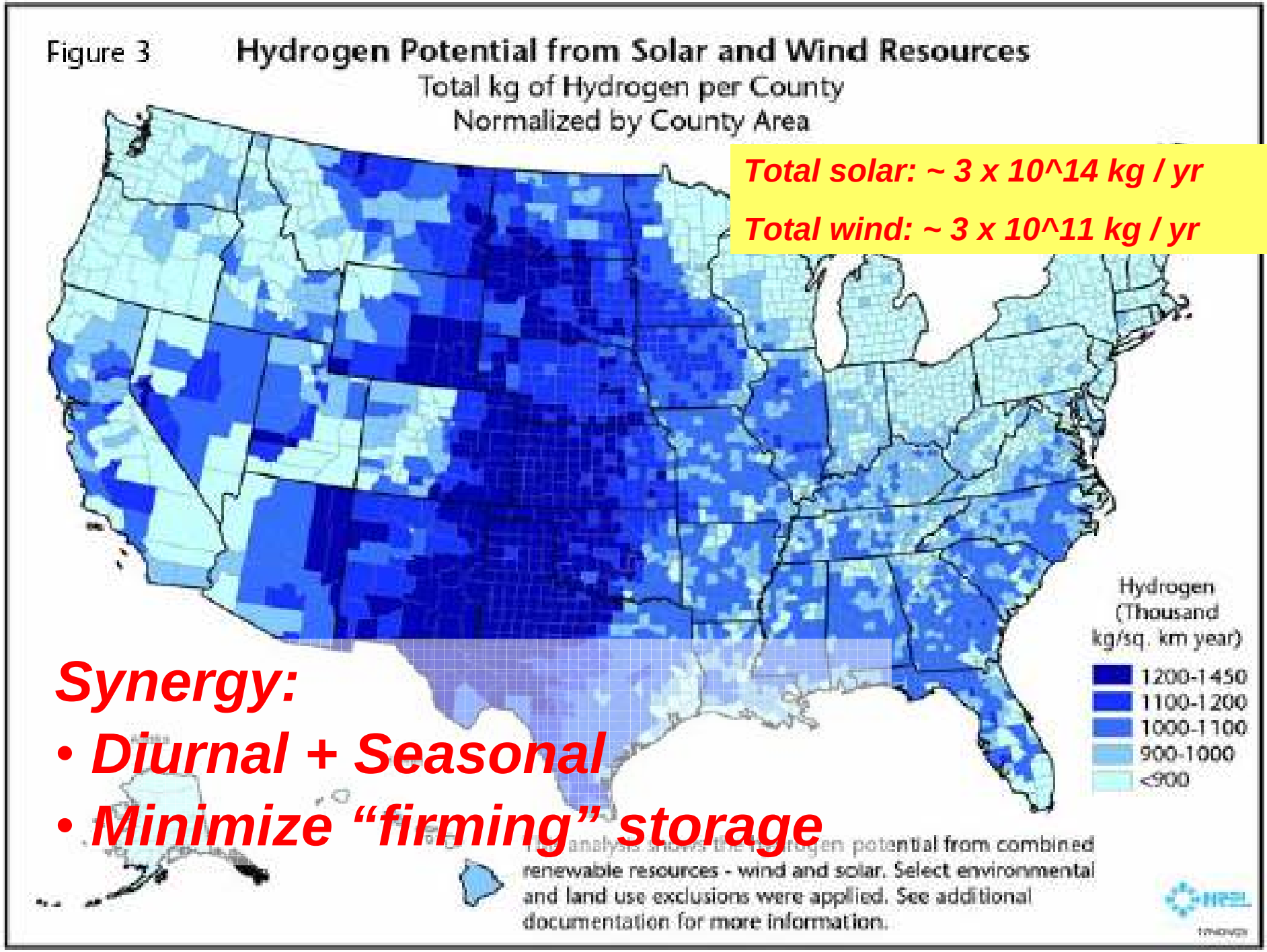


Figure 3
Hydrogen Potential from Solar and Wind Resources
Total kg of Hydrogen per County
Normalized by County Area
Total solar: ~ 3 x 10^14 kg / yr
Total wind: ~ 3 x 10^11 kg / yr
Rich, stranded Resources
Hydrogen (Thousand kg/sq. km year)
1200-1450
1100-1200
1000-1100
900-1000
<900
Hawaii
This analysis 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 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**

“ 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.

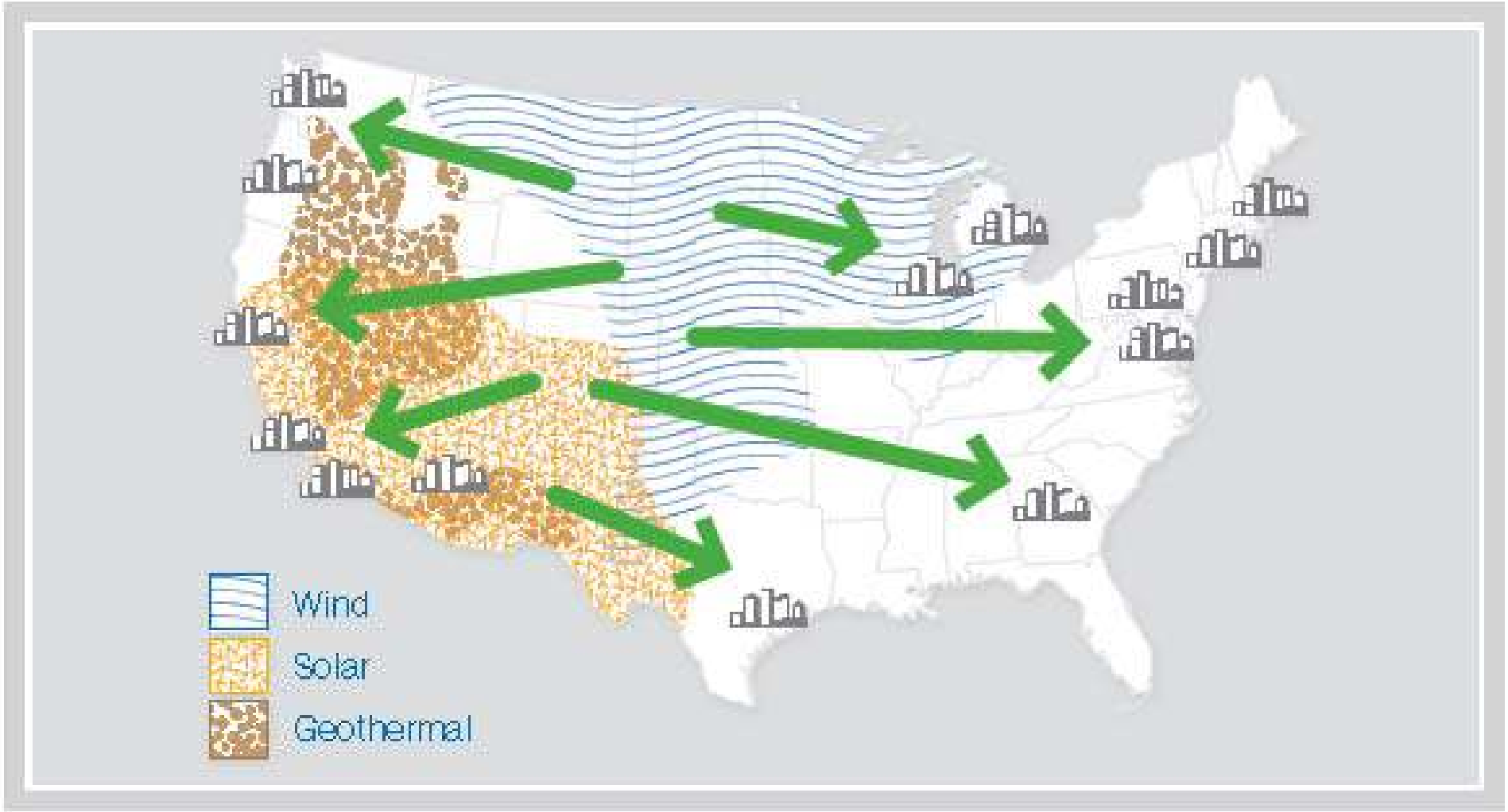
Dan Reicher

Major Electricity Transmission Studies

• EWITS-NREL	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	**~ 1,000**	**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

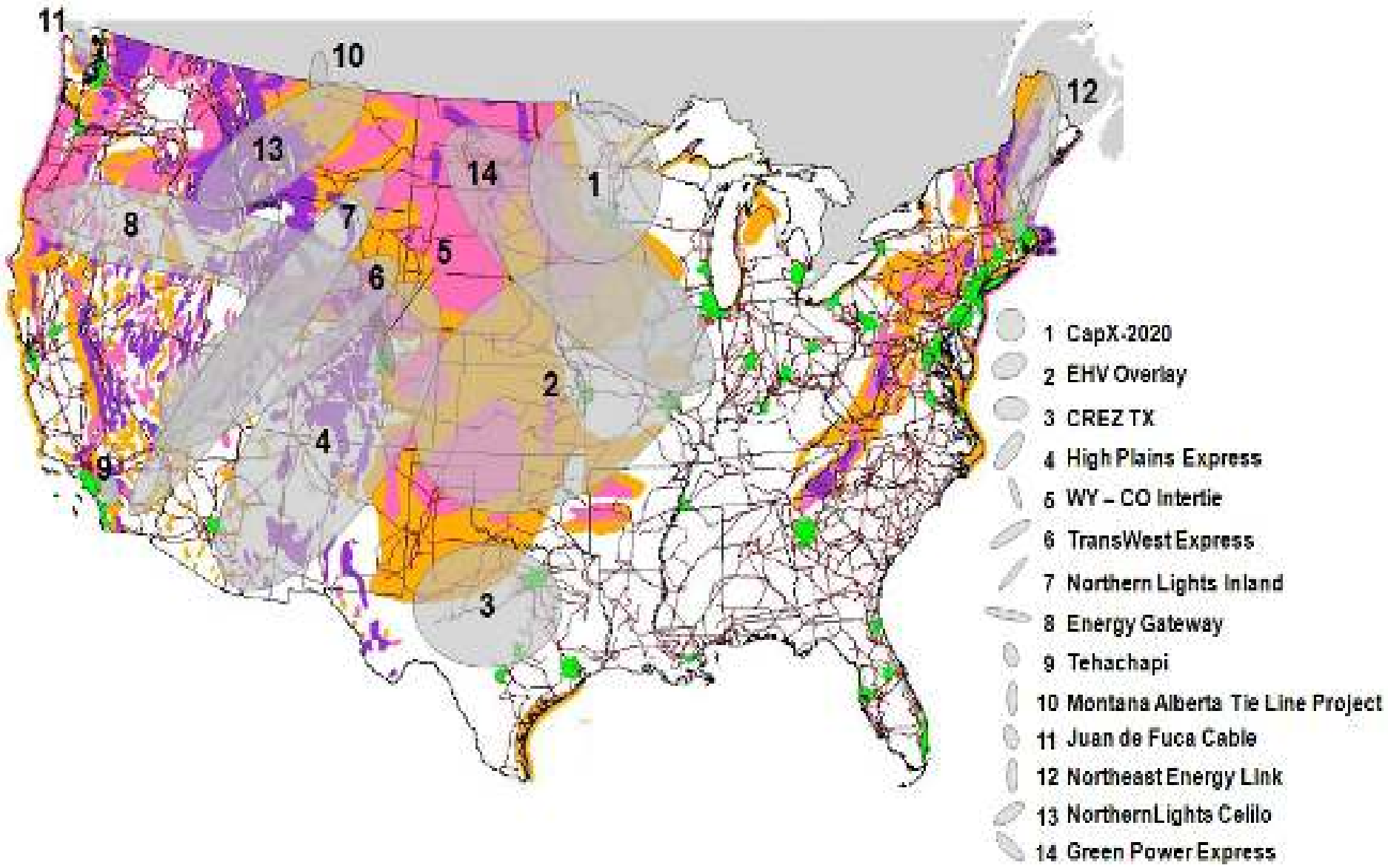


Source: AWEA and SEIA

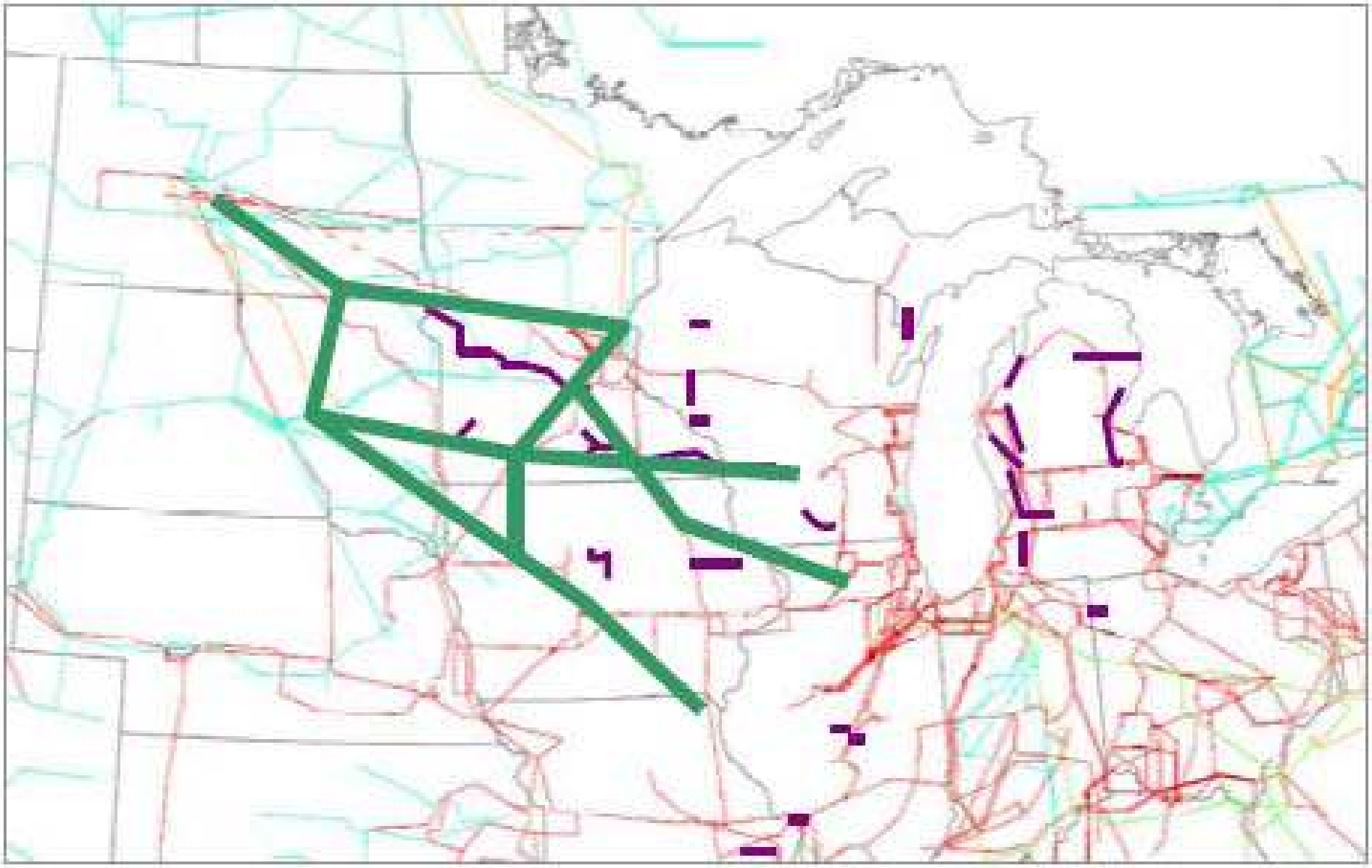
SEIA – AWEA Feb 09

"Green Power Superhighways:

Building a Path to America's Clean Energy Future"

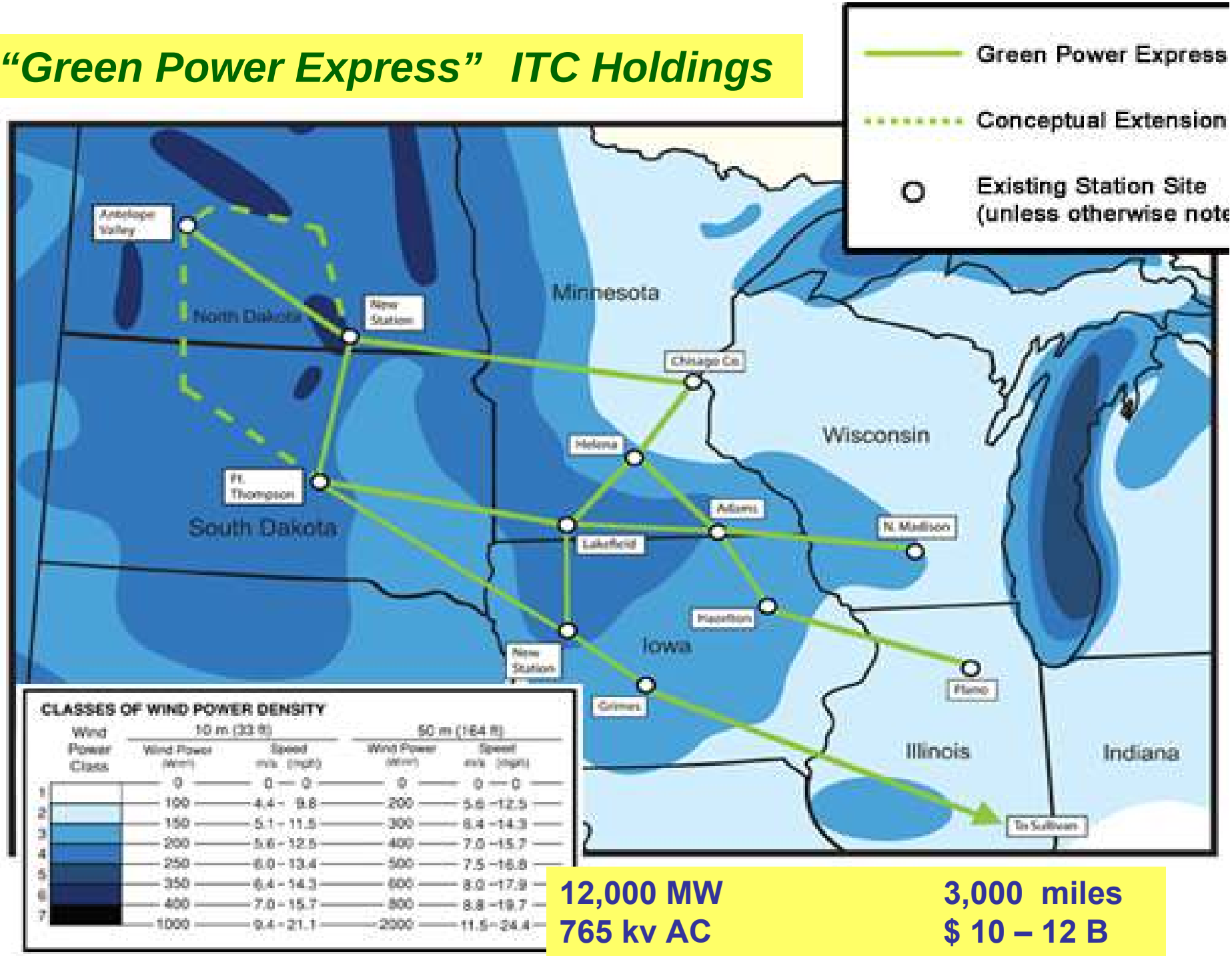


Emerging Energy Research LLC



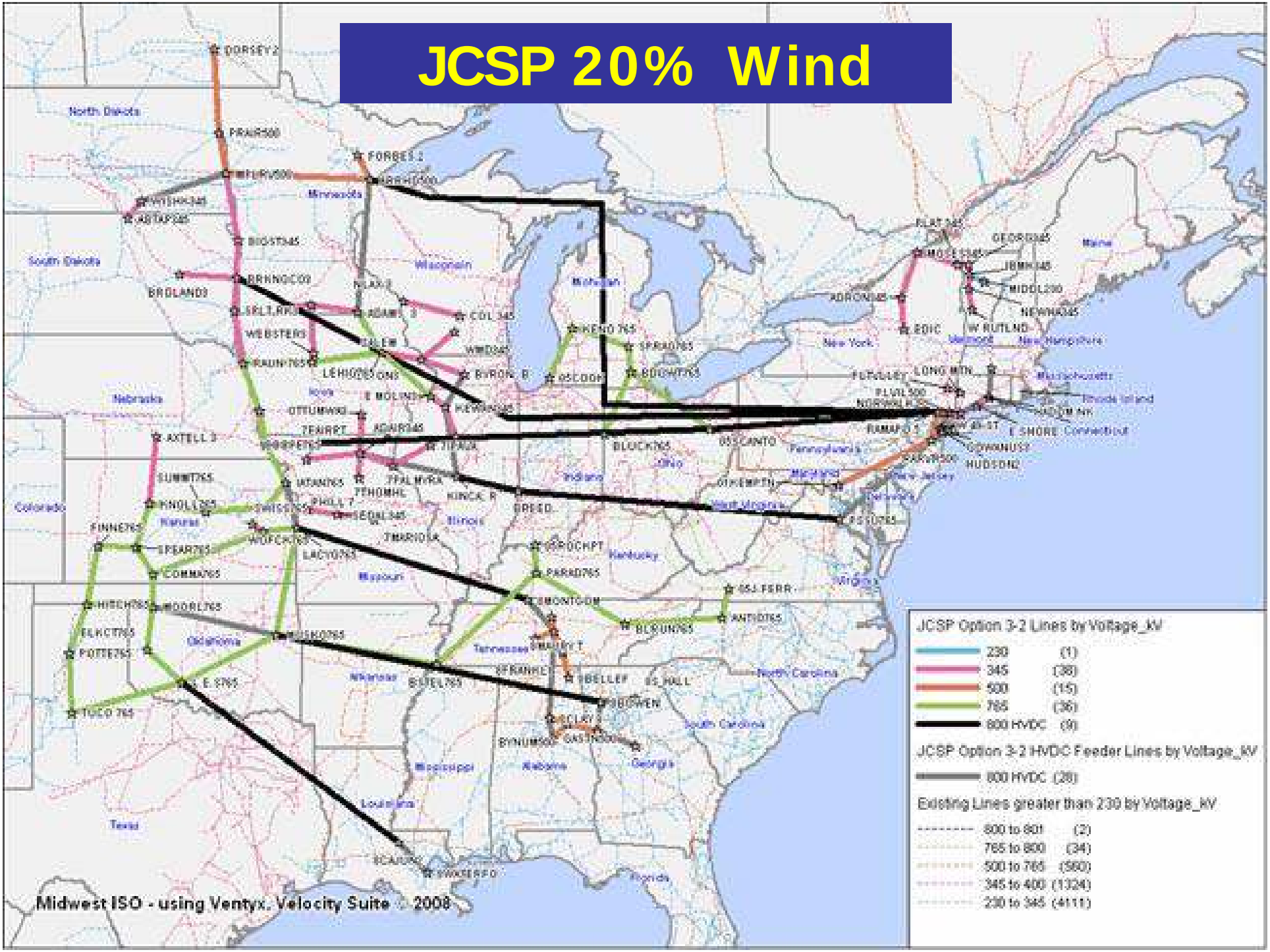
Brattle Group

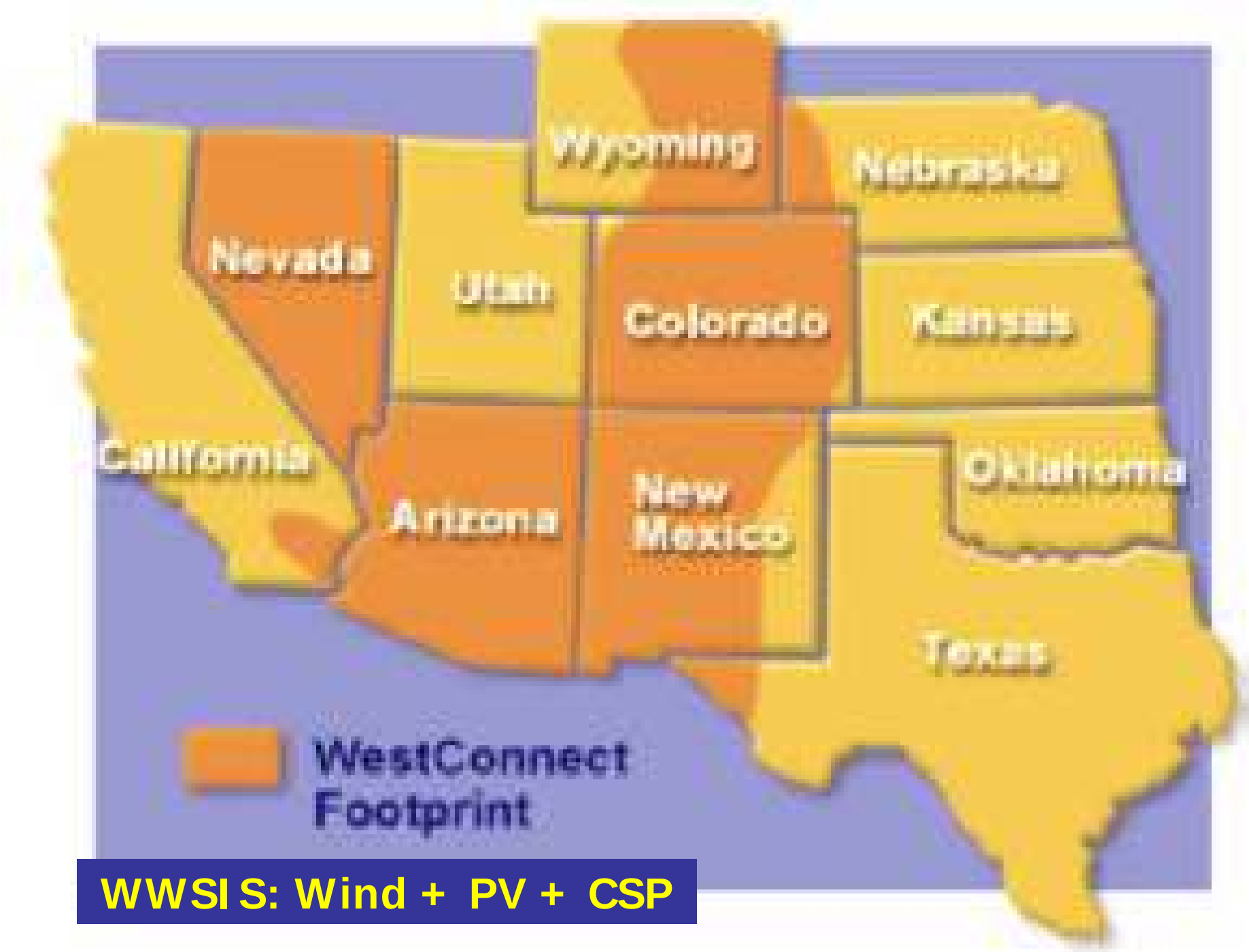
"Green Power Express" ITC Holdings



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

JCSP 20% Wind

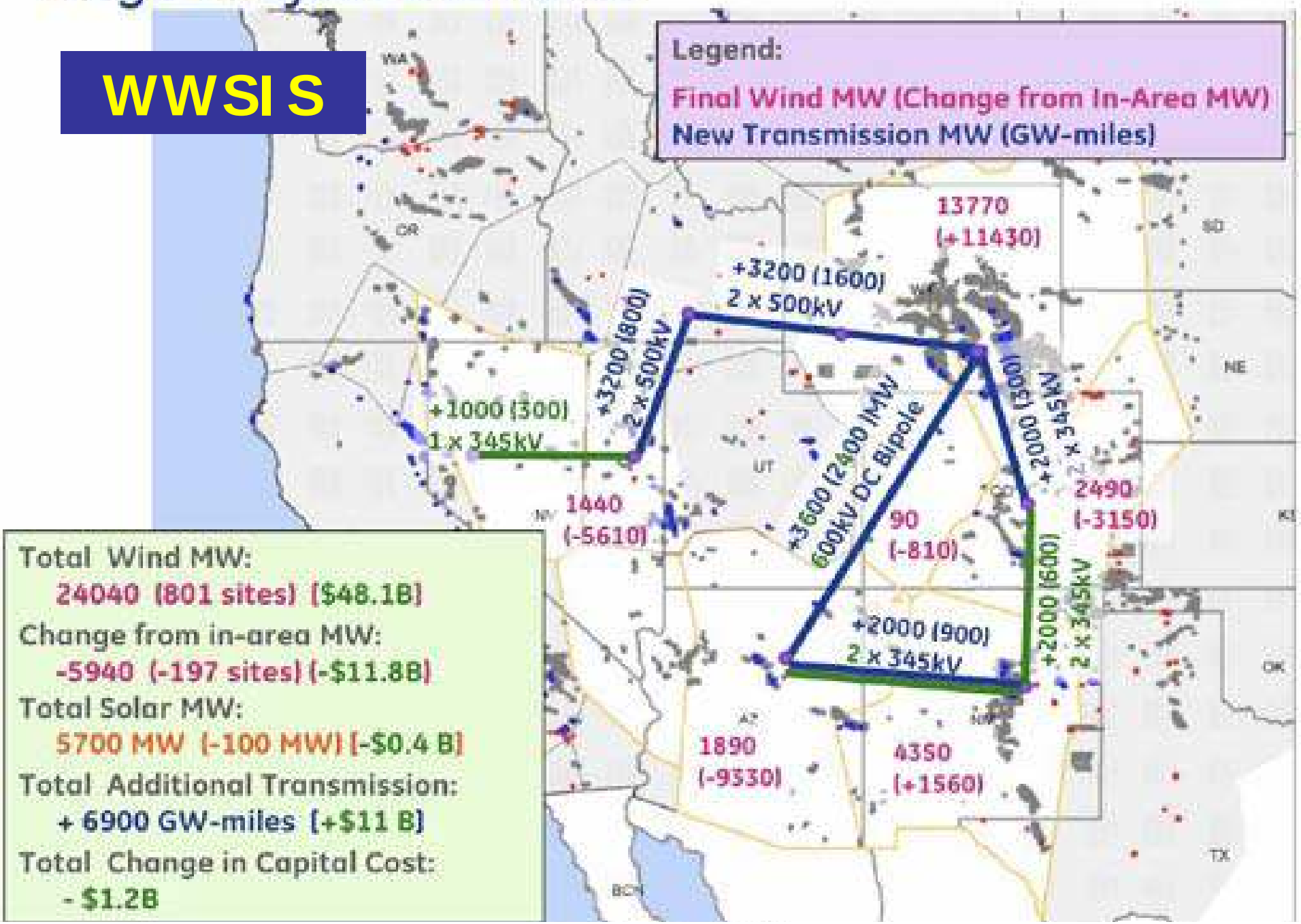

JCSP Option 3-2 Lines by Voltage_kV
230 (1)
345 (38)
500 (15)
765 (36)
800 HVDC (9)
JCSP Option 3-2 HVDC Feeder Lines by Voltage_kV
800 HVDC (28)
Existing Lines greater than 230 by Voltage_kV
800 to 801 (2)
765 to 800 (34)
500 to 765 (560)
345 to 400 (1324)
230 to 345 (4111)
Midwest ISO - using Ventyx,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



WWSIS: Wind + PV + CSP

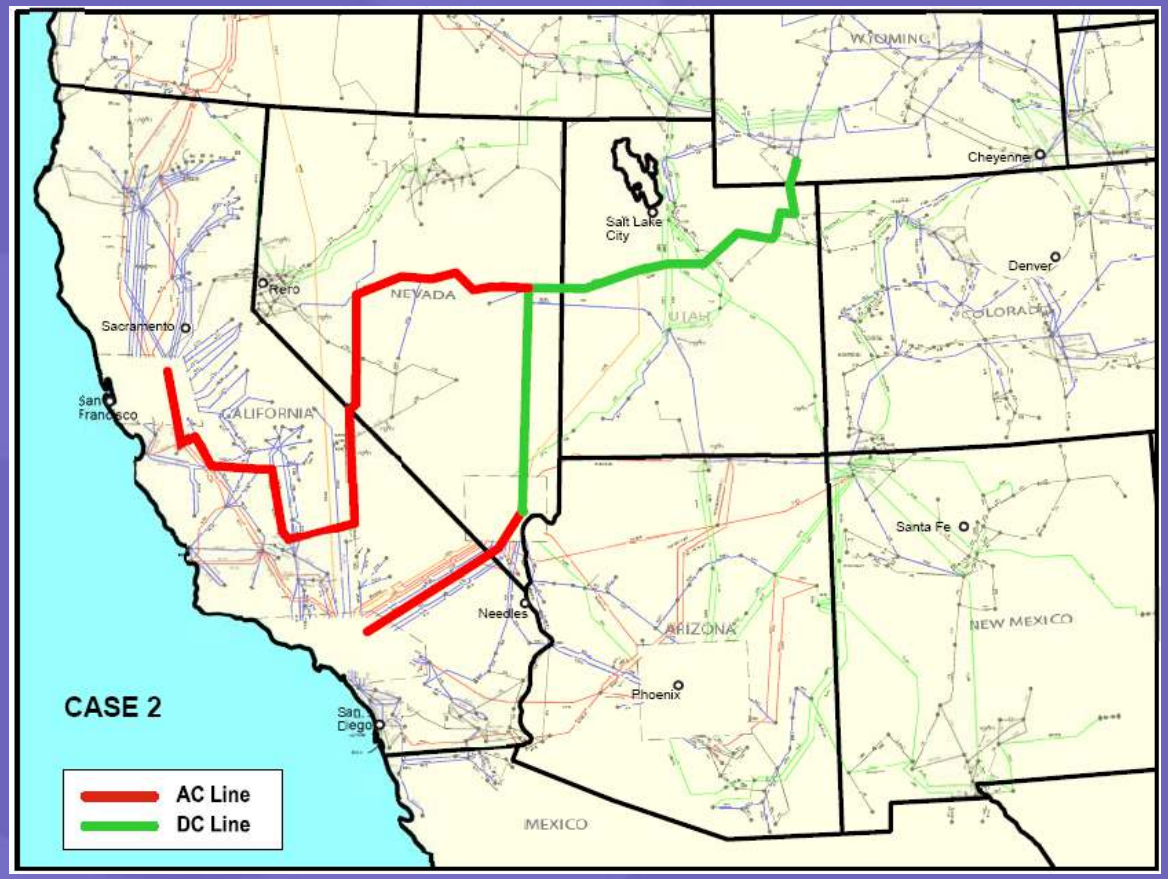
Mega Project Scenario

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

Frontier Line

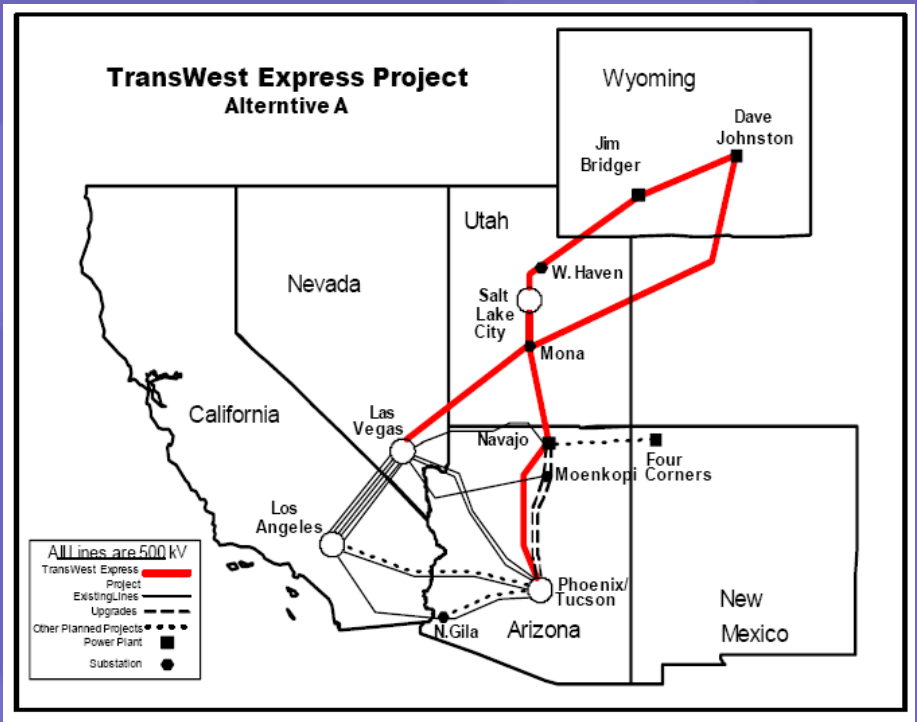


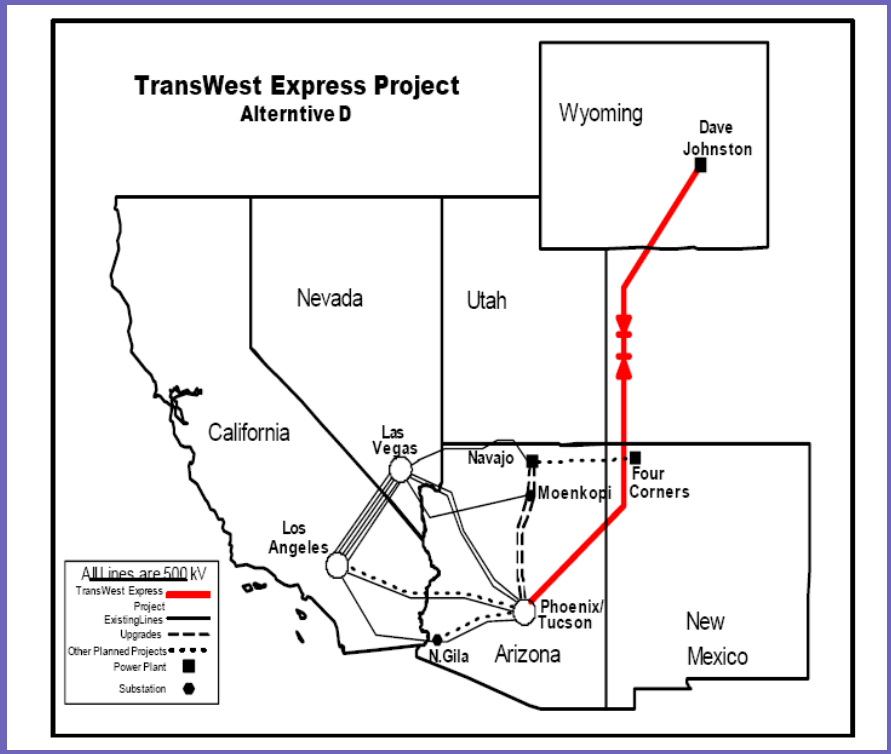
Example pathway by California Energy Commission, *Wyoming-California Corridor Transmission Expansion Study,* Global Energy Decisions, June 2006, CEC-700-2006-008.

- 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:





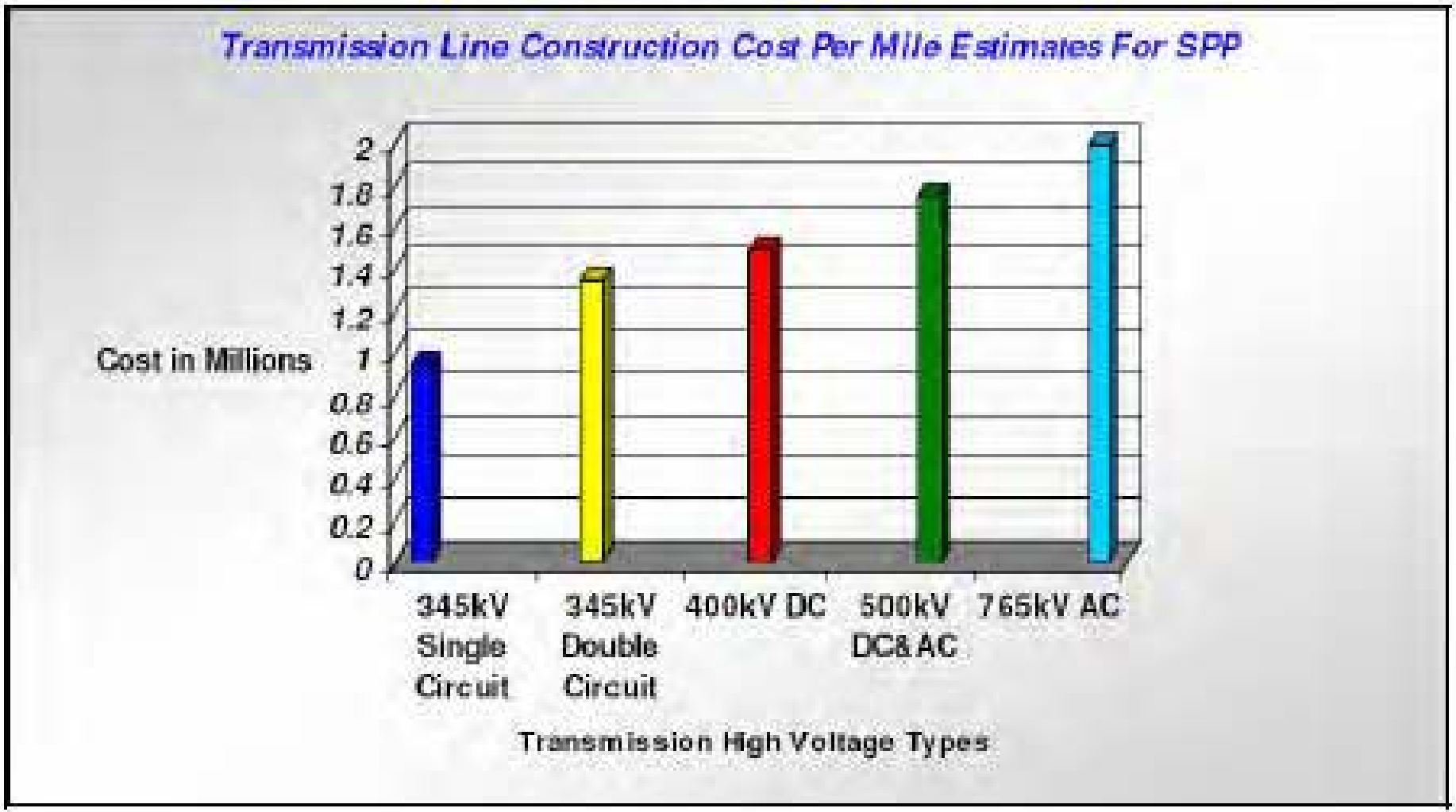
Statement of Robert Smith on behalf of Arizona Public Service Company and the TransWest Express Project before the House Subcommittee on Water and Power and the House Subcommittee on Forests and Forest Health, June 27, 2006.

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"



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 ?			2.5

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

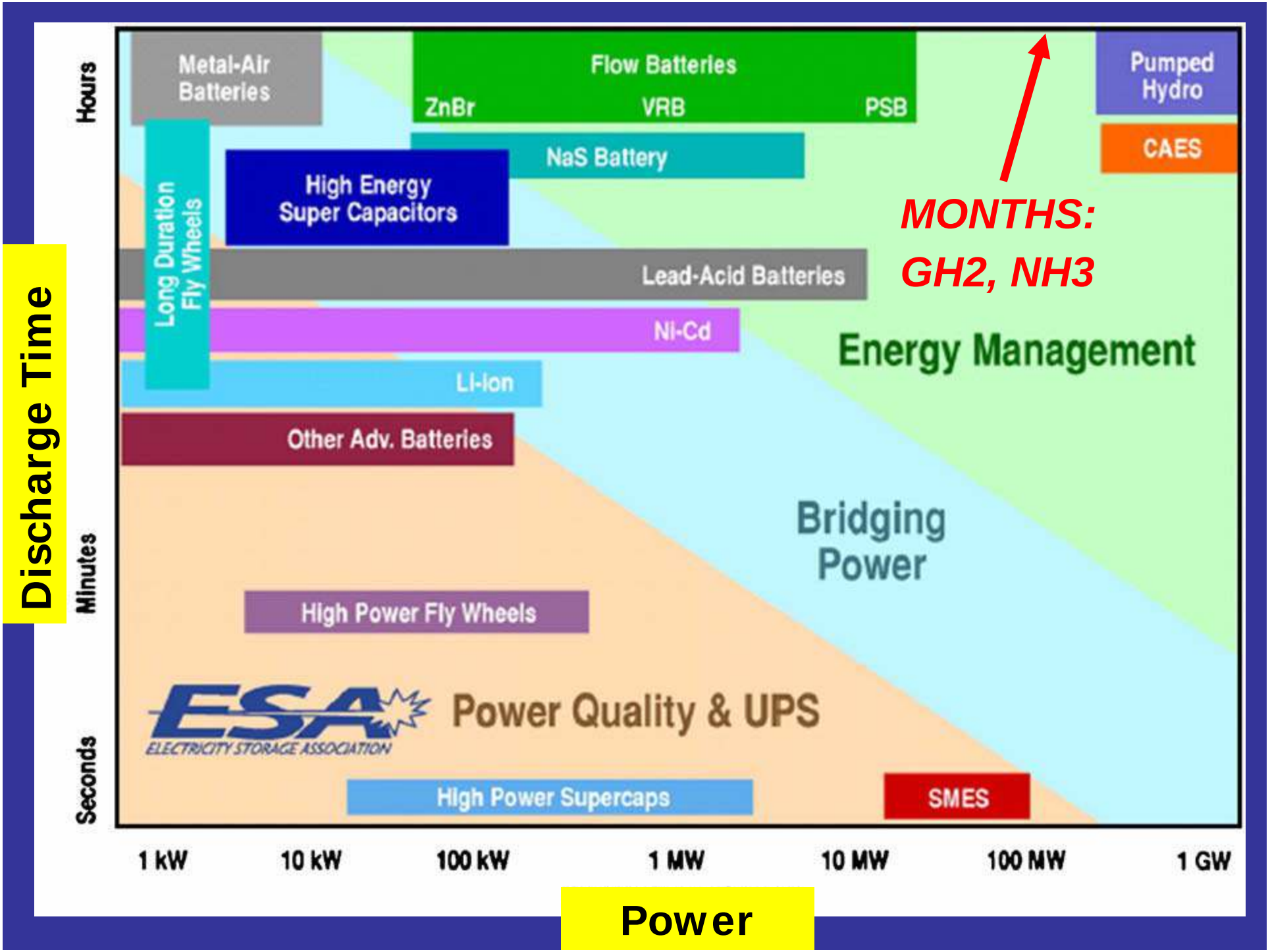
- Every hour, every year
- Dispatchable
- Strategically: indigenous, secure
- Market price: worth more
- Bankable large projects
- Risk avoidance:
  - Rapid climate change
  - Economic chaos

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 ?

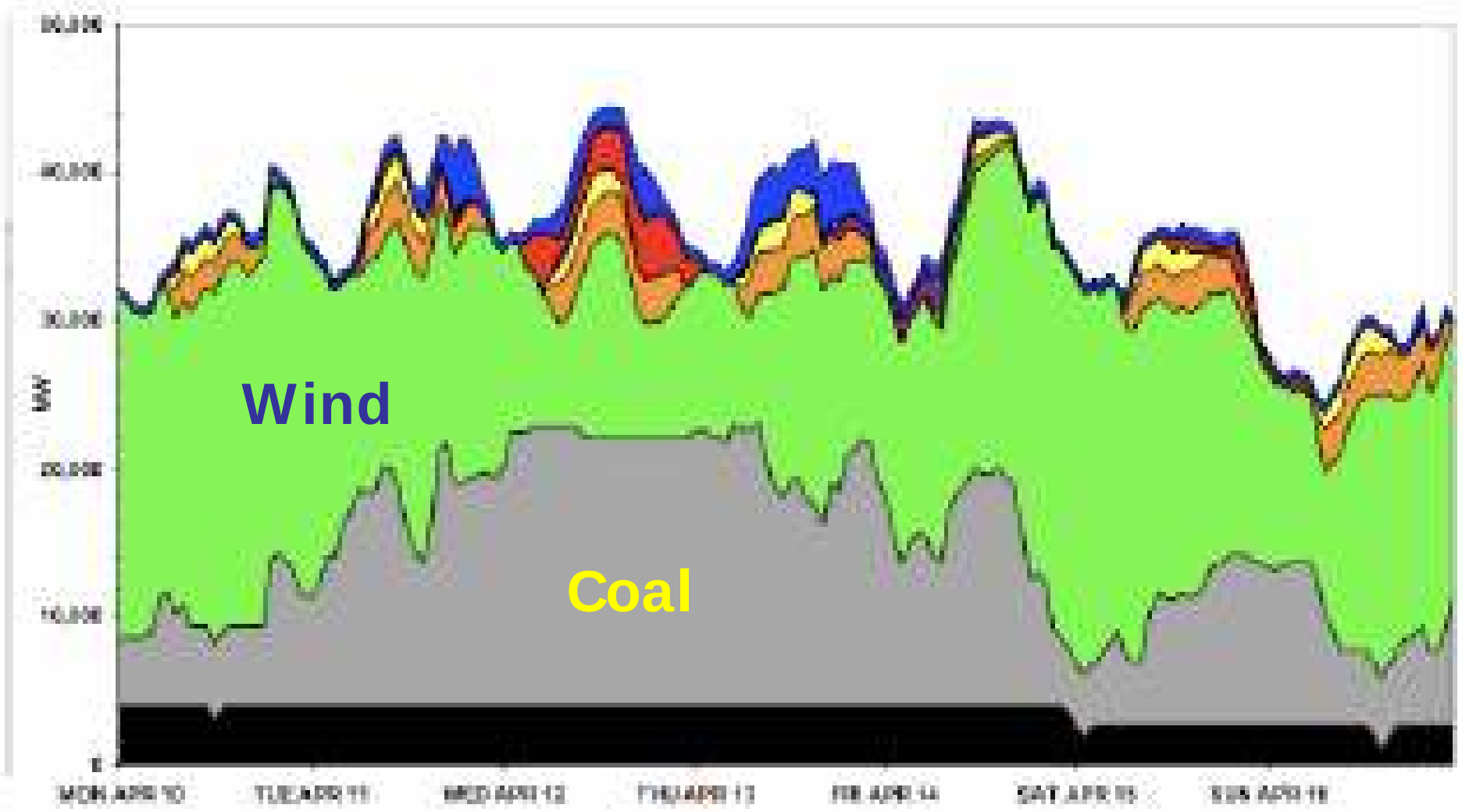
- *Storage capacity (Mwh, scf, nM3, Mt, gallons ….)*
- *Power (MW, scfm ….) In / Out rate*
- *Costs*
  - *Capital*
  - *O&M*
- **Efficiency**
- **Response time**
- **Durability (cycling capacity)**
- **Reliability**
- **Autonomy**
- **Self-discharge**
- **Depth of discharge**
- **Adaptation to the generating 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

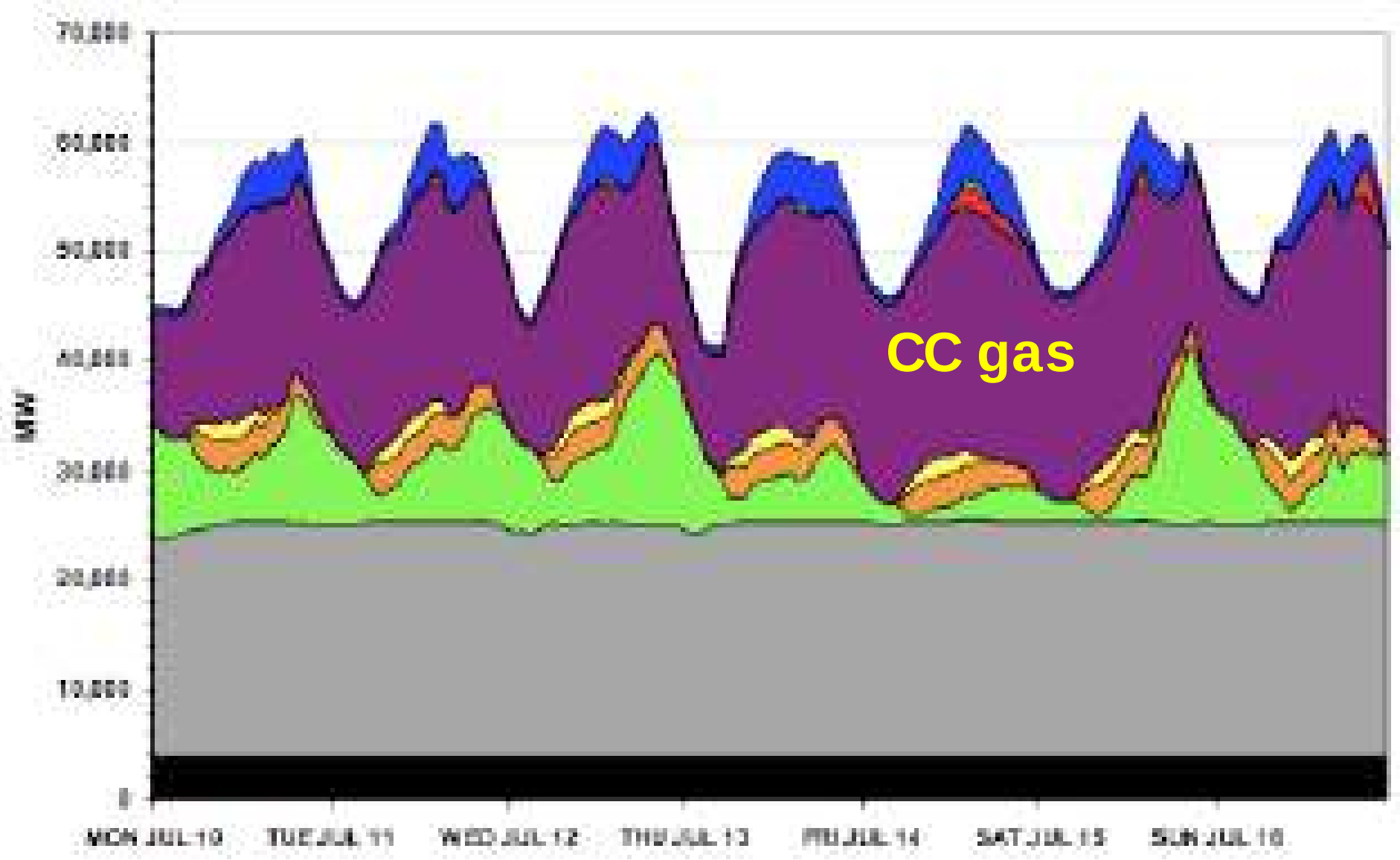
Trouble with Renewables: Electricity Transmission

- 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

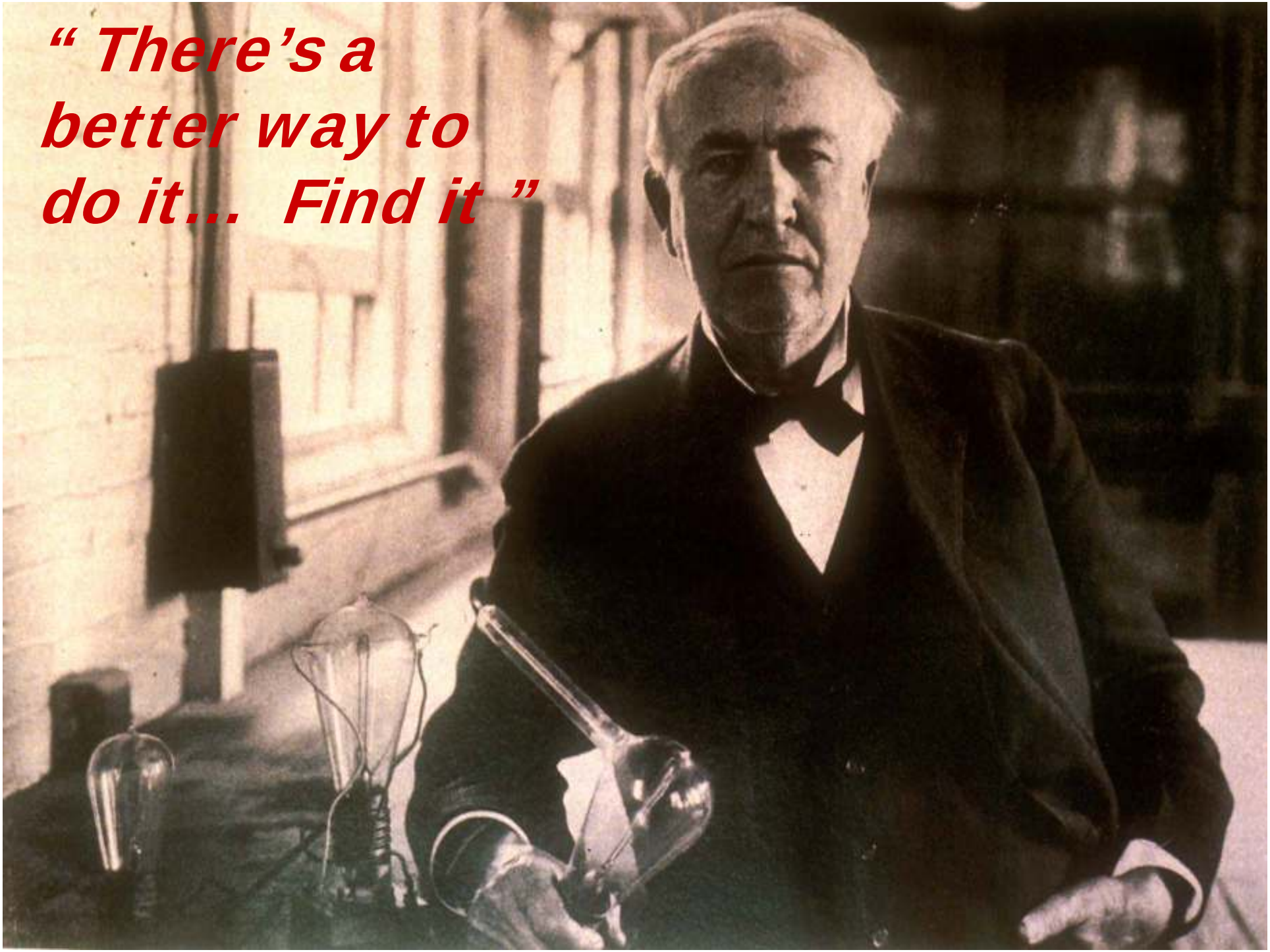

Zion, IL
Near Zion nuclear plant, Oct 02



WWSIS: April week: ~30% RE

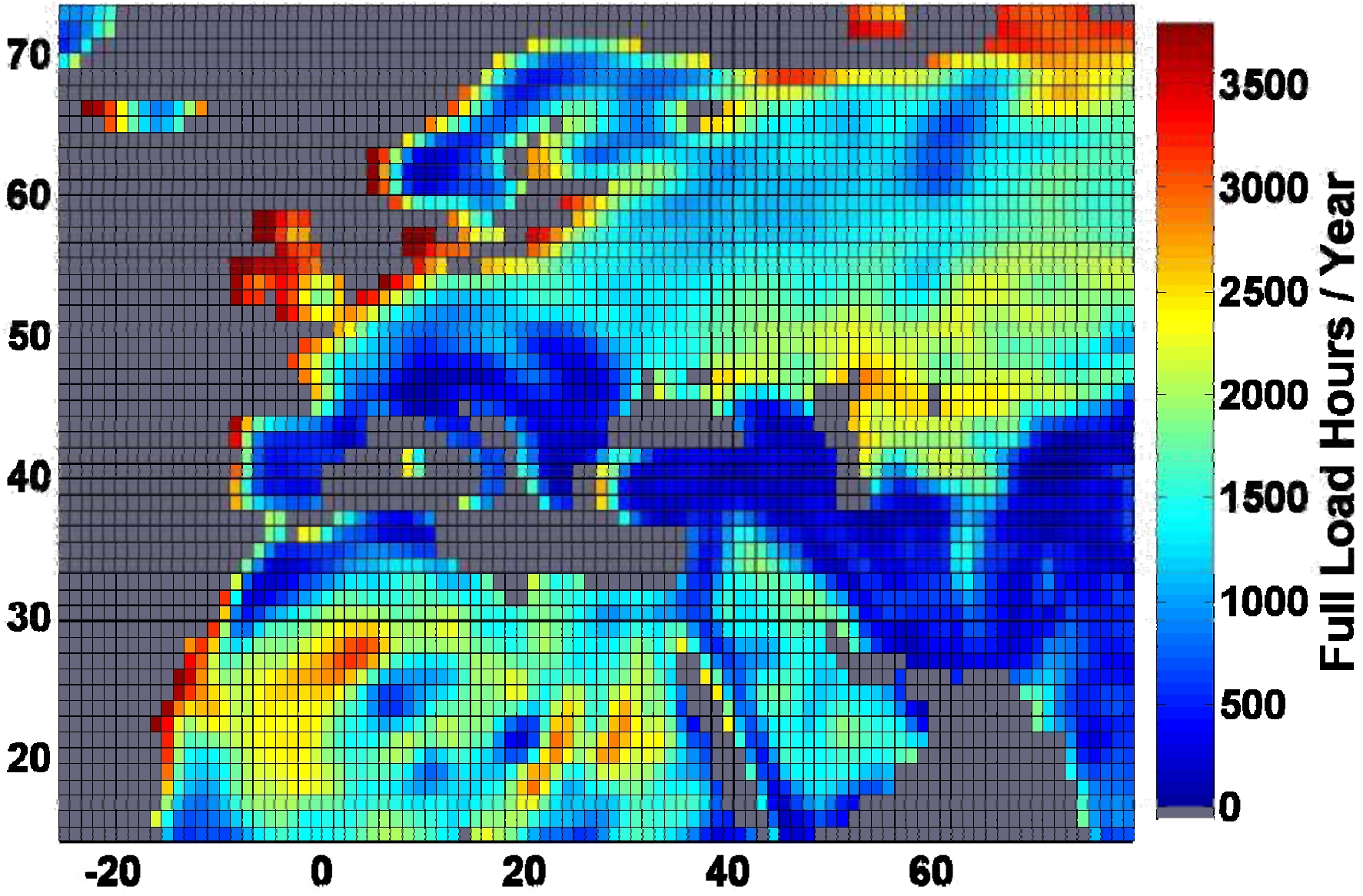


WWSIS: July week: ~10% RE


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

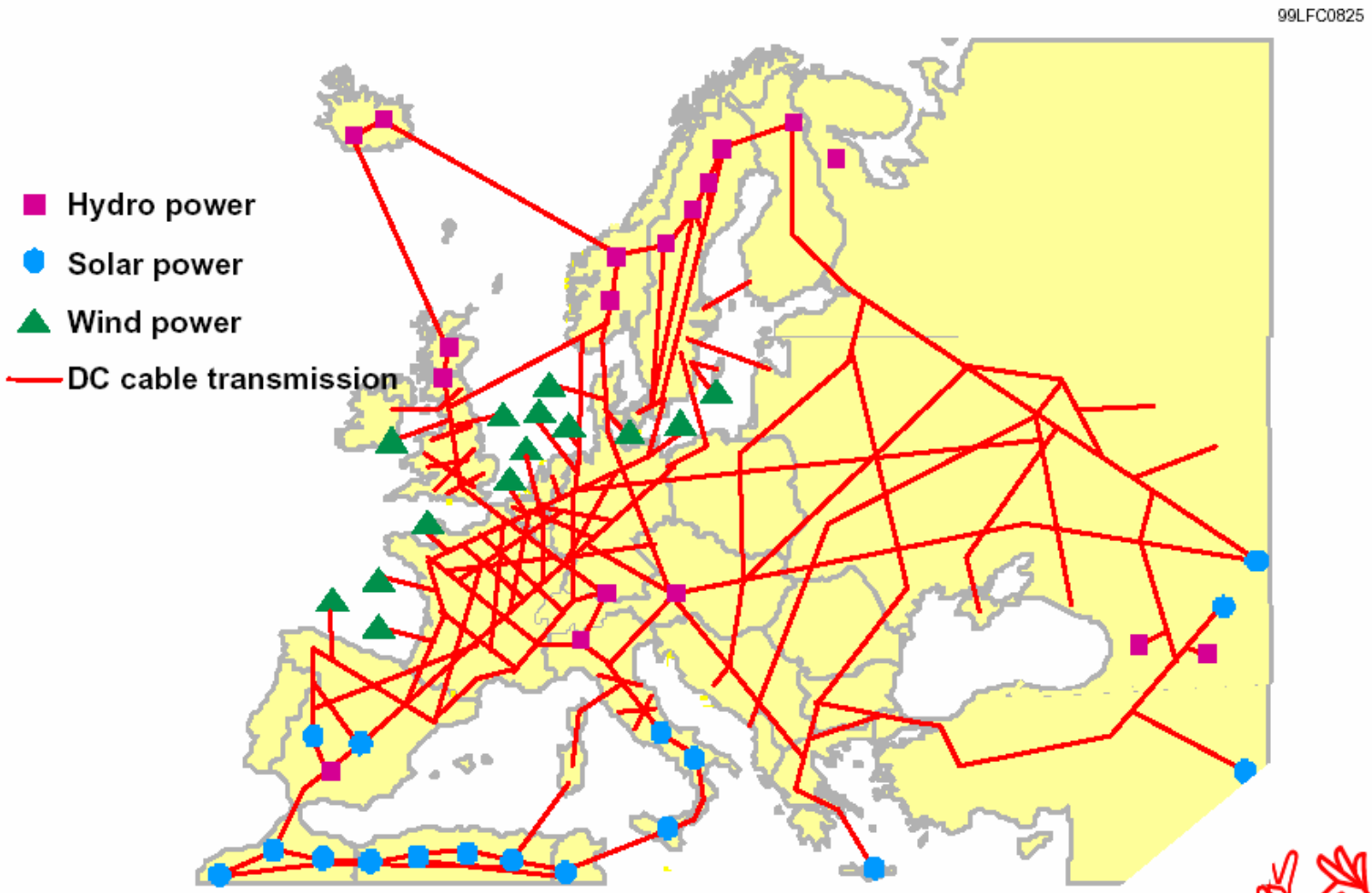
ABB, ISET Kassel "Huge Catchment Area"

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



Vision: Remote renewable energy sources

connected to loads by DC grid



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

Wind seasonality, Great Plains

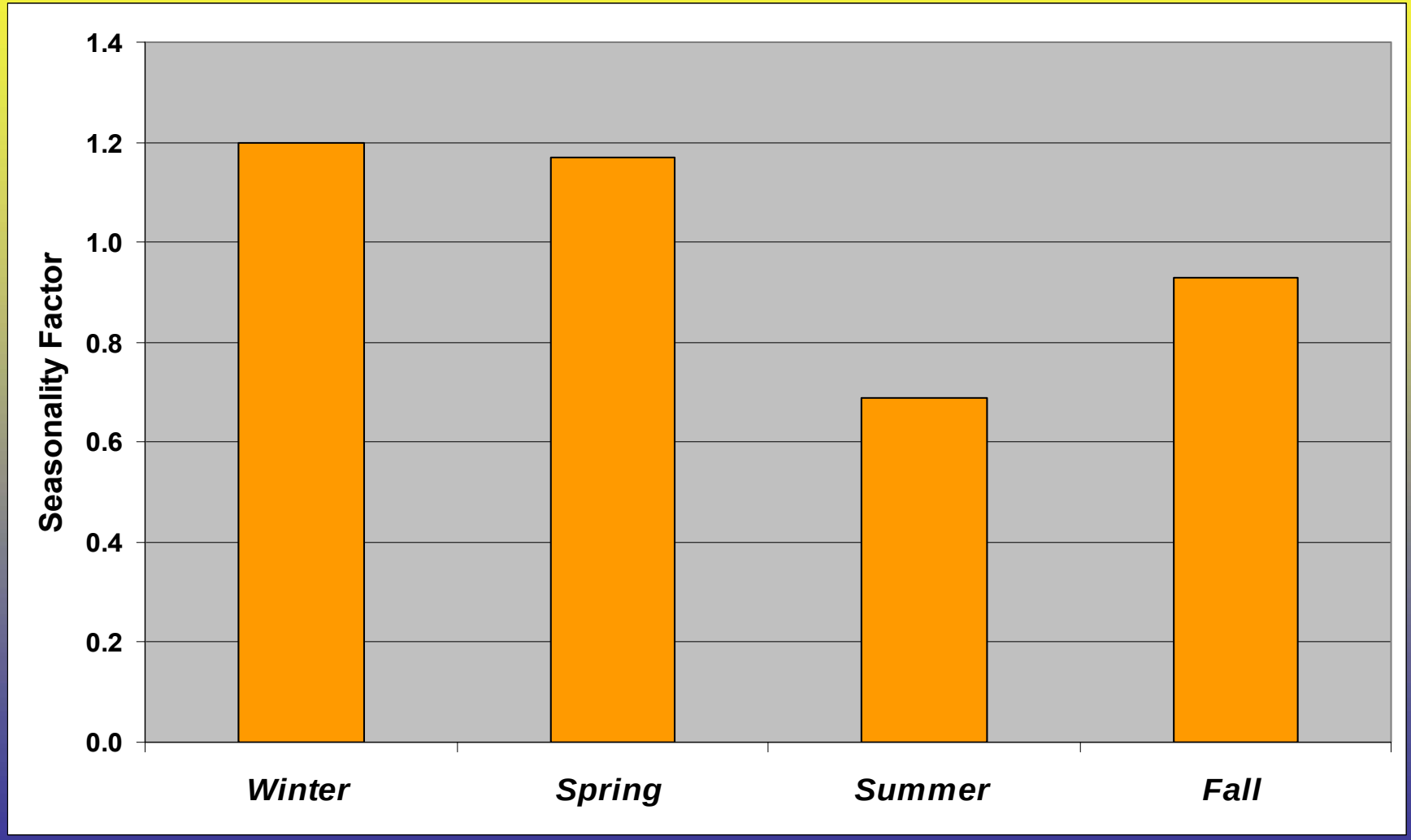
Normalized to 1.0

- **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



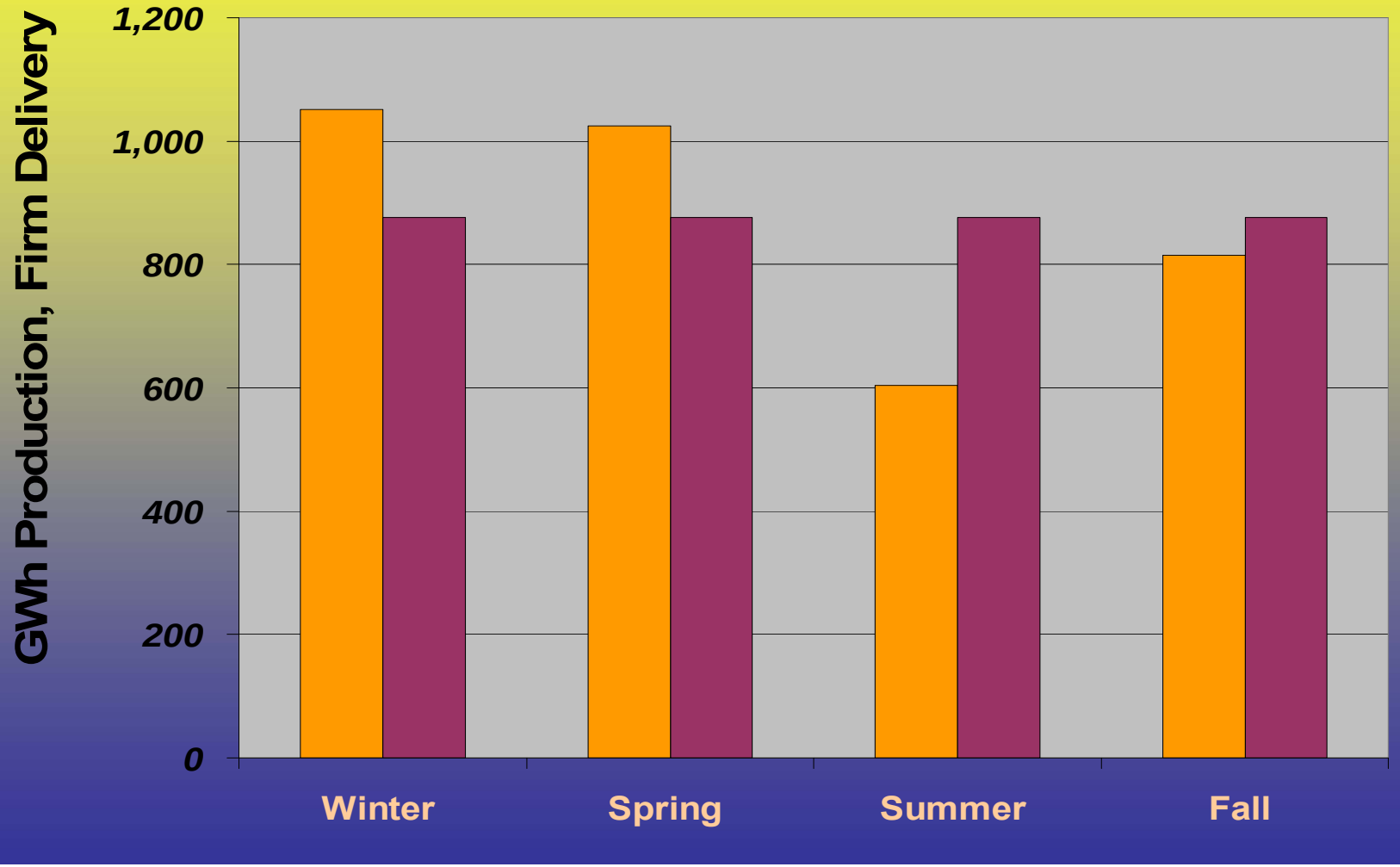
Wind Seasonality, Northern Great Plains

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

"Firm" goal = 875 GWh / season

Storage: 320 GWh per 1,000 MW wind

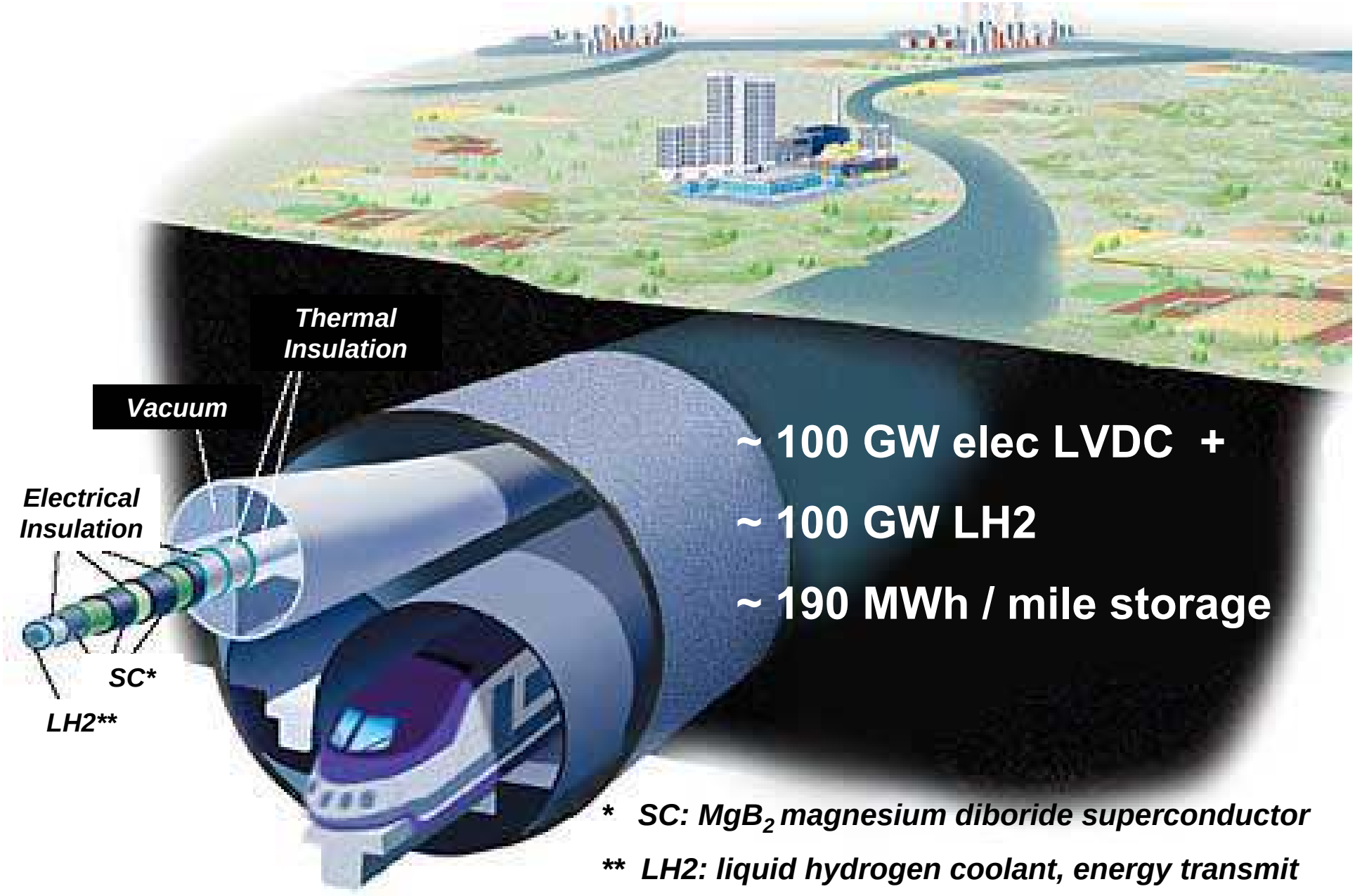
Source: NREL, D. Elliott



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**

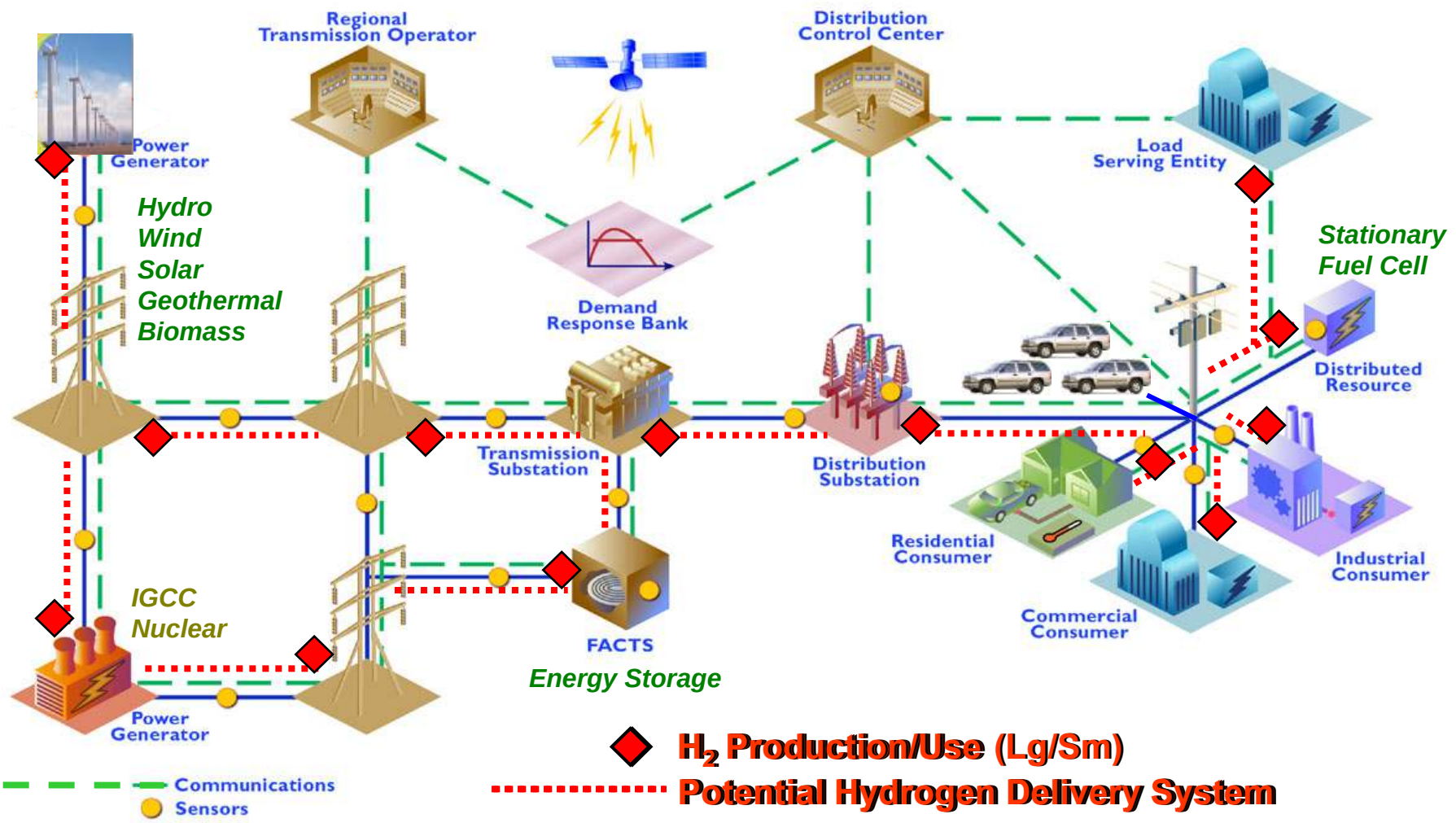


* SC: MgB_2 magnesium diboride superconductor

** LH2: liquid hydrogen coolant, energy transmit

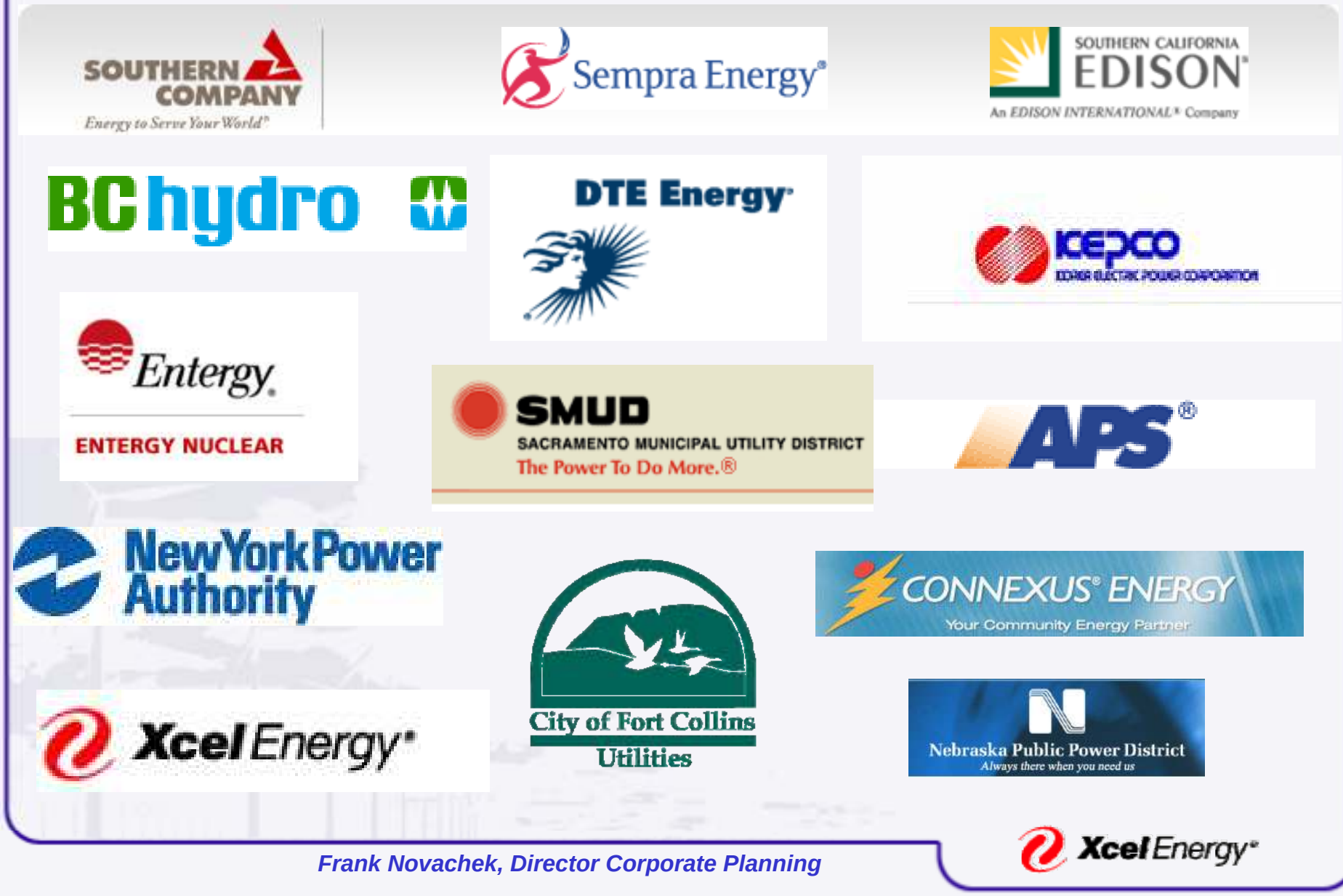
Continental Supergrid – EPRI concept "Energy Pipeline"

Energy System of the Future



Frank Novachek, Director Corporate Planning

Hydrogen Utility Group (HUG)



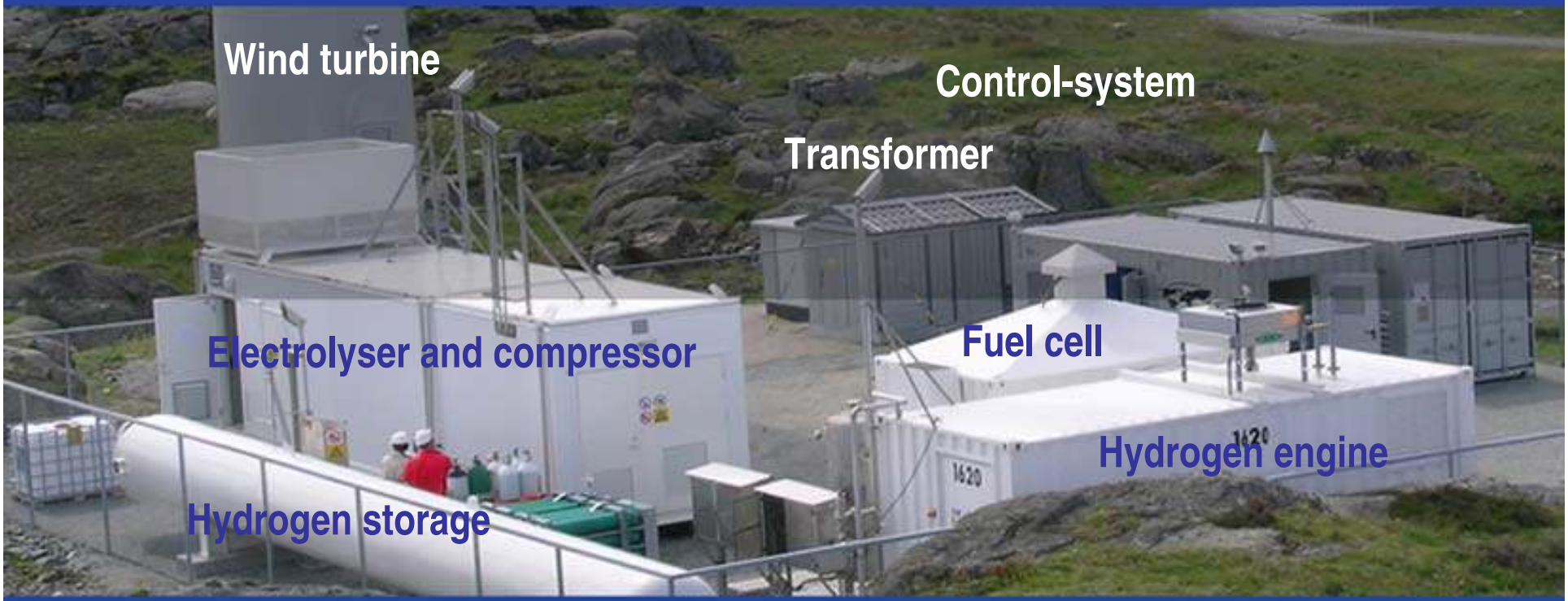
Frank Novachek, Director Corporate Planning

Xcel Energy®

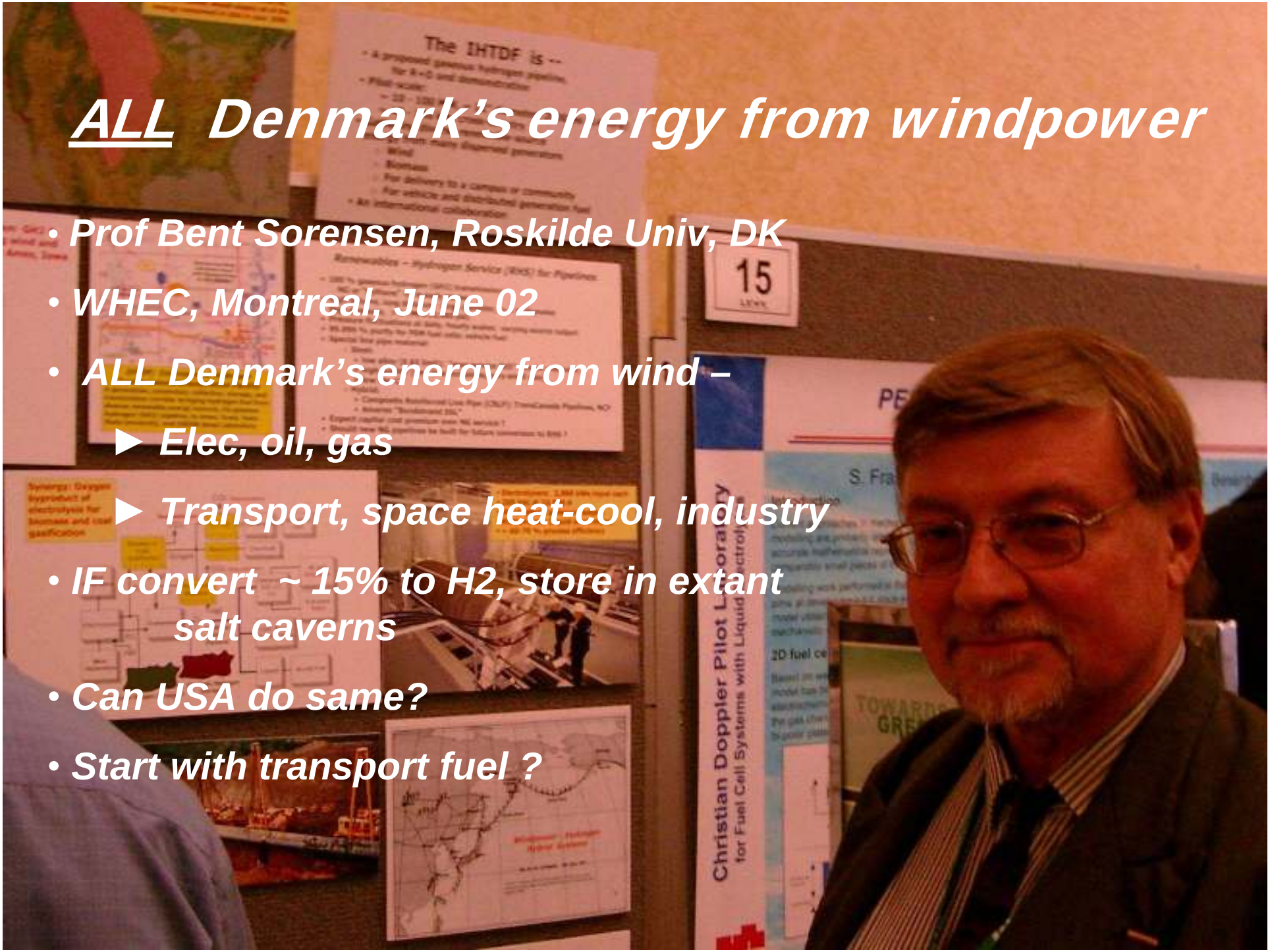
Utsira Island, Norway

The wind – hydrogen plant at Utsira

A vision becoming reality



HYDRO

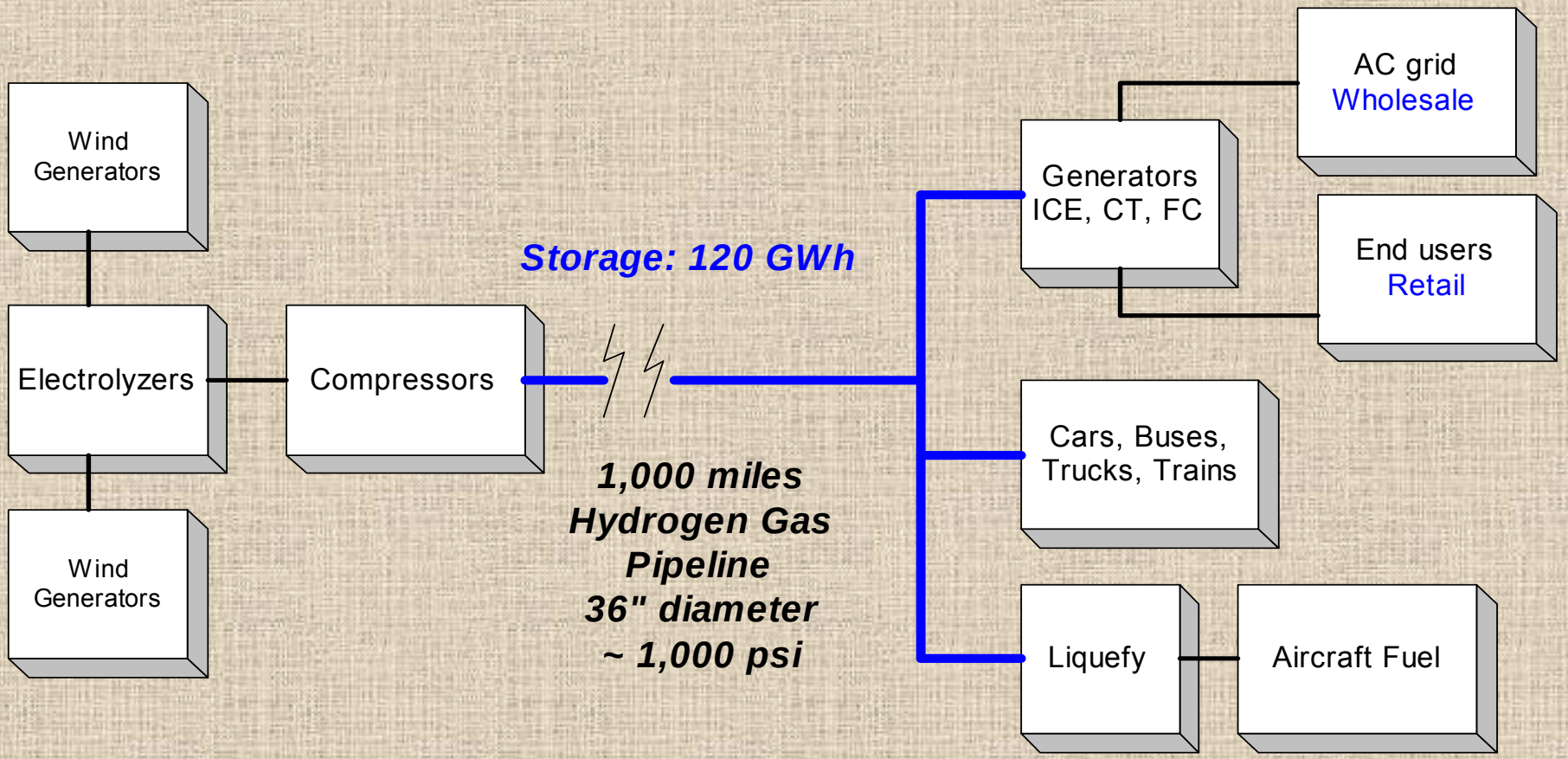


ALL Denmark's energy from windpower

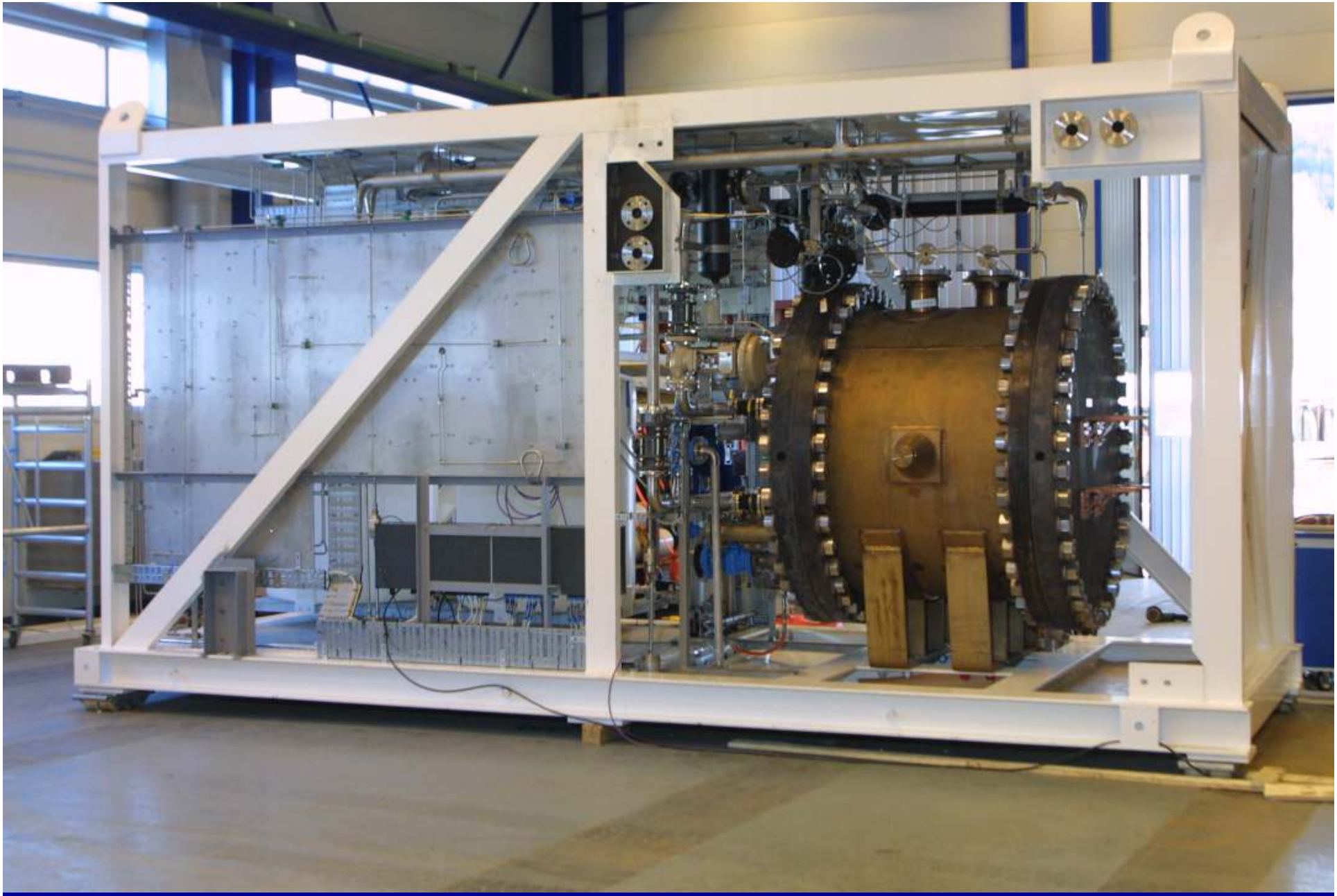
- Prof Bent Sorensen, Roskilde Univ, DK
- WHEC, Montreal, June 02
- ALL Denmark's energy from wind –
  - ► Elec, oil, gas
  - ► Transport, space heat-cool, industry
- IF convert ~ 15% to H2, store in extant salt caverns
- Can USA do same?
- Start with transport fuel ?

Hydrogen Transmission Scenario

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

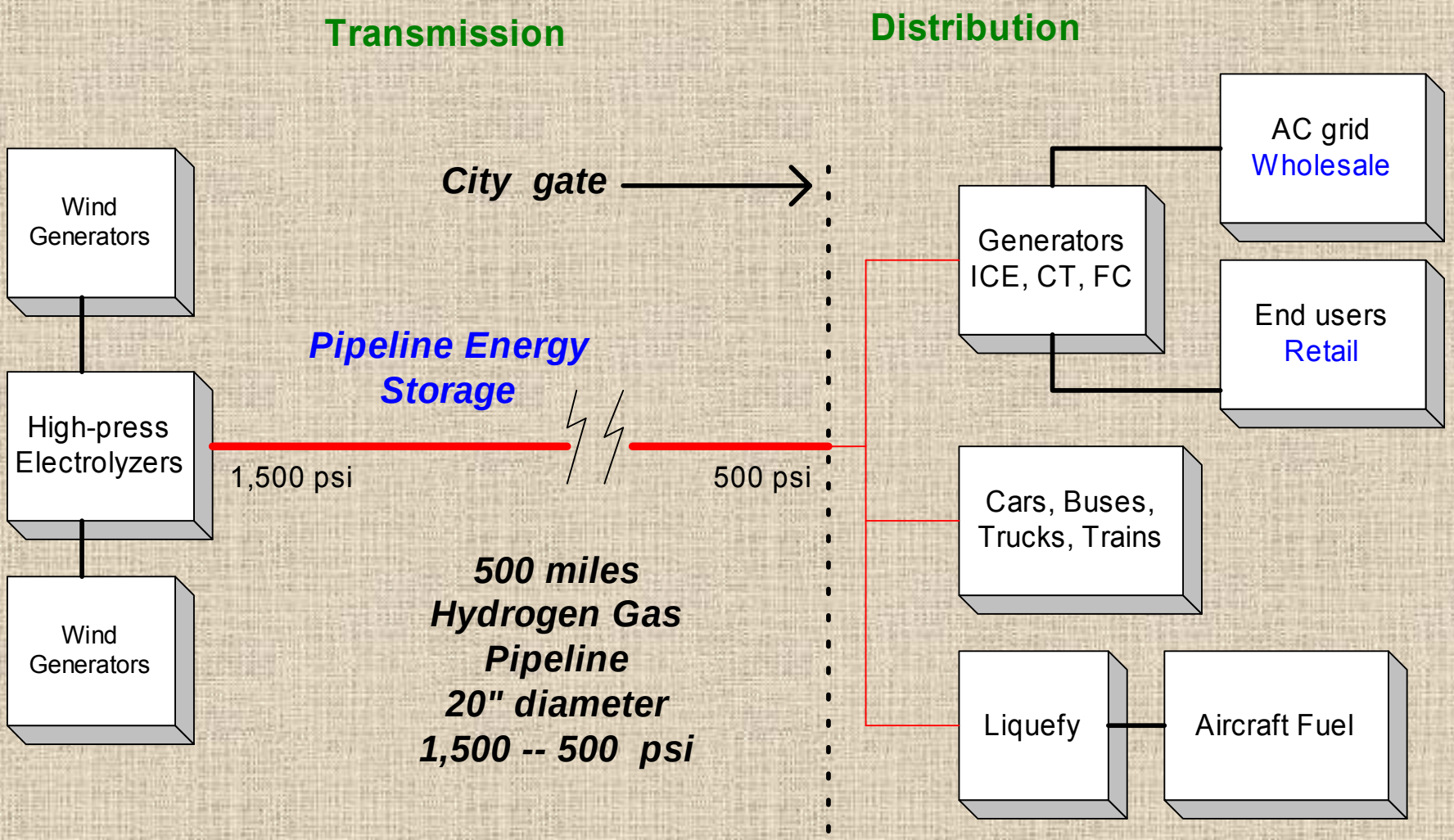


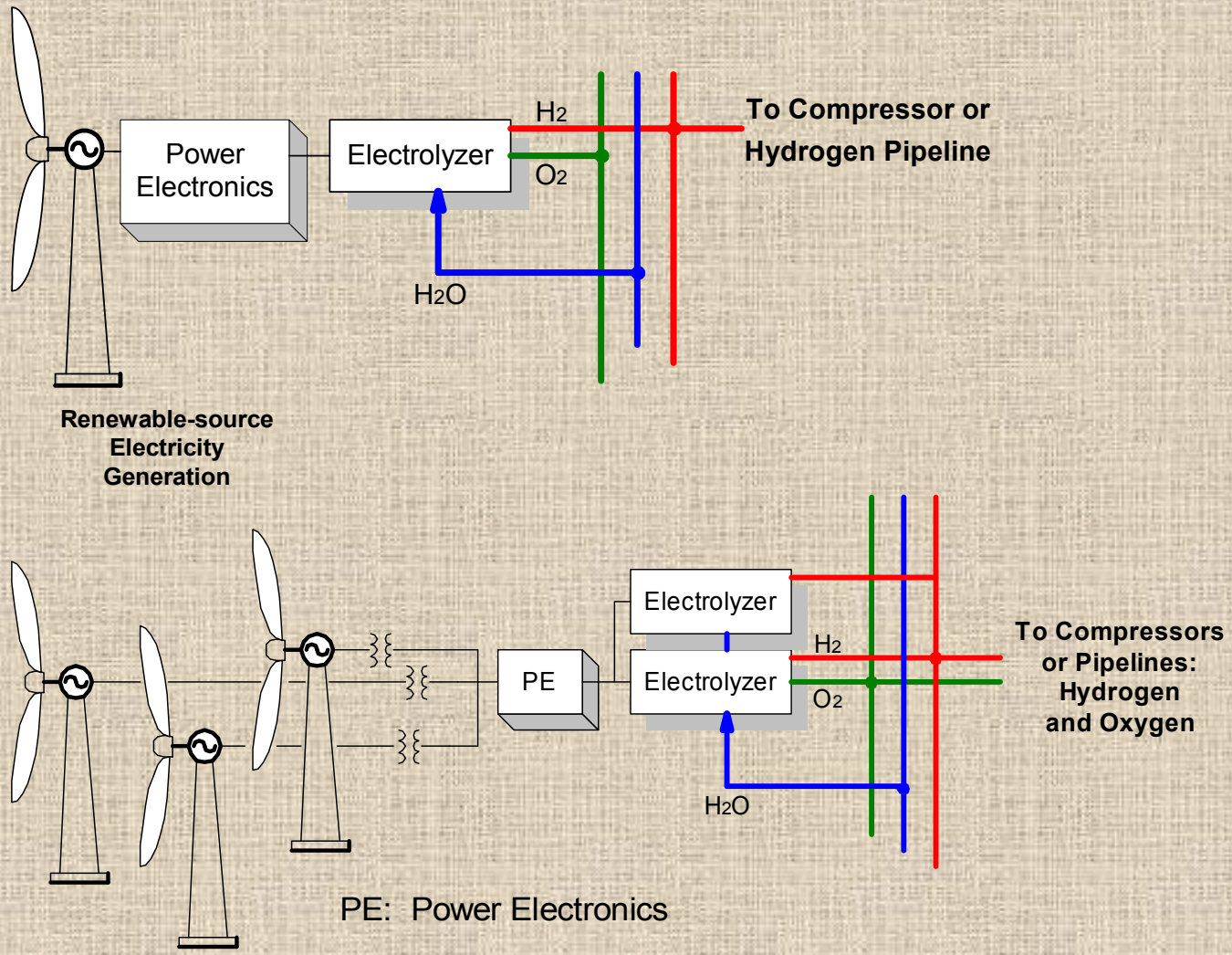

Norsk Hydro
Electrolyzers
2 MW each



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

Compressorless system: No geologic storage

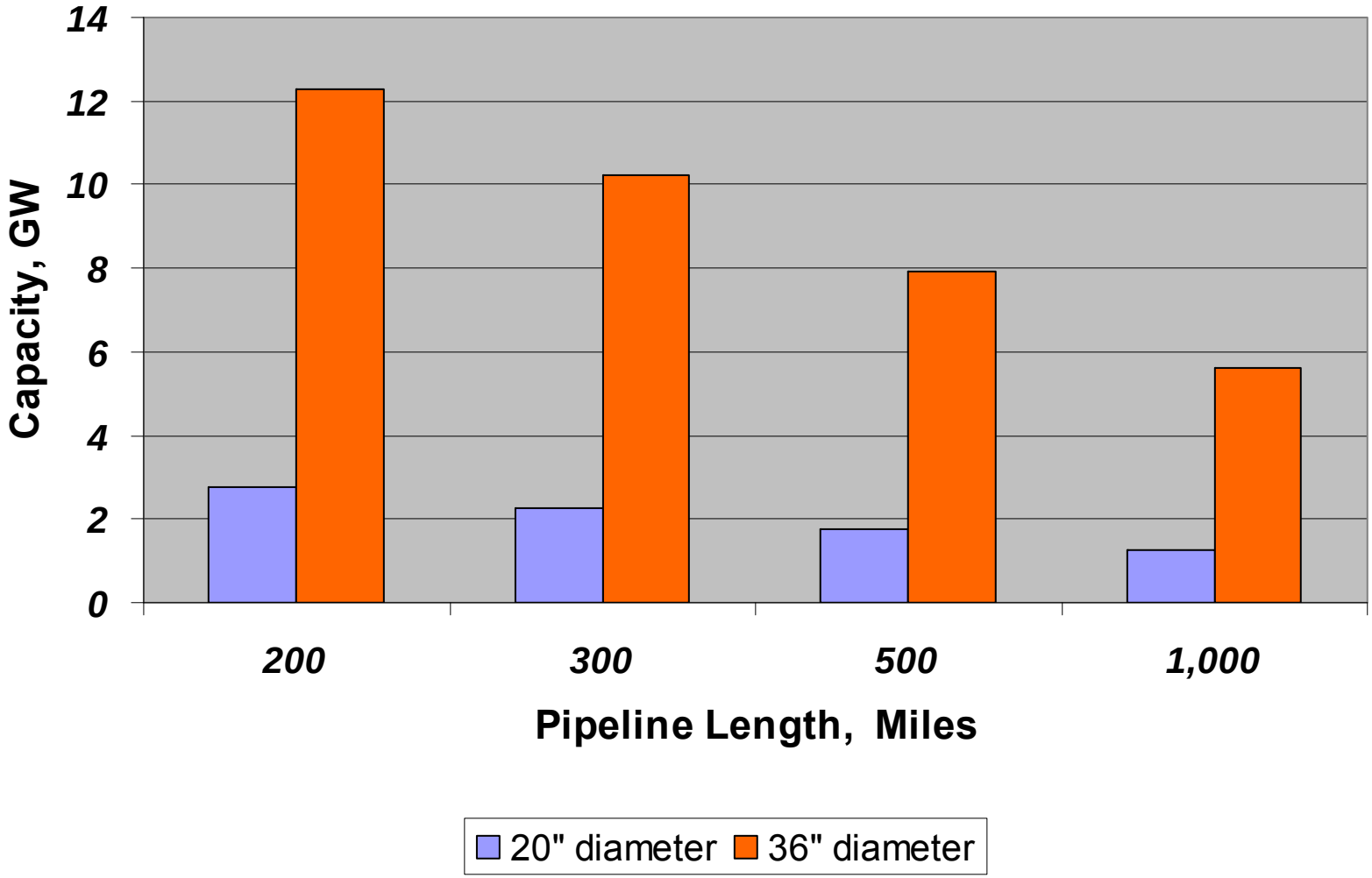




Topology Options: H_2 and O_2 Production and Gathering from Renewable Energy Generation

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

Capital Cost per GW-mile

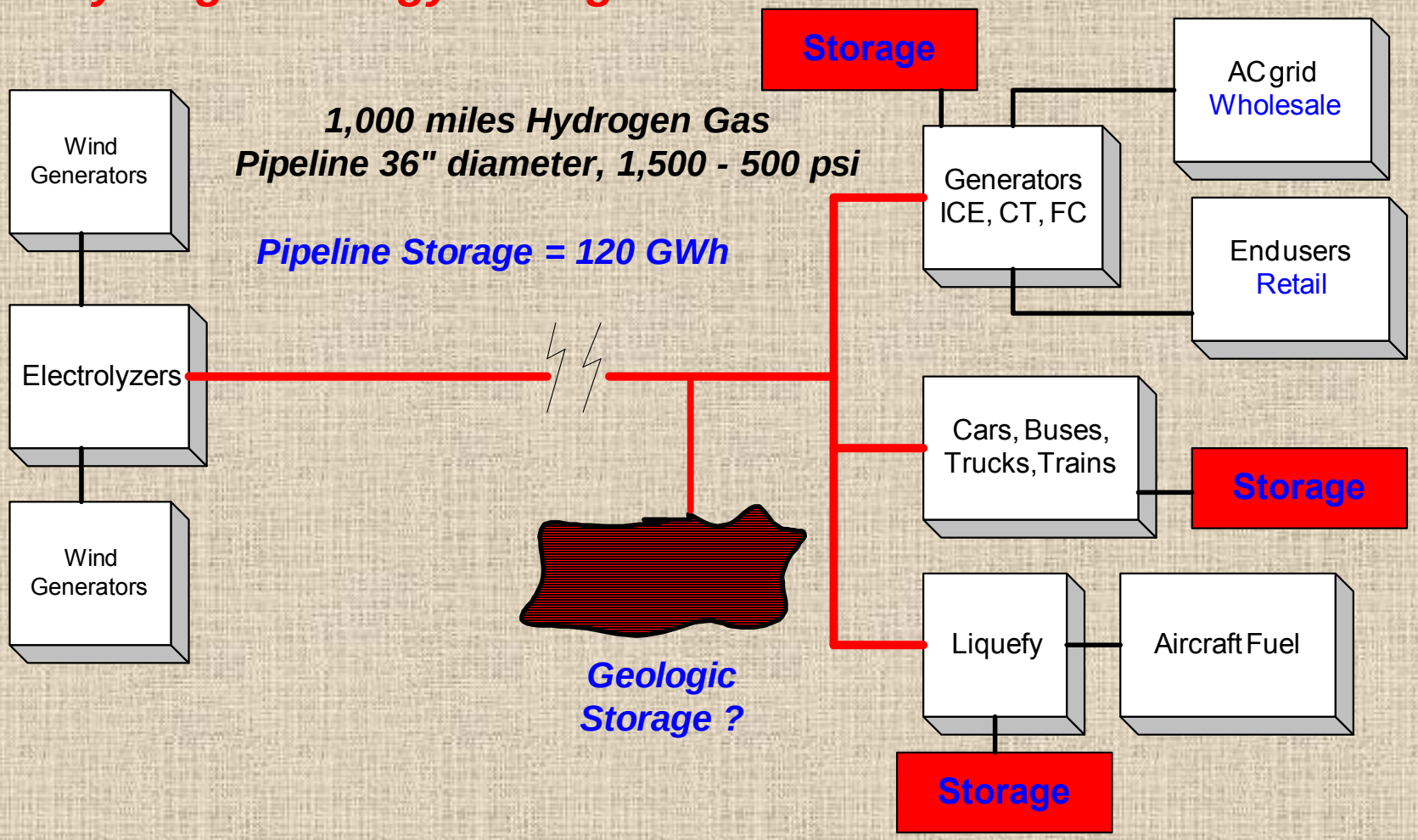
Electricity :	KV	Capacity MW	$M / GW-mile
• SEIA:	765	5,000	1.3
	345	1,000	2.6
• AEP-AWEA	765	5,000	3.2
Consensus ?			2.5

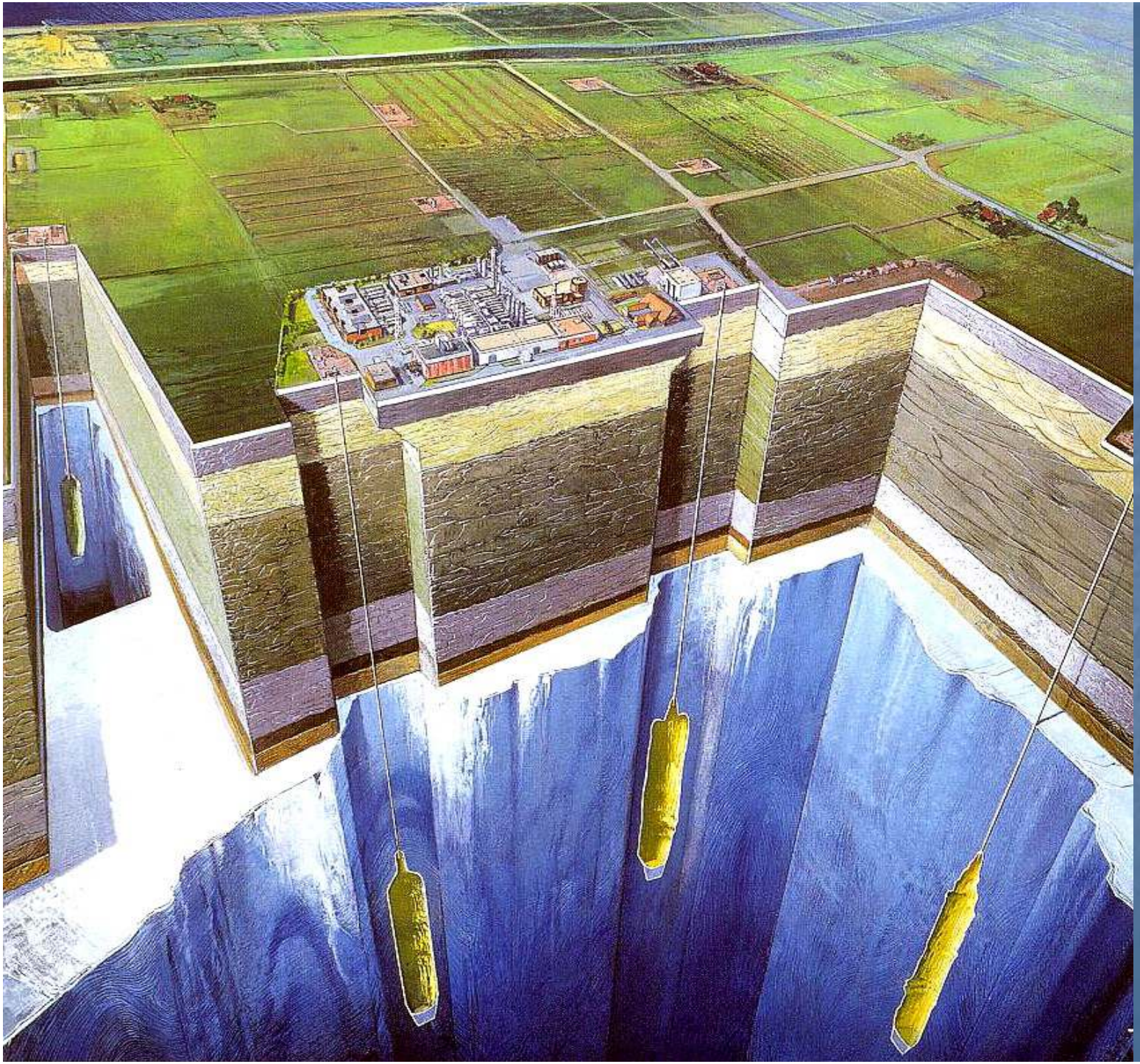
Hydrogen pipeline:

36”, 100 bar, 500 mi, no compress 0.3

(100 bar = 1,500 psi)

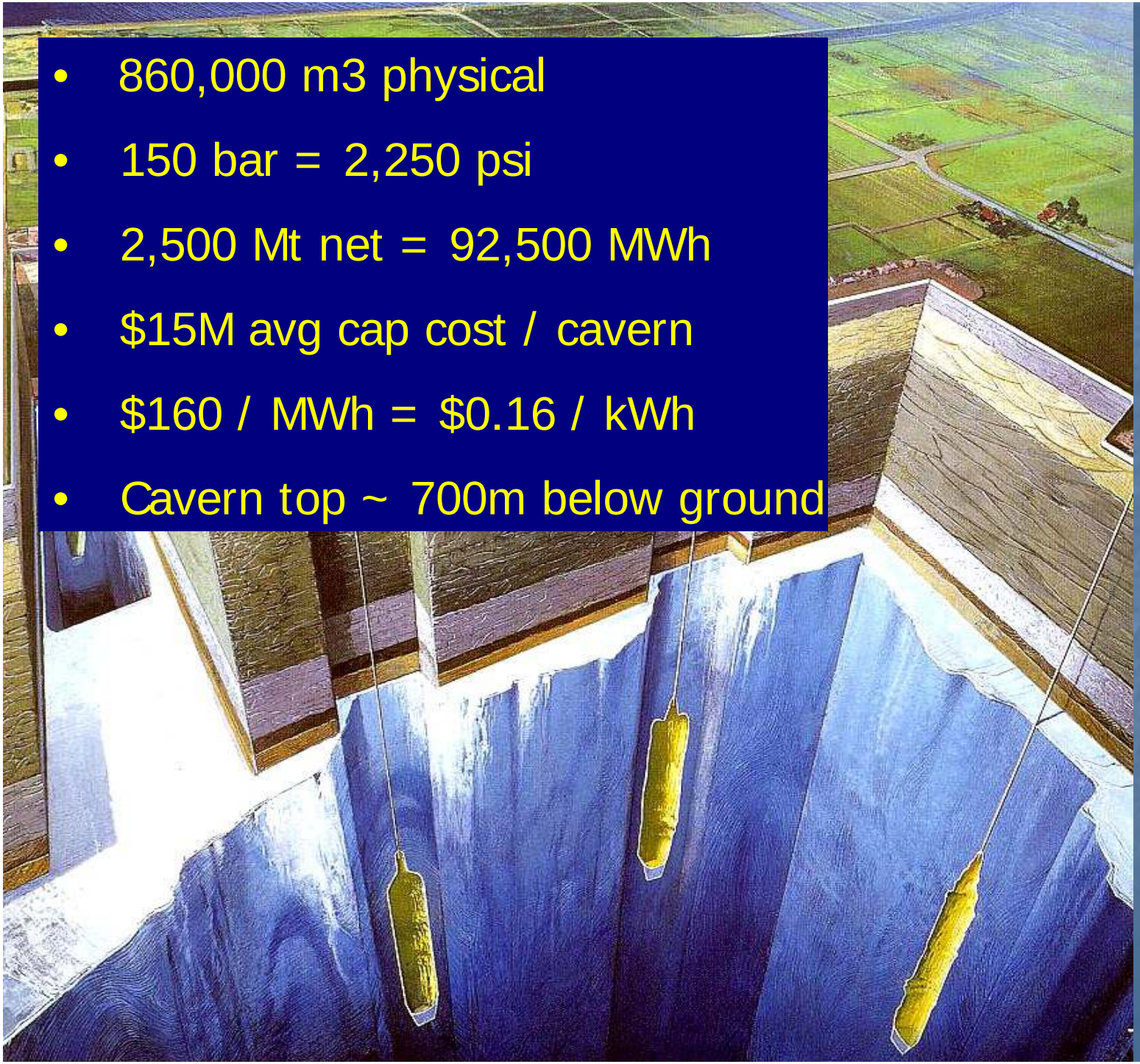
Hydrogen Energy Storage





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 = $0.16 / kWh
- Cavern top ~ 700m below ground

Domal Salt Storage Caverns

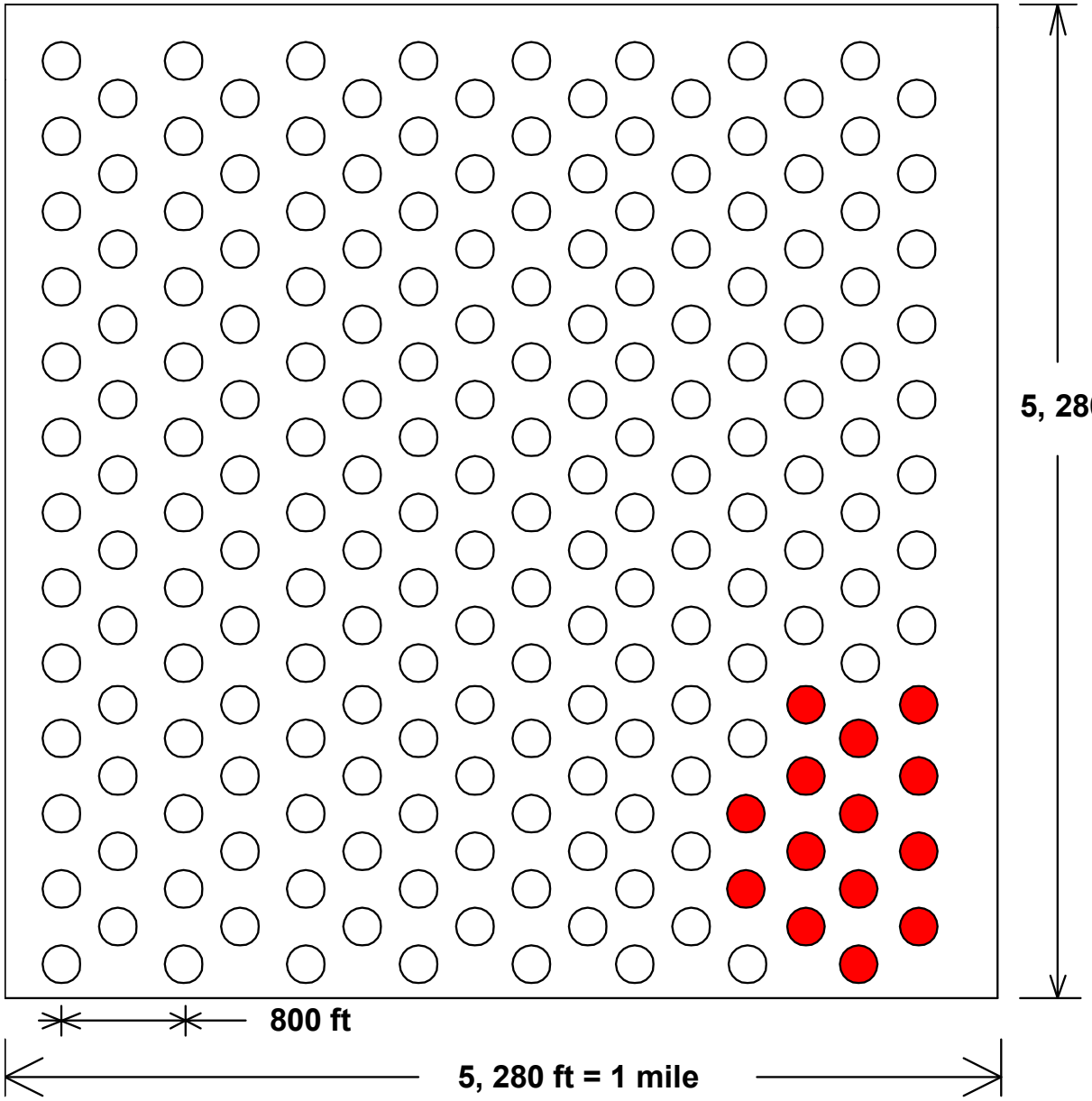
Texas

“Clemens Terminal” Conoco Phillips 20 years

Praxair ‘07

PB ESS

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

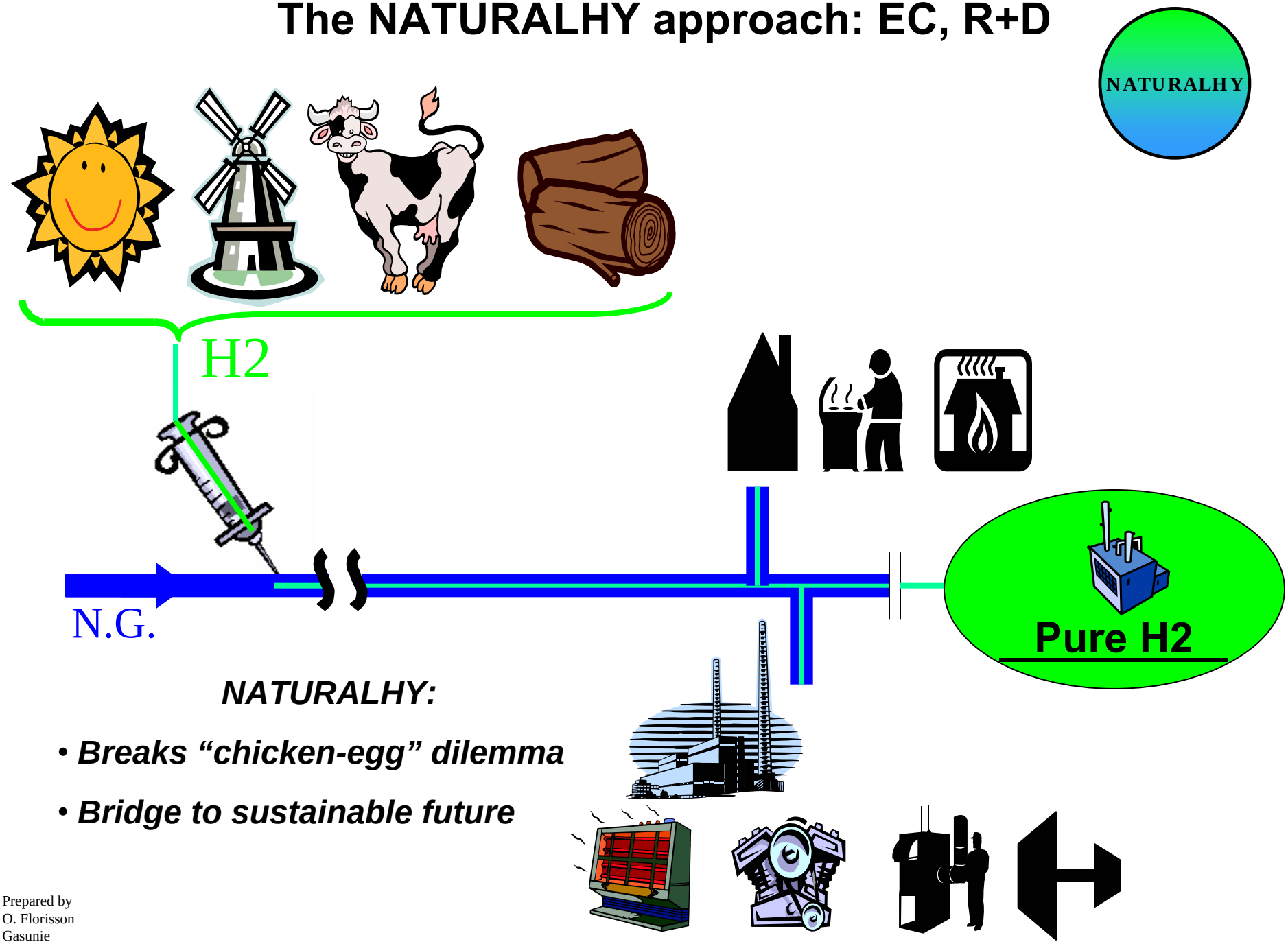
Windplant size **1,000 MW**

	[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

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 ?

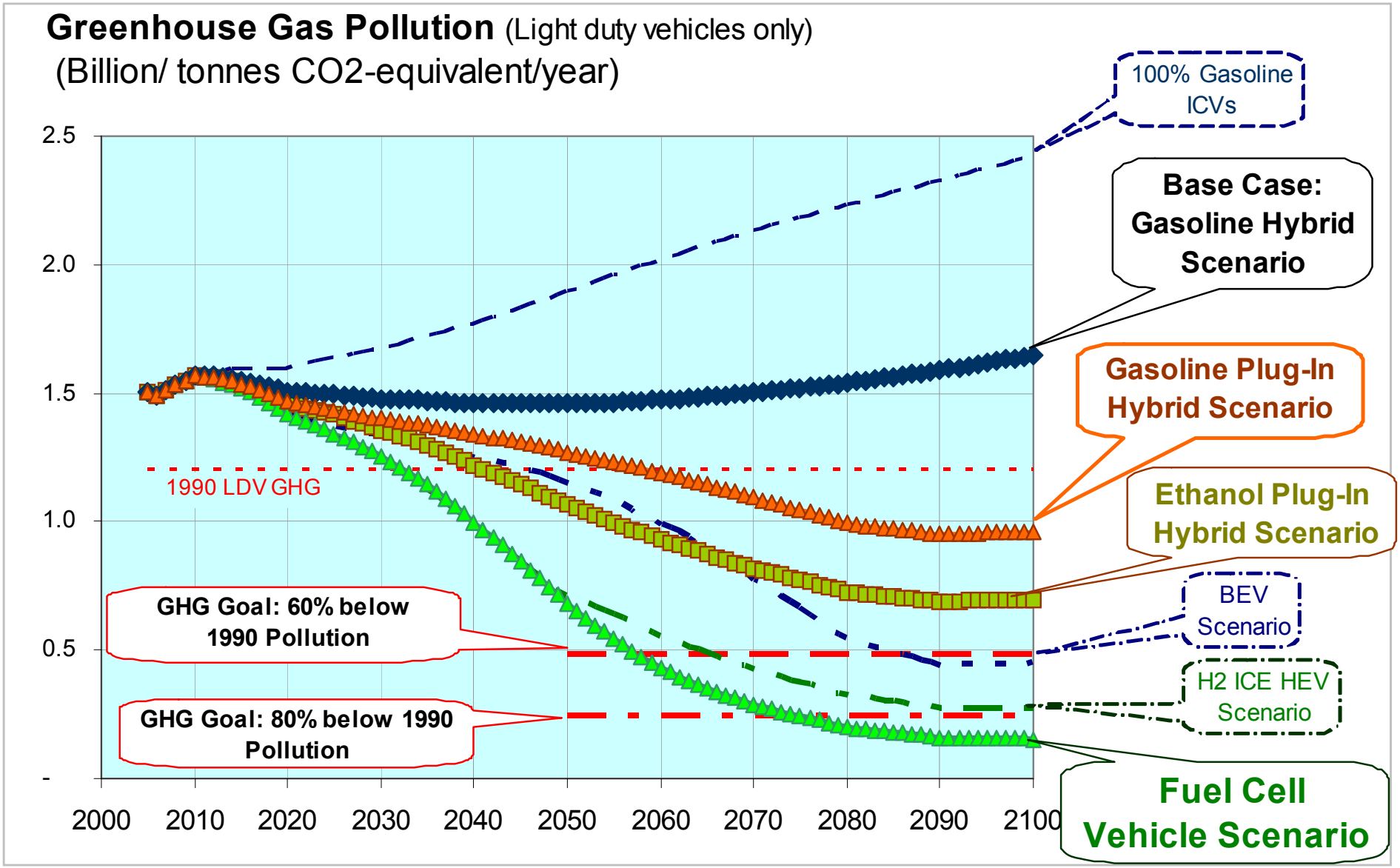
- **9 Sept 09** "Letter of Understanding"
- Carmakers:

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


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

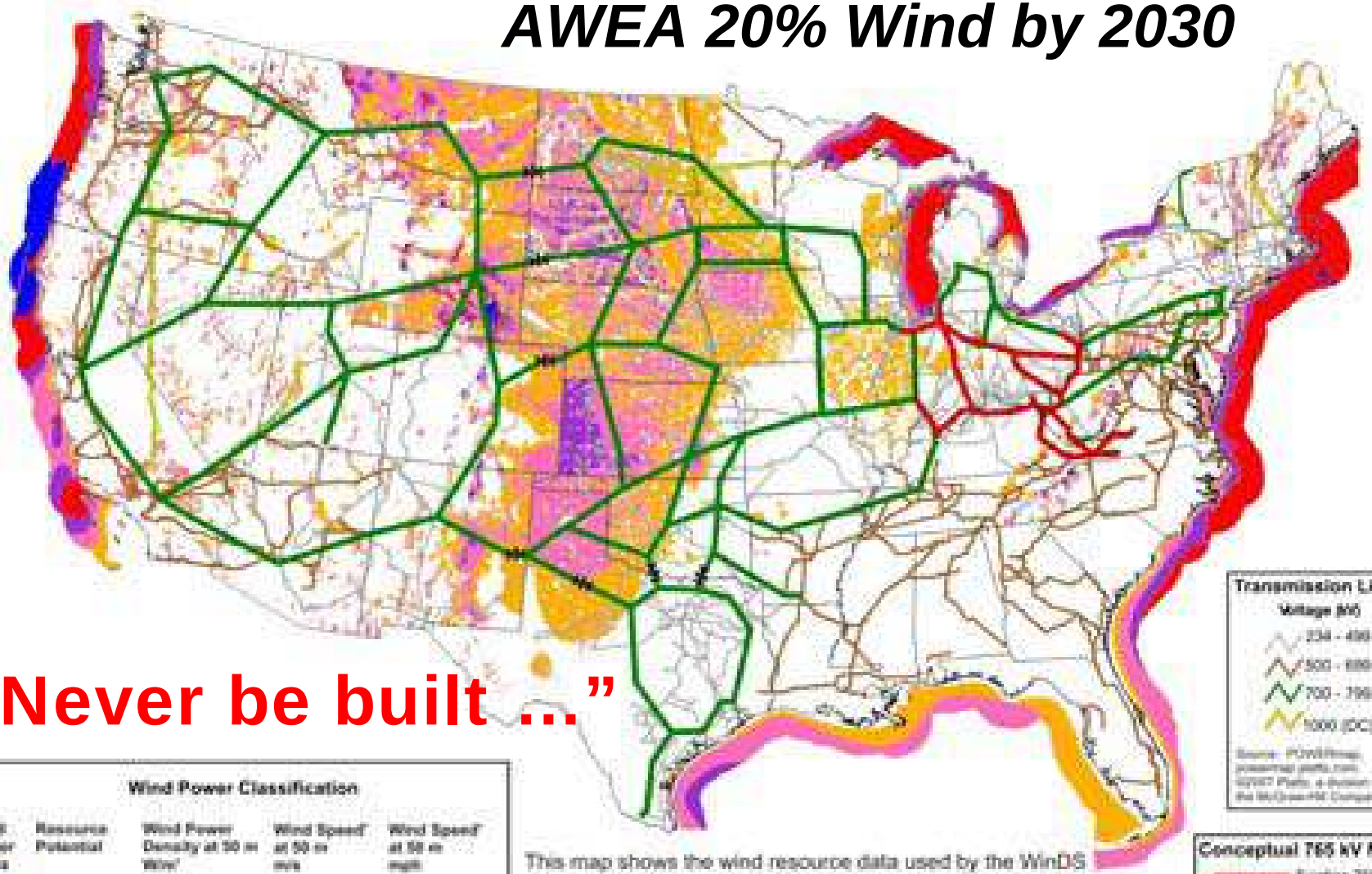
CA: 20% of "cars" hydrogen fueled by 2030

- **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 …"

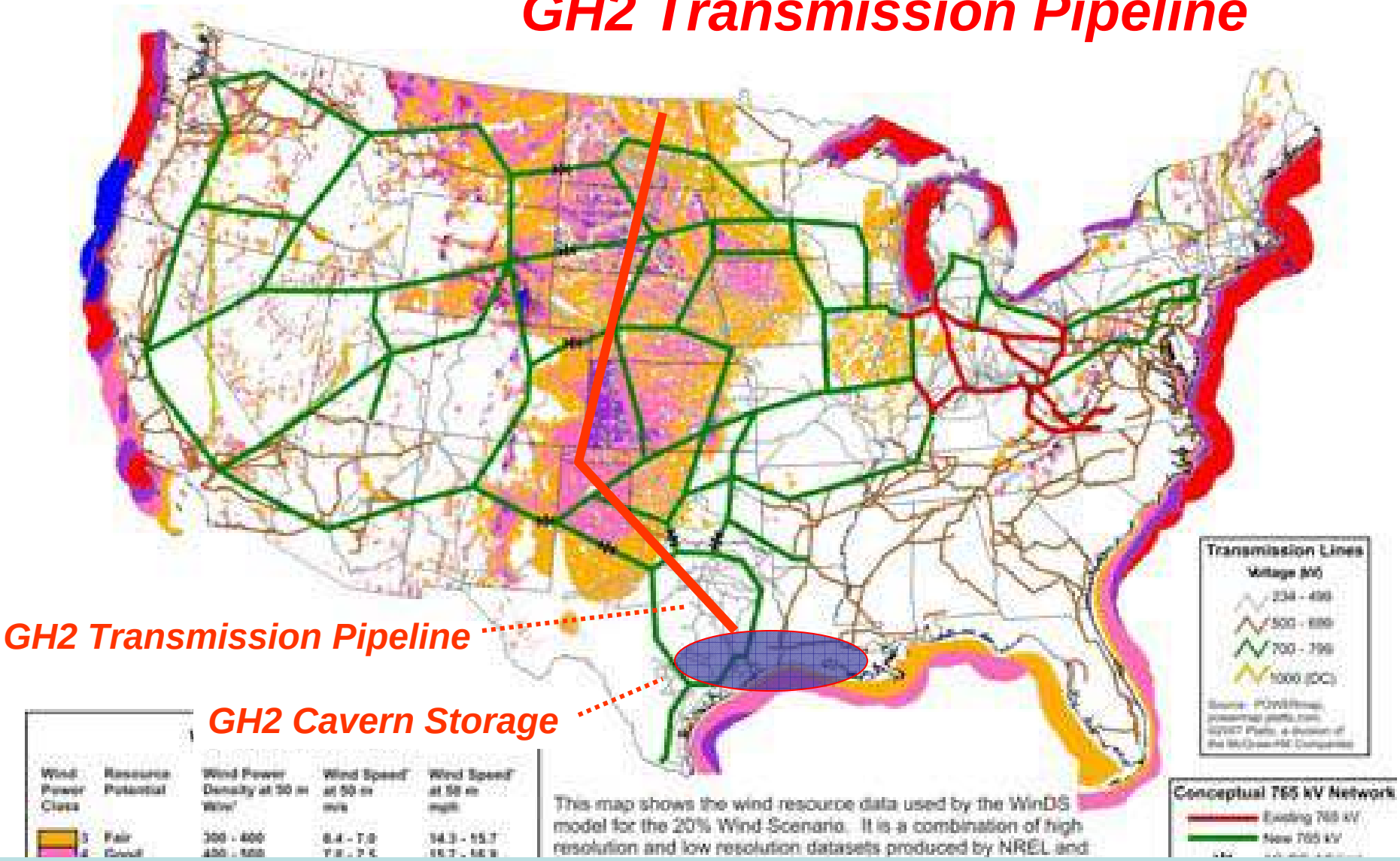
Wind Power Classification

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

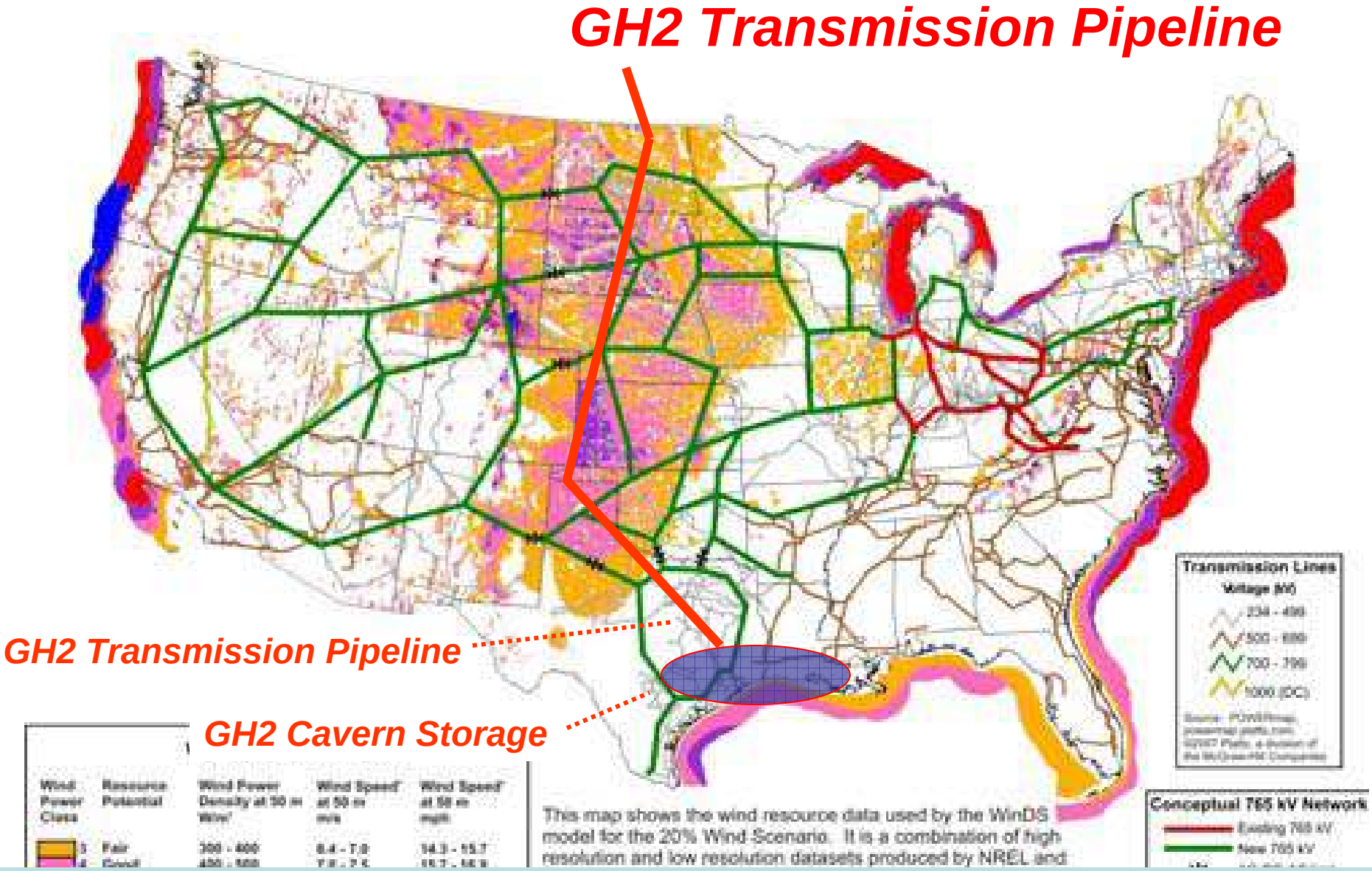
This map shows the wind resource data used by the WinDS model for the 20% Wind Scenario. It is a combination of high resolution and low resolution datasets produced by NREL and other organizations. The data was screened to eliminate areas unlikely to be developed onshore due to land use or environmental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

GH2 Transmission Pipeline



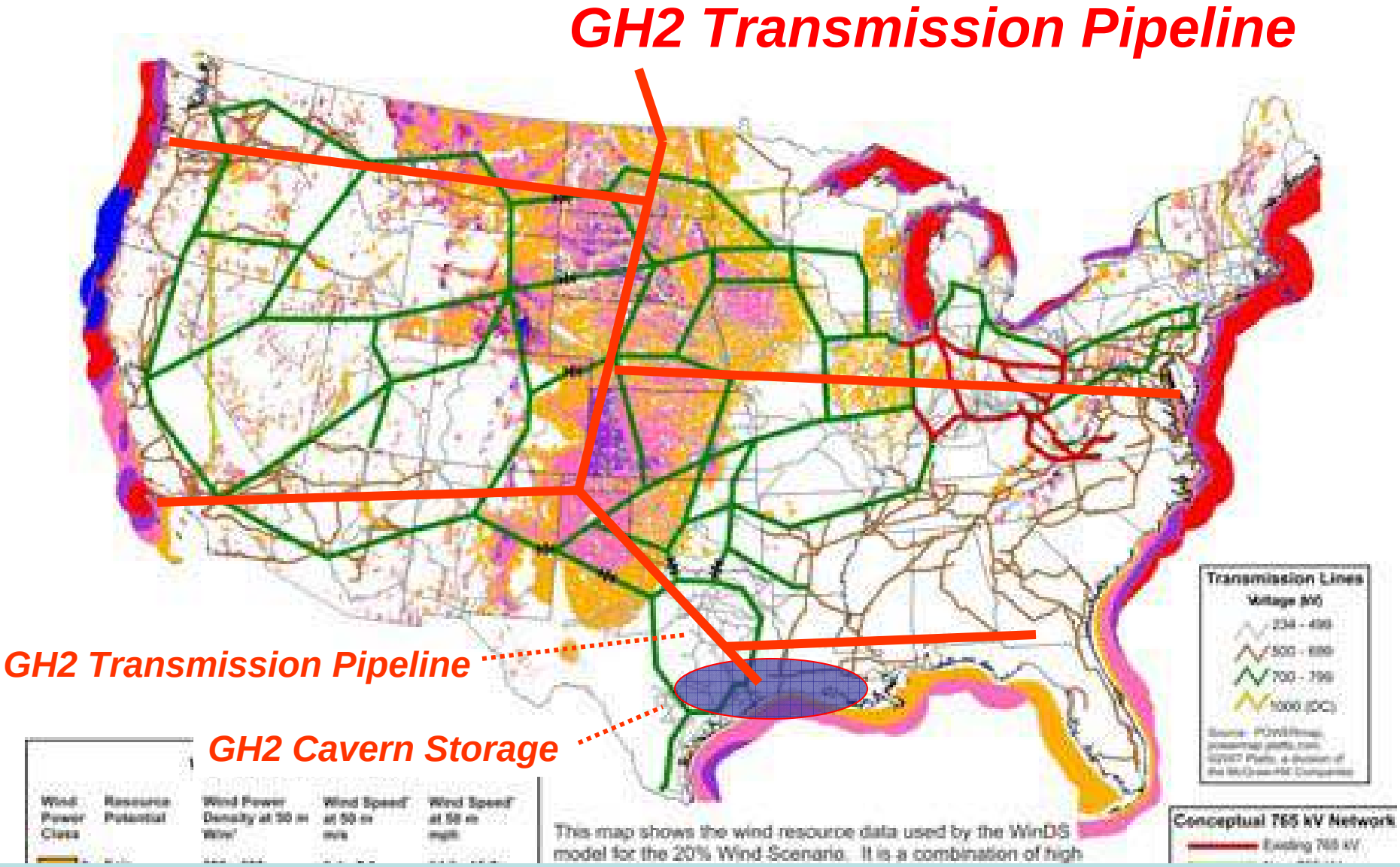
Wind Potential ~= 3,000 GW

12 Great Plains states



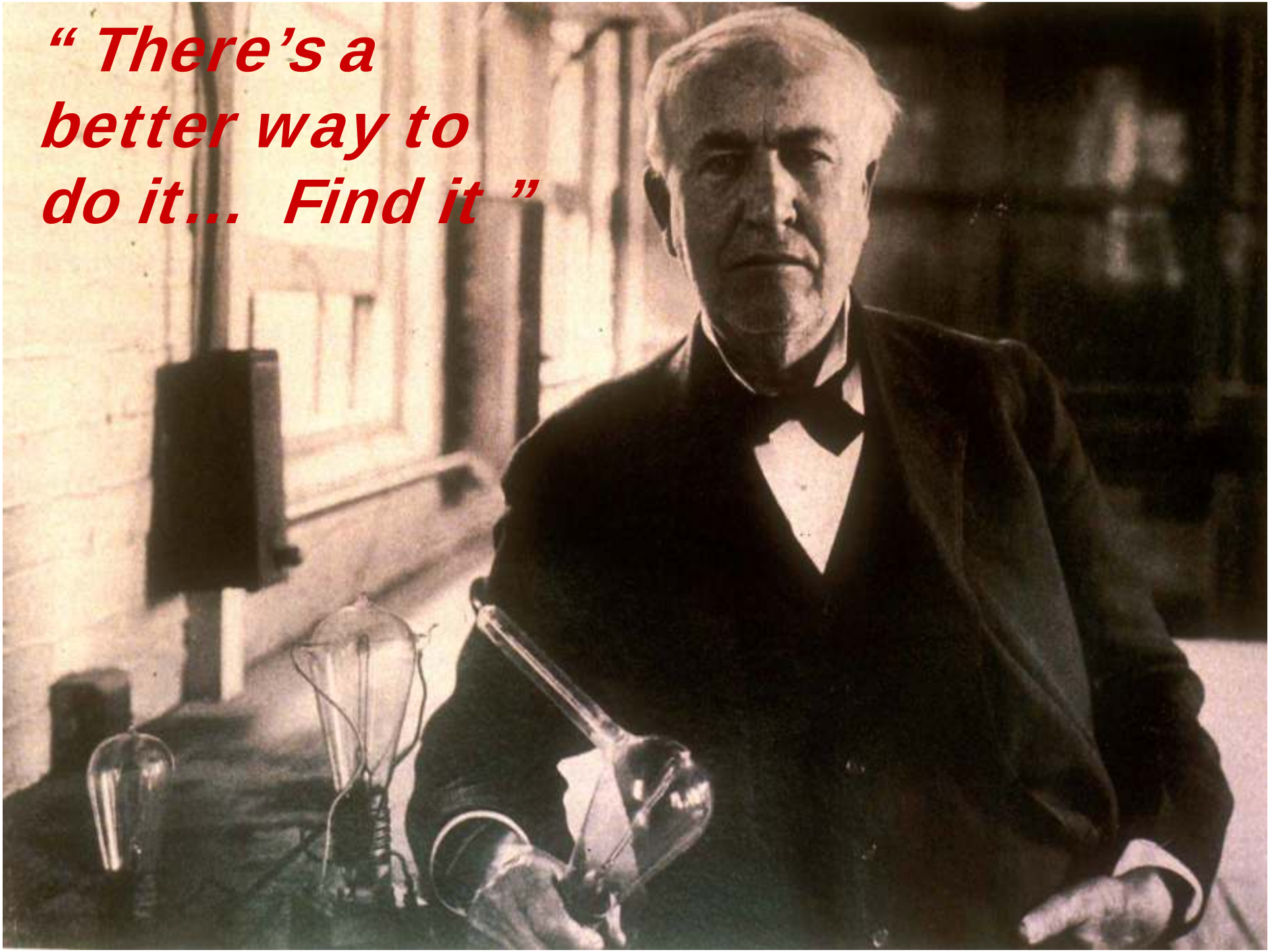
Wind Potential ~= 3,000 GW

12 Great Plains states



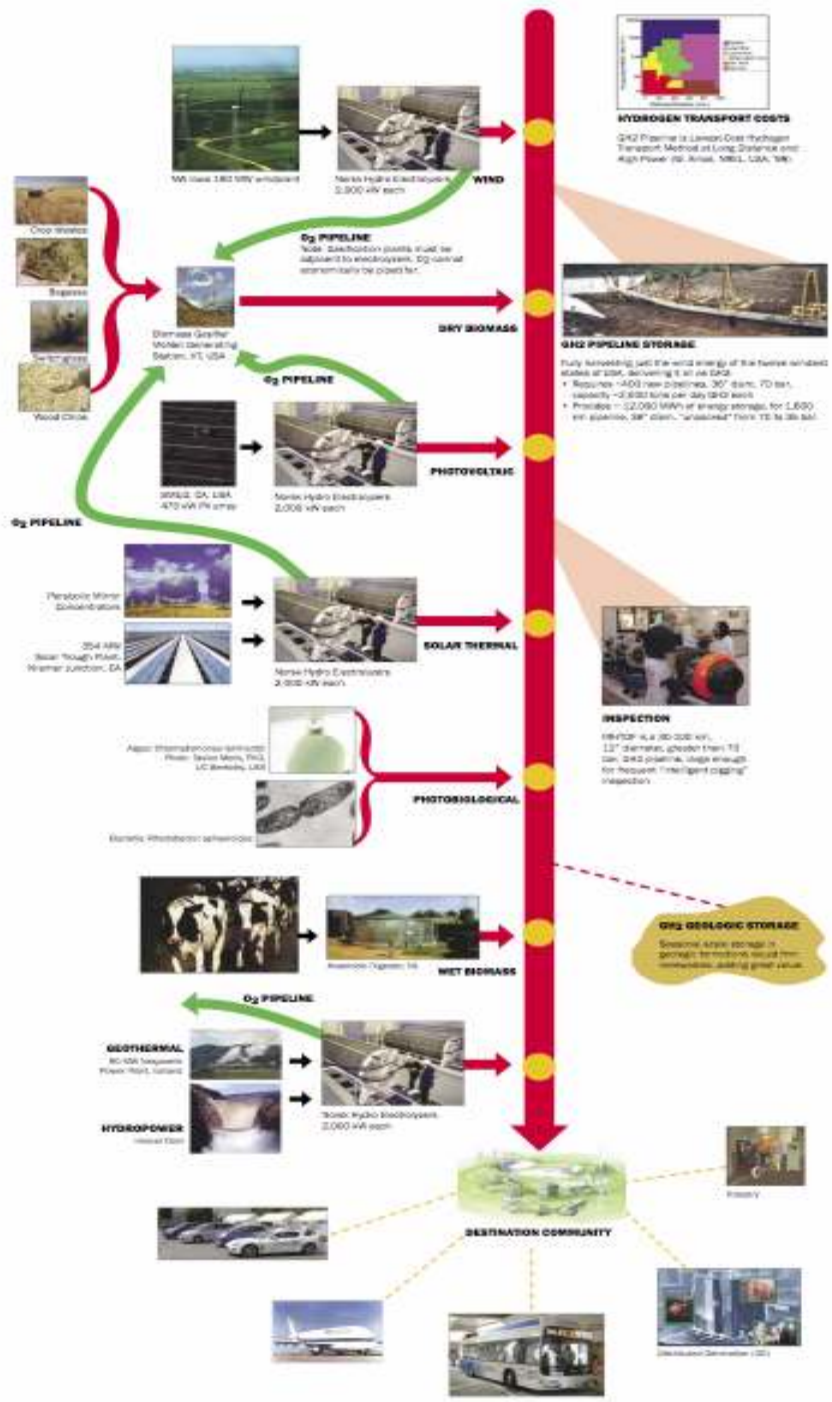
Wind Potential ~= 3,000 GW

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**
- **US, Japan, Canada, IPHE → " IRHTDF "**

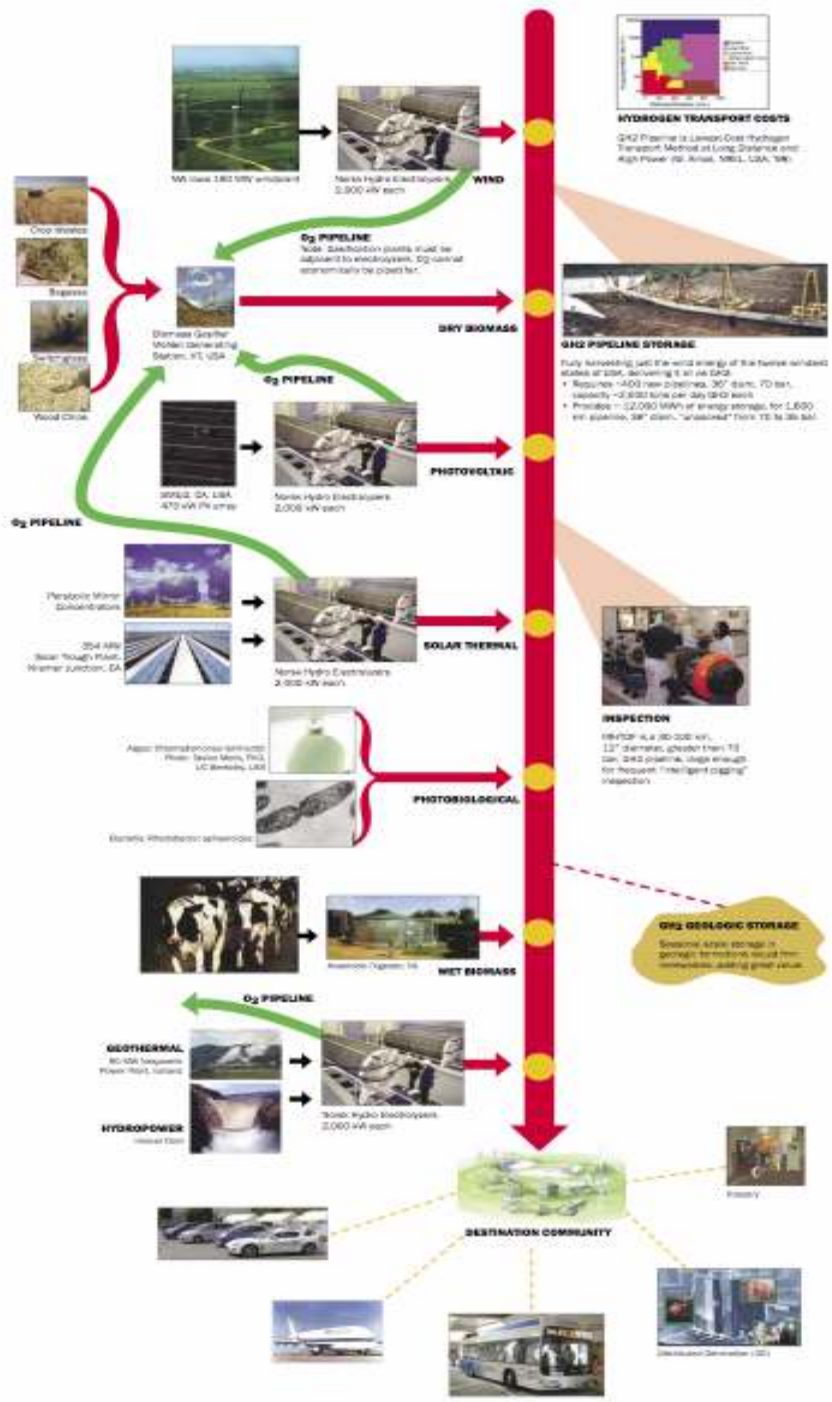


International Renewable Hydrogen Transmission Demonstration Facility

(IRHTDF)

Pilot plant

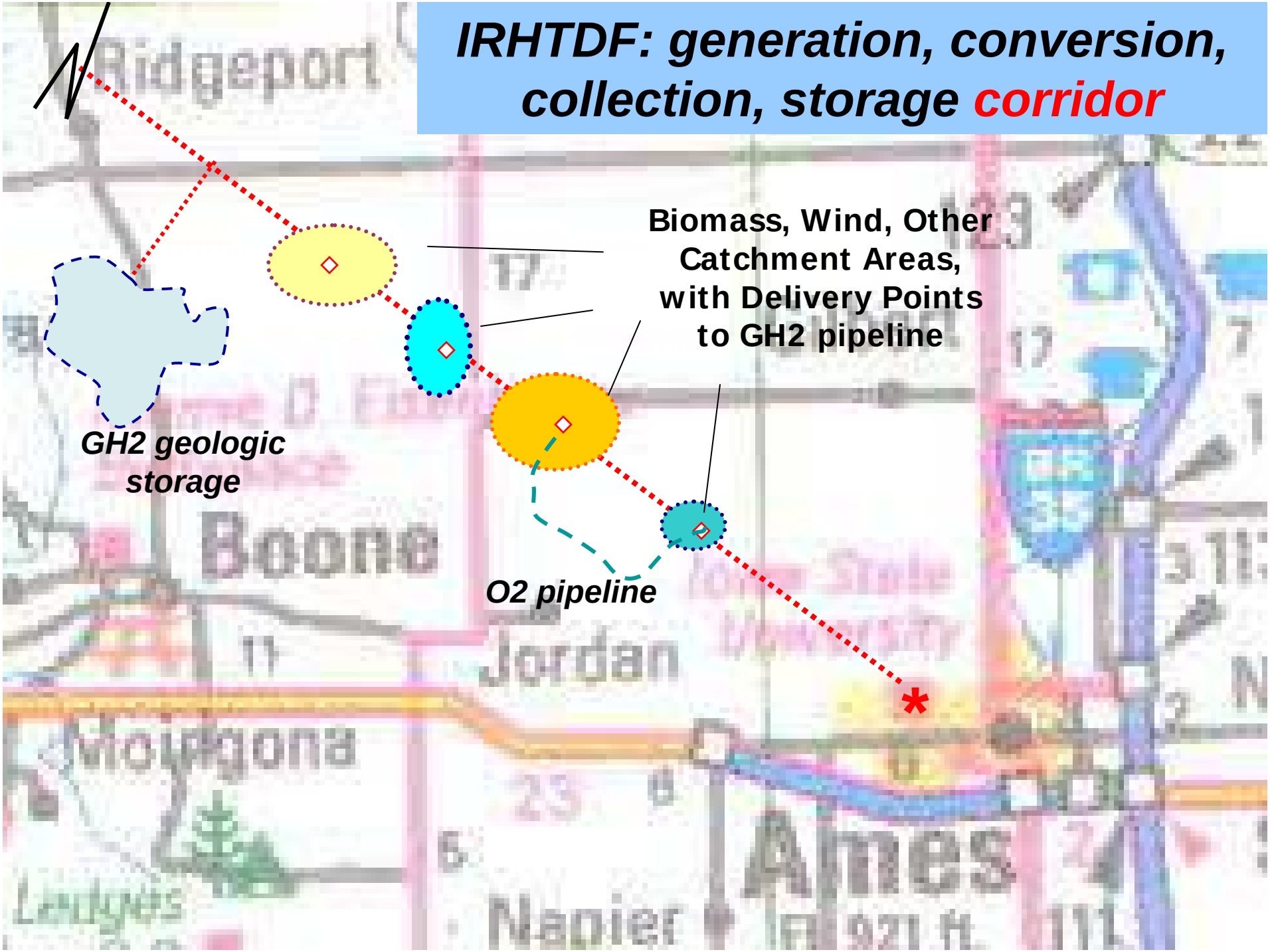
Global opportunity: IPHE project



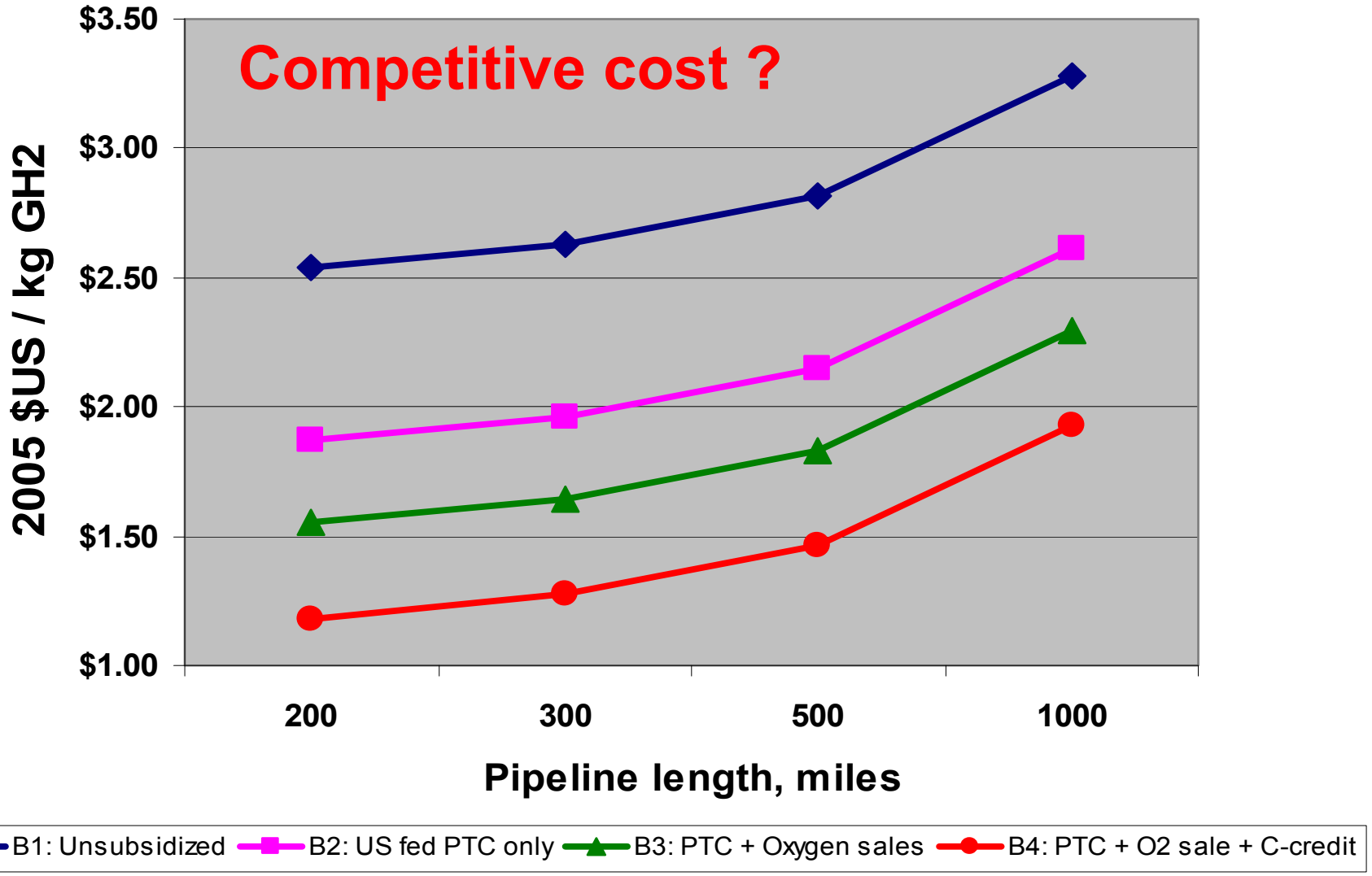
Pilot-scale Hydrogen Pipeline System: Renewables

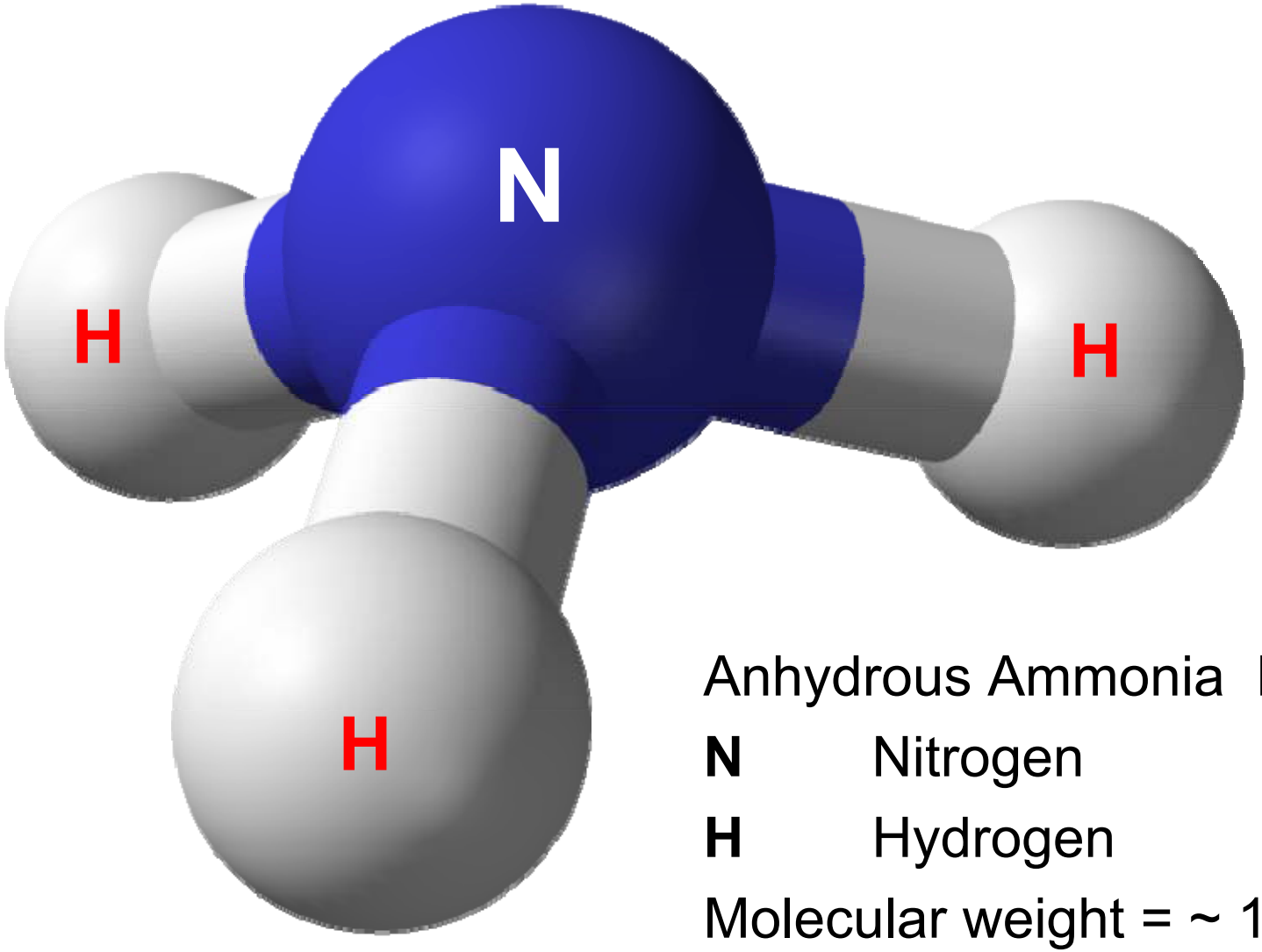
- *Diverse*
- *Dispersed, diffuse*
- *Large-scale*
- *Stranded*
  - *Remote*
  - *No transmission*

IRHTDF: generation, conversion, collection, storage corridor



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





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 and 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

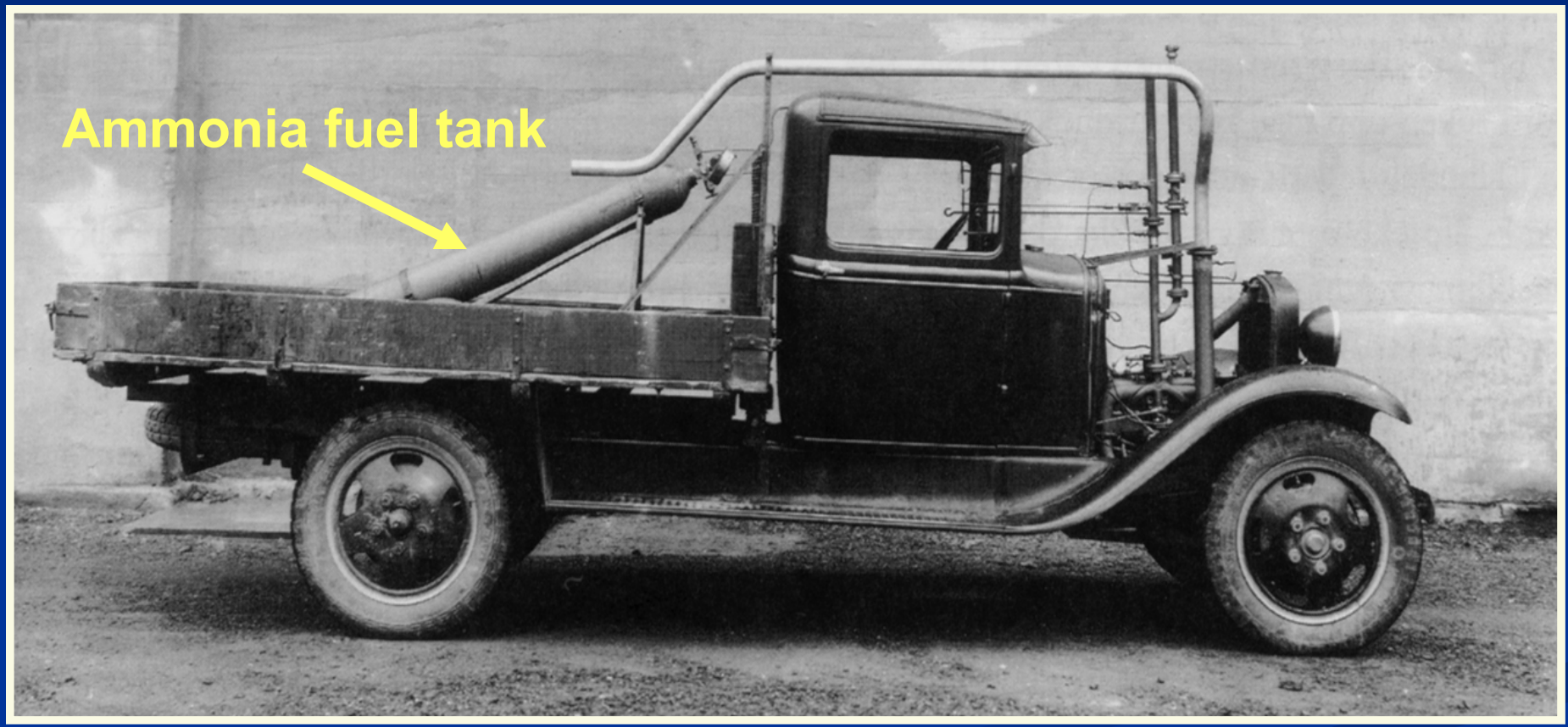
Streetcar

New Orleans

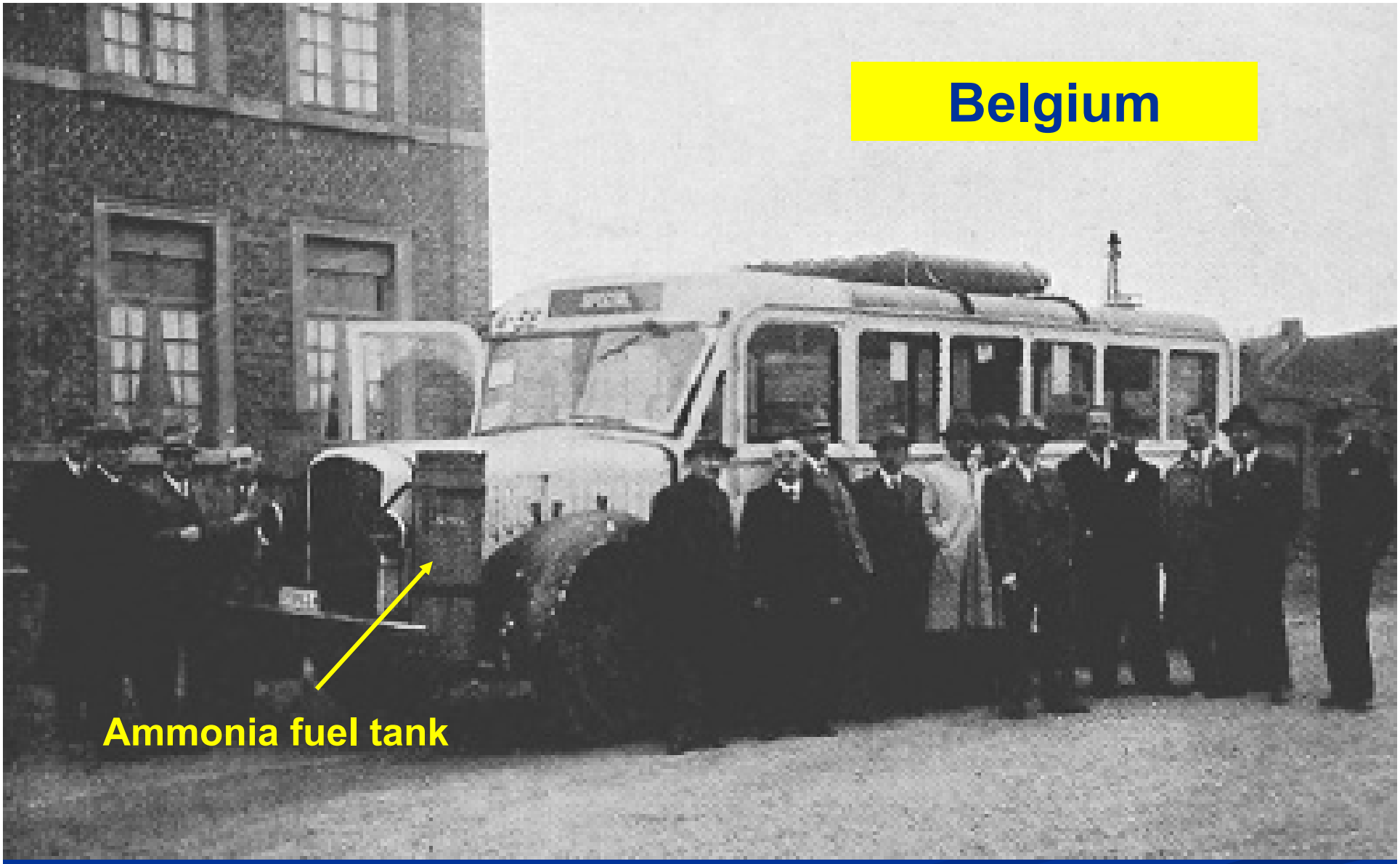
“Ammoniacal Gas Engine”

1871

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

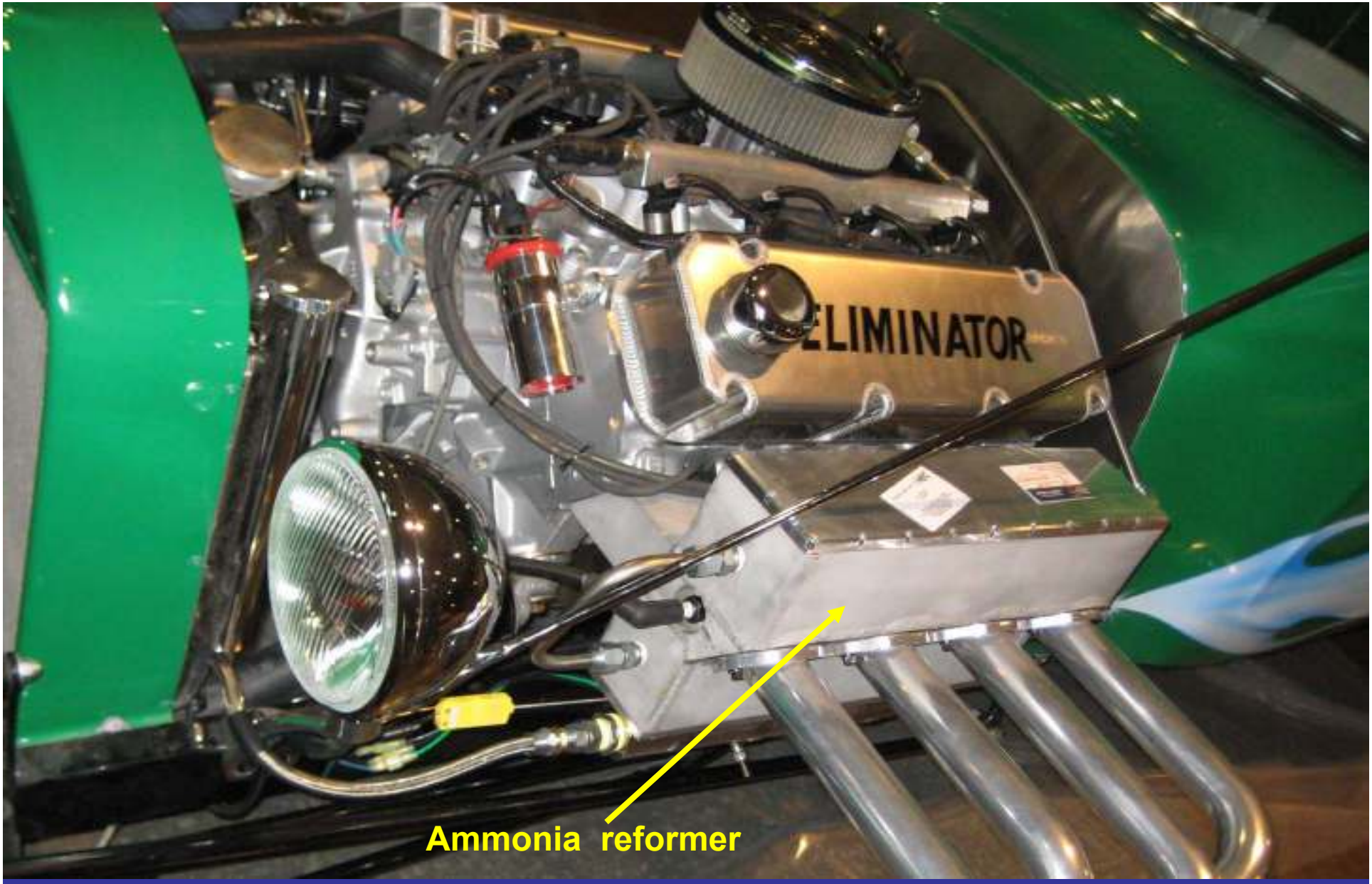
Ammonia + Gasoline Powered

- Idle: gasoline
- Full power: 80% ammonia

Summer ’07 Detroit → San Francisco

2007

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



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

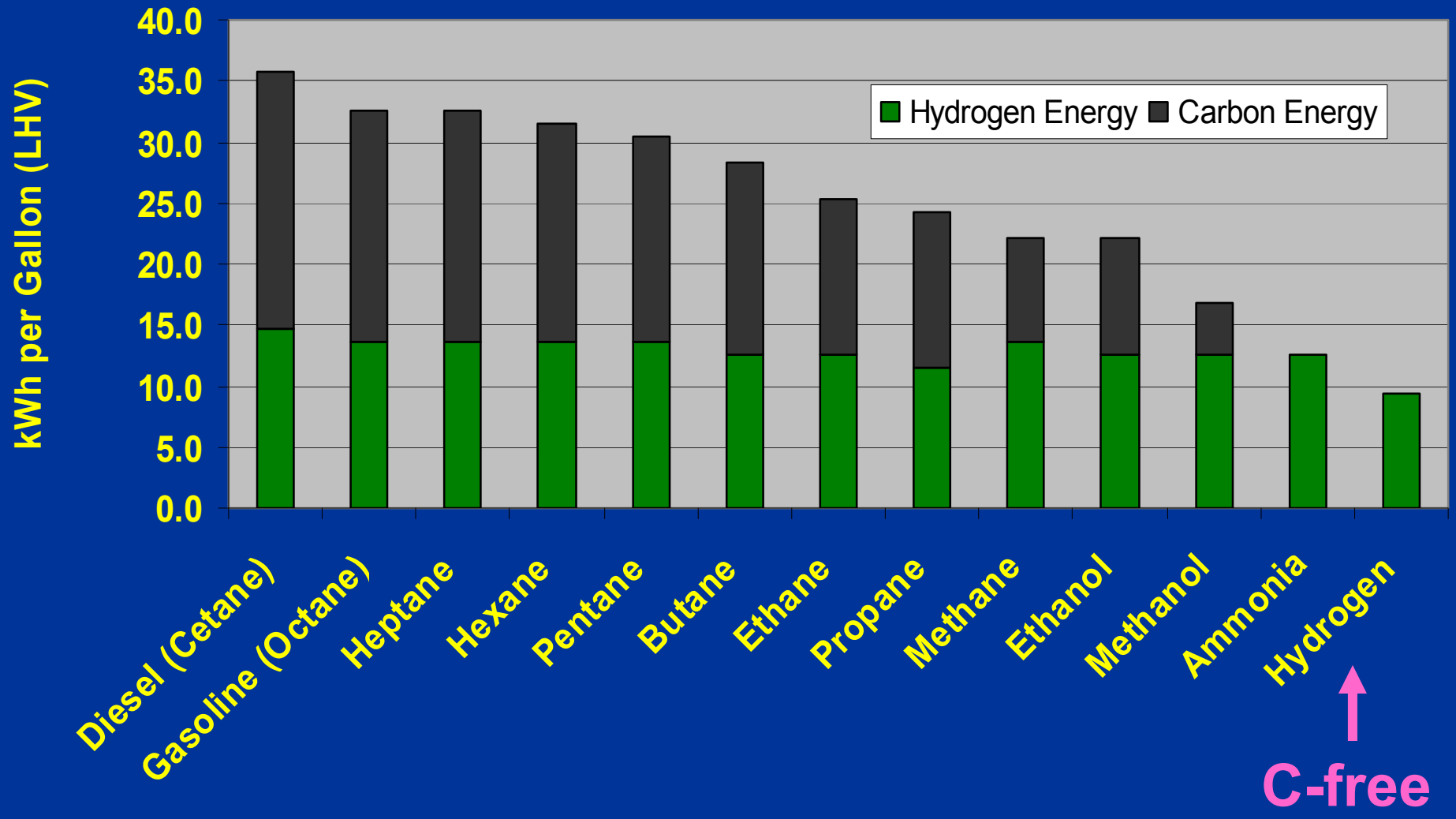
Hydrogen Engine Center, Algona, IA

2009

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: $2NH_3 \rightarrow 3H_2 + N_2$

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



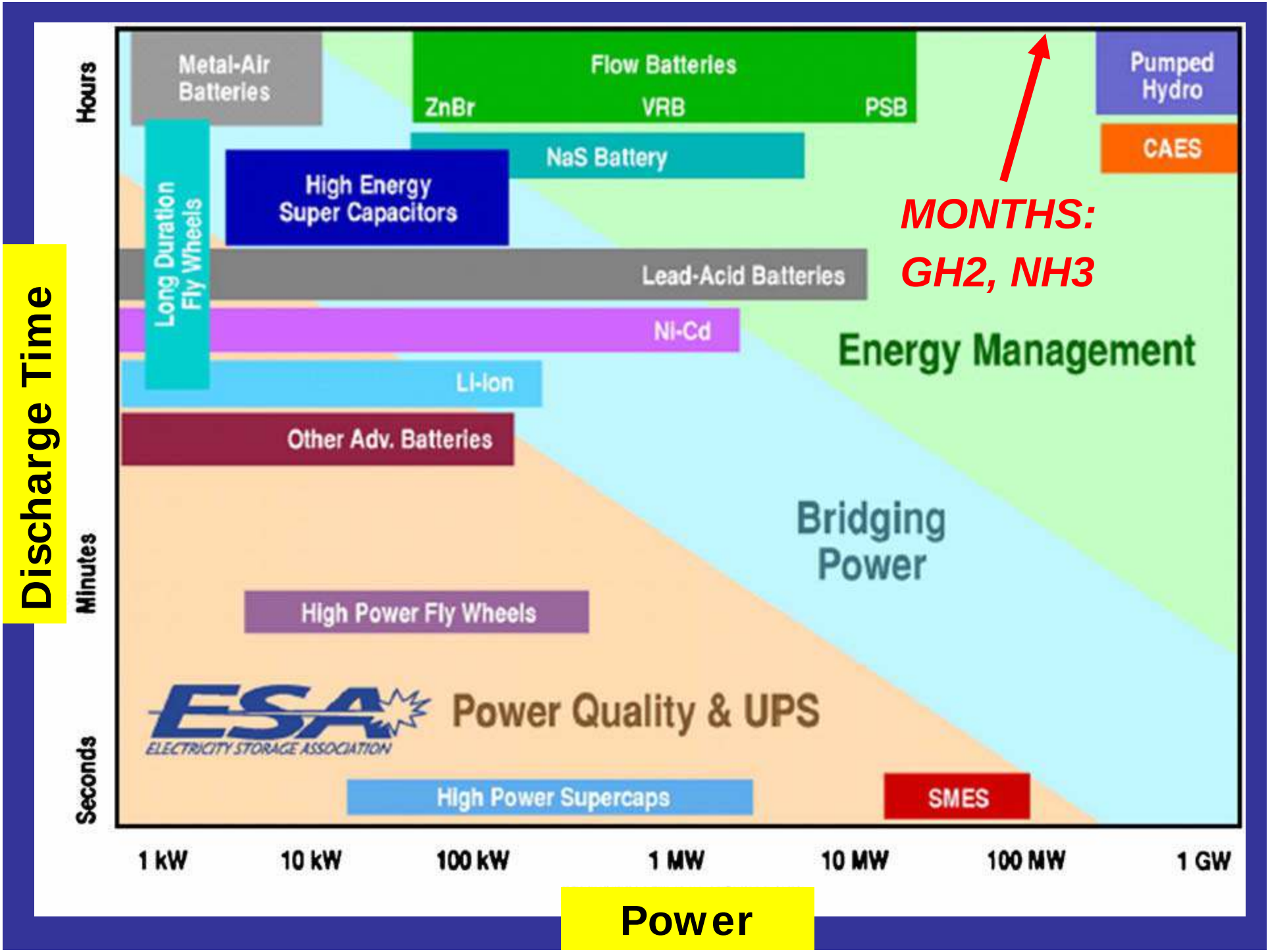
Ammonia Properties

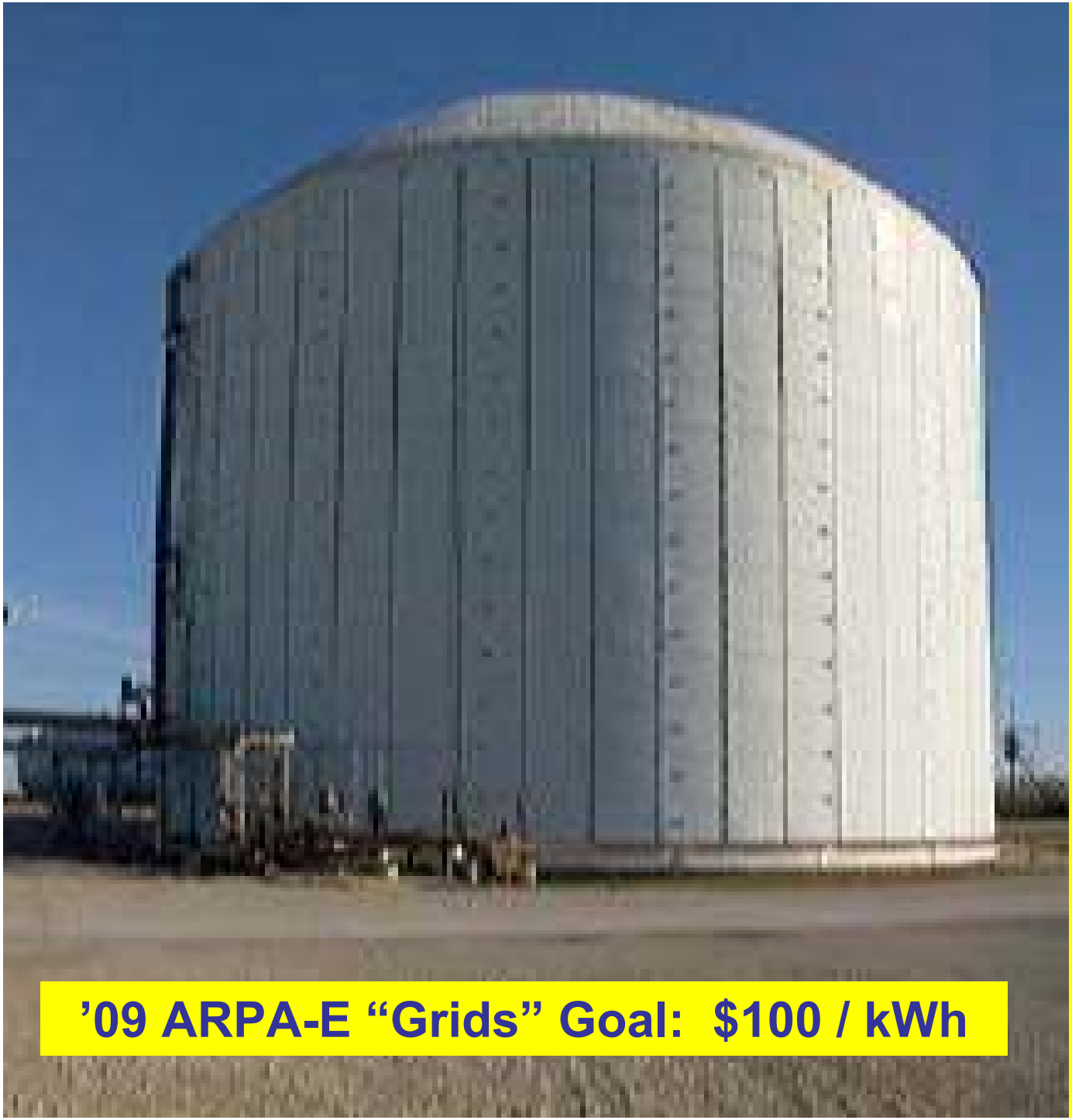
- C-free fuel: unique physical, chemical properties
- Carbon-free energy cycle, system
- Liquid at >125 psi at room temperature
- ~ Half energy density gasoline or diesel,
  volume or weight
- Low flammability, flame spread
- Easily “cracked” to H_2 + N_2 at end-use
- # 2 global industrial chemical trade
- Now 95% from stranded natural gas
  - ~ $1.00 / MMbtu
  - Trinidad, Australia, Quatar, Algeria, Russia
  - 5% from coal gasification → hydrogen + Haber-Bosch

Ammonia Properties

- Fertilizer forms:
  - "Anhydrous" NH_3 (only useful fuel)
  - Urea: (2) $NH_3 + CO_2$
  - Ammonium nitrate: NH_4NO_3
  - UAN: aqueous urea + ammonium nitrate
- Decades infrastructure + safety record

  ~14 MMt / year in USA, mostly fertilizer
  - Inhalation hazard; detected @ 5 ppm
  - OSHA, NIOSH regs + exposure limits
  - Toxic to aquatic life


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



’09 ARPA-E “Grids” Goal: $100 / kWh

“Atmospheric” Liquid Ammonia Storage Tank (corn belt)

30,000 Tons

190 GWh

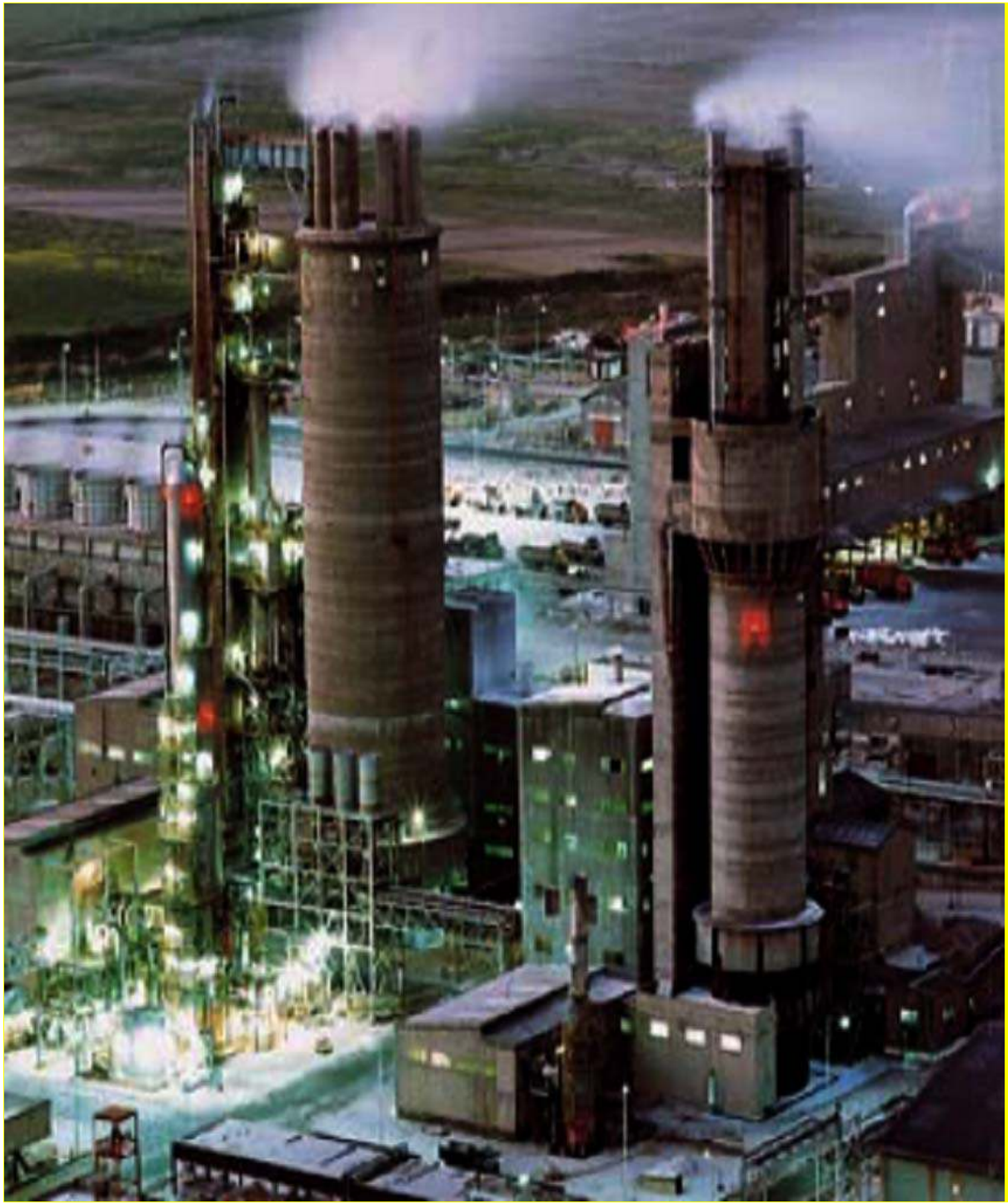
$ 15M turnkey

$ 80 / MWh

$ 0.08 / kWh

-33 C

1 Atm



95% Global Ammonia

Synthesis Plant

Natural Gas

1 – 3,000 tpd

Haber-Bosch process

Fritz Haber

Haber-Bosch Process

1909 – 1913 BASF

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

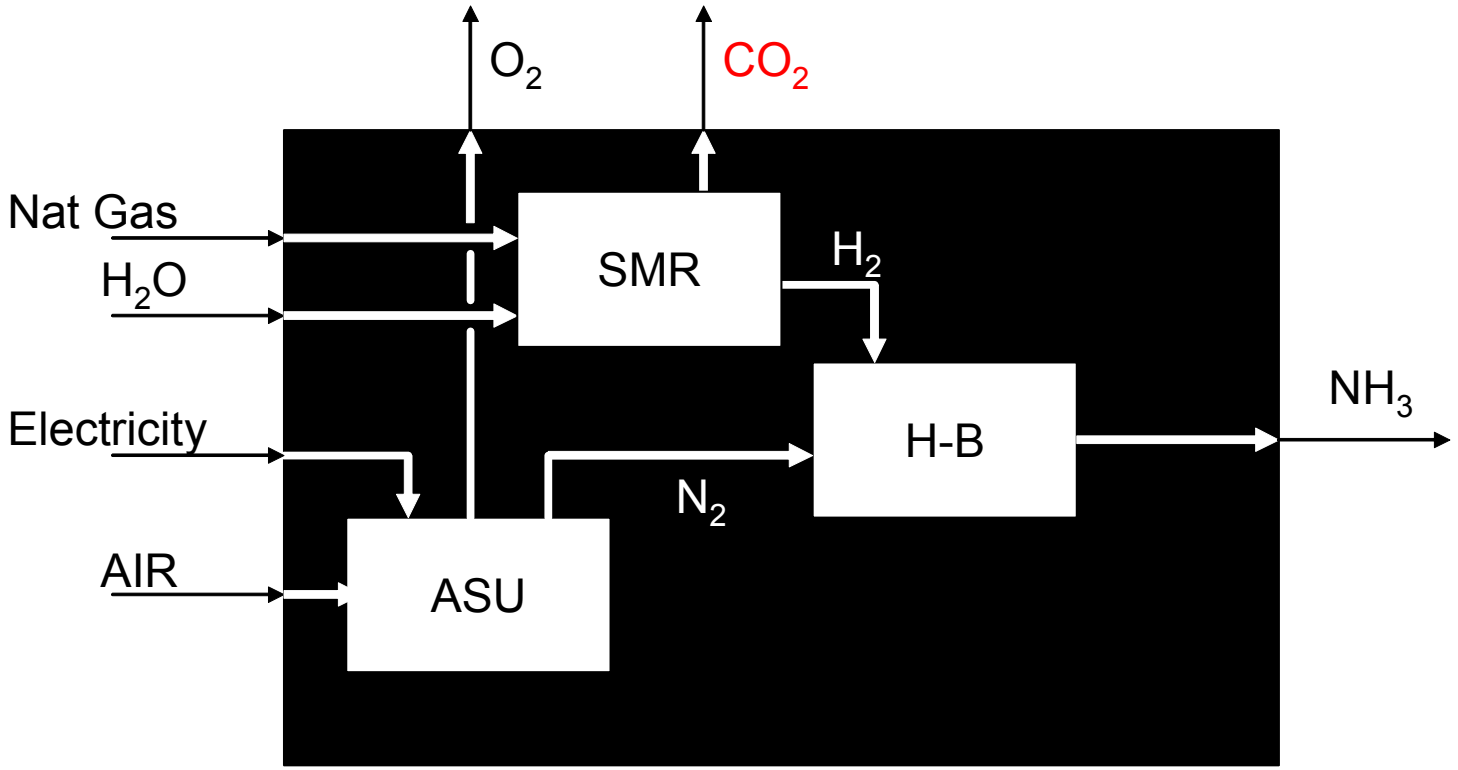
Haber-Bosch Reactor

1921

Ludwigshafen, Germany

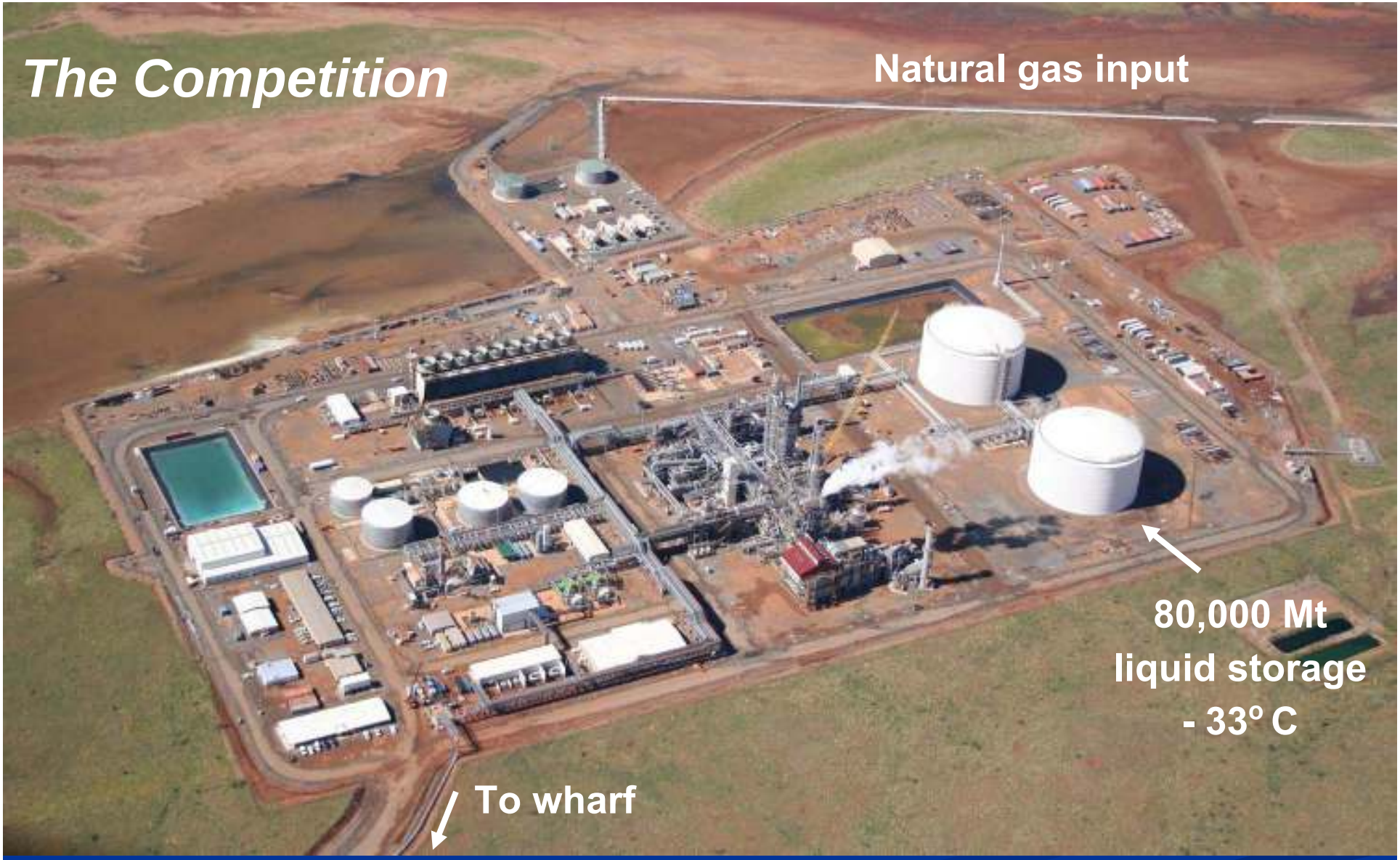
Inside the Black Box: Steam Reforming + Haber-Bosch (H-B)

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



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

The Competition



Burrup Peninsula, NW Australia, Natural Gas to Ammonia Plant

760,000 Mt / year

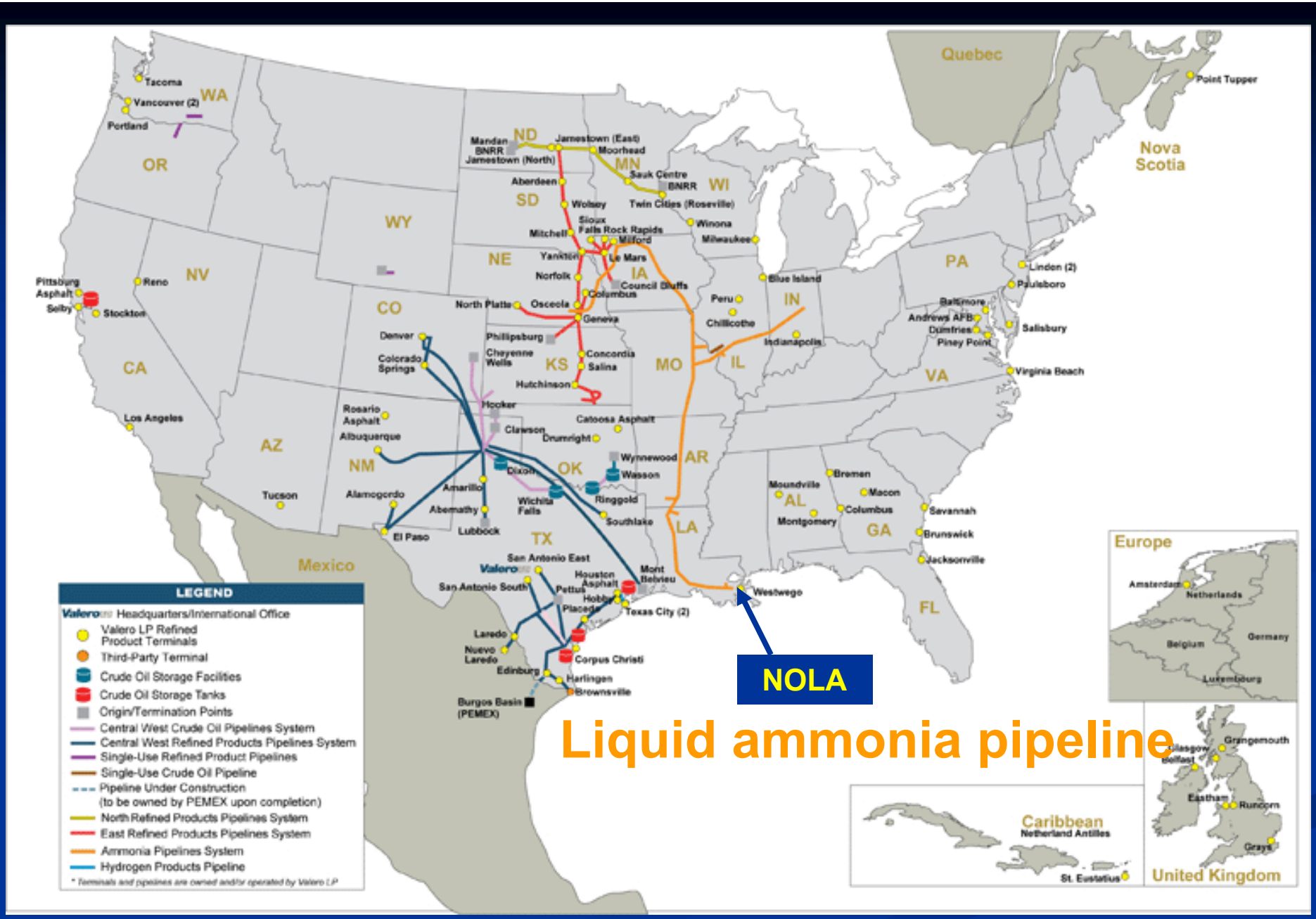
$US 650 million capital cost ‘06

Ammonia Tanker
Burrup Peninsula
Western Australia

Ammonia or LPG Tanker

To 35,000 Mt

Refrigerated



Valero LP Operations

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 miles, no compress 0.3

Ammonia pipeline:

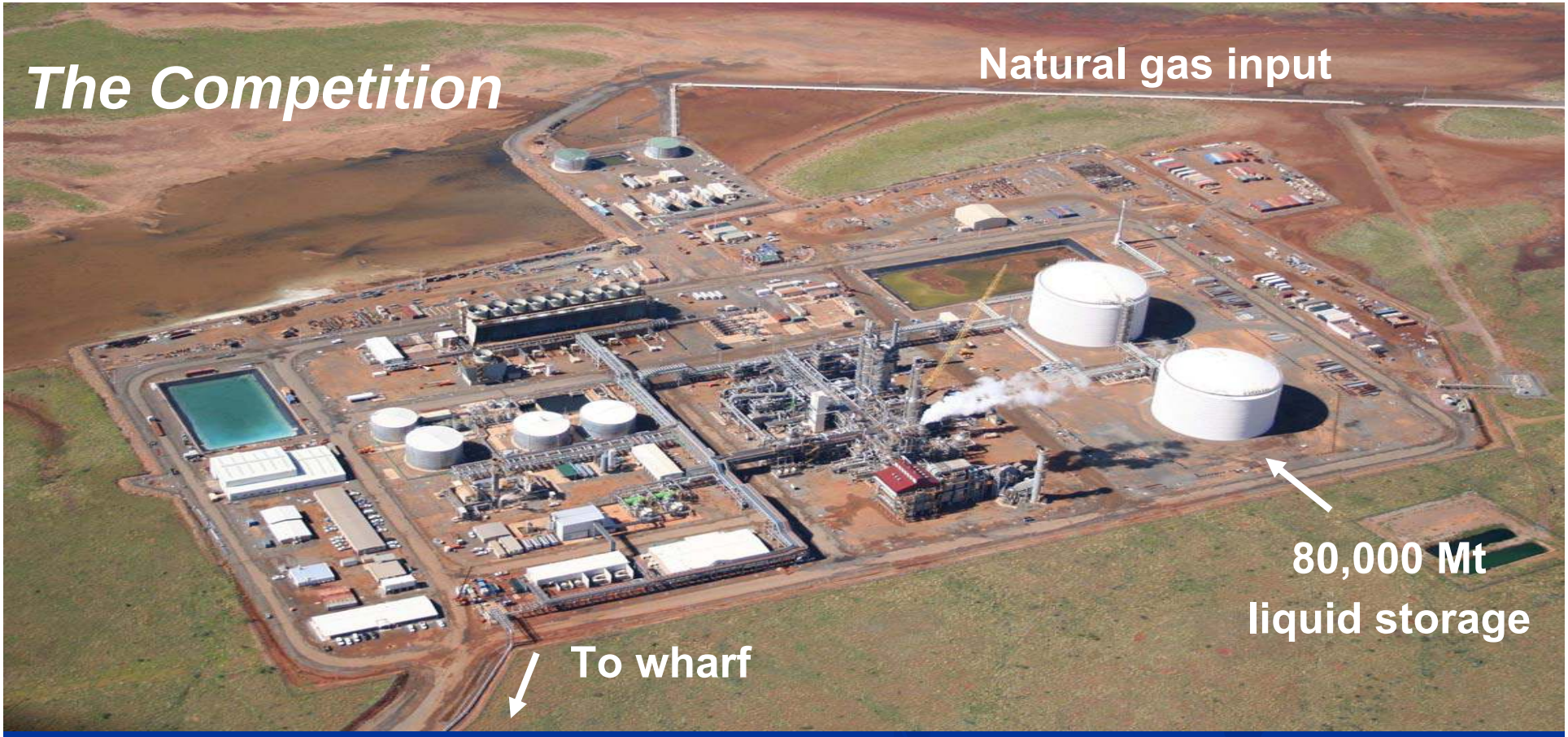
10” , liquid, 500 miles, with pumping 0.2


Ammonia Storage Terminal
Mississippi River
Winona, MN

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

The Competition



Global Ammonia = 140 million Mt / year

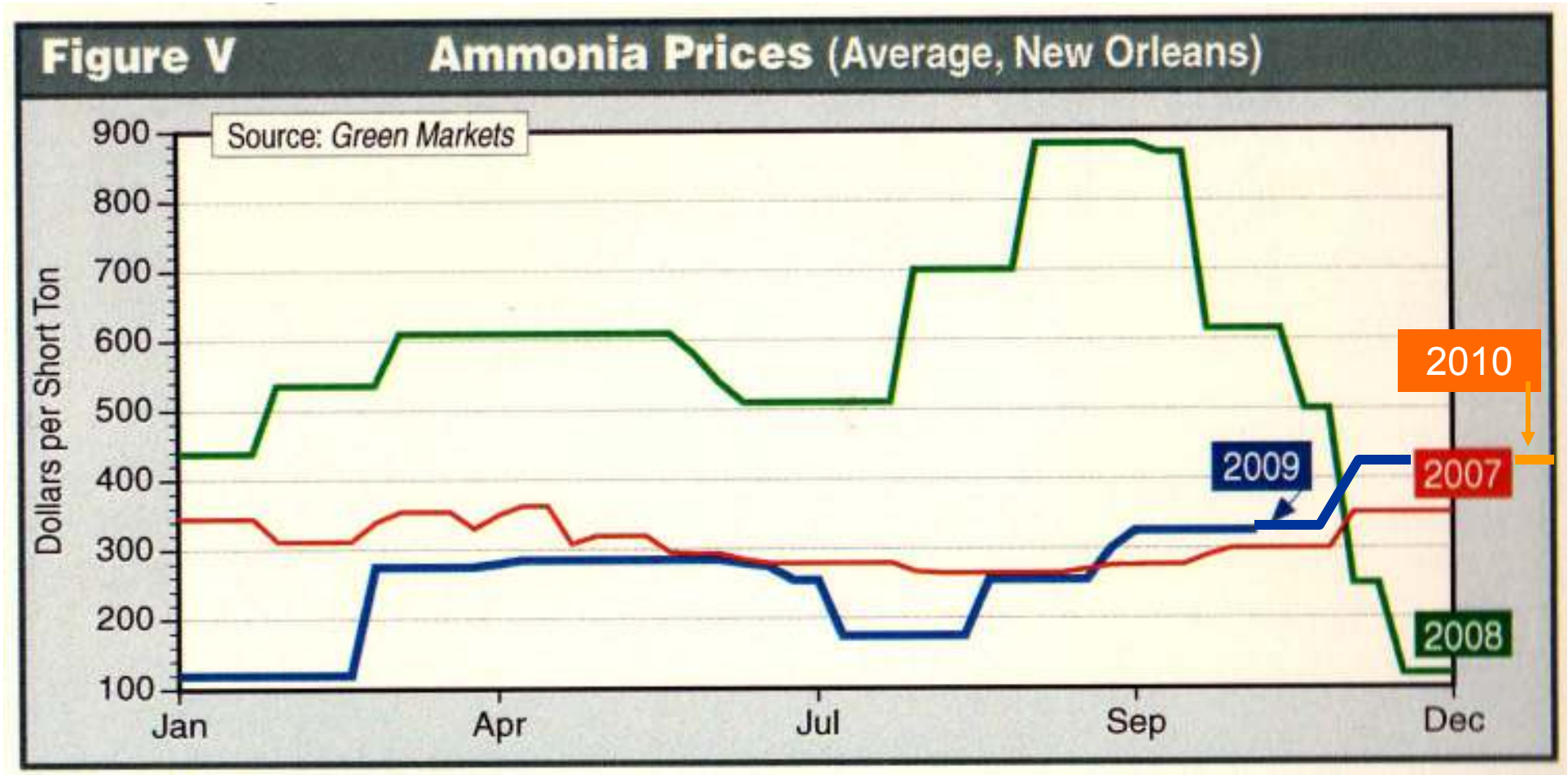
- **#2 chemical**
- **200 plants, nat gas + coal**
- **~ 500 Million Bbl oil**
- **~ 2% oil**
- **~ 0.5% energy**

14 million Mt / yr USA; 60% imported; corn ethanol

Cost: Ammonia from Stranded Natural Gas (NG)

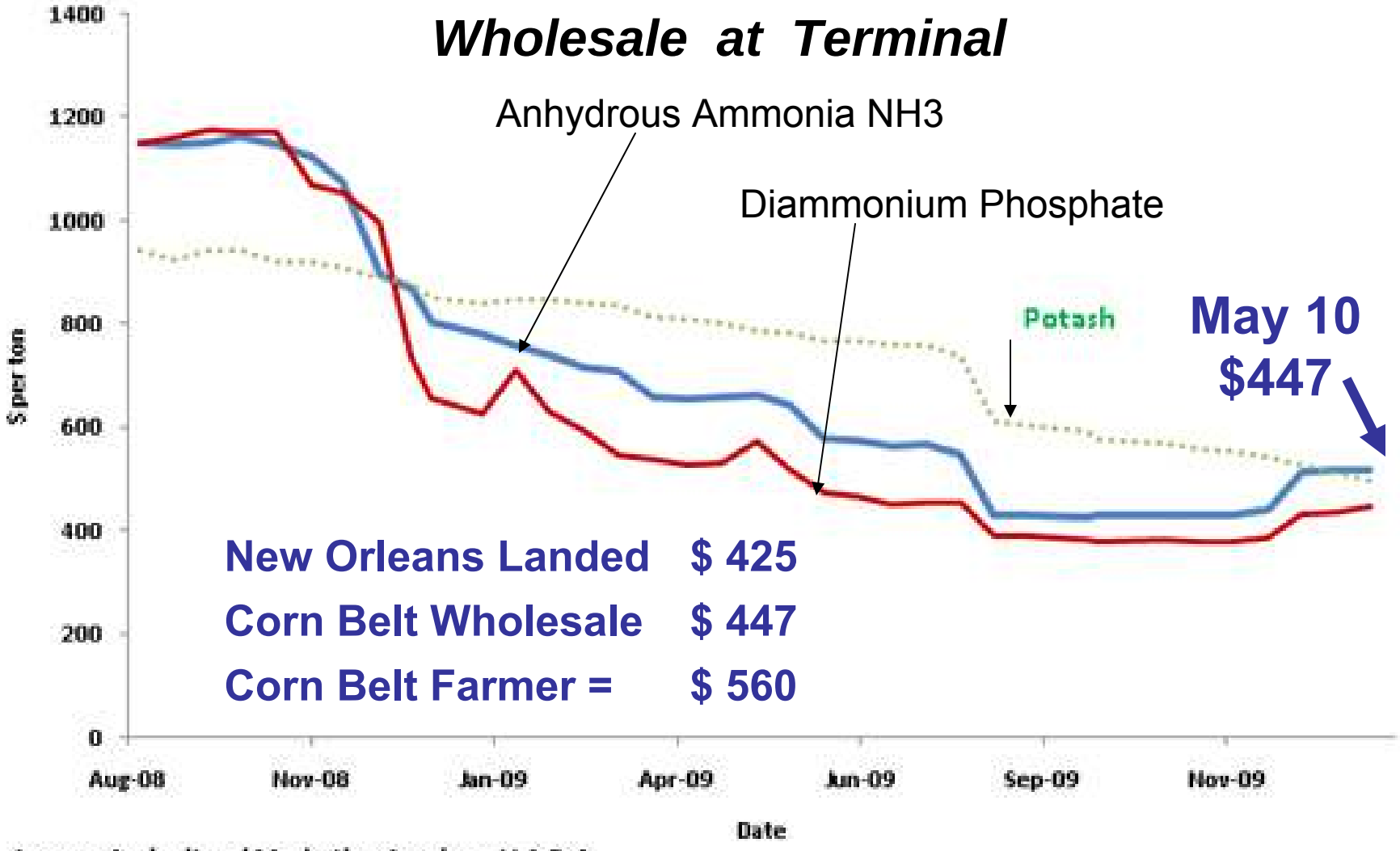
> Burrup, Australia Plant: 750,000 Mt / year
> $650M capital @ 15% capital recovery factor (CRF)
> 34 MMBtu NG / Mt NH3
> NG cost $1.20 / MMBtu long-term
> Tanker shipping to New Orleans, LA (NOLA) $50 / Mt
> CO2 emission 1.8 Mt / Mt NH3

	C-tax 0	C-tax $50 / Mt CO2	C-tax $100 / Mt CO2
Capital	98	98	98
NG	41	41	41
Shipping	50	50	50
C-tax	0	90	180
Plant O&M	2	2	2
Total NOLA / Mt	**$191**	**$281**	**$371**



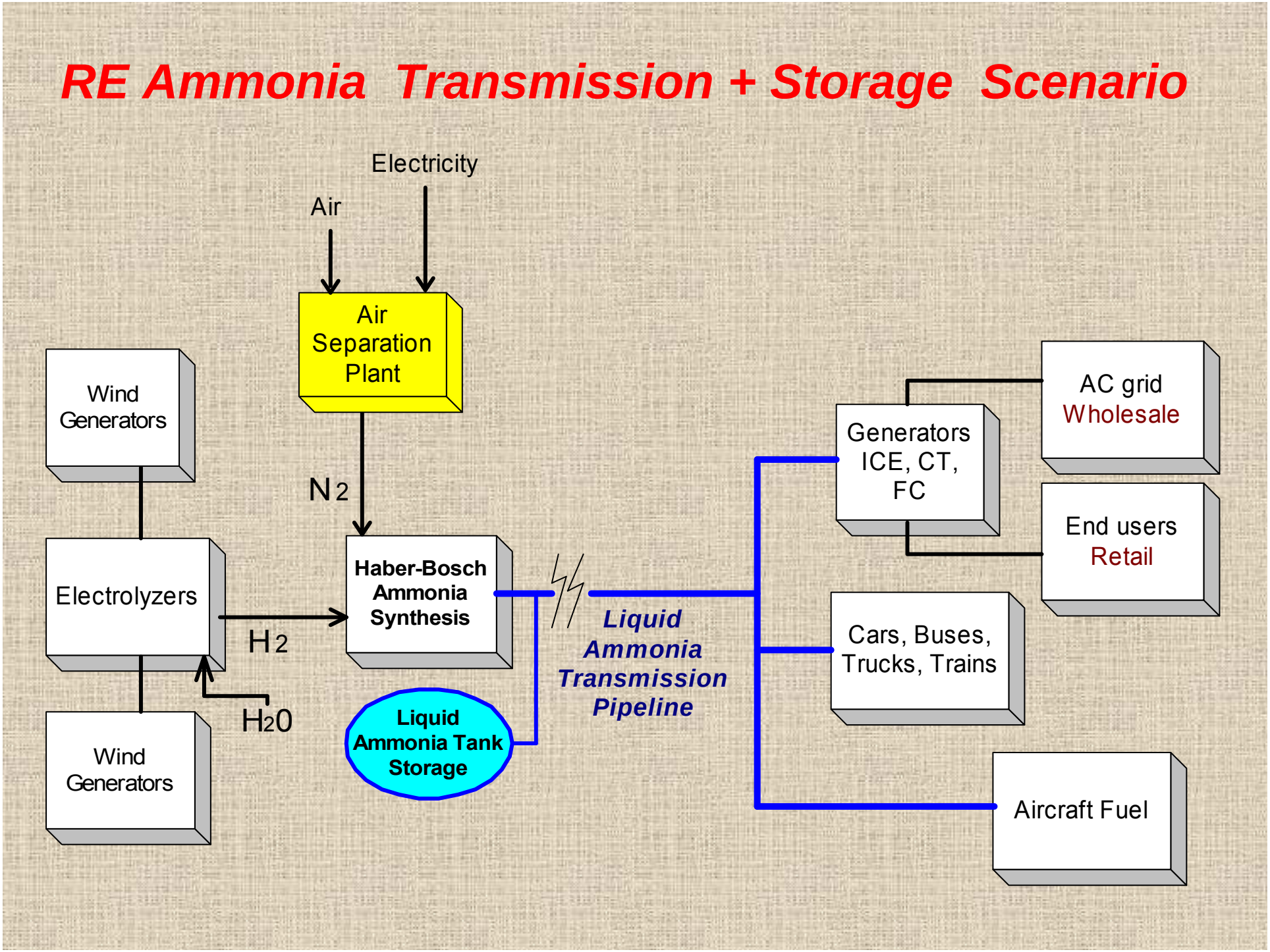
Anhydrous Ammonia (NH3) wholesale price, NOLA (New Orleans, LA)

Fertilizer Prices in Illinois ($ per ton)
Wholesale at Terminal



Source: Agricultural Marketing Services, U.S.D.A.

RE Ammonia Transmission + Storage Scenario

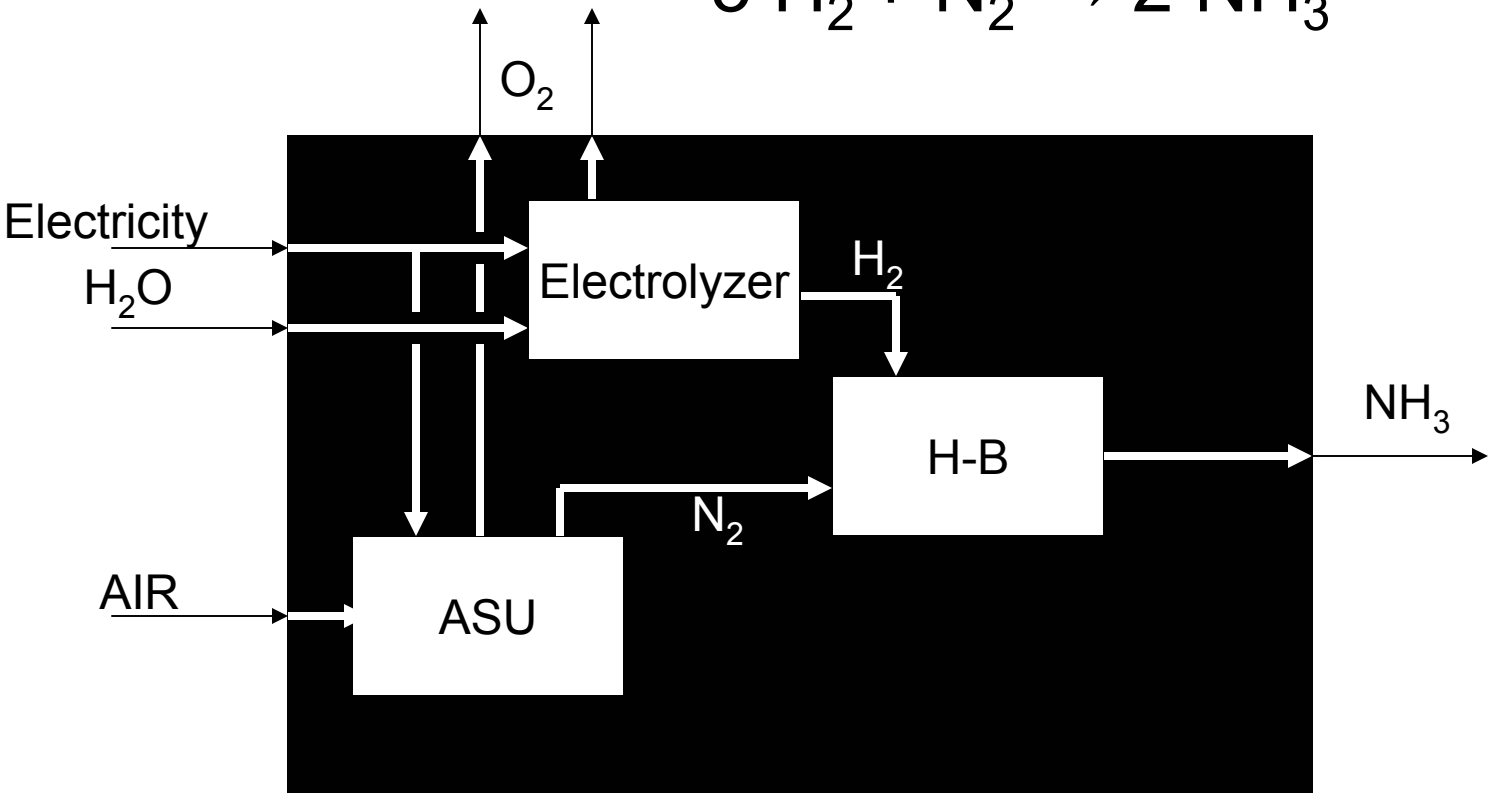


Wind – to – Ammonia Potential, NW Iowa


Norsk Hydro
Electrolyzers
2 MW each
Ammonia from
hydrogen
from zero-cost
off-peak hydro

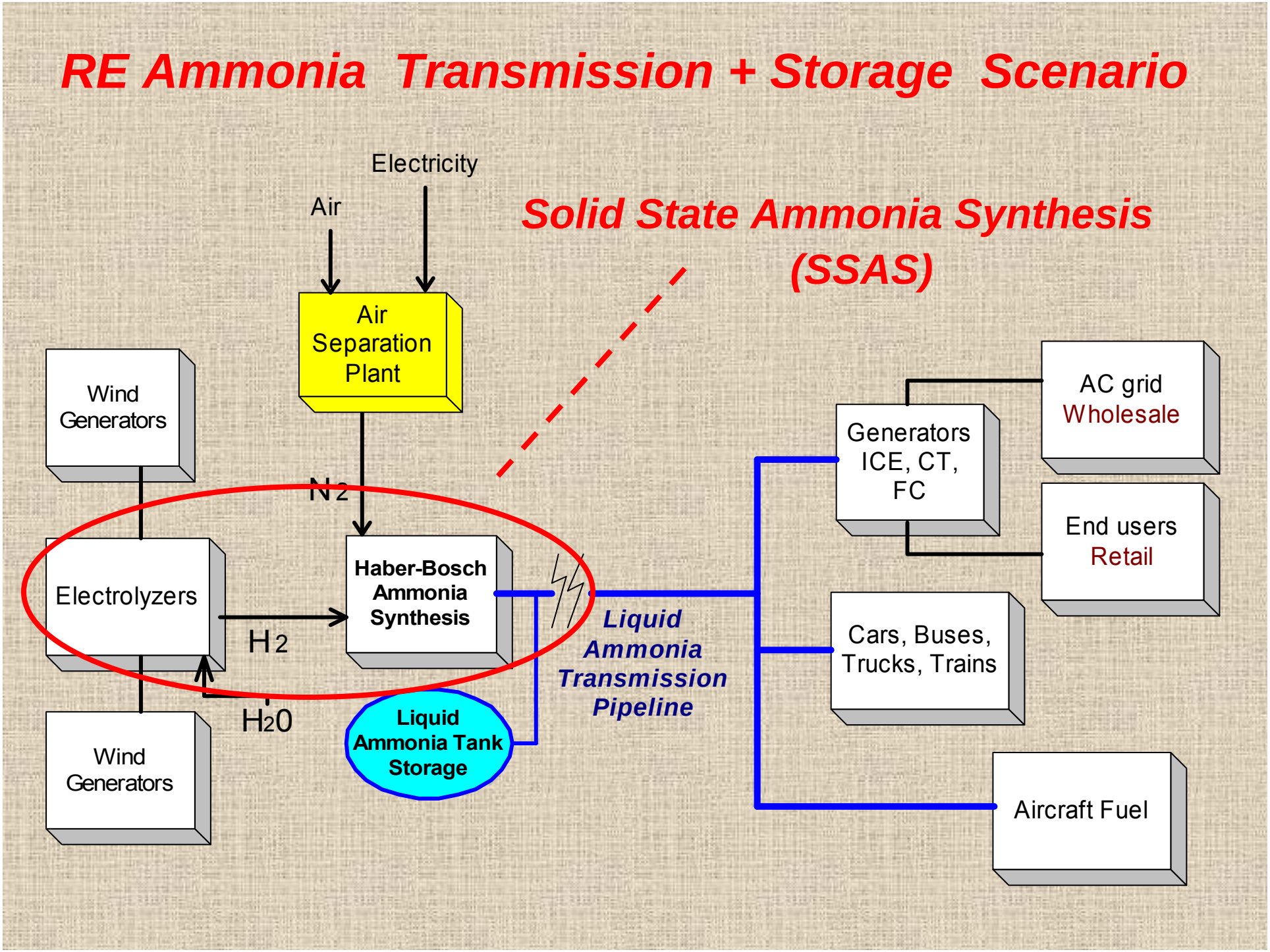
Inside the Black Box: HB Plus Electrolysis

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



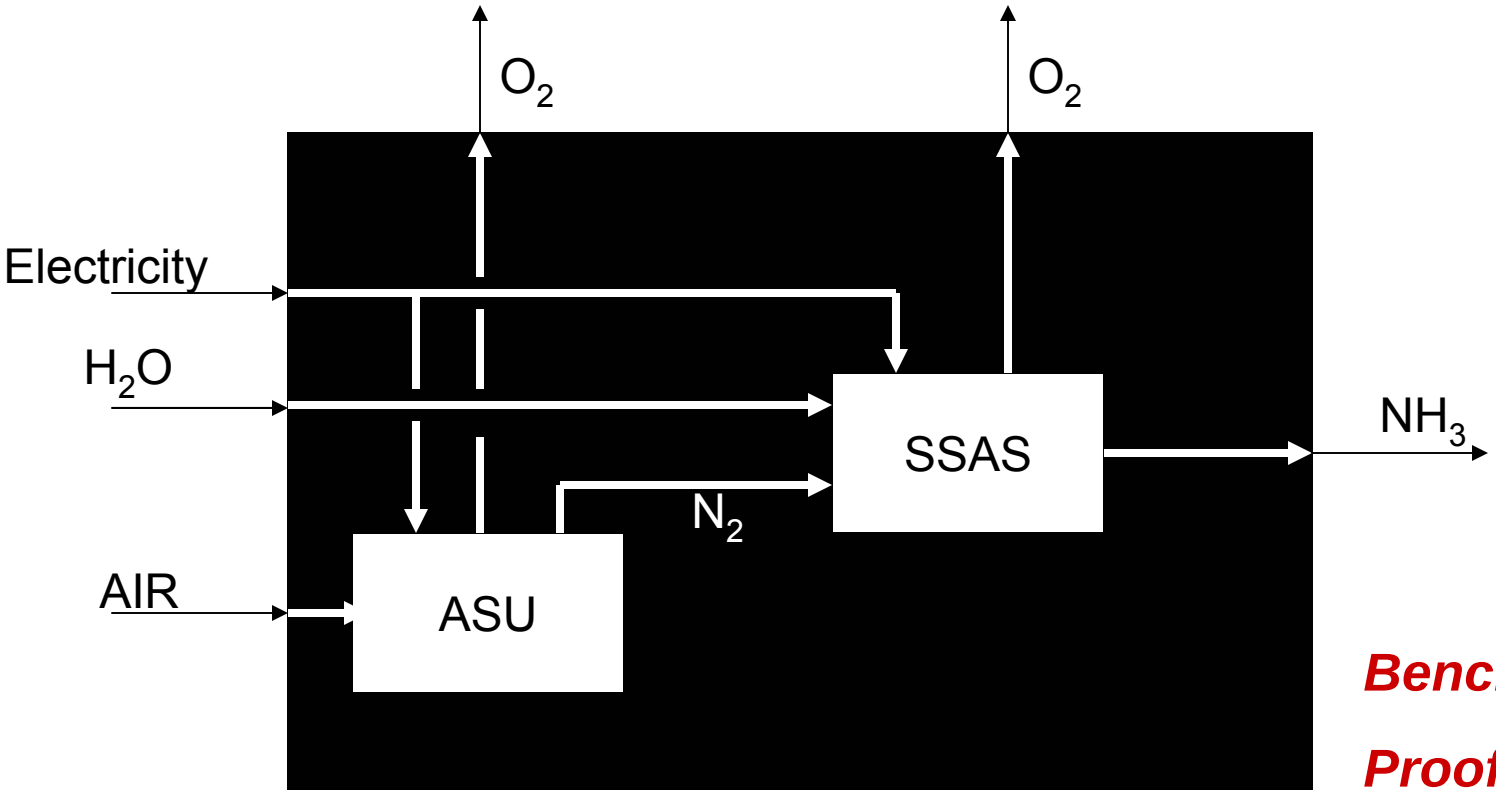
Energy consumption ~12,000 kWh per ton NH_3

RE Ammonia Transmission + Storage Scenario



Inside the Black Box: Solid State Ammonia Synthesis

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

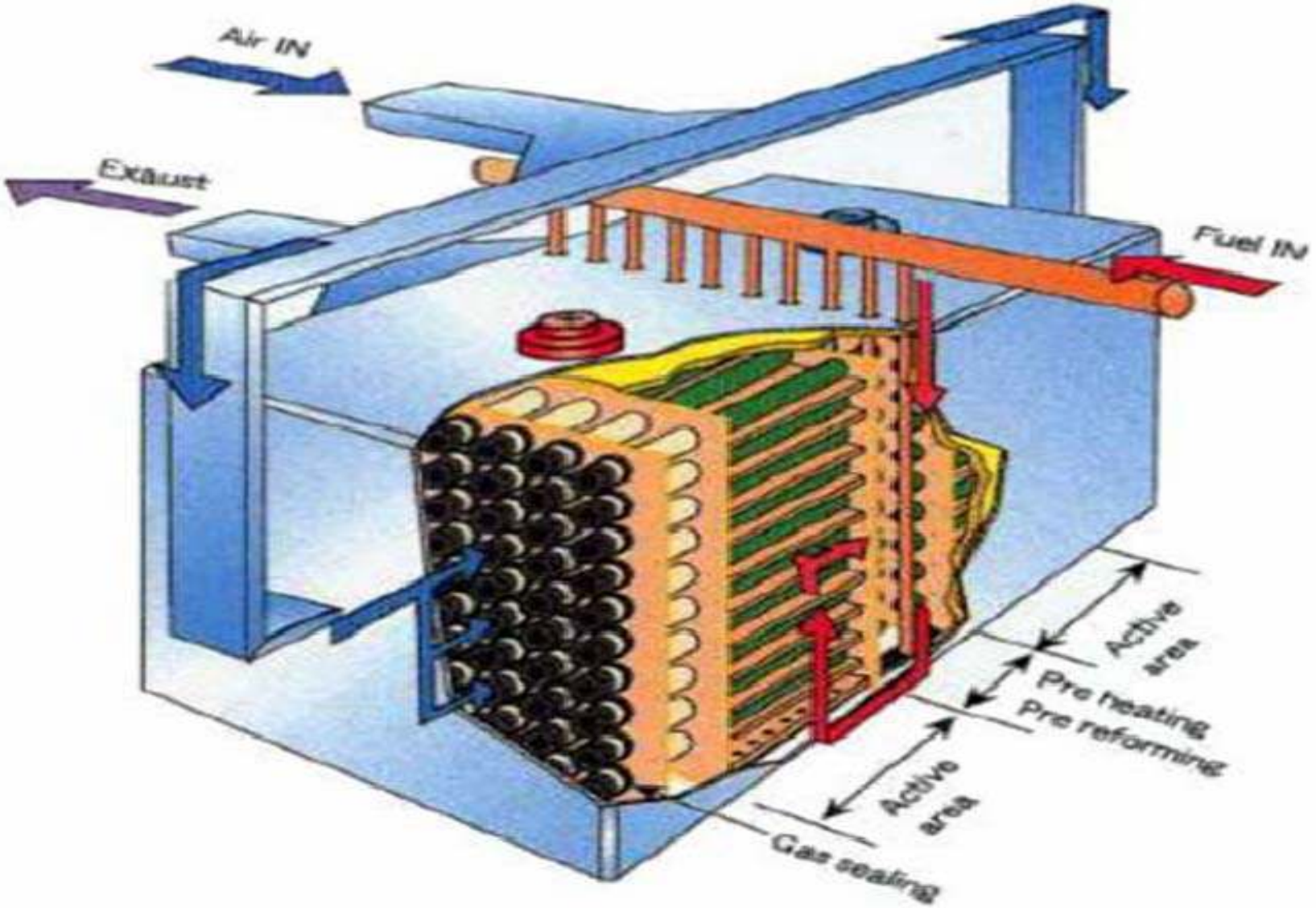


Benchtop

Proof-of-concept

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

Solid State Ammonia Synthesis (SSAS)
NHThree LLC patent



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

"Green" Ammonia (NH3) Output

- *> 2,000 MW Adak Wind-to-ammonia Plant*
- *> $5 B total capital @ $2,500 / kW*
- *> 45% Capacity Factor (CF)*

Windplant Annual Energy Production: 7,884,000 MWh / year

Convert to NH3 by:

	Electrolysis + H-B @ 12 MWh / Mt	SSAS @ 7.5 MWh / Mt
Mt (tons) / year	**657,000**	**1,050,000**
Sales @ $300 / Mt (plant gate)	**$197 M**	**$315 M**
Simple ROI	**4%**	**6%**

"Green" Ammonia (NH3) Output

- *> 2,000 MW Adak Wind- to- ammonia plant*
- *> $5 B total capital @ $2,500 / kW*
- *> 45% Capacity Factor (CF)*
- *> 15% Capital Recovery Factor (CRF)*

Windplant Annual Energy Production: 7,884,000 MWh / year

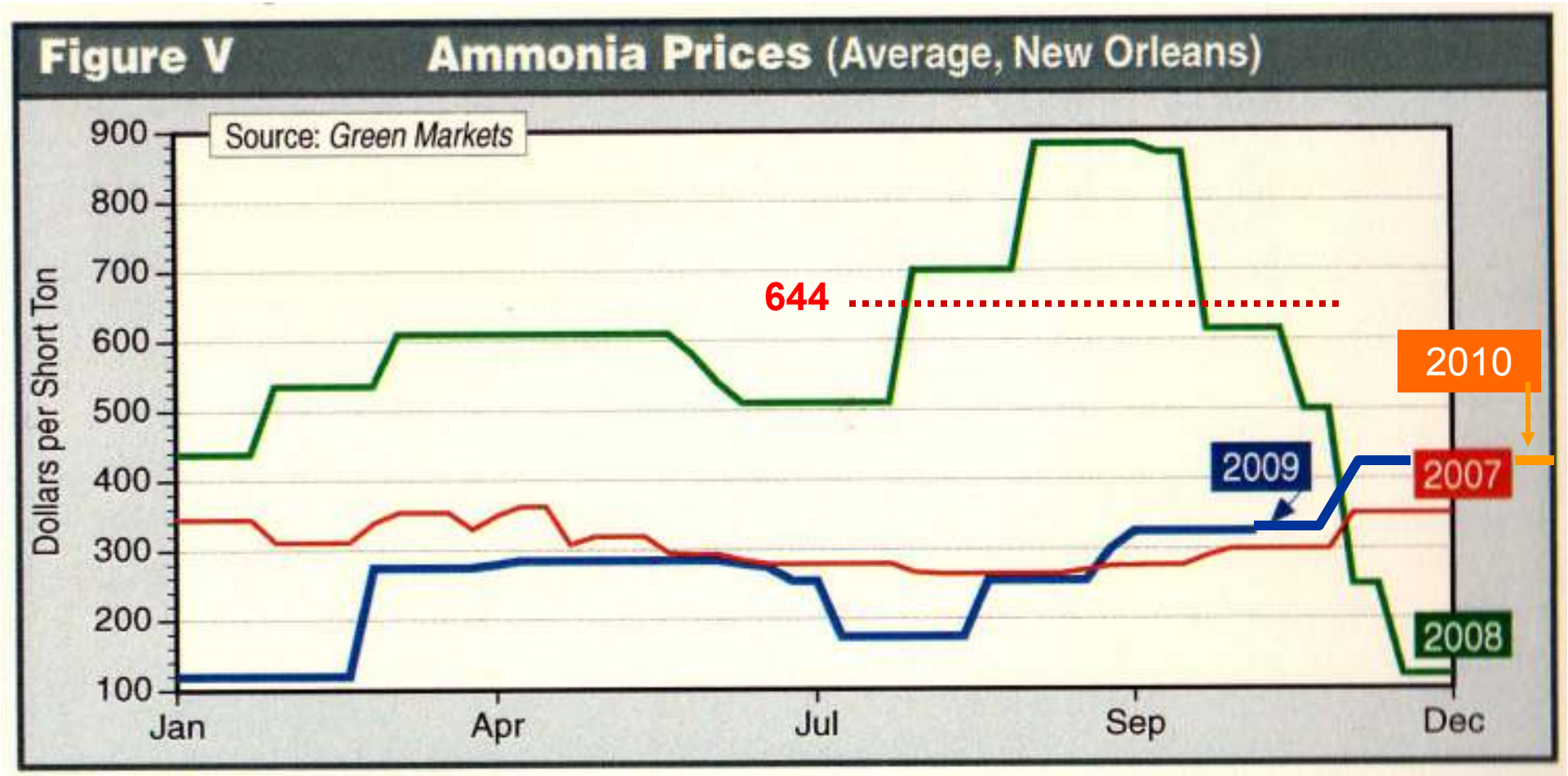
	Electrolysis + H-B	SSAS
Sales: Mt (tons) / year	657,000	1,050,000
Total Cost of Sales:		
Capital @ 15% CRF	$750M	$750M
Plant O&M @ $0.03 / kWh	24M	24M
Input energy	0	0
TOTAL	$774M	$774M
Cost / Mt NH3 (plant gate)	$1,178	$ 737
Shipping @ $50 / Mt	50	50
Total NOLA / Mt	$1,228	$ 787

"Green" Ammonia (NH3) Output

- *> 2,000 MW Adak Wind- to- ammonia plant*
- *> $5 B total capital @ $2,500 / kW*
- *> 45% Capacity Factor (CF)*
- *> 12% Capital Recovery Factor (CRF)*

Windplant Annual Energy Production: 7,884,000 MWh / year

	Electrolysis + H-B	SSAS
Sales: Mt (tons) / year	657,000	1,050,000
Total Cost of Sales:		
Capital @ 12% CRF	$600M	$600M
Plant O&M @ $0.03 / kWh	24M	24M
Input energy	0	0
TOTAL	$624M	$624M
Cost / Mt NH3	$ 949	$ 594
Shipping @ $50 / Mt	50	50
Total NOLA / Mt	$ 999	$ 644



Anhydrous Ammonia (NH3) wholesale price, NOLA (New Orleans, LA)

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

Humanity's Goal

A global, sustainable,

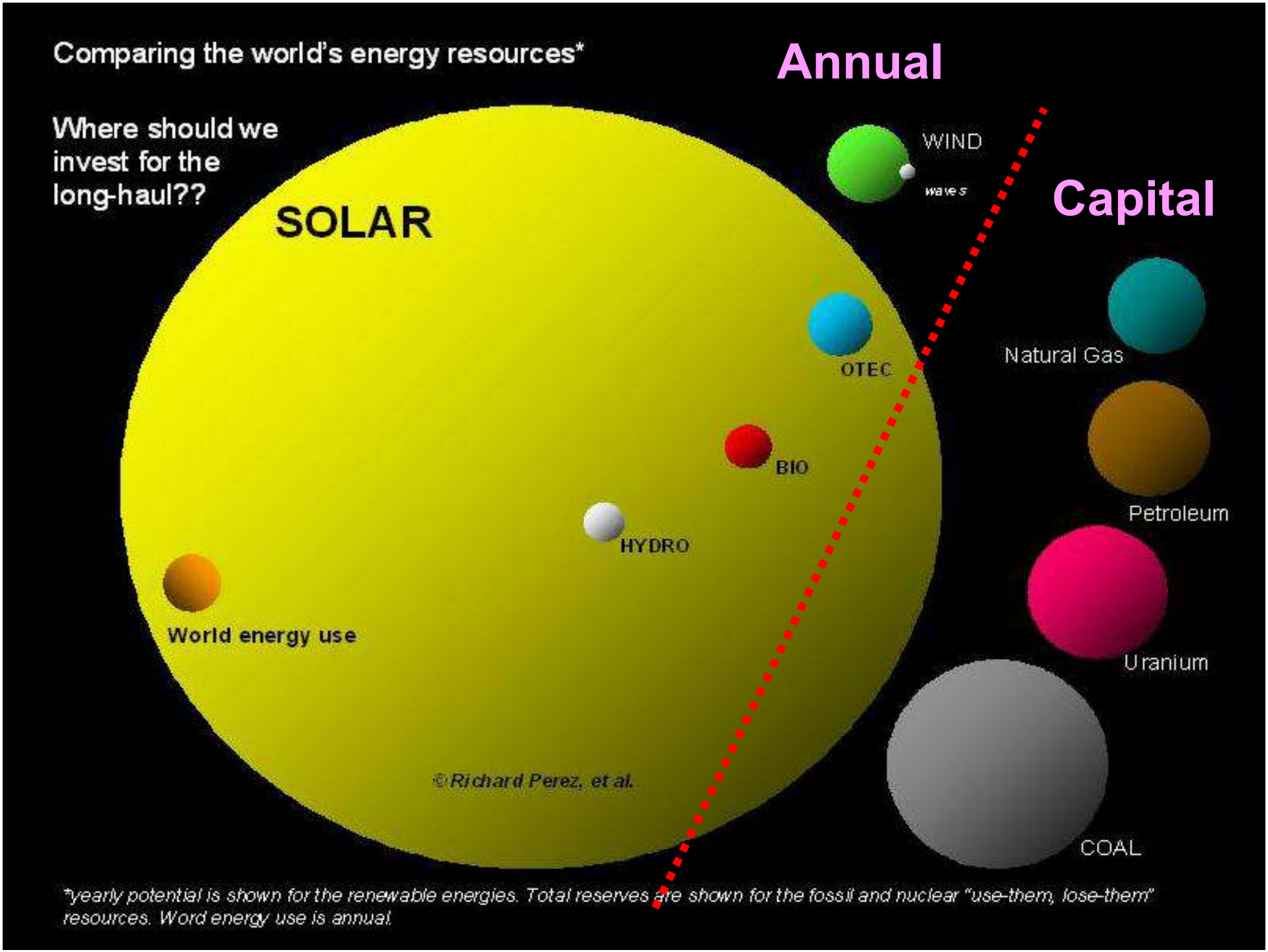
benign-source, equitable,

energy economy

- **CANNOT with only electricity transmission**
- **"Transmission" → 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


Comparing the world's energy resources*
Where should we invest for the long-haul??
Annual
Capital
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.

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
- Nascent markets: transport fuel, other
- Integration
  - Continental energy system
  - Elec grid quality
  - Elec grid generation O+M: fatigue, wear, efficiency

Alternatives to Electricity for Transmission and Annual-scale Firming Storage for Diverse Renewable Energy Resources: Hydrogen and Ammonia Fuels

DVD's available

ASME Power
14 July 10, Chicago

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

END presentation

Following slides are supplemental

Jon Wellinghof

FERC* Chairman

About new coal + nuclear plants:

“ We may not need any, ever ”

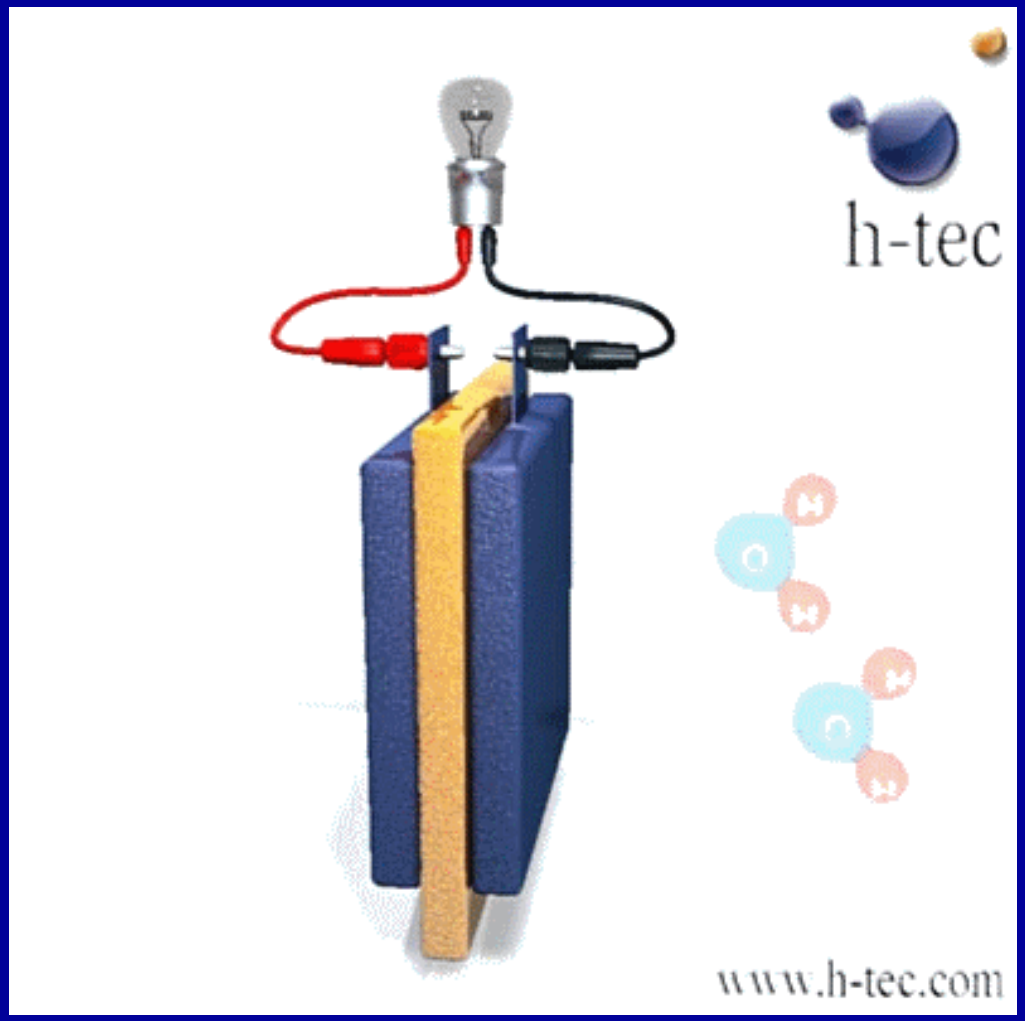
NY Times, 22 Apr 09

*** FERC = Federal Energy Regulatory Commission**

Hydrogen Fuel Cell

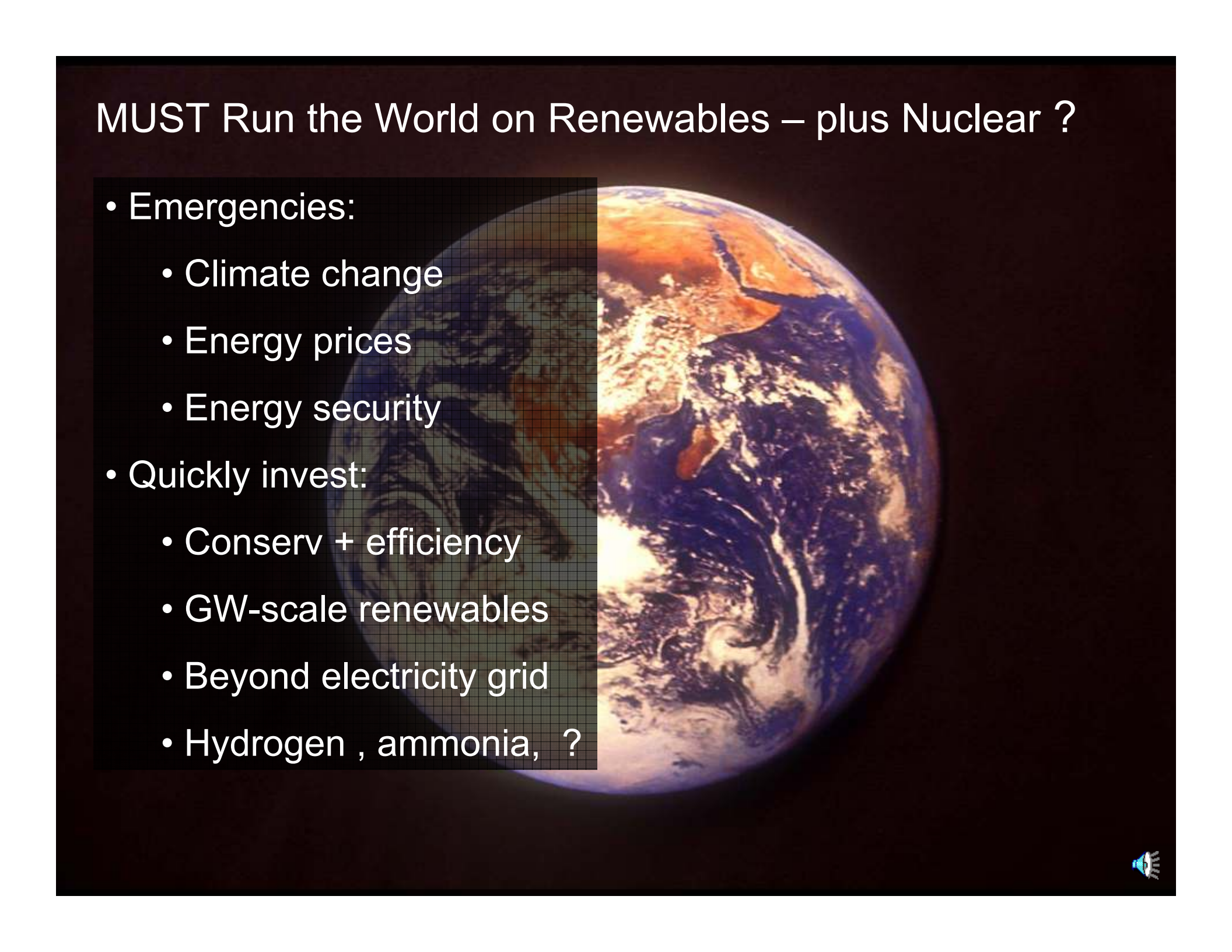
Proton Exchange Membrane (PEM) type

Hydrogen (H_2) combines with Oxygen (O_2) to make electricity + heat + water (H_2O)



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

Sea of Okhotsk

KAMCHATKA

Bering Strait

Monday

Sunday

N

ALASKA

Bering Sea

SHEMYA

ATTU

AGATTU

KISKA

AMCHITKA

Aleutian Islands

DUTCH HARBOR

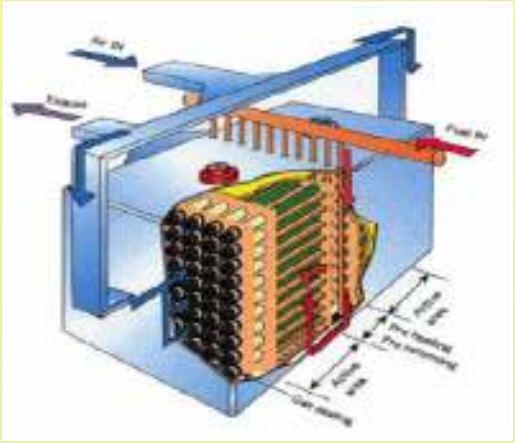
0 100 200 300

MILES

Adak

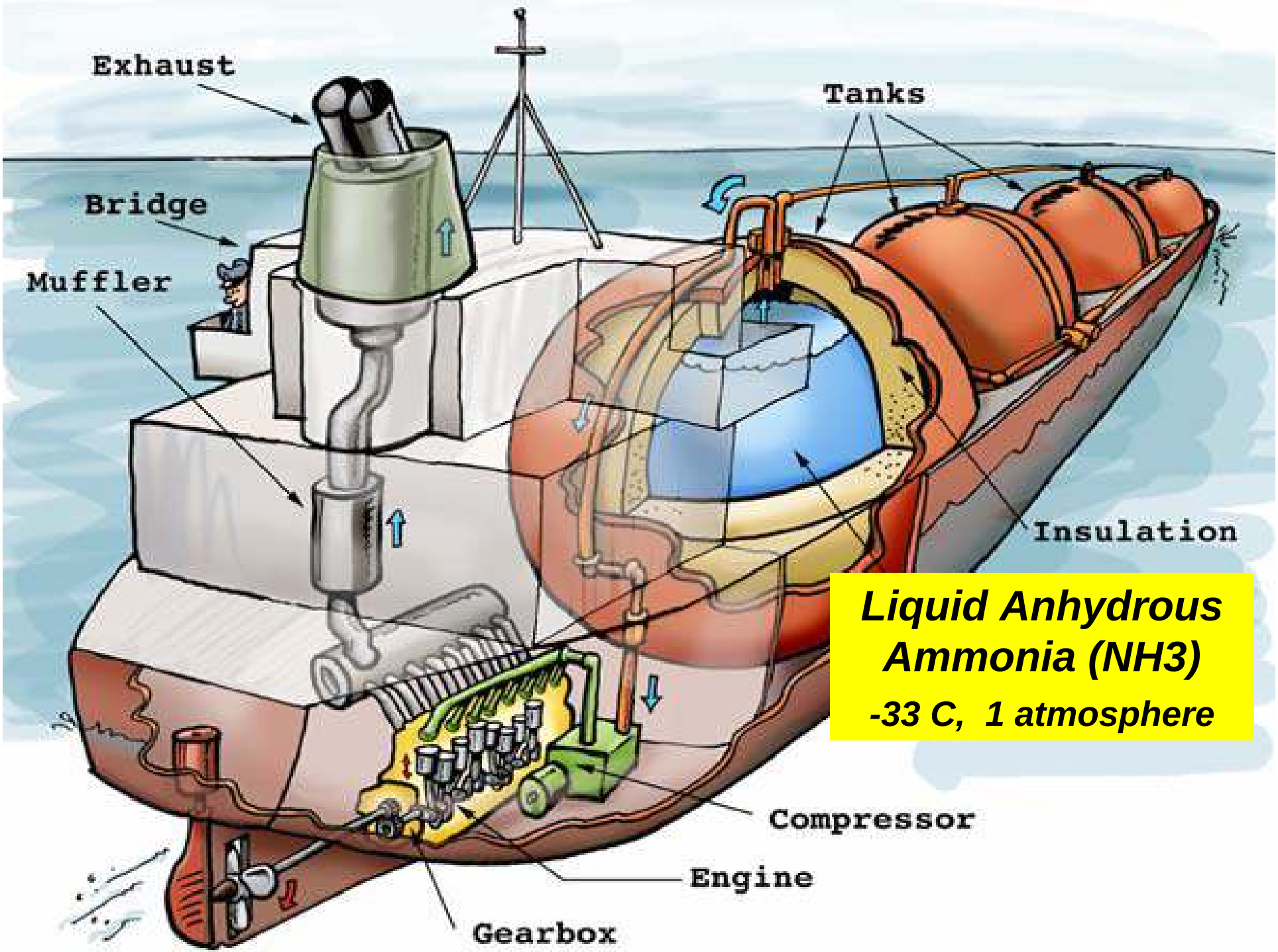
Pacific Ocean

Solid State Ammonia Synthesis (SSAS)



- Goals:
  - Renewables-source ammonia (NH3)
  - Compete with natural gas source NH3
- High energy conversion efficiency
  - ~50% better than electrolysis → hydrogen + H-B
  - No hydrogen production
- Electricity + water + nitrogen → ammonia
- ~ 50% lower capital cost
- SSAS reactor: SOFC * in reverse

*** SOFC: Solid oxide Fuel Cell**


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

Electricity Capital Cost per GW-mile

- **ICF International "Wyoming Collector and Transmission System Conceptual Design"**
- **http://icfi.com/docs/wyoming-collector-transmission-final.pdf**
- **http://icfi.com/docs/wyoming-transmission.pdf**
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