Compressorless Hydrogen Transmission Pipelines Deliver Large-scale Stranded Renewable Energy at Competitive Cost

23rd World Gas Conference,
Amsterdam, 5-9 June 06

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When we realize these as emergencies:

- Global Warming, Climate Change
- Energy Security and Cost
- Peak Oil and Natural Gas

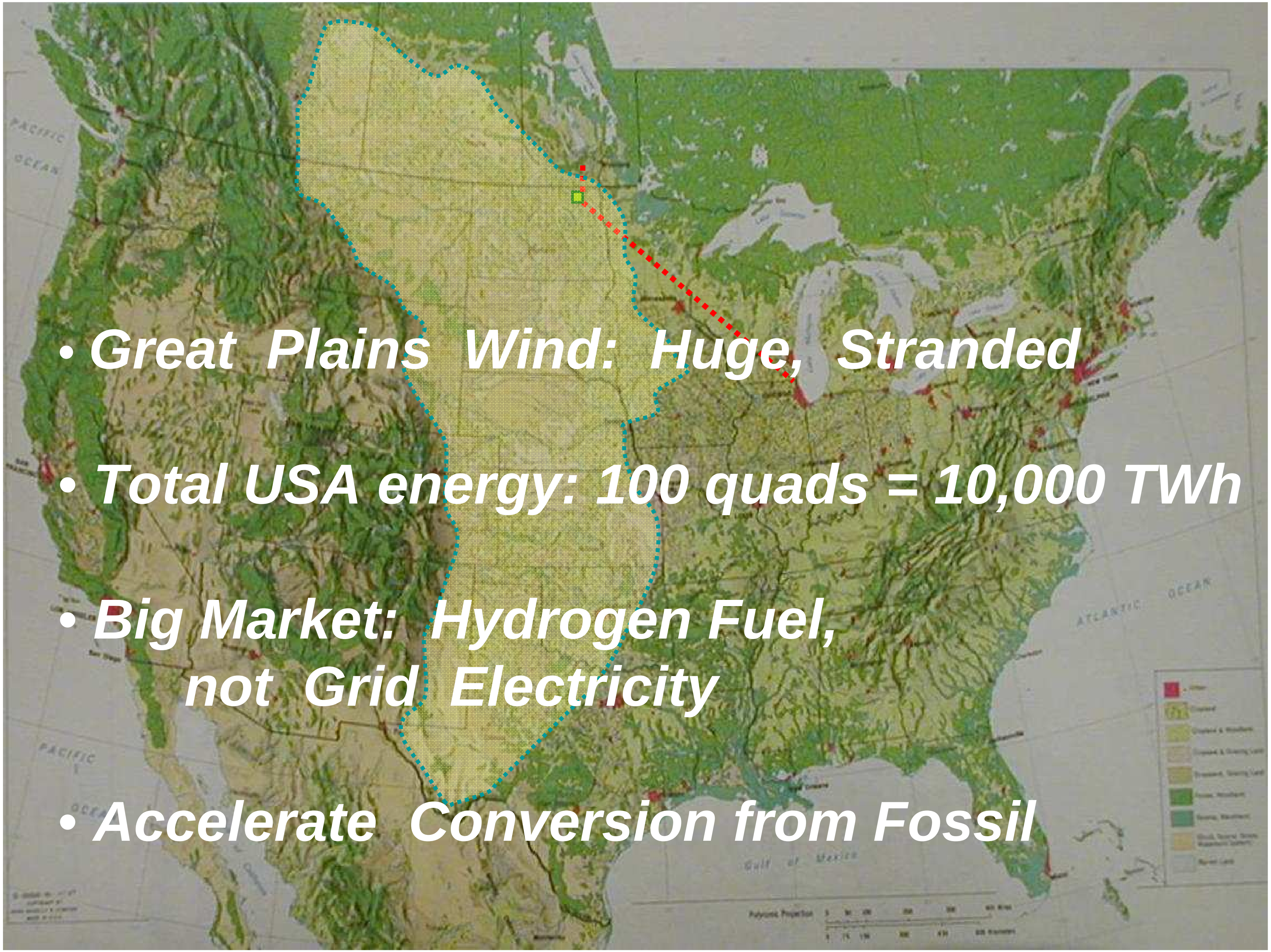
We must quickly invest in:

- Energy conservation, efficiency
- Large, new energy supplies:
  - CO_2-emissions-free
  - Indigenous
  - Both Distributed, Centralized

Shortest path to benign, secure, abundant energy ?

- Renewables
  - Diverse
  - Diffuse
  - Dispersed
- Centralized:
  - large, rich; lower cost than distributed ?
  - but **stranded (no transmission)**
- Gaseous hydrogen (GH2) pipelines
  - Conversion, gathering
  - Transmission
  - Storage
  - Distribution
- Geologic storage “firms”
- Pilot plant needed:
  - every major new industrial process
  - IRHTDF

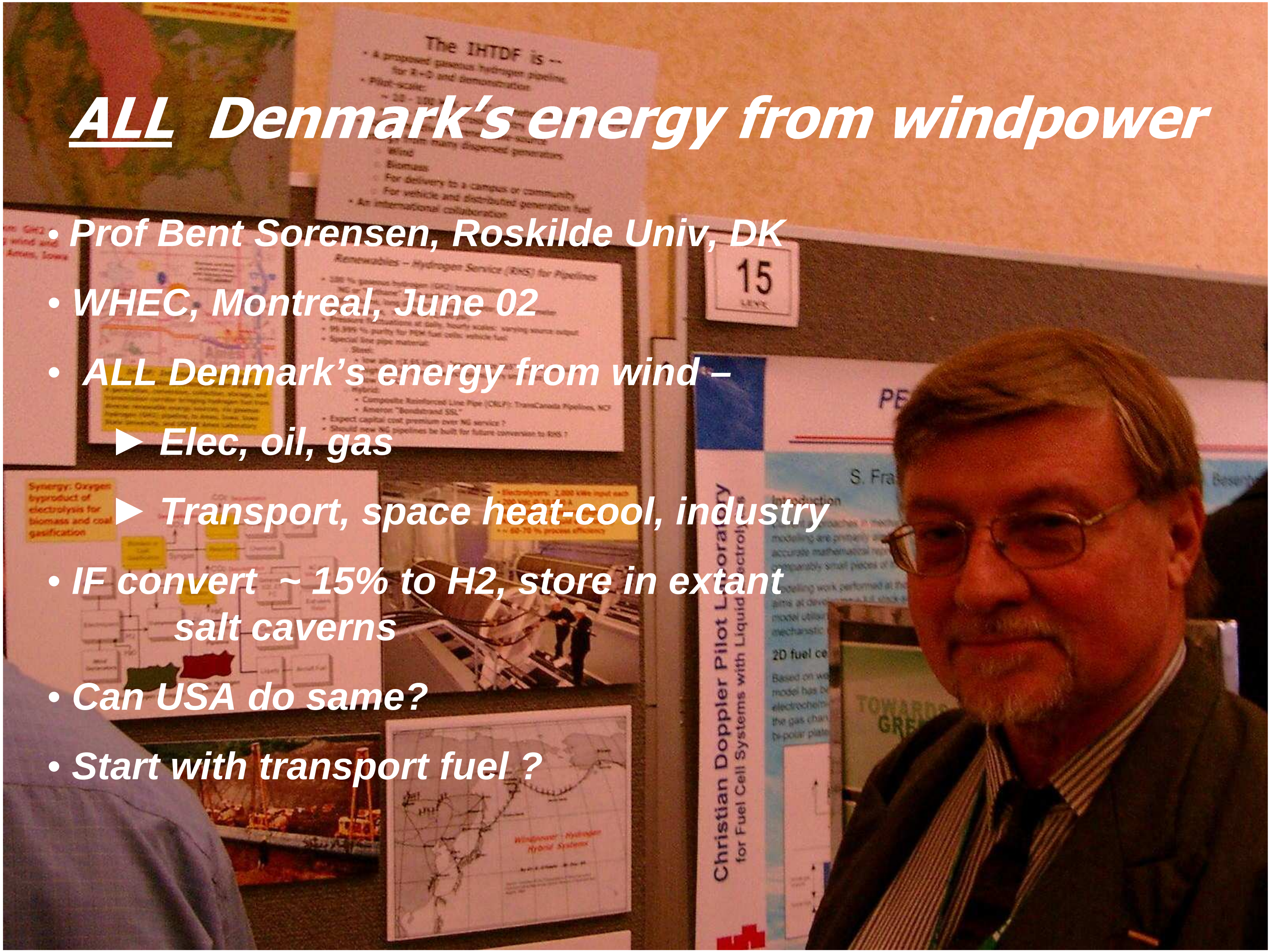
The Great Plains Wind Resource



- ***Great Plains Wind: Huge, Stranded***
- ***Total USA energy: 100 quads = 10,000 TWh***
- ***Big Market: Hydrogen Fuel, not Grid Electricity***
- ***Accelerate Conversion from Fossil***

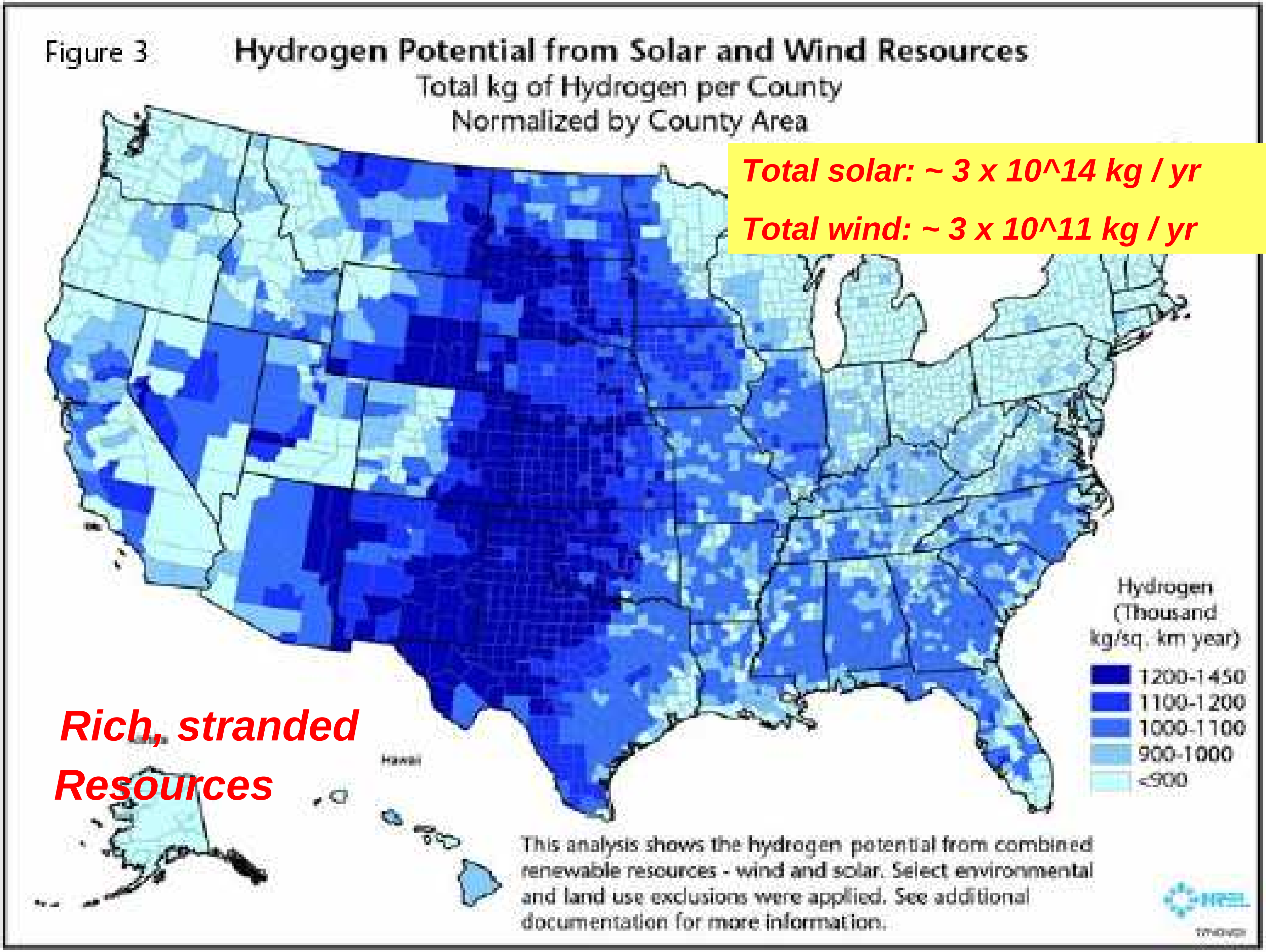
ALL *Denmark's energy from windpower*

- *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 ?*



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

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



Rich, stranded Resources


The Great Plains Wind Resource
How shall we bring the large, stranded, Great Plains renewables to market ?
PACIFIC OCEAN
ATLANTIC OCEAN
Gulf of Mexico

Why Hydrogen ?

- Bring diverse, stranded, large-scale, renewables to distant markets
- Firm time-varying-output renewables
  - seconds, seasons
  - energy storage
    - Pipelines
    - Geologic: salt caverns, other

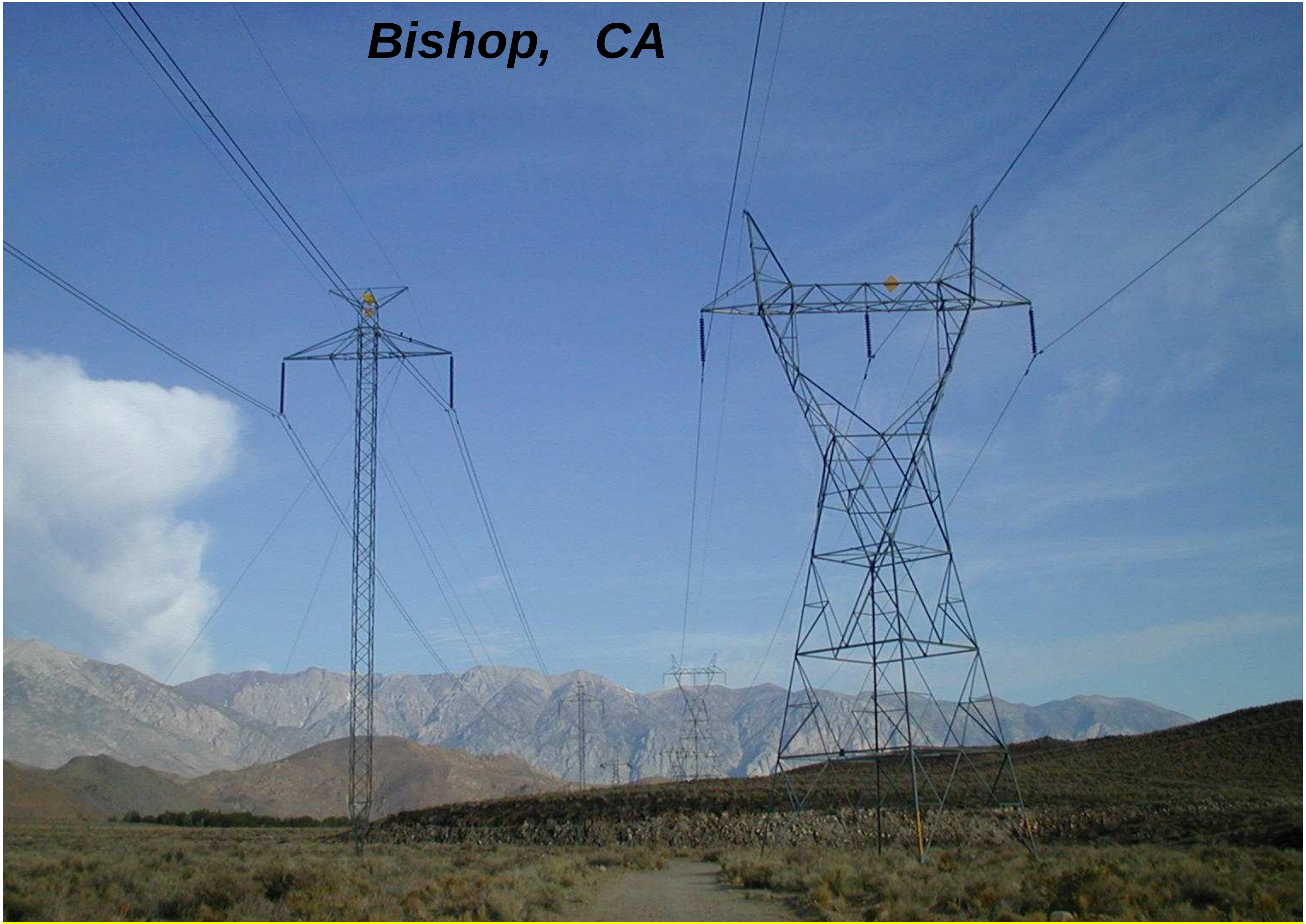
Exporting From 12 Windiest Great Plains States

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

Wind energy source: PNL-7789, 1991

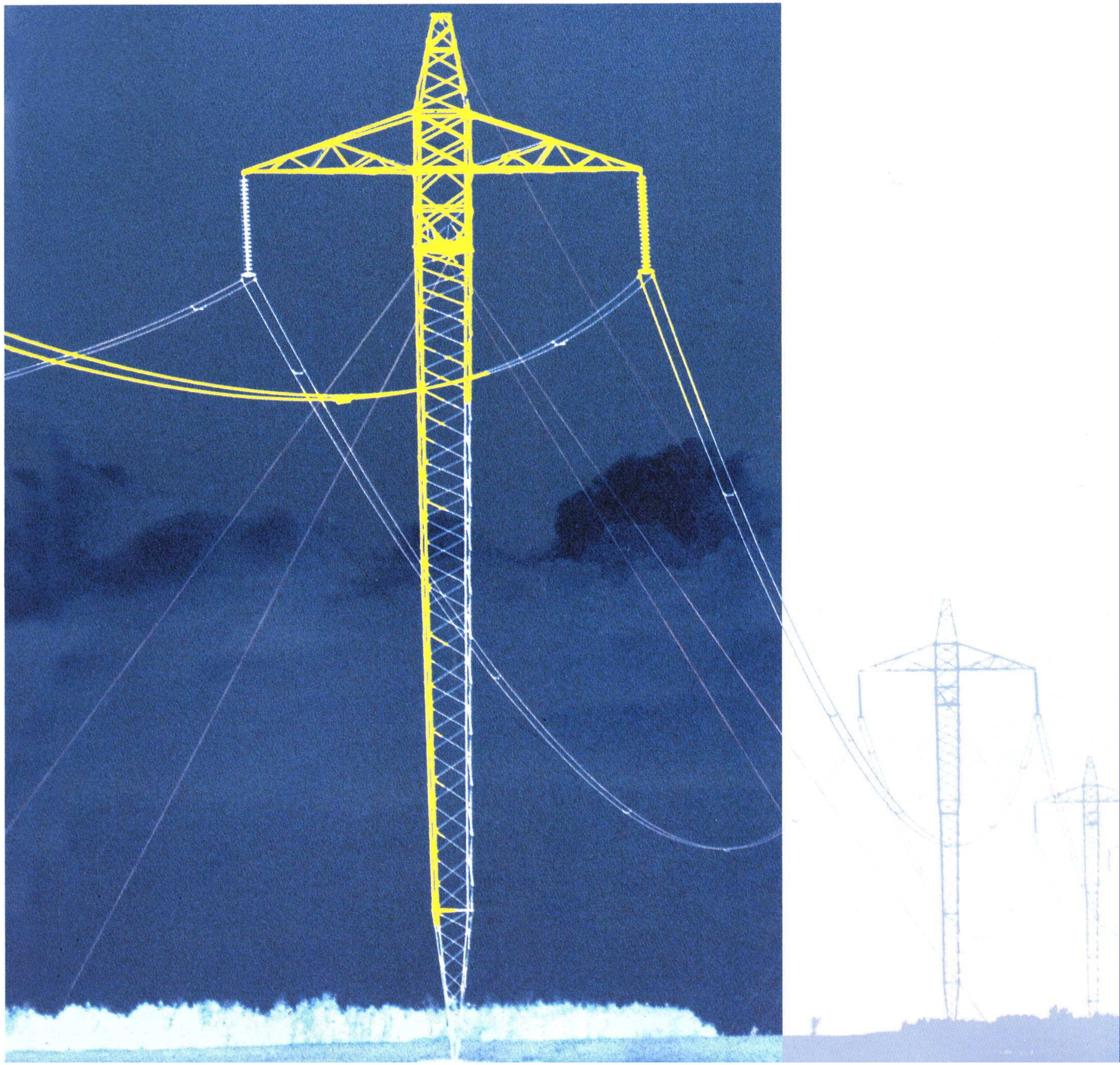
* at 500 miles average length

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



Left: 3,000 MW HVDC (Pacific DC Intertie, PDCI) Right: HVAC

High Voltage
Direct Current Transmission



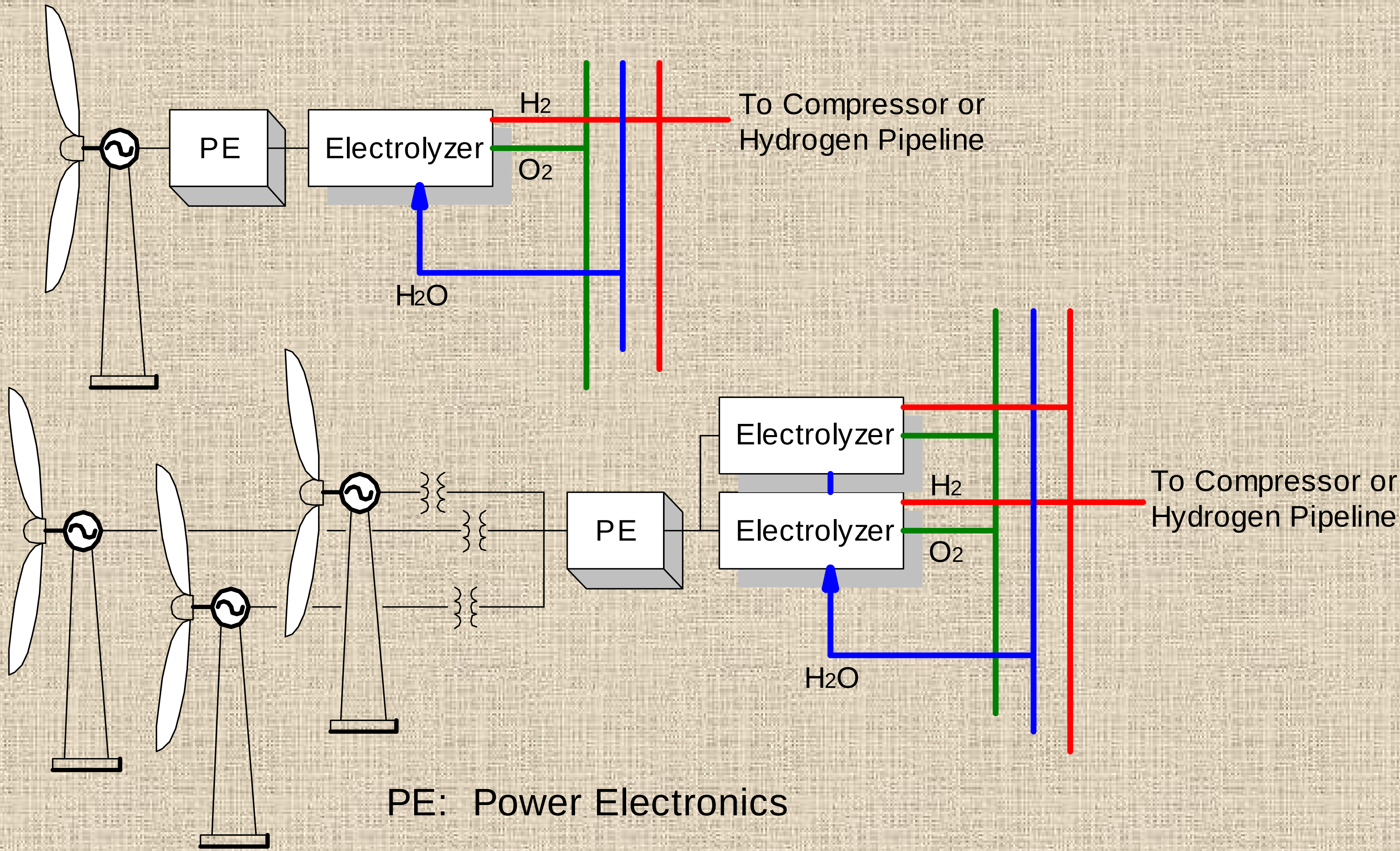
North Dakota
wind needs
115 new lines
at 3,000 MW
each

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

SIEMENS
HVDC line
+/- 500 kv

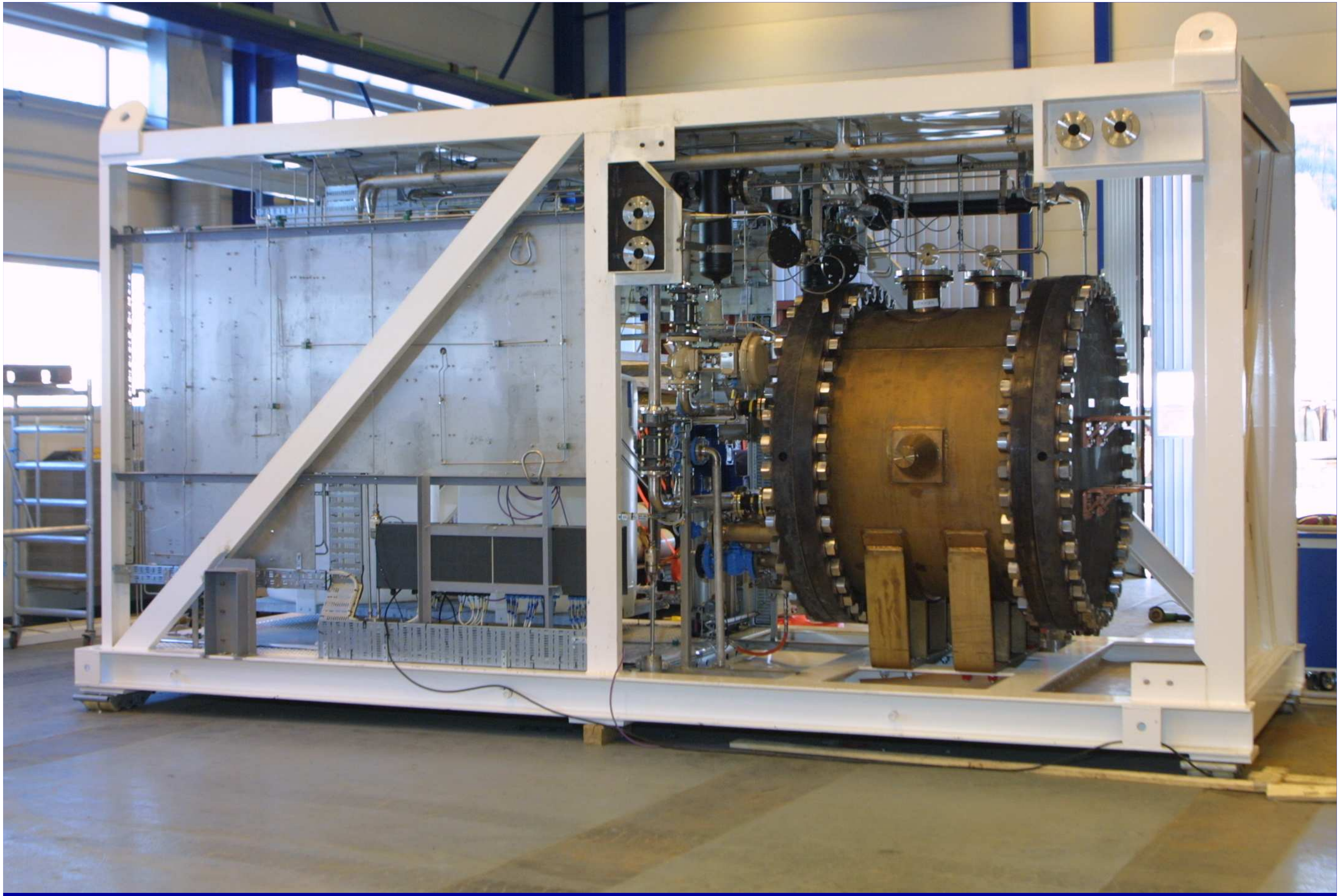
"Hydrogen Transmission Scenario"

Collection Topology Options:
Electrolyzer and Rectifier Location



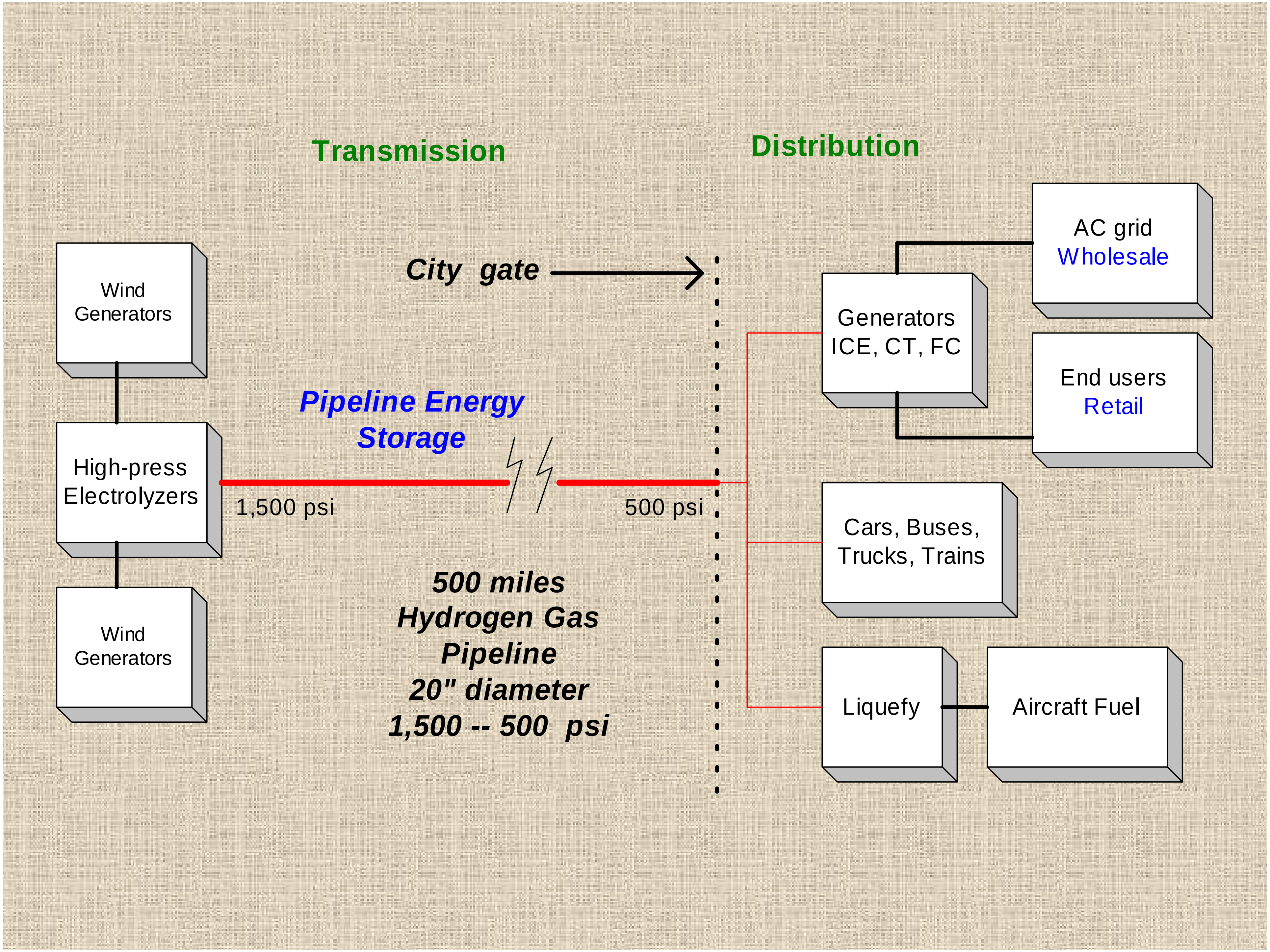
PE: Power Electronics

Norsk Hydro Electrolyzers 2 MW each



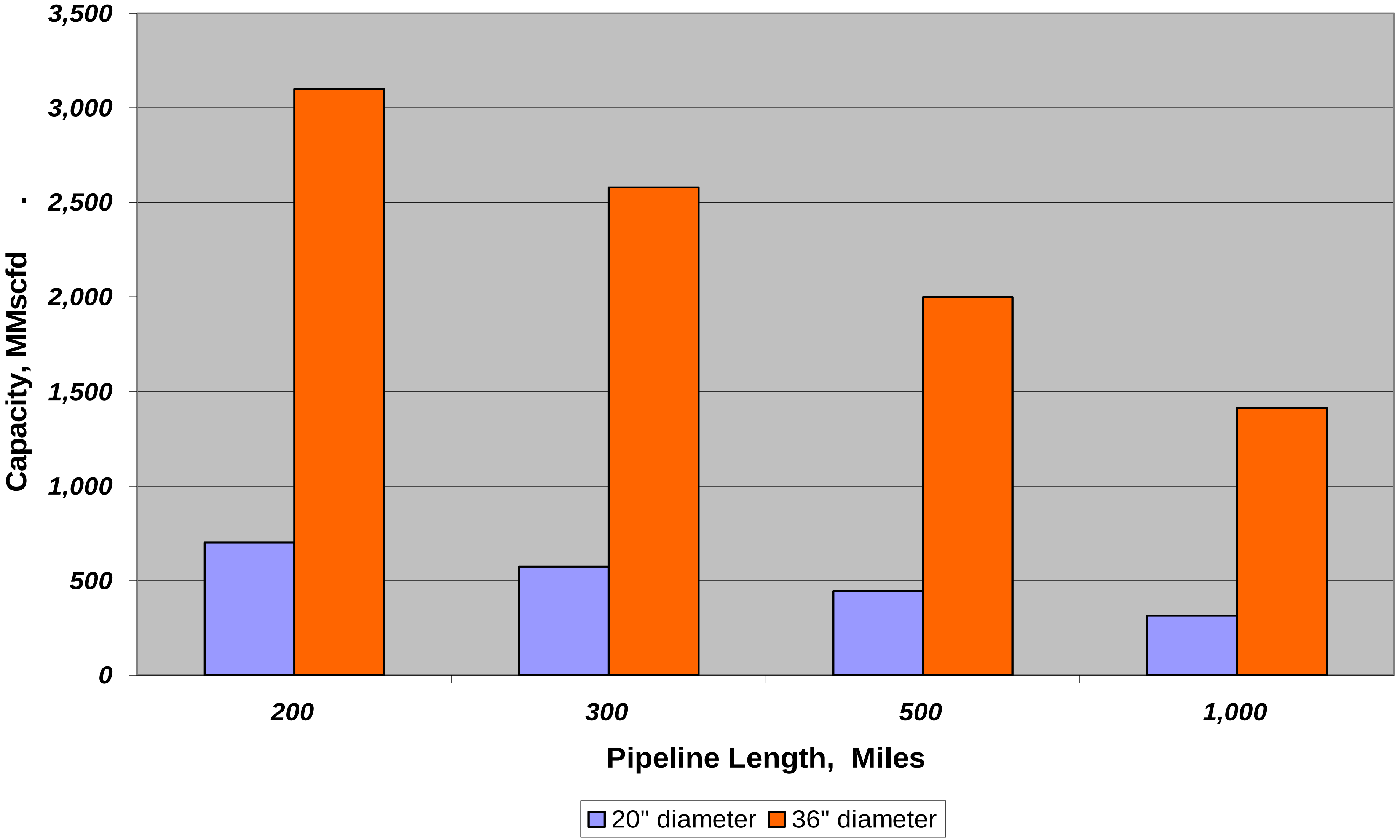
Norsk Hydro electrolyzer, KOH type

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


Transmission
Distribution
City gate
Wind Generators
High-press Electrolyzers
Wind Generators
Pipeline Energy Storage
1,500 psi
500 psi
500 miles
Hydrogen Gas
Pipeline
20" diameter
1,500 -- 500 psi
AC grid
Wholesale
Generators
ICE, CT, FC
End users
Retail
Cars, Buses,
Trucks, Trains
Liquefy
Aircraft Fuel

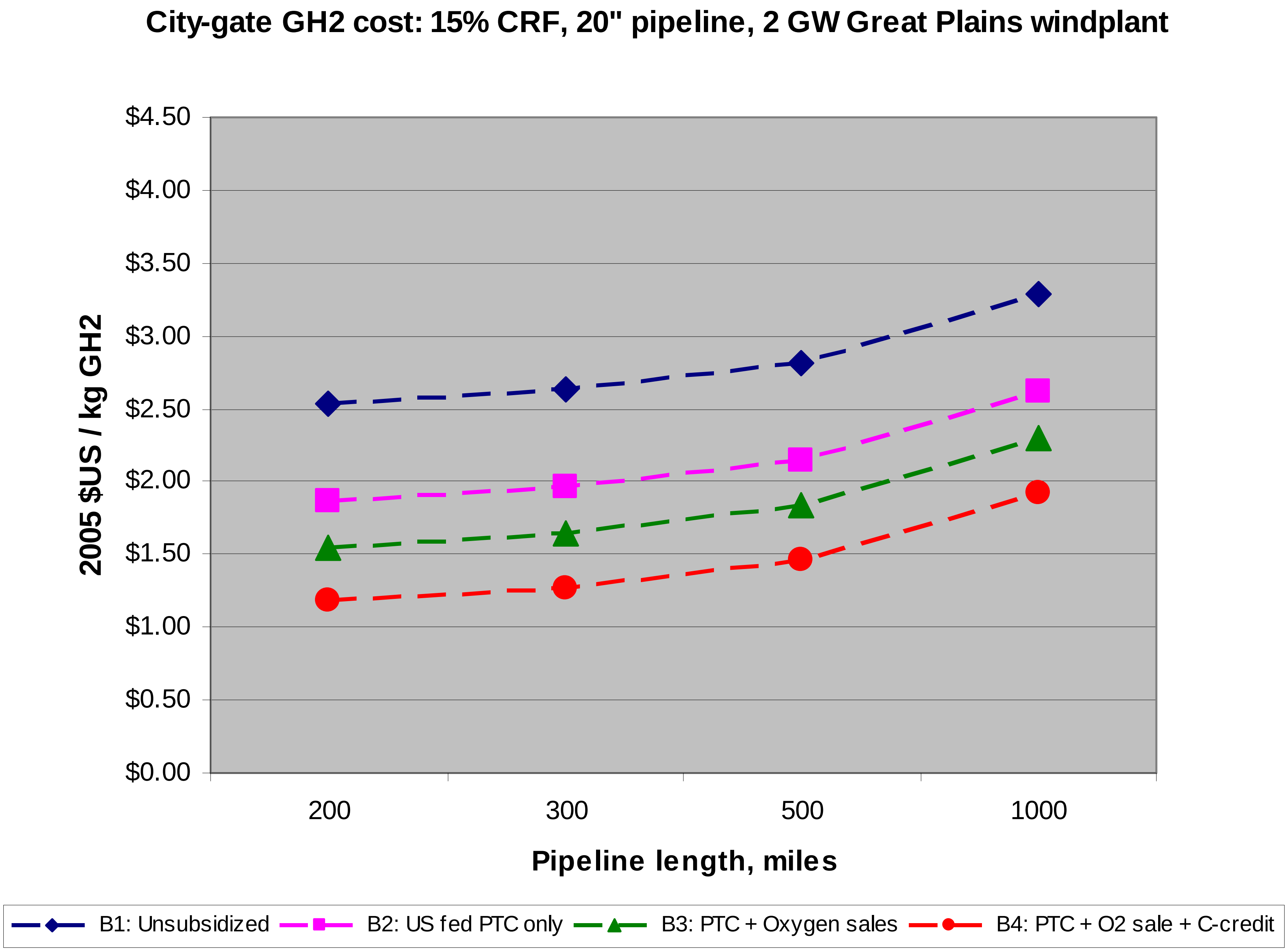
20”, 36” GH2 Pipeline Capacity

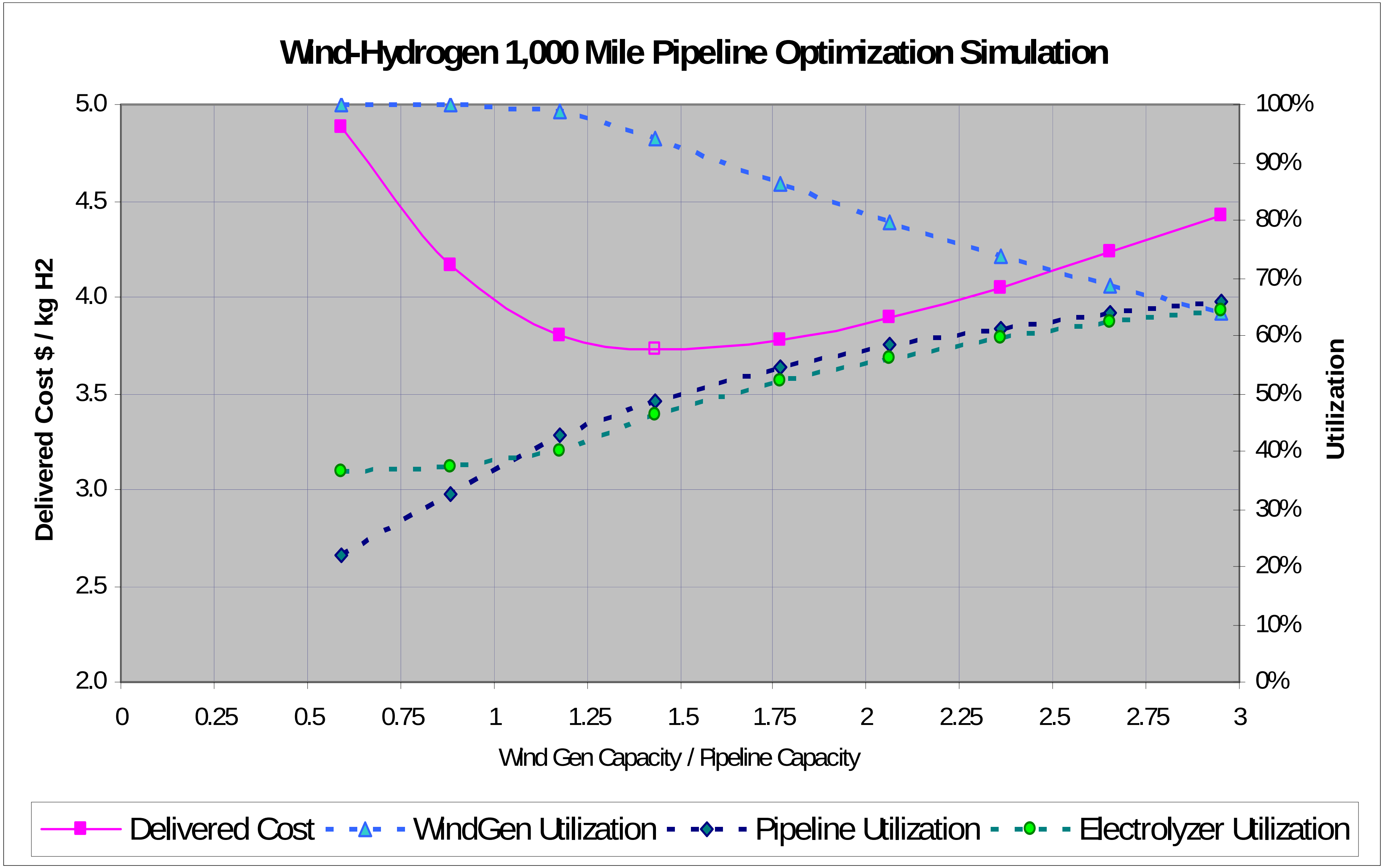
1,500 psi IN / 500 psi OUT



Total Installed Capital Cost 1,000 mile pipeline, $US million

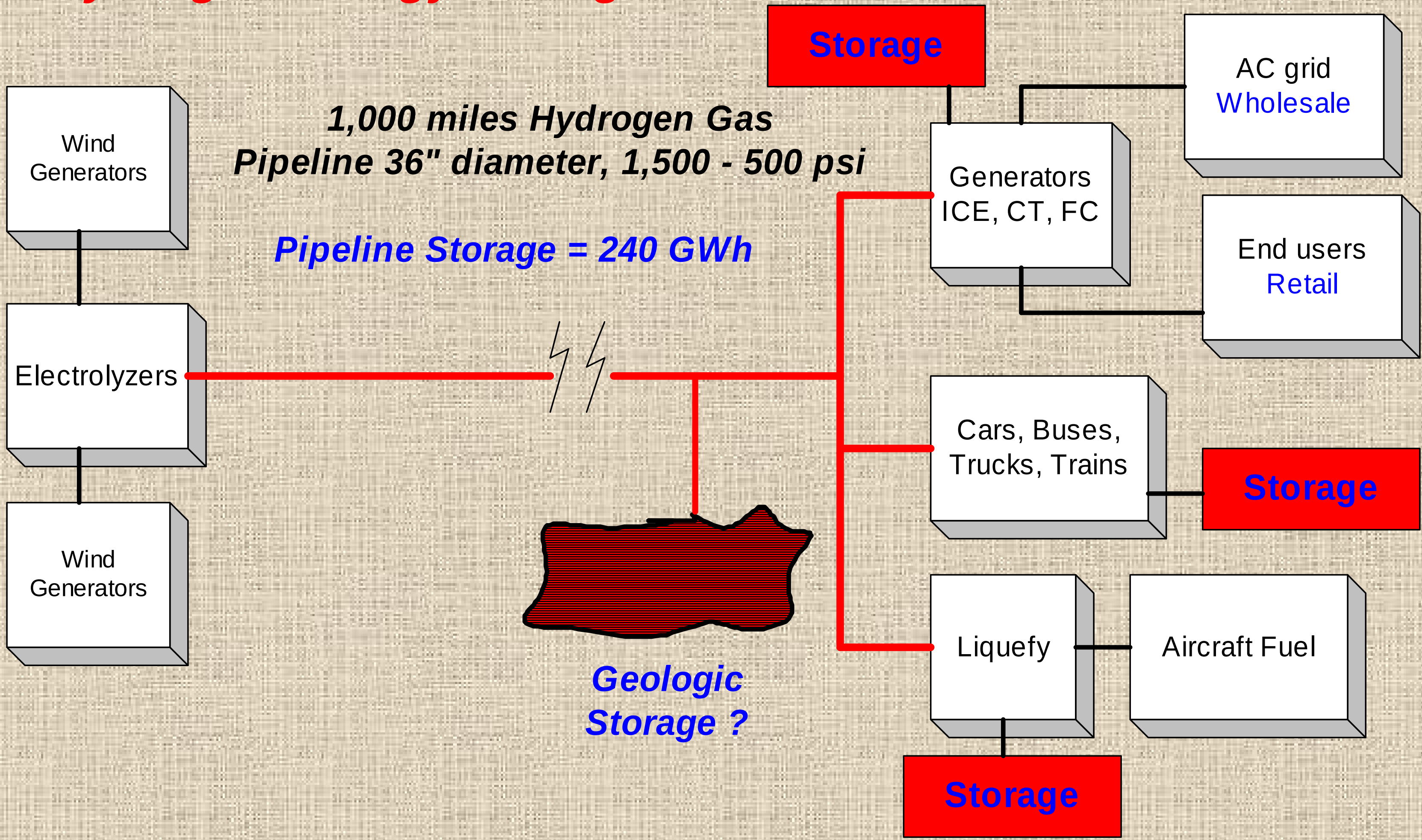
Windplant size	**1,000 MW**	**2,000 MW**
Wind generators	$ 1,000	$ 2,000
Electrolyzers	500	1,000
Pipeline, 20”	930	930
TOTAL	$ 2,430	$ 3,930


City-gate GH2 cost: 15% CRF, 20" pipeline, 2 GW Great Plains windplant
2005 $US / kg GH2
$4.50
$4.00
$3.50
$3.00
$2.50
$2.00
$1.50
$1.00
$0.50
$0.00
200
300
500
1000
Pipeline length, miles
B1: Unsubsidized
B2: US fed PTC only
B3: PTC + Oxygen sales
B4: PTC + O2 sale + C-credit

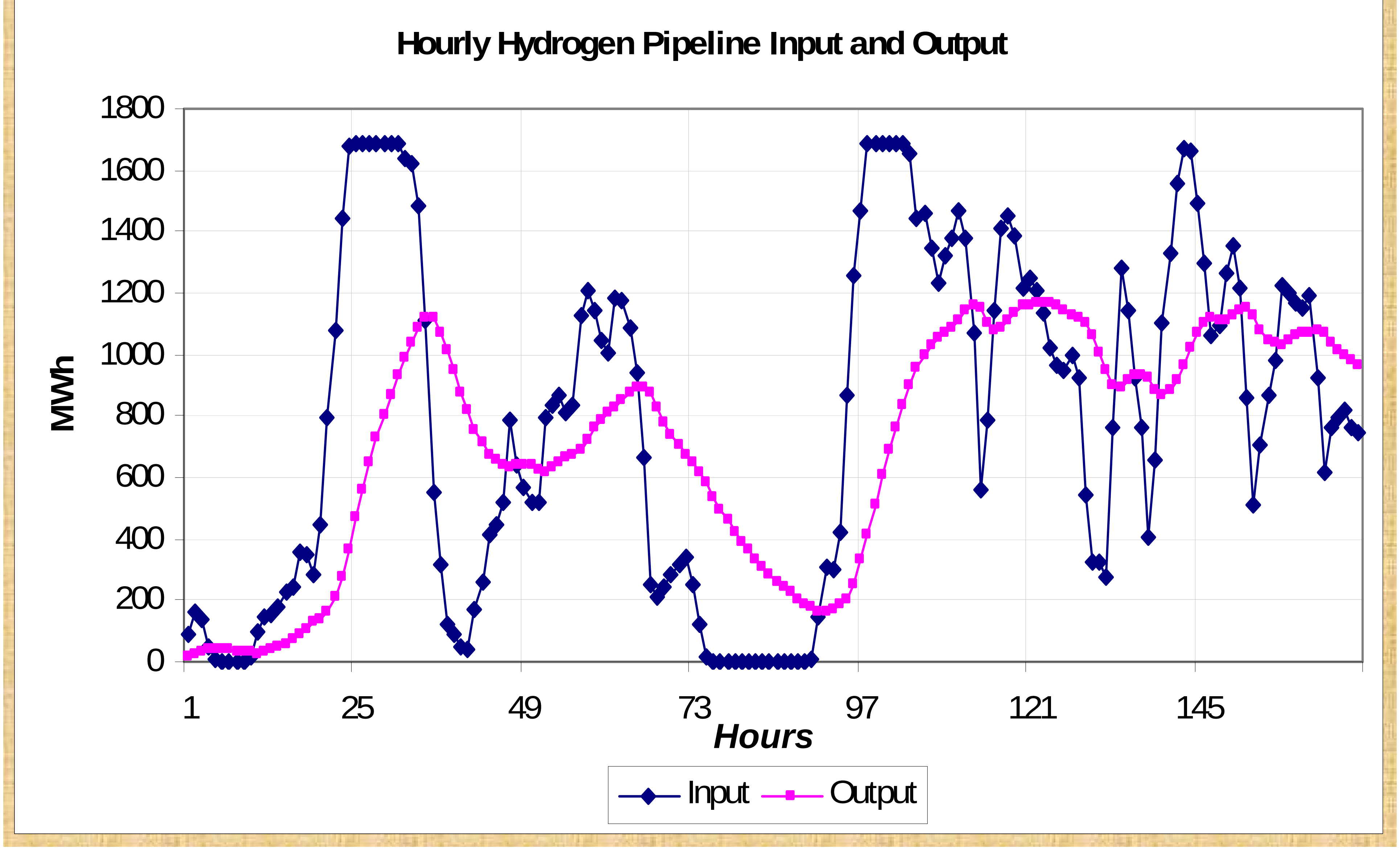


Wind-Hydrogen 1,000 Mile Pipeline Optimization Simulation
Delivered Cost $ / kg H2
5.0
4.5
4.0
3.5
3.0
2.5
2.0
Utilization
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
2.75
3
Wind Gen Capacity / Pipeline Capacity
Delivered Cost
WindGen Utilization
Pipeline Utilization
Electrolyzer Utilization

Hydrogen Energy Storage

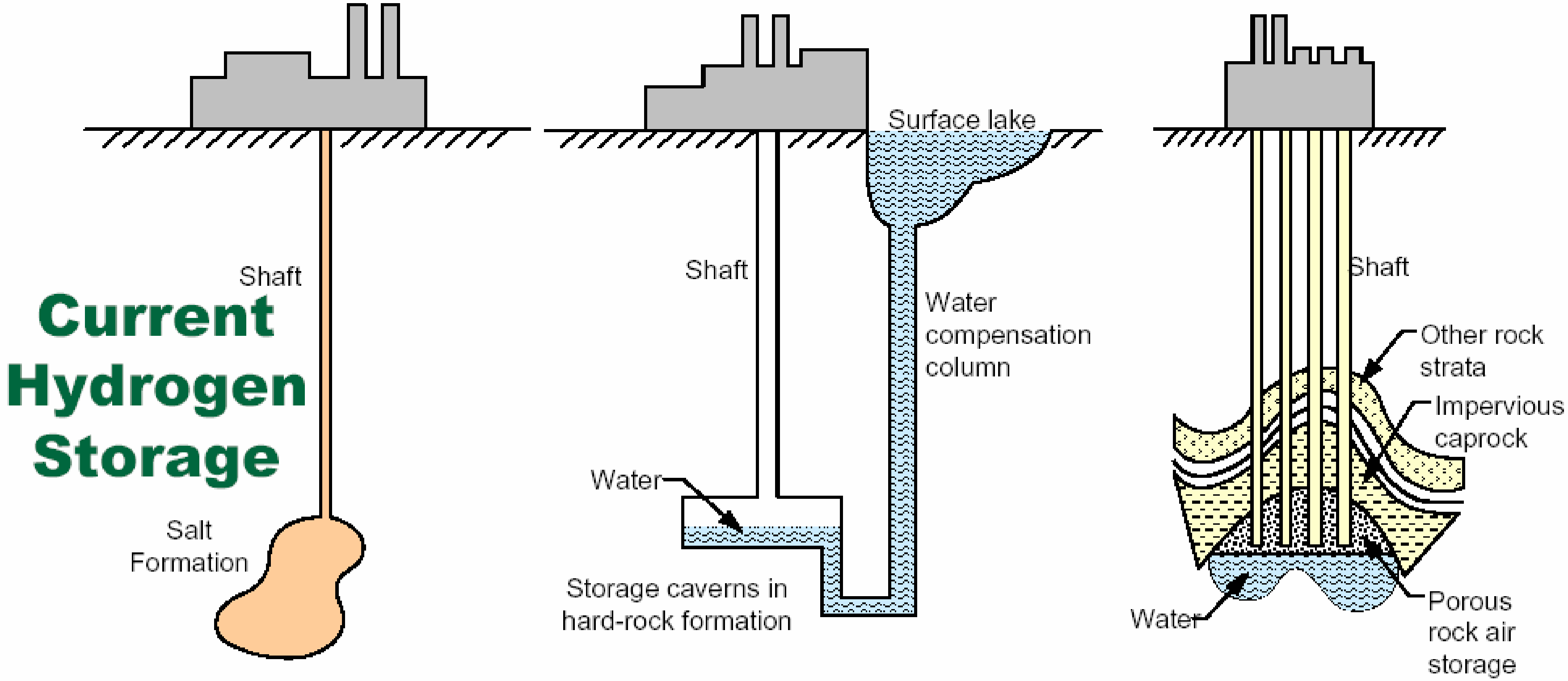


Great Plains Windplant, Pipeline Hourly Output for Typical Week



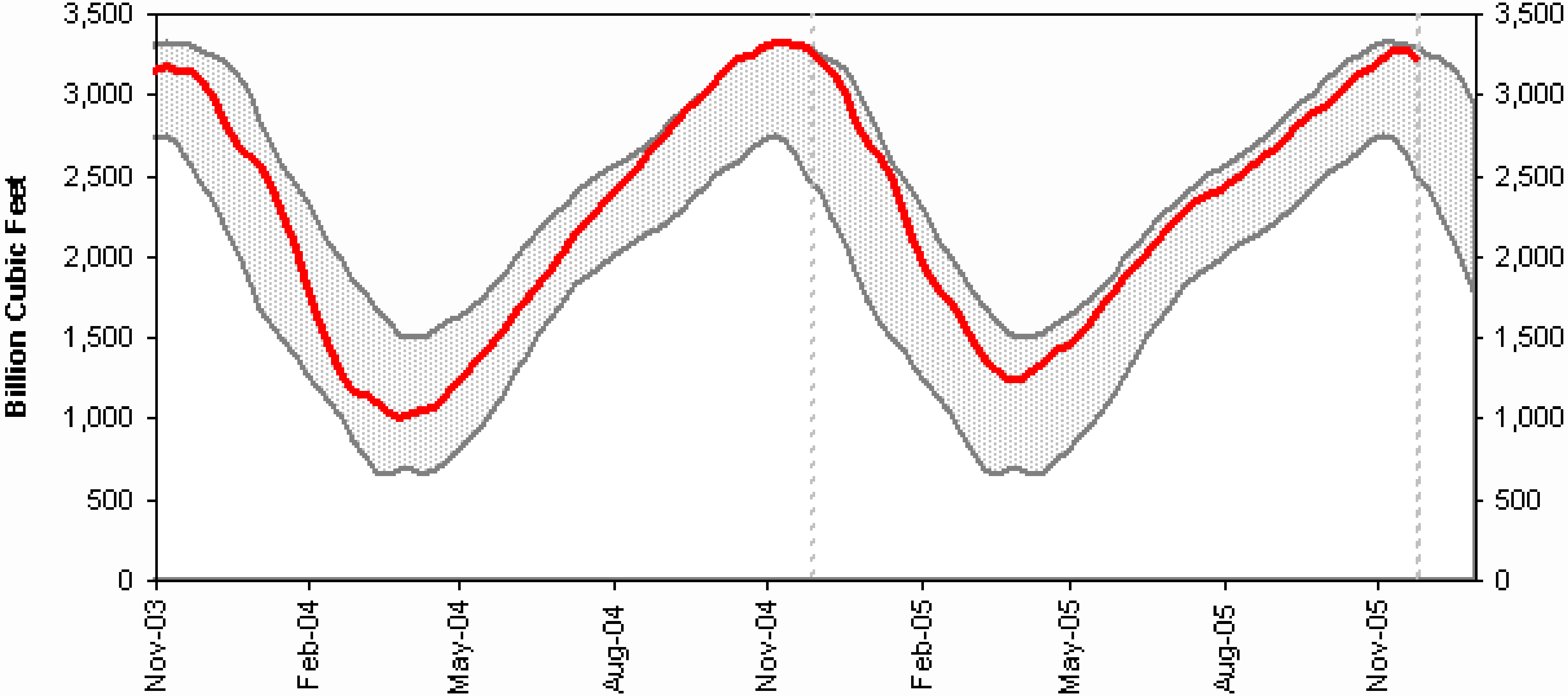
From: Charles W. Forsberg, ORNL, 17th NHA Conference, 12-16 Mar 06

Hydrogen Can Be Stored Underground At Low Costs



Natural Gas Stored Underground

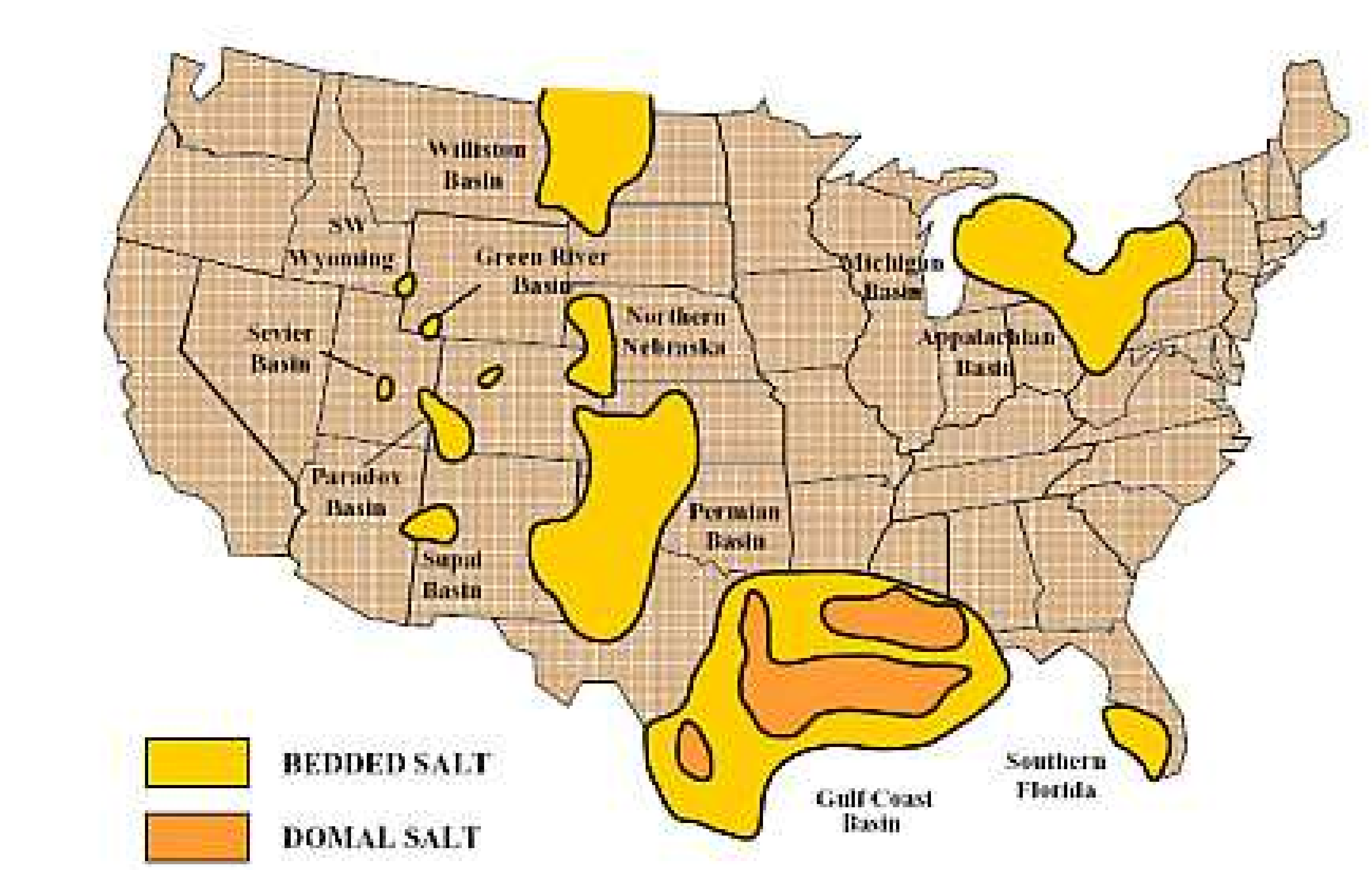
Working Gas in Underground Storage Compared with 5-Year Range



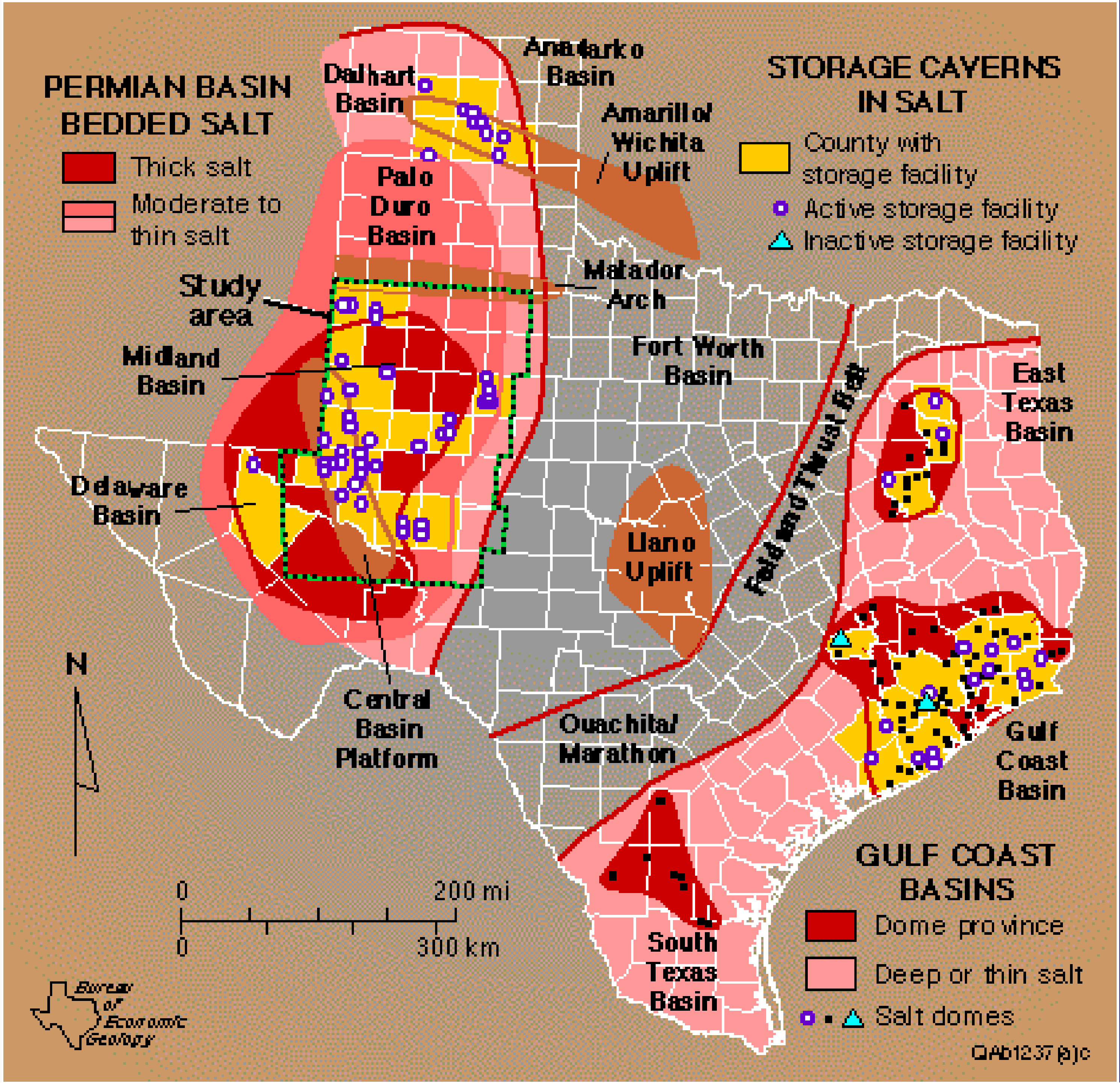
Total USA Natural Gas Underground Storage

Source: USDOE, EIA http://tonto.eia.doe.gov/oog/info/ngs/ngs.html

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



Geologic Salt: "Domal" , "Bedded"



"Dome" salt deposits are thicker and more homogeneous than "bedded"

ChevronPhilips GH2 Storage Cavern

- **Near Freeport, TX**
- **Solution-mined**
- **Estimated capital cost ’05 ~ $5 M**
- **20 years old**
- **2,200 psi design -- 2,000 psi operating**
- **Cavern roof 2,800 ft below surface**
- **160 ft diam x 1,000 ft high**
  – **580,000 m^3**
  – **6.4 million ft^3**

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TOTAL	$ 2,430	$ 3,930

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

Windplant size	**1,000 MW**	**2,000 MW**
	[million]	[million]
Wind generators	$ 1,000	$ 2,000
Electrolyzers	500	1,000
Pipeline	930	930
# storage caverns	[4]	[8]
Caverns @ $5M ea	20	40
Cushion gas @ $5M ea	20	40
TOTAL	$ 2,470	$ 4,010

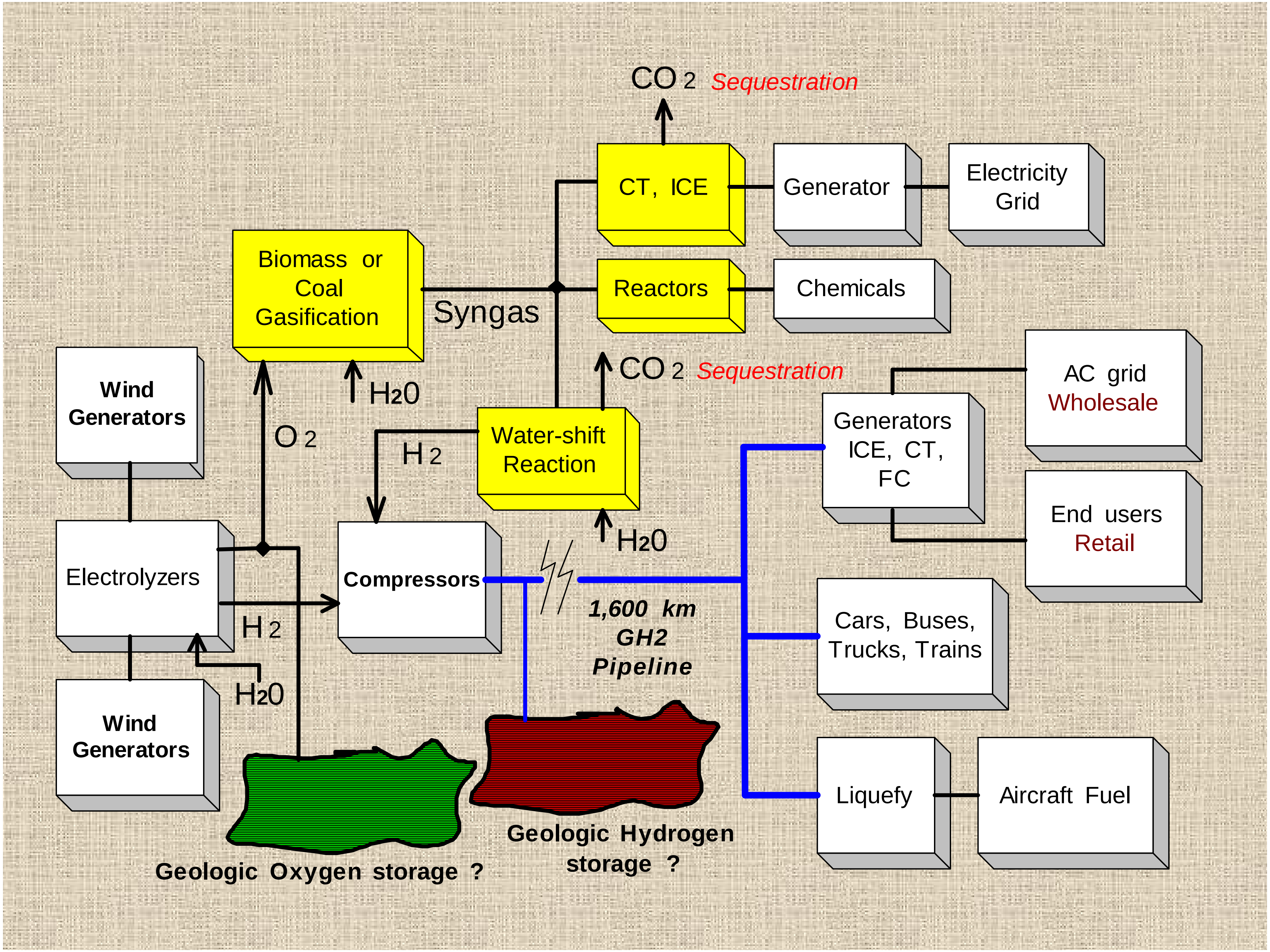
Cavern storage: 1.6% total capital cost

“Firming” GH2 Cavern Storage for ALL Great Plains Wind

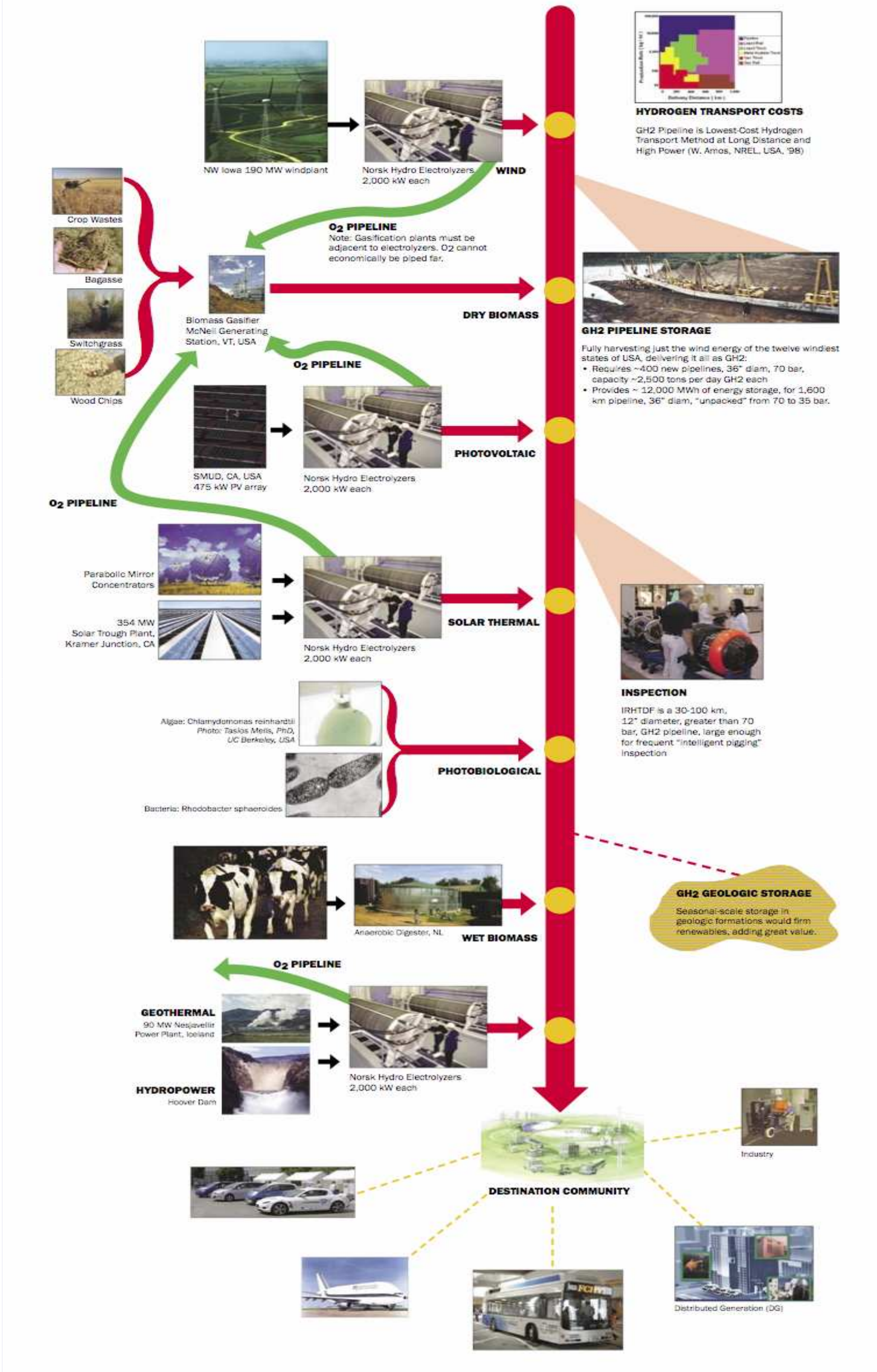
~ 12,000 caverns

Excavate:	$5 M each	$ 60 B
Cushion gas:	$5 M each	$ 60 B
Total		$120 B

Adds VALUE: strategic, market



CO2 Sequestration
CT, ICE
Generator
Electricity Grid
Biomass or Coal Gasification
Syngas
Reactors
Chemicals
Wind Generators
H2O
O2
CO2 Sequestration
AC grid Wholesale
Water-shift Reaction
H2
Generators ICE, CT, FC
Electrolyzers
Compressors
H2O
End users Retail
1,600 km GH2 Pipeline
H2
Cars, Buses, Trucks, Trains
H2O
Wind Generators
Liquefy
Aircraft Fuel
Geologic Hydrogen storage ?
Geologic Oxygen storage ?



International Renewable Hydrogen Transmission Demonstration Facility

(IRHTDF)

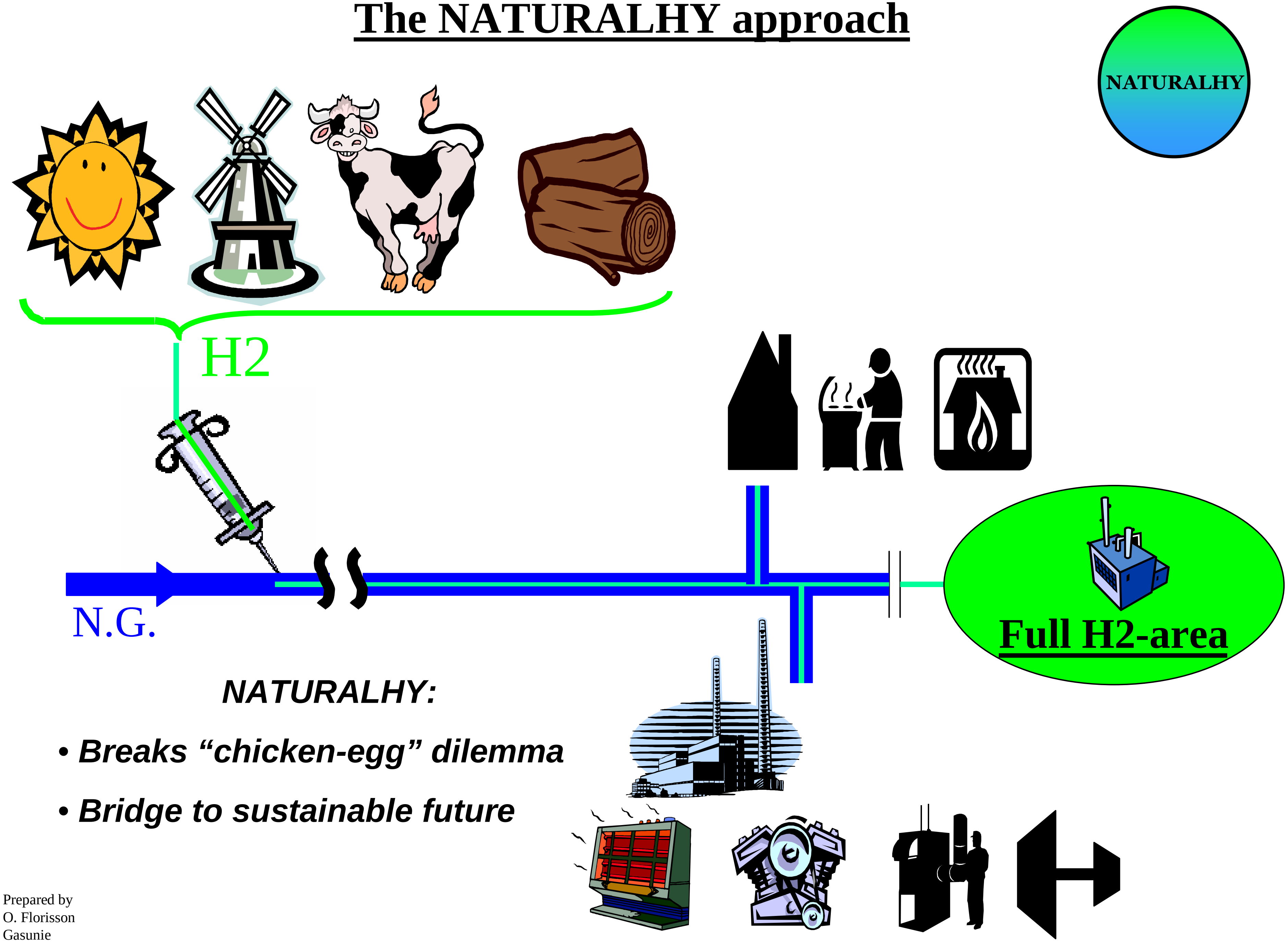
Pilot plant

Global opportunity: IPHE project

IRHTDF startup

- $150K "champion" funding: AASI
- Coalition of interest
  - Renewables sources: wind, CSP, biomass
  - Automakers
  - USDOE, Labs
  - Industry: GE, APCI, BP, Shell, automakers
  - Great Plains states: MN, UMHI
  - Japan, NAGPF
  - Environ, trade, policy groups
- Revise concept
- Econ + tech
  - Feasibility studies;
  - Catalog R+D to precede it
- Preliminary design
- IPHE project proposal (via ILC): sponsors, site

The NATURALHY approach



NATURALHY:

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

Prepared by
O. Florisson
Gasunie

When we realize these as emergencies:

- Global Warming, Climate Change
- Energy Security and Cost
- Peak Oil and Natural Gas

We must quickly invest in:

- Energy conservation, efficiency
- Large, new energy supplies:
  - CO_2-emissions-free
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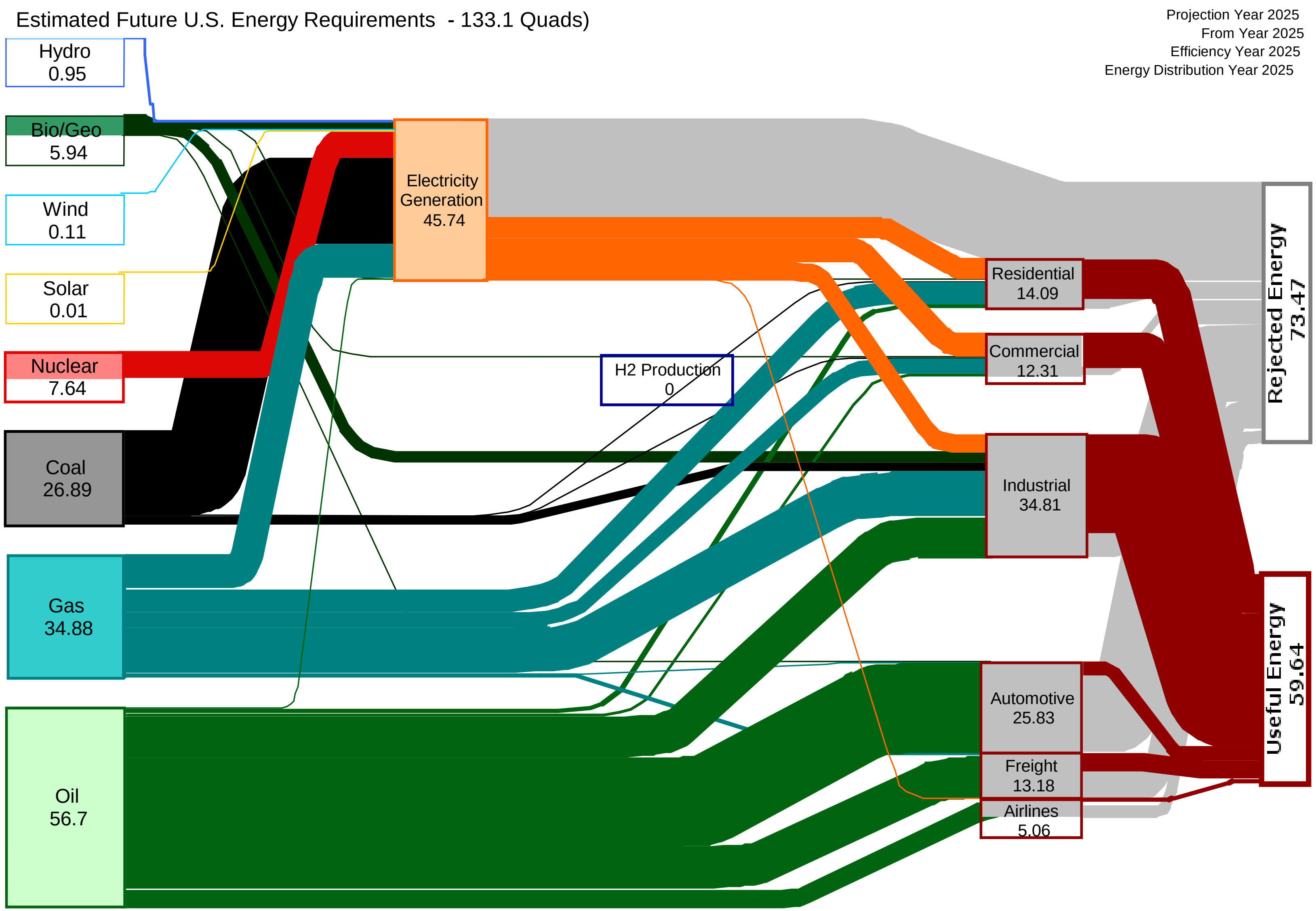
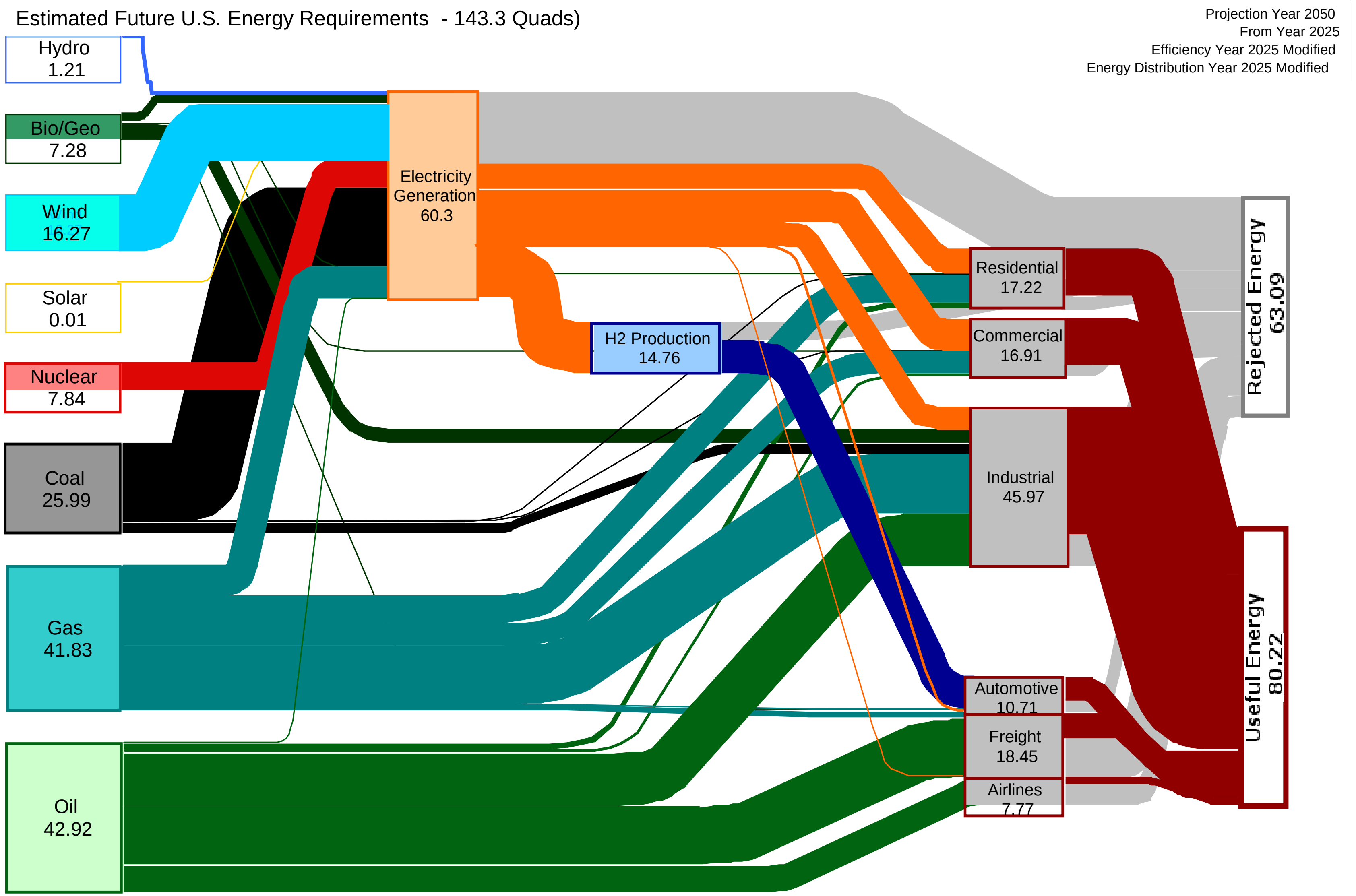
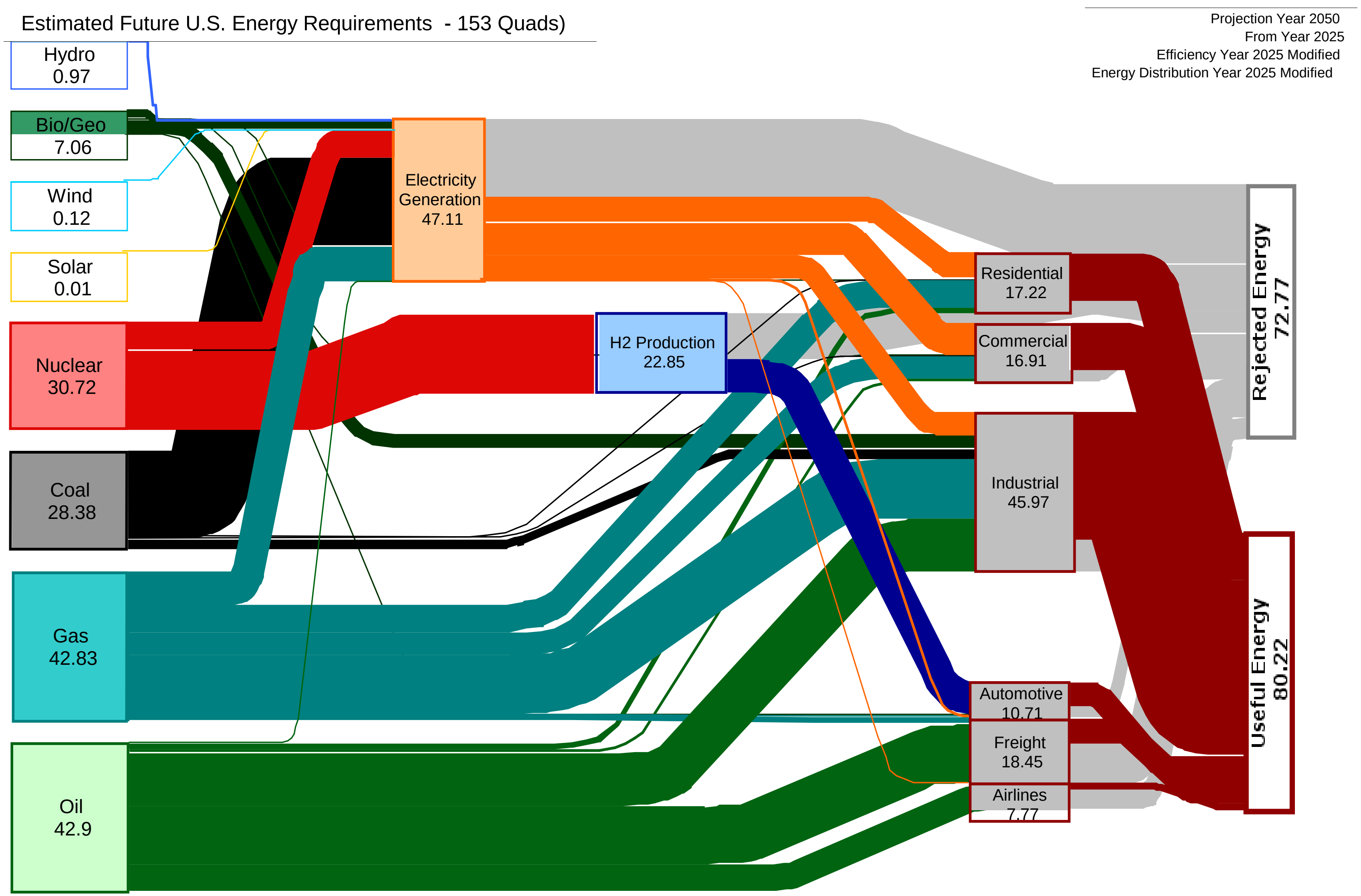
EIA estimated 2025 energy use

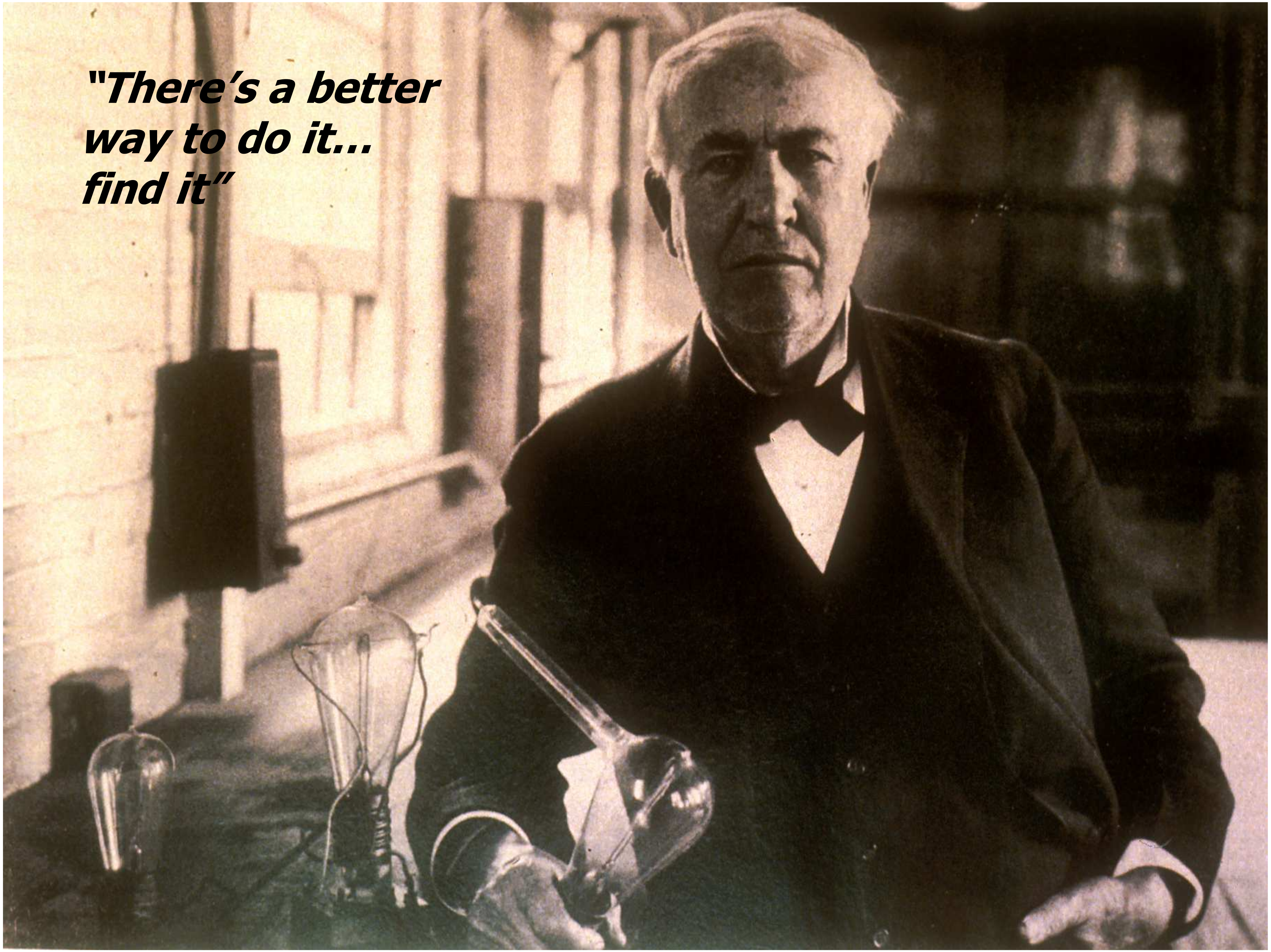


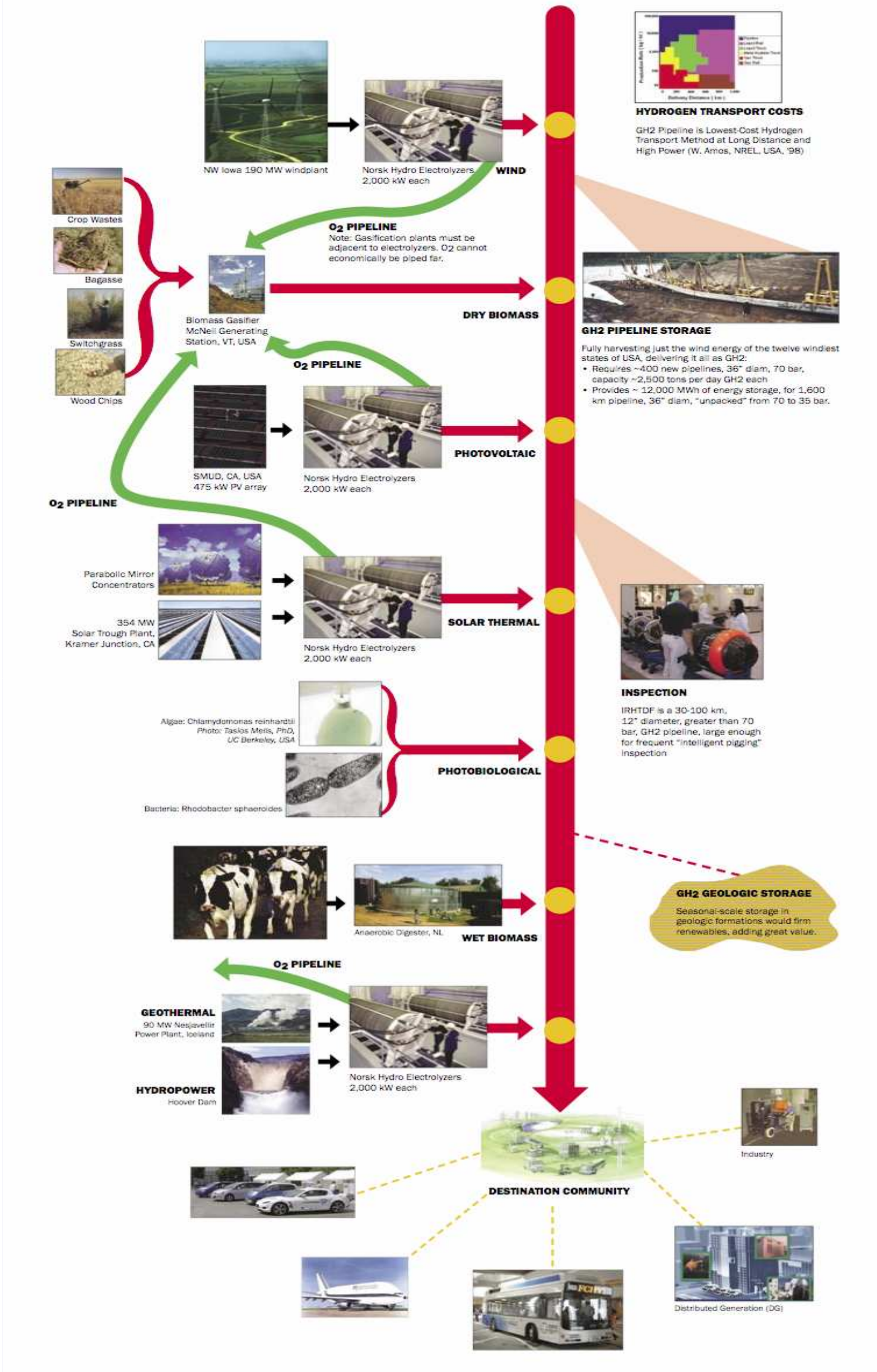
Estimated 2050 energy use
(H_2 fleet using wind electrolysis)



Estimated 2050 energy use
(H_2 fleet using nuclear thermochemical)




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



International Renewable Hydrogen Transmission Demonstration Facility

(IRHTDF)

Pilot plant

Global opportunity: IPHE project

I R H T D F

- *Pilot plant: Every new industrial process*
- *Renewables-hydrogen* ***system***
  - *Generation*
  - *Conversion*
  - *Collection*
  - *Transmission*
  - *Storage*
  - *Distribution, end users*
  - *Synergy: O2, seasonal*

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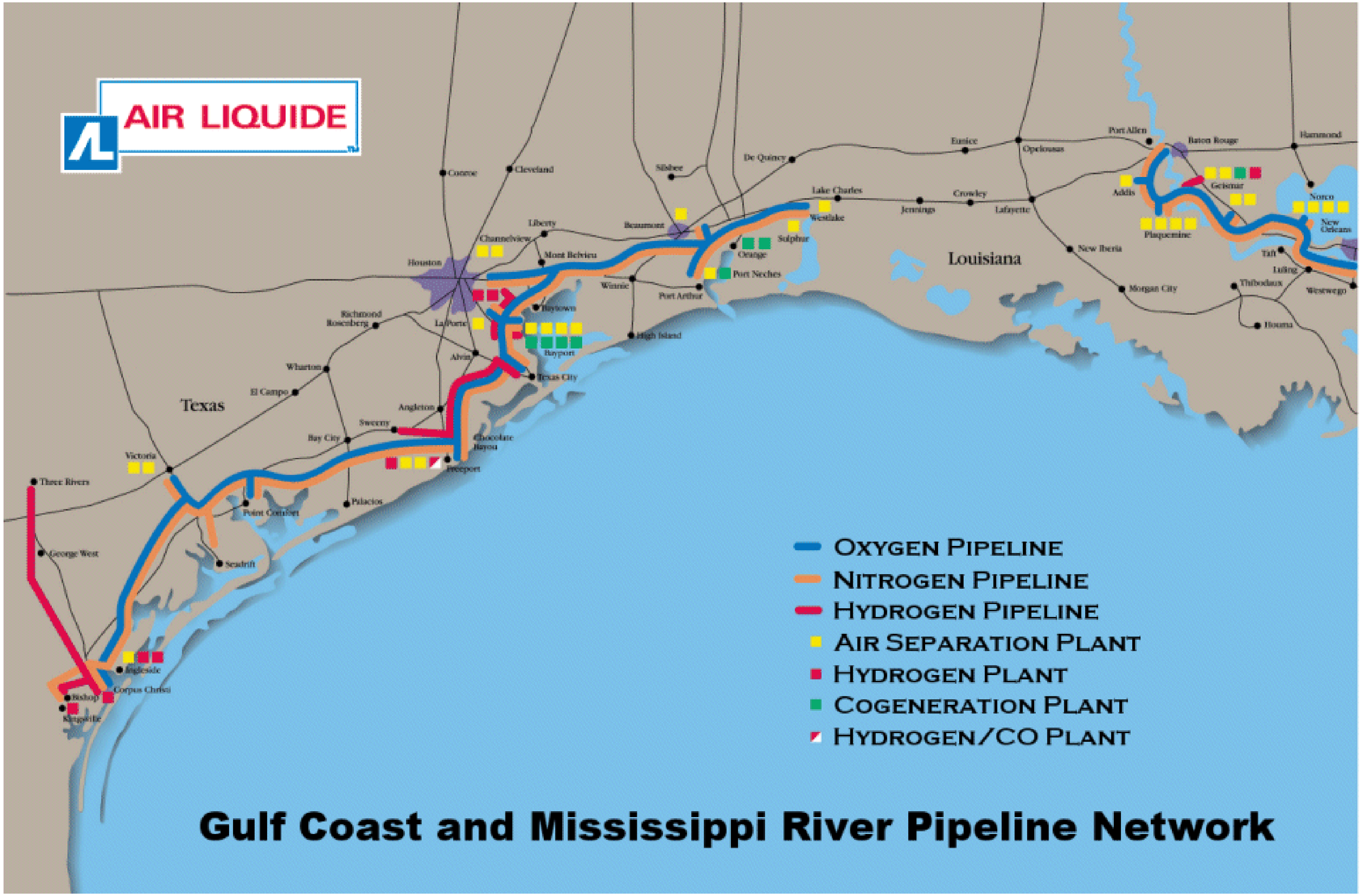

AIR LIQUIDE
Texas
Louisiana
Houston
Beaumont
Lake Charles
Baton Rouge
New Orleans
Corpus Christi
Freeport
Port Arthur
Baytown
Texas City
Victoria
Oxygen Pipeline
Nitrogen Pipeline
Hydrogen Pipeline
Air Separation Plant
Hydrogen Plant
Cogeneration Plant
Hydrogen/CO Plant
Gulf Coast and Mississippi River Pipeline Network

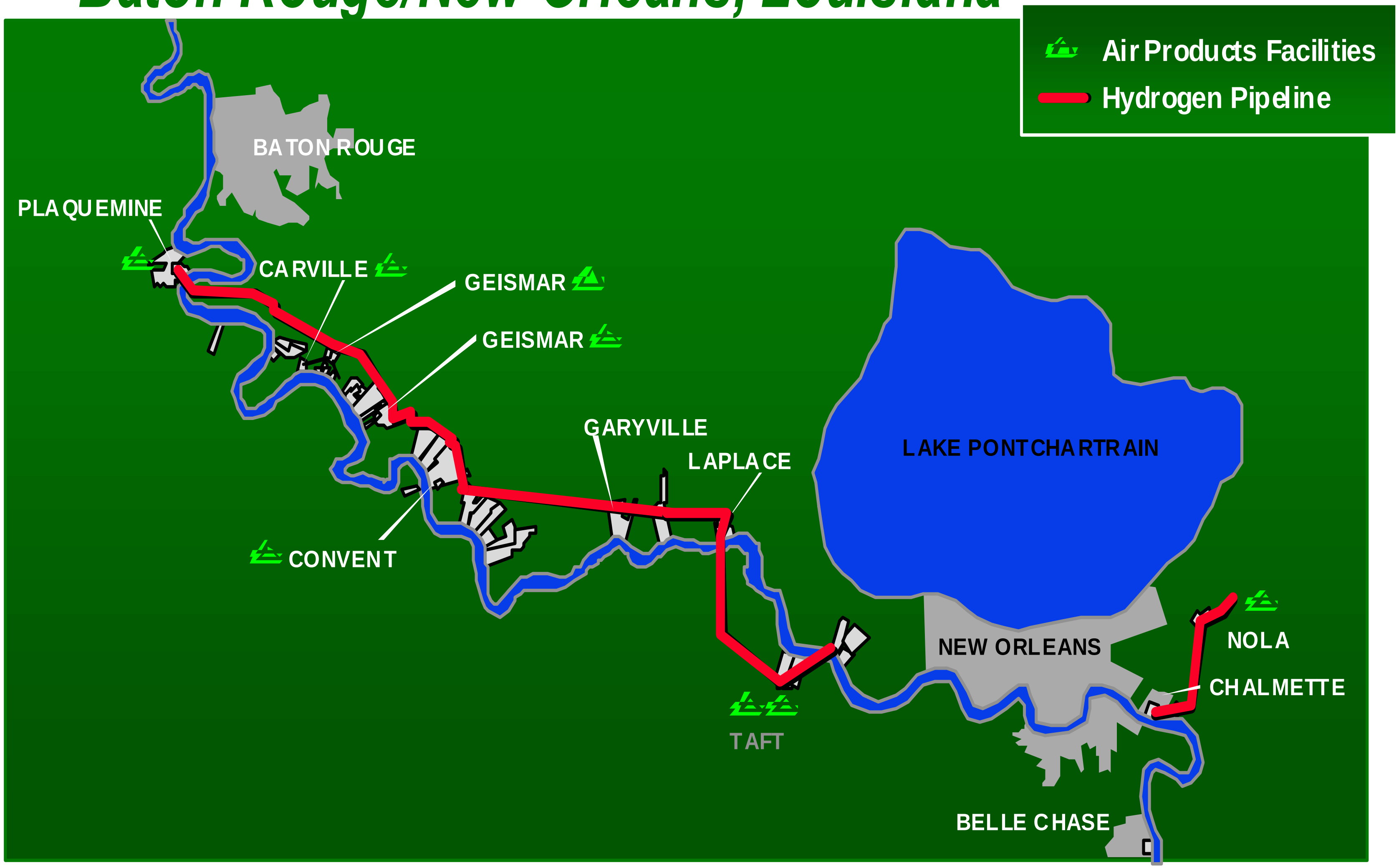
"We know how to pipeline hydrogen" Air Products

~ 10,000 miles of GH2 pipeline, worldwide

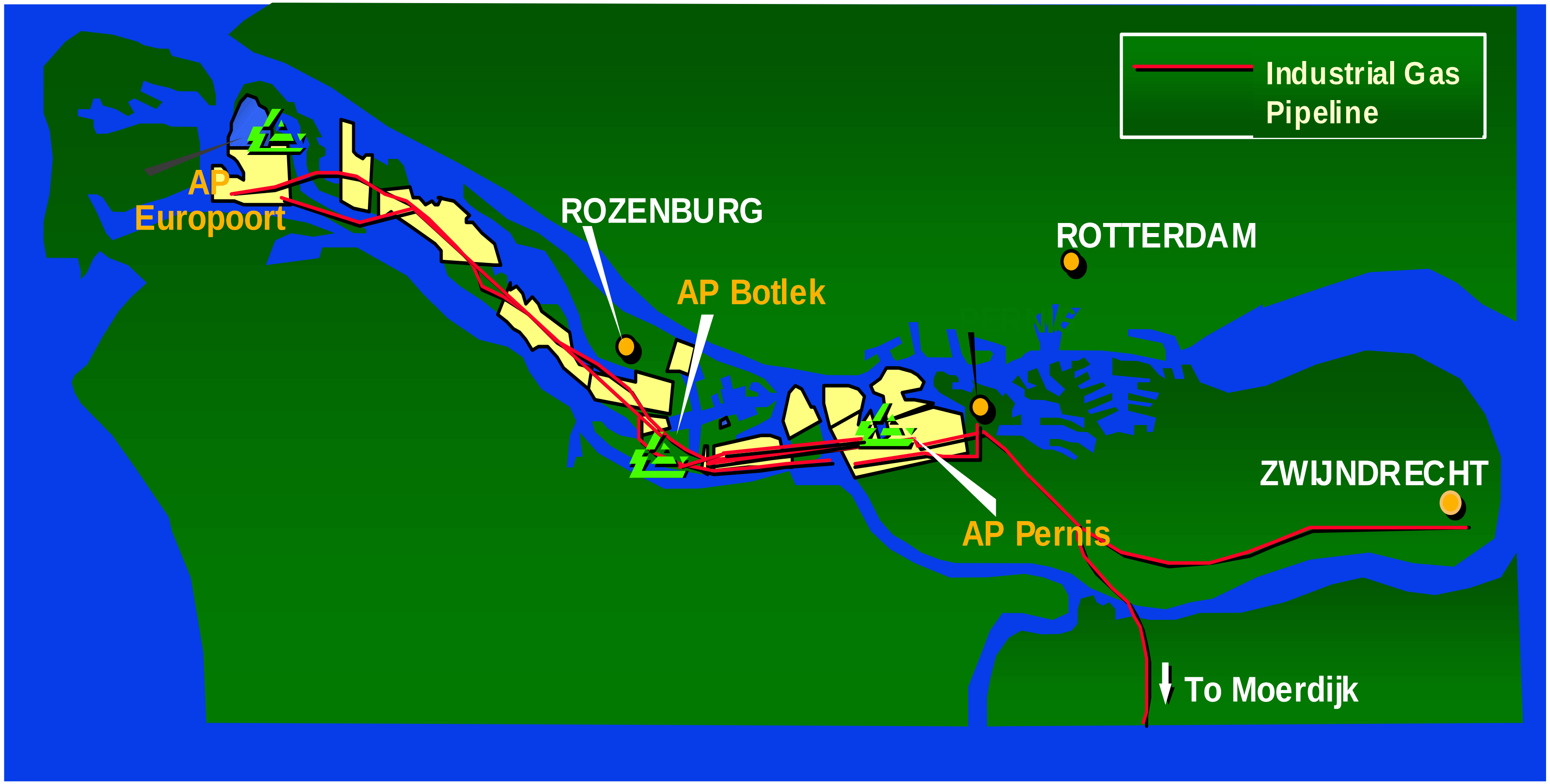
Air Products H_2 / CO Pipeline - *Texas Gulf Coast*

abc

Air Products H_2 Pipeline
Baton Rouge/New Orleans, Louisiana



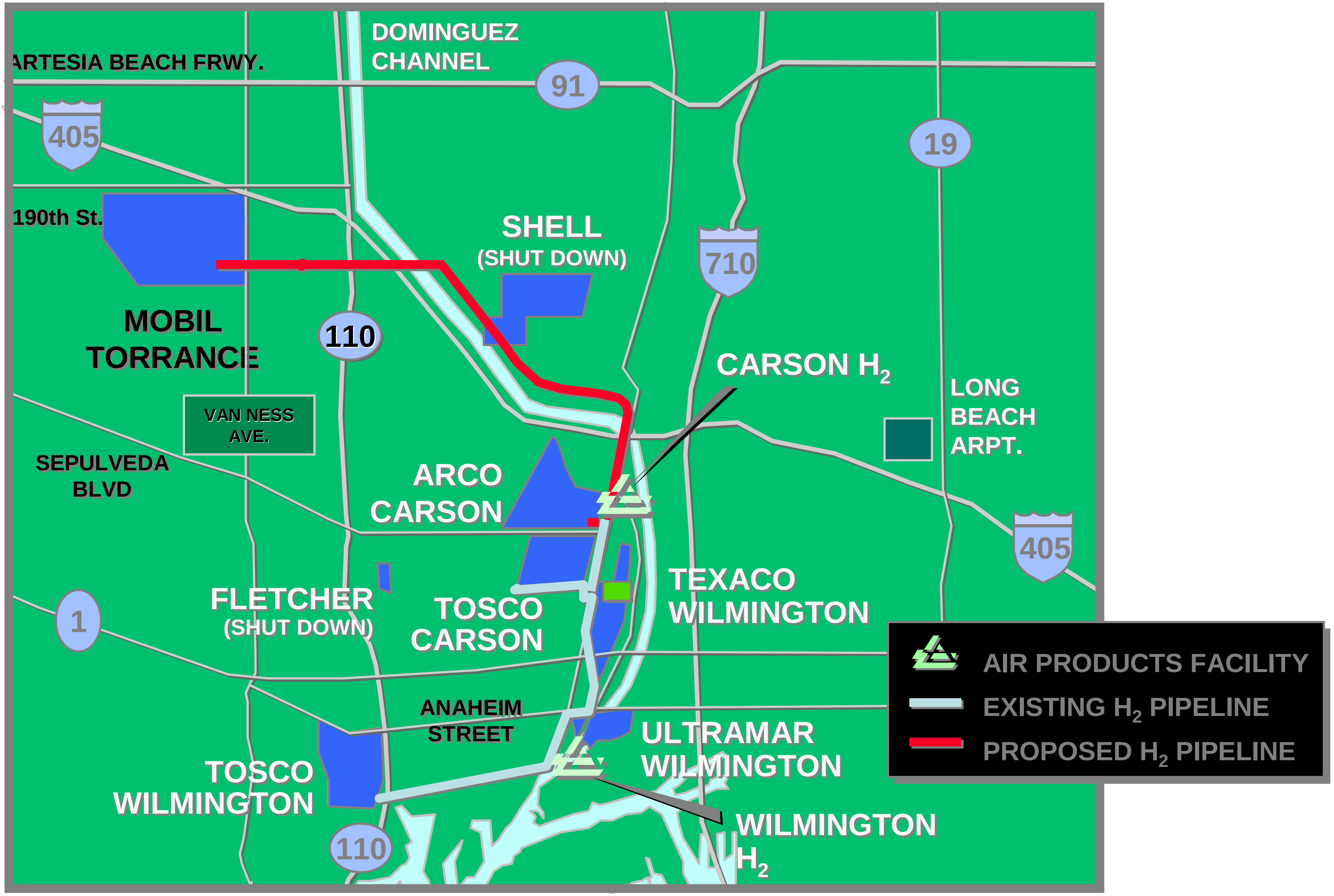
Rotterdam Pipeline System



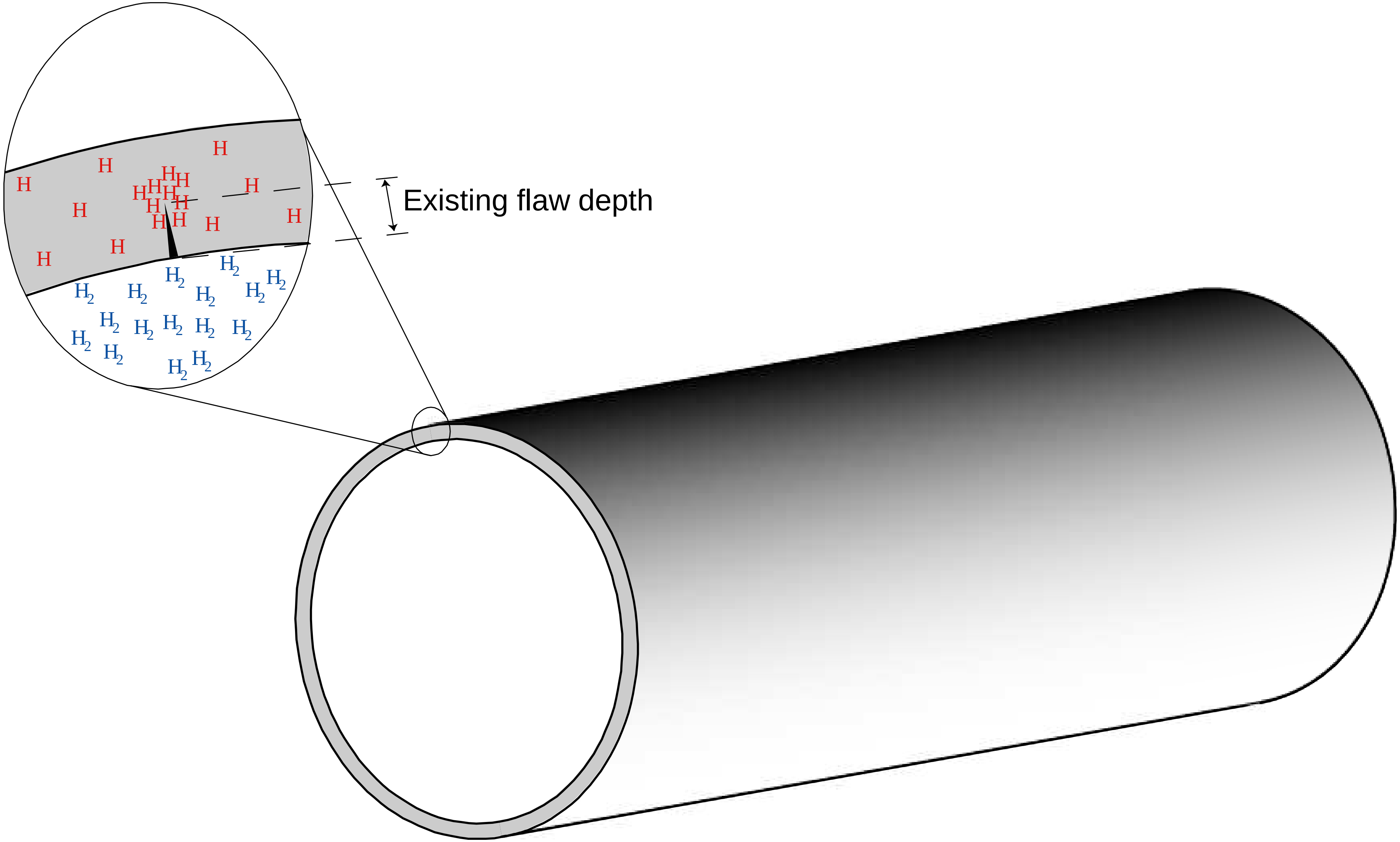
Air Products Company

REFINERY ACTIVITY

LOS ANGELES BASIN, CALIFORNIA



Hydrogen Embrittlement (HE) of Pipeline Steel



Industrial H2 Pipelines

- 3,000 km worldwide
- Industrial corridors; on-site
- 30% SMYS typical *
- Constant pressure; low fatigue
- Low-alloy, low-strength steel
- Re-purposed oil pipelines

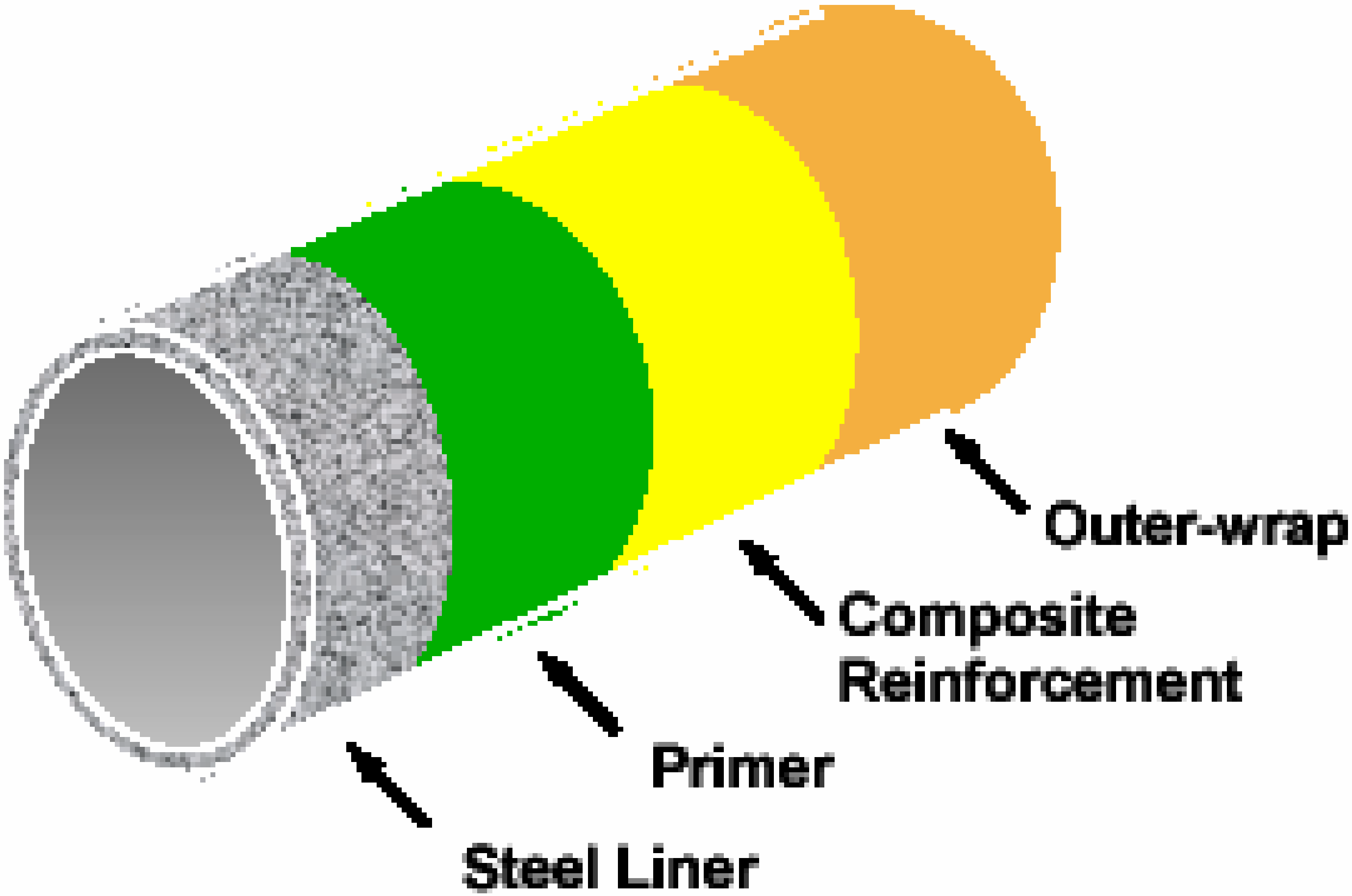
**** Specified Minimum Yield Strength***

Line Pipe Material Options

- Control Hydrogen Embrittlement (HE)
- Minimize energy-distance cost (kg-km)
- “Sour service” X65 steel
- HTUFF by Nippon Steel: microstructure
- CRLP by TransCanada and NCF
- New ?

Composite Reinforced Line Pipe (CRLP)

TransCanada Pipelines & NCF Industries



Composite – Reinforced Line Pipe (CRLP)

3,400 psi, .75" X70 steel plus .75" composite

NCF Industries and TransCanada Pipelines
ASME International Pipeline Conference and Exposition,
Calgary, AB, Canada, October 02.

Composite Reinforced Line Pipe (CRLP)

42" diameter
3,400 psi
.75" X70 steel
.75" composite

NCF Industries and TransCanada Pipelines

ASME International Pipeline Conference and Exposition, Calgary, AB, Canada, October 02.

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CRLP™ is manufactured under license from NCF Industries, Inc. U.S. and Foreign patents have been issued and are pending.


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NCF

Wrapper, composite splice

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