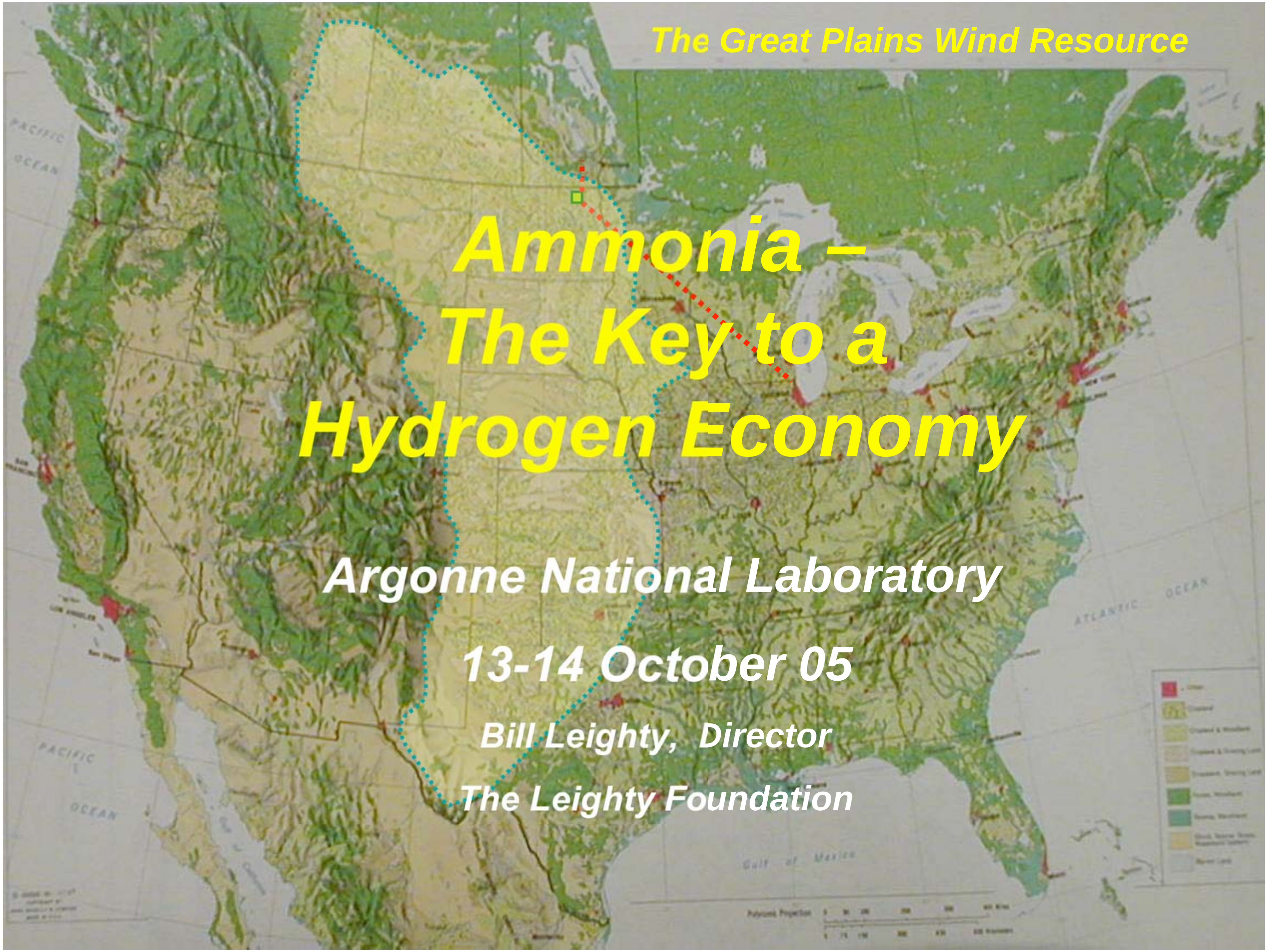


Ammonia – The Key to a Hydrogen Economy

Argonne National Laboratory

13-14 October 05

Bill Leighty, Director

The Leighty Foundation

The Great Plains Wind Resource

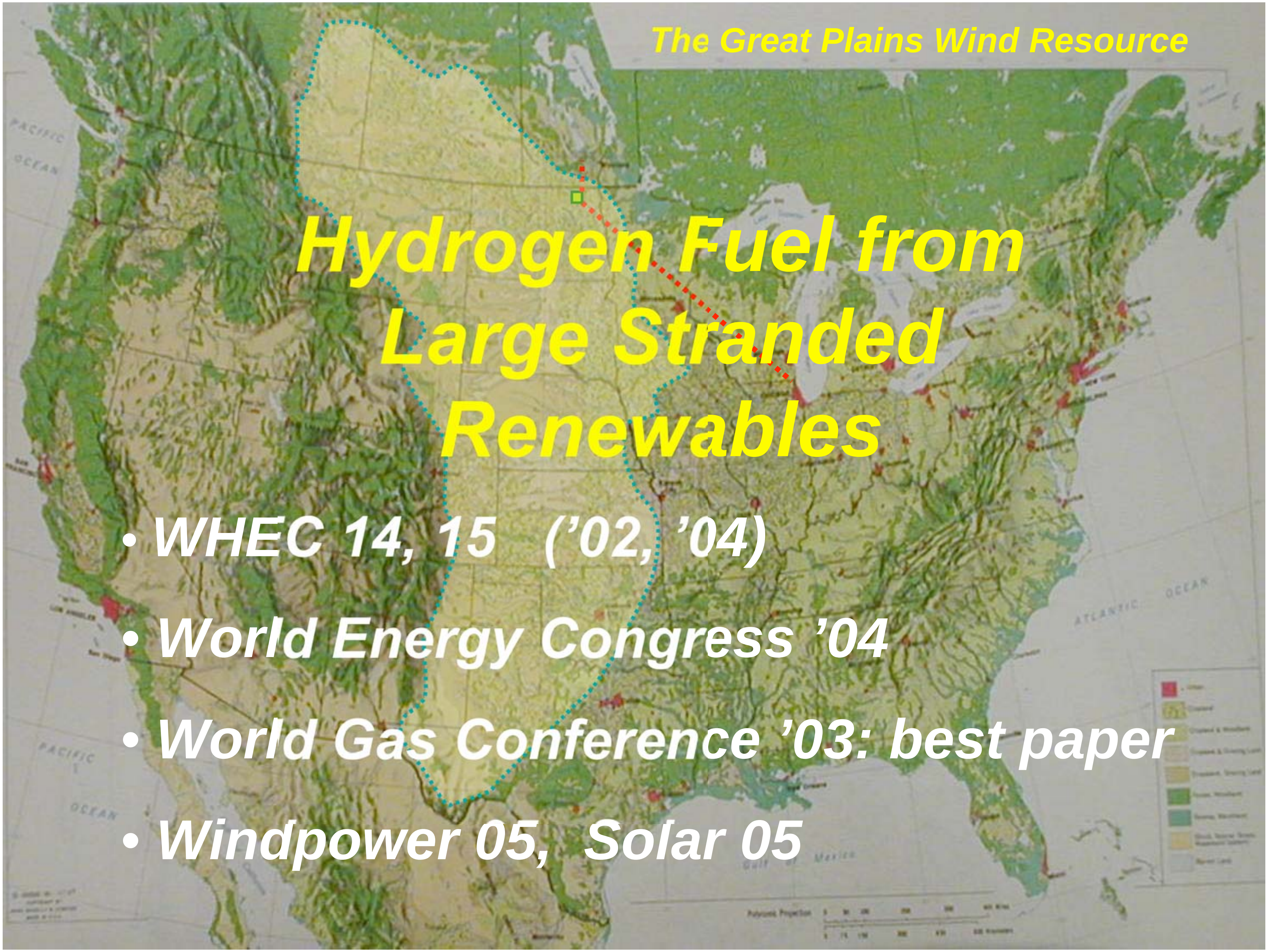
- ***Wind transmission via gaseous hydrogen (GH2) pipelines***

- ***Norsk Hydro electrolyzer presentation***

- ***IRHTDF pilot plant proposal***

- ***Hydro conf call 0730 14th: your questions***

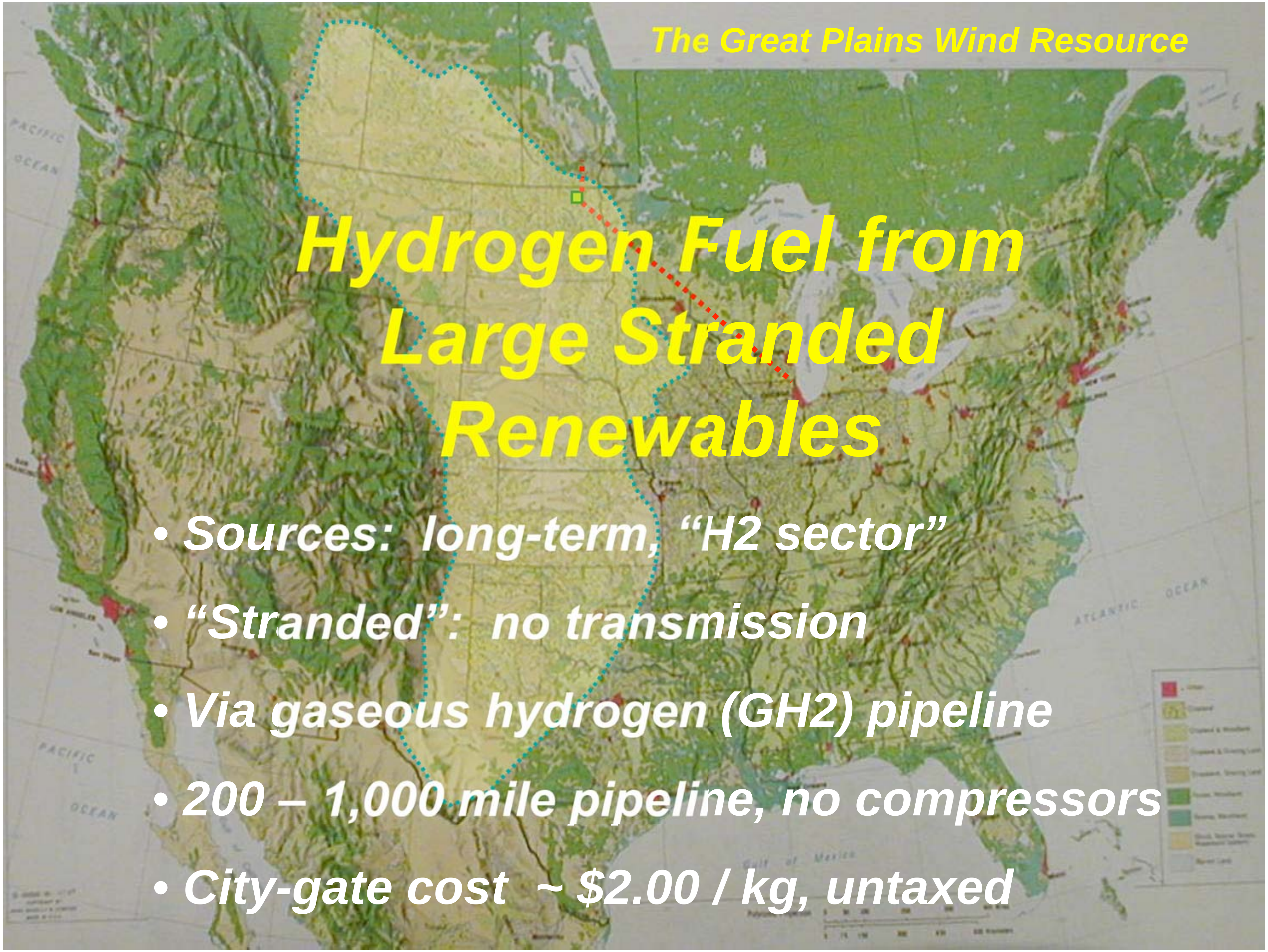
- ***CD, DVD: presentations***



The Great Plains Wind Resource

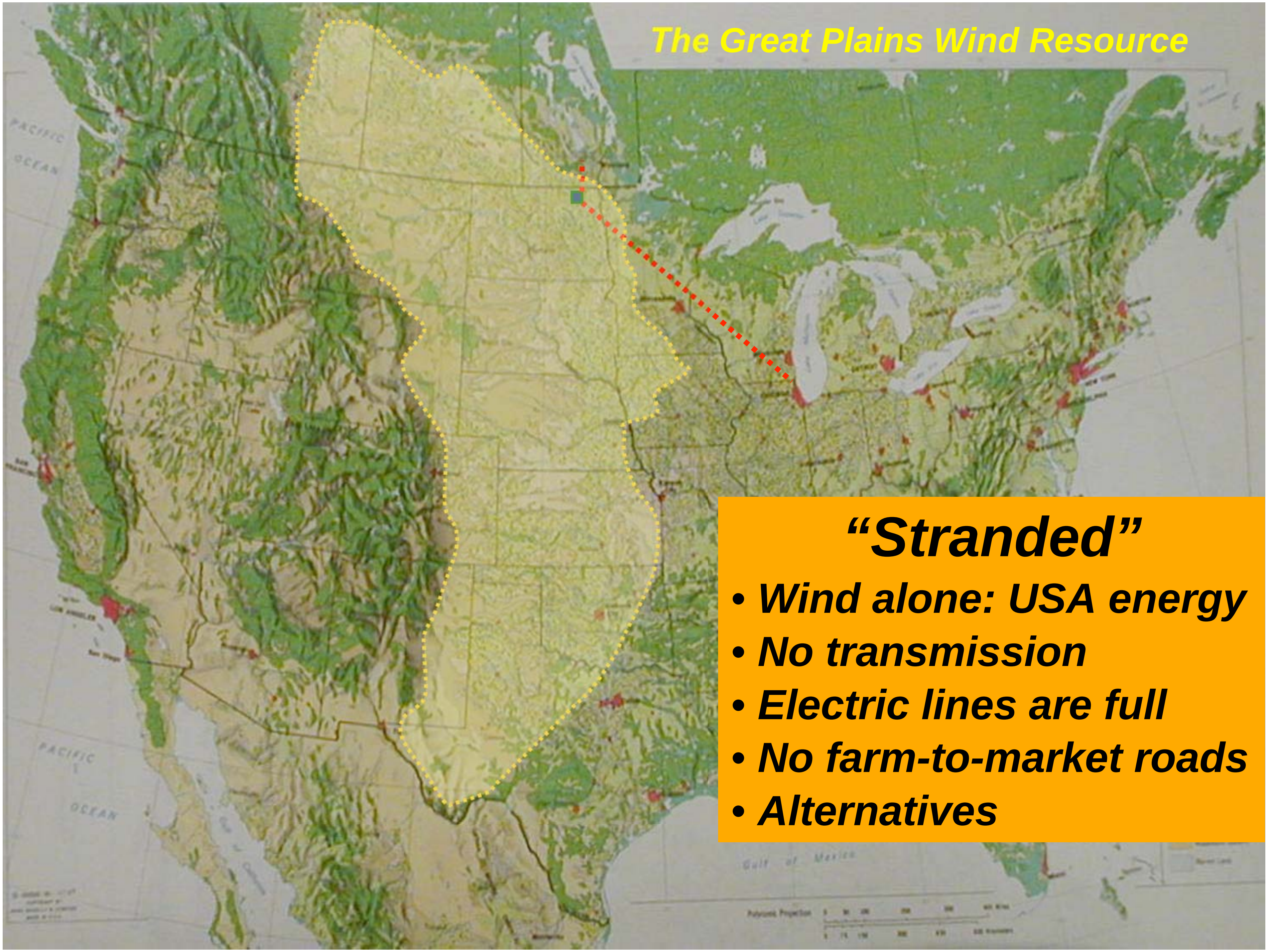
Hydrogen Fuel from Large Stranded Renewables

- WHEC 14, 15 ('02, '04)
- World Energy Congress '04
- World Gas Conference '03: best paper
- Windpower 05, Solar 05

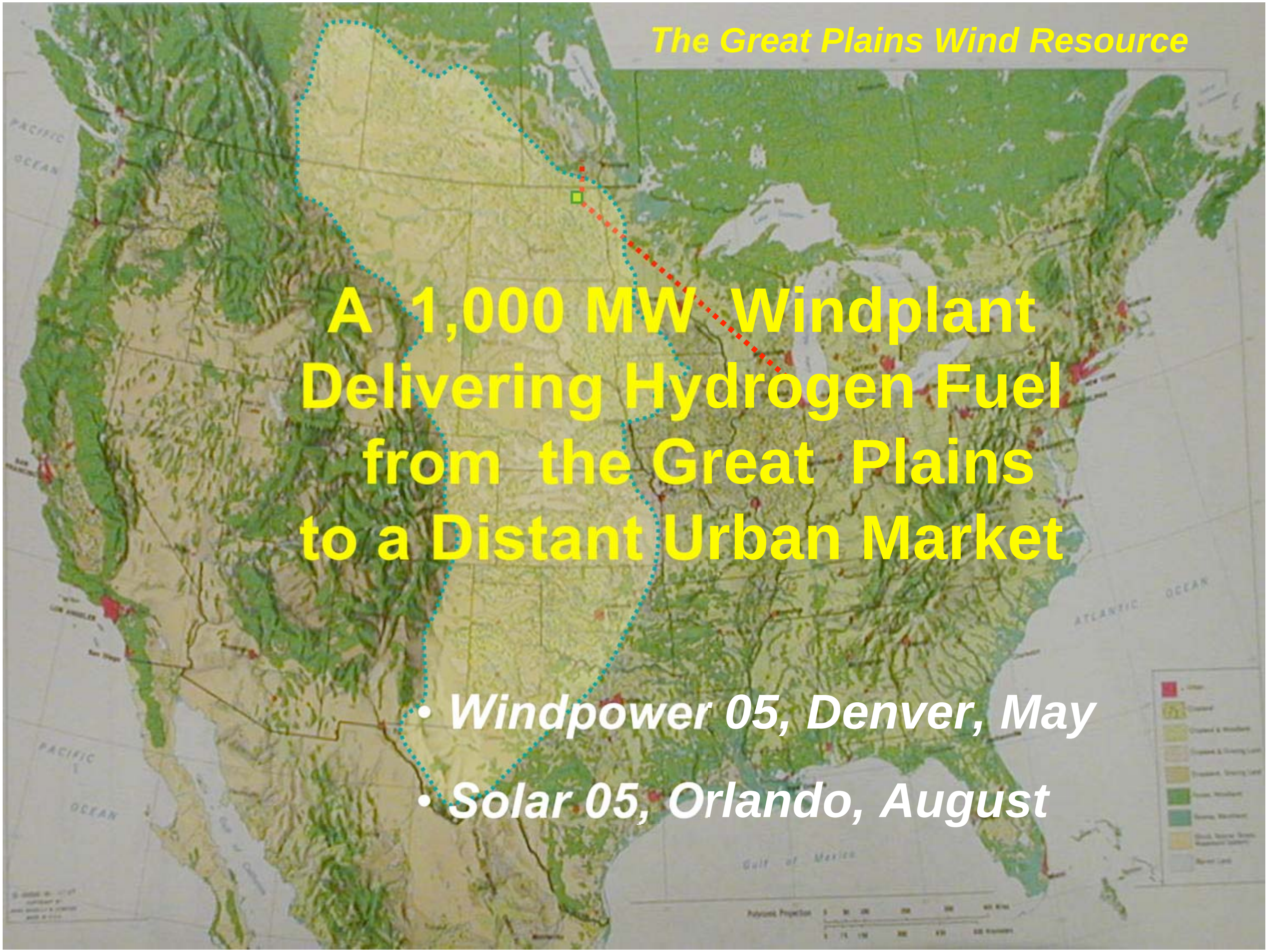


Hydrogen Fuel from Large Stranded Renewables

- Sources: long-term, “H2 sector”
- “Stranded”: no transmission
- Via gaseous hydrogen (GH2) pipeline
- 200 – 1,000 mile pipeline, no compressors
- City-gate cost ~ $2.00 / kg, untaxed


The Great Plains Wind Resource
"Stranded"
• Wind alone: USA energy
• No transmission
• Electric lines are full
• No farm-to-market roads
• Alternatives


The Great Plains Wind Resource
A 1,000 MW Windplant
Delivering Hydrogen Fuel
from the Great Plains
to a Distant Urban Market
PACIFIC OCEAN
ATLANTIC OCEAN
Gulf of Mexico



A 1,000 MW Windplant Delivering Hydrogen Fuel from the Great Plains to a Distant Urban Market

- *Windpower 05, Denver, May*
- *Solar 05, Orlando, August*

A 1,000 MW Windplant Delivering Hydrogen Fuel from the Great Plains to a Distant Urban Market

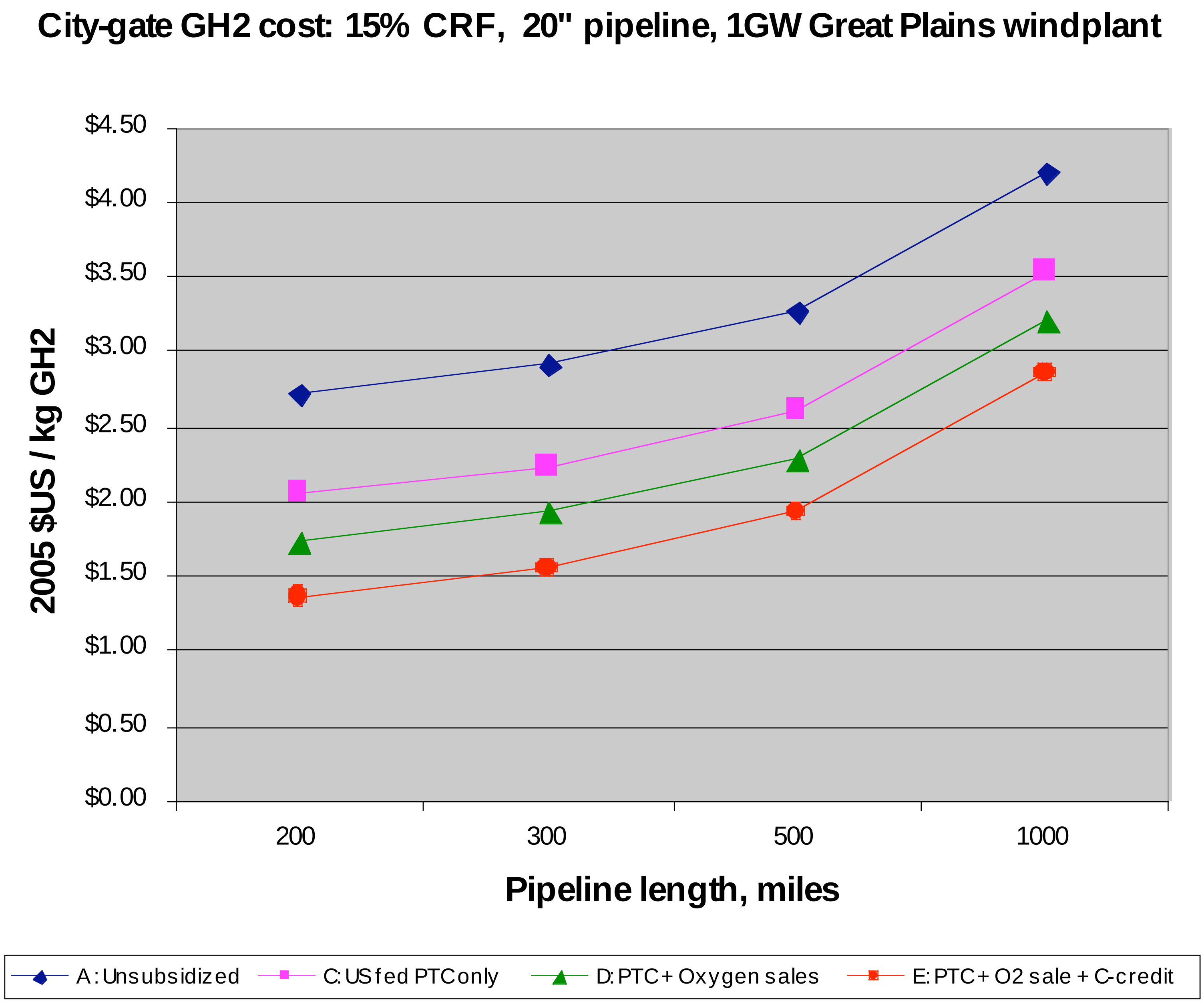
Jeff Holloway
Pipeline Technologies, Inc., Calgary, AB, Canada

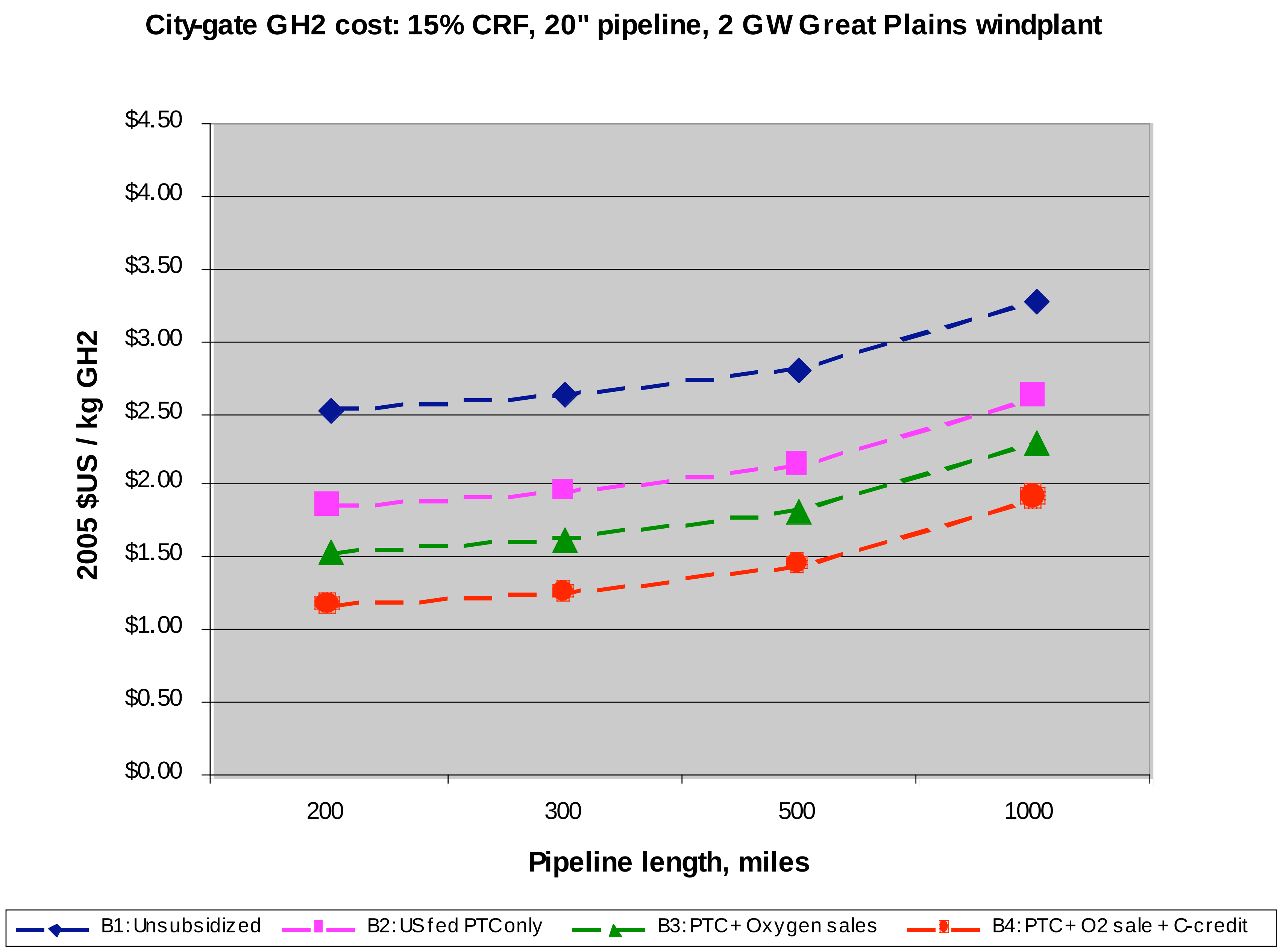
Rupert Merer
Stuart Energy Systems, Mississauga, ON Canada

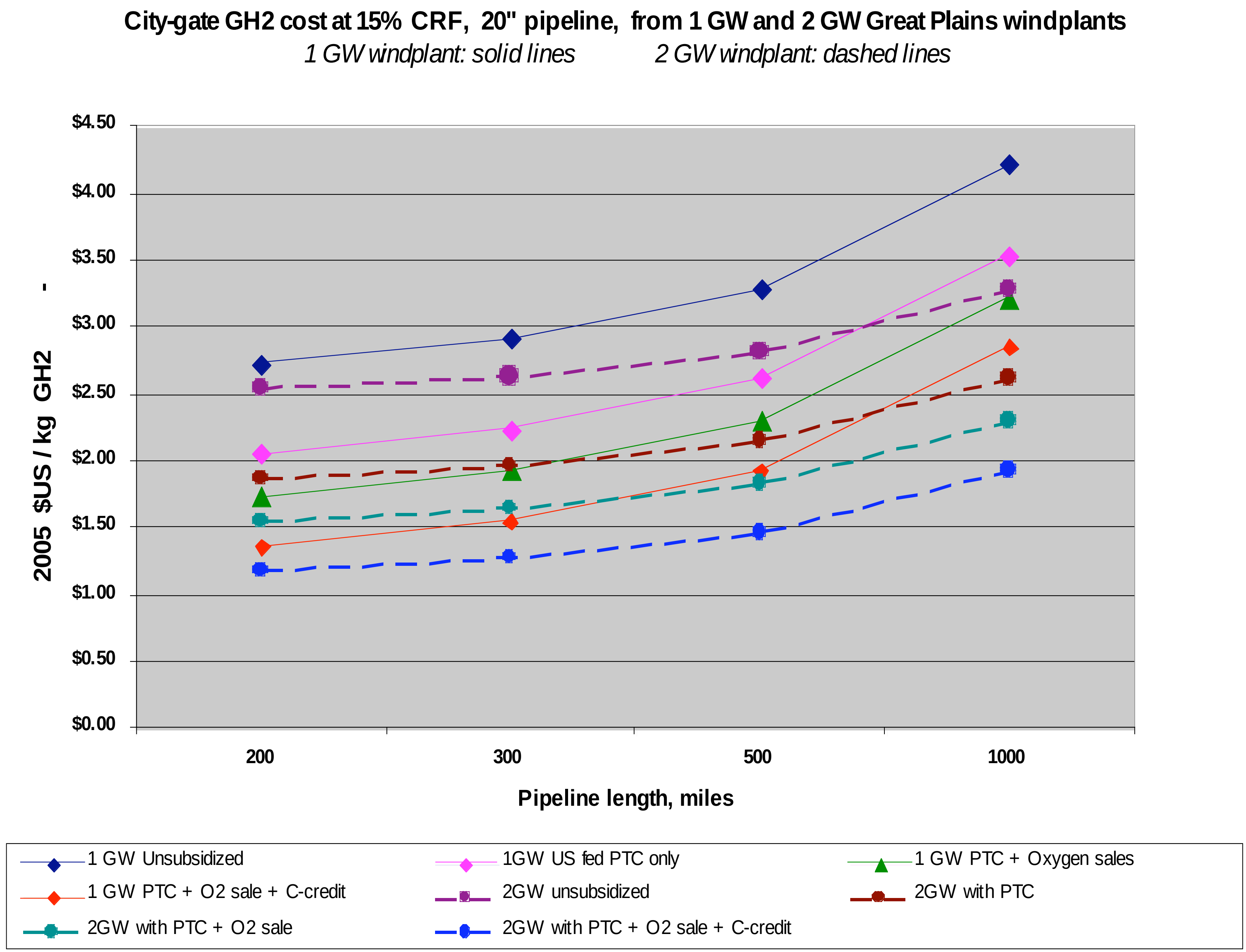
Dr. Brian Somerday *Dr. Chris San Marchi*
Sandia National Laboratory, Livermore, CA

Geoff Keith *Dr. David White*
Synapse Energy Economics, Cambridge, MA

William C. Leighty
Director, The Leighty foundation, Juneau, AK


City-gate GH2 cost: 15% CRF, 20" pipeline, 1GW Great Plains windplant
$4.50
$4.00
$3.50
$3.00
$2.50
$2.00
$1.50
$1.00
$0.50
$0.00
2005 $US / kg GH2
200
300
500
1000
Pipeline length, miles
A: Unsubsidized
C: US fed PTC only
D: PTC + Oxygen sales
E: PTC + O2 sale + C-credit


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



City-gate GH2 cost at 15% CRF, 20" pipeline, from 1 GW and 2 GW Great Plains windplants
1 GW windplant: solid lines
2 GW windplant: dashed lines
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
1 GW Unsubsidized
1GW US fed PTC only
1 GW PTC + Oxygen sales
1 GW PTC + O2 sale + C-credit
2GW unsubsidized
2GW with PTC
2GW with PTC + O2 sale
2GW with PTC + O2 sale + C-credit

1,000 MW = 1 GW (gigawatt): A very big windplant

- **Total world ~ 50 GW**
- **USA ~ 8 GW**

Exporting From 12 Windiest Great Plains States

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

Wind energy source: PNL-7789, 1991 * at 500 miles average length

State	AEP, TWh	Wind Gen MW (nameplate) (40 % CF)	6 GW 36" GH2 export pipelines	$ Billion Total Capital Cost *	3 GW export HVDC lines	$ Billion Total Capital Cost *
North Dakota	1,210	345,320	50	50	100	60
Texas	1,190	339,612	48	48	100	60
Kansas	1,070	305,365	43	43	100	60
South Dakota	1,030	293,950	41	41	100	60
Montana	1,020	291,096	41	41	90	54
Nebraska	868	247,717	35	35	80	48
Wyoming	747	213,185	30	30	70	42
Oklahoma	725	206,906	29	29	60	36
Minnesota	657	187,500	26	26	60	36
Iowa	551	157,249	22	22	50	30
Colorado	481	137,272	19	19	40	24
New Mexico	435	124,144	17	17	40	24
TOTALS	9,984	2,849,316	401	$ 401	890	$ 534

Stanford wind energy study: 2003

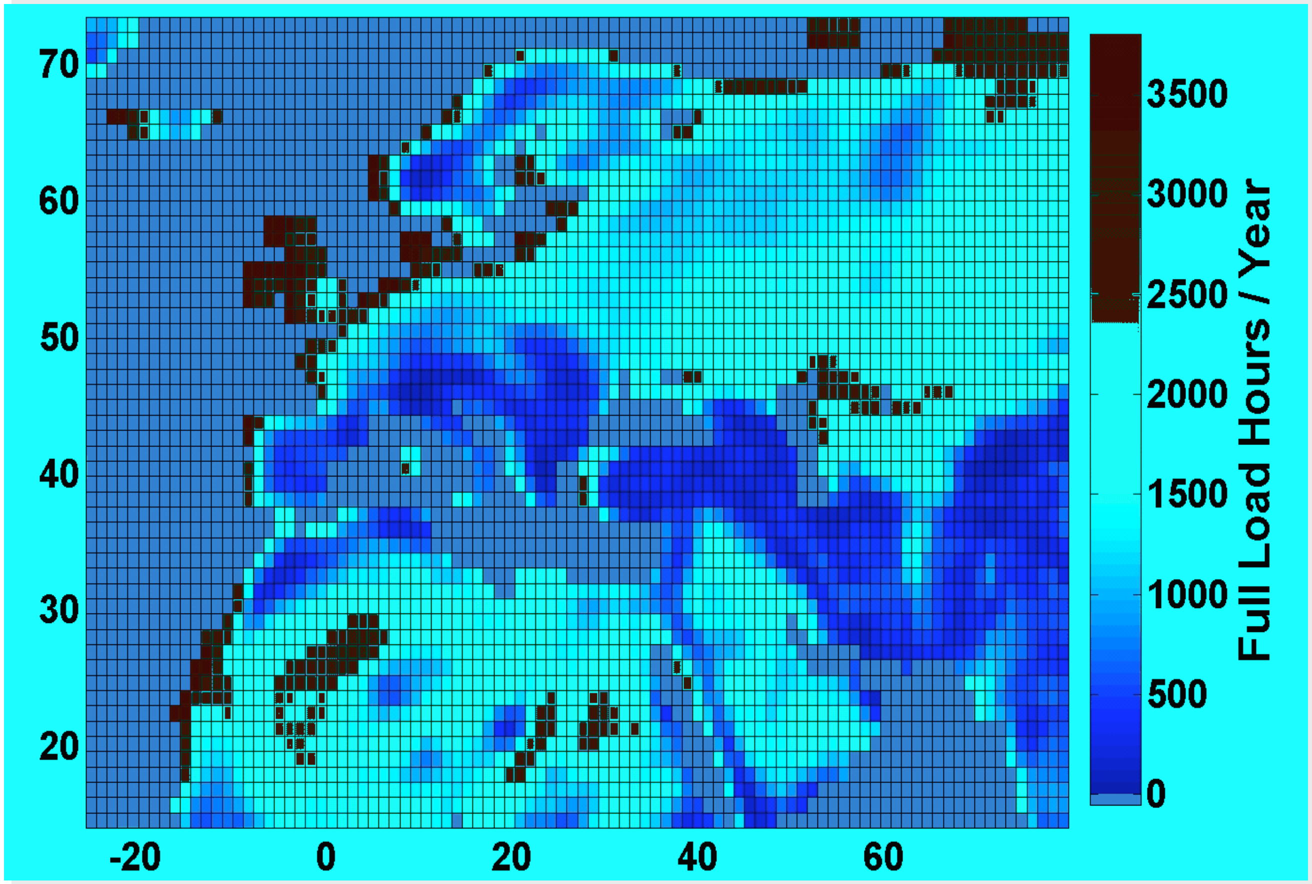
- Underestimated: PNNL, NREL
- 80 m hub height
- 1.3 – 1.7 m/s faster windspeed
- Transmission network:

  steady, reliable, abundant supply

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

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. D9, 4289, 2003

Mean Annual Production of 1.5 MW Variable Speed Wind Turbines (Hub = 80 m) on Land Sites in Europe and its Neighbourhood



Electricity Demand
EU & Norway:
2100 TWh

Potential Wind Energy
Prod. on land sites wit
more than 1500 FLH
at 4-8 MW/km^2:
120 000-240 000 TWh

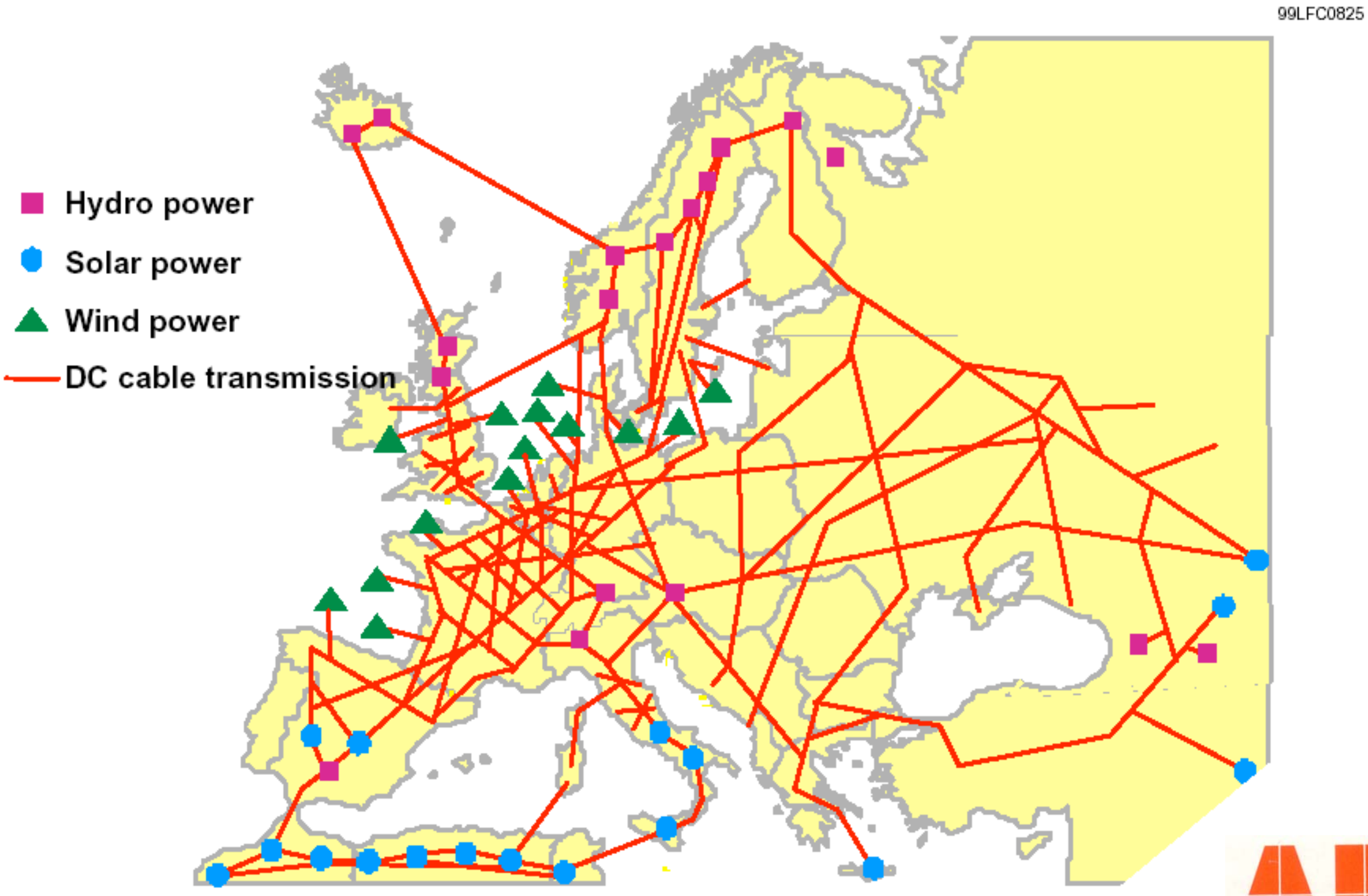
Mean Prod. at this site
2050 FLH

Meteorological data: ECMWF, ERA-15, 1979-1992

G. Czisch, AWEA 2001

Vision: Remote renewable energy sources

connected to loads by DC grid



ABB

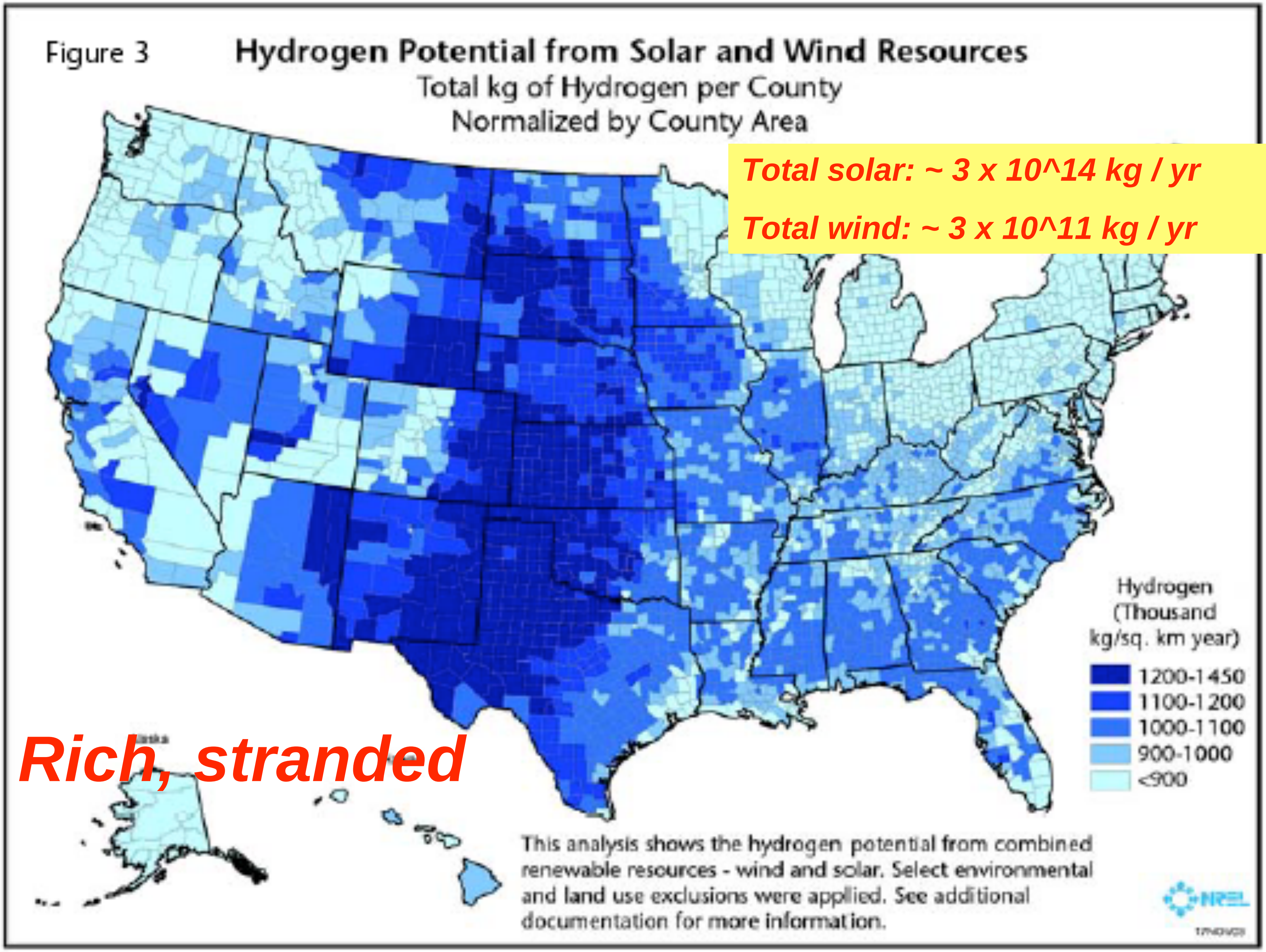


Figure 3
Hydrogen Potential from Solar and Wind Resources
Total kg of Hydrogen per County
Normalized by County Area
Total solar: ~ 3 x 10^14 kg / yr
Total wind: ~ 3 x 10^11 kg / yr
Rich, stranded
Hydrogen (Thousand kg/sq. km year)
1200-1450
1100-1200
1000-1100
900-1000
<900
This analysis shows the hydrogen potential from combined renewable resources - wind and solar. Select environmental and land use exclusions were applied. See additional documentation for more information.
NREL

Emergencies

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

Quickly invest:

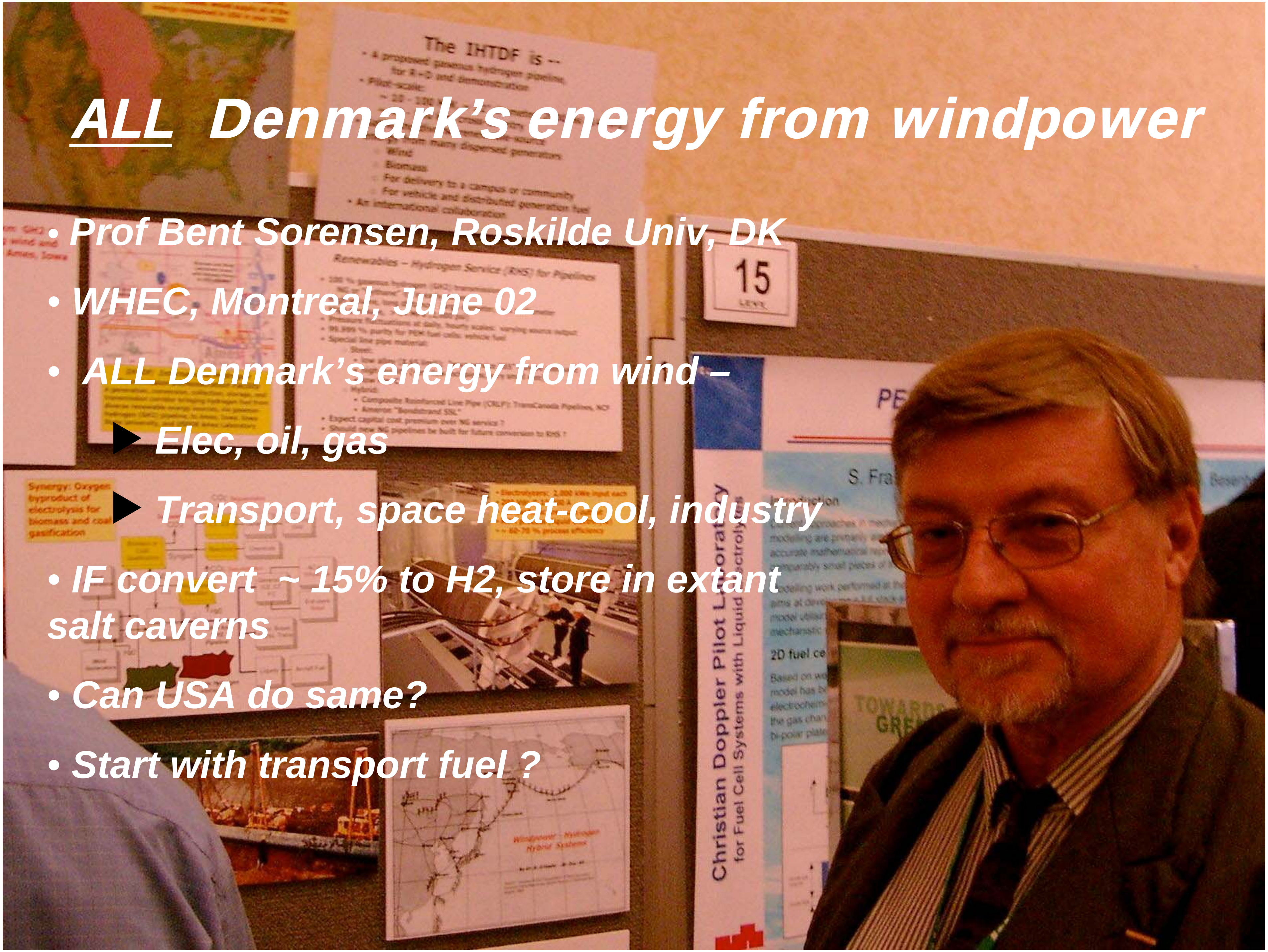
- Energy conservation, efficiency
- Large, new energy supplies:
  - CO_2-emissions-free
  - Indigenous
  - Distributed + centralized

FreedomCAR

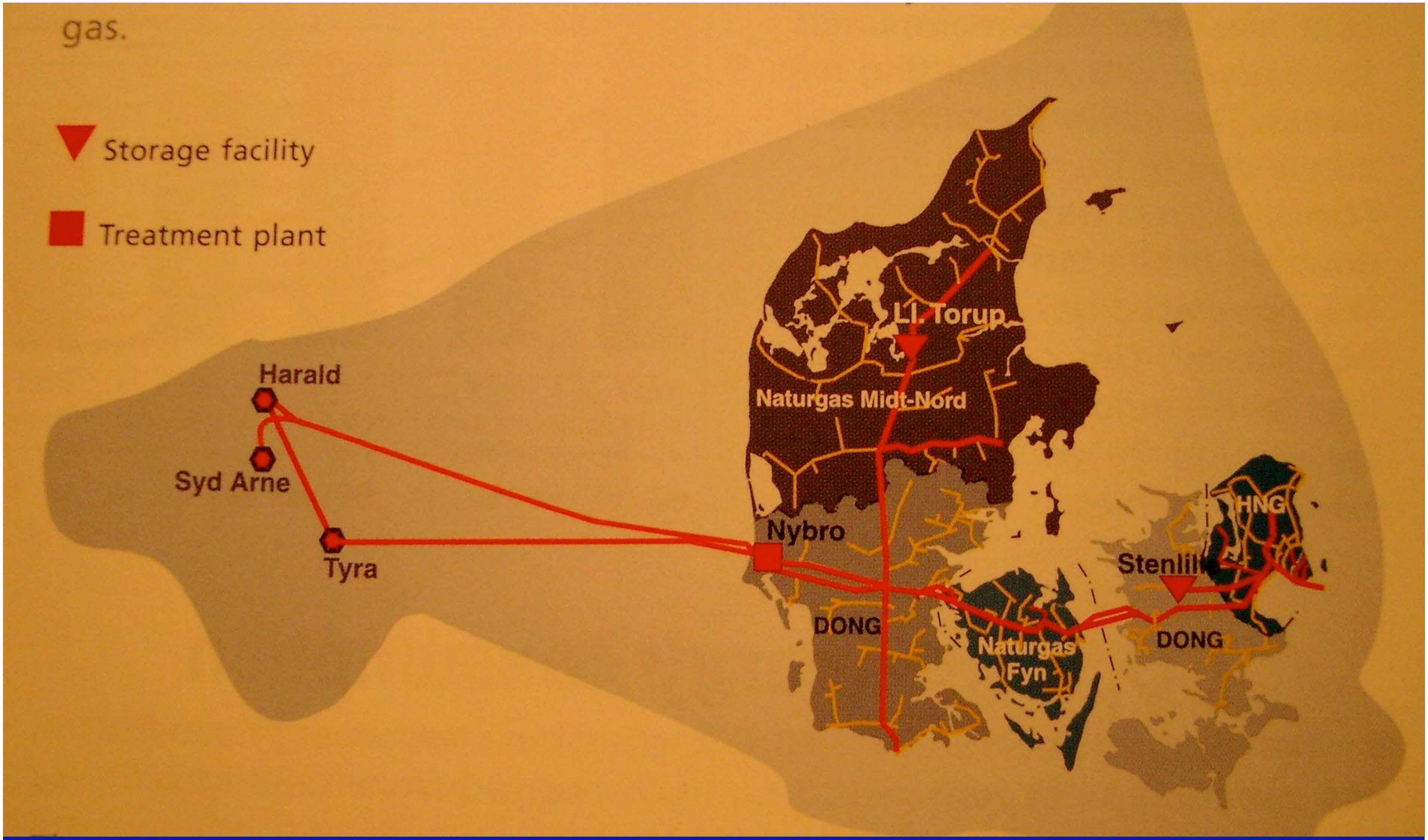
Long Term Vision

A transportation system powered by hydrogen from renewable resources

ALL *Denmark's energy from windpower*

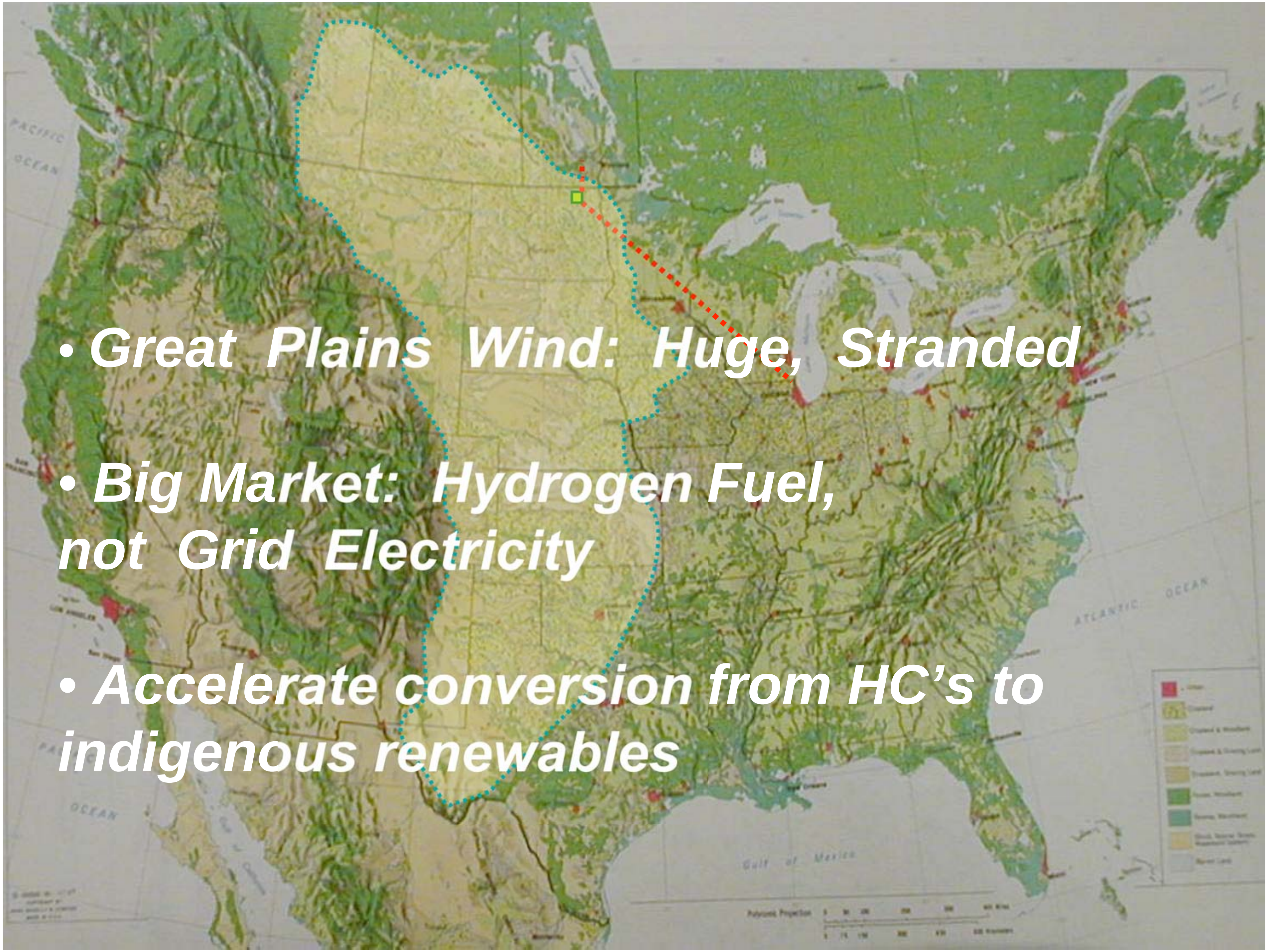


- ***Prof Bent Sorensen, Roskilde Univ, DK***
- ***WHEC, Montreal, June 02***
- ***ALL Denmark's energy from wind –***
  - ***Elec, oil, gas***
  - ***Transport, space heat-cool, industry***
- ***IF convert ~ 15% to H2, store in extant salt caverns***
- ***Can USA do same?***
- ***Start with transport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



Denmark natural gas system: pipelines and geologic storage

AIR PRODUCTS



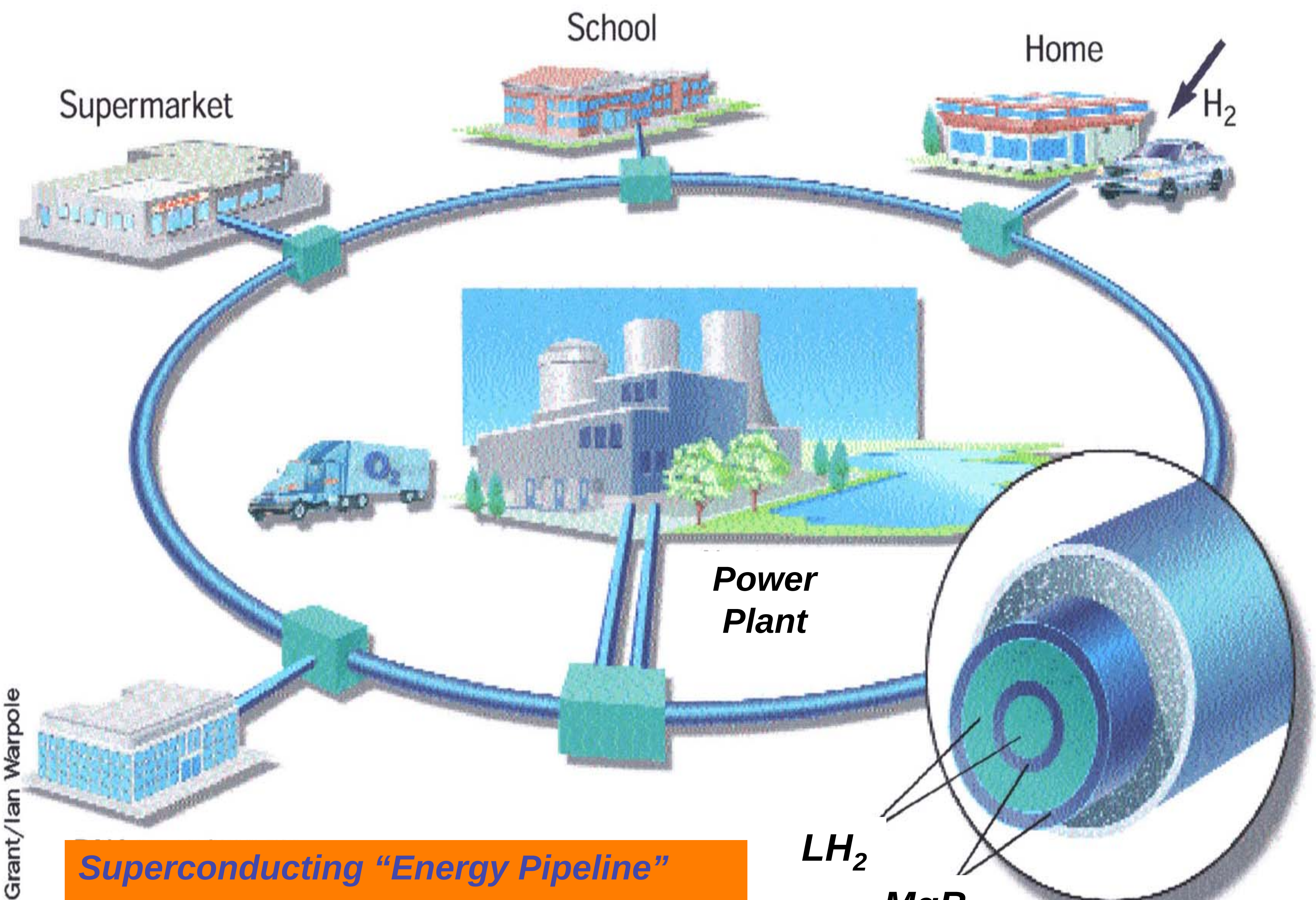
- *Great Plains Wind: Huge, Stranded*
- *Big Market: Hydrogen Fuel, not Grid Electricity*
- *Accelerate conversion from HC's to indigenous renewables*

The Great Plains Wind Resource

How shall we bring the large, stranded, Great Plains wind to market ?

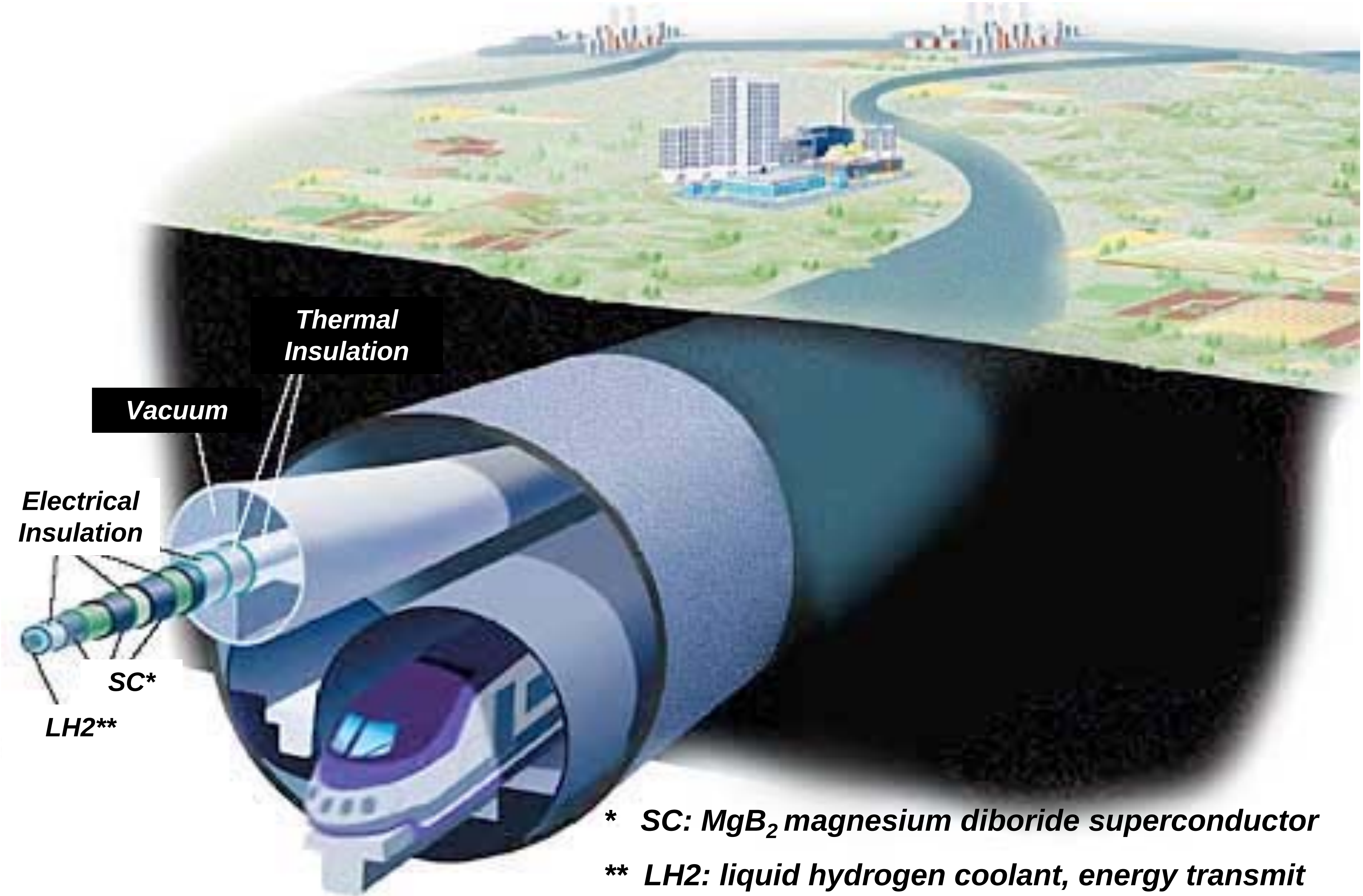
GW-scale Transmission Options: Stranded Renewables

- Electricity:
  - Overhead: HVAC, HVDC
  - Underground: HVDC
- Gaseous Hydrogen (GH2) pipeline
- Liquid Hydrogen (LH2) pipeline, rail car, ship
- Liquid Ammonia (NH_3):
  - Pipeline, rail, truck
  - Argonne "Ammonia-Hydrogen Economy"13-14 Oct 05
- Liquid synthetic HC's – zero net C
  - CH_3OH (methanol); DME (dimethyl ether)
  - Cyclohexane – benzene (2 pipelines)
  - Silanes: $Si_{10}H_{22}$
- "Energy Pipeline": EPRI
  - SC, LVDC: ~ 100 GW
  - LH2: ~ 100 GW



Superconducting "Energy Pipeline"
Paul Grant, EPRI
~ 100 GW electrical + 100 GW LH2

Natural Gas Pipelines in Shield Tunnel
“Energy Engineering”, Nippon Steel, 2001



* SC: MgB_2 magnesium diboride superconductor

** LH2: liquid hydrogen coolant, energy transmit

Continental Supergrid – EPRI concept “Energy Pipeline”


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

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

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New Mexico	435	124,144	17	17	40	24
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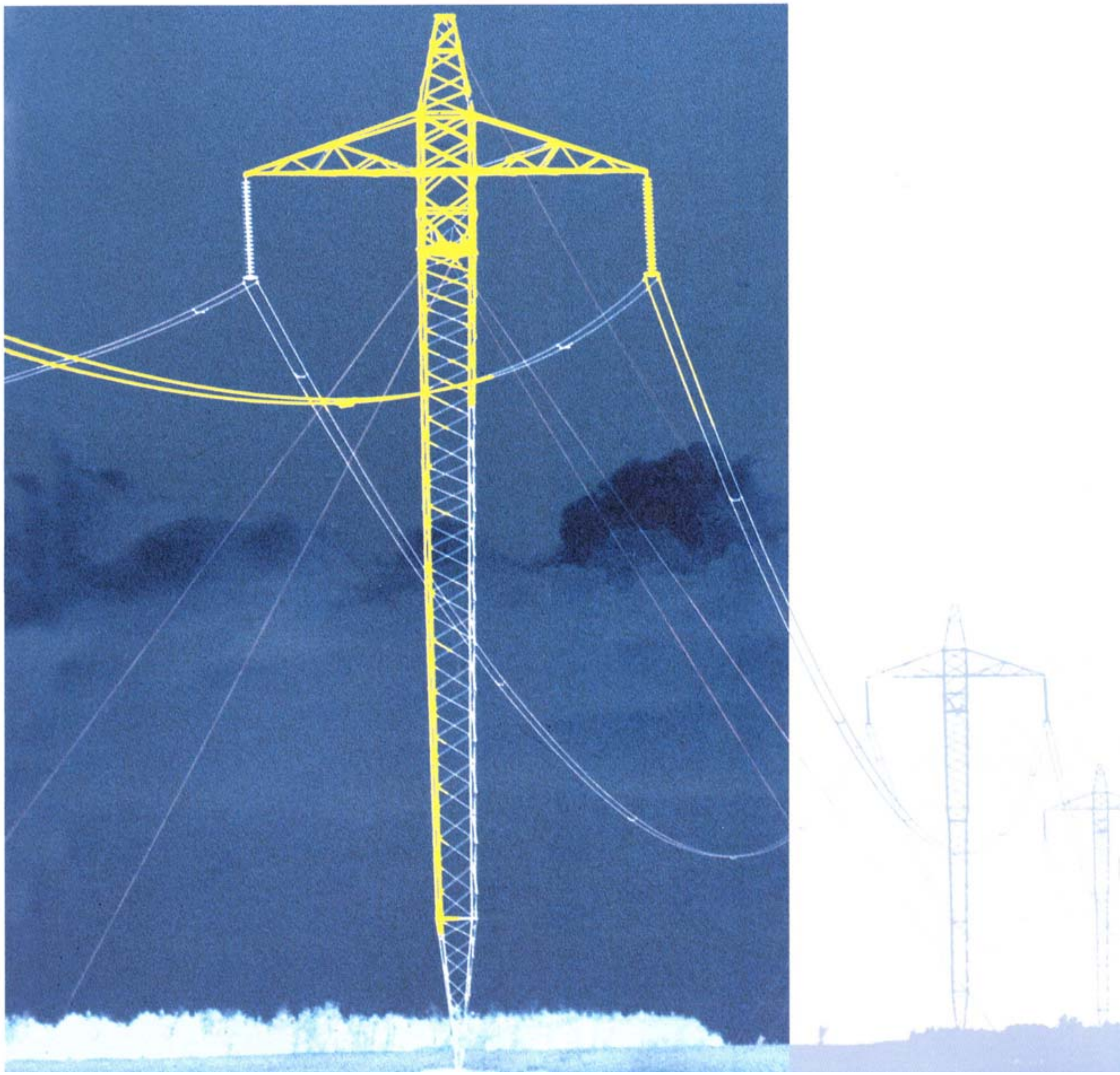
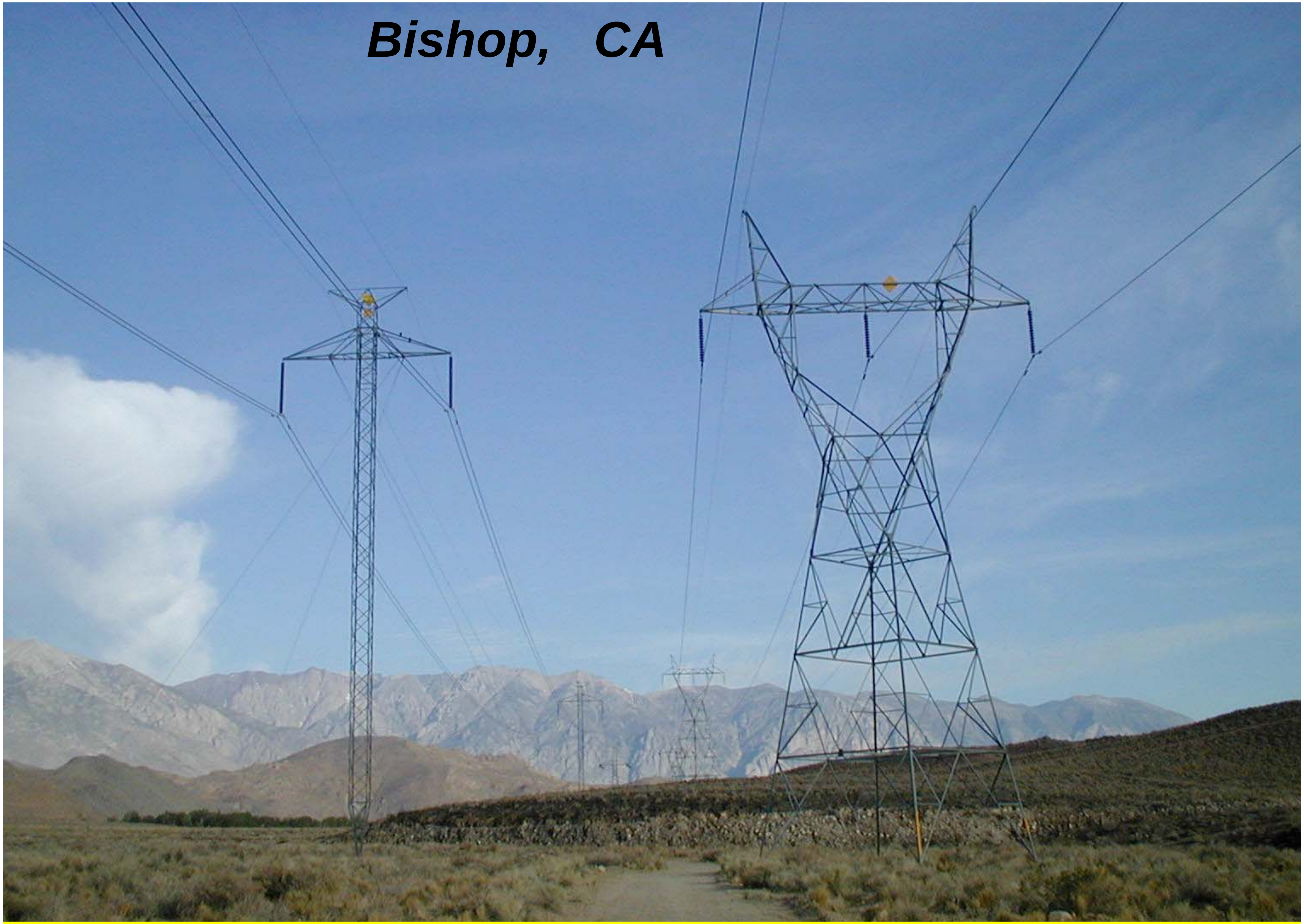
High Voltage
Direct Current Transmission



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



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

How much can we upgrade capacity of extant ROW and structures, with "no net loss of perceived or real safety or tranquility" ?

Zion nuclear plant: 2 of 3 tower systems

HVDC potential: 6 bipoles @ 3,000 MW = 18,000 MW

GW-scale Transmission Options: Stranded Renewables

- Electricity:
  - Overhead: HVAC, HVDC
  - Underground: HVDC
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- Liquid Hydrogen (LH2) pipeline, rail car, ship
- Liquid Ammonia (NH_3):
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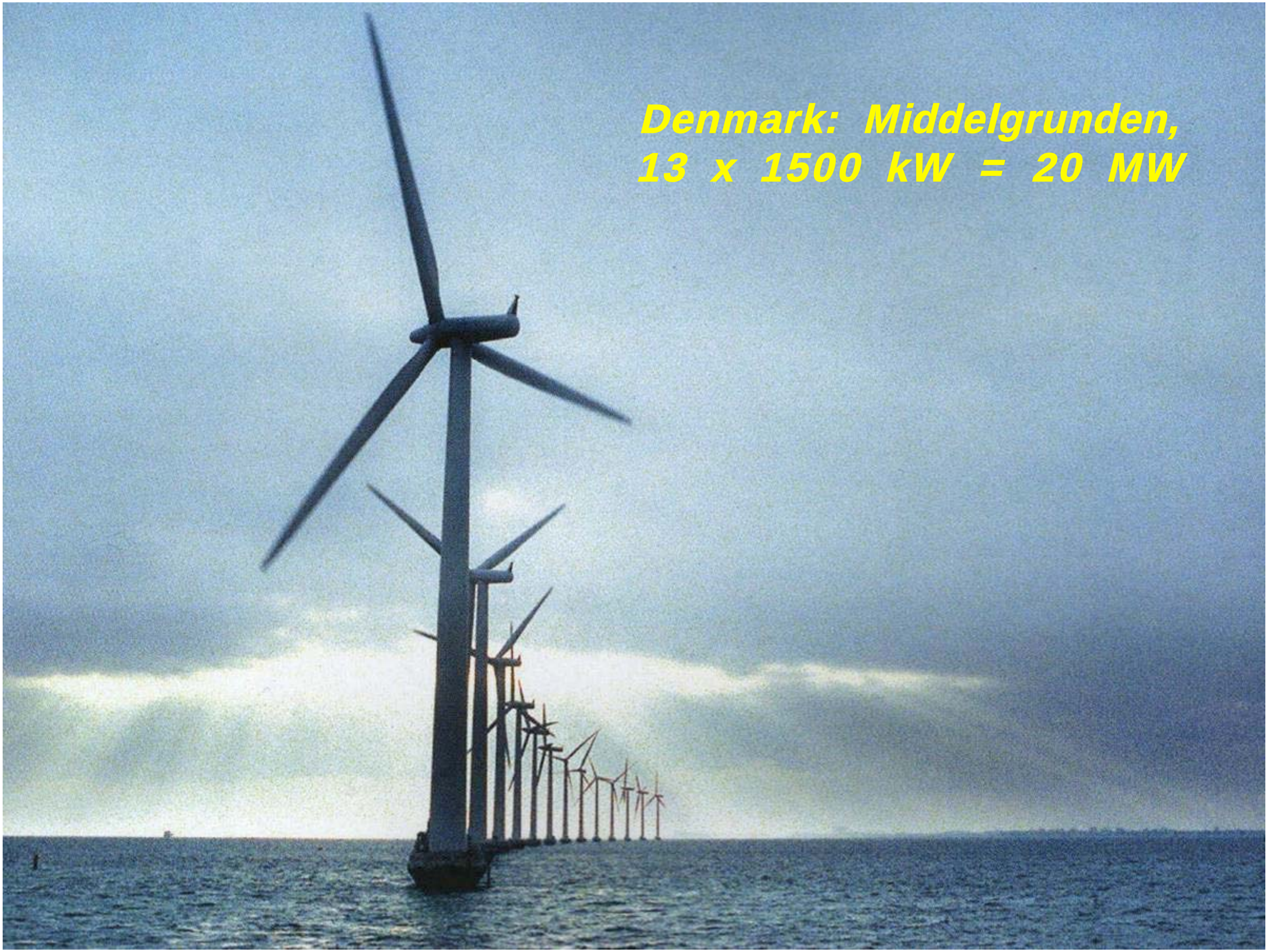
  - Cyclohexane – benzene (2 pipelines)
  - Silanes: $Si_{10}H_{22}$
- "Energy Pipeline": EPRI
  - SC, LVDC: ~ 100 GW
  - LH2: ~ 100 GW

NW Iowa 190 MW windplant


Denmark: Middelgrunden,
13 x 1500 kW = 20 MW

Norsk Hydro Electrolyzers 2 MW each

Compressor

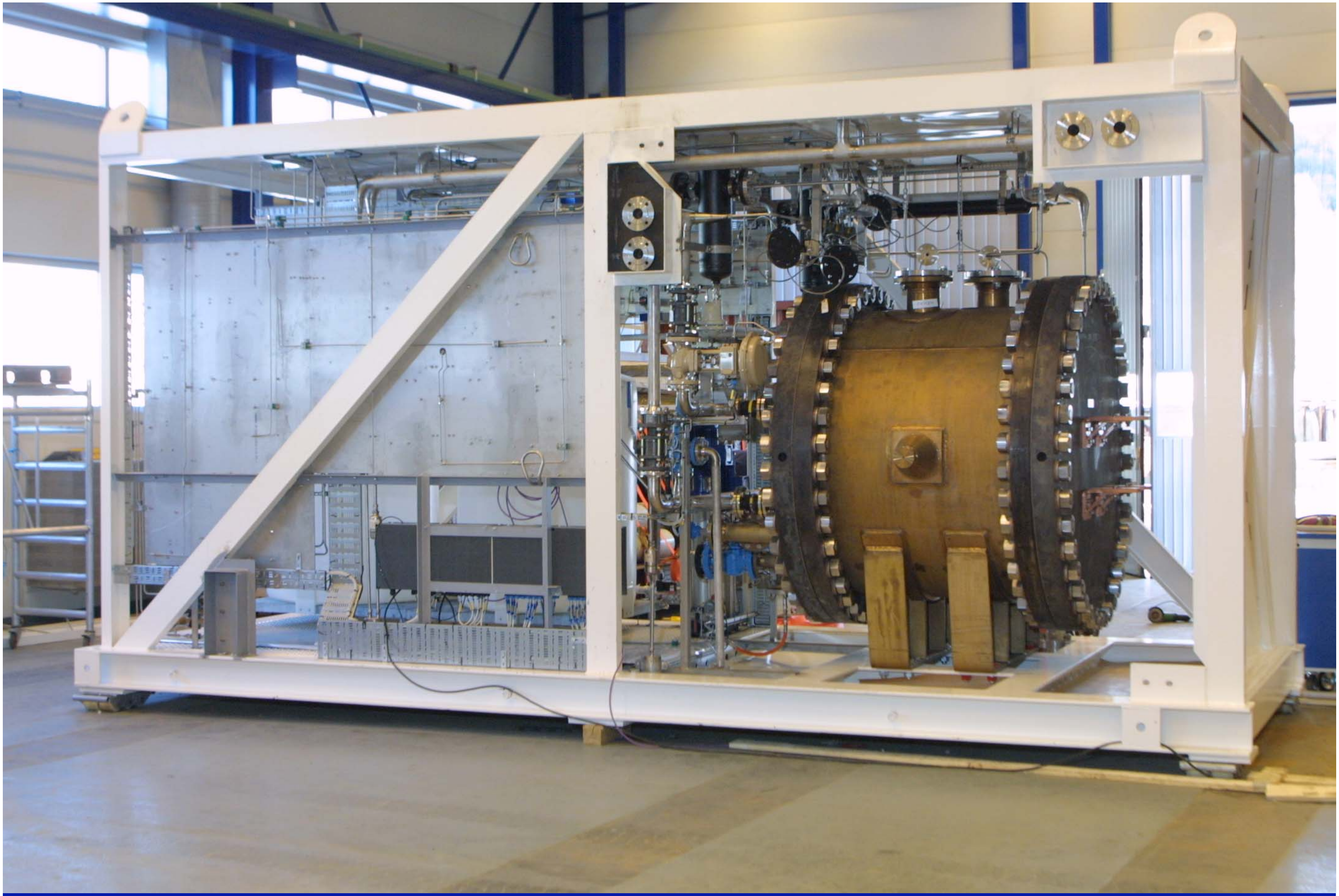
Reciprocating

Natural gas

3,000 hp

Electric Motor

Drive



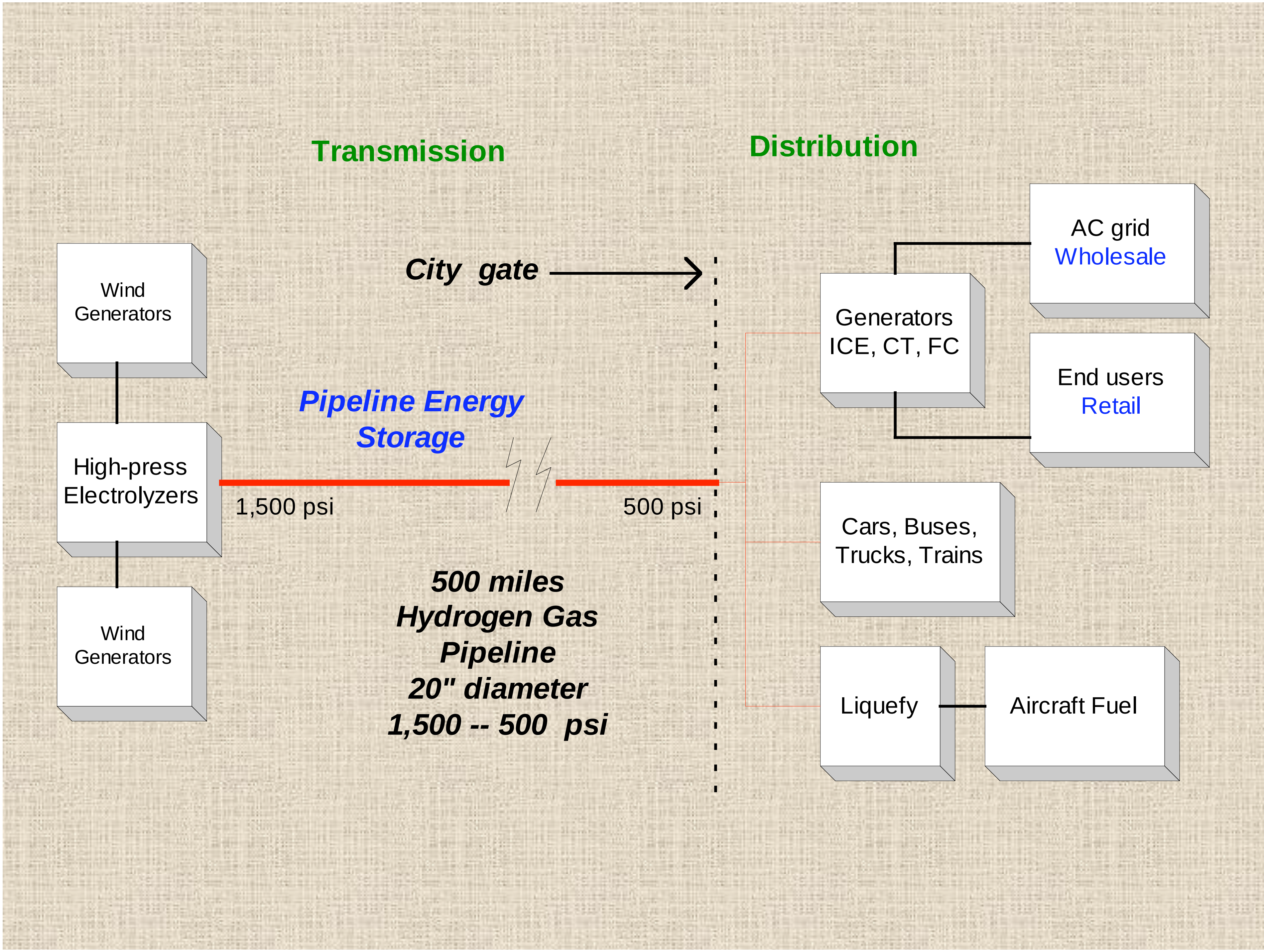
Norsk Hydro electrolyzer, KOH type
560 kW input, 130 Nm3 / hour at 450 psi (30 bar)

36” diam Natural Gas
Alliance Pipeline, 3000 miles, 1740 psi

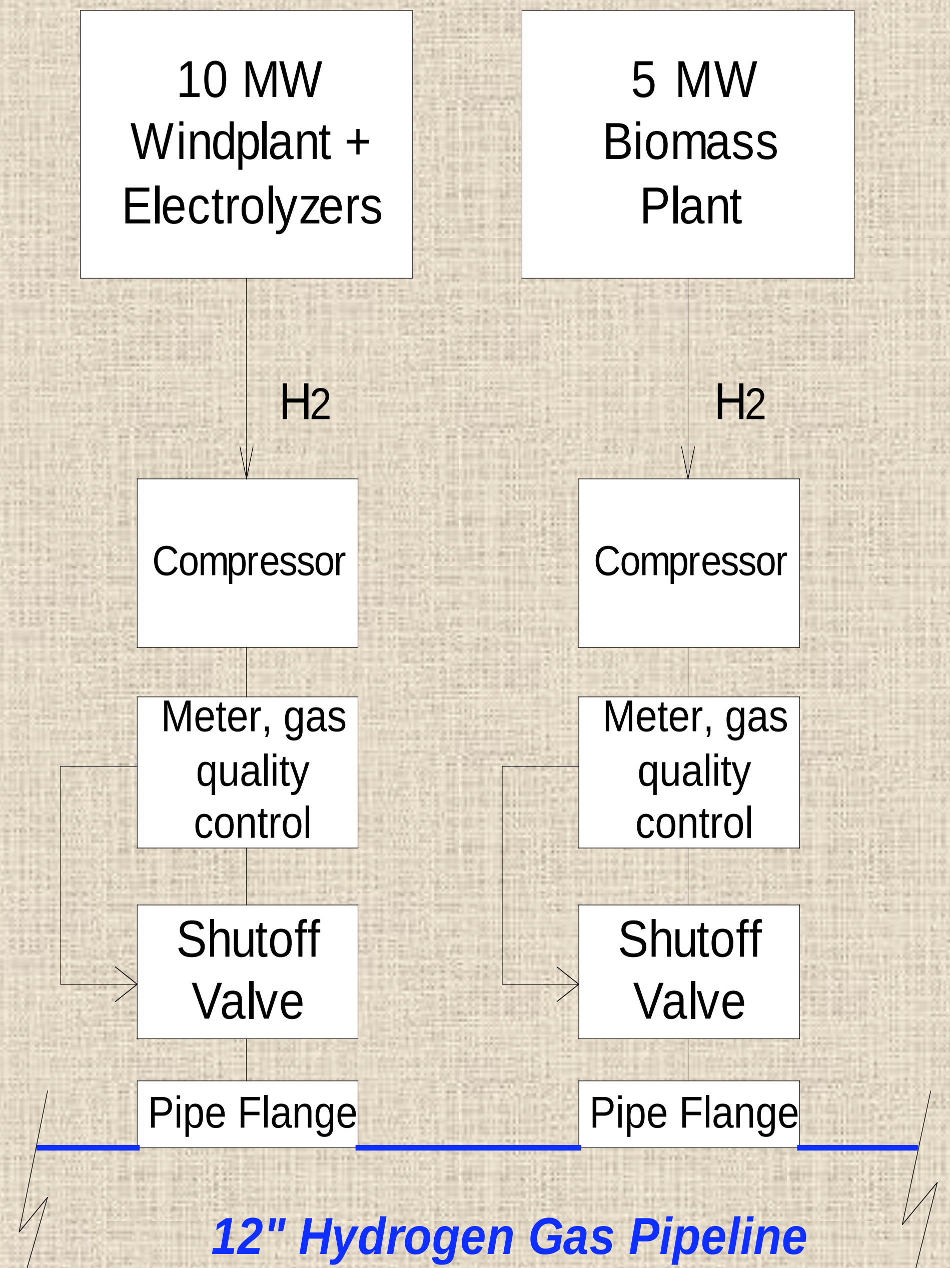
Twelve Great Plains states wind needs ~ 400 H2 gas Pipelines

36" diameter
14 MPa = 1000 psi = 65 bar
Each: 2,500 tons GH2 / day = 6,000 MW

Back-up Power System
Fleet Fueling
Community Fueling
ACME ELECTRONICS
Industrial Application
Home Fueling
Primary Electricity
Hydrogen
Hydrogen-Generated Electricity
H_2 Generation Module
H_2 Storage Module
Power Module
Fuel Dispensing Module
Personal Energy Station (PES)
PES Storage Module
Hydrogen Tank


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
Generators ICE, CT, FC
AC grid Wholesale
End users Retail
Cars, Buses, Trucks, Trains
Liquefy
Aircraft Fuel

Airbus Industrie concept: liquid hydrogen fueled

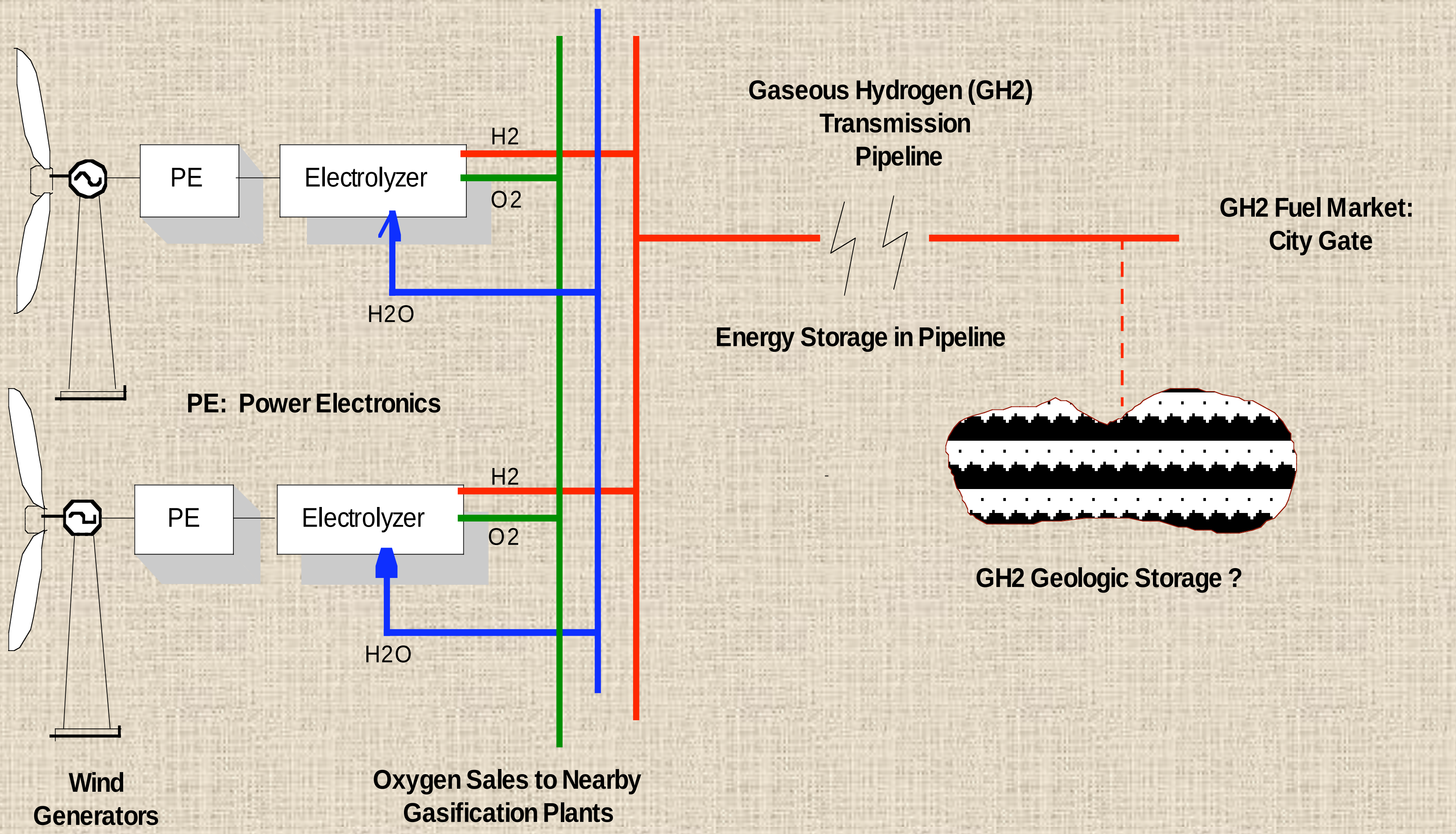


Pipeline Delivery Nodes

- ***Simple***
- ***Low cost***
- ***Large or small***
- ***Closely spaced***

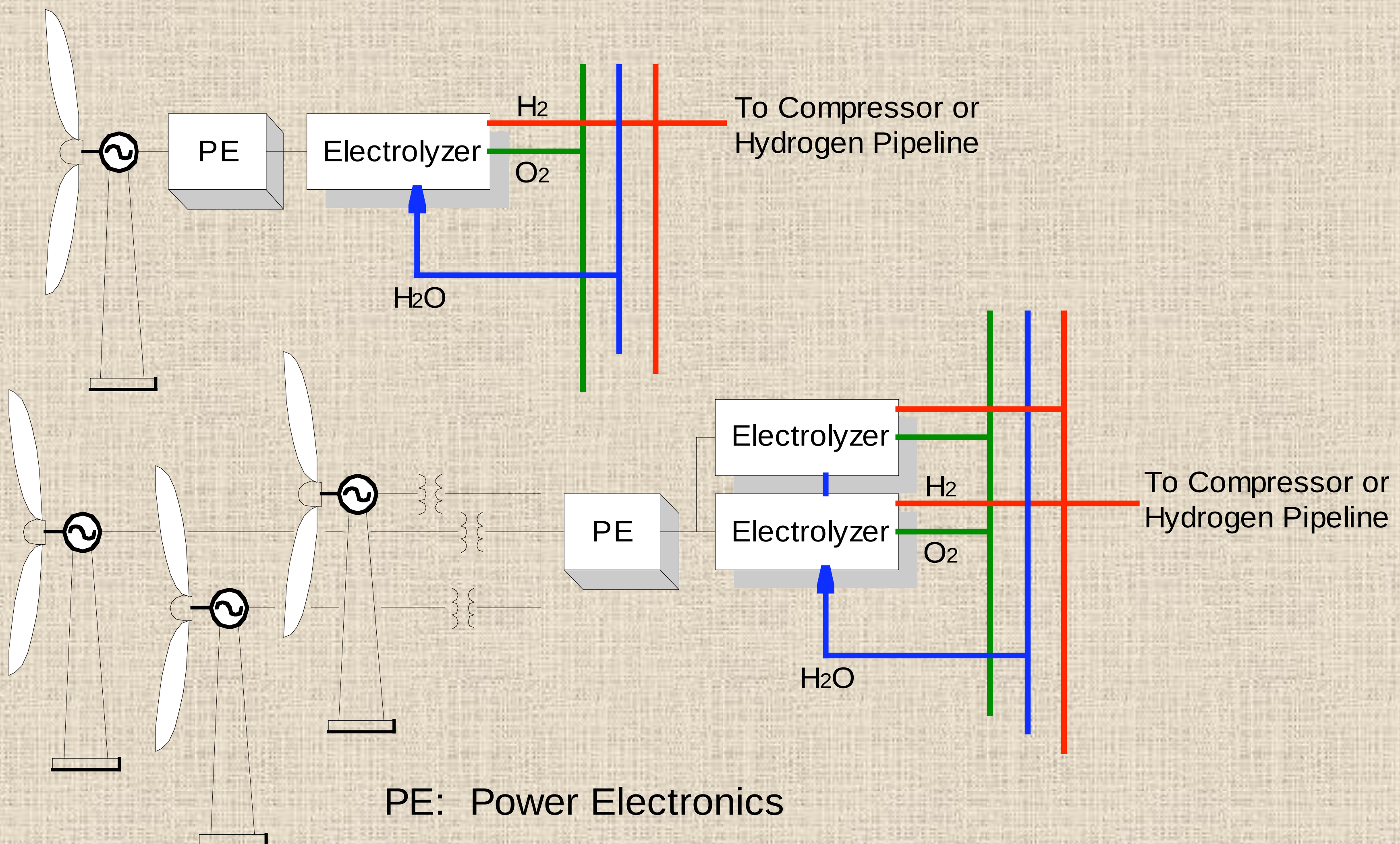

500 MW HVDC Converter Station
Ireland undersea cable

Hydrogen Transmission Scenario
Storage: Pipeline smoothing, geologic firming



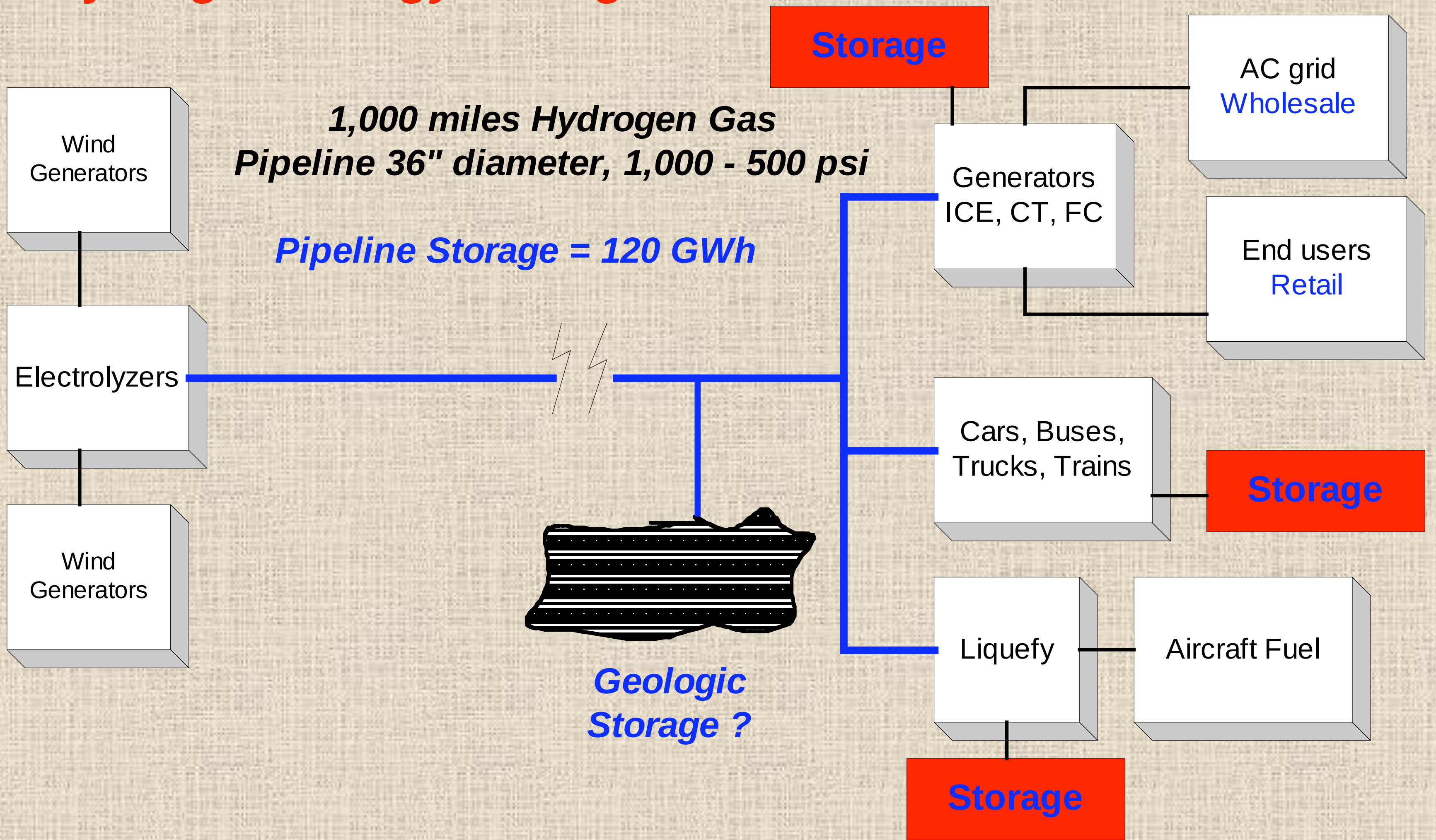
"Hydrogen Transmission Scenario"

PE synergy: sharing, topology options



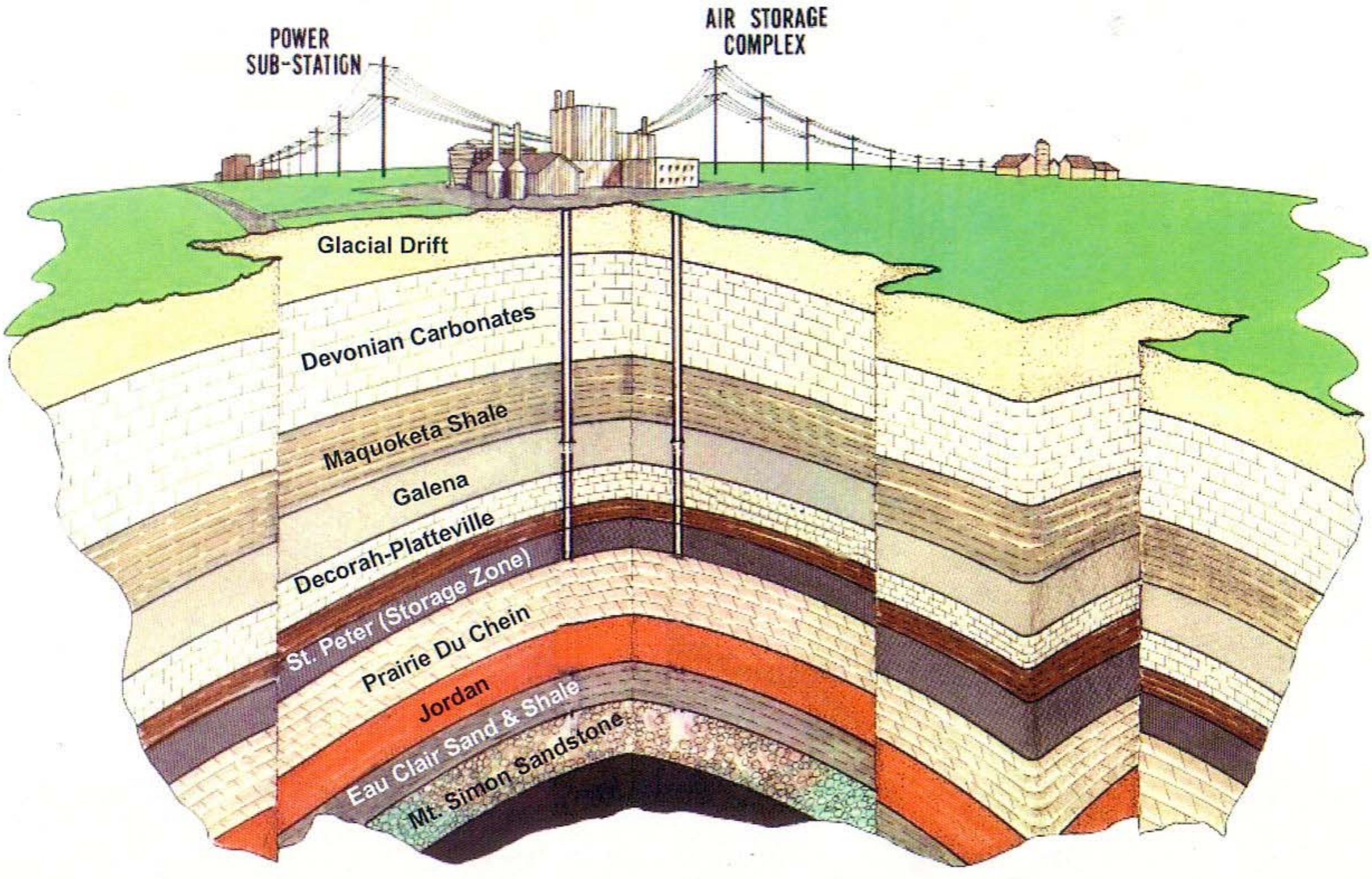
PE: Power Electronics

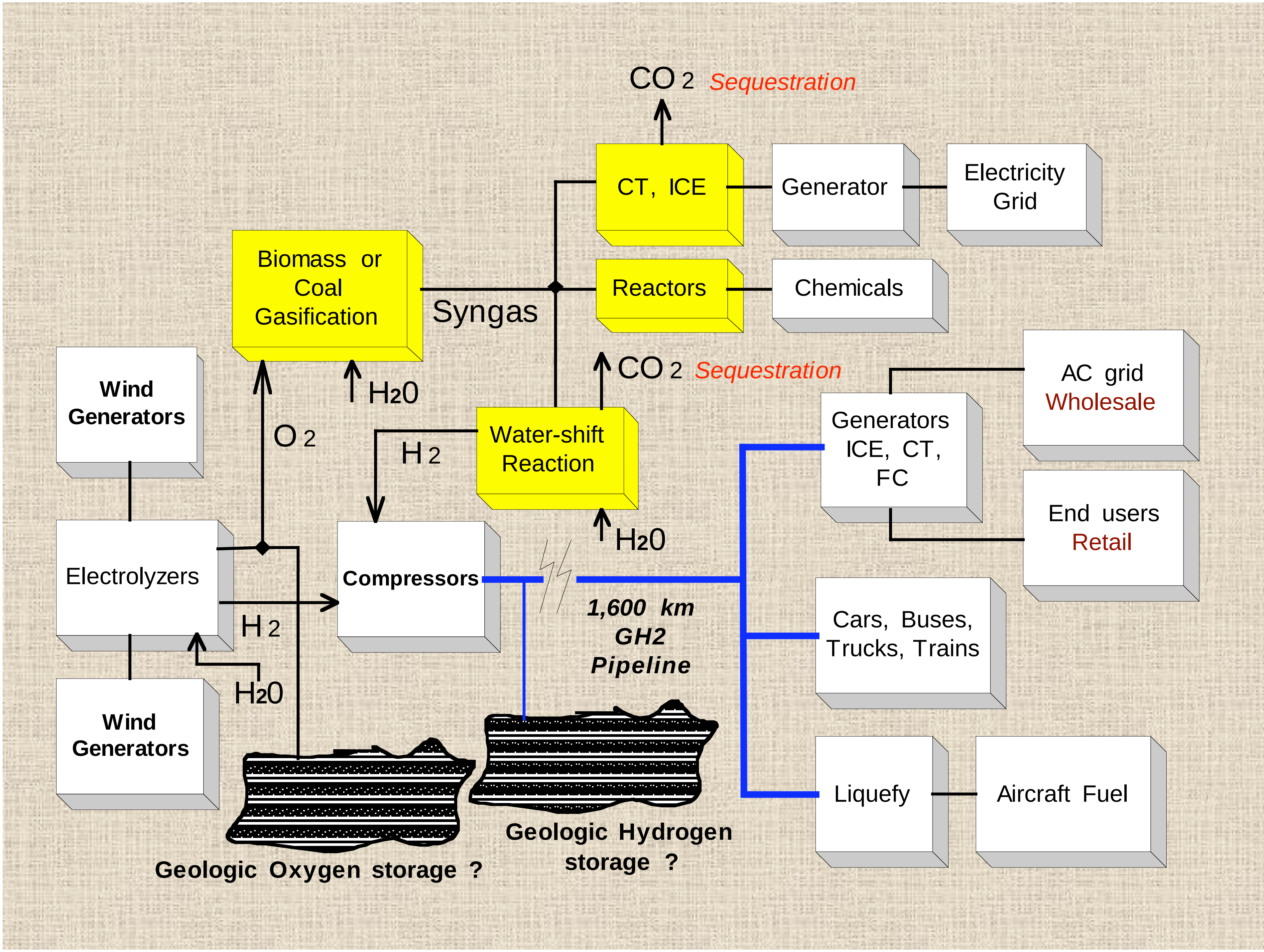
Hydrogen Energy Storage

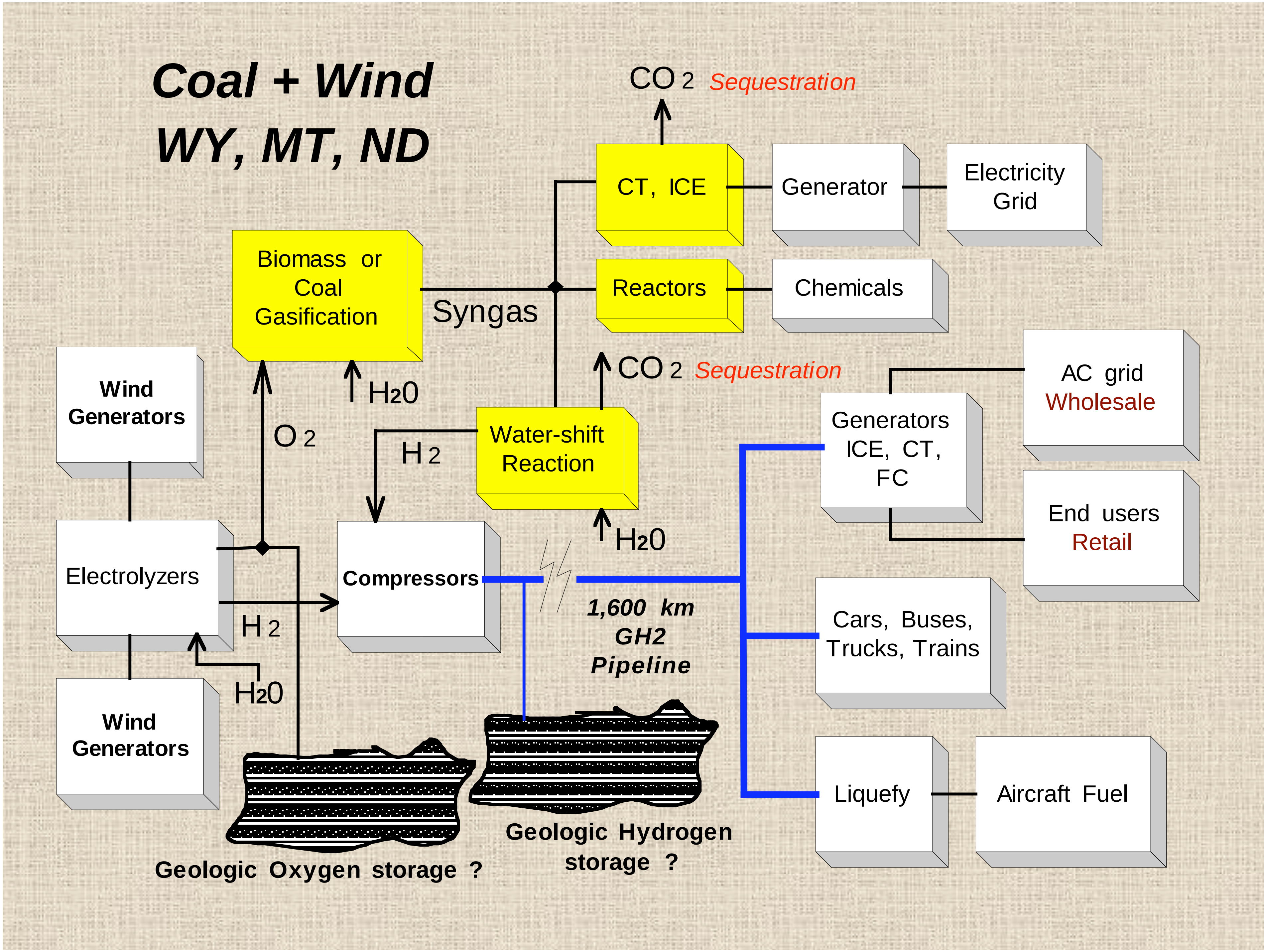


Compressed air energy storage

Iowa geology




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

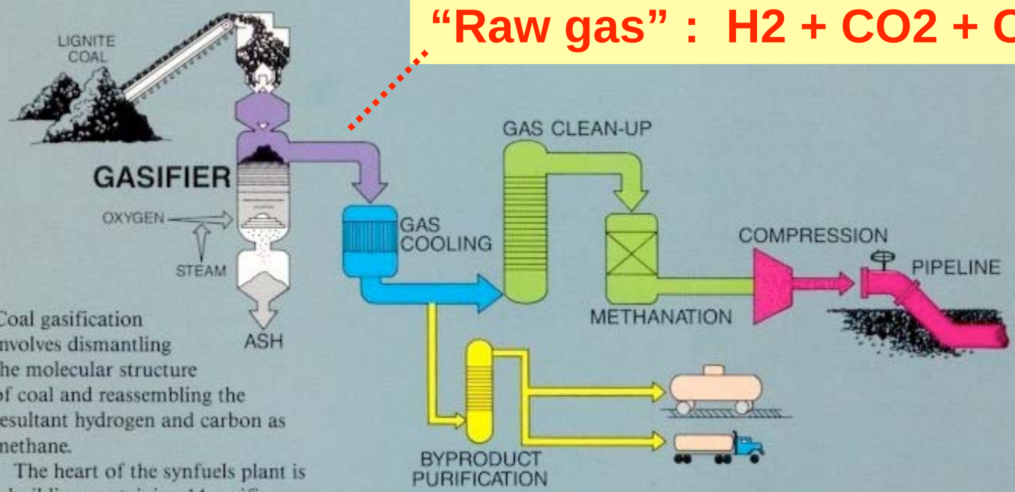

Coal + Wind
WY, MT, ND
CO 2 Sequestration
CT, ICE
Generator
Electricity Grid
Biomass or Coal Gasification
Syngas
Reactors
Chemicals
H2O
O 2
CO 2 Sequestration
Wind Generators
Water-shift Reaction
H 2
AC grid Wholesale
Generators ICE, CT, FC
End users Retail
H2O
Electrolyzers
Compressors
1,600 km GH2 Pipeline
H 2
Cars, Buses, Trucks, Trains
H2O
Wind Generators
Liquefy
Aircraft Fuel
Geologic Hydrogen storage ?
Geologic Oxygen storage ?

"Zero Emissions" Coal Synergy

- **ND, MT, WY are wind and coal states**
- **Oxygen byproduct of electrolysis to "zero emissions" coal gasification plants**
- **4,000 MW windplant produces –**
  - **~ 3.1 million tons O_2 per year**
  - **value ~ $ 19.17 / ton at coal plant**
  - **$ 59 million per year delivered O_2**
- **Share transmission; CF improve ?**
- **Is "zero emissions" coal "clean" ?**
- **Will CO_2 sequestration work ?**

The coal gasification process

"Raw gas" : $H_2 + CO_2 + CO + CH_4 + H_2O$



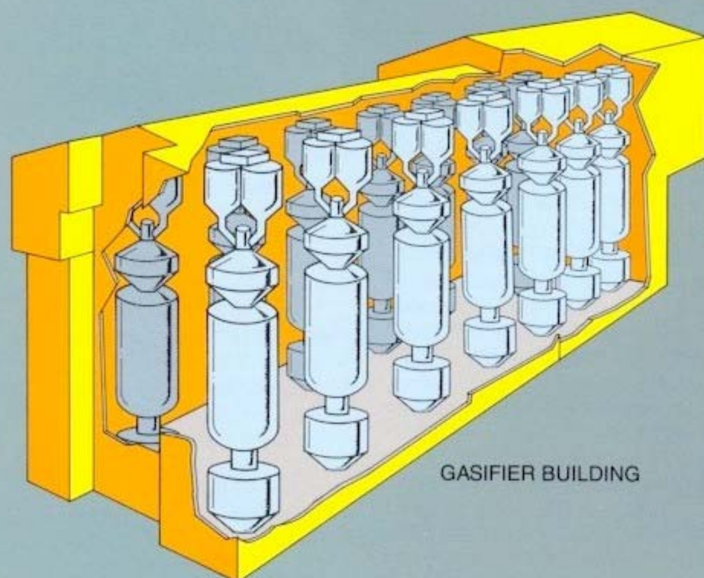
Coal gasification involves dismantling the molecular structure of coal and reassembling the resultant hydrogen and carbon as methane.

The heart of the synfuels plant is a building containing 14 gasifiers. The gasifiers are cylindrical pressure vessels 40-feet high with an inside diameter of 13 feet.

Each day 16,000 tons of lignite are fed into the top of the gasifiers. Steam and oxygen are fed into the bottom of the coal beds causing intense combustion (2,200 degrees Fahrenheit). Resulting hot gases break down the molecular bonds of coal and steam, releasing compounds of carbon, hydrogen, sulfur, nitrogen and other substances to form a raw gas that exits the gasifiers. Ash is discharged from the bottom of the gasifiers.

The raw gas goes to the gas cooling area where the tar, oils, phenols, ammonia and water are condensed from the gas stream. These byproducts are sent on for purification and transportation. Other byproducts are stored for later use as boiler fuel for steam generation.

The gas is moved to a cleaning area where further impurities are removed. Some of these substances with additional refining could become valuable byproducts in the future.

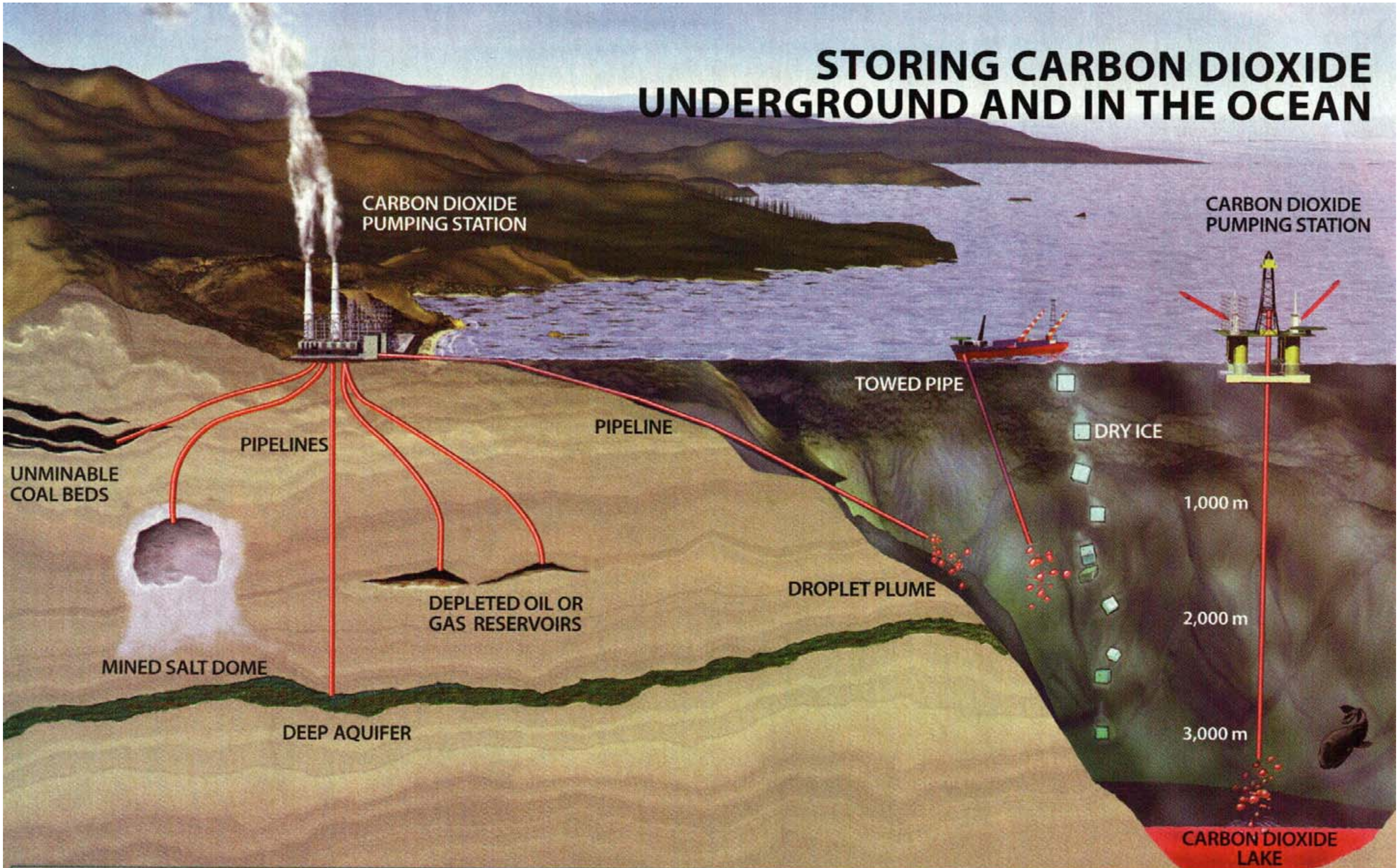


Methanation is the next step. Methanation takes place by passing the cleaned gas over a nickel catalyst causing carbon monoxide and most remaining carbon dioxide to react with free hydrogen to form methane. Final cleanup removes traces of carbon monoxide.

The gas is then cooled, dried and compressed, entering the pipeline with a heating value of 975 Btu per cubic foot.

Dakotas Gasification Company

Beulah, ND



STORAGE UNDERGROUND	ADVANTAGES	DISADVANTAGES
Coal Beds	Potentially low costs	Immature technology
Mined Salt Domes	Custom designs	High costs
Deep Saline Aquifers	Large capacity	Unknown storage integrity
Depleted Oil or Gas Reservoirs	Proven storage integrity	Limited capacity

STORAGE IN OCEAN	ADVANTAGES	DISADVANTAGES
Droplet Plume	Minimal environmental effects	Some leakage
Towed Pipe	Minimal environmental effects	Some leakage
Dry Ice	Simple technology	High costs
Carbon Dioxide Lake	Carbon will remain in ocean for thousands of years	Immature technology

The World Leader in on-site hydrogen solutions

Norsk Hydro Electrolysers AS

Knut Harg, Roy Grelland, Andres Cloumann
Hydro Oil & Energy
2005-10-03

A viable society. A need. An idea. 36,000 professionals. Energy. Cooperation. Aluminium. Determination. Pushing boundaries. Respect. Nature. Courage. 100 years. Thinking ahead.

Hydro's mission

Hydro creates a more viable society by developing natural resources and products in innovative and efficient ways

HYDRO

Building on competitive strengths

- **Operating revenue 2004 :** **18.883 mill €**
- **Net income :** **1.526 mill €**
- **No. of employees :** **34.648**
- **Total exploration O&G:** **2.076 mill boe**
- **Power production :** **8 TWh**
- **Alumina production :** **1,572,000 tonnes**
- **Aluminium metal production :** **1,720,000 tonnes**
- **Aluminium remelting :** **1,733,000 tonnes**

HYDRO

Developing our oil and energy business

- 2nd largest offshore operator on Norwegian Continental Shelf
- Strong production growth through 2007
- Strengthening our international oil and gas position
- Operating the Ormen Lange field development – the world's most challenging gas field at 850 –1100 m below sea
- Significant energy provider to the European market: oil and gas

HYDRO

Hydro – the company

The largest European aluminium company and among the top three world wide

The second largest producer of oil and gas on the Norwegian Continental Shelf

The world's leading supplier of plant nutrients

YARA

Agri spun off 25. March 2004 to become Yara

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Hydro's involvement in new energy

Tradition | **Present** | **Future**

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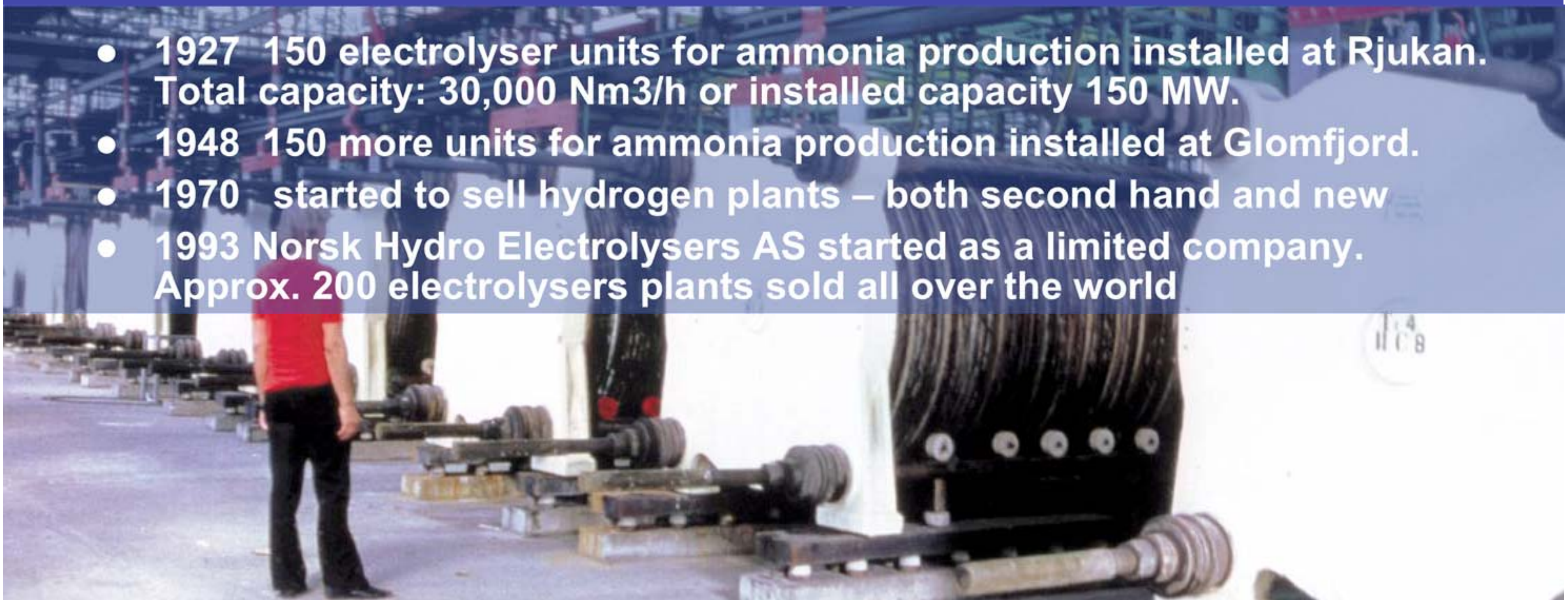
Electrolysis activities within Norsk Hydro

- 1927 150 electrolyser units for ammonia production installed at Rjukan. Total capacity: 30,000 Nm3/h or installed capacity 150 MW.
- 1948 150 more units for ammonia production installed at Glomfjord.
- 1970 started to sell hydrogen plants – both second hand and new
- 1993 Norsk Hydro Electrolysers AS started as a limited company. Approx. 200 electrolysers plants sold all over the world



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Industrial products and services from Hydro, Electrolysers

Atmospheric electrolysers

Capacities: 50 – 485 Nm^3/h

High pressure electrolysers

Capacities : 10 – 65 Nm^3/h

Parts and services of

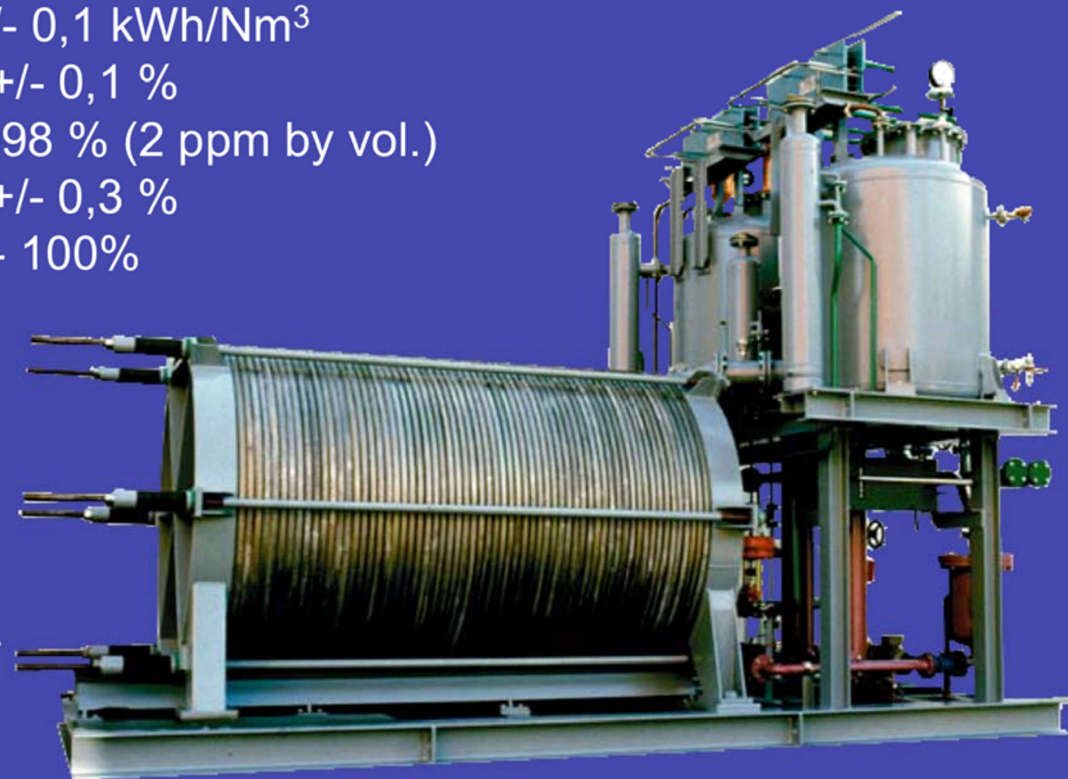
NHEL & BBC electrolysers

Atmospheric Electrolysers (The Hydro Workhorse)

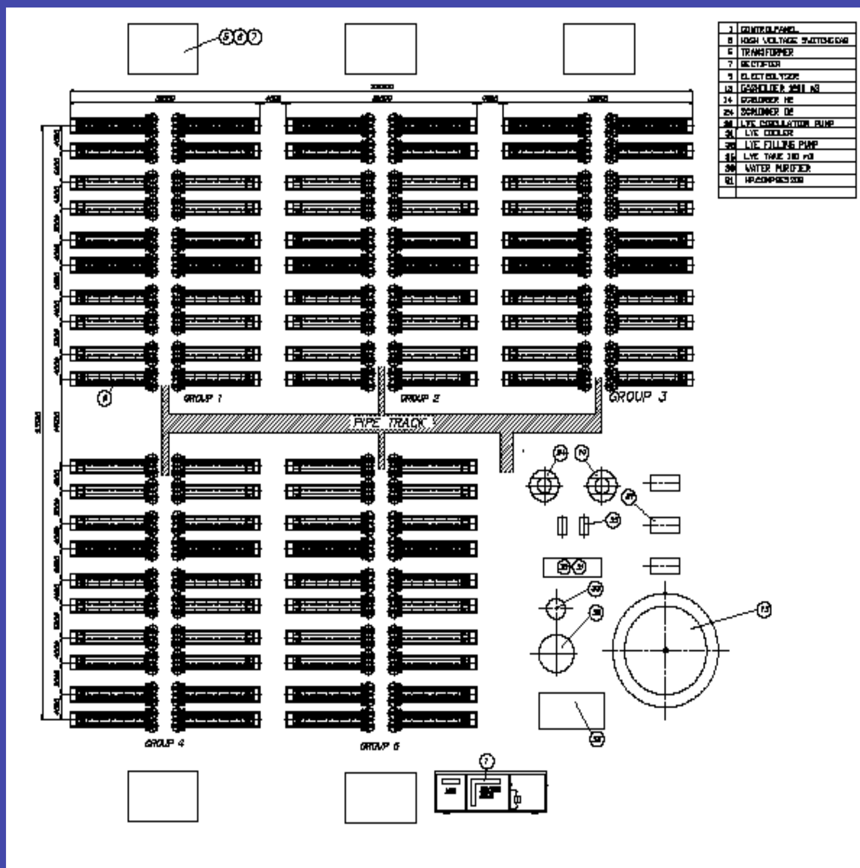
Capacity:	50 – 485 Nm^3/h
Energy consumption:	4,1 +/- 0,1 kWh/Nm^3
	4,3 +/- 0,1 kWh/Nm^3
Hydrogen purity %:	99,9 +/- 0,1 %
After purification:	99,9998 % (2 ppm by vol.)
Oxygen purity:	99,5 +/- 0,3 %
Operation:	20% - 100%

New developments:

- Rubber frames to replace metal
- Moderate pressure option

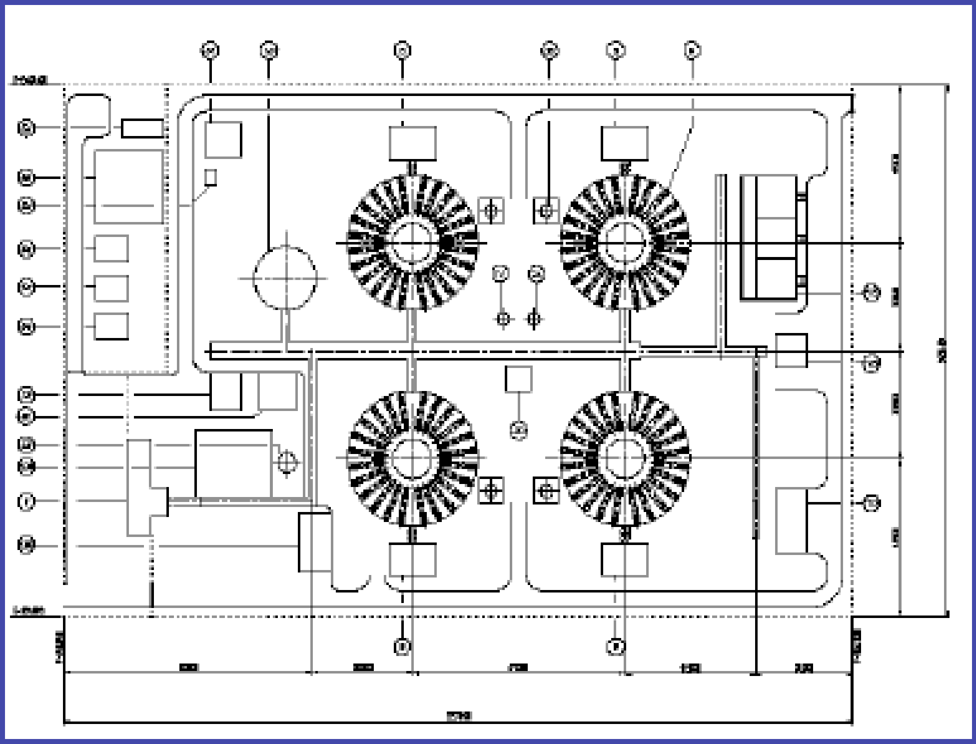


Typical Lay-out of Large scale Hydrogen Plant Electrolyser configuration: “Rectangular”



- Each electrolyser has individual gas/lye separation equipment piped together in common gas and lye system.
- Electrically the electrolysers are divided into units connected partly in parallel and partly in series.
- Five groups are shown, each consisting of 20 electrolysers. 10 and 10 of these are in parallel, the half groups are in series.

Typical Lay-out of Large scale Hydrogen Plant Electrolyser configuration: “Star”



- **The electrolysers in a group form a circular ”star” with the front facing common gas/ electrolyte separators at the centre.**
- **The centre area contains the piping arrangement for electrolyte distribution to the electrolysers.**
- **The “star” configuration reduces the amount of equipment such as instruments, valves and pipes compared to the “rectangular” configuration**
- **Electrically the electrolysers are connected parallel.**

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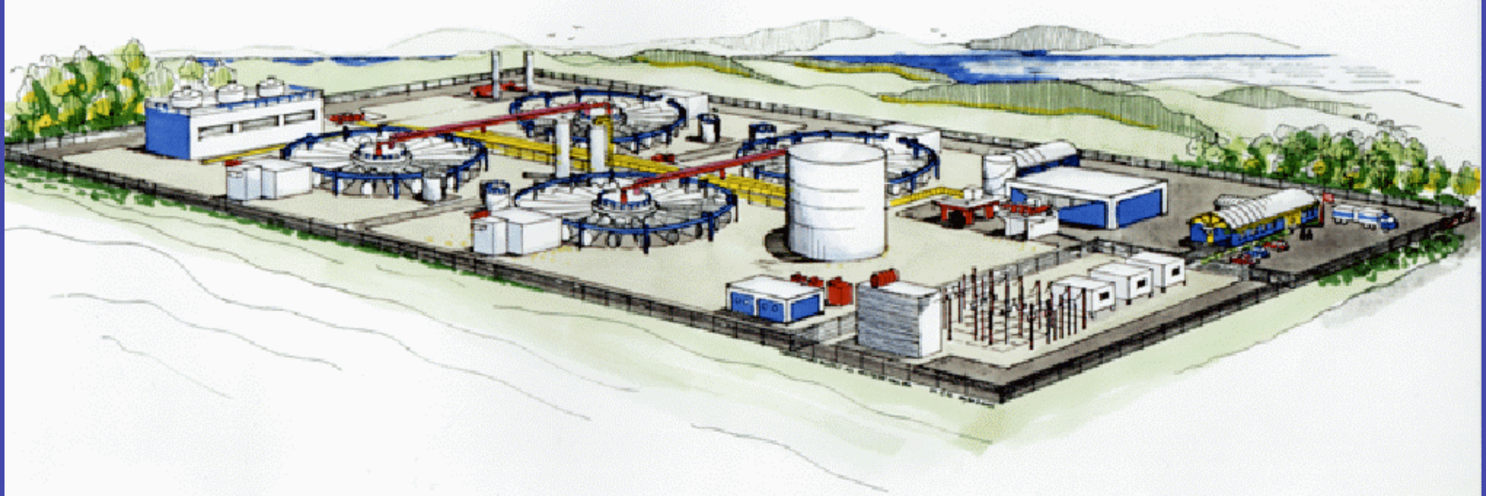
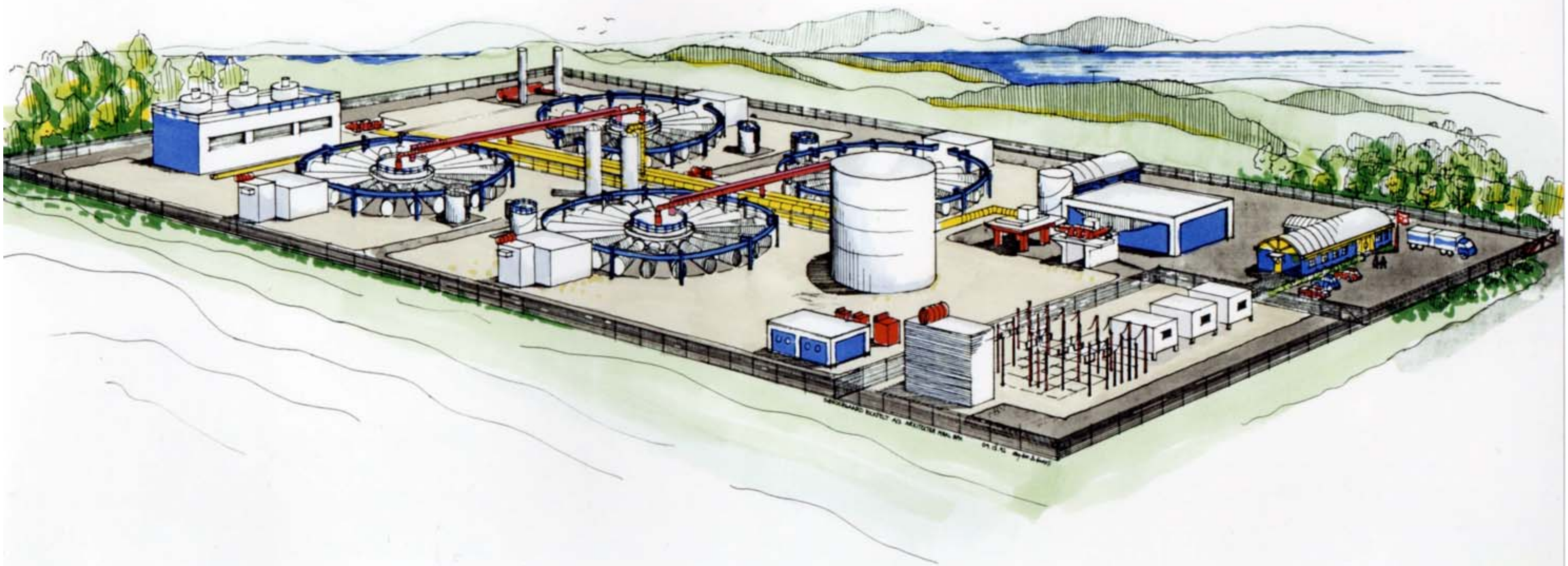
Artistic view of a 230 MW Hydrogen Plant based on "Star" Configuration



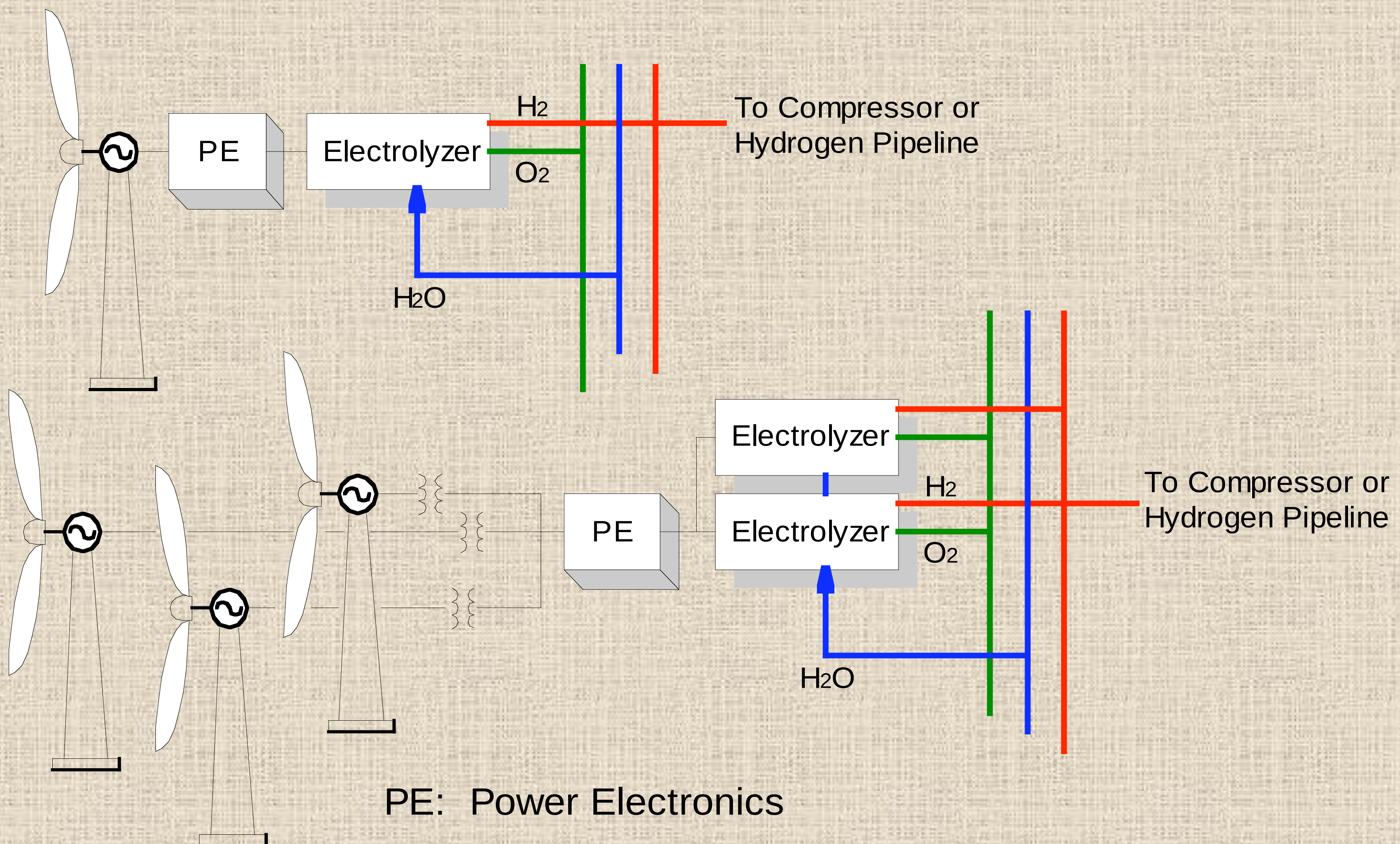
Plot area: 257.2 x 105.4 metres

Norsk Hydro Complete Electrolyzer Plant
KOH (potassium hydroxide liquid)
265 MWe input capacity



"Hydrogen Transmission Scenario"

PE synergy: sharing, topology options



PE: Power Electronics

Process Concept (230 MW)

- **4 electrolyser groups (”Star config.”)**
  - 24 electrolysers each group
    - 5,150 Amps, 485 Nm3 / h each electrolyser
  - Common gas/electrolyte separation system
  - Common transformer/rectifier
- **1 common gasholder**
- **1 Low pressure compressor – water injected screw type – 1.02 to 8 bar.**
- **1 reciprocating compressor – 8 to 33 bar.**
- **Plot area: 257.2 x 105.4 m**
- **Plant capacity: 46,560 Nm3/h**

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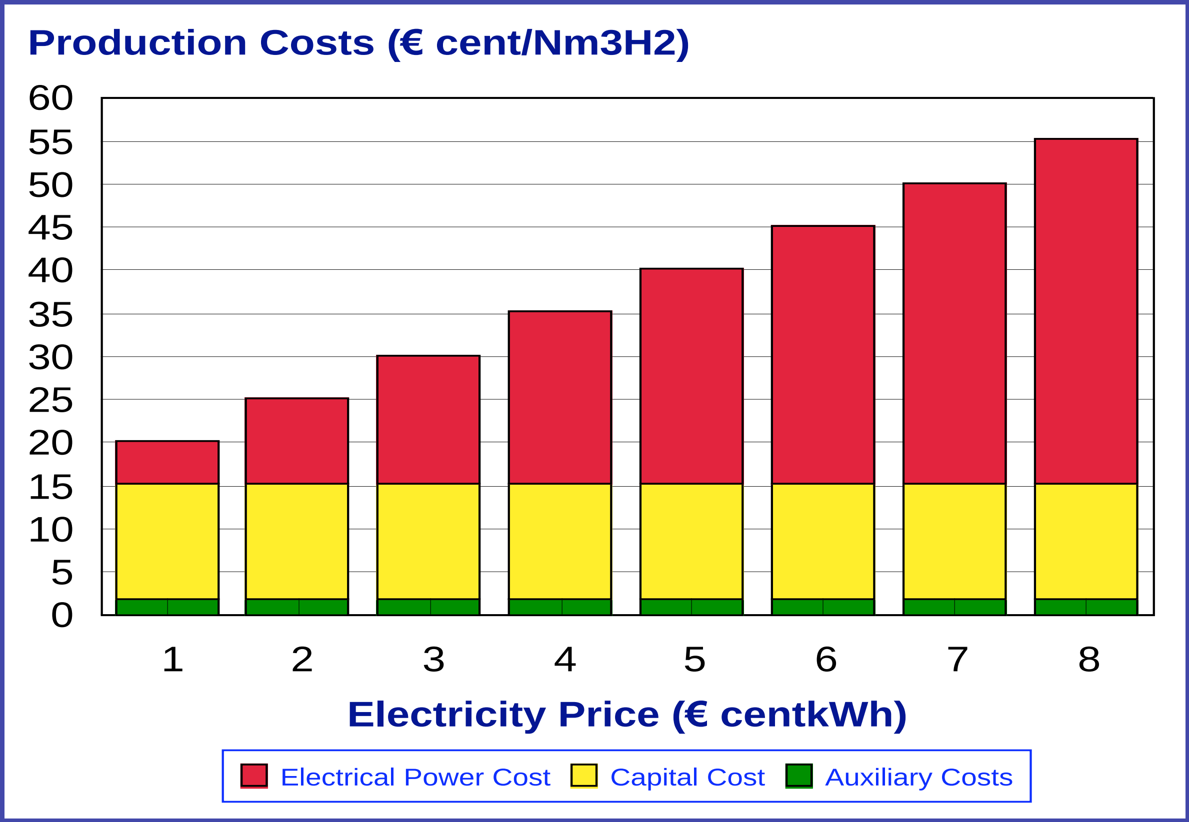
Cost Basis and Limitations

- Autonomous site with own administration, maintenance and plant control facilities and infrastructure.
- The climate conditions is so that it is not necessary to provide building for process equipment with exceptions for electrical equipment.
- High voltage power supply and utilities such as treated and untreated water are readily available at reasonable cost.
- Hydrogen to be delivered at plant battery at 33 bar.
- Oxygen is vented to atmosphere.
- Waste heat could not be commercialised.

Hydrogen Production Costs, Case 1



Cost Basis and Limitations (continued)

Case 1

- **Capacity utilisation rate 100 %**
- **Operation period 210 days.**
- **Plant availability 93.84 % (Operation period 197 days).**
- **8 electrolysers reactivated/overhauled every year**

Case 2

- **Capacity utilisation rate 100 %**
- **Continuous operation through the year.**
- **Operation period 325 days a year. (20+20 days reserved for peak demand for power and maintenance).**
- **14 electrolysers reactivated/overhauled every year**

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Cost estimates

• **Investment cost:**	**175 M €**
• **Annual capital cost:**	**29.25 M €**
- Lifetime of plant:	25 years
- Interest rate:	10 % p.a
• **Auxiliary cost (*)**	
- Case 1	4.5 M €
- Case 2	6.8 M €

(*) Labour cost, maintenance, reactivation, chemicals and water

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Cost estimates (continued)

- **Total production:**
  - Case 1 — 220 M Nm3/year
  - Case 2 — 363 M Nm3/year
- **Capital cost**
  - Case 1 — 13.3 € cent/Nm3
  - Case 2 — 8.05 € cent/Nm3
- **Auxiliary cost**
  - Case 1 — 2.0 € cent/Nm3
  - Case 2 — 1.9 € cent/Nm3

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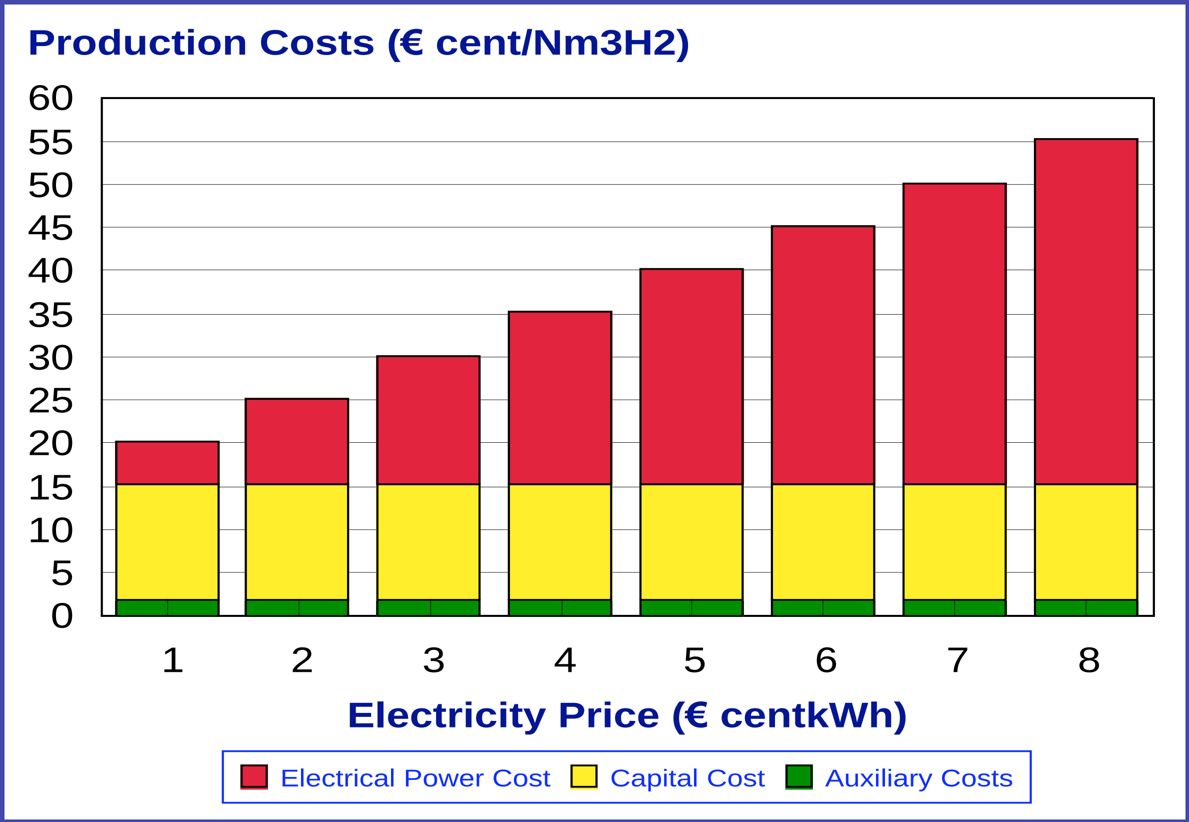
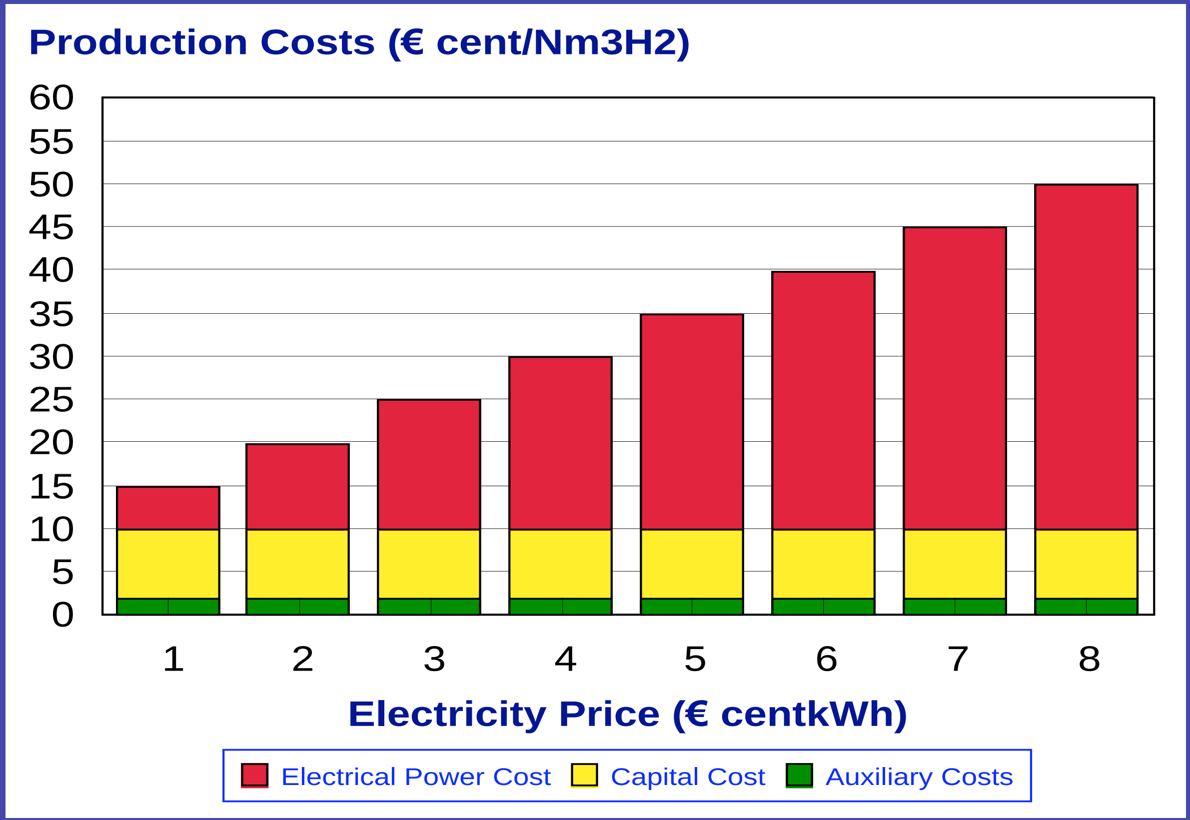
Hydrogen Production Costs, Case 1



Hydrogen Production Costs, Case 2



What is needed in the future?

- Flexibility
  - **Wide capacity range**
  - **Expandable**
  - **Wide operating range**
- Low costs
  - **Reduced capital cost**
  - **High energy efficiencies**
  - **Long life**
- Simple and safe operation
  - **Unattended operation, self-diagnosis**
  - **Fail-safe design**
- Quality service
  - **On-call expertise**
  - **Short response time**

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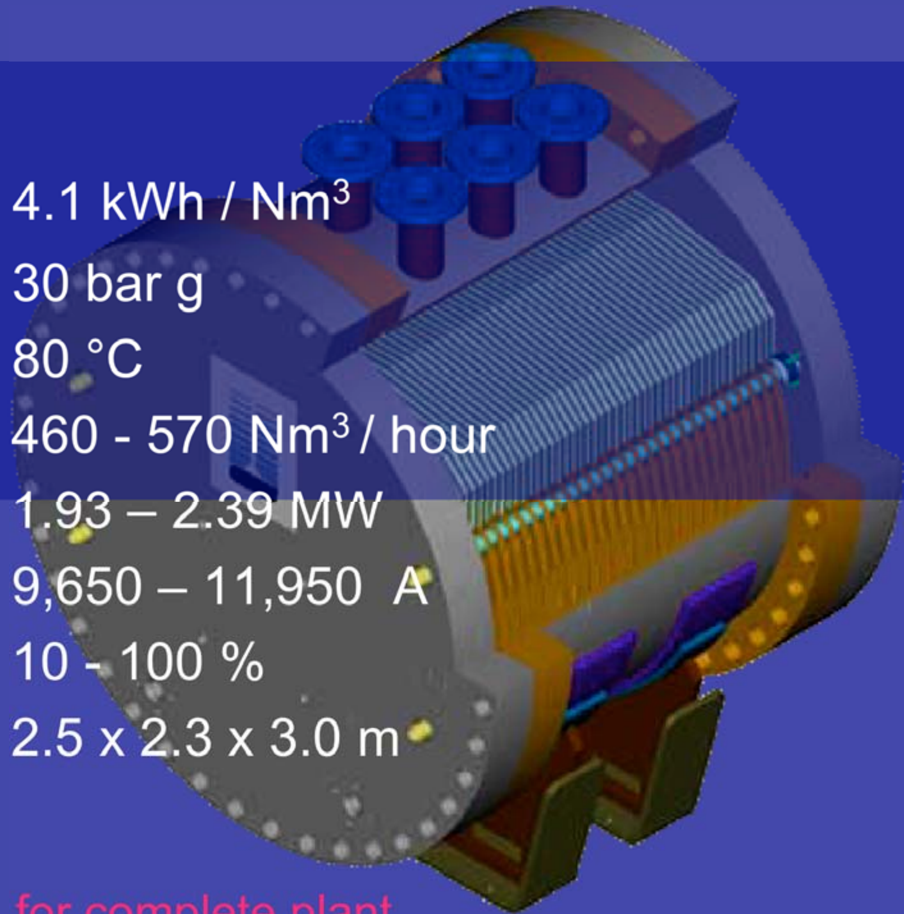
New high performance electrolysers (HPE)
Small footprint, higher efficiency

Targets for New Generation:



Energy consumption *	4.1 kWh / Nm^3
Operating pressure	30 bar g
Operating temperature	80 °C
Maximum output capacity	460 - 570 Nm^3 / hour
Input energy @ 80% efficiency	1.93 – 2.39 MW
Input current @ 200 vdc	9,650 – 11,950 A
Operational range, CF	10 - 100 %
Foot print	2.5 x 2.3 x 3.0 m

* Electrolyzer only; 4.2 kWh / Nm3 for complete plant

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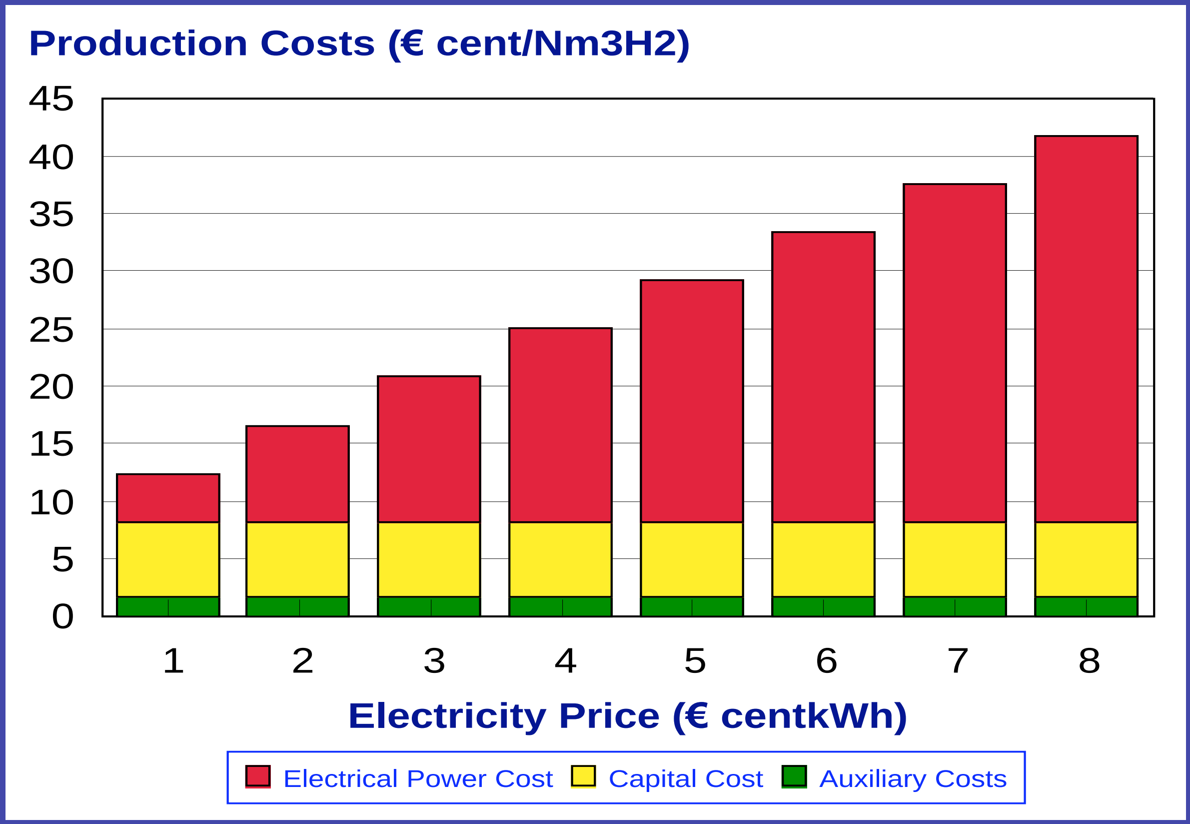
Hydrogen Production Costs, HPE-30



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Cost and Assumptions for 210 MW Hydrogen Plant based on the HPE-30 Electrolyser

- **Electrolyser rating:**
  - 500 Nm3 / h output
  - 30 bar H_2, O_2 output
  - 2.1 MWe input
- **Number of electrolysers:** **100**
- **Plant capacity:** **50,000 Nm3 / hour**
- **Plant electric energy input:** **210 MWe**
- **Energy consumption for electrolyser only:** **4.1 kWh / Nm3 H_2**
- **Energy consumption for the plant:** **4.2 kWh / Nm3 H_2**
- **Energy conversion efficiency:** **80 %**
- **Plant Capacity Factor (CF):** **100 %**
- **Operation period:** **325 days a year.**
  - Continuous operation through the year.
- **Turnkey cost of 100-electrolyser plant:** **150 Million EUR (*)**
  $US 181 Million @ $1.21 / EUR

(*) Turnkey includes building cost. $US 181 Million at $US 1.21 / Euro

Assume that auxiliary costs, interest rate and life time are same as for the atmospheric plant.

Cost and Assumptions for 210 MW Wind-driven Hydrogen Plant based on the HPE-30 Electrolyser: W.C. Leighty analysis

- Turnkey plant capital cost: $US 860 / kWe input
  - Less: 30% saving in large-scale production: (260)
  - Less: 10% delete transformer-rectifier and controls: (90)
  - Net $US 510 / kWe input
- Installed plant nameplate capacity ratio: wind generation / electrolyzer = 125 %
- Electrolyzer capital cost per kW wind generator capacity = $US 410
- Assumed electrolyzer cost in Windpower05 paper:
  - Electrolyzer stack $US 330
  - Power electronics + controls increment 50
  - Total $US 380 / kWe input

Challenges for 100 bar vs. 30 bar
Large-scale Electrolysers

- Metallic materials are more vulnerable to Stress Corrosion Cracking (SCC) in alkaline and enriched oxygen environment at increasing oxygen pressure.
- Chances for hydrogen embrittlement (HE) at this high pressure. Higher nickel content materials chosen to reduce or eliminate the stress corrosion may have the opposite effect on HE.
- Narrower operational range. Higher minimum power may be necessary due to gas impurity problems as a result of more dissolved gases in the electrolyte
- Synthetic materials used in the cell stack at high oxygen pressure
  - More prone to increased oxidation
  - Lower self ignition temperature.

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Other Considerations for 100 bar vs. 30 bar Large-scale Electrolysers

- **For ammonia synthesis: Fewer problems introduced by following the usual process:**
  - Compressing mixed N2 + H2 gases;
  - Instead of mixing the gases at high pressure.

- **Byproduct oxygen:**
  - Have value?
  - Market nearby?
  - At what pressure?

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Large-scale Windplant – Electrolyzer Topology Options
W. Leighty Analysis

- **One electrolyzer per wind generator:**
  - 2 MW wind / 1.6 MW electrolyzer
  - 200 vdc @ 10,000 A
  - Poor Z match for wind gen power electronics (PE)
- **Five electrolyzers per seven wind generators**
  - 14 MW wind / 10 MW electrolyzers
  - 5 electrolyzers in series @ 200 vdc @ 10,000 A on 1,000 vdc bus
  - Good Z match for wind gen PE
- **210 MW electrolyzer plant for 265 MW wind = 130 wind gen's**
  - Series-parallel "modules": 5 elec + 7 wind gen
  - 5 electrolyzers in series @ 200 vdc @ 10,000 A on 1,000 vdc bus
  - Good Z match for wind gen PE
  - Electricity + Fluid handling: controls electricity, H20, H2, O2, byproduct heat
  - Deliver H2 + O2: pipeline, NH3 plant, gasification plant
- **GW-scale: modular array; delivery to pipeline or NH3 plant**

The Utsira demonstration project

- **Project purpose**
  - Demonstrate how renewable energy can provide a safe and efficient energy supply to isolated areas
- **Project goals**
  - Full scale demonstration and testing of a wind - H_2 energy system
- **Project partners**
  - Norsk Hydro and Enercon; Enova, NFR, SFT

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Utsira is unique because it is the first full-scale stand-alone wind-hydrogen project in the world

- Hydrogen is used to store wind energy
- A fuel cell and a hydrogen combustion engine is producing power from stored hydrogen when no wind energy available
- Ten private households are part of the demo
- Remote-operated autonomous energy system

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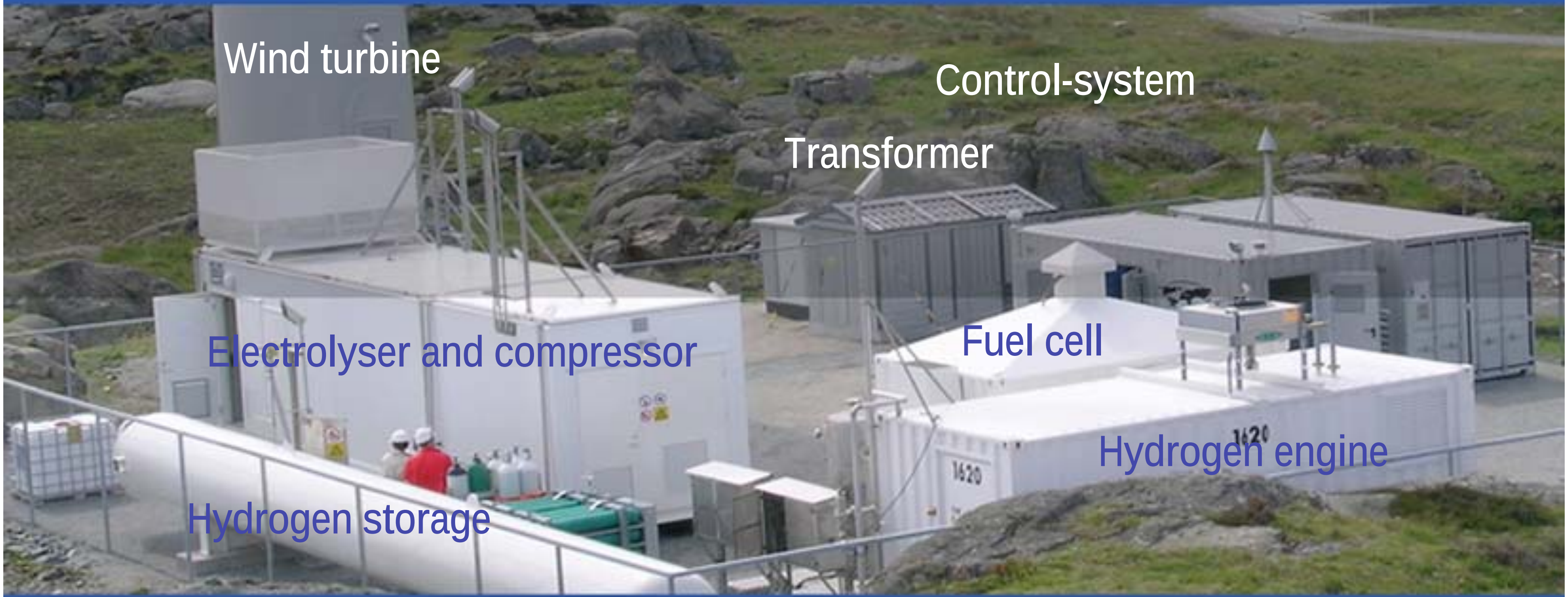
The wind – hydrogen plant at Utsira

A vision becoming reality



Main components

Wind turbines	2 * 600 kW
Hydrogen engine	55 kW
Fuel cell	10 kW
Electrolyser	10 Nm^3/h, 48 kW
Compressor	5,5 kW
Hydrogen storage capacity	2400 Nm^3, 200 bar
Flywheel	5 kWh
Master Synchronous Machine	100 kVA

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Hydro is a Fortune 500 energy and aluminium supplier founded in 1905, with 36,000 employees in nearly 40 countries. We are a leading offshore producer of oil and gas, the world's third-largest integrated aluminium supplier and a pioneer in renewable energy and energy-efficient solutions. As we look forward to our next 100 years, we celebrate a century of creating value by strengthening the viability of the customers and communities we serve.

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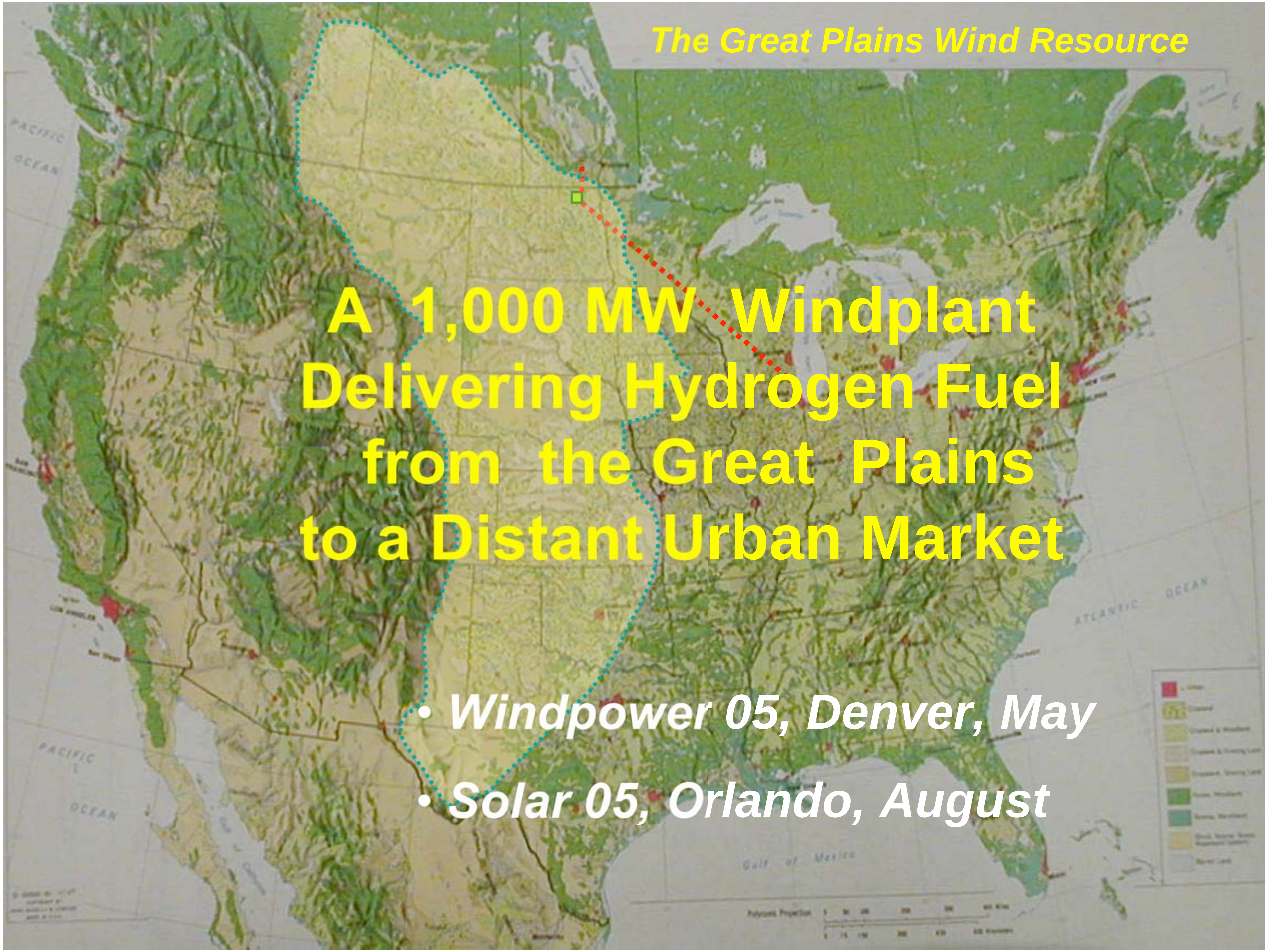
Progress of a different nature

www.hydro.com

NREL Electrolyzer Goals

Source: "Optimized Hydrogen and Electricity Generation from the Wind"
L.J. Fingersh, NREL/TP-500-34364, Table 1

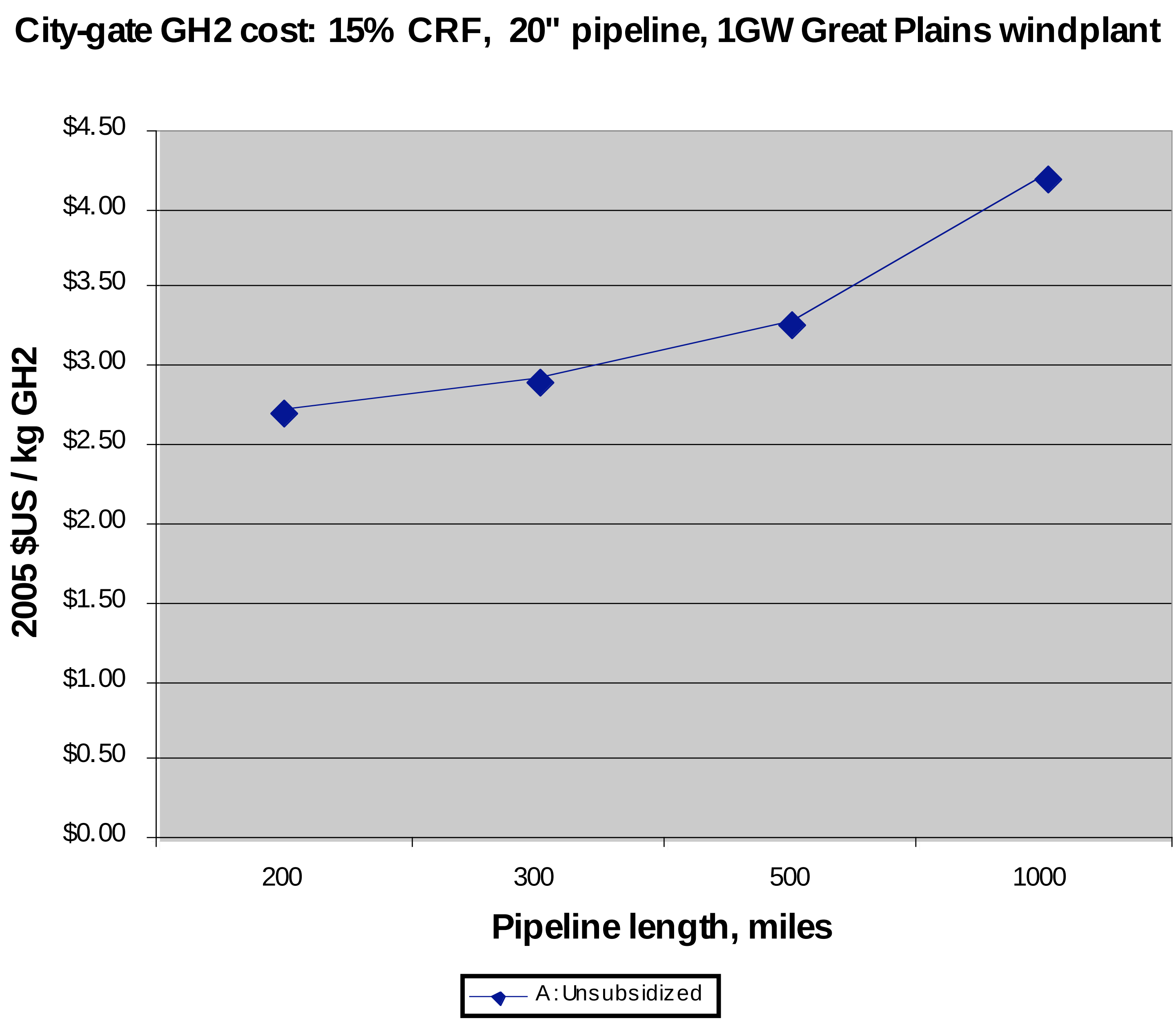
	4.5 MW		**1.5 MW**		**500 kW**	
	2003 Status	**2010 Target**	**2003 Status**	**2010 Target**	**2003 Status**	**2010 Target**
Power conditioning cost	$120	$95	$150	$120	$160	$140
Efficiency (LHV)	95%	97%	95%	97%	95%	97%
Cell stack assembly cost	$205	$55	$255	$70	$280	$80
Efficiency (LHV)	97%	98%	97%	98%	97%	98%
Balance of plant cost	$45	$20	$55	$30	$70	$40
Efficiency (LHV)	97%	98%	97%	98%	97%	98%
System labor cost	$15	$10	$25	$15	$40	$20
TOTAL cost	$385	$180	$485	$235	$550	$280
TOTAL system efficiency (LHV)	66%	77%	66%	77%	66%	77%



The Great Plains Wind Resource

A 1,000 MW Windplant Delivering Hydrogen Fuel from the Great Plains to a Distant Urban Market

- *Windpower 05, Denver, May*
- *Solar 05, Orlando, August*


City-gate GH2 cost: 15% CRF, 20" pipeline, 1GW 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
A: Unsubsidized

Interpretation, Context

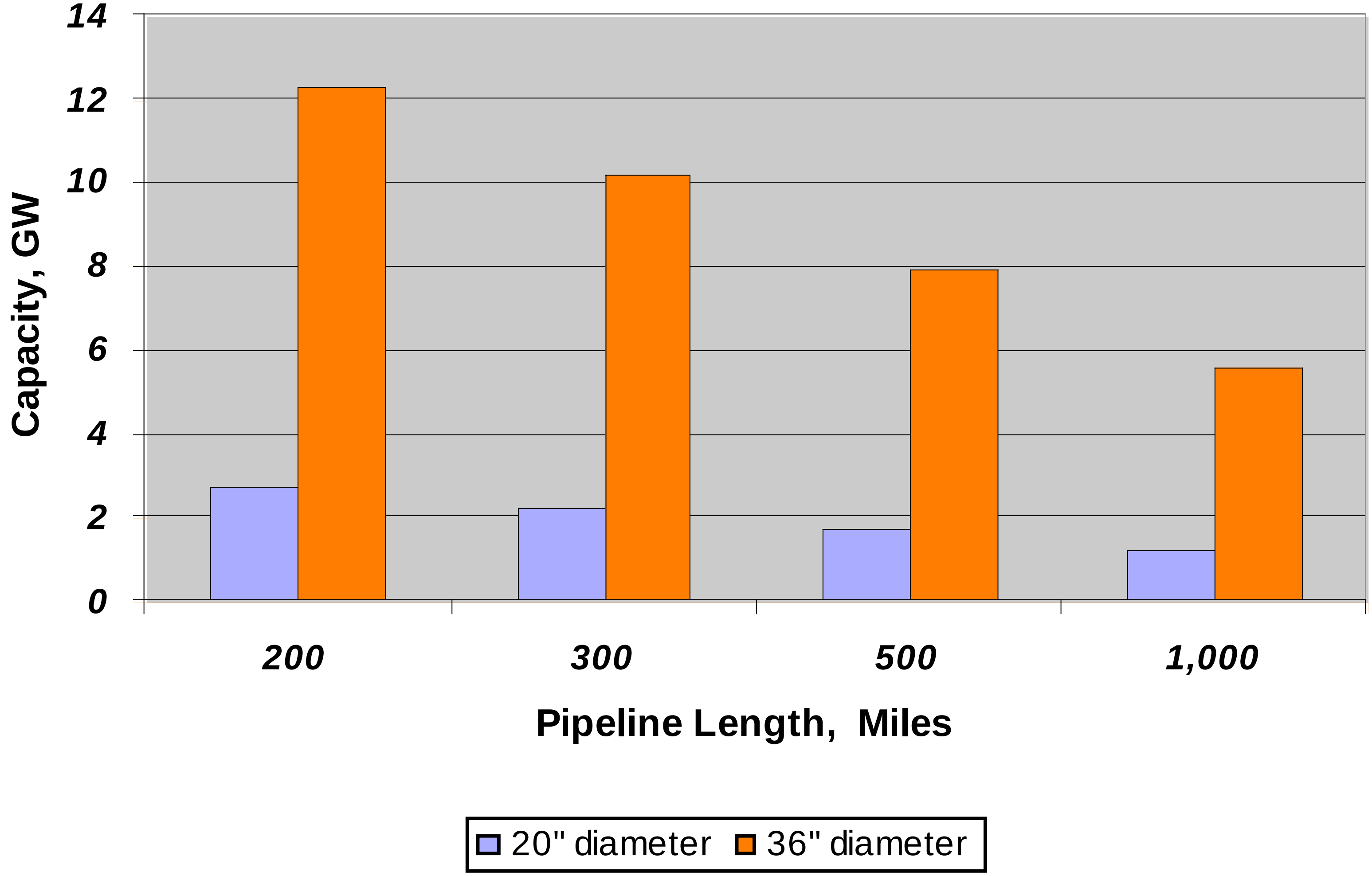
- Energy content:

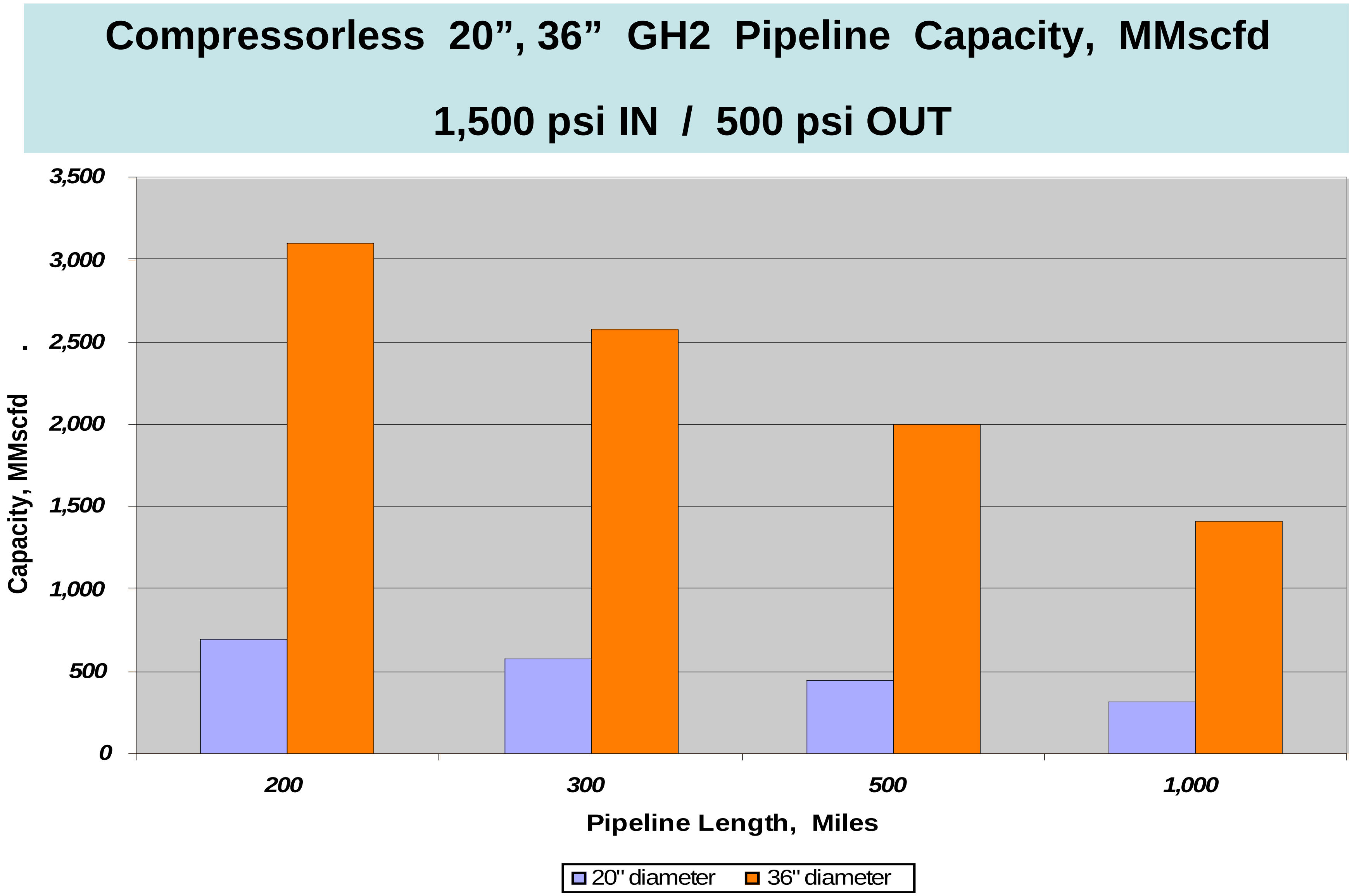
  1 kg hydrogen = 1 gallon gasoline
- 20” pipeline @ 500 miles = 1.8 GW capacity
- Untaxed: $ 0.42 / gal total: USA average
- FCHEV ***** ~ 2x mileage of ICEHV *****

  Fuel Cell Hybrid Electric Vehicle

  Internal Combustion Engine Hybrid Vehicle

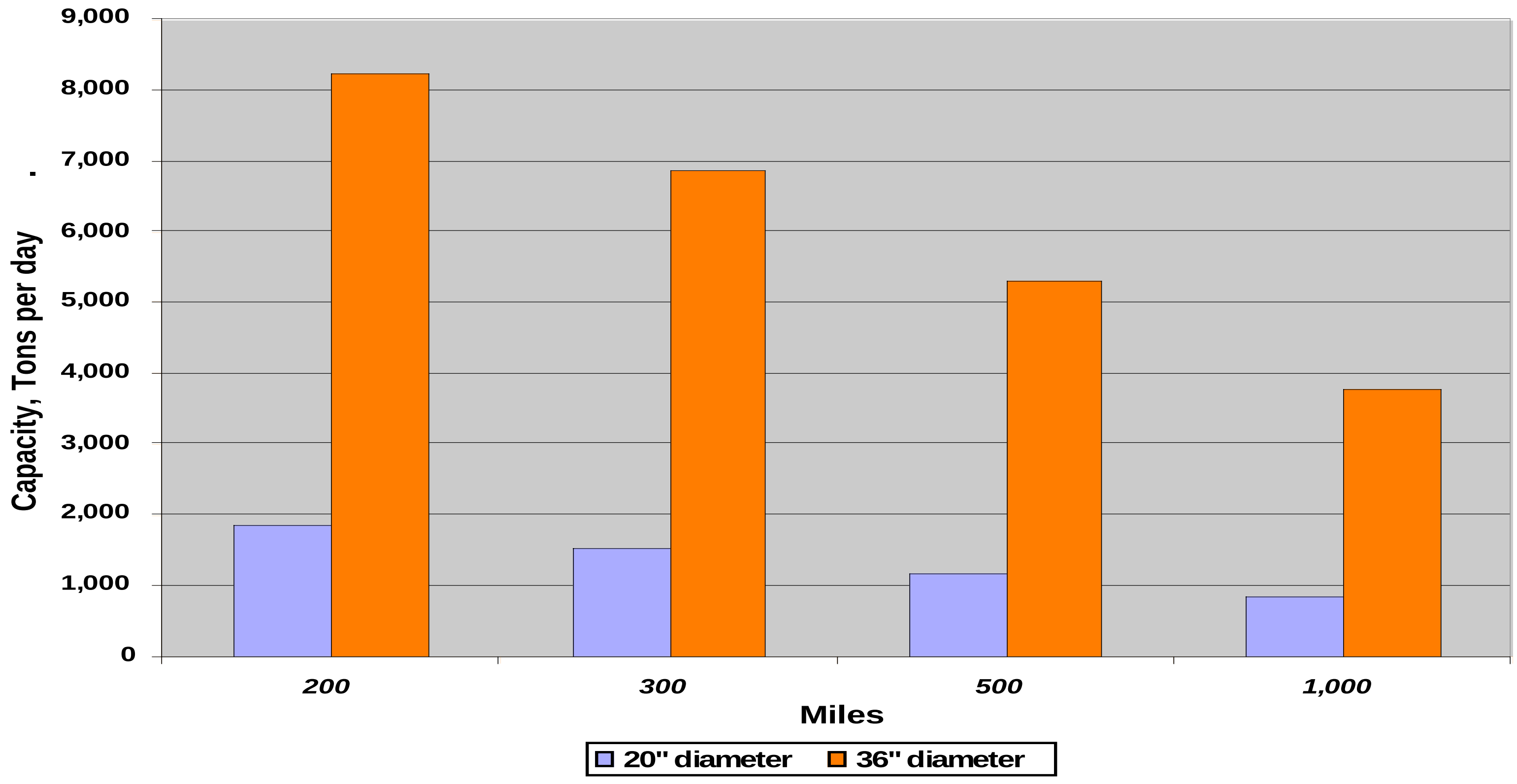
Compressorless 20”, 36” GH2 Pipeline Capacity, GW
1,500 psi IN / 500 psi OUT




Compressorless 20", 36" GH2 Pipeline Capacity, MMscfd
1,500 psi IN / 500 psi OUT
Capacity, MMscfd
3,500
3,000
2,500
2,000
1,500
1,000
500
0
200
300
500
1,000
Pipeline Length, Miles
20" diameter
36" diameter

Compressorless 20”, 36” GH2 Pipeline Capacity, Tons per day

1,500 psi IN / 500 psi OUT

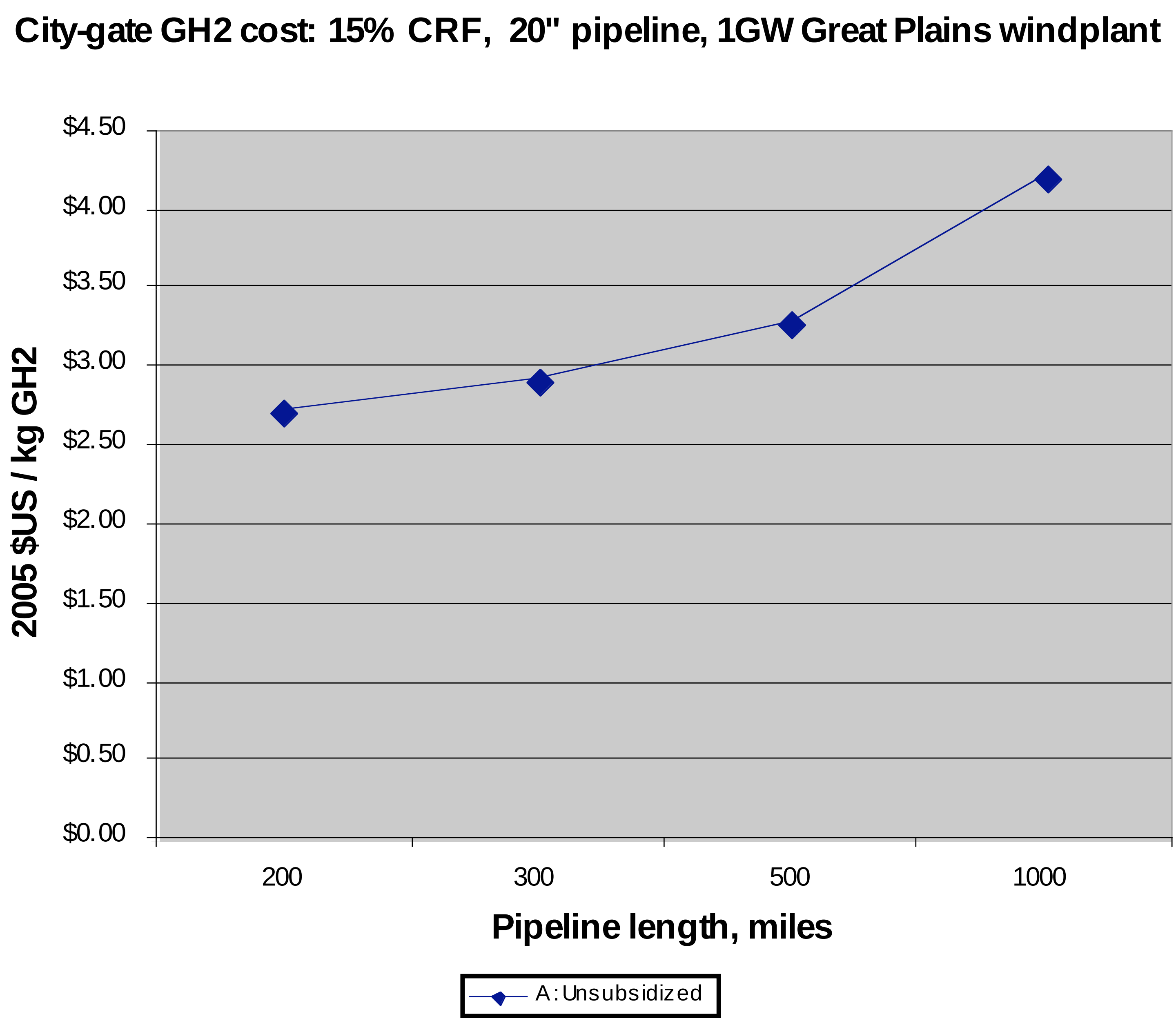


Energy Storage in Pipeline

Distance Km; miles	Outside Diam, inches	Volume, Cubic Meters	Inlet Press, psi	Delivery Press, psi	Energy Storage, Nm3	Energy Storage, MMscf	Energy Storage, Tons	Energy Storage, GWh	Energy Storage, Days *
800; 500	20	146,338	1500	500	9,954,938	352	936	33	3.5
800; 500	36	468,605	1500	500	31,877,861	1,126	2,997	107	11.2
800; 500	20	146,338	600	300	2,986,481	105	281	10	1.0
800; 500	36	468,605	600	300	9,563,358	338	899	32	3.3
1600; 1000	20	292,675	1500	500	19,909,875	703	1,872	67	7.0
1600; 1000	36	937,209	1500	500	63,755,722	2,251	5,994	214	22.3
1600; 1000	20	292,675	600	300	5,972,963	211	562	20	2.1
1600; 1000	36	937,209	600	300	19,126,717	675	1,798	64	6.7

Cases:
1 GW and 2 GW windplant

- Unsubsidized
- Fed PTC only ($ 0.019 / kWh)
- PTC + Oxygen sale
- PTC + Oxygen sale + C-offset ($ 0.01 / kWh)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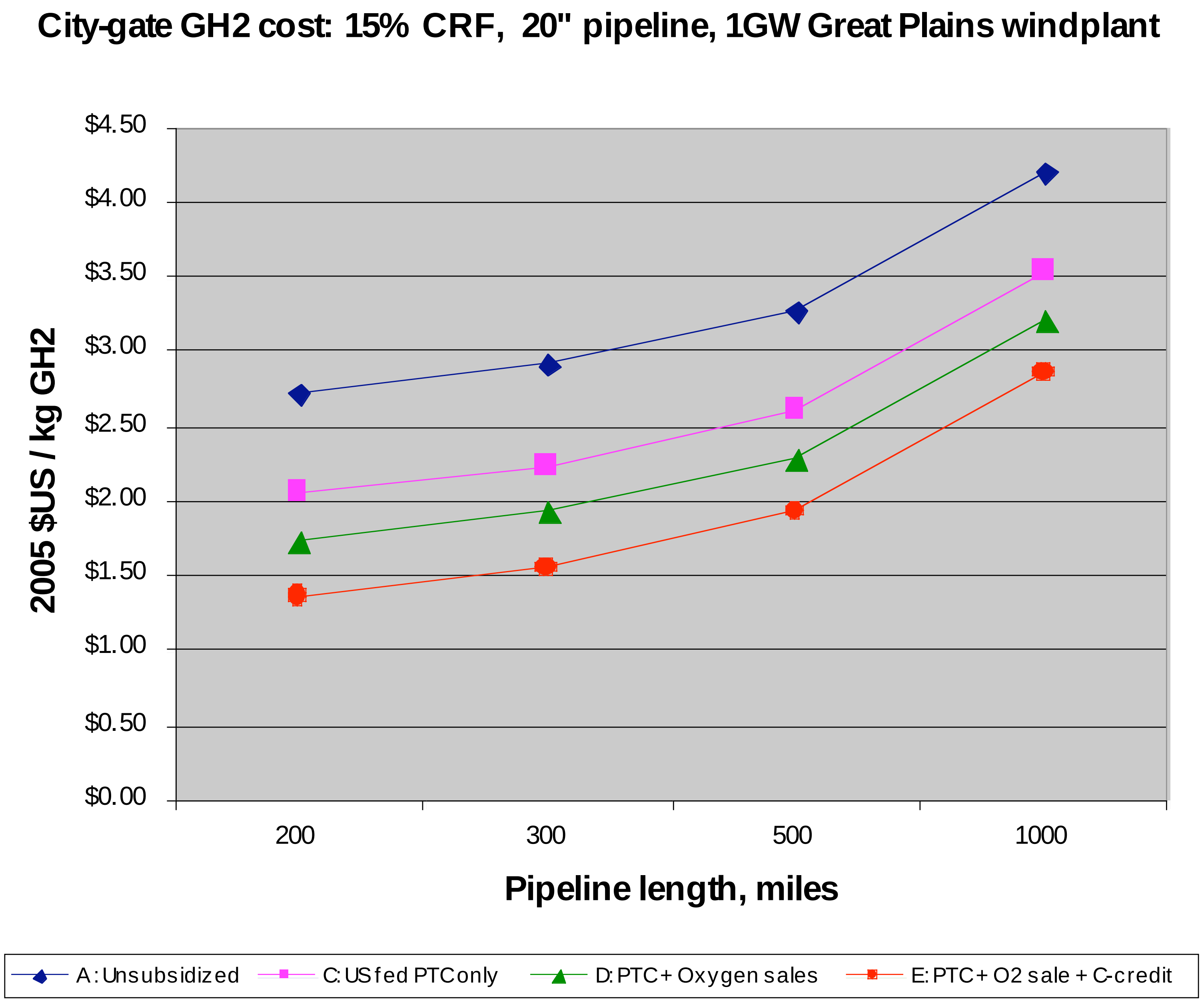
$4.00
$3.50
$3.00
$2.50
$2.00
$1.50
$1.00
$0.50
$0.00
200
300
500
1000
Pipeline length, miles
A: Unsubsidized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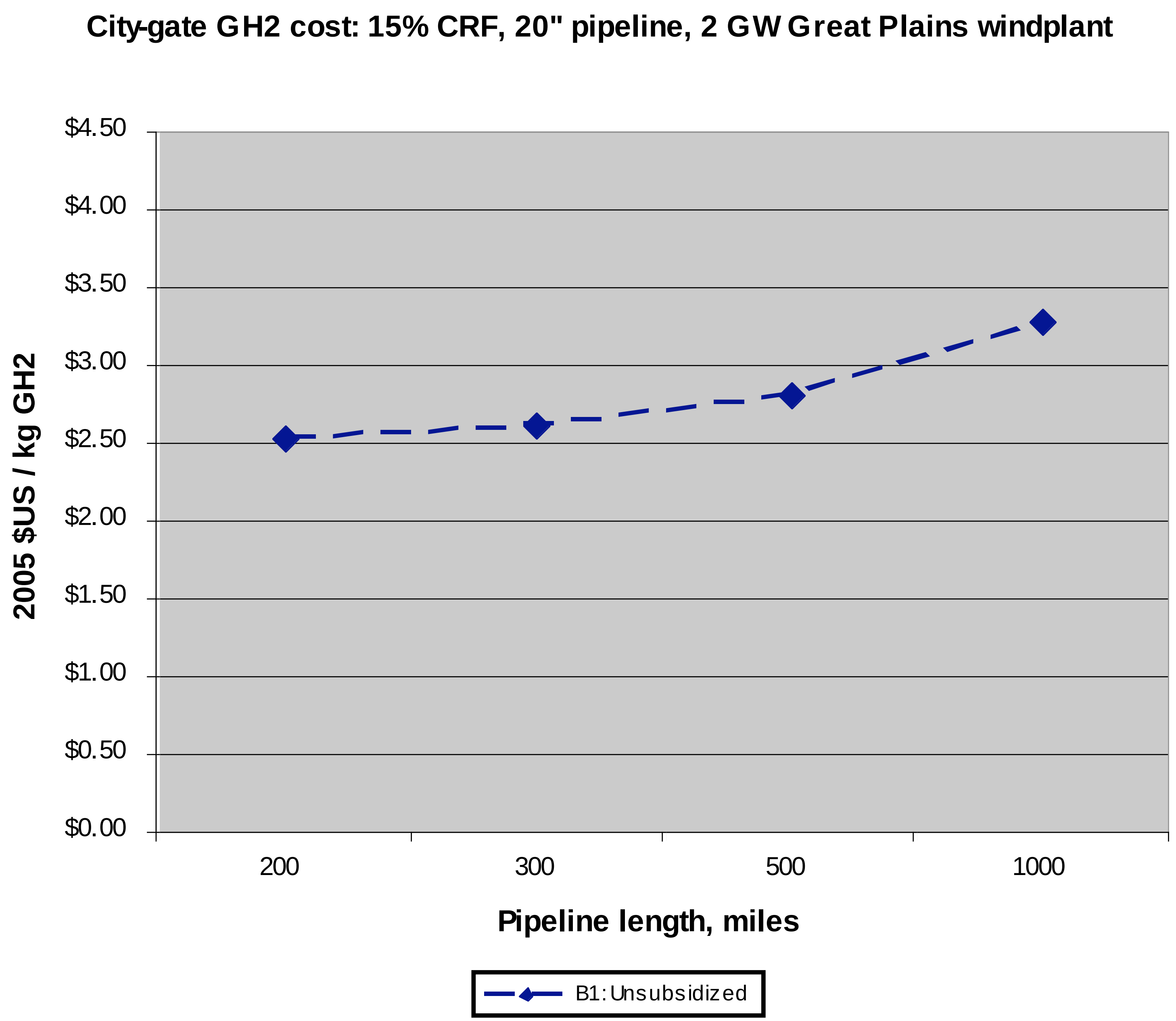
$4.50
$4.00
$3.50
$3.00
$2.50
$2.00
$1.50
$1.00
$0.50
$0.00
2005 $US / kg GH2
200
300
500
1000
Pipeline length, miles
A: Unsubsidized
C: US fed PTC only
D: PTC + Oxygen sales
E: PTC + O2 sale + C-credit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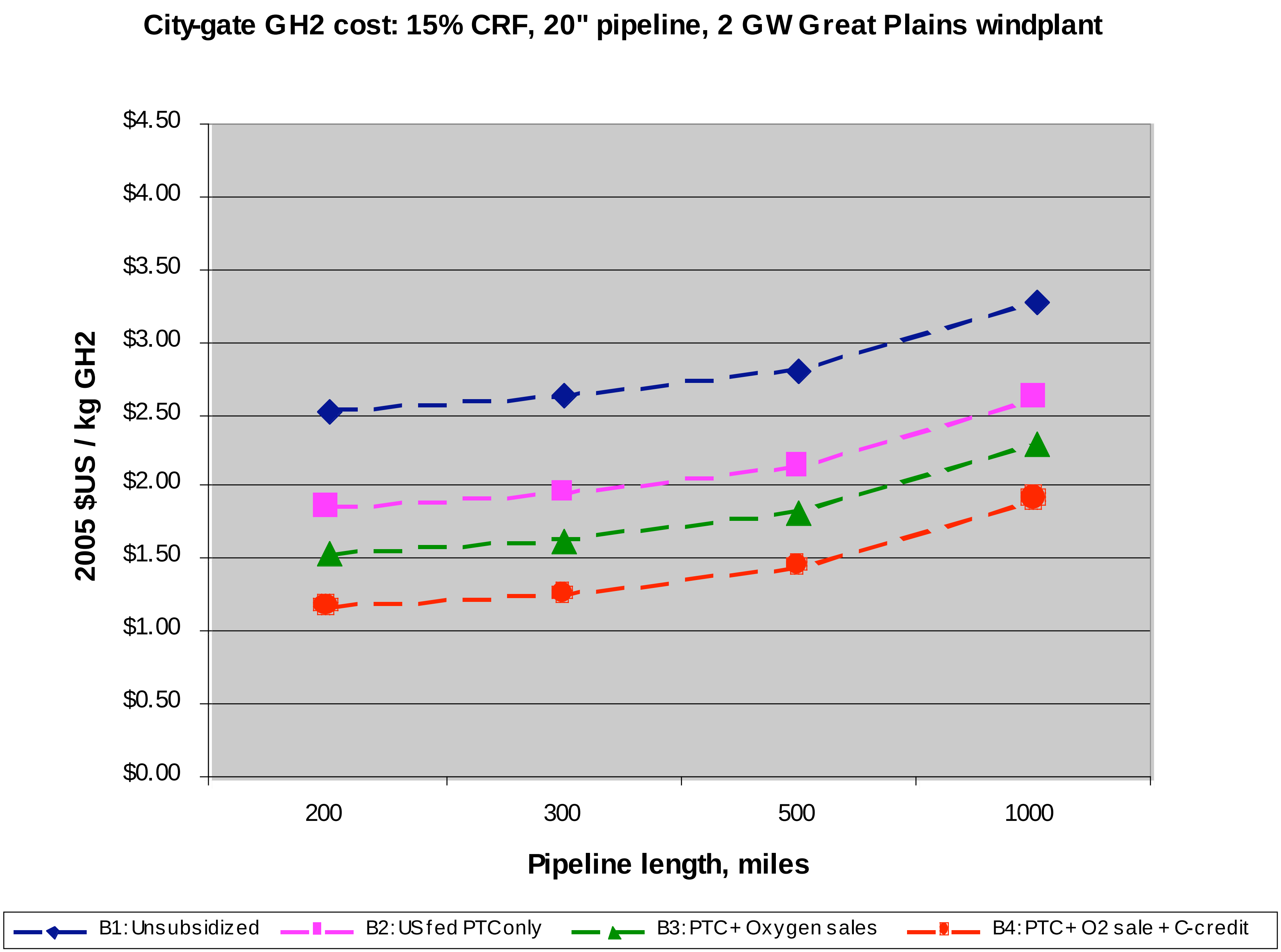
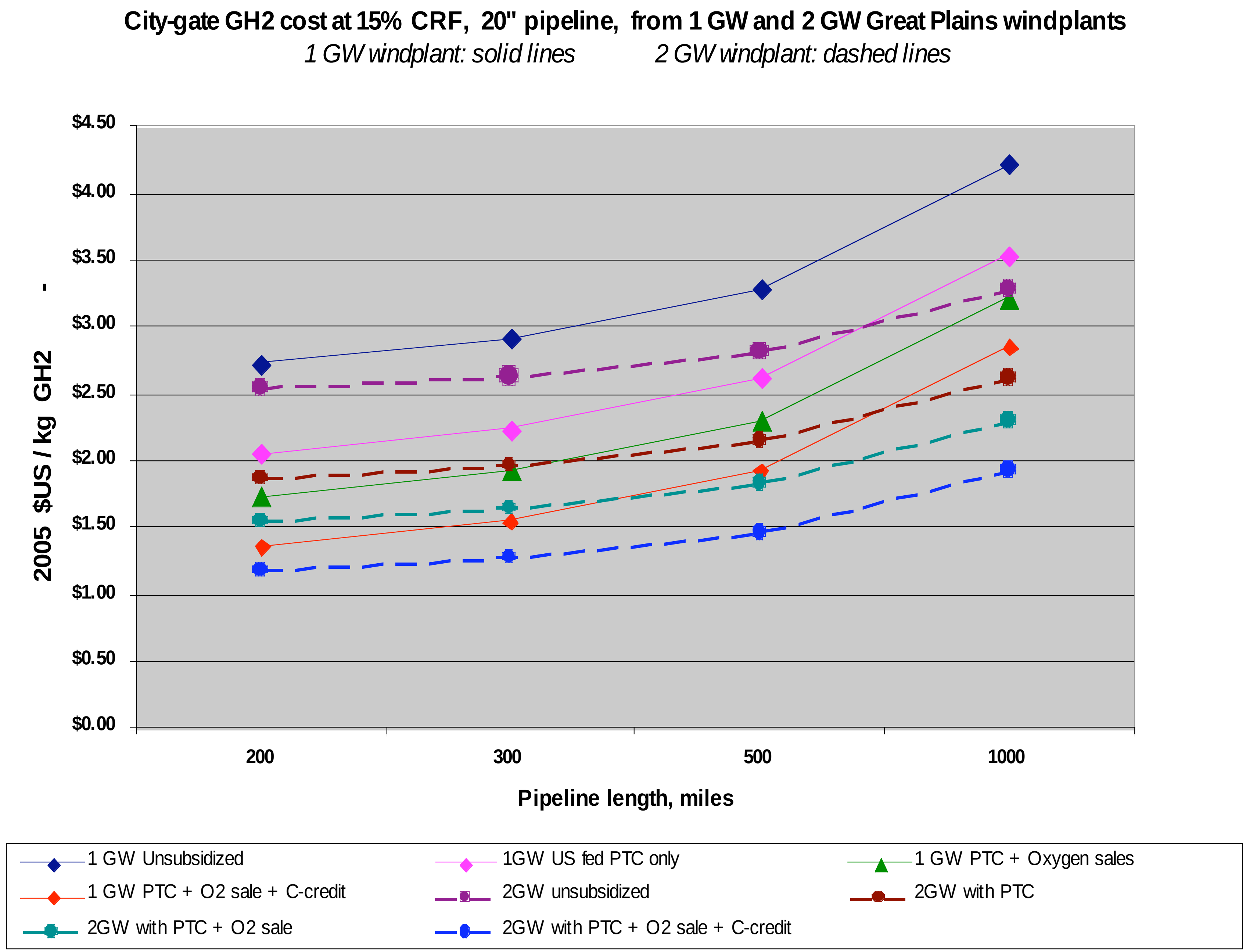
$4.50
$4.00
$3.50
$3.00
$2.50
$2.00
$1.50
$1.00
$0.50
$0.00
200
300
500
1000
Pipeline length, miles
B1: Unsubsidized



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



City-gate GH2 cost at 15% CRF, 20" pipeline, from 1 GW and 2 GW Great Plains windplants
1 GW windplant: solid lines
2 GW windplant: dashed lines
$4.50
$4.00
$3.50
$3.00
$2.50
$2.00
$1.50
$1.00
$0.50
$0.00
2005 $US / kg GH2 -
200
300
500
1000
Pipeline length, miles
1 GW Unsubsidized
1GW US fed PTC only
1 GW PTC + Oxygen sales
1 GW PTC + O2 sale + C-credit
2GW unsubsidized
2GW with PTC
2GW with PTC + O2 sale
2GW with PTC + O2 sale + C-credit

Why Wind → Hydrogen → Pipeline ?

- GW / GCC emergency:
  - Quickly
  - Large-scale
  - Carbon-free energy
  - Renewables
- Vehicle fuel: buses, cars
- DG electricity: retail side of meter

Why Wind → Hydrogen → Pipeline ?

- Wind is lowest-cost renewable
- Largest, richest, wind resources stranded
- Potential:
  - Supply all USA energy
  - Worldwide application
- New electric transmission lines:
  - Difficult to route, site, permit
  - Low capacity factor (CF) if dedicated to wind
  - No energy storage
  - Vulnerable: nature, man
  - Large capital investment

Why Wind → Hydrogen → Pipeline ?

- New hydrogen transmission pipelines:
  - Underground: more acceptable, permittable, secure
  - Energy storage:
    - Pipeline smooths wind; cannot firm
    - Geologic storage: seasonal scale, to firm
  - About same capital cost as electric lines
  - Multiple hydrogen sources: synergy
  - Hydrogen embrittlement problem: materials
- Nascent market for hydrogen fuel:
  - Vehicle fuel – buses, cars
  - Distributed generation of electricity – retail side meter

Why Wind → Hydrogen → Pipeline ?

- How far pipeline renewable-source GH2 ?
- What is city-gate, end-of-pipe cost ?
- GH2 compression costly: eliminate it ?
- Pilot plant
  - All new industrial processes
  - Validate our models
  - IRHTDF – poster
  - $50 million

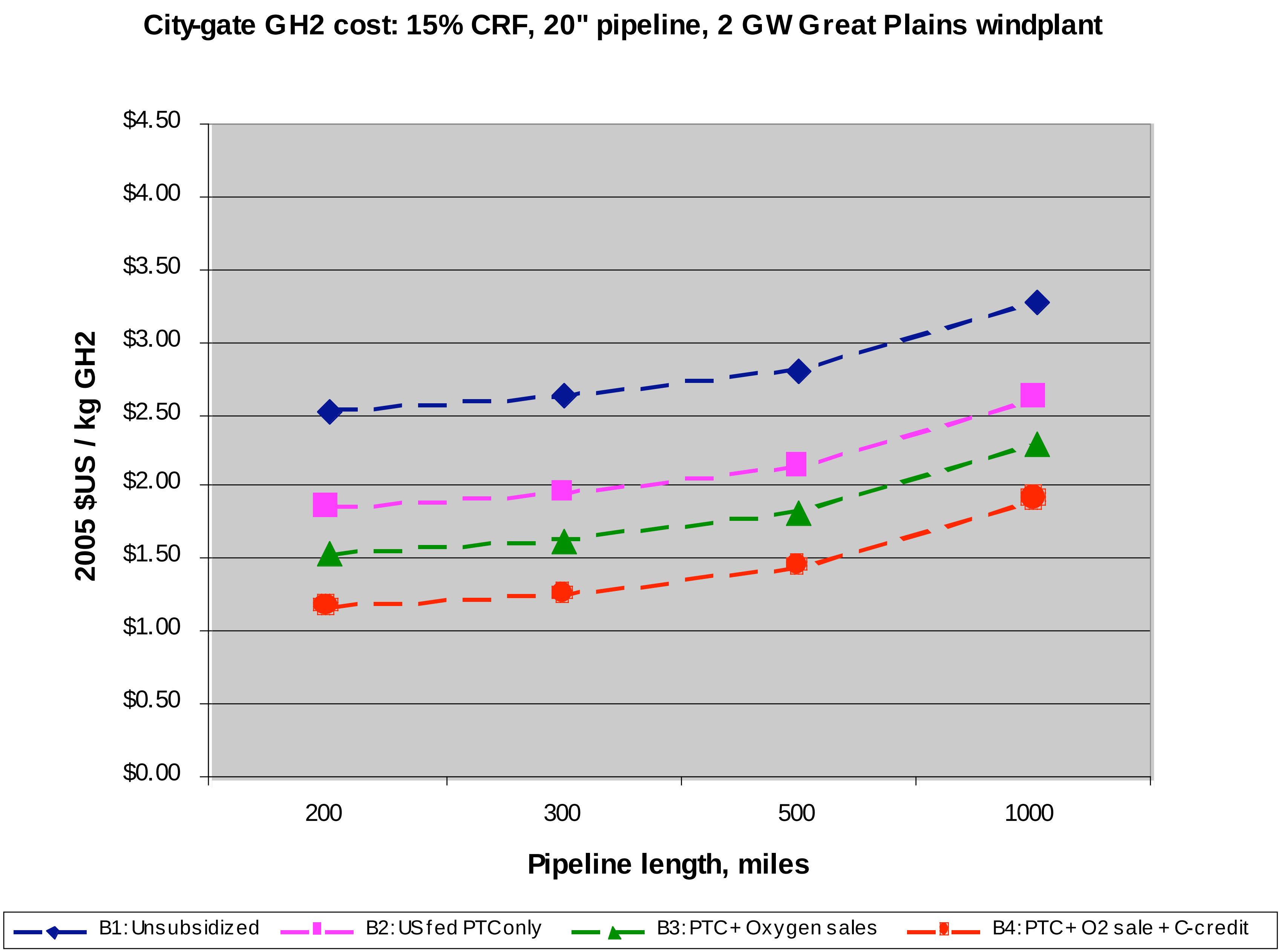
Methods

- Hydraulic modeling of pipeline: NG practice
- Wind generator, electrolyzer:
  - industry consensus
  - performance
  - costs: capital, O&M
- Simple capital recovery factor (CRF) costs
- Hydrogen embrittlement discussion:

  Sandia National Lab

Pipelining GH2 Costly

- ~ 1.5 – 2 x NG, per energy - distance
- 1/3 energy density of natural gas (NG) by volume
- ~ 2x compressor power: NG
- ~ 3x compressor energy: NG
- Hydrogen embrittlement of steel

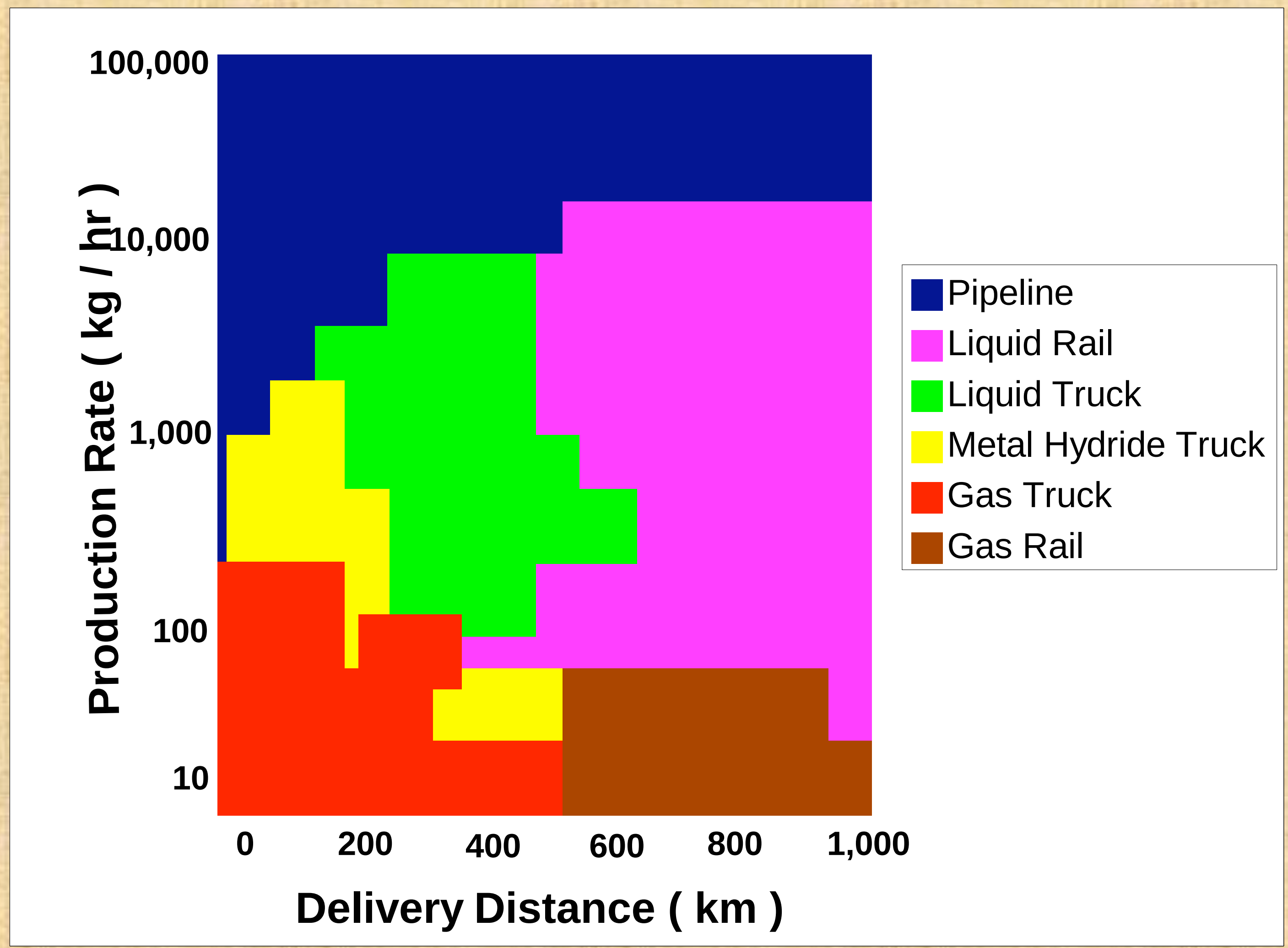

City-gate GH2 cost: 15% CRF, 20" pipeline, 2 GW Great Plains windplant
2005 $US / kg GH2
$4.50
$4.00
$3.50
$3.00
$2.50
$2.00
$1.50
$1.00
$0.50
$0.00
200
300
500
1000
Pipeline length, miles
B1: Unsubsidized
B2: US fed PTC only
B3: PTC + Oxygen sales
B4: PTC + O2 sale + C-credit

Key Assumptions

- Stranded: new transmission needed
- Market for gaseous hydrogen (GH2) fuel
- High-press-output electrolyzers: 1,500 psi (100 bar)
- 1,500 psi (MAOP) pipeline acceptable
- 500 psi city gate delivery pressure ideal
- Hydraulic modeling of pipeline
- GH2, NG (natural gas) pipelines same cost:
  - Same pressure, diameter
  - Capital
  - O&M
  - GH2 pipeline has 1/3 capacity of NG pipeline

Key Assumptions

- NREL study: GH2 transmission, pipelines
- Four economic cases:
  - No subsidy, no value-adders
  - USA federal production tax credit (PTC)
  - PTC plus byproduct oxygen (O2) sale
  - PTC plus O2 sale plus carbon-offset credit
- Two system capacities: 1 GW, 2 GW (eight total cases)

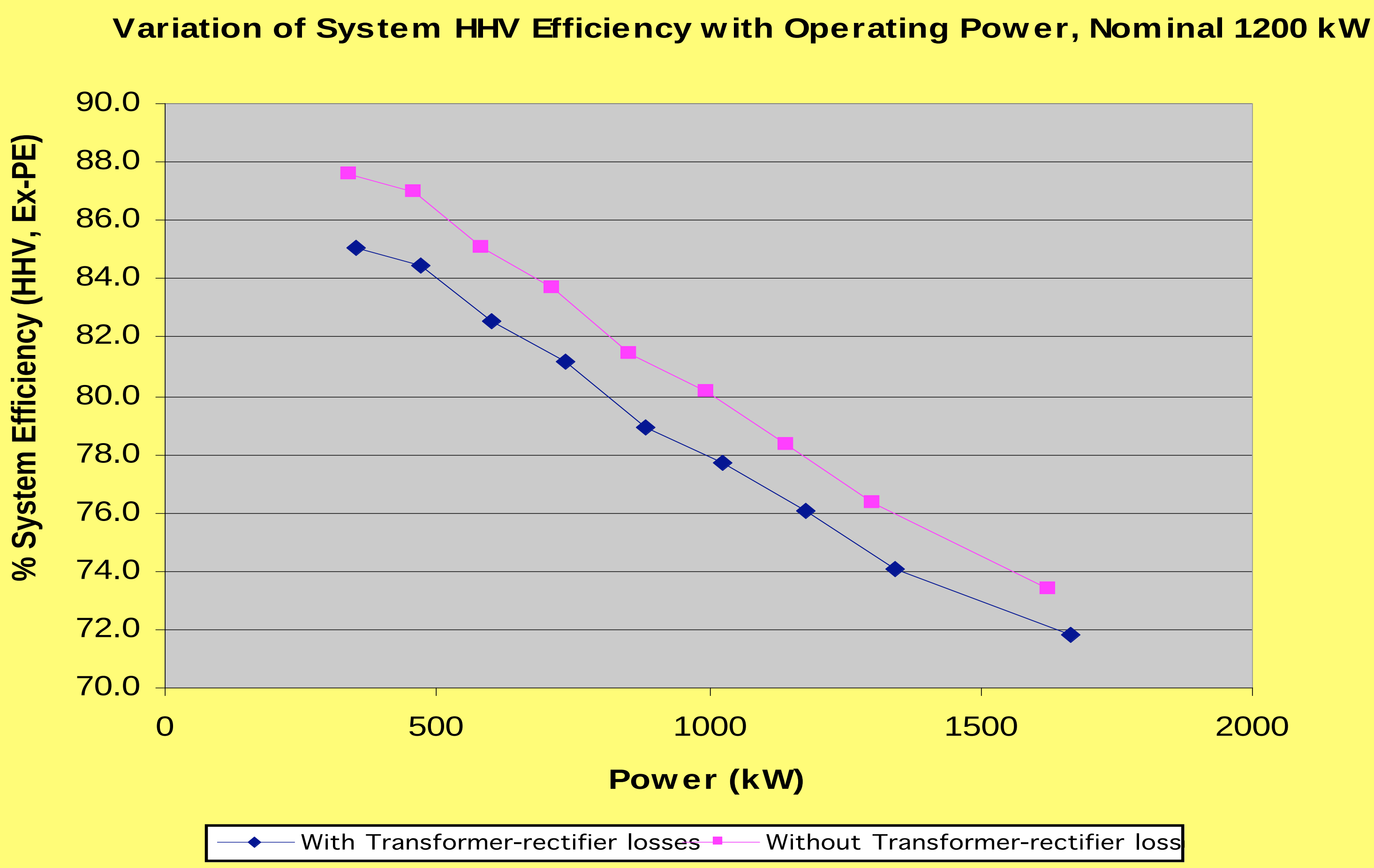


GH2 Pipeline is Lowest-cost Hydrogen Transport Method, at Long Distance and High Power (W. Amos, NREL, USA)

Key Assumptions: Total Installed Capital Cost

- Pipeline system $ 29 / inch diam / meter length (terrestrial)
- Wind generators $ 830 / kW (with PE)
- Electrolyzers (1,500 psi output)
  - $ 330 / kWe input
  - 80% efficient

Electrolyzer Efficiency ~ 80%

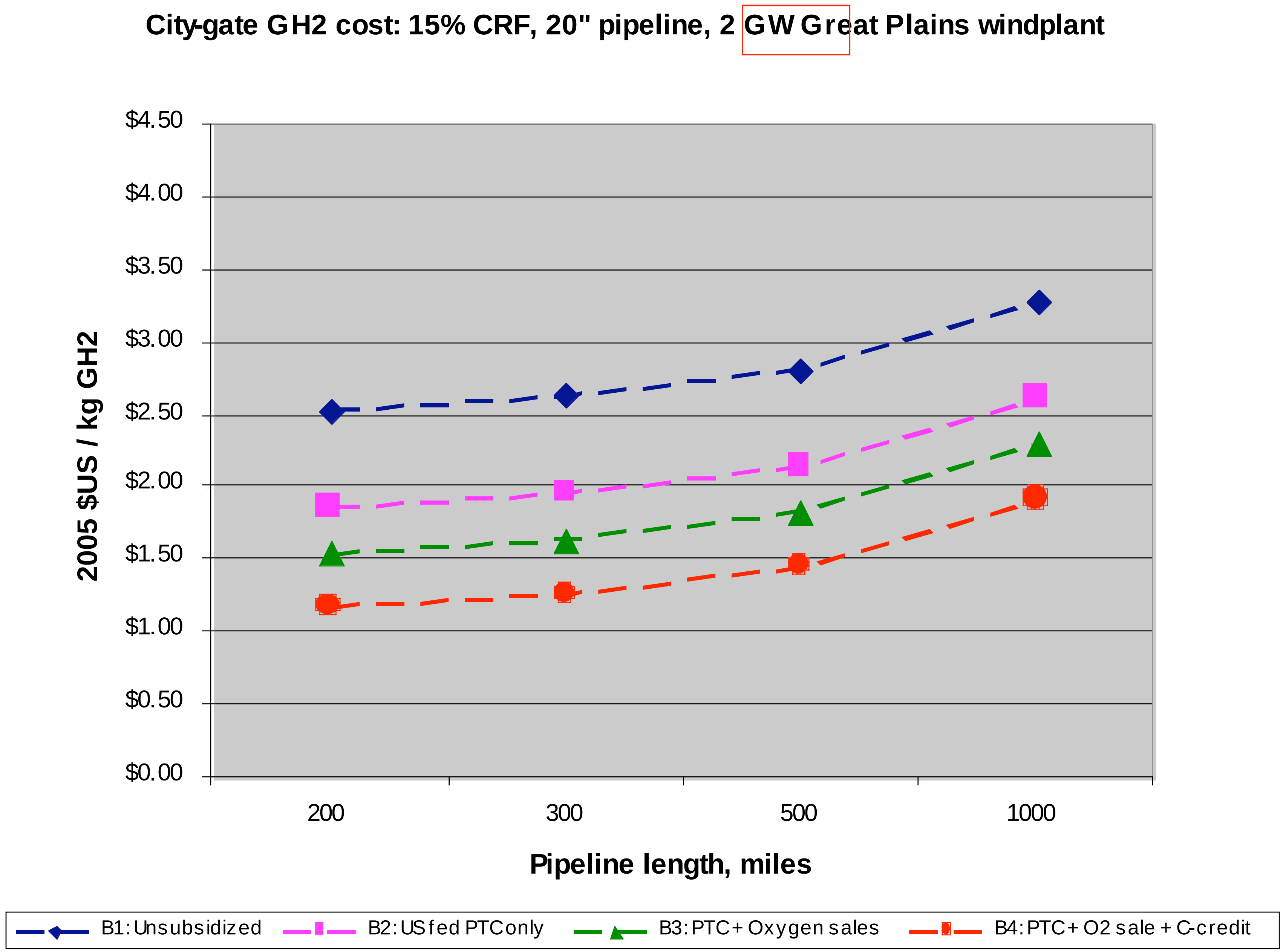


Total Installed Capital Cost
500 mile wind-pipeline SYSTEM
$US million

Windplant size	**1 GW**	**2 GW**
Wind generators	$ 830	$ 1,660
Electrolyzers	423	846
Pipeline	464	464
TOTAL	**$ 1,717**	**$ 2,970**

Key Assumptions

- Capital Recovery Factor (CRF) = 15 %
- Byproduct oxygen (O_2) sale @ $ 19.00 / ton



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
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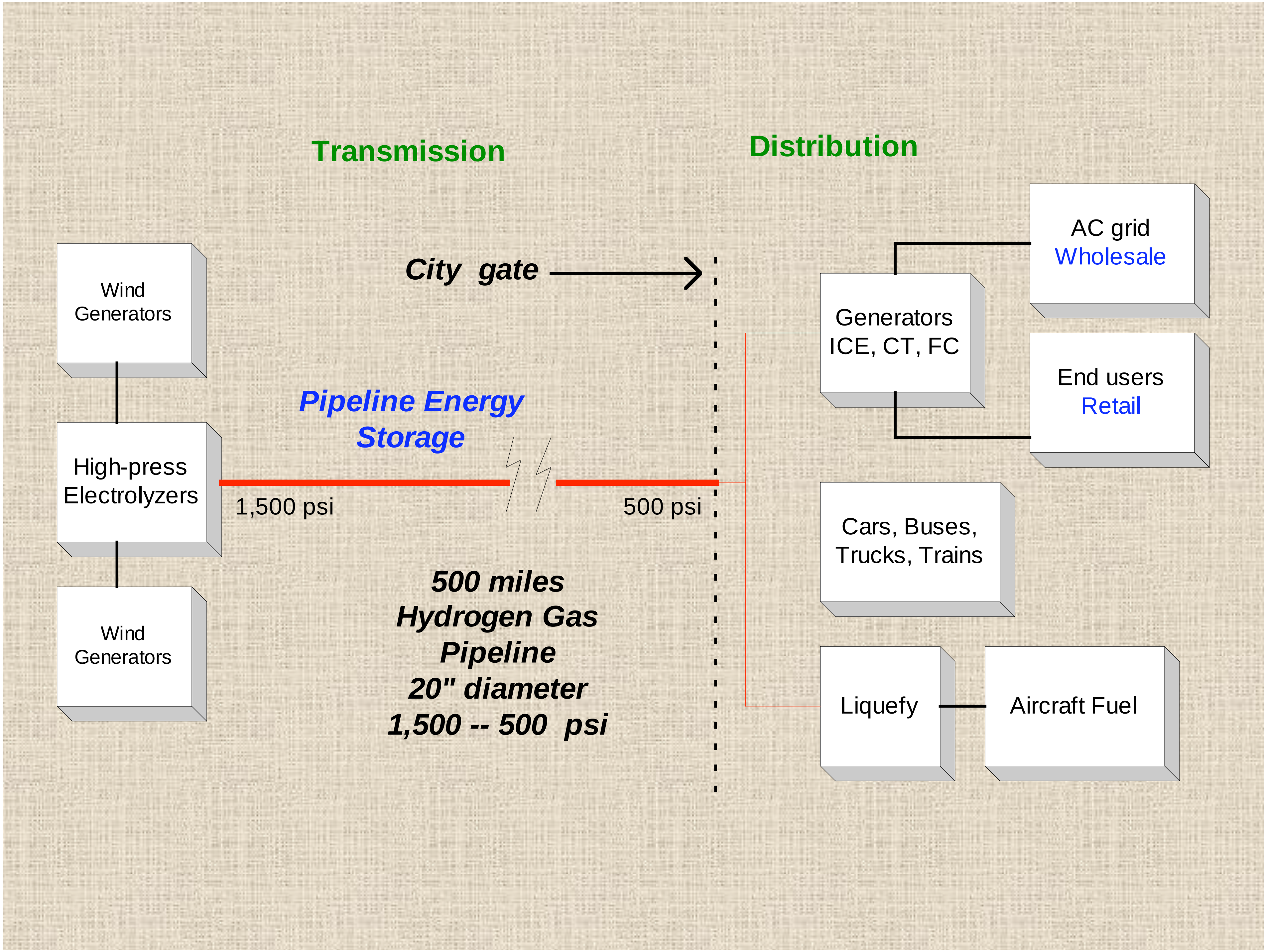
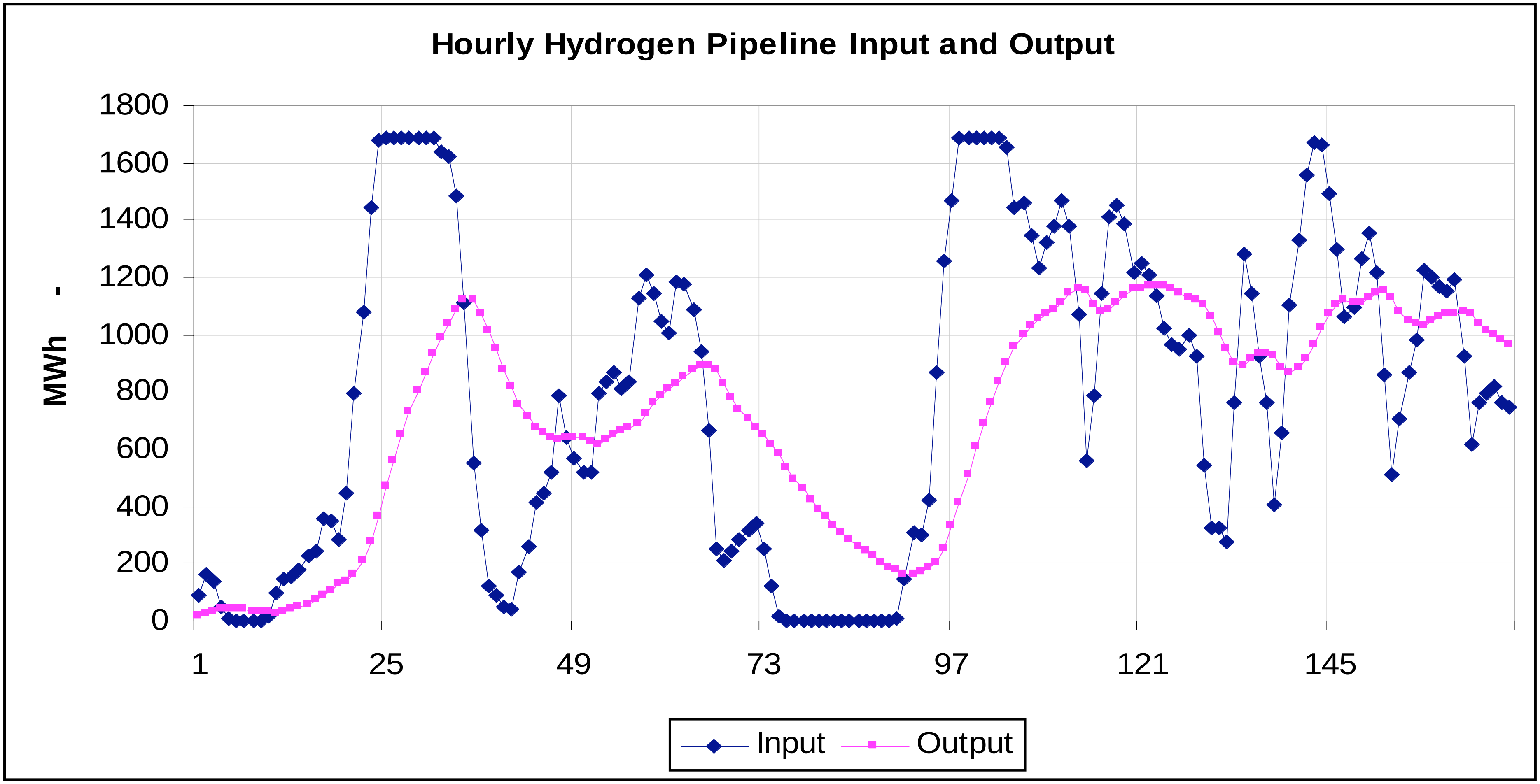
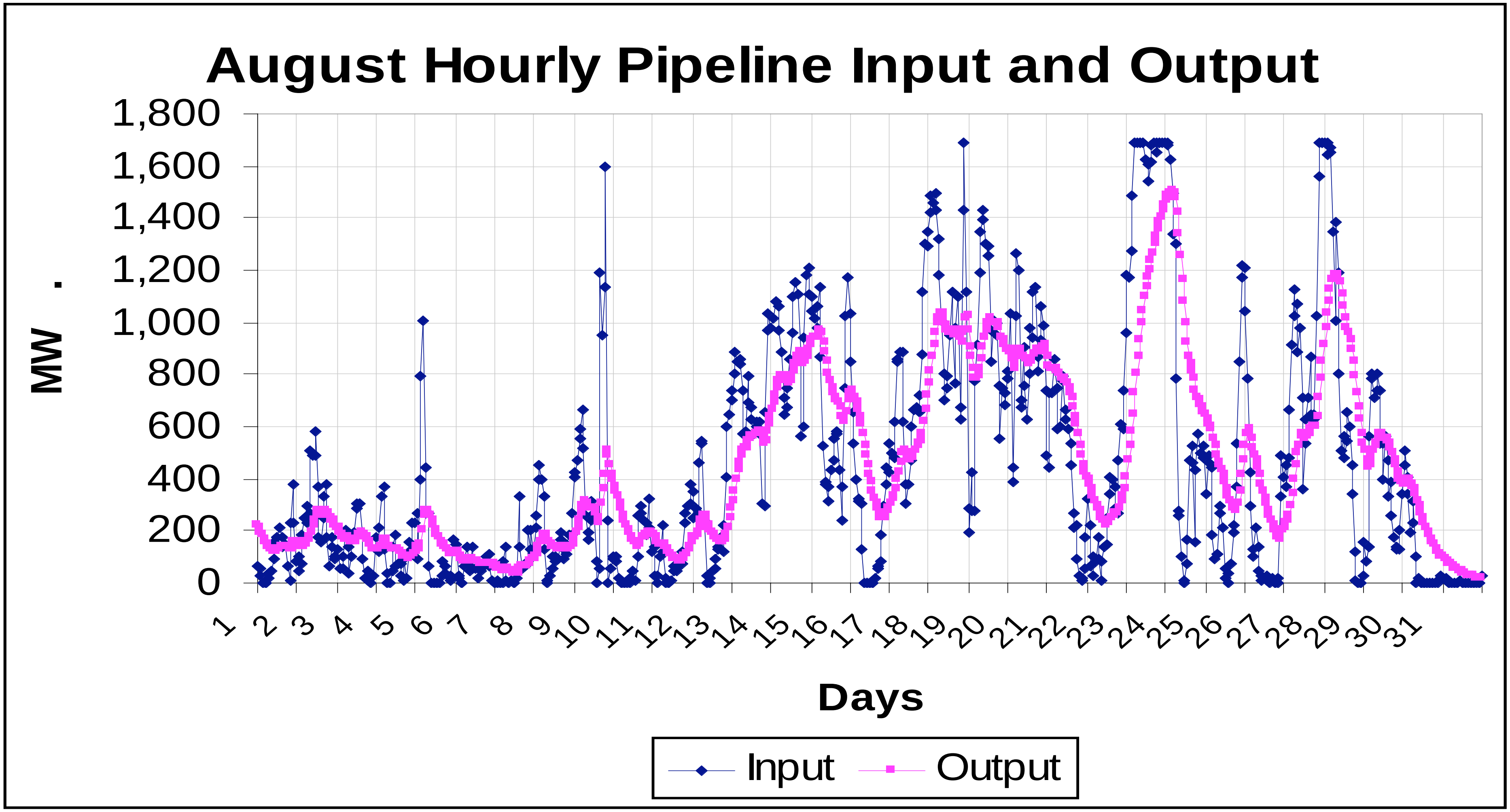

Transmission
Distribution
City gate
Wind Generators
High-press Electrolyzers
Wind Generators
Pipeline Energy Storage
1,500 psi
500 psi
500 miles
Hydrogen Gas
Pipeline
20" diameter
1,500 -- 500 psi
Generators ICE, CT, FC
AC grid
Wholesale
End users
Retail
Cars, Buses, Trucks, Trains
Liquefy
Aircraft Fuel

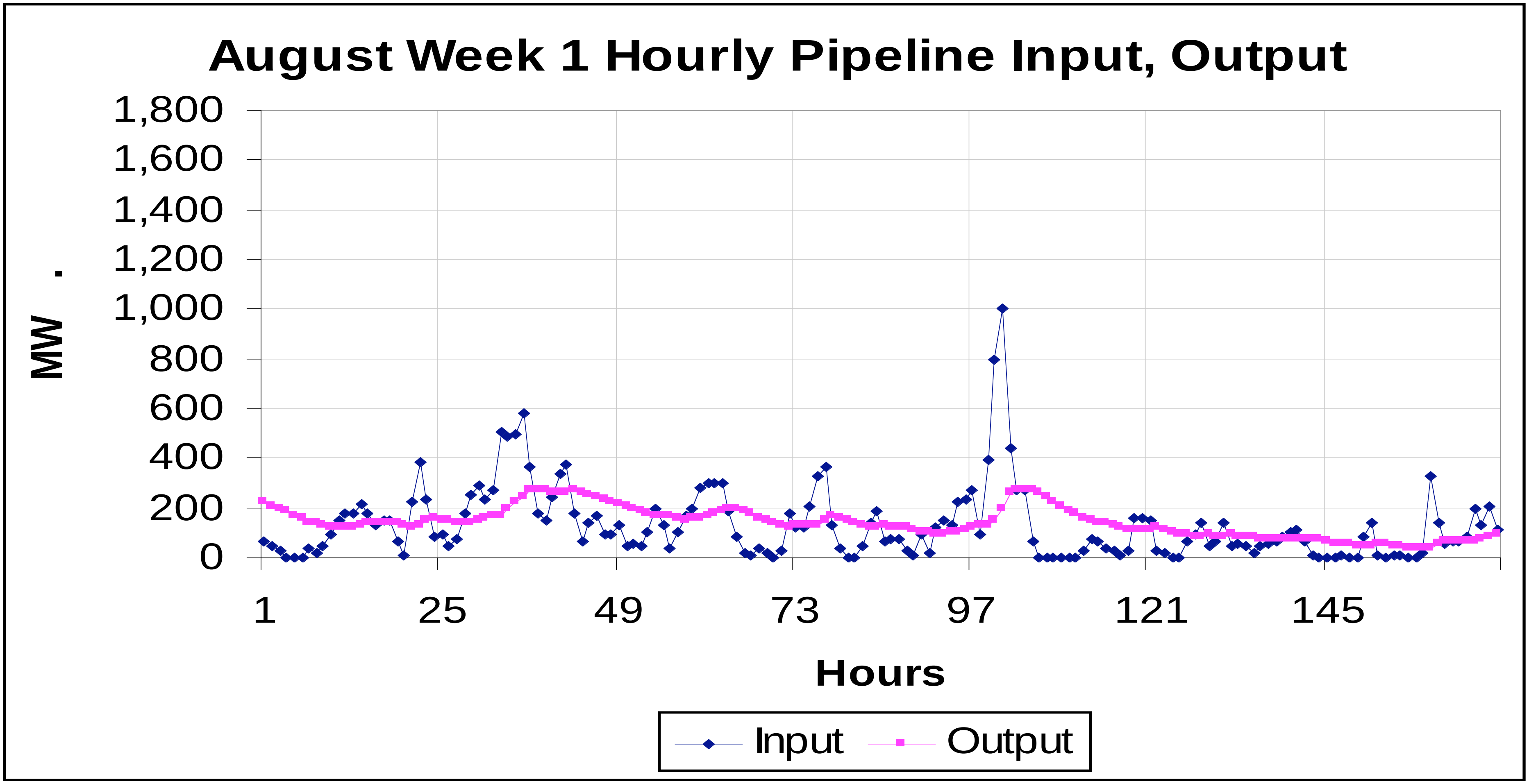
Great Plains Windplant, 500 mile Pipeline: Hourly Output for Typical Week



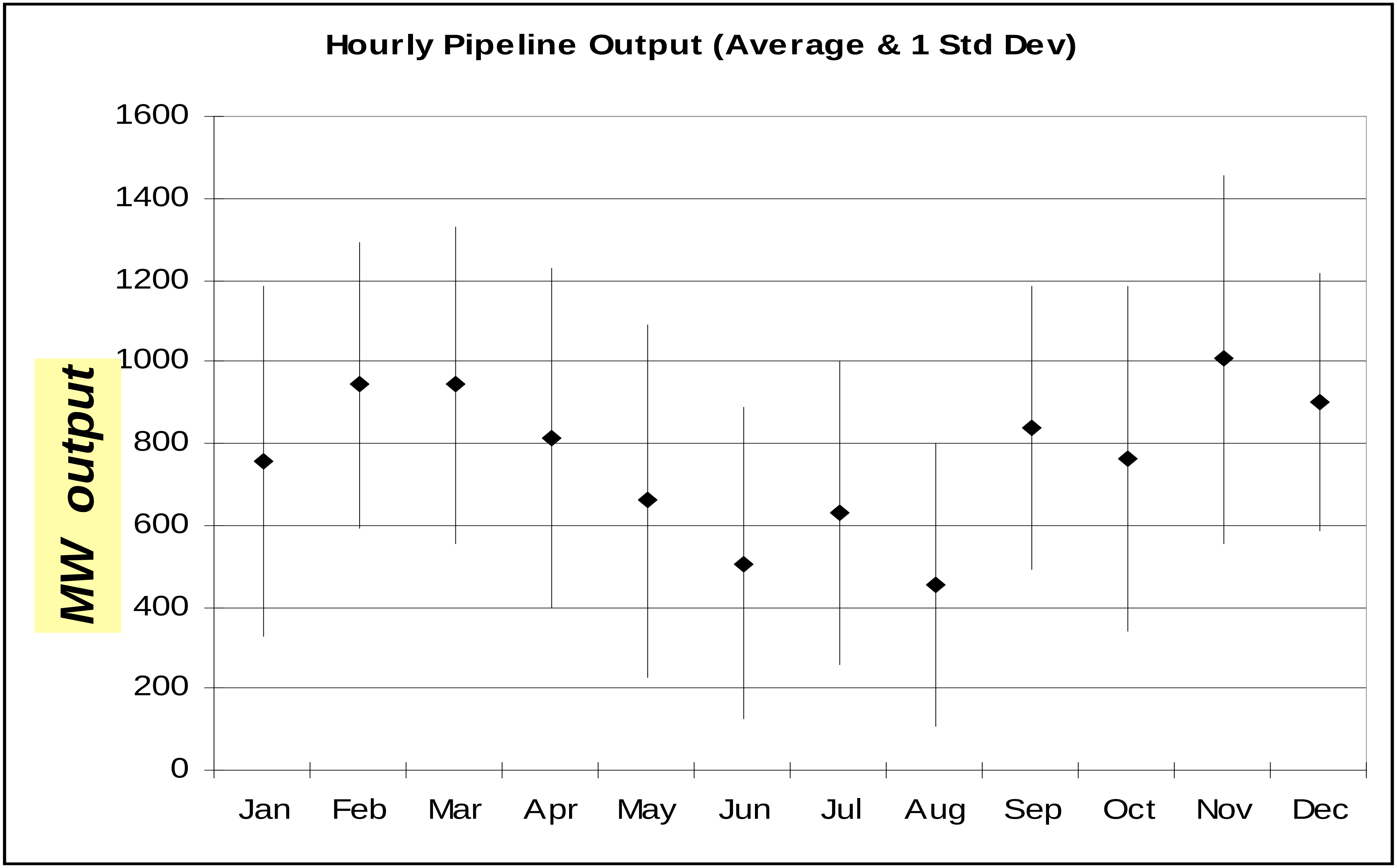
Hours

Great Plains Windplant, 500 mile Pipeline: Actual Hourly Output

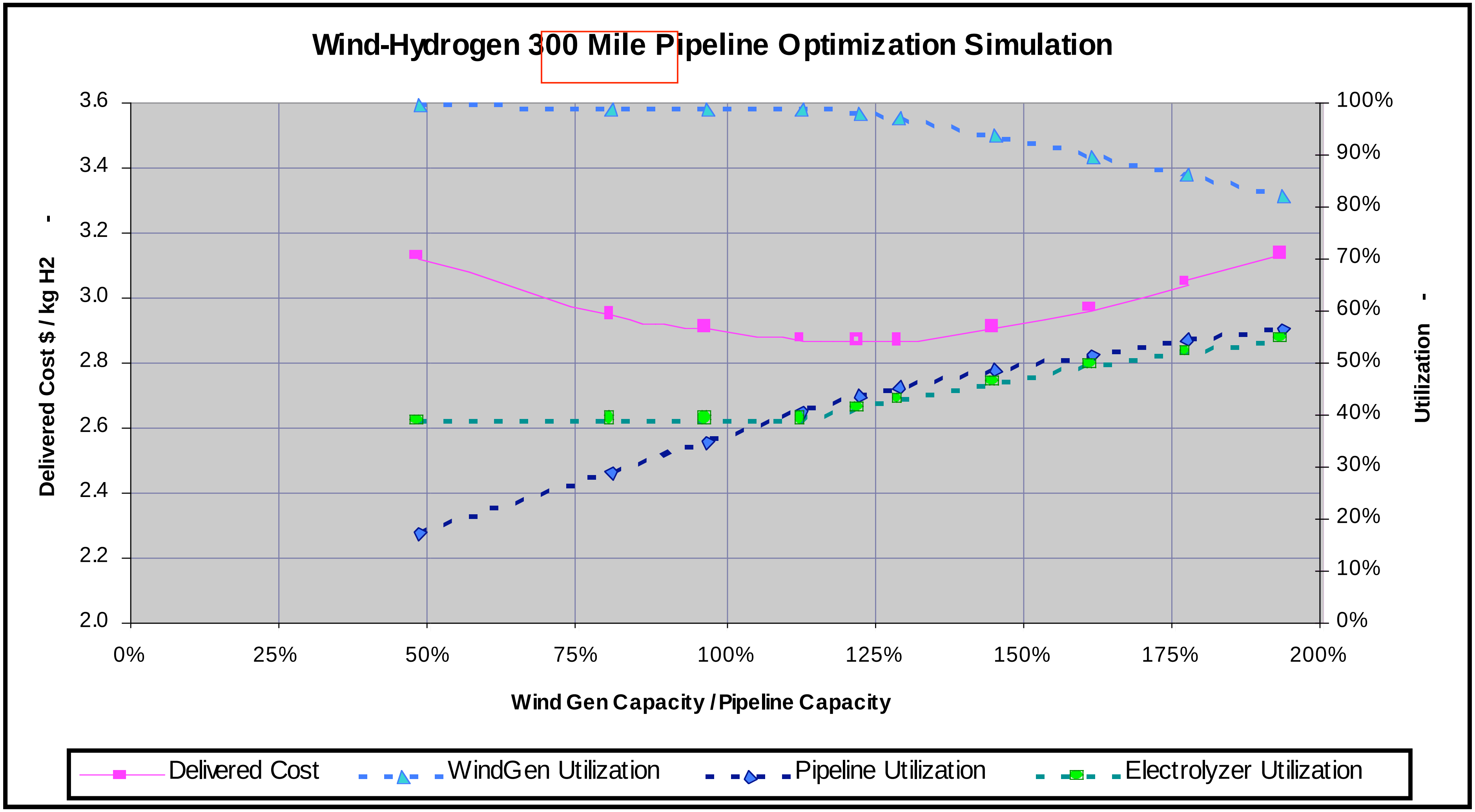


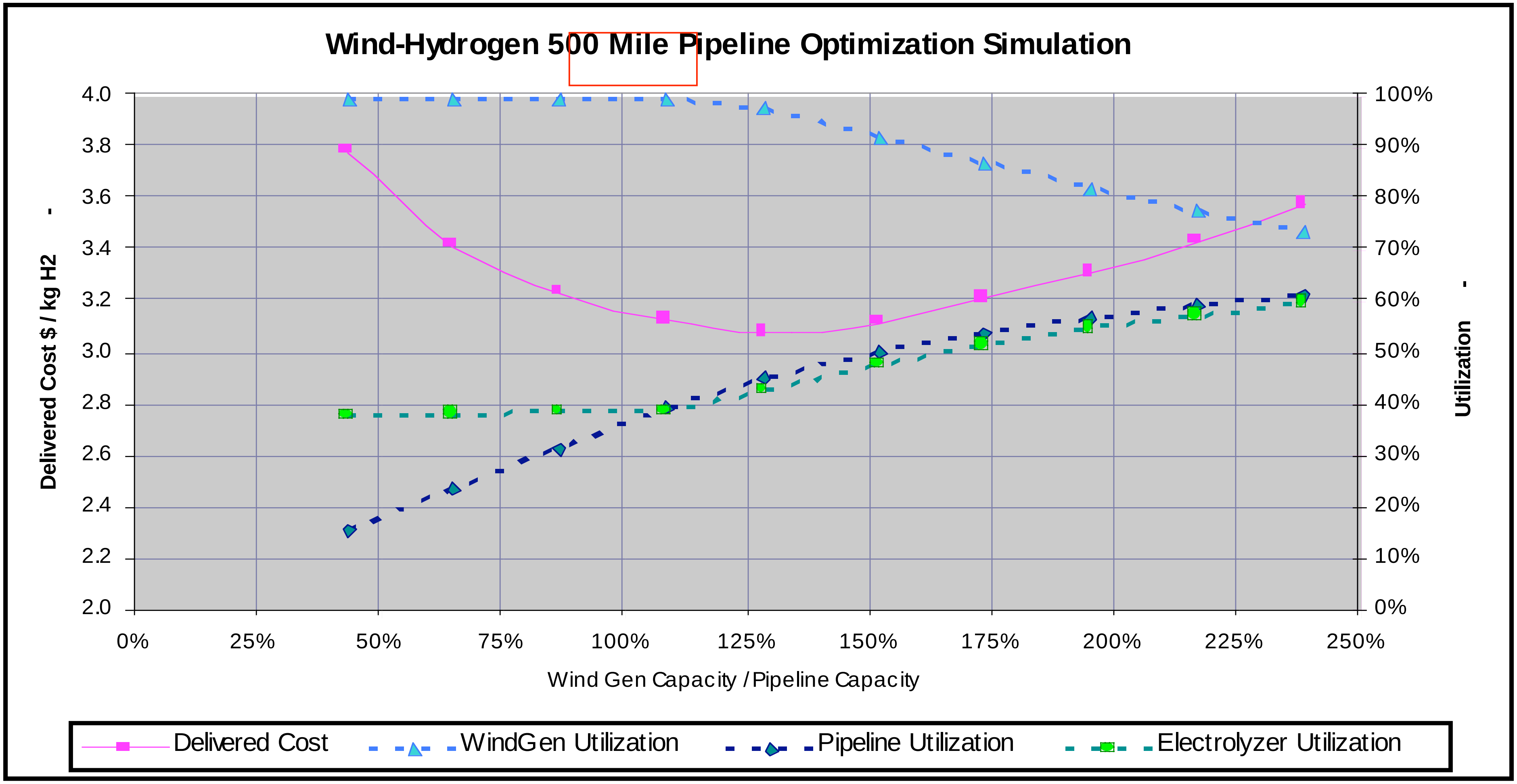


August Week 1 Hourly Pipeline Input, Output
MW
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
1
25
49
73
97
121
145
Hours
Input
Output

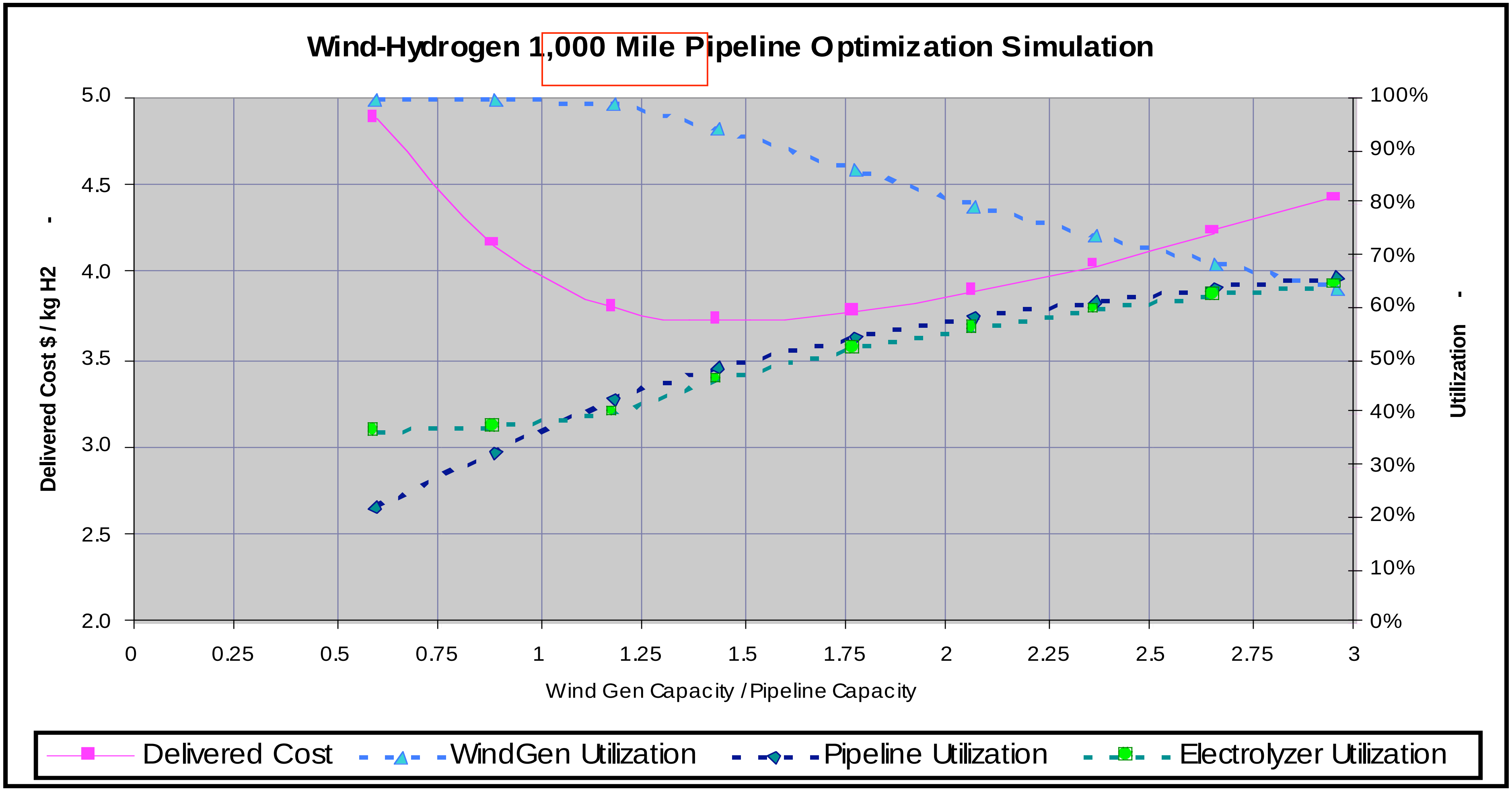


Hourly Pipeline Output (Average & 1 Std Dev)
MW output
1600
1400
1200
1000
800
600
400
200
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Wind-Hydrogen 300 Mile Pipeline Optimization Simulation
Delivered Cost $ / kg H2
Utilization
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0%
25%
50%
75%
100%
125%
150%
175%
200%
Wind Gen Capacity / Pipeline Capacity
Delivered Cost
WindGen Utilization
Pipeline Utilization
Electrolyzer Utilization

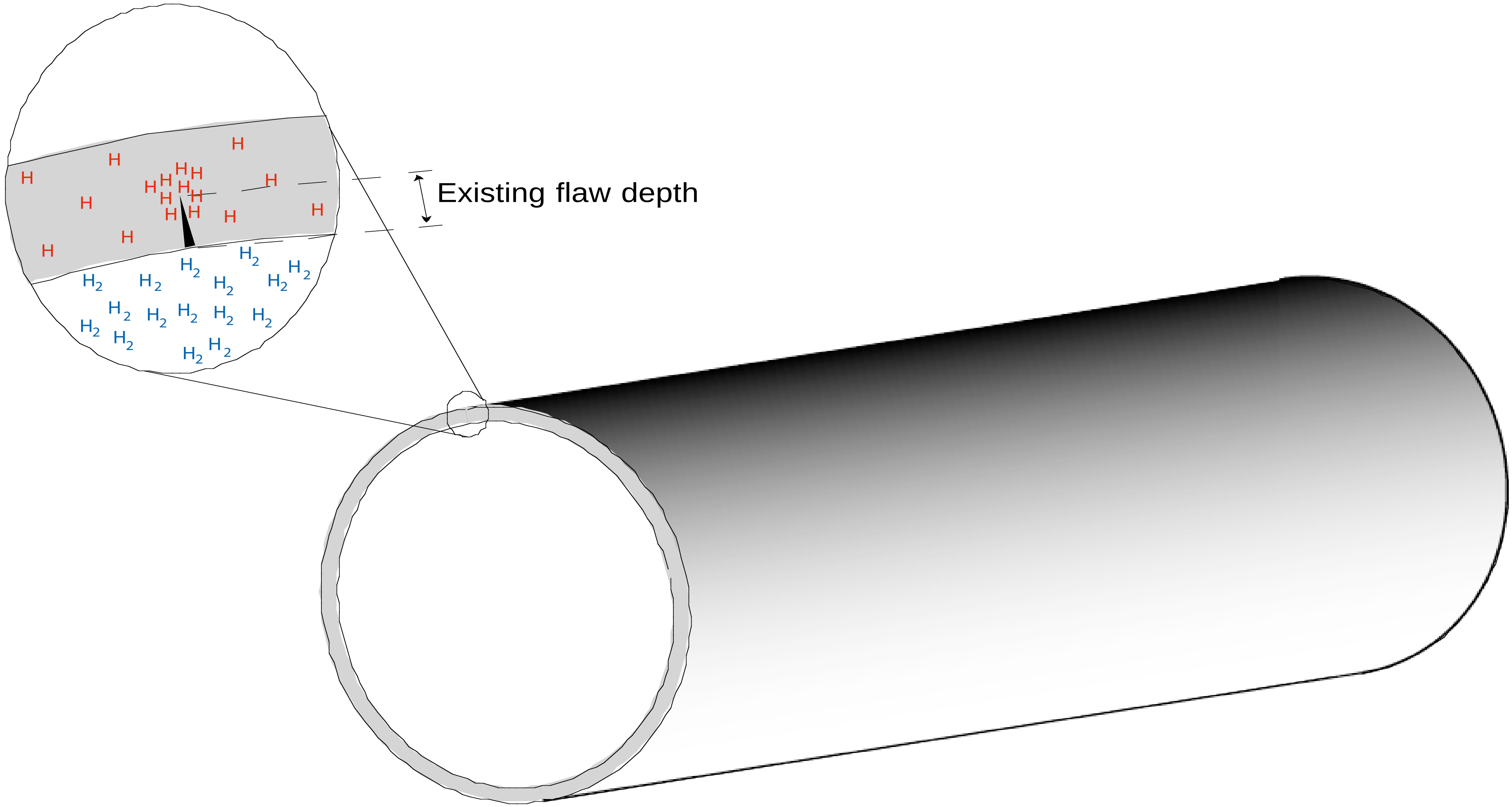


Wind-Hydrogen 500 Mile Pipeline Optimization Simulation
Delivered Cost $ / kg H2
Utilization
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0%
25%
50%
75%
100%
125%
150%
175%
200%
225%
250%
Wind Gen Capacity / Pipeline Capacity
Delivered Cost
WindGen Utilization
Pipeline Utilization
Electrolyzer Utilization


Wind-Hydrogen 1,000 Mile Pipeline Optimization Simulation
Delivered Cost $ / kg H2
Utilization
5.0
4.5
4.0
3.5
3.0
2.5
2.0
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 Embrittlement

- Sandia National Laboratory, CA
- Pipeline steel
- Flaws, cracks: depth, propagation
- Materials, metallurgy: choice, specs
- Must be controlled
- Composite Reinforced Line Pipe (CRLP) ?



H
H
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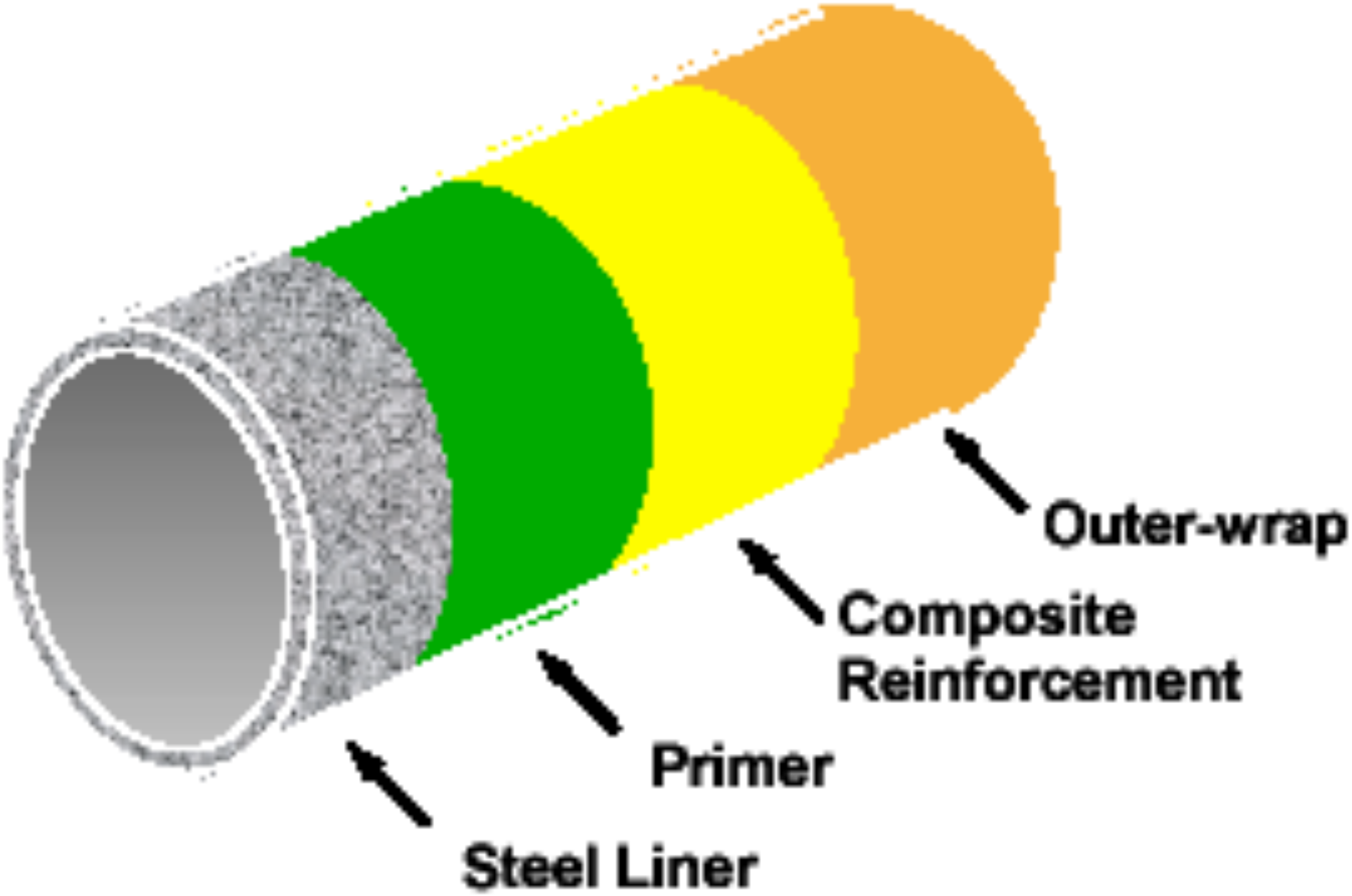
H
H
Existing flaw depth
H_2
H_2
H_2
H_2
H_2
H_2
H_2
H_2
H_2
H_2
H_2
H_2
H_2
H_2
H_2
H_2
H_2
H_2

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

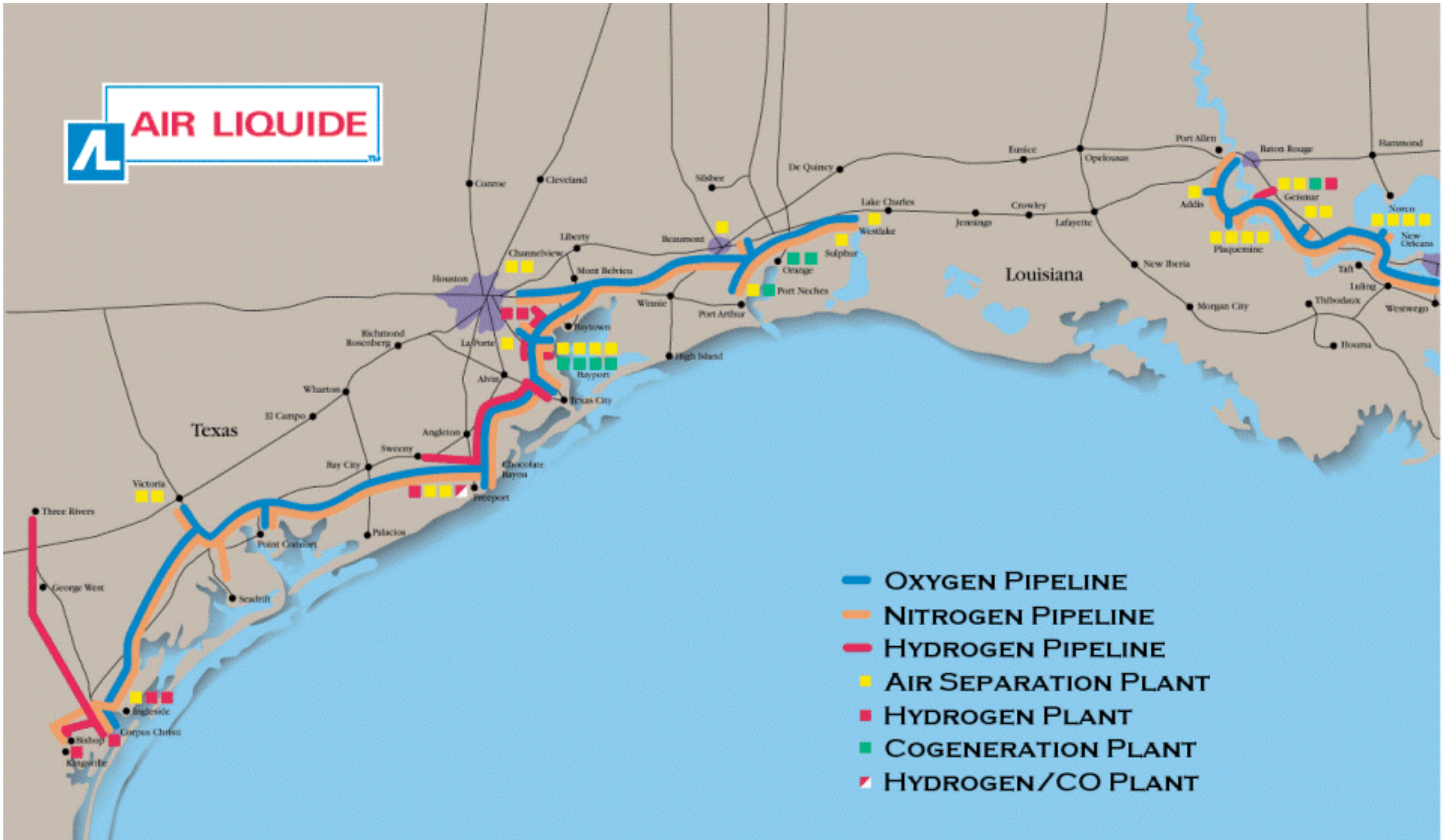


Composite Reinforced Line Pipe (CRLP)

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.

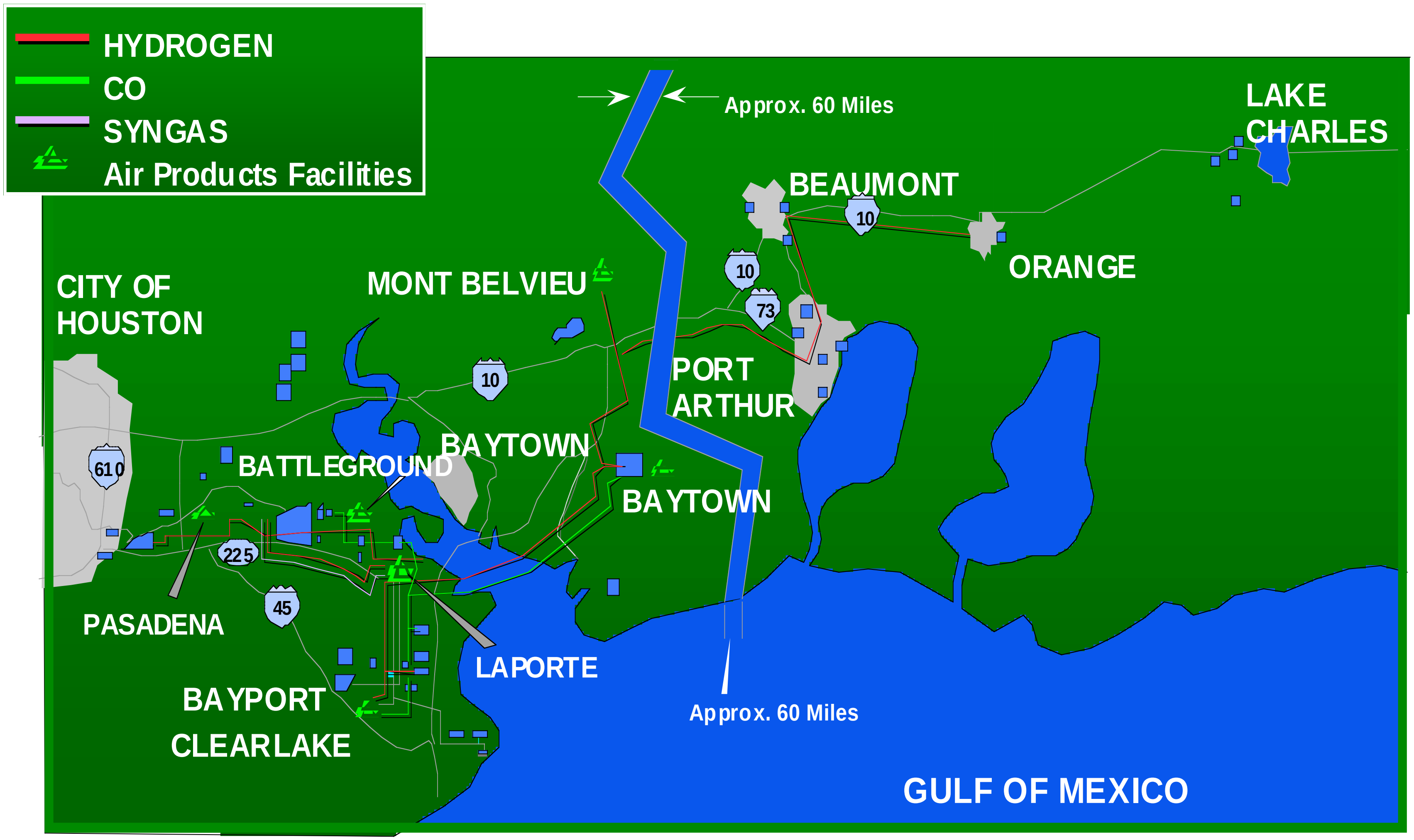


Gulf Coast and Mississippi River Pipeline Network

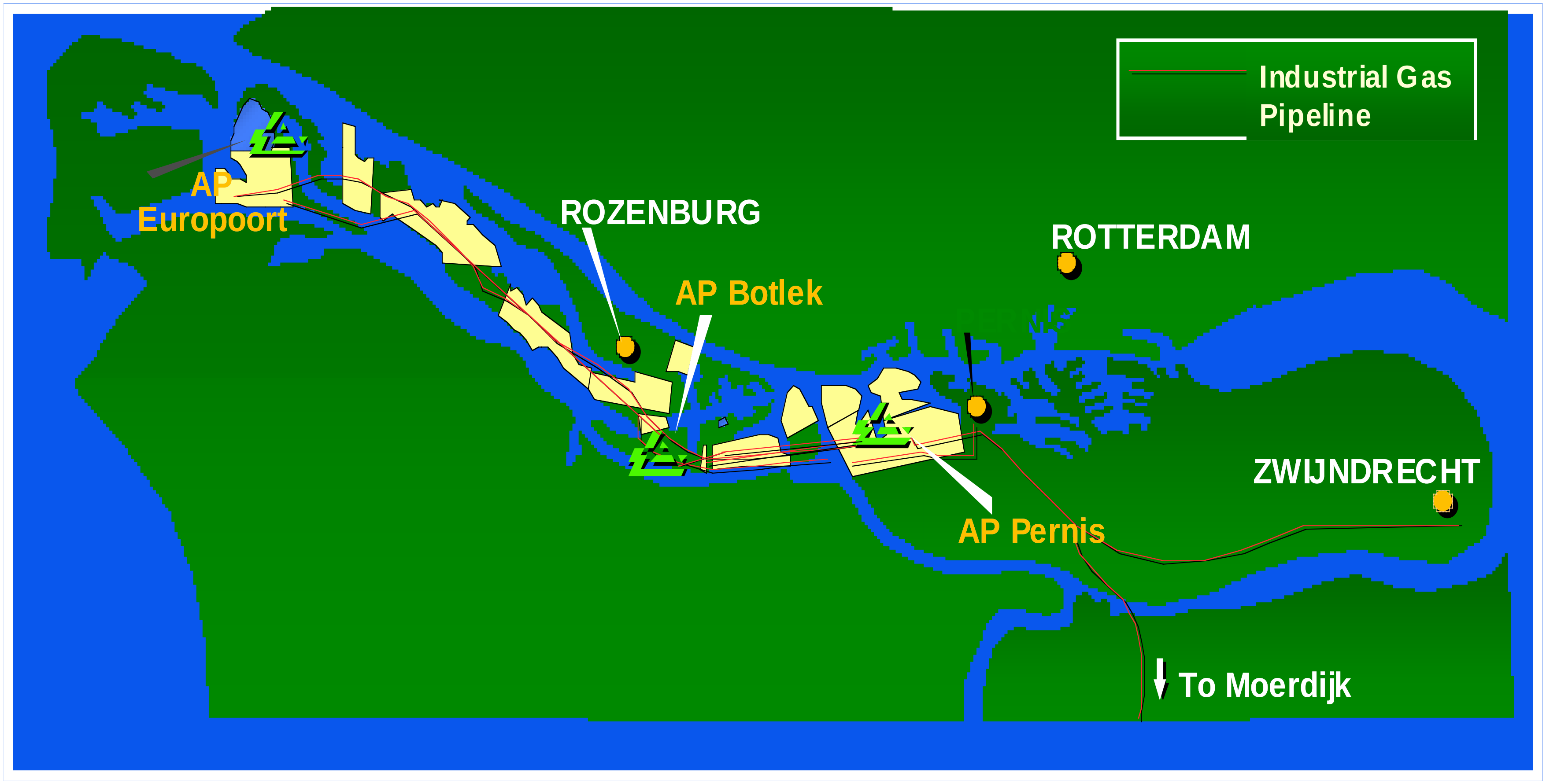
"We know how to pipeline hydrogen" Air Products

~ 10,000 miles of GH2 pipeline, worldwide

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



Rotterdam Pipeline System



Air Products Company

REFINERY ACTIVITY
LOS ANGELES BASIN, CALIFORNIA

GH2 Pipeline Success

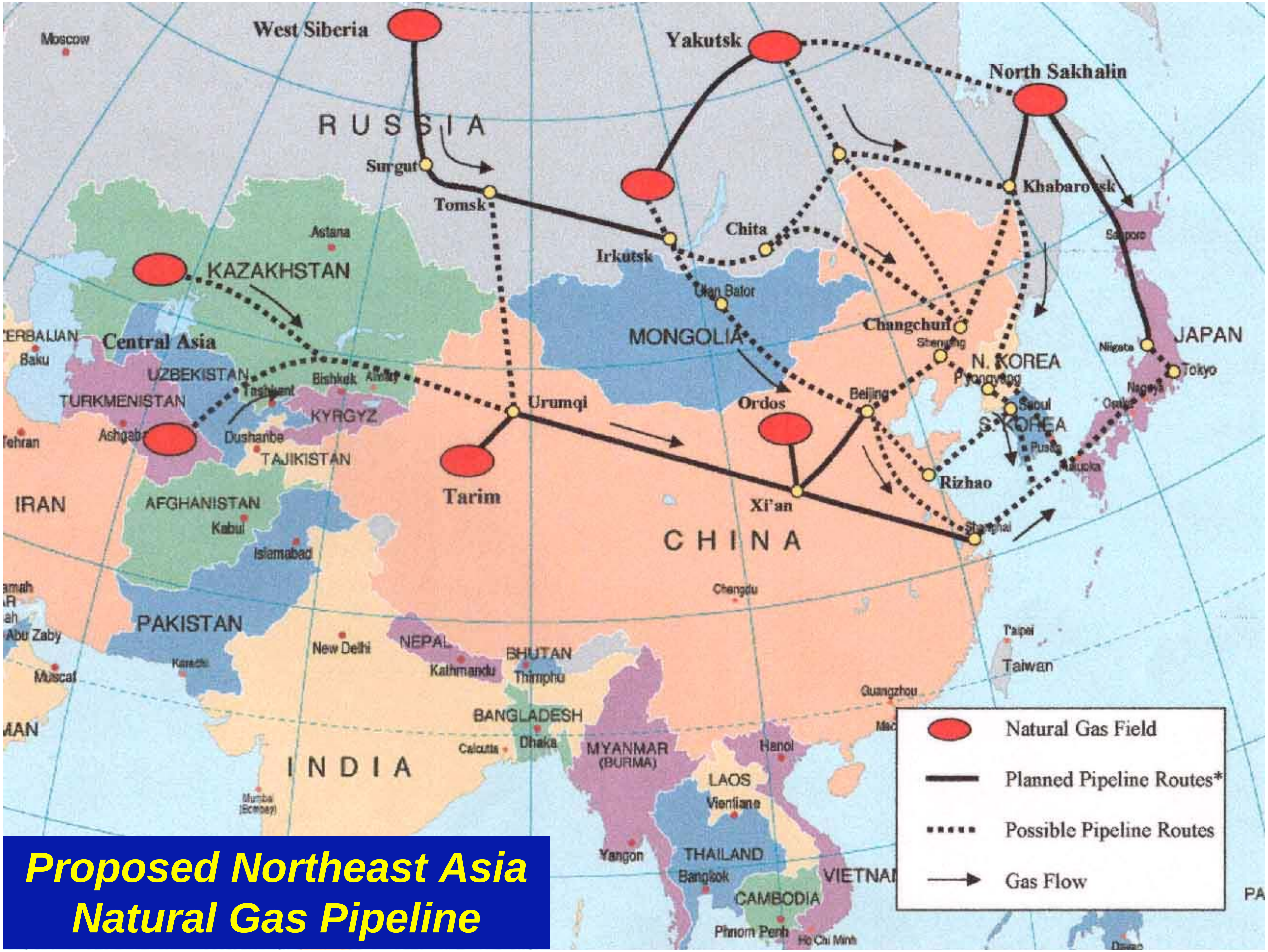
- 3,000 km, worldwide
- Low capacity
- Low pressure: ~ 30% SMYS
- Constant pressure
- Short distance: not transmission
- Captive; in-plant
- Extant corridors

Different: Renewables – Hydrogen Service (RHS) for GH2 pipelines

- 100% GH2: low energy density (volume)
- Large-scale:
  - 36” diam, 14 MPa (2,000 psi)
  - ~ 2,500 tons / day = 25 Million Nm3 / day = 6,000 MW
  - Long distance (1,500 km), cross-country
- From renewables: remote, diverse, dispersed, diffuse,
- Time-varying output: large, frequent pressure cycles
- Transmission a large fraction of delivered GH2 fuel cost

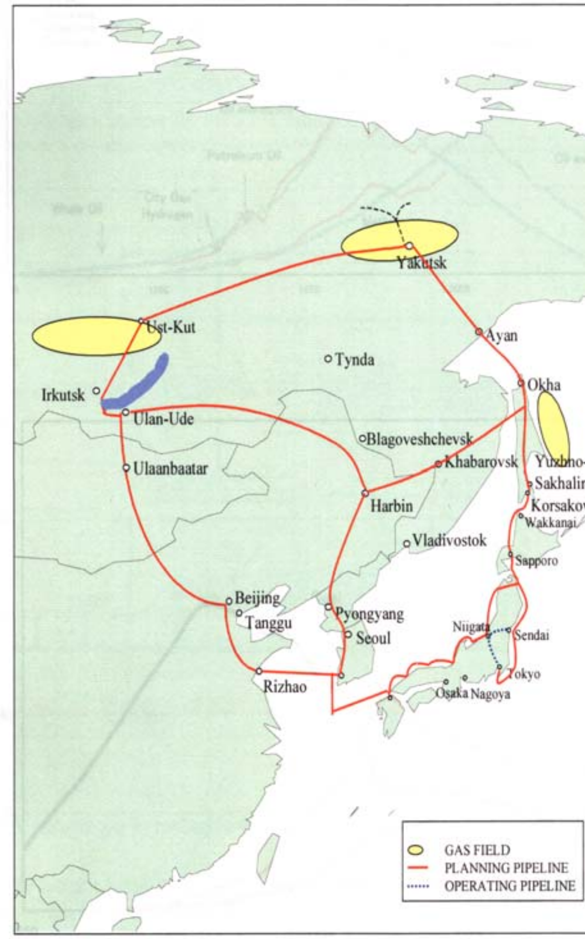
Twelve Great Plains states wind needs ~ 400 H2 gas Pipelines

Each: 2,500 tons GH2 / day = 6,000 MW
36" diameter
14 MPa = 1000 psi = 65 bar

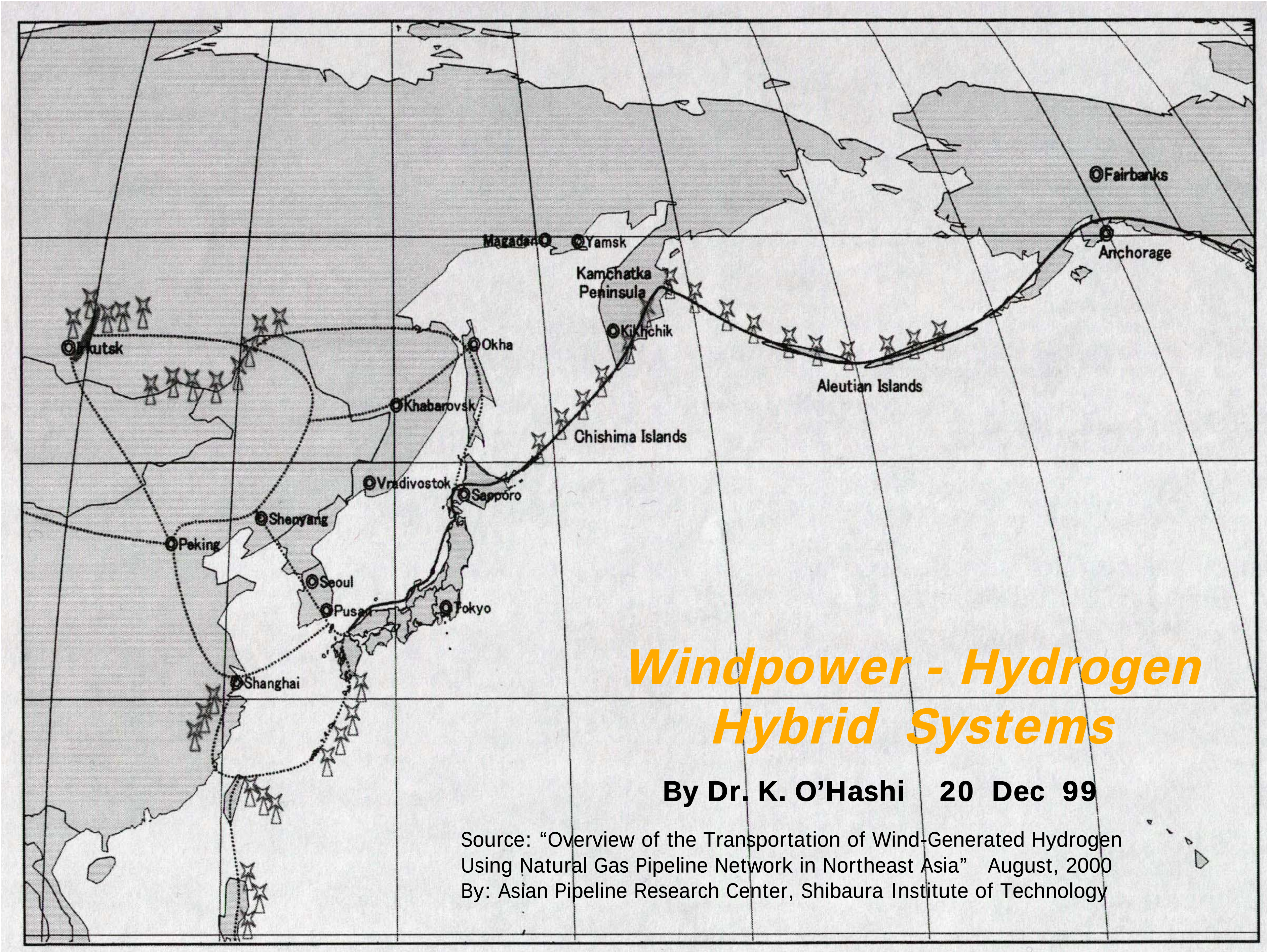


Proposed Northeast Asia Natural Gas Pipeline

Proposed Natural Gas Pipeline Network in North East Asia



Large Renewable Resources ?



Windpower - Hydrogen Hybrid Systems

By Dr. K. O'Hashi 20 Dec 99

Source: "Overview of the Transportation of Wind-Generated Hydrogen Using Natural Gas Pipeline Network in Northeast Asia" August, 2000
By: Asian Pipeline Research Center, Shibaura Institute of Technology

Northeast Asia

- Asian Pipeline Research Society of Japan
- Northeast Asian Natural Gas Pipeline Forum (NAGPF)
- 9th NAGPF meeting 23-26 Sep 05, Seoul

" Proposal for a Northeast Asian Hydrogen Highway: From a Natural-gas-based to a Hydrogen-based Society "

Hydrogen Highways

- California
- Upper Midwest "H"
- Northeast Asia
- "NaturalHY", EU
- Alaska ANS gas line (NG)

250 hydrogen "gas stations"

Of 10,000 CA total

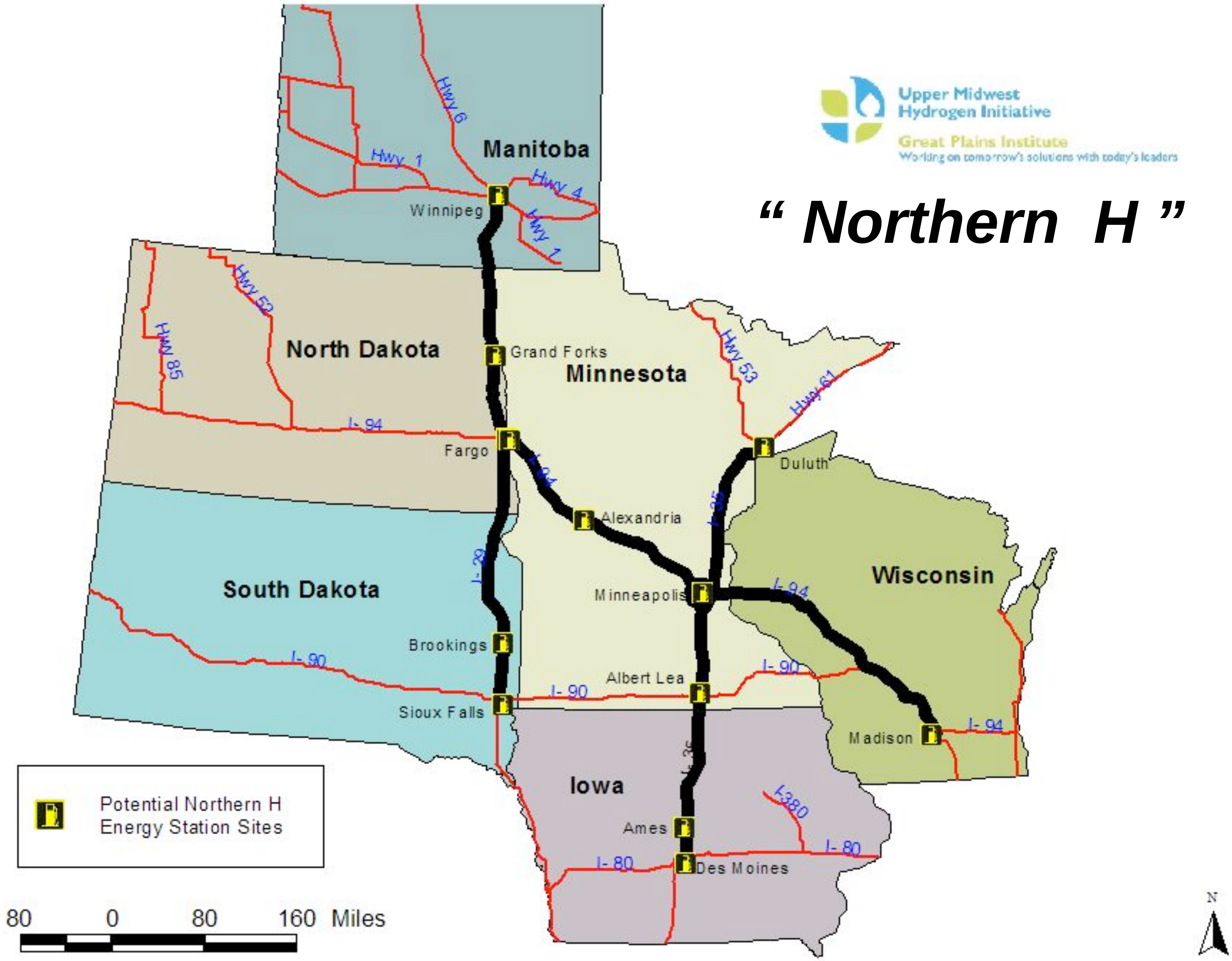
Whence the hydrogen ?

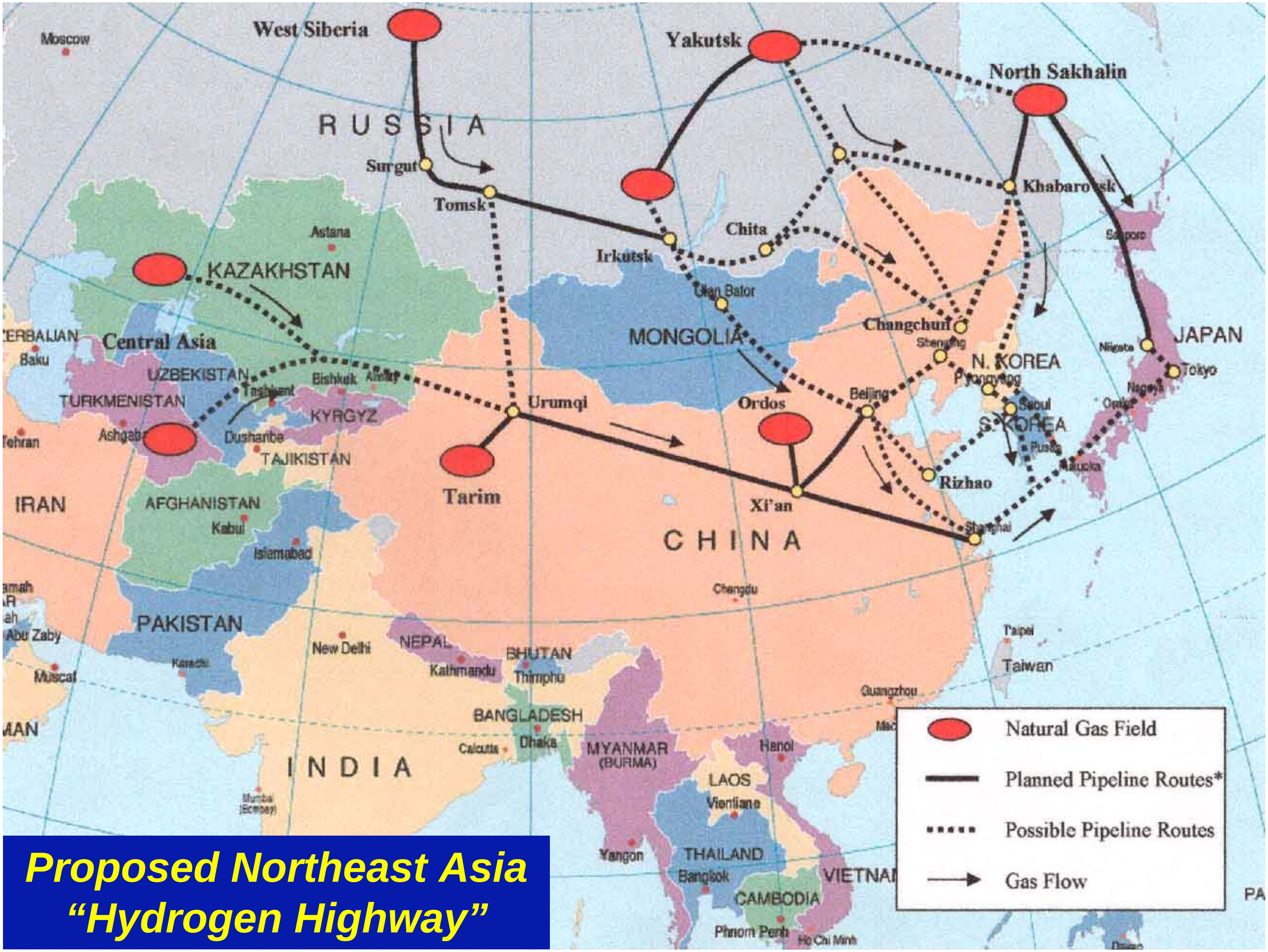
Upper Midwest Hydrogen Initiative

Great Plains Institute

Working on tomorrow's solutions with today's leaders

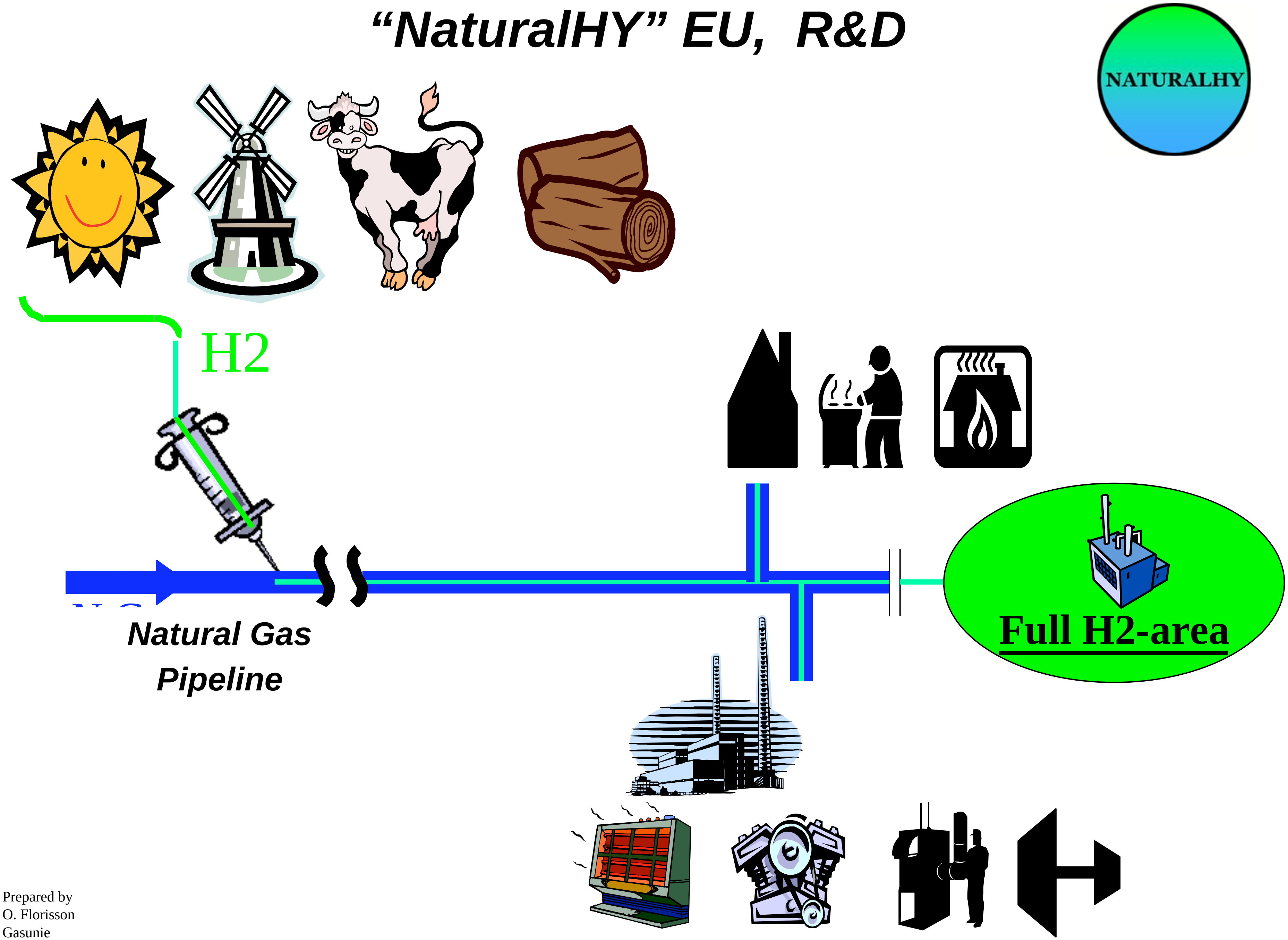
“ Northern H ”





Proposed Northeast Asia "Hydrogen Highway"

"NaturalHY" EU, R&D

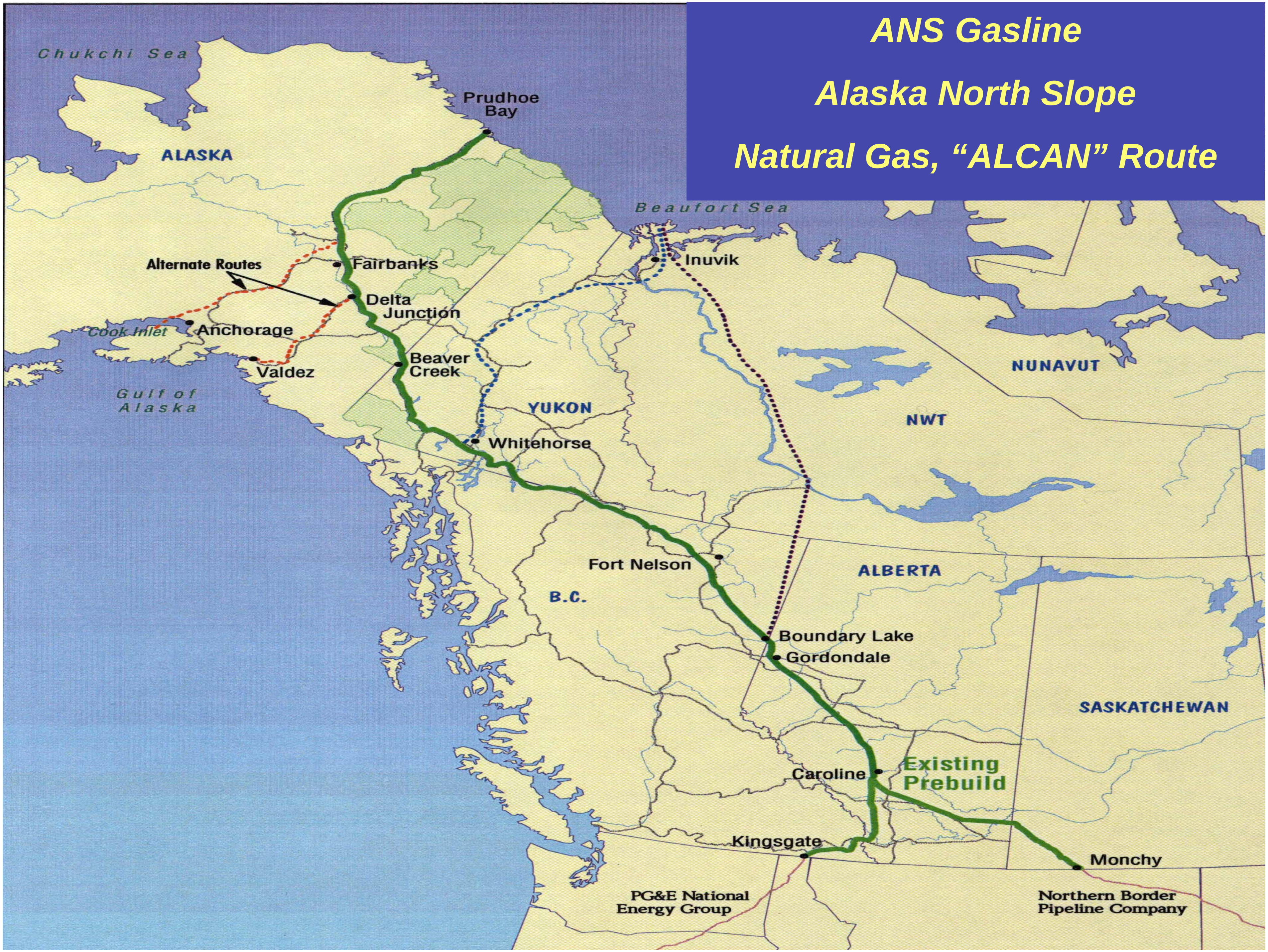


Prepared by
O. Florisson
Gasunie

ANS Gasline

Alaska North Slope

Natural Gas, "ALCAN" Route



Wind-Hydrogen Fuel Cost in Chicago
No PTC subsidy

Wind-generated electricity in ND	$ 0.045 / kWh
Hydrogen conversion and 1,000 miles transmission	0.052 / kWh
Wholesale price of GH2 fuel in Chicago, end-of-pipe	$ 0.097 / kWh
Equivalent per-gallon-gasoline-energy price *	$ 3.49 / gal
Distribution and fuel station cost	$ 0.79 – 1.45 / gal
Retail price of GH2 fuel in Chicago	$ 4.28 – 4.94 / gal
Drive train efficiency ratio: FCEV / ICEV = 2	
Equivalent retail price GH2 fuel per vehicle-mile	**$ 2.14 – 2.47 / gal**

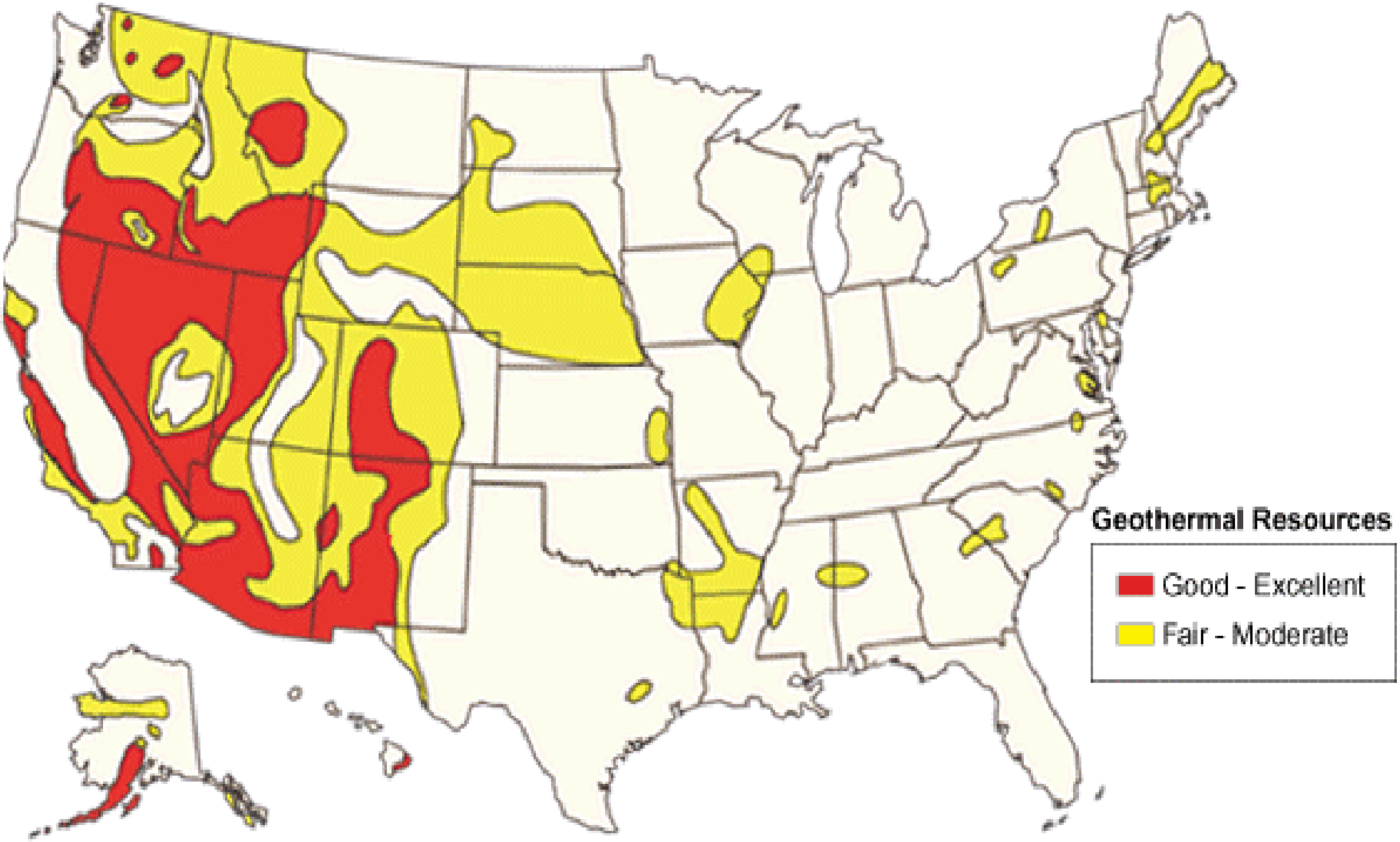
* 1 GJ = 278 kWh; 1 gallon gasoline = 0.13 GJ (HHV) = 36 kWh @ $ 0.08 / kWh = $ 2.89 / gallon
HHV means higher heating value of hydrogen.
GH2 means compressed gaseous hydrogen

Diverse Renewables

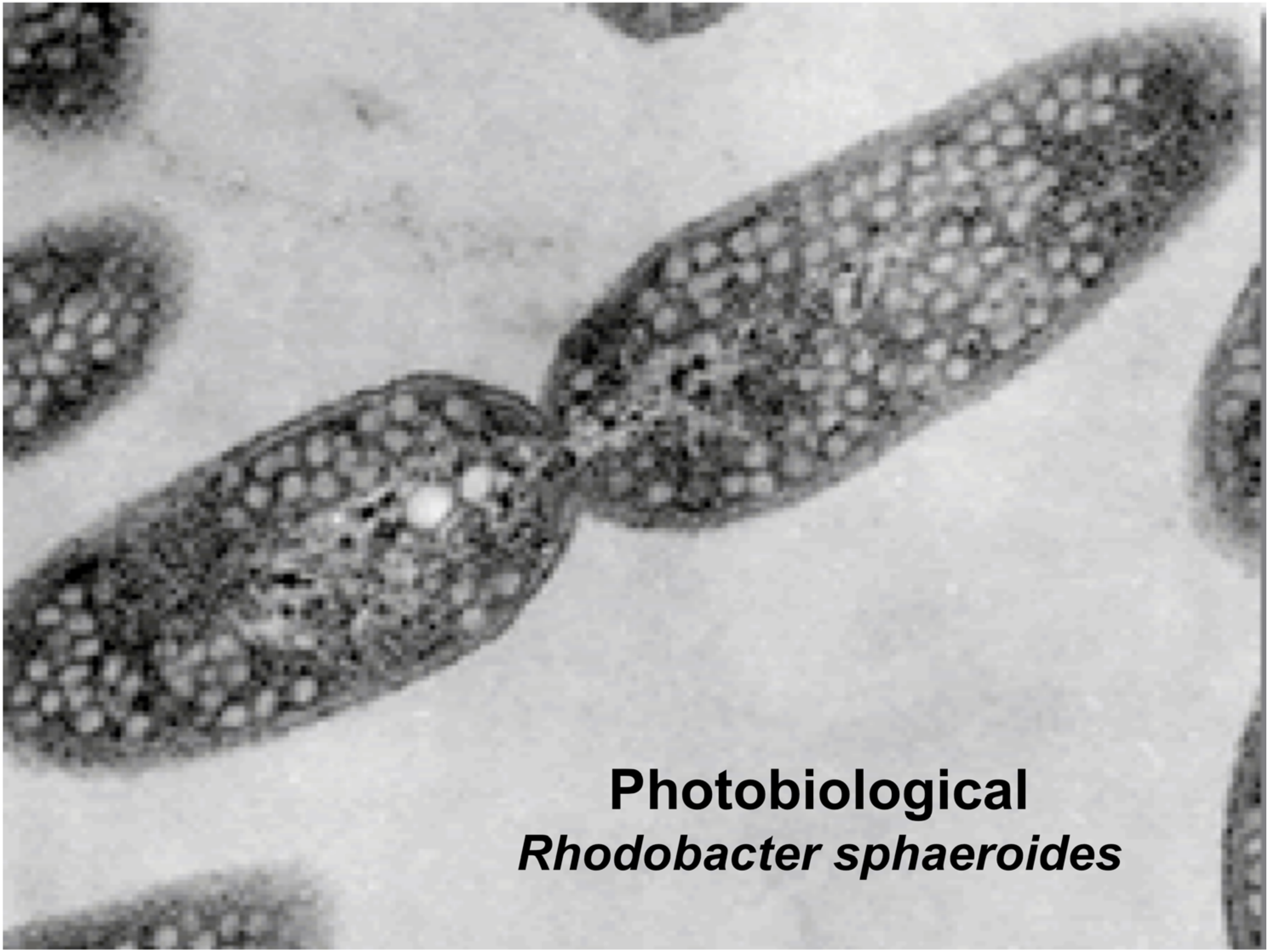
NW Iowa 190 MW windplant

Hydro

Hoover Dam



Geothermal Resources


Photobiological
Rhodobacter sphaeroides

Algae:
Chlamydomonas reinhardtii

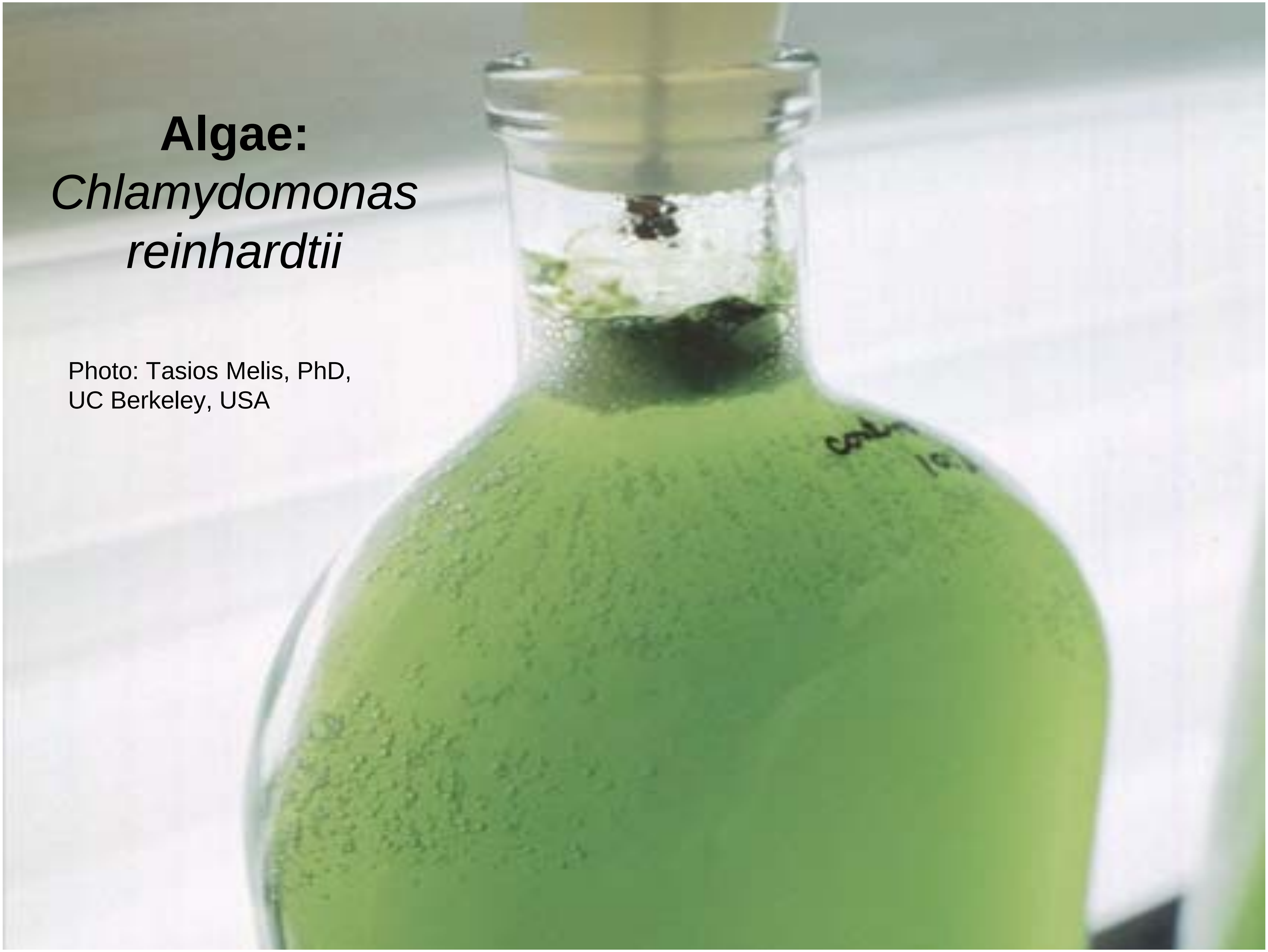
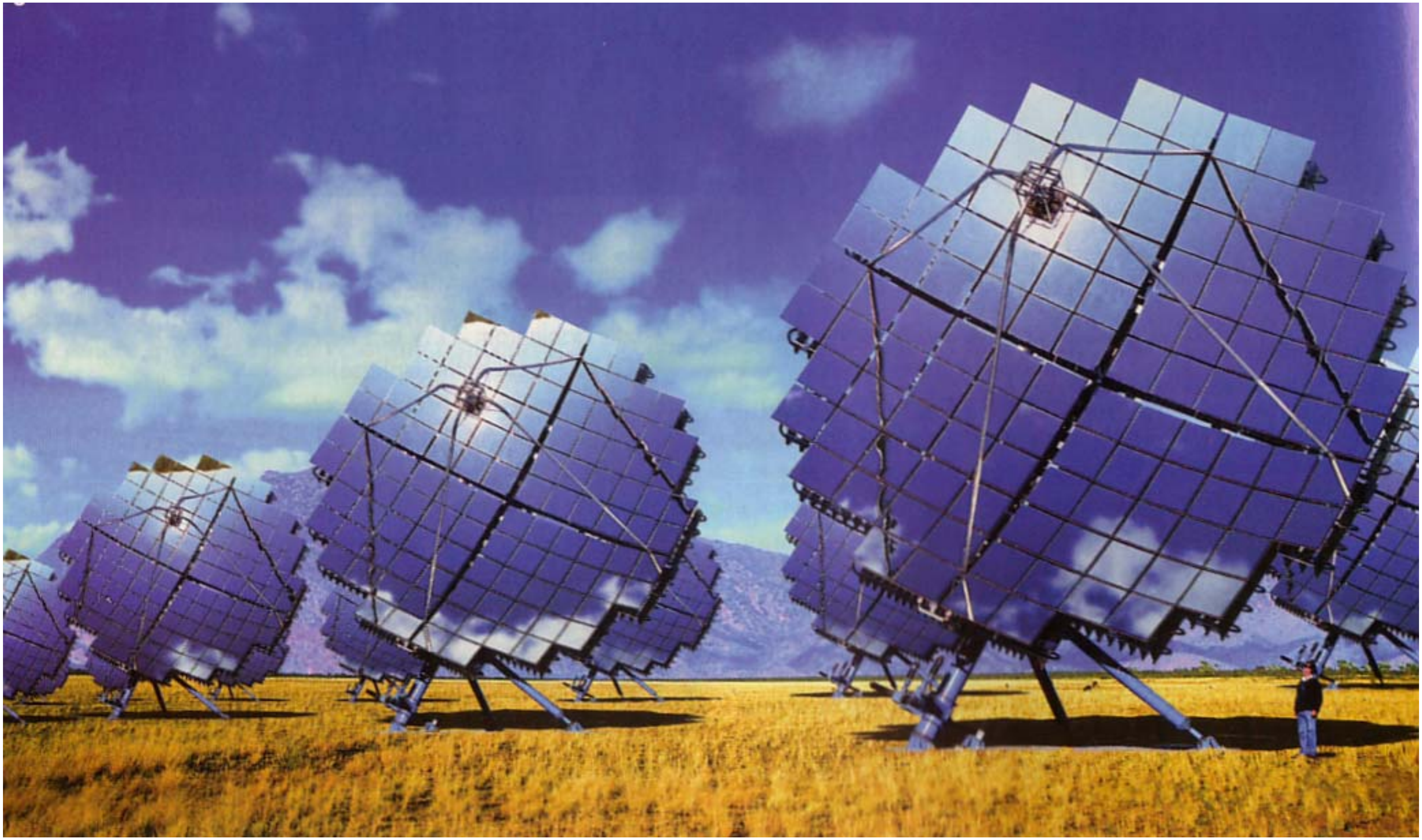


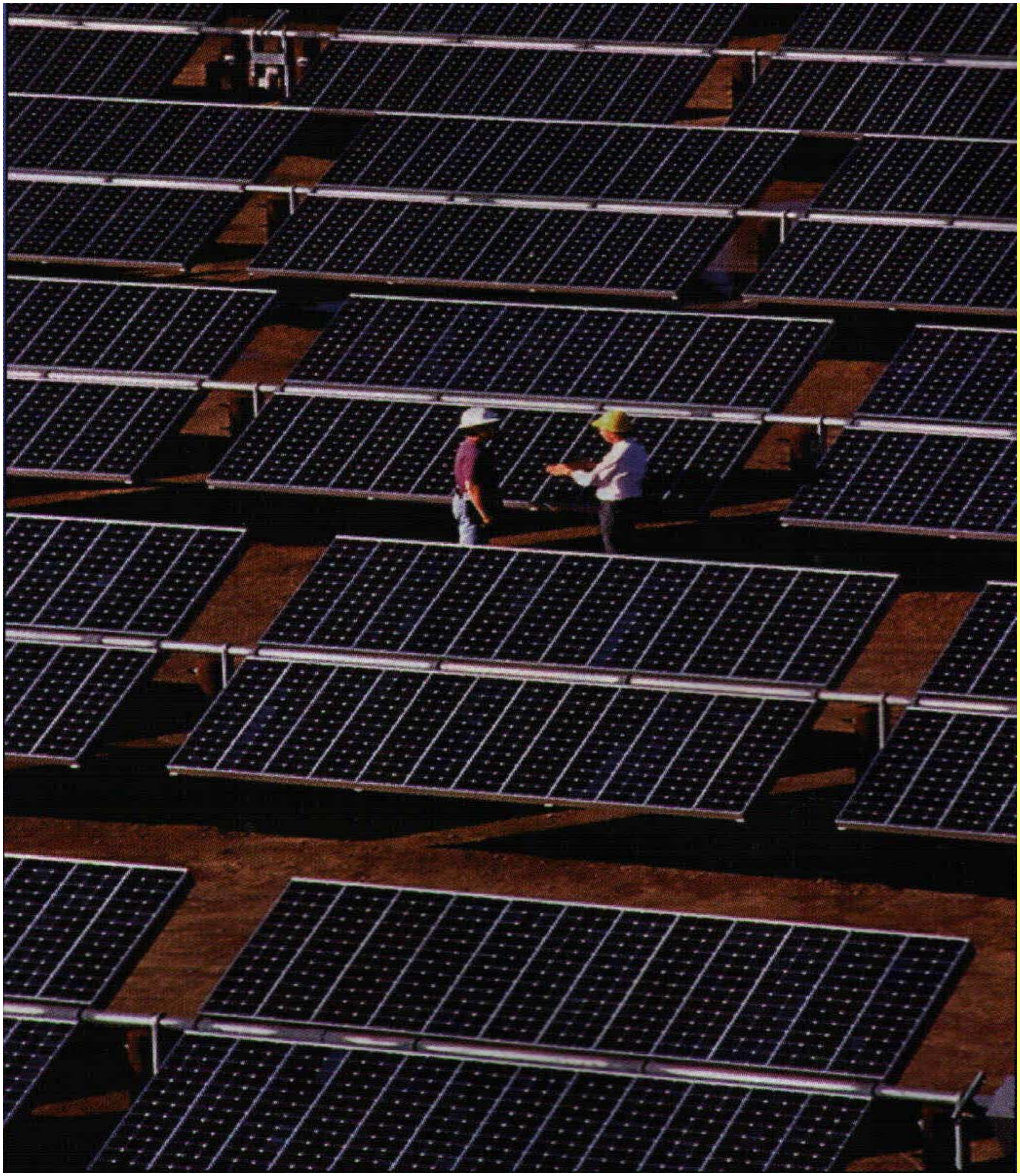
Photo: Tasios Melis, PhD,
UC Berkeley, USA



Solar thermal

Stirling Energy Systems, Inc.

850 MW, SCE, CA, 2005



Photovoltaic

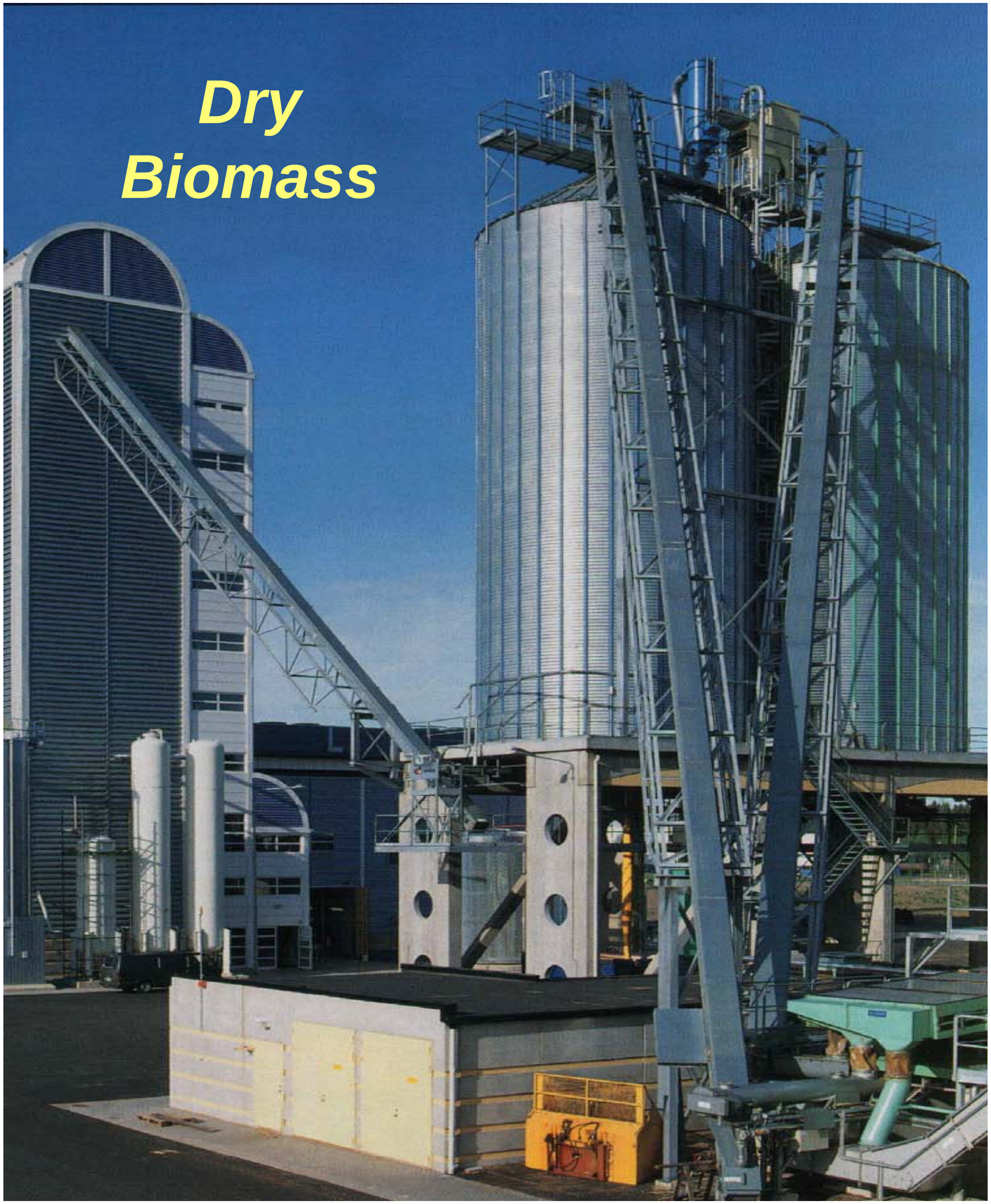
(PV)

Example: Vision of a bright future

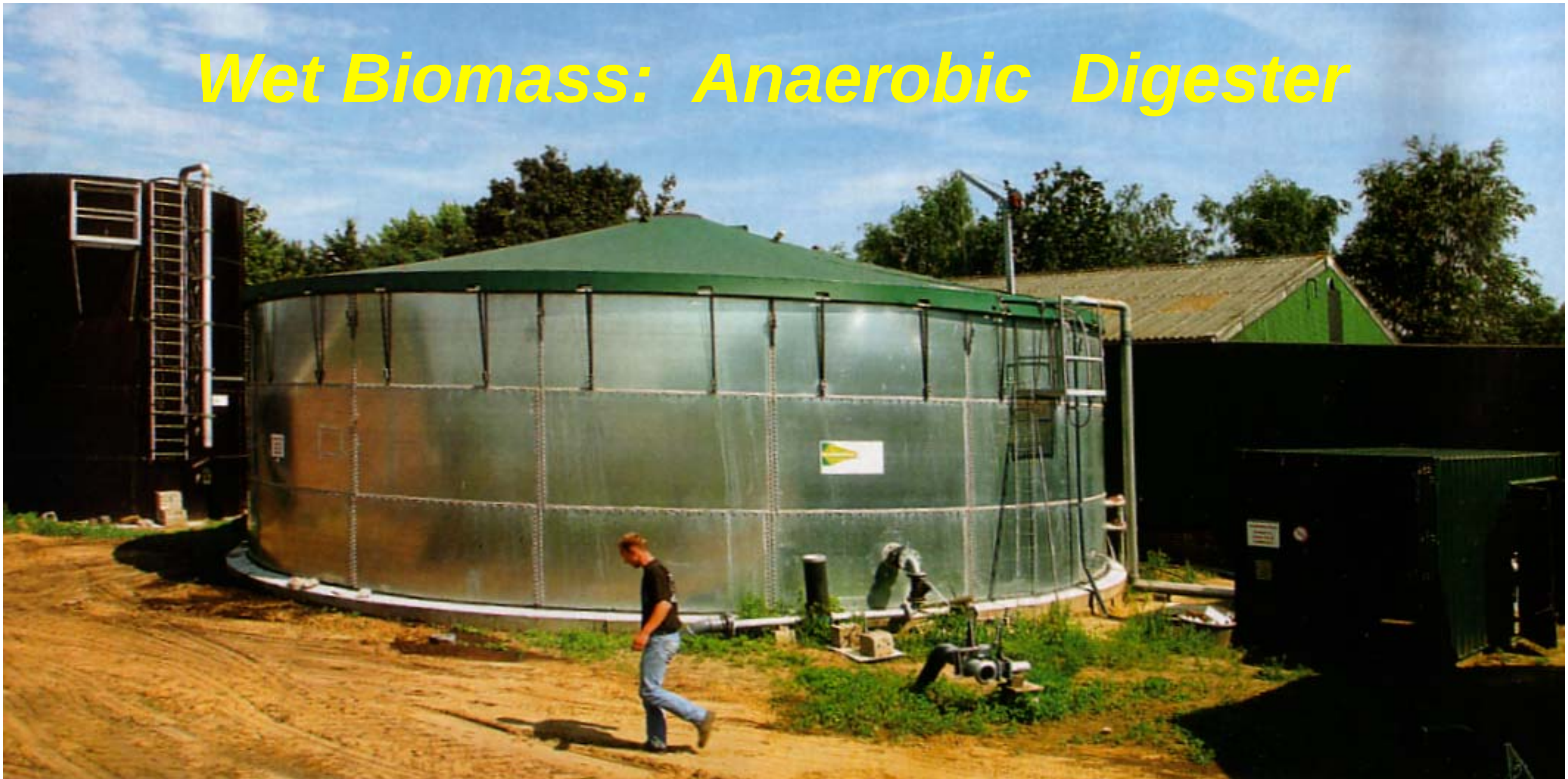
*The Silk Road Genesis Project**

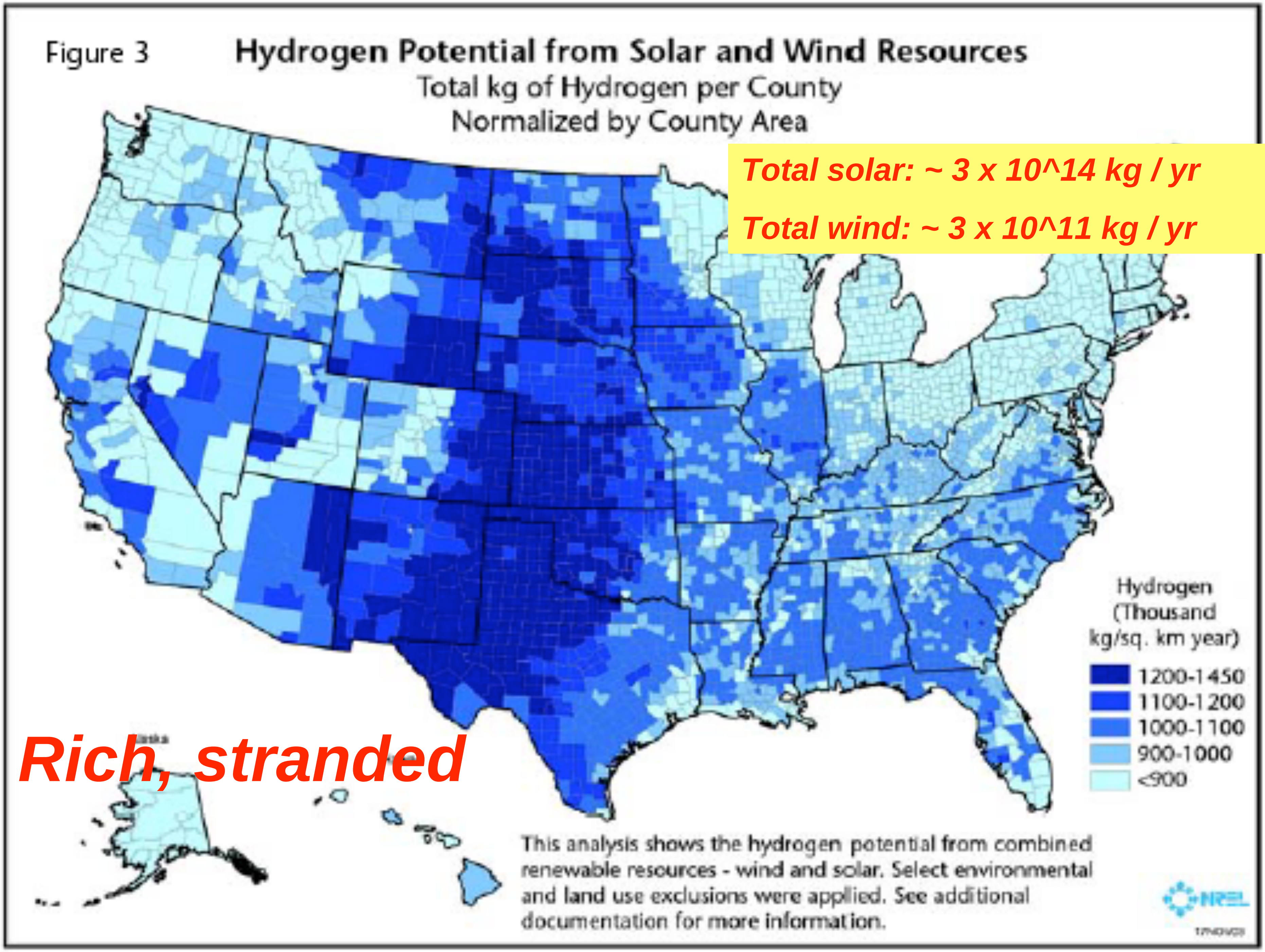
**proposed by Sanyo*

Vision of solar farms in China along the historic silk road to cover $^1/_3$ of China's energy demand in 2030


Dry
Biomass

Wet Biomass: Anaerobic Digester

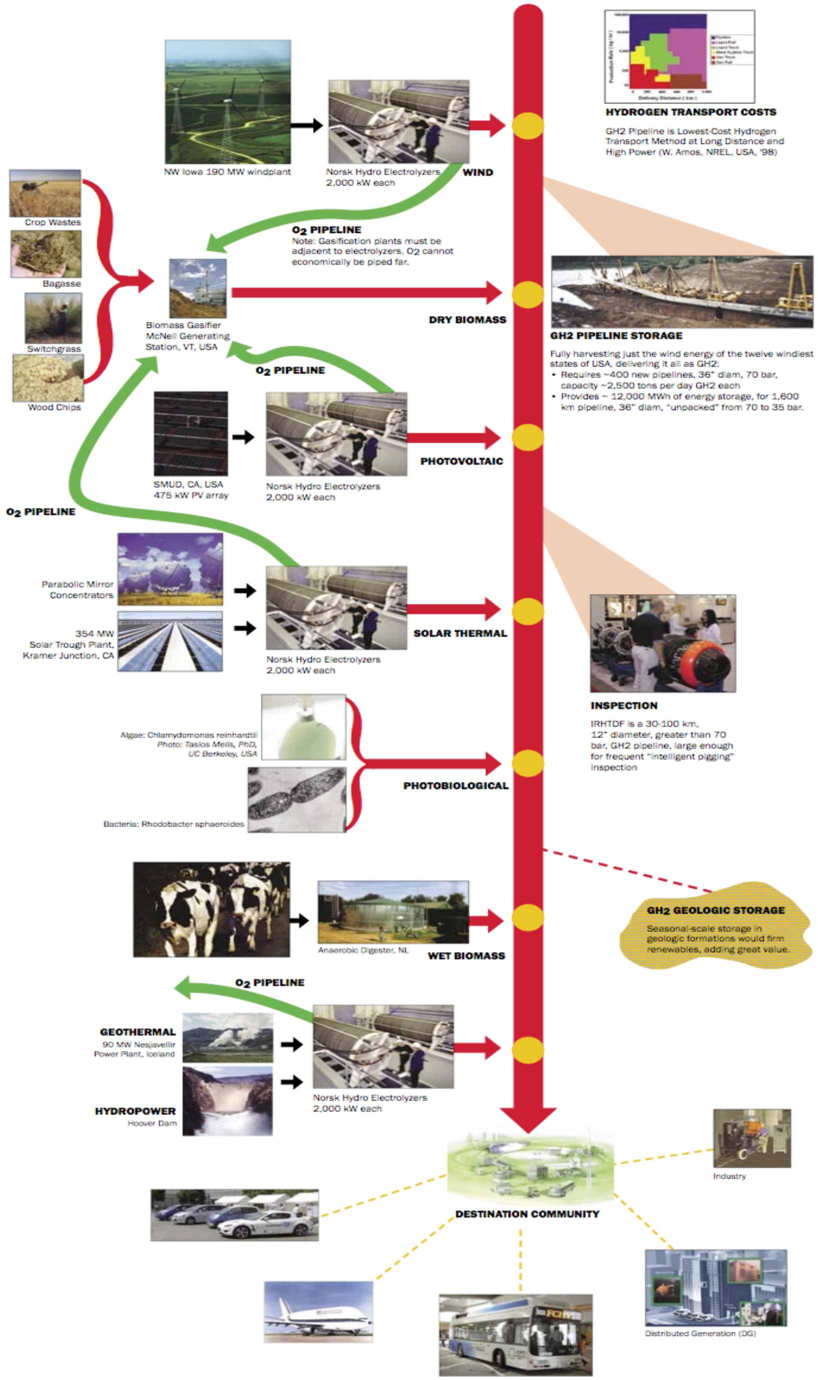




Total solar: ~ 3 x 10^14 kg / yr

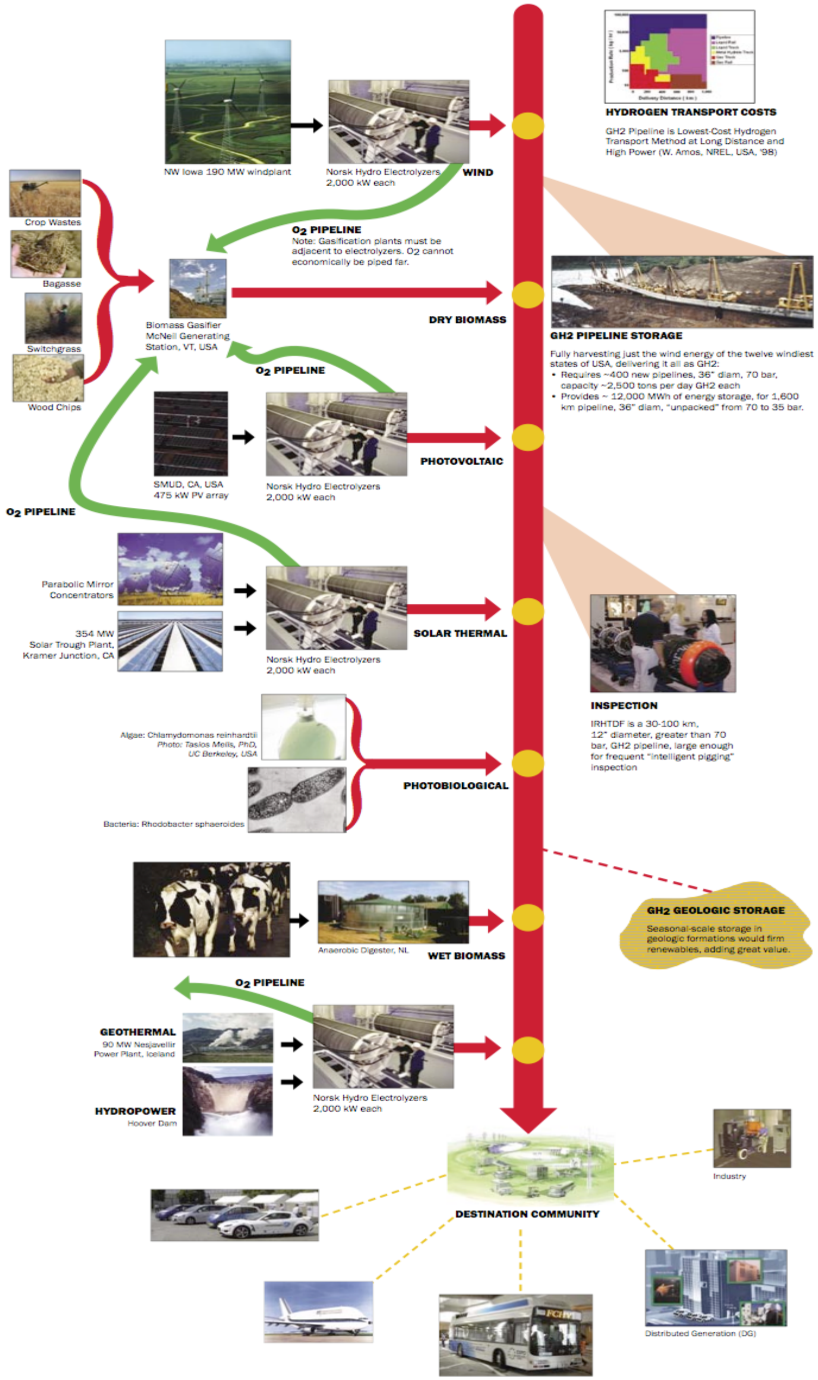
Total wind: ~ 3 x 10^11 kg / yr

Rich, stranded



Pilot-scale Hydrogen Pipeline System

- ***Diverse***
- ***Dispersed***
- ***Diffuse***
- ***Large-scale***
- ***Renewables***
- ***Stranded***
  - ***Remote***
  - ***No transmission***

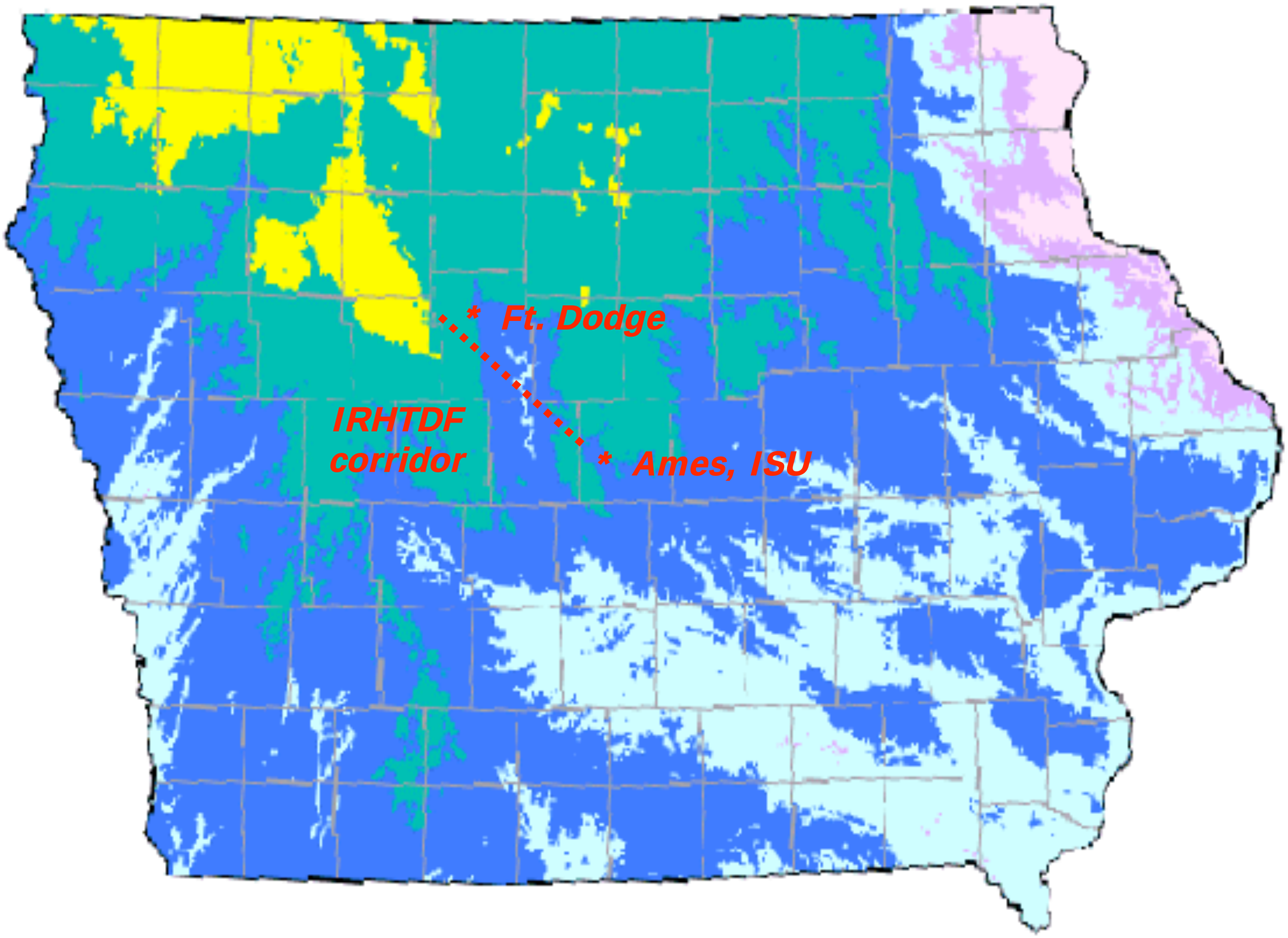


IRHTDF

International Renewable Hydrogen Transmission Demonstration Facility

Estimated Average Annual Wind Speeds

Typical average wind speeds on well exposed sites at 50 m above ground



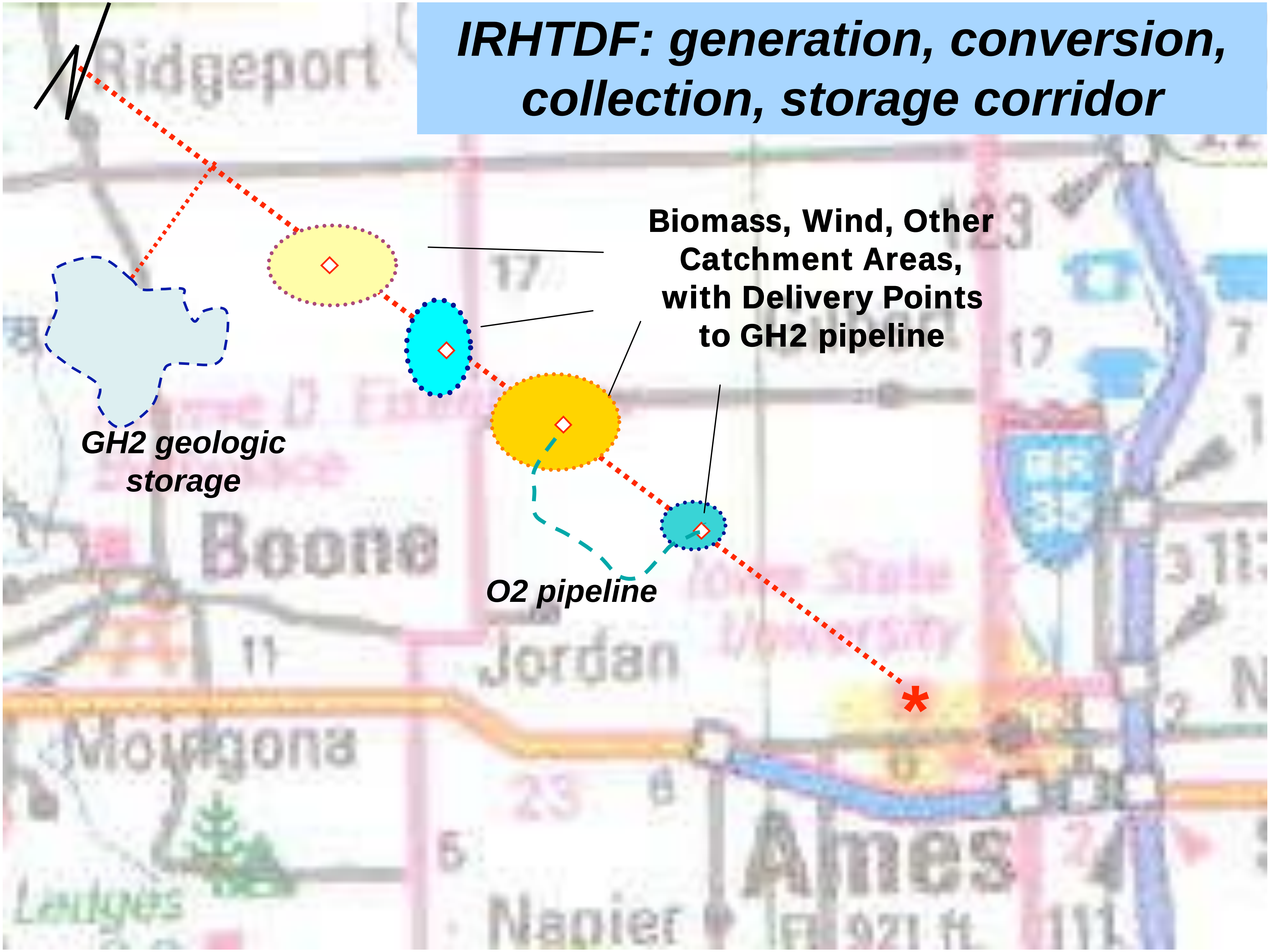
MPH		m/s
>19.0		>8.5
17.9-19.0		8.0-8.5
16.8-17.9		7.5-8.0
15.7-16.8		7.0-7.5
14.5-15.7		6.5-7.0
13.4-14.5		6.0-6.5
12.3-13.4		5.5-6.0
<12.3		<5.5

Iowa Energy Center

This map was generated from data collected by the Iowa Wind Energy Institute under Iowa Energy Center Grant No. 93-04-02. The map was created using a model developed by Brower & Company, Andover, MA.

Iowa Energy Center, 2521 Elwood Dr., Suite 124, Ames, IA 50010-8263 515-294-8819 FAX -9912

IRHTDF: generation, conversion, collection, storage corridor



IRHTDF

- ***I**nternational Renewable **H**ydrogen **T**ransmission **D**emonstration **F**acility*
- *Pilot-scale pipeline system*
- *Can we deliver renewable-source H2 fuel to major urban markets for $2.00 / gallon-gasoline-energy-equivalent?*
- *Prove our models: "1,000 MW Windplant …"*
- *Necessary: critical path to conversion*

I R H T D F

- *Pilot scale renewables-hydrogen **system***
  - *Generation*
  - *Conversion*
  - *Collection*
  - *Transmission*
  - *Storage*
  - *Distribution, end users*
  - *Synergy: O2, seasonal*
- *~ 10 – 100 MW*
- *50 - 100 km pipeline*
- *Defining it reveals R+D to precede it*
- *Next steps: design, propose RFP*

I R H T D F

- *R&D → Test → Demonstration facility:*
  through "back yards", reliable fuel delivery
- *Allay public fears of H_2*
- *Building it proves feasibility, acceptance*
- *Operating it proves*
  - *technology maturity*
  - *economics*
  - *safety*
- *Upper Midwest location ?*
- *$ 40 – 50 million investment: IPHE ?*

IRHTDF

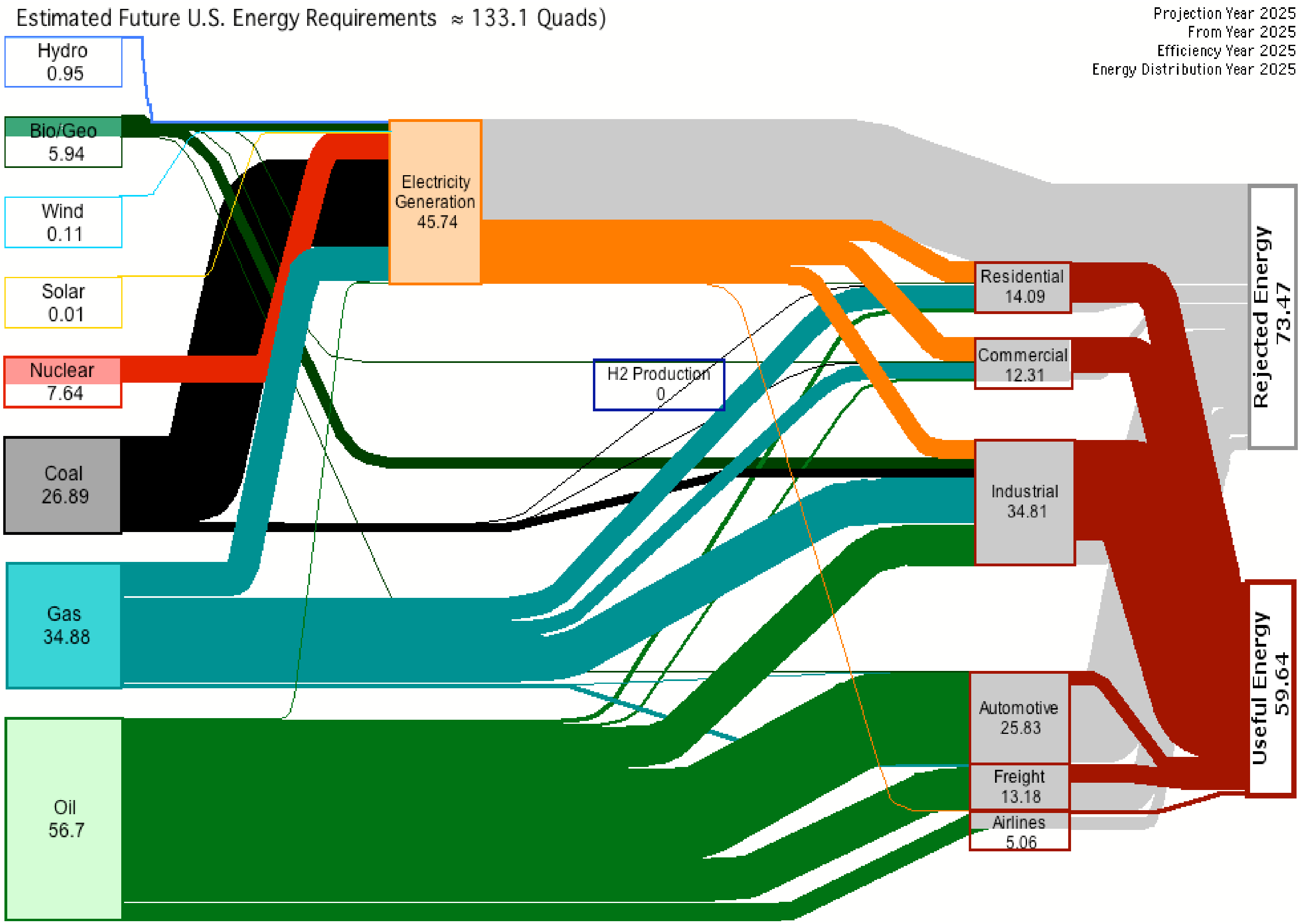
- USA project proposal to IPHE Implementation and Liaison Committee (ILC), 23-25 Mar 05, Rio, Brazil
- IPHE status unknown

IRHTDF

- ASME “International Pipeline Conference”, Calgary, Oct 04 (IPC04)
- “Challenges of Hydrogen Pipeline Transmission”, full day workshop
- 12 Panelists

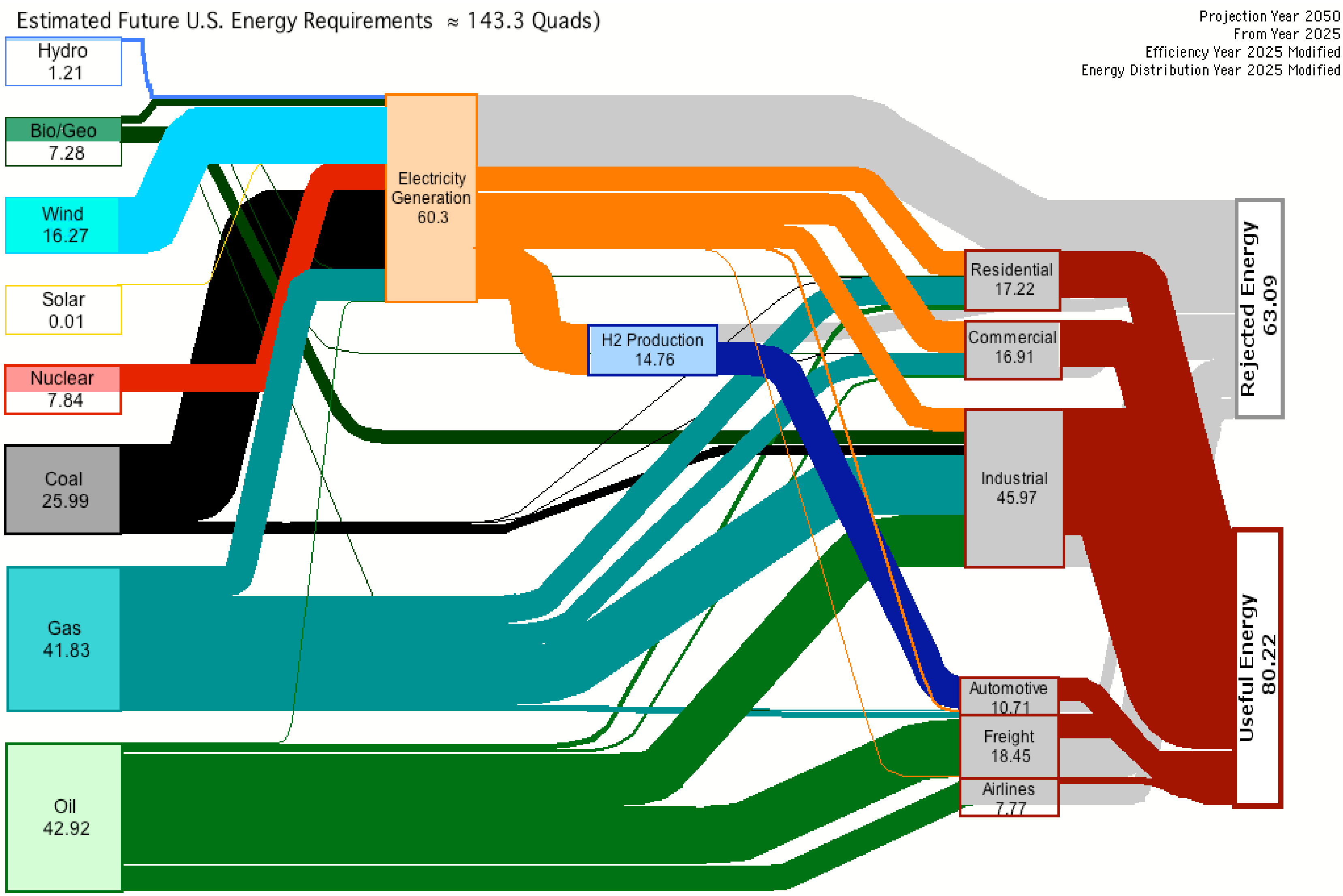
EIA* estimated 2025 US energy use

* Energy Information Administration, USDOE

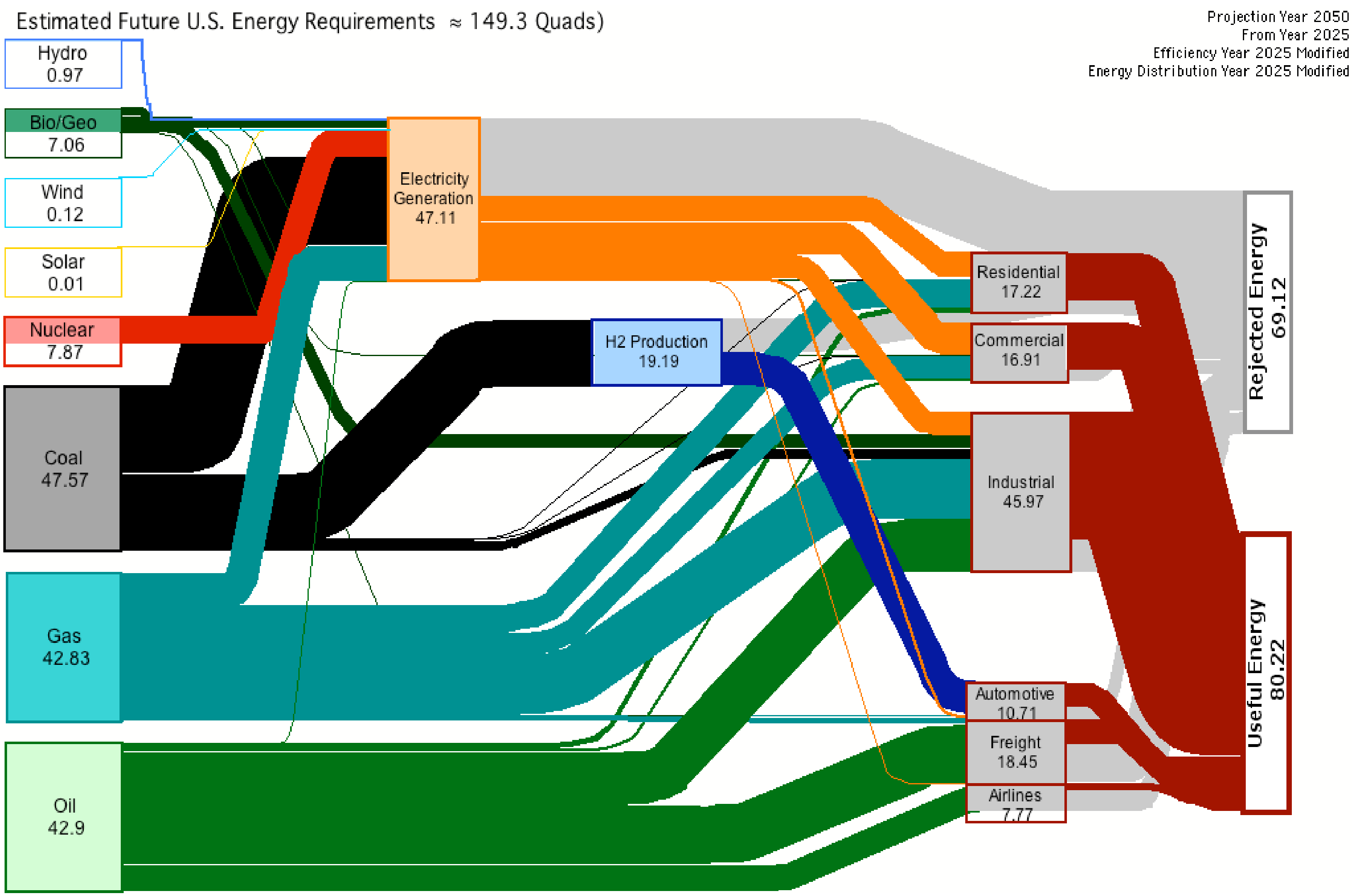


EIA estimated 2050 US energy use

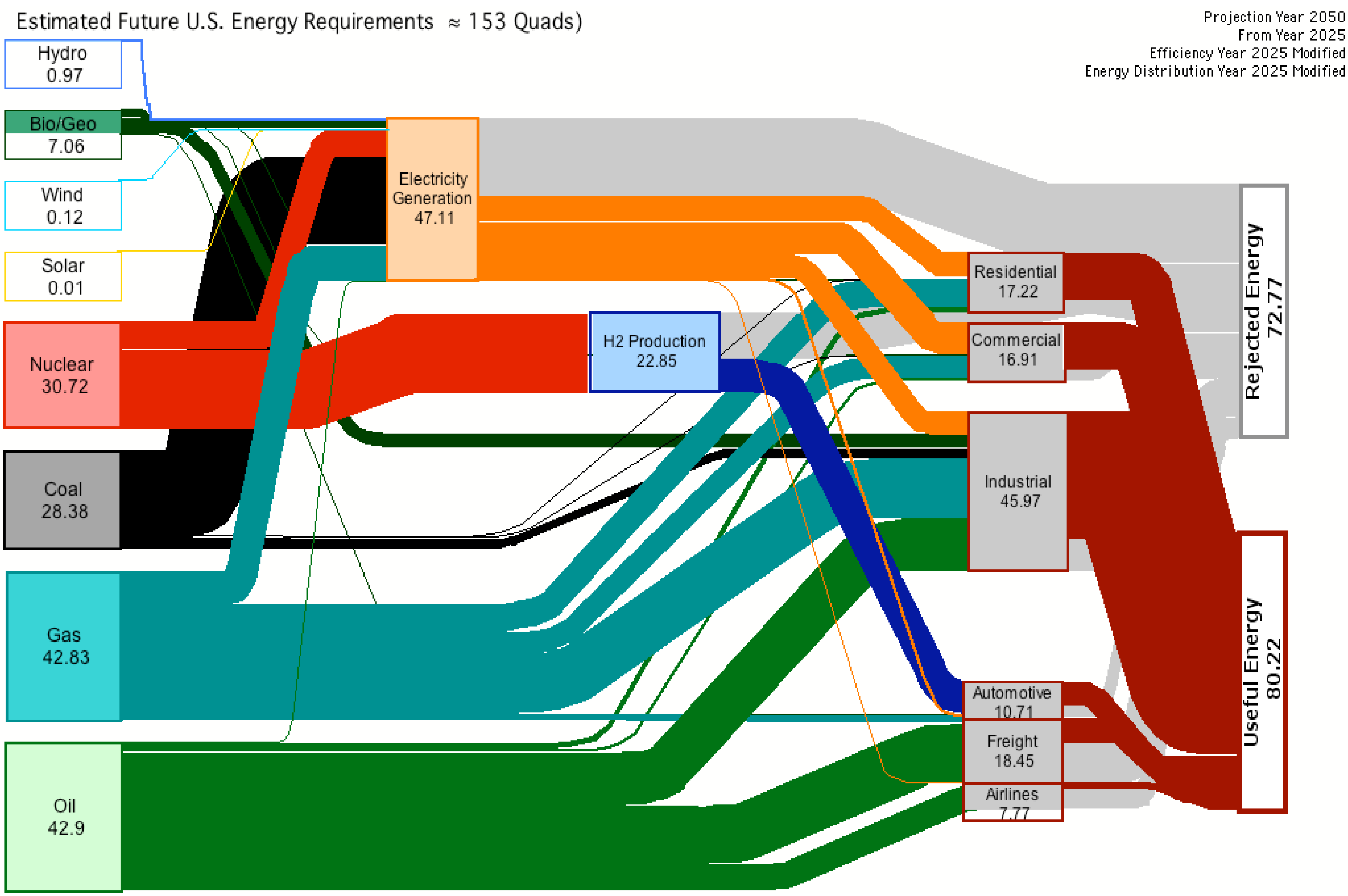
(H_2 fleet using wind electrolysis)

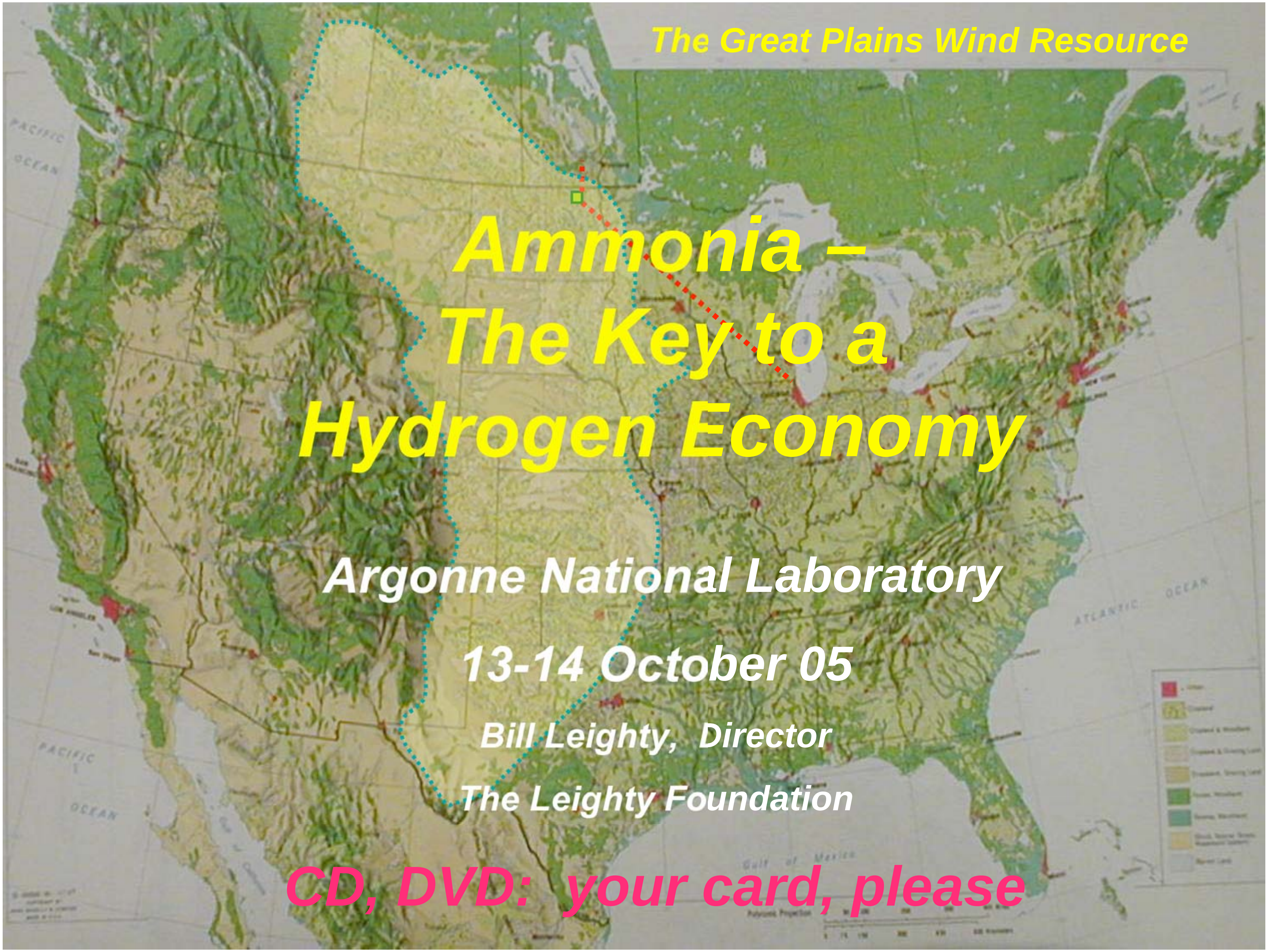


Estimated 2050 energy use
(H_2 fleet using coal gasification)



Estimated 2050 energy use
(H_2 fleet using nuclear thermochemical)





The Great Plains Wind Resource

Ammonia – The Key to a Hydrogen Economy

Argonne National Laboratory

13-14 October 05

Bill Leighty, Director

The Leighty Foundation

CD, DVD: your card, please

End of Argonne Ammonia Presentation

- 13 October 05, Argonne National Laboratory, Chicago
- The following slides are supplemental
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