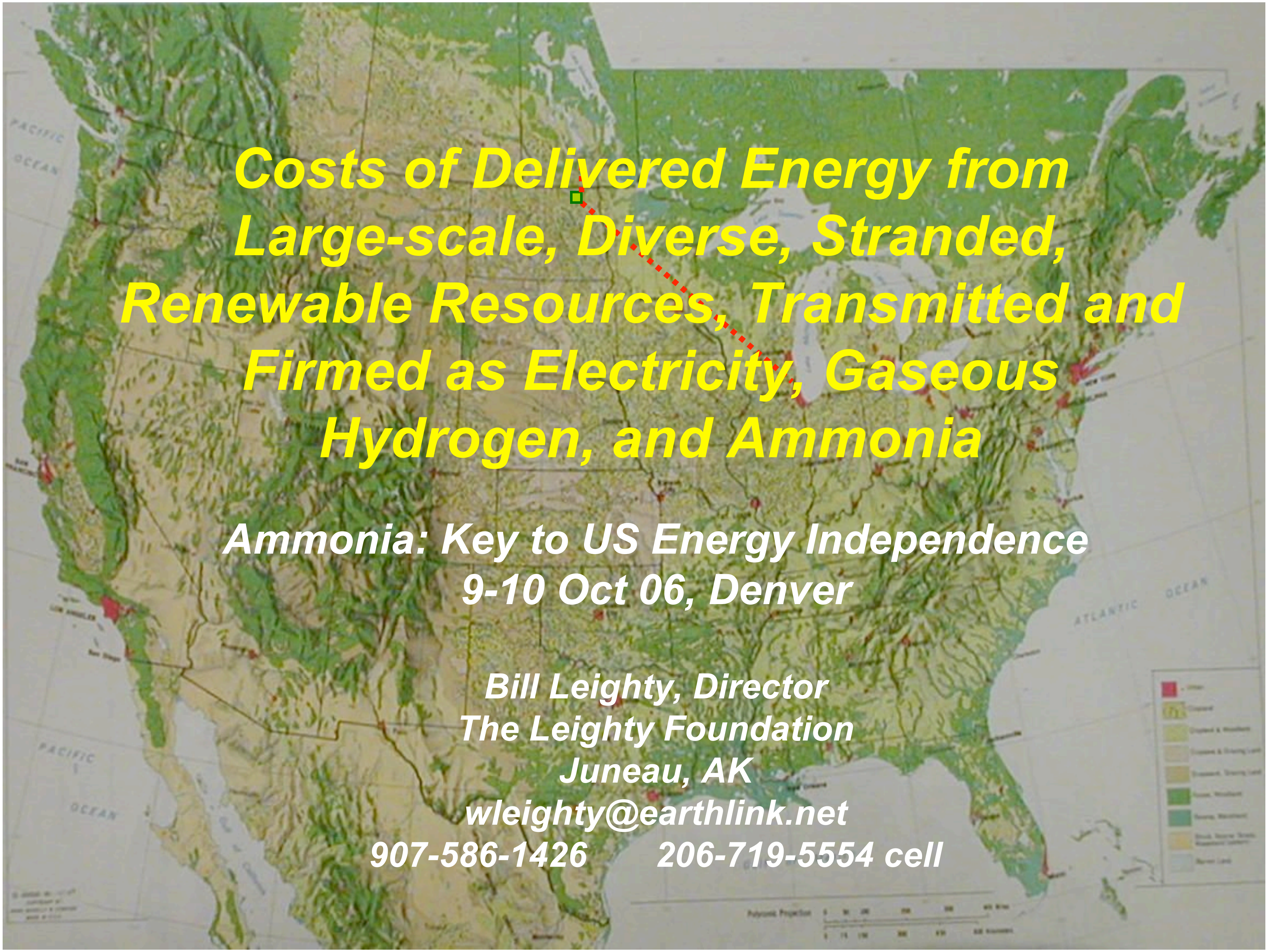


Costs of Delivered Energy from Large-scale, Diverse, Stranded, Renewable Resources, Transmitted and Firmed as Electricity, Gaseous Hydrogen, and Ammonia

Ammonia: Key to US Energy Independence
9-10 Oct 06, Denver

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

Preliminary Study

- Not rigorous; no charts; Holbrook: sanity checks
- Complete for future paper ?
- 2,000 MW (nameplate) Great Plains windplant
  - 40% CF
  - Large-scale, economies-of-scale
- What delivering? Where?
  - To "city gate" wholesale or end-users ?
  - Electricity, wholesale
  - Hydrogen
  - Ammonia: anhydrous, NH3
- Econ: Simple CRF (capital recovery factor) model, 15%. Low ?
- "Firm" renewables at annual scale ?
  - Add strategic, market value
  - Electricity: chemical "batteries"
  - Hydrogen: GH2, geologic, salt caverns
  - Ammonia: refrig tanks, 60K ton, $25M capital + $30K / year

Key Assumptions

1. 2,000 MW windplant = 2,000 MWh / hr at full output
2. AEP: 2,000 MW (nameplate) Great Plains windplant
   @ 40% CF, 100% energy equivalent:
   - 7,008,000 MWh / yr
   - 195,754 tons H2 / yr
   - 1,087,523 tons NH3 / yr
3. 1,000 mile transmission to city gate market
   - 20” GH2 pipeline
   - 10” NH3 pipeline
4. Installed capital costs year 2020 @ year ’05 $US:
   - Wind generators: $1,000 / kW
   - Electrolyzers: $350 / kW
5. Benchmark: actual Xcel Energy wind-generated electric energy, at wind plant gate:
   - $ 0.057 / kWh unsubsidized
   - $ 0.038 / kWh with PTC = $ 0.019 / kWh

Key Assumptions

6. NH3 delivered as liquid; no reforming to H2
7. NH3 tank storage at sources; maximize pipeline CF
8. 500 and 1,000 mile pipelines (2 cases) (only 1,000 mile here)
9. Large-scale for all components:
   - GW sources and conversions (synthesis, cracking)
   - >10,000 ton liquid NH3 storage
10. 150 tph pipeline, 10” diam, .25” wall thick, 1,300 psi nominal, 1,500 MAOP
11. X42 or Grade B carbon steel line pipe, welded, 35 – 42,000 psi
12. 150 tph flow = 300,000 lbs / hr = 52,817 gal / hr
13. Annual capital cost @ 15% CRF

Further study; major uncertainties

- Both 500 and 1,000 mile transmission distance
- NH3 reformer (dissociator, cracker) capital costs, efficiency
- Use higher, less-optimistic capital costs
- Use higher CRF (capital recovery factor): 18% ? 20% ? Risk premium ?
- More accurate NH3 pipeline pumping power and cost analysis
- More accurate NH3 synthesis plant capital costs and efficiencies, when H2 supplied by 30-bar-output electrolyzers

Cases considered:
2,000 MW (nameplate)Great Plains Windplant

1. HVDC electricity: 50% of 3,000 MW line
2. Elec → GH2 → Gas Pipeline → City gate wholesale
   a. Without firming storage
   b. With firming storage
3. Elec → GH2 → NH3 → Liquid Pipeline → City gate wholesale
   a. Without firming storage
   b. With firming storage
4. Elec → GH2 → NH3 → Liquid Pipeline → Reform to H2
   a. Without firming storage
   b. With firming storage

Conclusions: Cases 1 - 4

Conversion + transmission costs per kg H2

	No firming	**Firmed**
1: HVDC electricity	$ 0.54	----
2: GH2 pipeline	$ 1.94	$ 2.01
3: NH3 pipeline, deliver NH3	$ 2.57	$ 2.65
4: NH3 pipeline, deliver GH2	$ 3.20	$ 3.28

Trouble with Renewables

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

Trouble with Electricity Transmission

- Grid nearly full
  - New wind must pay for transmission
  - Costly: AC or DC
- NIMBY
- Low capacity factor or curtailment
- No storage: smoothing or firming
- Overhead towers vulnerable: God or man
- Underground: Only HVDC

Trouble with GW-scale wind today

- Grid nearly full
  - New wind must pay for transmission
  - Costly: AC or DC
- "Cherry-picked" windplants, to date
  - Best wind sites
  - Low-cost transmission access
- Depend on PTC: $ 0.019 / kWh
- No storage: smoothing or firming

2,000 MW windplant output

100 % Capacity Factor

	MWh/day	tons/hr	tons/day	tons/yr
As electricity	48,000			
As H_2		311	1,342	489,776
As NH_3		1,726	7,455	2,720,980
10” NH_3 pipeline capacity as NH_3		150	3,600	1,314,000
10” NH_3 pipeline capacity as H_2		27	648	236,520

40 % Capacity Factor

	MWh/day	tons/hr	tons/day	tons/yr
As electricity	19,200			
As H_2		124	537	195,910
As NH_3		690	2,982	1,088,392
10” NH_3 pipeline capacity as NH_3		60	1,440	525,600
10” NH_3 pipeline capacity as H_2		11	259	94,608

NH3 Pipeline Capacity

- 10” diam
  - 150 tons per hour (tph)
  - 1.3 million tons per year (tpy)
- Extrapolation
  - 8” diam =~ 90 tph
  - 6” diam =~ 50 tph
  - 4” diam =~ 15 tph
- Total USA annual NH3 use:

  3-5 million tons, as anhydrous

Total Windplant – H2 System Installed Capital Cost: GW scale $US million

Windplant size	**1,000 MW**	**2,000 MW**
Wind generators	$ 1,000	$ 2,000
Electrolyzers	500	1,000
Transmission	??	??
TOTAL	$ 1,500	$ 3,000
@ 15% CRF*	$ 225	$ 450
Average cost / kWh (unsubsidized)	$ 0.064	$ 0.064

* Capital Recovery Factor: annual cost

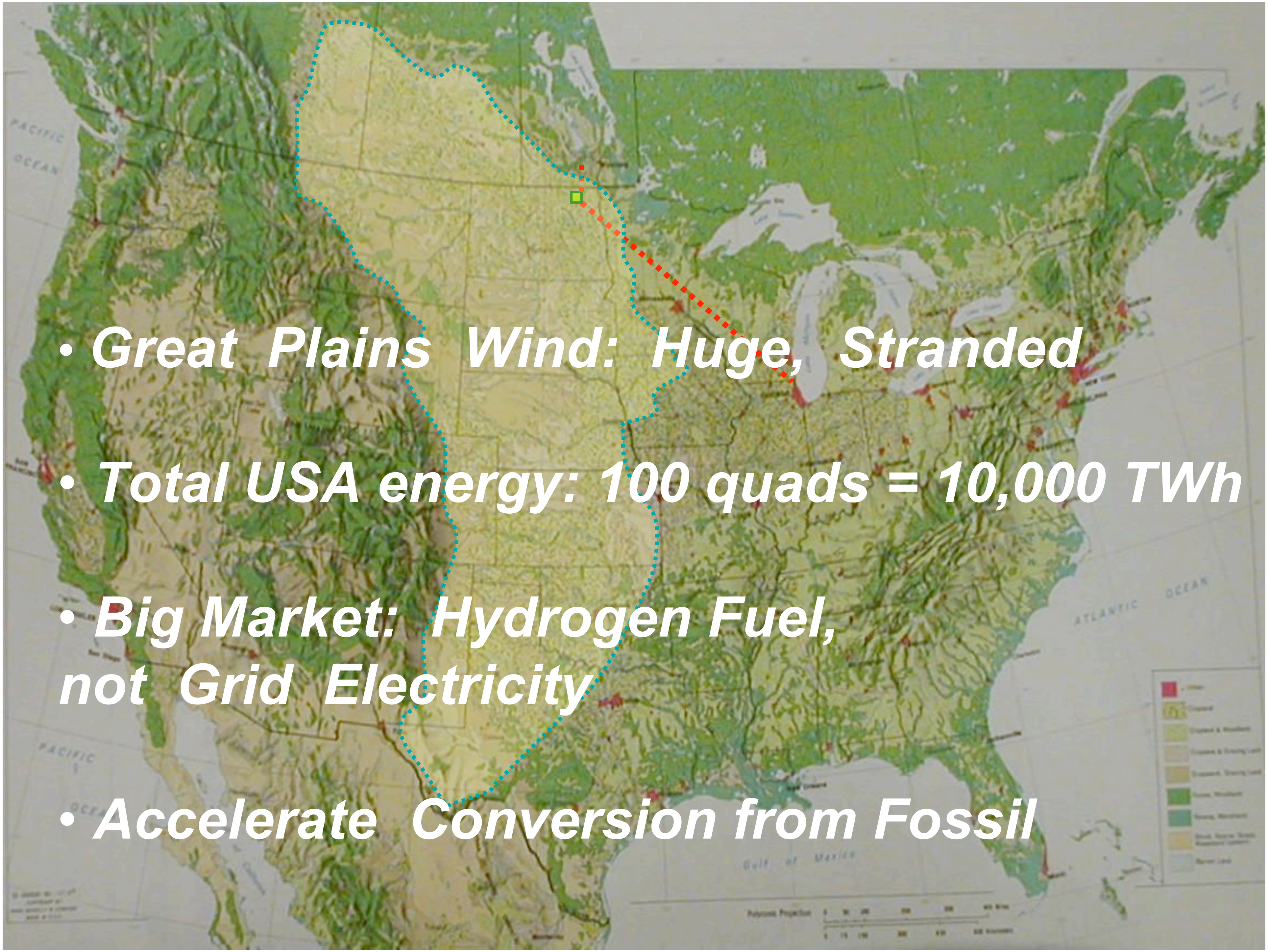
The Great Plains Wind Resource
PACIFIC OCEAN
ATLANTIC OCEAN
Gulf of Mexico

Exporting From 12 Windiest Great Plains States

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

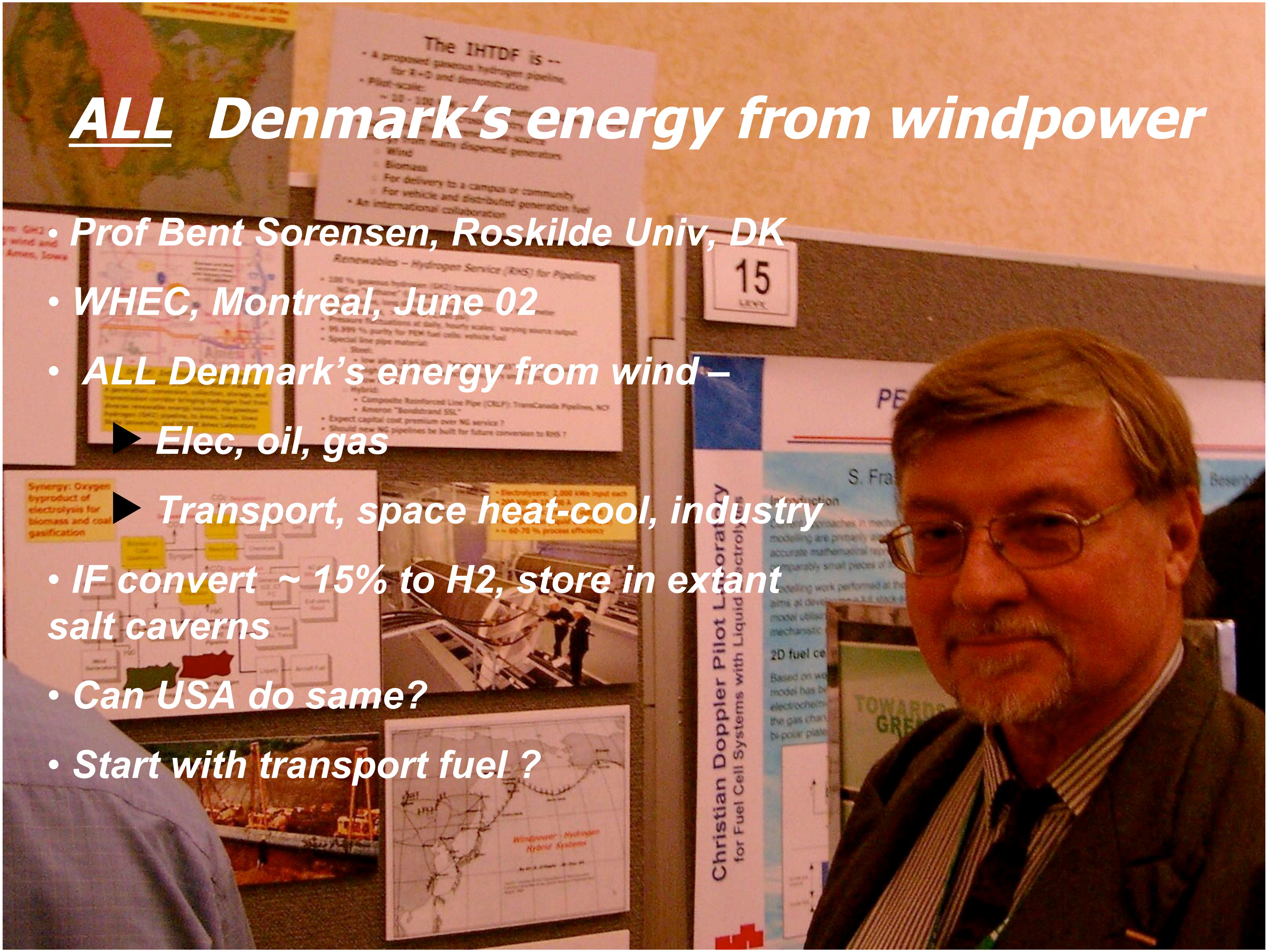
Wind energy source: PNL-7789, 1991 * at 500 miles average length

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



- *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 ?

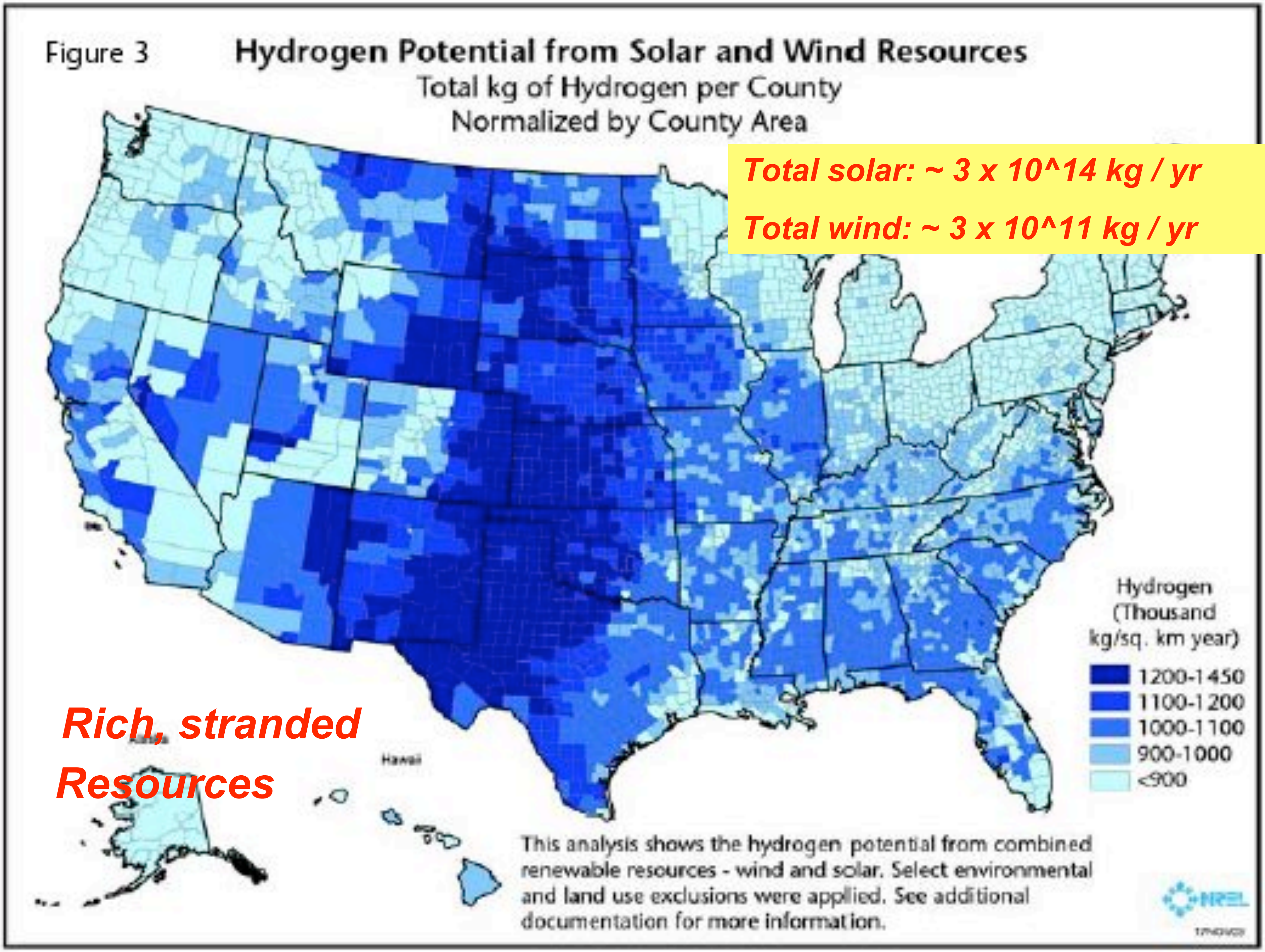


Figure 3
Hydrogen Potential from Solar and Wind Resources
Total kg of Hydrogen per County
Normalized by County Area
Total solar: ~ 3 x 10^14 kg / yr
Total wind: ~ 3 x 10^11 kg / yr
Hydrogen (Thousand kg/sq. km year)
1200-1450
1100-1200
1000-1100
900-1000
<900
Hawaii
Rich, stranded Resources
This analysis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


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

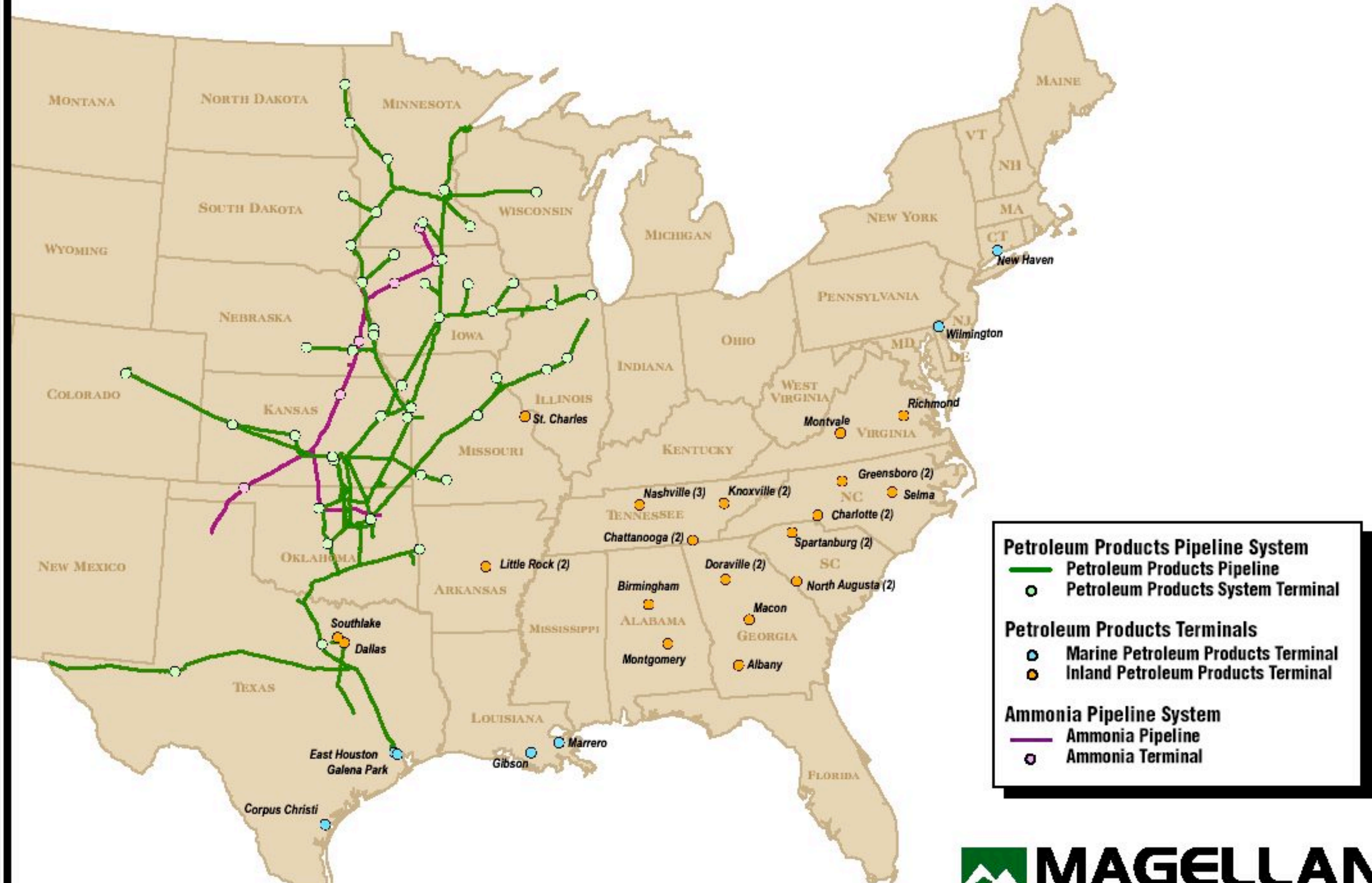
GW-scale Transmission Options: Stranded Renewables

- Electricity:
  - Overhead: HVAC, HVDC
  - Underground: HVDC
- Gaseous Hydrogen (GH2) pipeline
  - 100% GH2; purity
  - "Hythane"; "NaturalHY", EC, Gasunie Research NL
- Liquid Hydrogen (LH2) pipeline, truck, rail car, ship
- Ammonia (NH3) gas, liquid: pipeline, truck, rail car, ship
- Liquid synthetic HC's – zero net C
  - SNG, "synthane" CH4
  - FTL's: Fischer – Tropsch liquids
  - CH3OH (methanol); DME (dimethyl ether)
  - Cyclohexane – benzene (2 pipelines)
  - Silanes: $Si_{10}H_{22}$
- "Energy Pipeline": EPRI
  - SC, LVDC: ~ 100 GW
  - LH2: ~ 100 GW
- Al – Ga ← → Alumina

GW-scale Transmission Options: Stranded Renewables

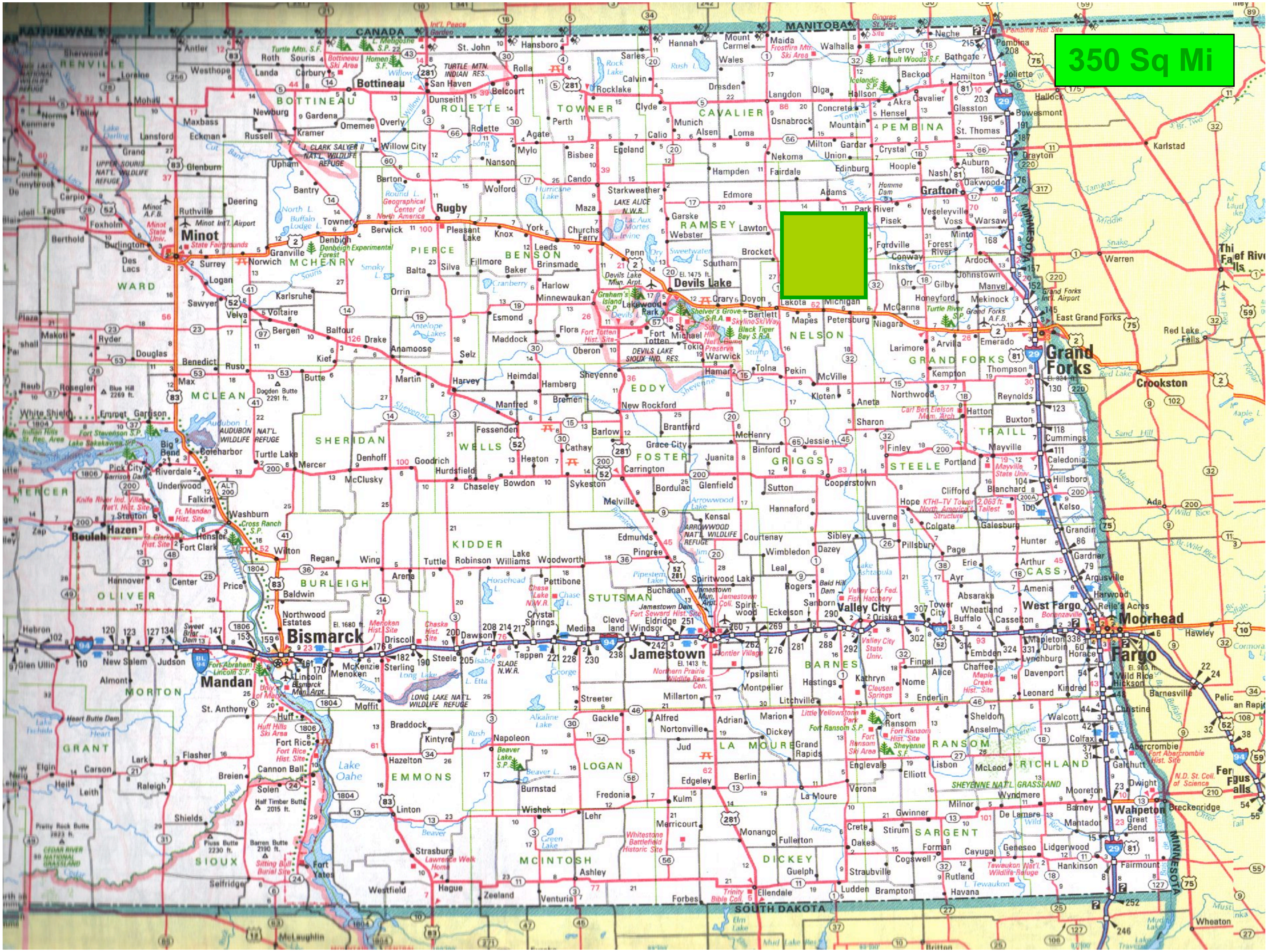
- Electricity:
  - **Overhead: HVDC, HVAC**
  - Underground: HVDC
- Gaseous Hydrogen (GH2) pipeline
  - 100% GH2; purity
  - "Hythane"; "NaturalHY", EC, Gasunie Research NL
- Liquid Hydrogen (LH2) pipeline, truck, rail car, ship
- Ammonia (NH3) gas, liquid: pipeline, truck, rail car, ship
- Liquid synthetic HC's – zero net C
  - SNG, "synthane" CH4
  - FTL's: Fischer – Tropsch liquids
  - CH3OH (methanol); DME (dimethyl ether)
  - Cyclohexane – benzene (2 pipelines)
  - Silanes: $Si_{10}H_{22}$
- "Energy Pipeline": EPRI
  - SC, LVDC: ~ 100 GW
  - LH2: ~ 100 GW
- Al – Ga ← → Alumina

Asset Portfolio

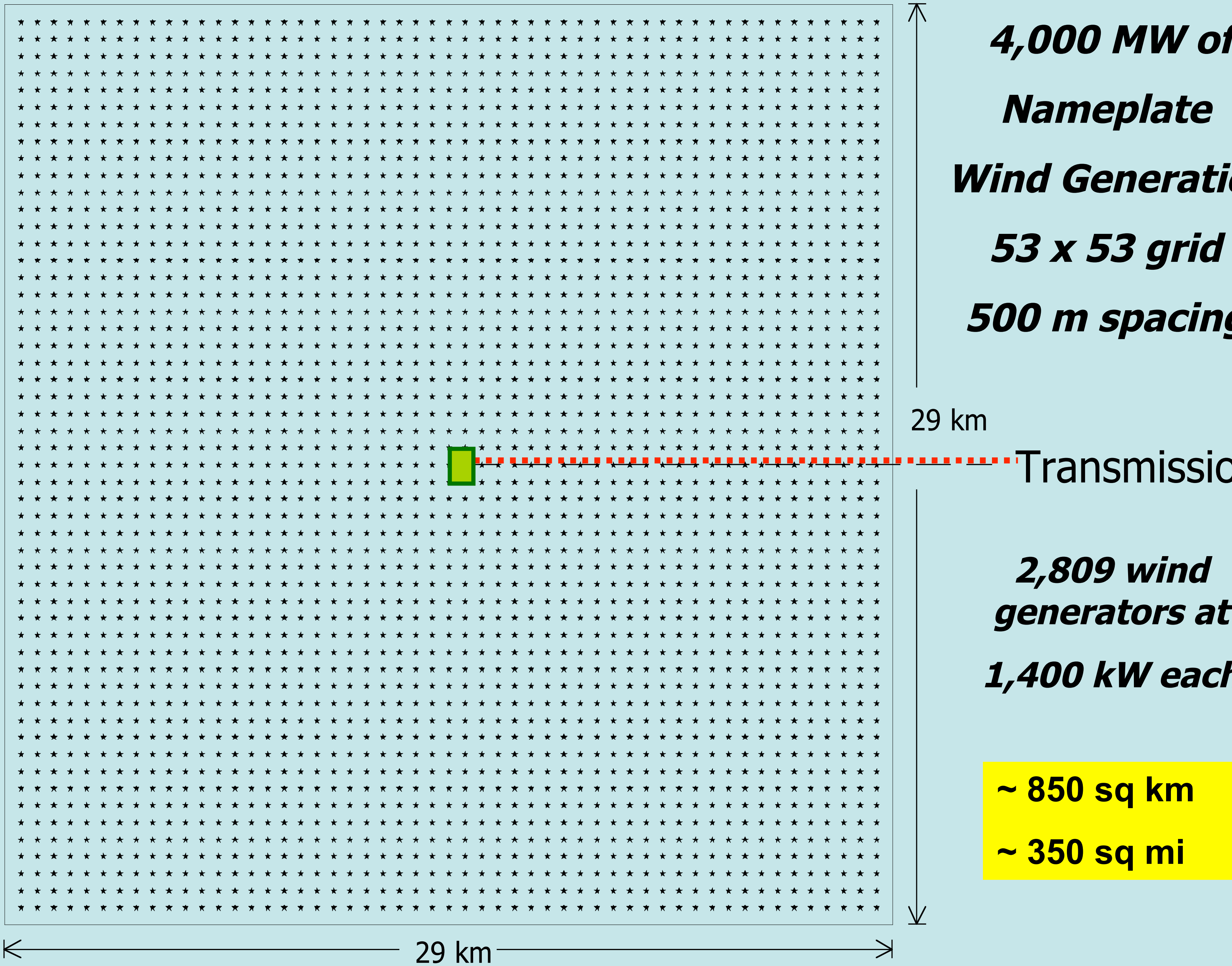


MAGELLAN® MIDSTREAM PARTNERS, L.P.

Valero LP Operations



350 Sq Mi
CANADA
MANITOBA
SOUTH DAKOTA
MINNESOTA
BOTTINEAU
ROLETTE
TOWNER
CAVALIER
PEMBINA
RENVILLE
WARD
MCHENRY
PIERCE
BENSON
RAMSEY
NELSON
GRAND FORKS
WALSH
MCLEAN
SHERIDAN
WELLS
EDDY
FOSTER
GRIGGS
STEELE
TRAILL
MERCER
OLIVER
KIDDER
STUTSMAN
BARNES
CASS
BURLEIGH
MORTON
GRANT
EMMONS
LOGAN
LA MOURE
RANSOM
RICHLAND
SIOUX
MCINTOSH
DICKEY
SARGENT
Minot
Bismarck
Mandan
Jamestown
Valley City
Fargo
West Fargo
Moorhead
Grand Forks
East Grand Forks
Devils Lake
Rugby
Wahpeton
Crookston



4,000 MW of Nameplate Wind Generation

53 x 53 grid

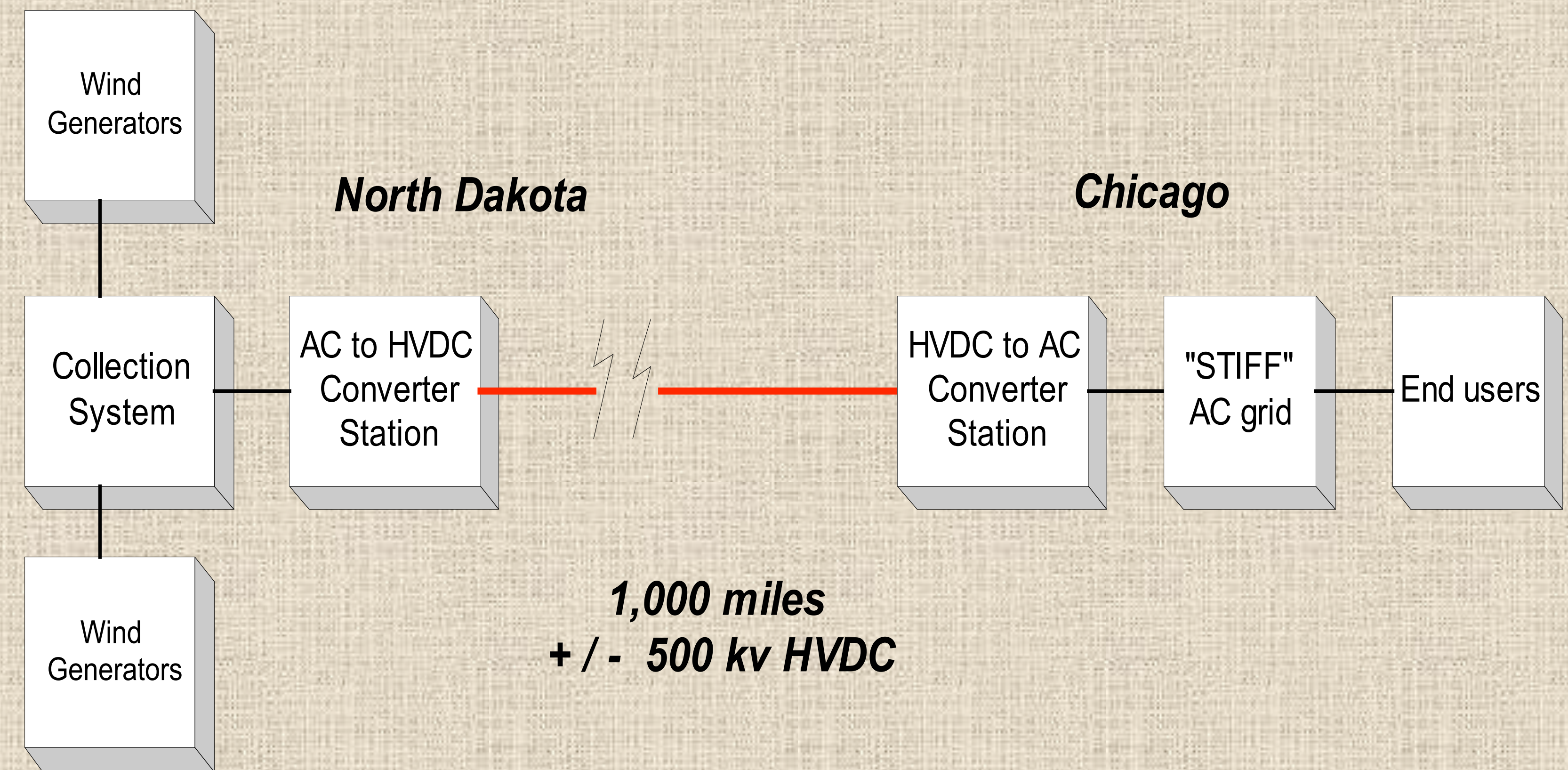
500 m spacing

2,809 wind generators at 1,400 kW each

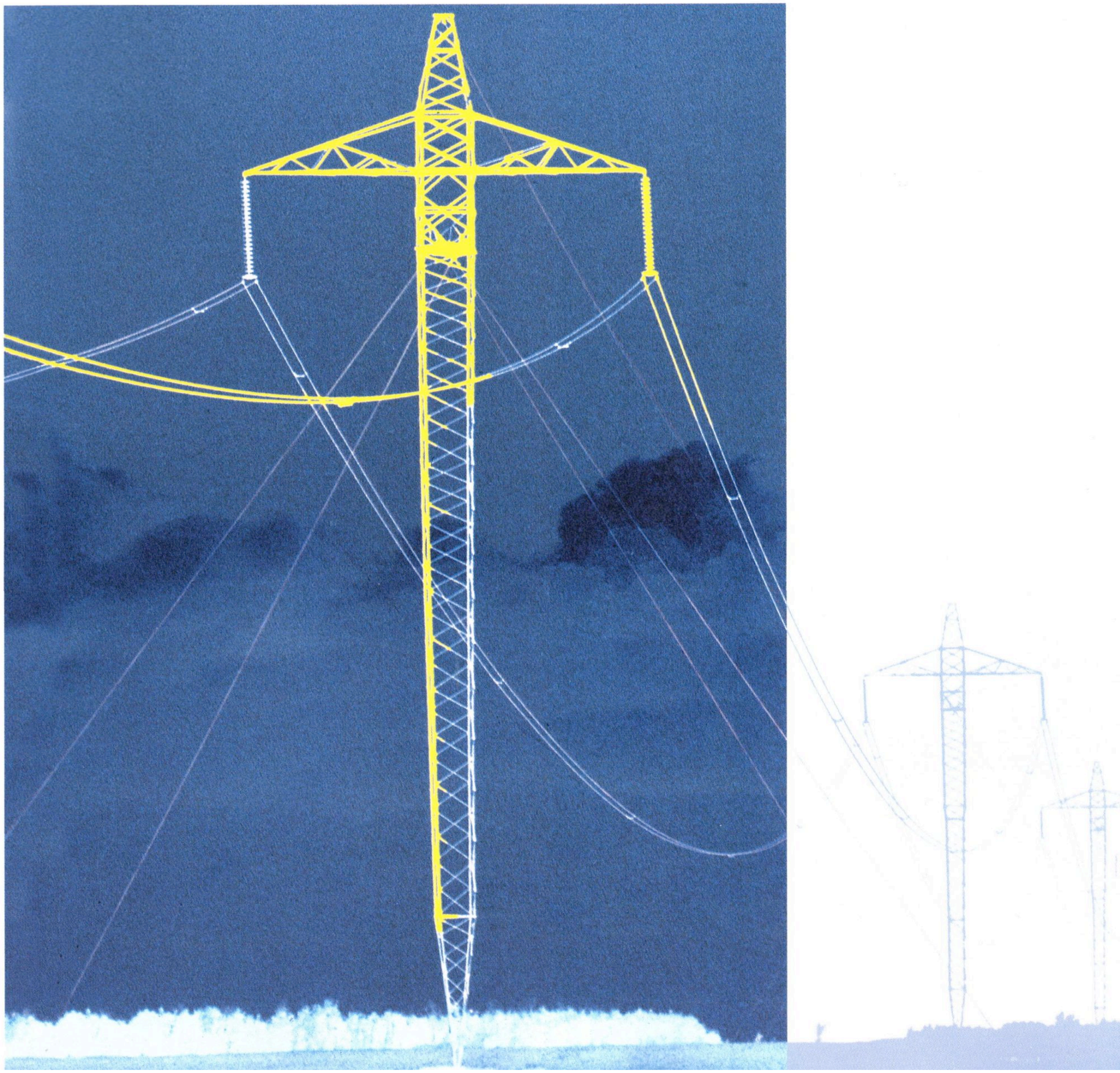
~ 850 sq km

~ 350 sq mi

"Electrical Transmission" Scenario



High Voltage
Direct Current Transmission

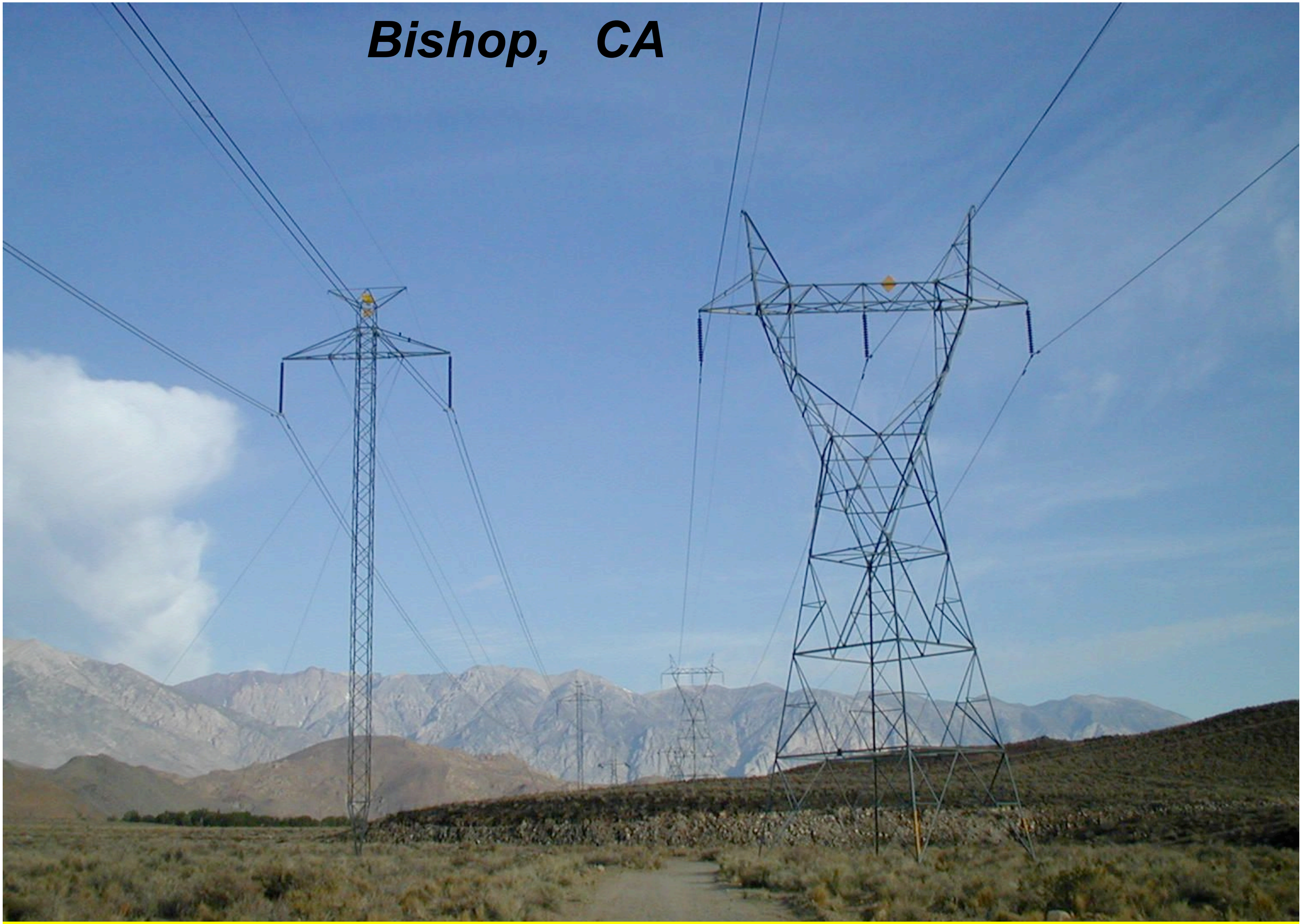


North Dakota wind needs
115 new lines
at 3,000 MW each

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

SIEMENS
HVDC line
+/- 500 kv

Bishop, CA



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

Case 1:
HVDC electricity: 50% of 3,000 MW line

- Point-to-point system: one “on ramp”
- Overhead lines, only
- Wholesale delivery to substation at city gate
- Capital costs
  - Converter station pair @ $140 / kW = $ 420 M
  - Line @ $500K / mile = $ 500 M
  - Design, permitting, etc. = $ 80 M
  - Total = $ 1,000 M
  - 50% allocated tp 2,000 MW windplant = $ 500 M

Case 1: Transmission annual costs
HVDC electricity
2,000 MW windplant AEP = 7,008,000 MWh

- Capital costs @ 15% CRF @ $ 500 M (allocated) — $ 75 M
- Conversion and Transmission losses:
  - Converter station pair @ 0.65% each = 1.3%
  - Lines @ 0.4% per 100 km @ 1,600 km = 6.4%
  - Total = 7.7% @ AEP = $399,456,000 = — $ 31 M

TOTAL annual costs — $ 106 M

Annual cost per ton H2 = $ 541

Annual cost per kg H2 = $ 0.54

Case 1: Firming storage
HVDC electricity: 50% of 3,000 MW line

Energy storage:

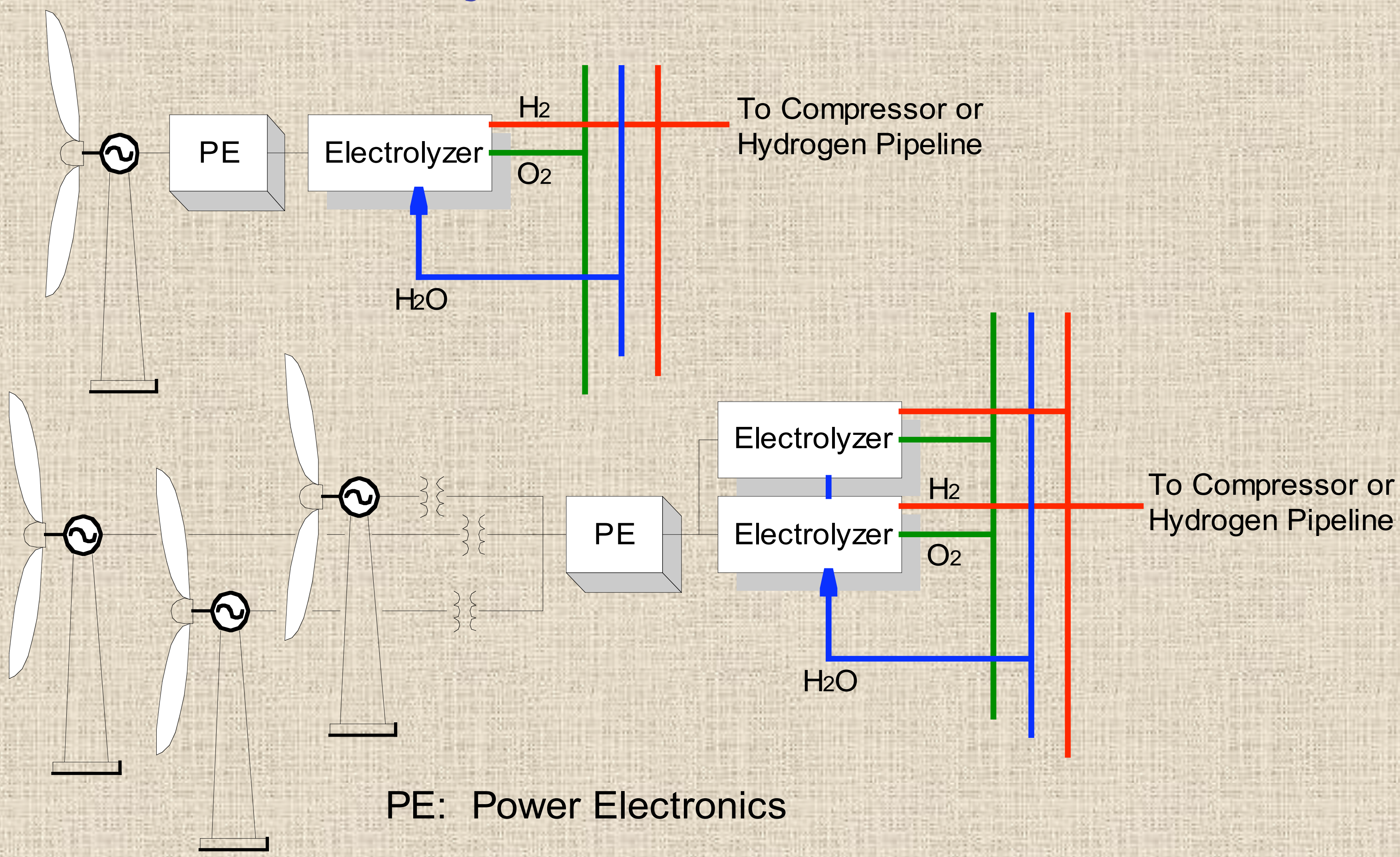
- **Sodium-sulfur battery:**
  - **1 MW, 7 MWh capacity = capital cost $300 / kW installed = $2.1 M**
  - **In / out efficiency ~ 85%**
  - **Assume**
    - **100 MW = 100 x $ 2.1 M = $ 210 M**

      Assume: 100 MW enough capacity to capture
    - **840,000 MWh seasonal firm = 120,000 x $ 1.5 M = $ 180 B**

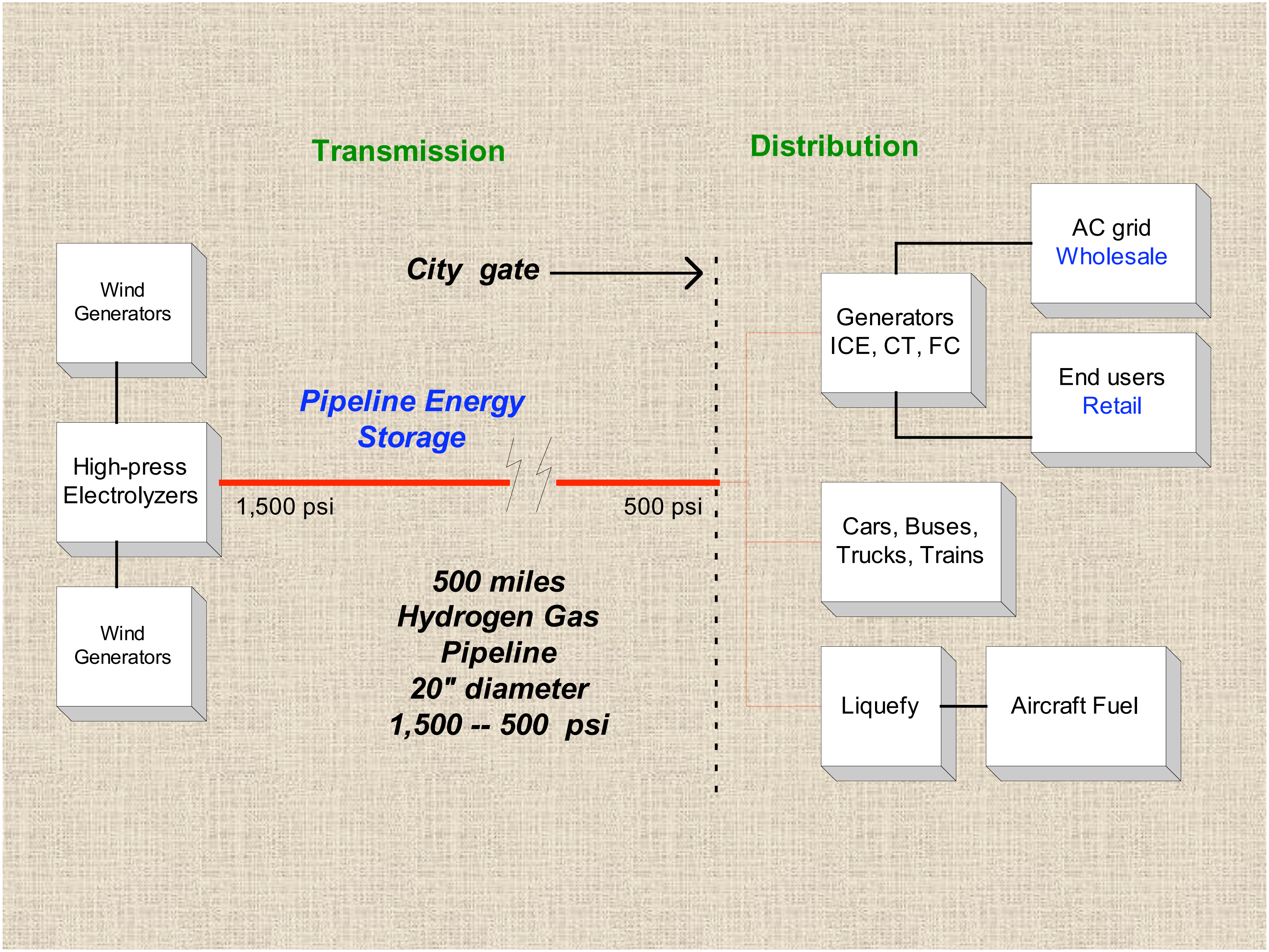
      Assume $ 1.5 M of $ 2.1 M is batteries
- **Vanadium-redox battery (VRB): should cost less; larger scale**

“Hydrogen Transmission Scenario”

Collection Topology Options:
Electrolyzer and Rectifier Location



PE: Power Electronics


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

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

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	[6]	[12]
Caverns @ $10M ea	60	120
Cushion gas @ $5M ea	20	40
TOTAL	$ 2,510	$ 4,050

Cavern storage: 6 % of total capital cost

Annual – scale "Firming"
Great Plains Wind

- **Potential, 12 states, ~50% land area:**
  - **10,000 TWh = 100 quads = entire USA energy**
  - **2,800,000 MW nameplate**
- **Seasonality:**
  - **Summer minimum**
  - **Spring – Summer maximum storage**
  - **"Firming" energy storage, per 1,000 MW wind:**
    - **as electricity = 450 GWh**
    - **as GH2 = 15,712 tons, metric @ 2,500 tons / cavern = 6 caverns**
    - **as NH3 = 87,291 tons, metric @ 60,000 tons / tank = 1.4 tanks**
  - **"Firming" energy storage, all great Plains wind:**
    - **as GH2 = 17,000 caverns @ $15M each = $264 billion**
    - **as NH3 = 5,000 tanks @ $25M each = $127 billion**

"Firming" Storage Capital Cost for ALL Great Plains Wind

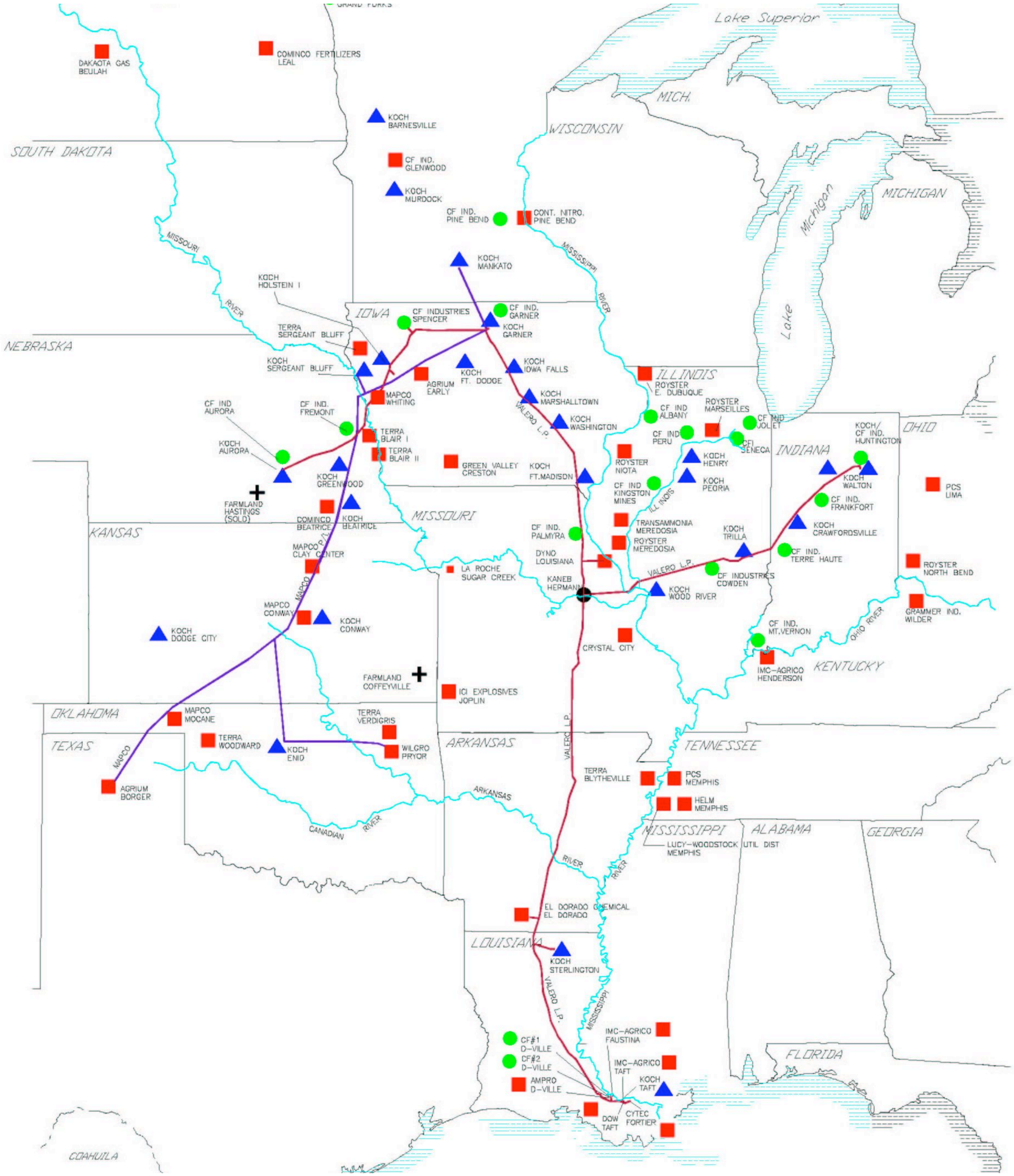
Adds VALUE: strategic, market

- Salt caverns: ~ 17,000

– Excavate:	$10 M each	$ 170 B
– Cushion gas:	$5 M each	$ 85 B
Total		**$255 B**

- NH3 tanks: ~ 5,000

– Capital	$25 M each	**$125 B**



Valero

Ammonia Pipeline and Customer Storage

Customers:

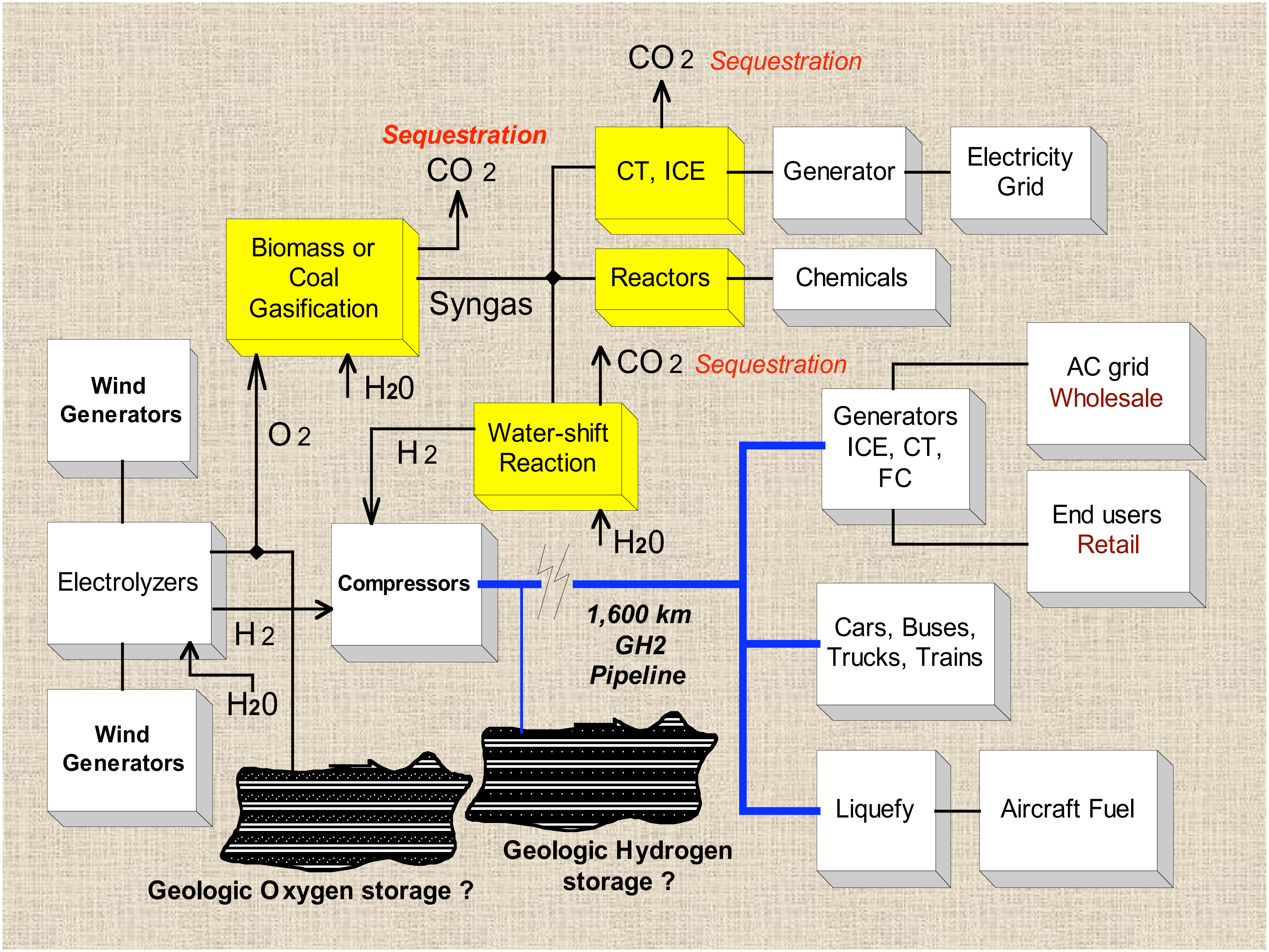
- Koch (26)
- CF Industries (20)
- Farmland (2)

Extant NH3 Storage in USA

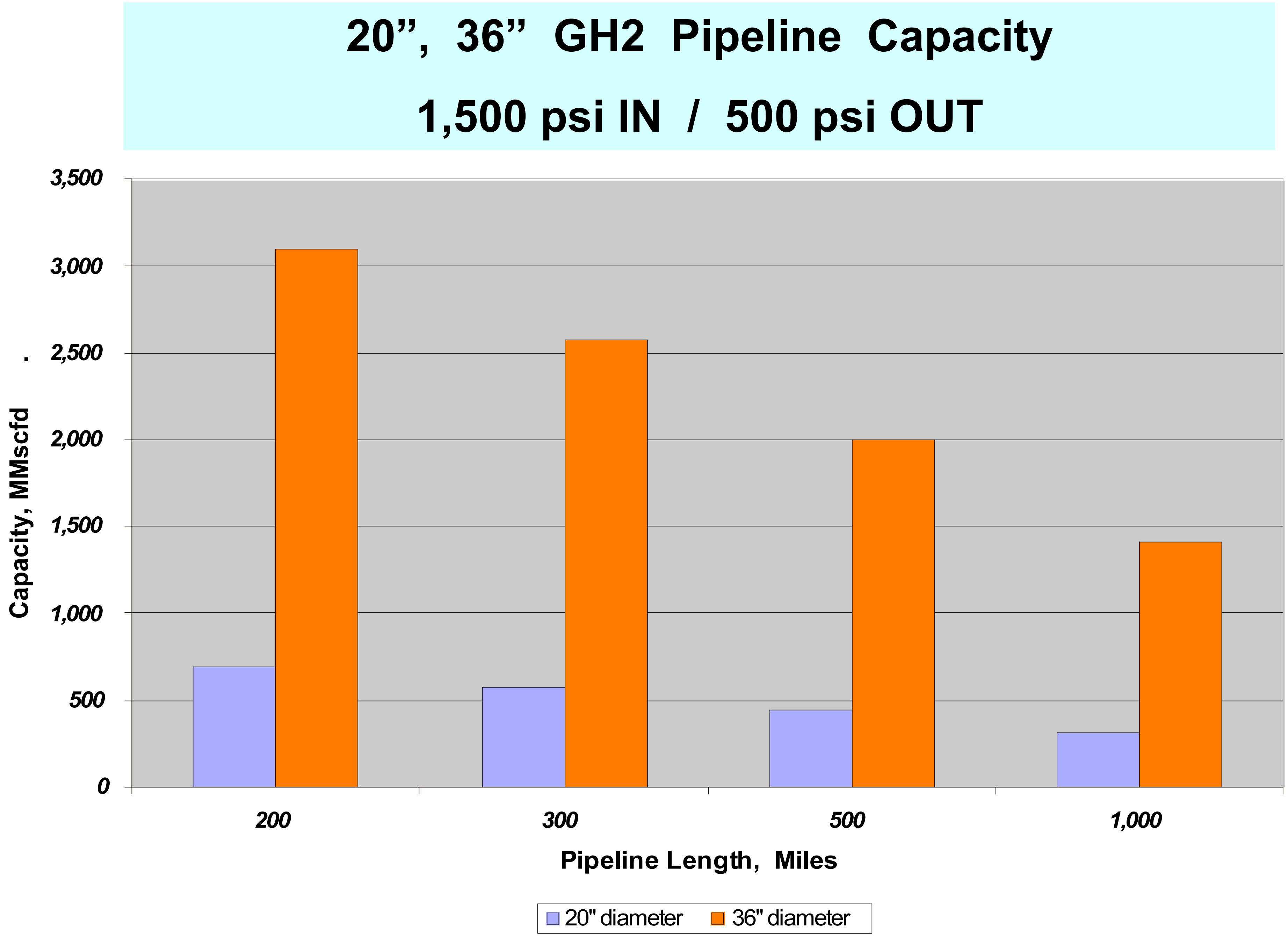
(estimated)

	Tanks	*Tons*
• **Valero**		
• **Magellan / Enterprise**		
• **Other**		
Total: 90 tanks @ 50,000 tons		**4,500,000**

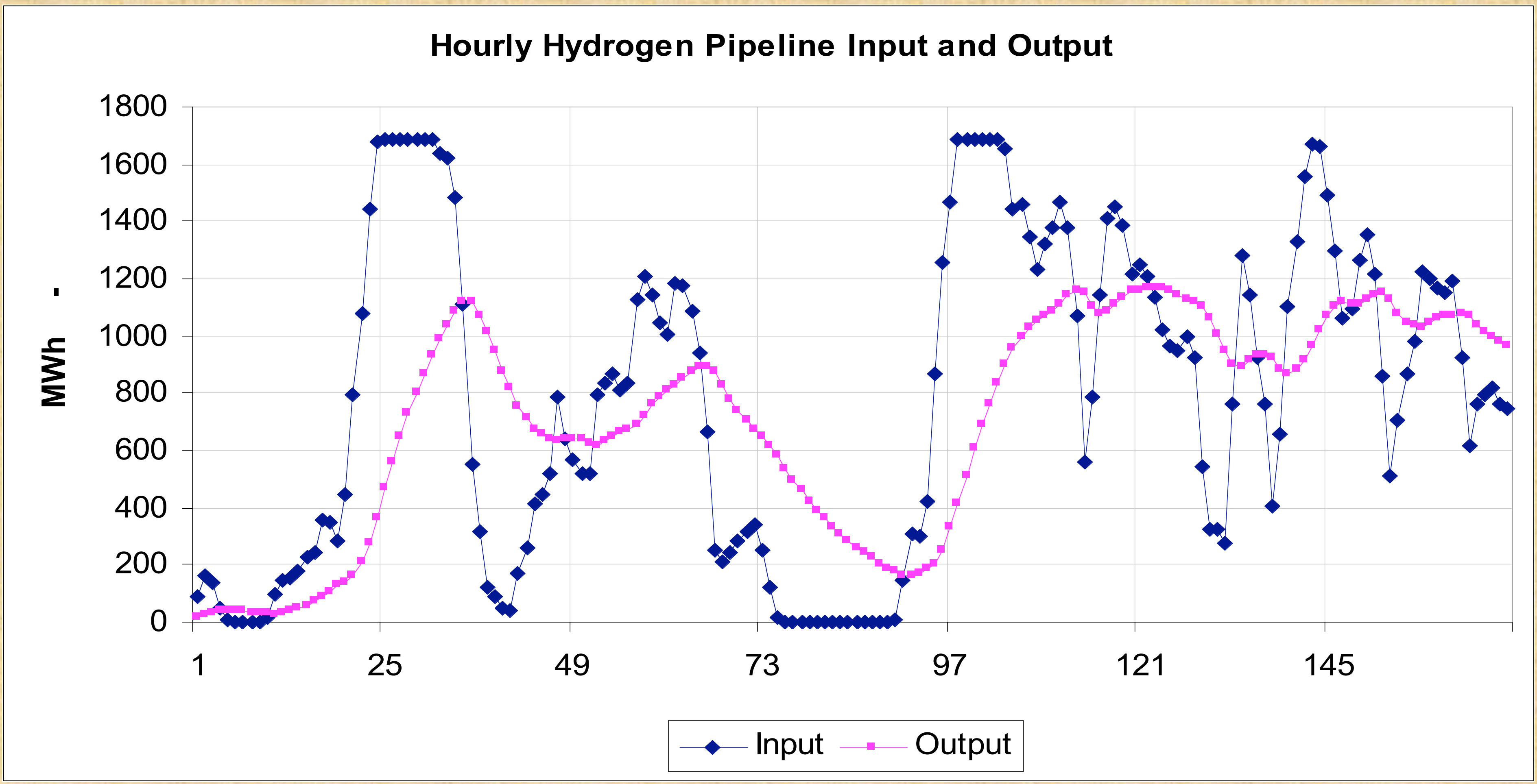
Equivalent:	**H2 (18%)**	**810,000**
	TWh	



CO 2 Sequestration
Sequestration
CO 2
CT, ICE
Generator
Electricity Grid
Biomass or Coal Gasification
Syngas
Reactors
Chemicals
H20
CO 2 Sequestration
AC grid Wholesale
Wind Generators
O 2
Water-shift Reaction
H 2
Generators ICE, CT, FC
End users Retail
Electrolyzers
Compressors
1,600 km GH2 Pipeline
Cars, Buses, Trucks, Trains
H 2
H20
H20
Wind Generators
Liquefy
Aircraft Fuel
Geologic Hydrogen storage ?
Geologic Oxygen storage ?


20", 36" GH2 Pipeline Capacity
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

Great Plains Windplant, Pipeline Hourly Output for Typical Week

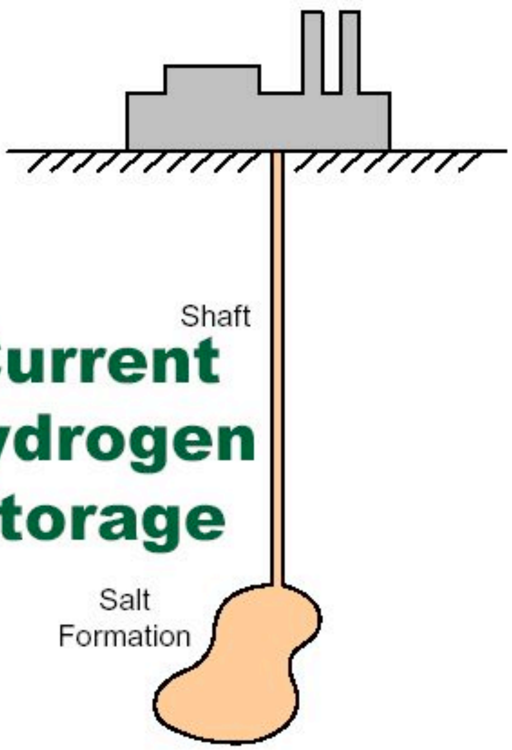


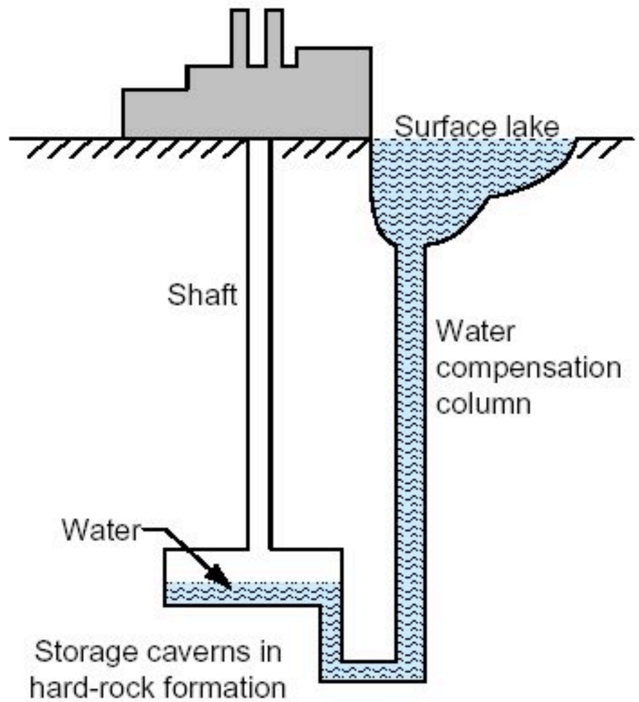
Hours

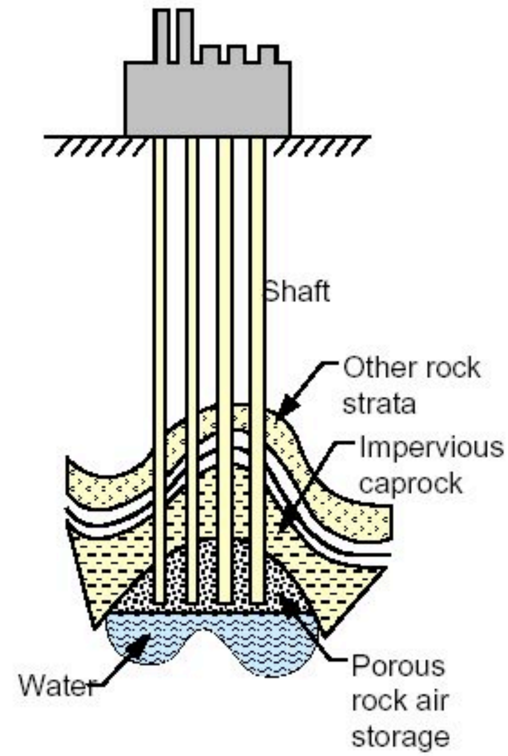
From: Charles W. Forsberg, ORNL, 17th NHA Conference, 12-16 Mar 06

Hydrogen Can Be Stored Underground At Low Costs

Current Hydrogen Storage







Natural Gas Stored Underground

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

Case 2a: No Firming

Elec → GH2 → GH2 pipeline → City gate

Capital costs

–	Electrolyzers, 1500 psi out @ $500 / kW	$ 1,000 M
–	Electrolyzer power electronics saving	$ 0 M
–	Compressors	$ 0 M
–	Pipeline, 20", 1500 psi	$ 1,000 M
	Total, without firming storage	$ 2,000 M

Case 2a: Annual costs, no firming

Elec → GH2 → GH2 pipeline → City gate

• Capital costs @ 15% CRF @ $2,000 M	$ 300 M
• Conversion and transmission losses	
– Electrolyzer conversion loss @ 20% AEP	$ 80 M
– Compression	$ 0 M
Total annual costs	$ 380 M

Annual cost per mton H2 AEP = $ 1,940

Annual cost per kg H2 AEP = $ 1.94

Case 2b: Firming

Elec → GH2 → GH2 pipeline + caverns → City gate

Capital costs

– Electrolyzers, 1500 psi out @ $500 / kW	$ 1,000 M
– Electrolyzer power electronics saving	$ 0 M
– Compressors	$ 0 M
– Pipeline, 20”, 1500 psi	$ 1,000 M
– Caverns, 12 @ $ 15M	$ 90 M
Total, with firming storage	$ 2,090 M

Incremental capital cost of caverns = 90 / 2090 = ~ 4%

Incremental capital cost of caverns, system = 90 / 4090 = ~ 2%

Case 2b: Annual costs, Firming

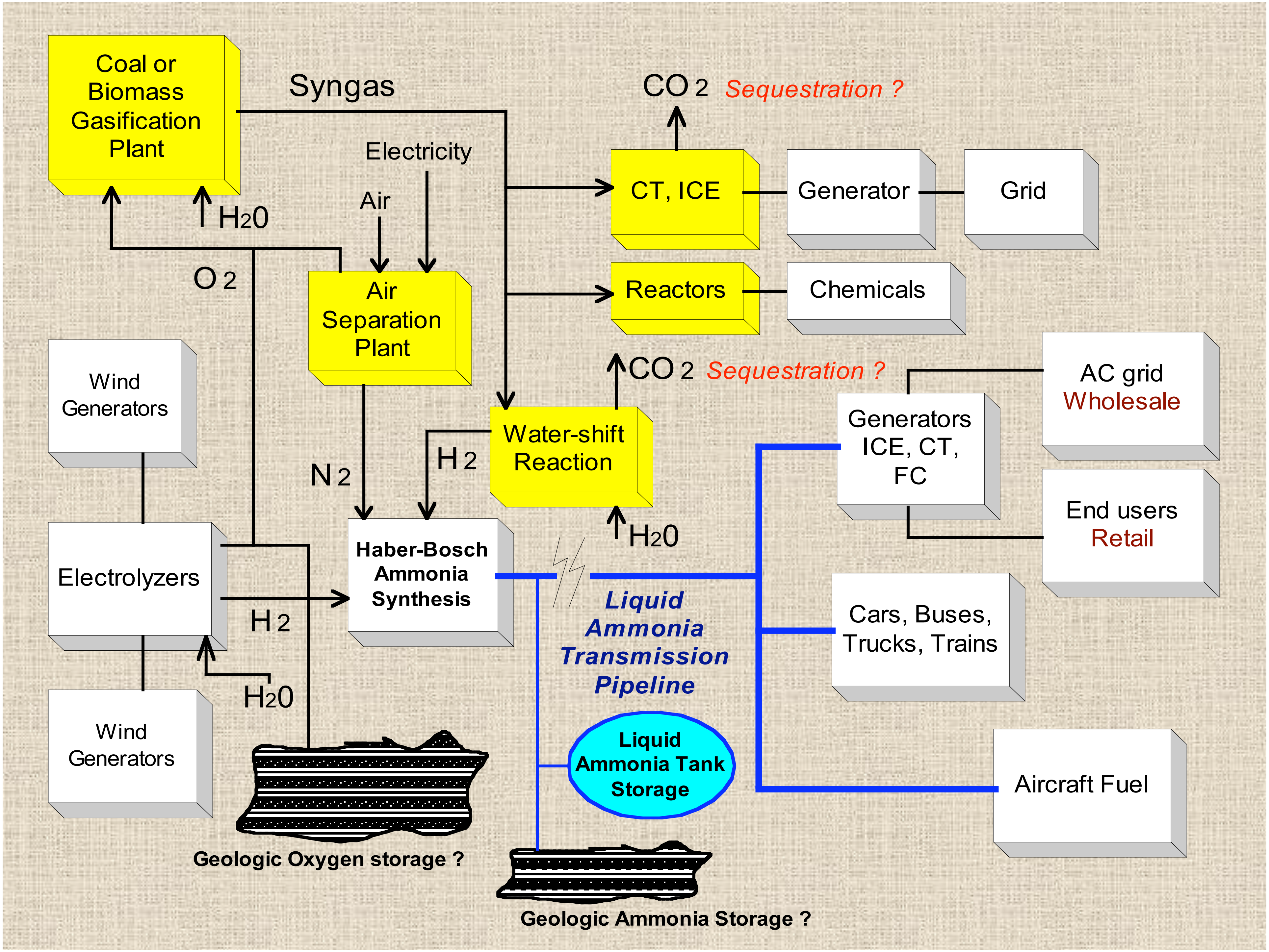
Elec → GH2 → GH2 pipeline → City gate

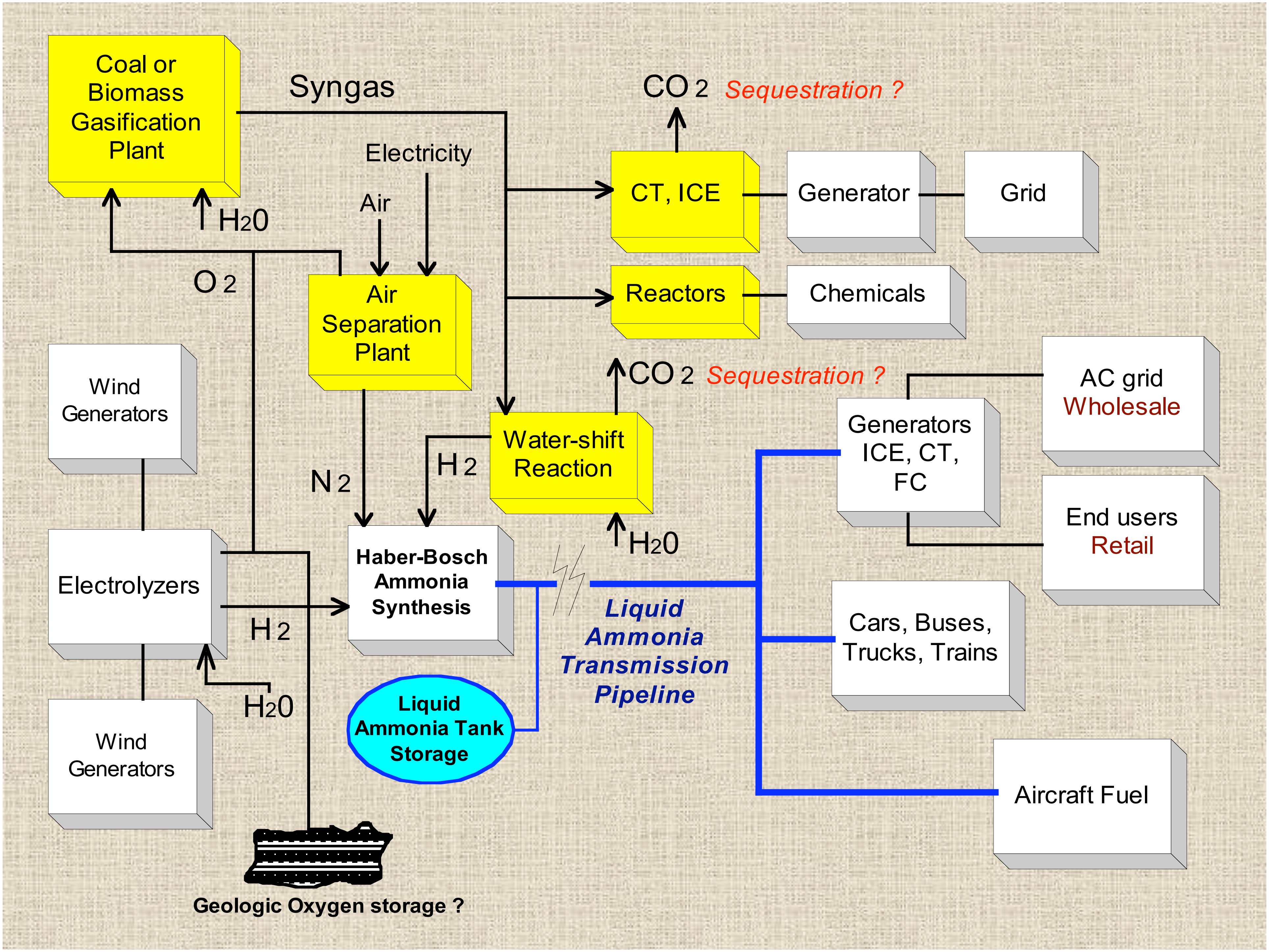
- Capital costs @ 15% CRF @ $2,090 M $ 313 M
- Conversion and transmission losses
  - Electrolyzer conversion loss @ 20% AEP $ 80 M
  - Compression $ 0 M
  - Caverns in / out $ 0 M

Total annual costs $ 393 M

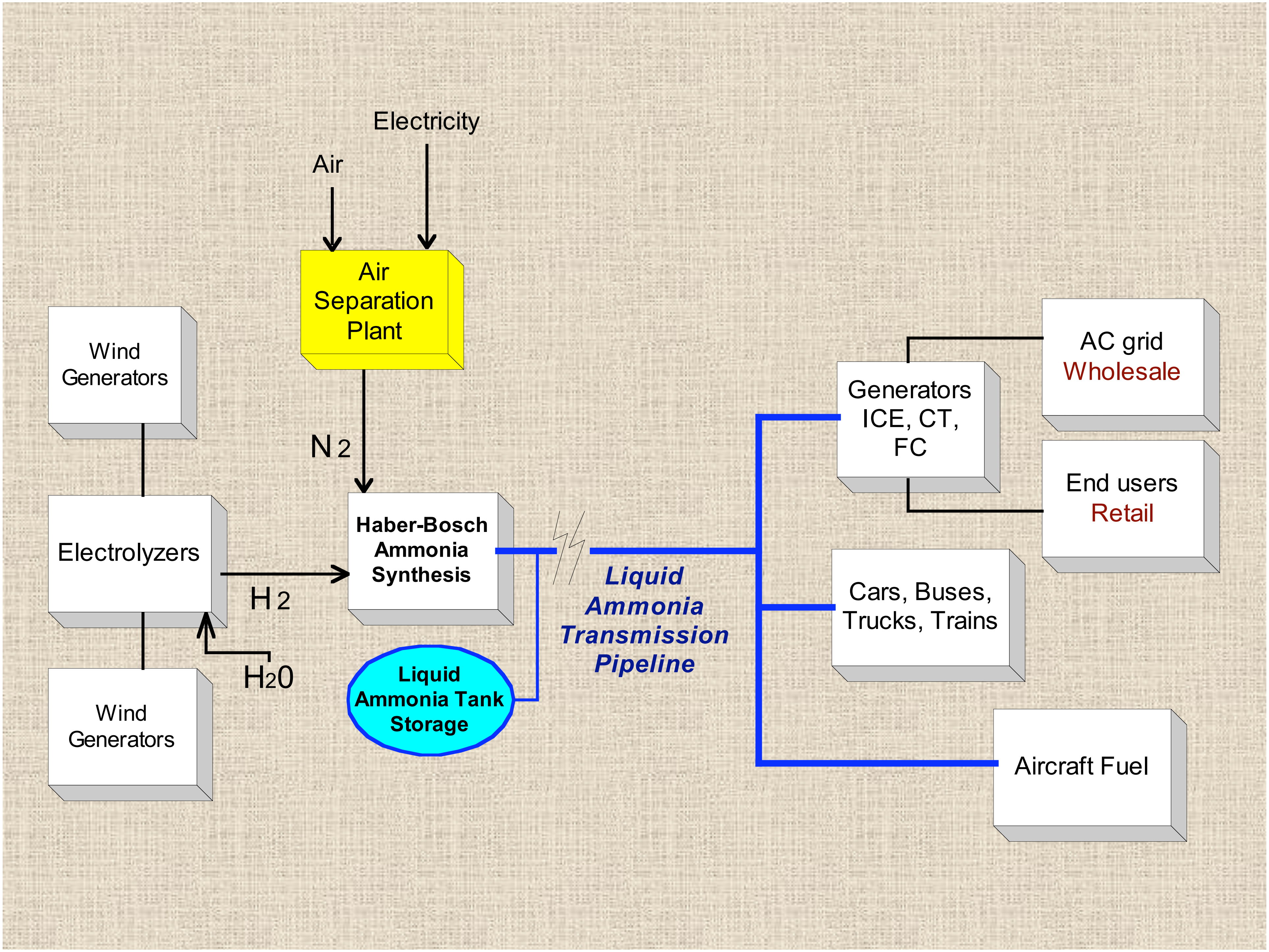
Annual cost per ton H2 = $ 2,010

Annual cost per kg H2 = $ 2.01


Coal or Biomass Gasification Plant
Syngas
CO 2
Sequestration ?
Electricity
Air
H20
O 2
CT, ICE
Generator
Grid
Air Separation Plant
Reactors
Chemicals
Wind Generators
CO 2
Sequestration ?
AC grid
Wholesale
Generators ICE, CT, FC
Water-shift Reaction
H 2
N 2
End users
Retail
H20
Electrolyzers
Haber-Bosch Ammonia Synthesis
Liquid Ammonia Transmission Pipeline
H 2
Cars, Buses, Trucks, Trains
H20
Wind Generators
Liquid Ammonia Tank Storage
Aircraft Fuel
Geologic Oxygen storage ?
Geologic Ammonia Storage ?



Coal or Biomass Gasification Plant
Syngas
CO_2 Sequestration ?
Electricity
Air
H_2O
CT, ICE
Generator
Grid
O_2
Air Separation Plant
Reactors
Chemicals
Wind Generators
CO_2 Sequestration ?
AC grid Wholesale
Generators ICE, CT, FC
Water-shift Reaction
H_2
N_2
End users Retail
H_2O
Electrolyzers
Haber-Bosch Ammonia Synthesis
Liquid Ammonia Transmission Pipeline
H_2
Cars, Buses, Trucks, Trains
H_2O
Liquid Ammonia Tank Storage
Wind Generators
Aircraft Fuel
Geologic Oxygen storage ?


Electricity
Air
Air Separation Plant
Wind Generators
N 2
Electrolyzers
Haber-Bosch Ammonia Synthesis
H 2
H20
Wind Generators
Liquid Ammonia Tank Storage
Liquid Ammonia Transmission Pipeline
Generators ICE, CT, FC
AC grid Wholesale
End users Retail
Cars, Buses, Trucks, Trains
Aircraft Fuel


Ammonia Plant 1,500 MTPD
Indonesia, 2002 Mitsubishi

2,000 MW windplant output

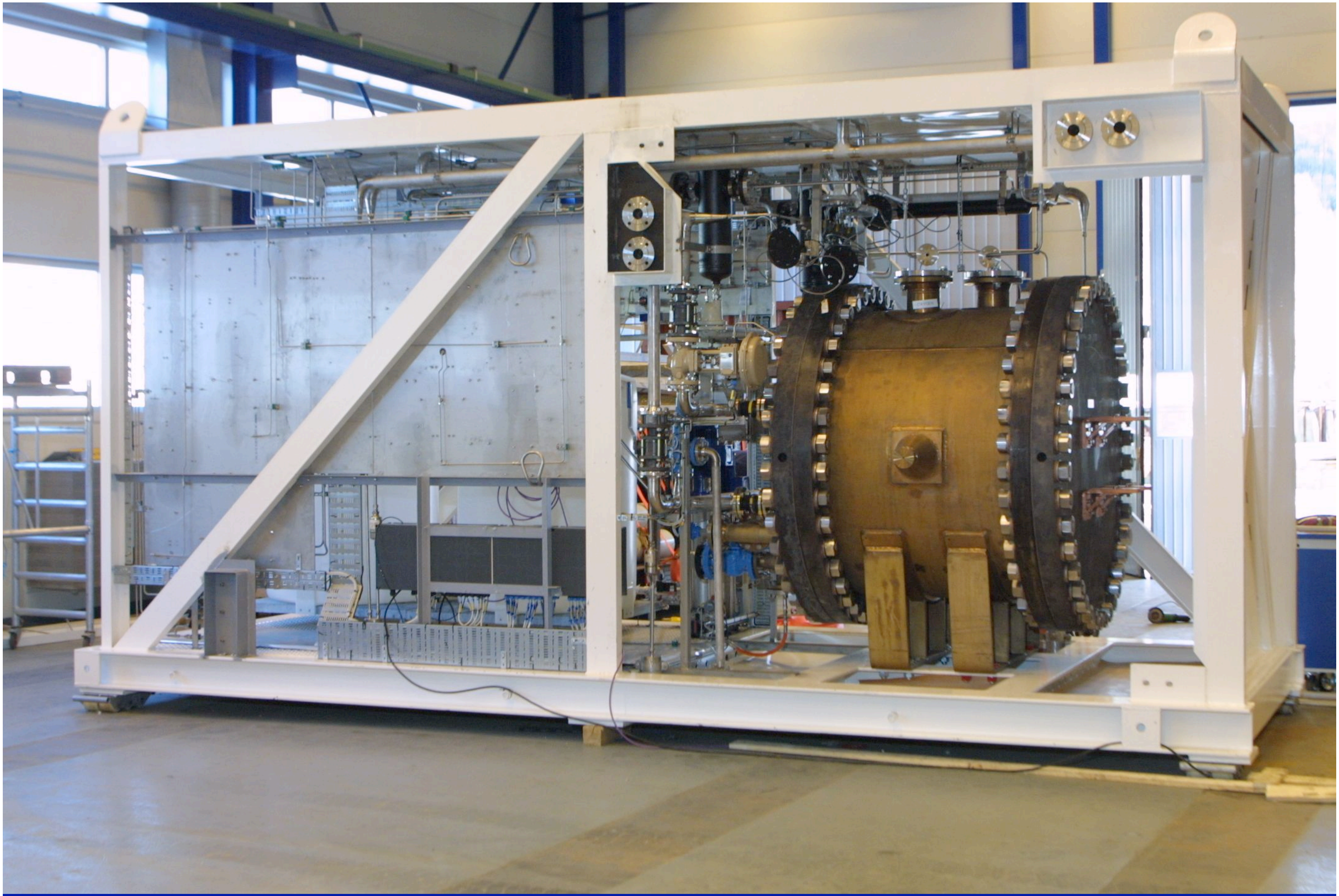
100 % Capacity Factor

	MWh/day	tons/hr	tons/day	tons/yr
As electricity	48,000			
As H2		311	1,342	489,776
As NH3		1,726	7,455	2,720,980
10" NH3 pipeline capacity as NH3		150	3,600	1,314,000
10" NH3 pipeline capacity as H2		27	648	236,520

40 % Capacity Factor

	MWh/day	tons/hr	tons/day	tons/yr
As electricity	19,200			
As H2		124	537	195,910
As NH3		690	2,982	1,088,392
10" NH3 pipeline capacity as NH3		60	1,440	525,600
10" NH3 pipeline capacity as H2		11	259	94,608

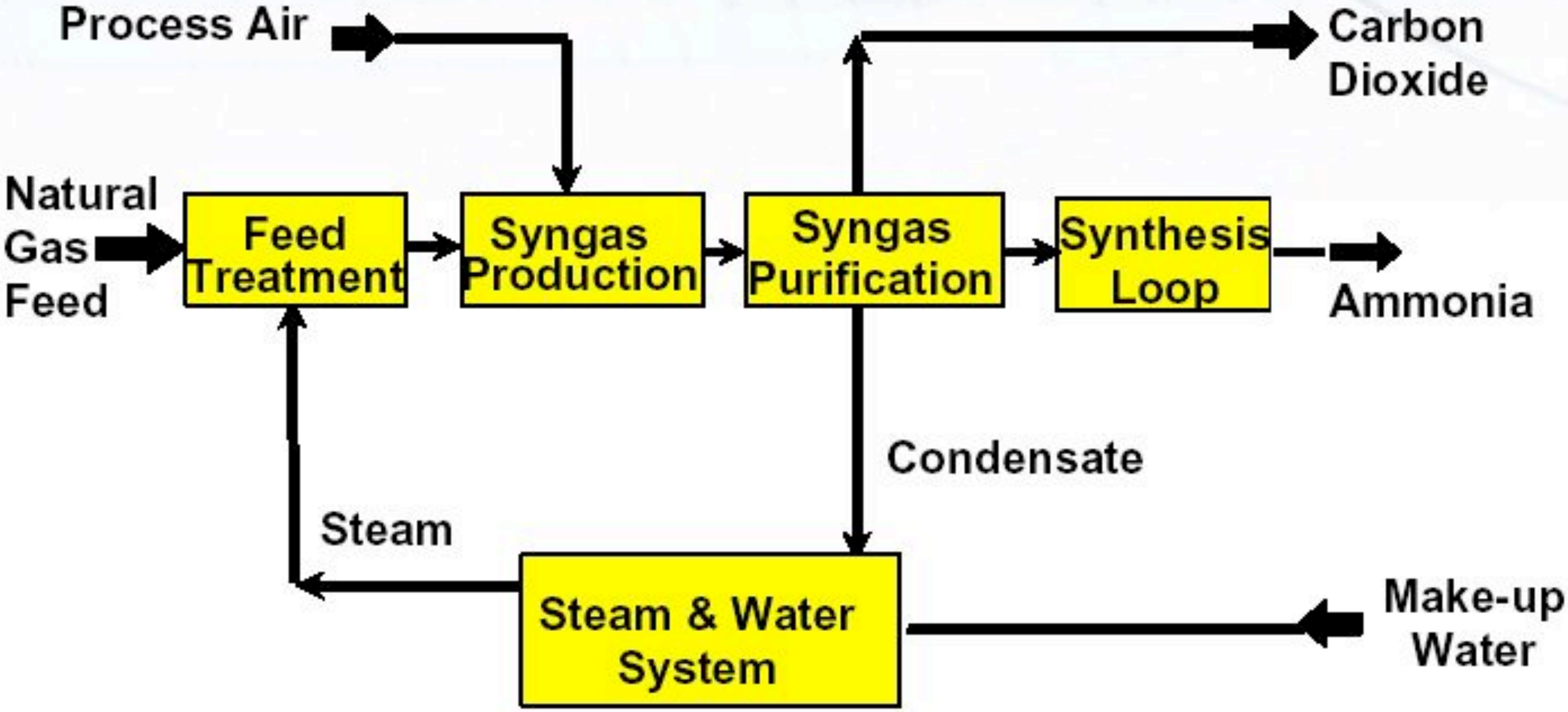
Norsk Hydro Electrolyzers 2 MW each



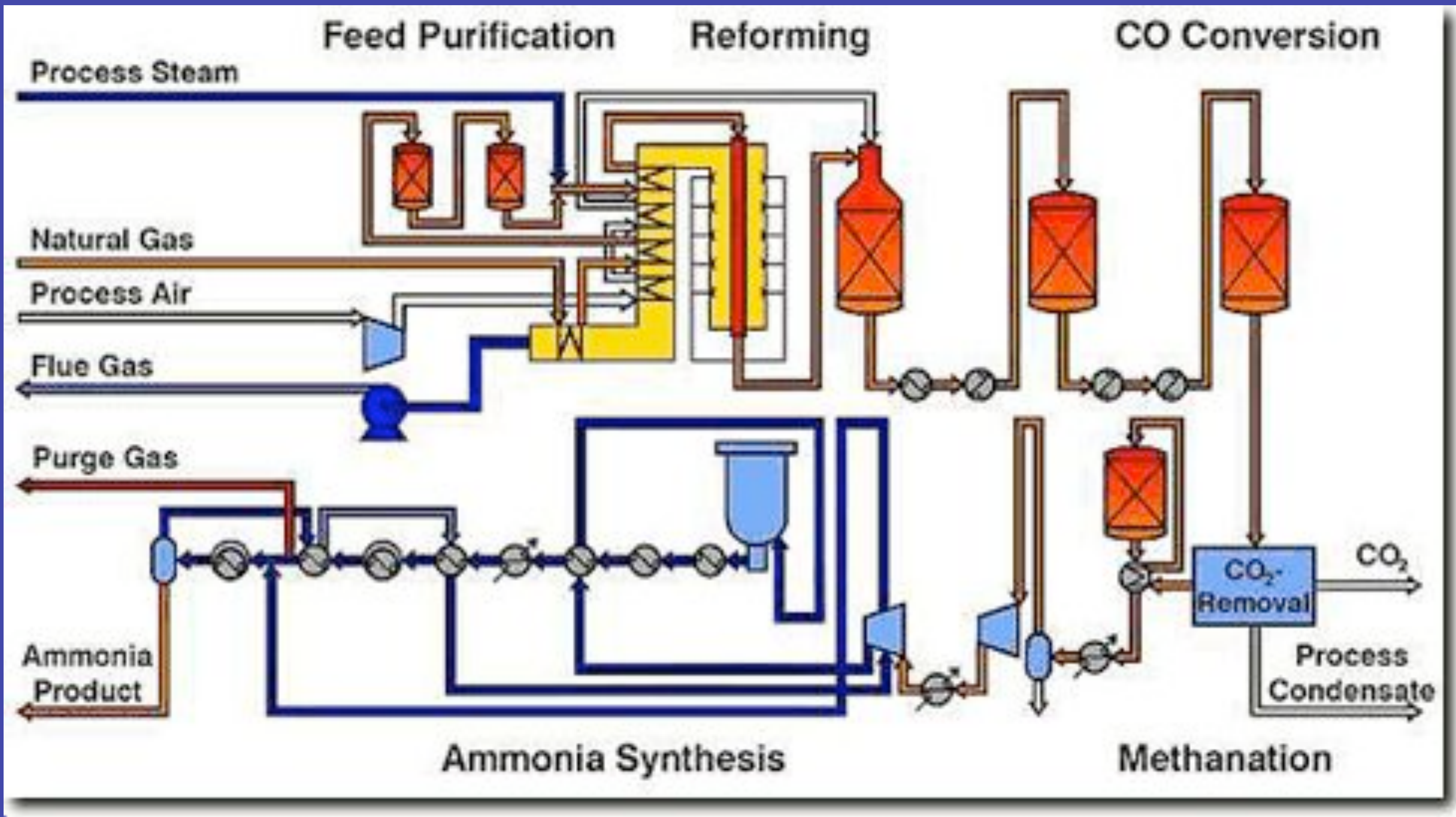
Norsk Hydro electrolyzer, KOH type

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

Sections in an Ammonia Plant



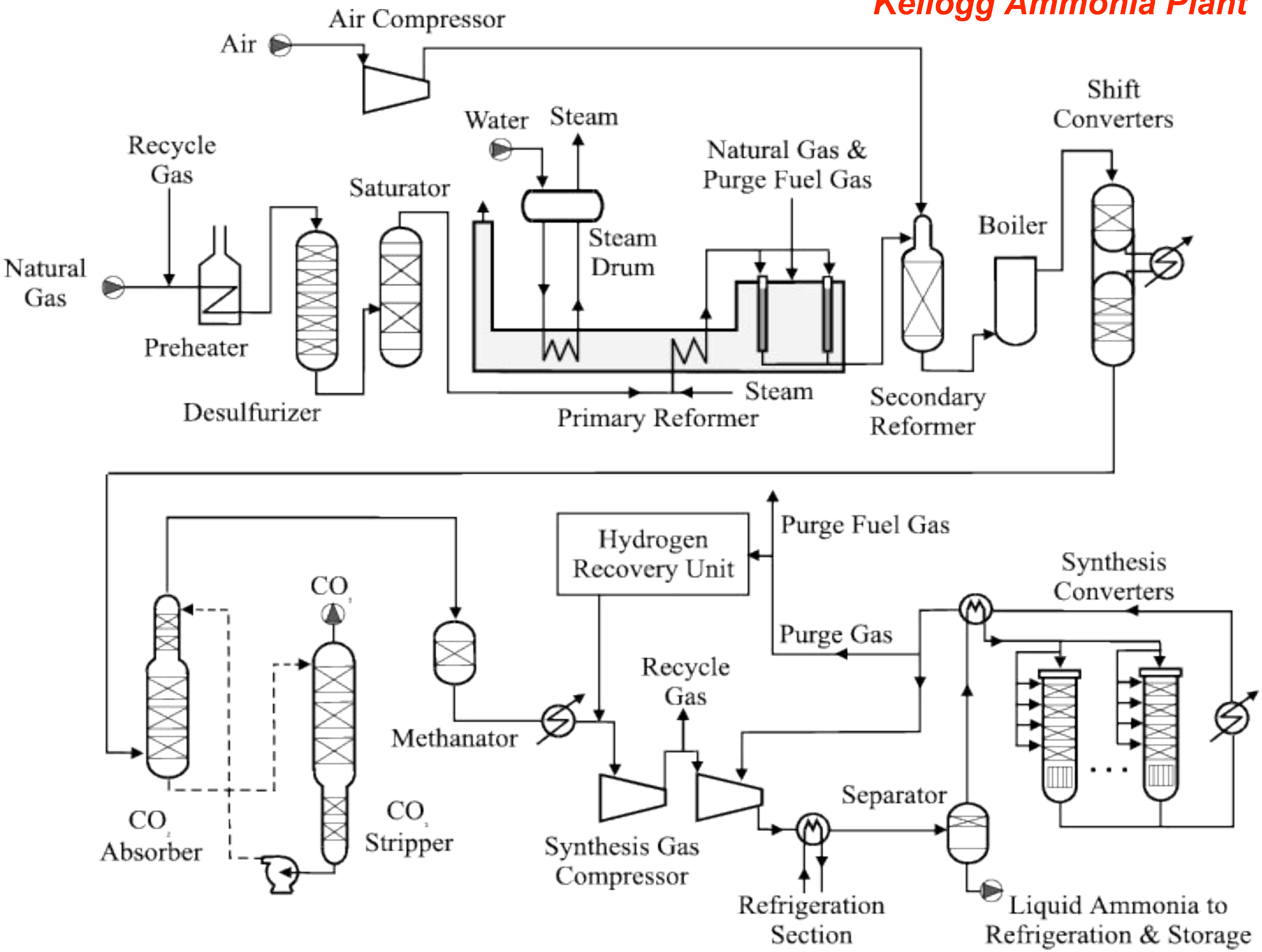
KBR
Energy and Chemicals



Natural Gas to Ammonia Plant

"Flue Gas": CO2

Kellogg Ammonia Plant



NH3 Synthesis Plant Cost

3,000 tpd NH3 = 675 tpd H2 @ 80% efficiency: Need TWO plants for 2,000 MW windplant

- Industry sources:
  - 2,000 mtd NH3, NG source, all costs $500M
  - 2,200 mtd NH3, NG source, all cocts $466M
  - 140 mmscfd H2 plant costs ~ $200M
  - NG conversion, all processes: ~ 60% of total capital cost
  - Delete NG conversion, must add N2 plant (ASP) (estim: $75M)
- 3,000 tpd NH3 plant, from renewable-source H2, costs:

– NG conversion (SMR +)	$ 0
– H-B reactor	$ 225 M
– Balance Of Plant	$ 75 M
– Add Air Separation Plant, for N2	$ 75 M
– Add H2 compressor (30 → 100 bar)	$ 5 M
TOTAL	**$ 380 M**
TWO PLANTS	**$ 760 M**

10” NH3 liquid pipeline cost

- Industry sources, all costs:
  - $750 – 900 K per mile, 10”,
    “uncongested area”
  - $250K per mile “small diameter”
- 1,000 mile pipeline @ 10” = $ 800M

Case 3a: No firming

Elec → GH2 → NH3 → Liquid Pipeline → City gate

Capital costs

–	Electrolyzers, 450 psi out @ $350 / kWe	$ 700 M
–	Electrolyzer power electronics saving	$ 0 M
–	H2 compressors	$ 10 M
–	NH3 synthesis plants (2)	$ 750 M
–	Pipeline	$ 800 M
–	Pipeline pumping	$ 6 M
–	Pipeline infrastructure	$ 2 M
Total, without firming storage		$ 2,268 M

Case 3a: Annual costs, no firming

Elec → GH2 → NH3 → Liquid Pipeline → City gate

- Capital costs @ 15% CRF @ $ 2,268 M — $ 340 M

- Conversion and transmission losses
  - Electrolyzer conversion loss @ 20% AEP — $ 80 M
  - Compression energy — $ 1 M

  - NH3 synthesis plant — $ 80 M
  - Pipeline pumping energy — $ 2 M
  - Pipeline misc O&M — $ 1 M

Total annual costs — $ 504 M

Annual cost per mton H2 = $ 2,572

Annual cost per kg H2 = $ 2.57

Case 3b: Firming storage, tanks

Elec → GH2 → NH3 → Liquid Pipeline + tanks → City gate

Capital costs

– Electrolyzers, 450 psi out @ $350 / kWe	$ 700 M
– Electrolyzer power electronics saving	$ 0 M
– H2 compressors	$ 10 M
– NH3 synthesis plant	$ 750 M
– Pipeline	$ 800 M
– Pipeline pumping	$ 8 M
– Pipeline infrastructure	$ 2 M
– Tanks: 4 tanks @ $ 25 M	$ 100 M
Total, with firming storage	$ 2,370 M

Incremental capital cost of caverns = 90 / 2370 = ~ 4%

Incremental capital cost of caverns, system = 90 / 4370 = ~ 2%

Case 3b: Annual costs, Firming storage, tanks

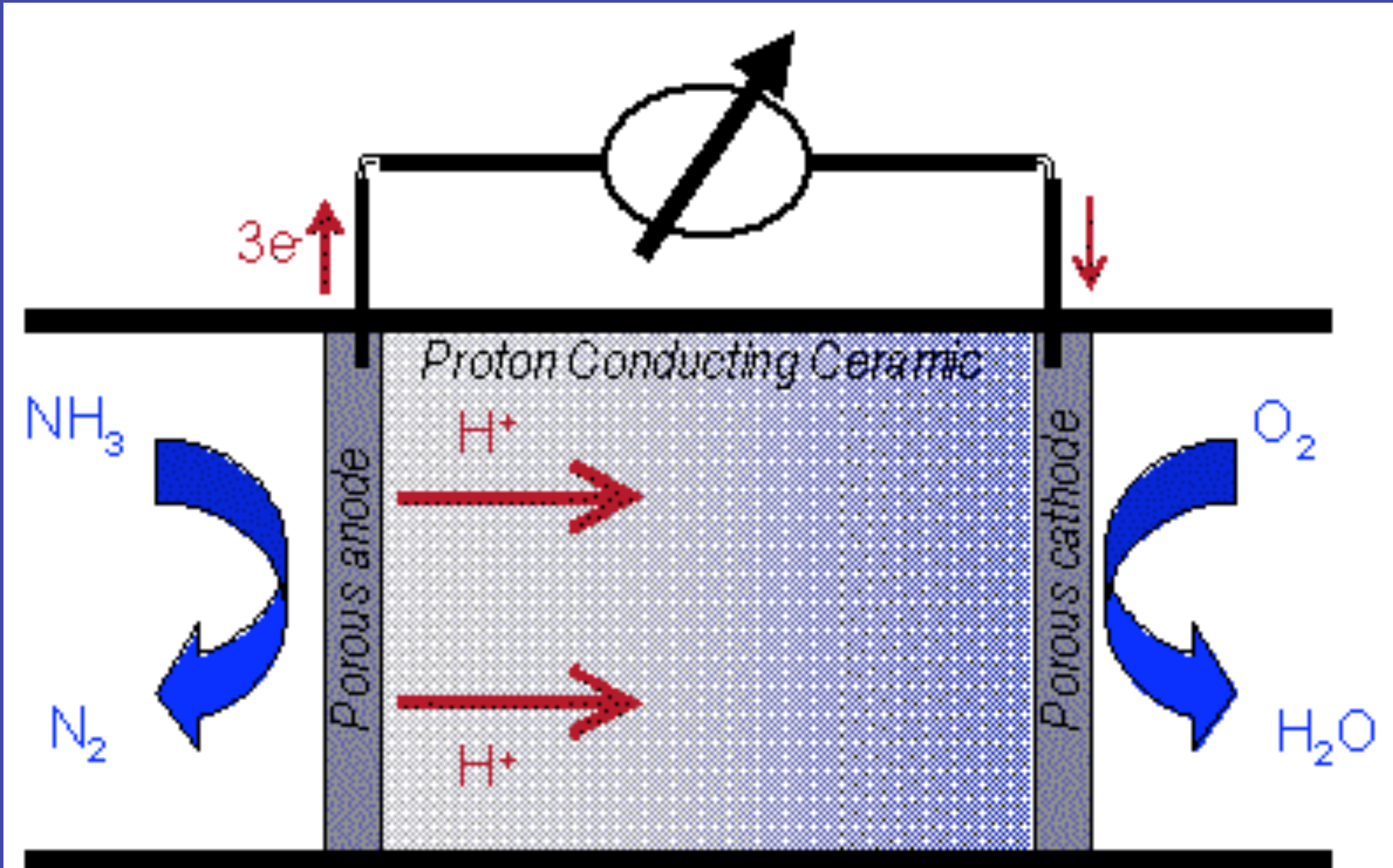
Elec → GH2 → NH3 → Liquid Pipeline + tanks → City gate

- **Capital costs @ 15% CRF @ $ 2,370** — **$ 356 M**
- **Conversion and transmission losses**
  - **Electrolyzer conversion loss @ 20% AEP** — **$ 80 M**
  - **Compression** — **$ 1 M**
  - **NH3 synthesis plants (2)** — **$ 80 M**
  - **Pipeline pumping energy** — **$ 2 M**
  - **Pipeline misc O&M** — **$ 1 M**
  - **Tank in / out** — **$ 0 M**

Total annual costs — **$ 520 M**

Annual cost per ton H2 = $ 2,650

Annual cost per kg H2 = $ 2.65



Direct Ammonia Fuel Cell using PCC Electrolyte

Case 4a: No firming

Elec → GH2 → NH3 → Liquid Pipeline → Reform to H2

Capital costs

– Electrolyzers, 450 psi out @ $350 / kWe	$	700 M
– Electrolyzer power electronics saving	$	0 M
– H2 compressors	$	10 M
– NH3 synthesis plants (2)	$	750 M
– Pipeline	$	800 M
– Pipeline pumping	$	8 M
– Pipeline infrastructure	$	2 M
– NH3 reformers (dissociate; crack)	$	418 M
Total, without firming storage	$	2,688 M

Case 4a: Annual costs, no firming

Elec → GH2 → NH3 → Liquid Pipeline → Reform to H2

- **Capital costs @ 15% CRF @ $ 2,688 M** — **$ 403 M**
- **Conversion and transmission losses**
  - **Electrolyzer conversion loss @ 20% AEP** — **$ 80 M**
  - **Compression energy** — **$ 1 M**
  - **NH3 synthesis plant** — **$ 80 M**
  - **Pipeline pumping energy** — **$ 2 M**
  - **Pipeline misc O&M** — **$ 1 M**
  - **Reformer conversion loss @ 15% AEP** — **$ 60 M**

Total annual costs — **$ 627 M**

Annual cost per mton H2 = $ 3,200

Annual cost per kg H2 = $ 3.20

Case 4b: Firming storage, tanks

Elec → GH2 → NH3 → Liquid Pipeline → Reform to H2

Capital costs

–	Electrolyzers, 450 psi out @ $350 / kWe	$ 700 M
–	Electrolyzer power electronics saving	$ 0 M
–	H2 compressors	$ 10 M
–	NH3 synthesis plant	$ 750 M
–	Pipeline	$ 800 M
–	Pipeline pumping	$ 8 M
–	Pipeline infrastructure	$ 2 M
–	Tanks: 4 tanks @ $ 25 M	$ 100 M
–	Reformers (dissociate, crack)	$ 418 M
Total, with firming storage		$ 2,788 M

Case 4b: Annual costs, Firming storage, tanks

Elec → GH2 → NH3 → Liquid Pipeline → Reform to H2

- **Capital costs @ 15% CRF @ $ 2,788 M — $ 418 M**
- **Conversion and transmission losses**
  - **Electrolyzer conversion loss @ 20% AEP — $ 80 M**
  - **Compression energy — $ 1 M**
  - **NH3 synthesis plant — $ 80 M**
  - **Pipeline pumping energy — $ 2 M**
  - **Pipeline misc O&M — $ 1 M**
  - **Reformer conversion loss @ 15% AEP — $ 60 M**

Total annual costs — $ 642 M

Annual cost per mton H2 = $ 3,277

Annual cost per kg H2 = $ 3.28

Conclusions: Cases 1 - 4

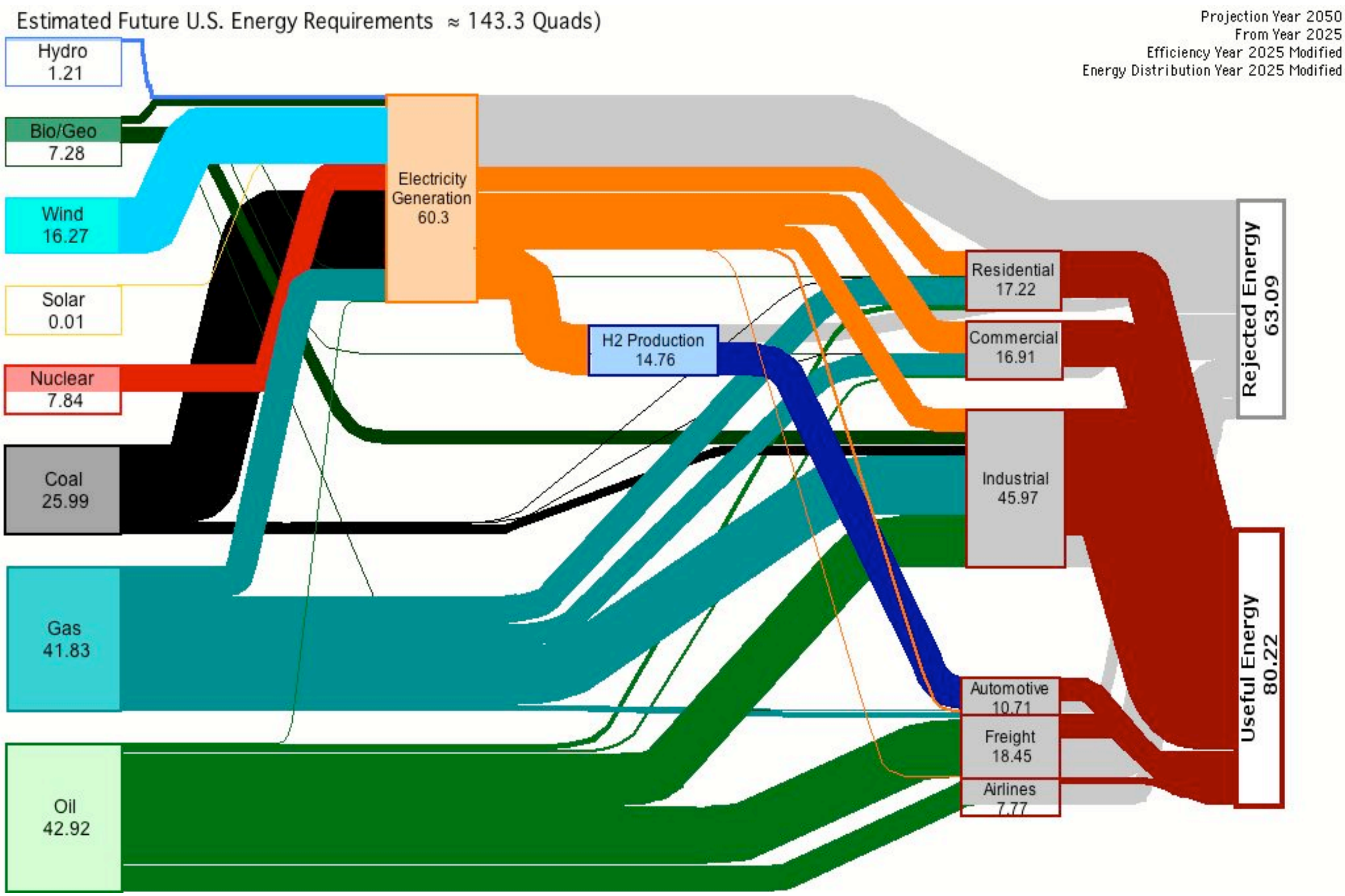
Conversion + transmission costs per kg H2

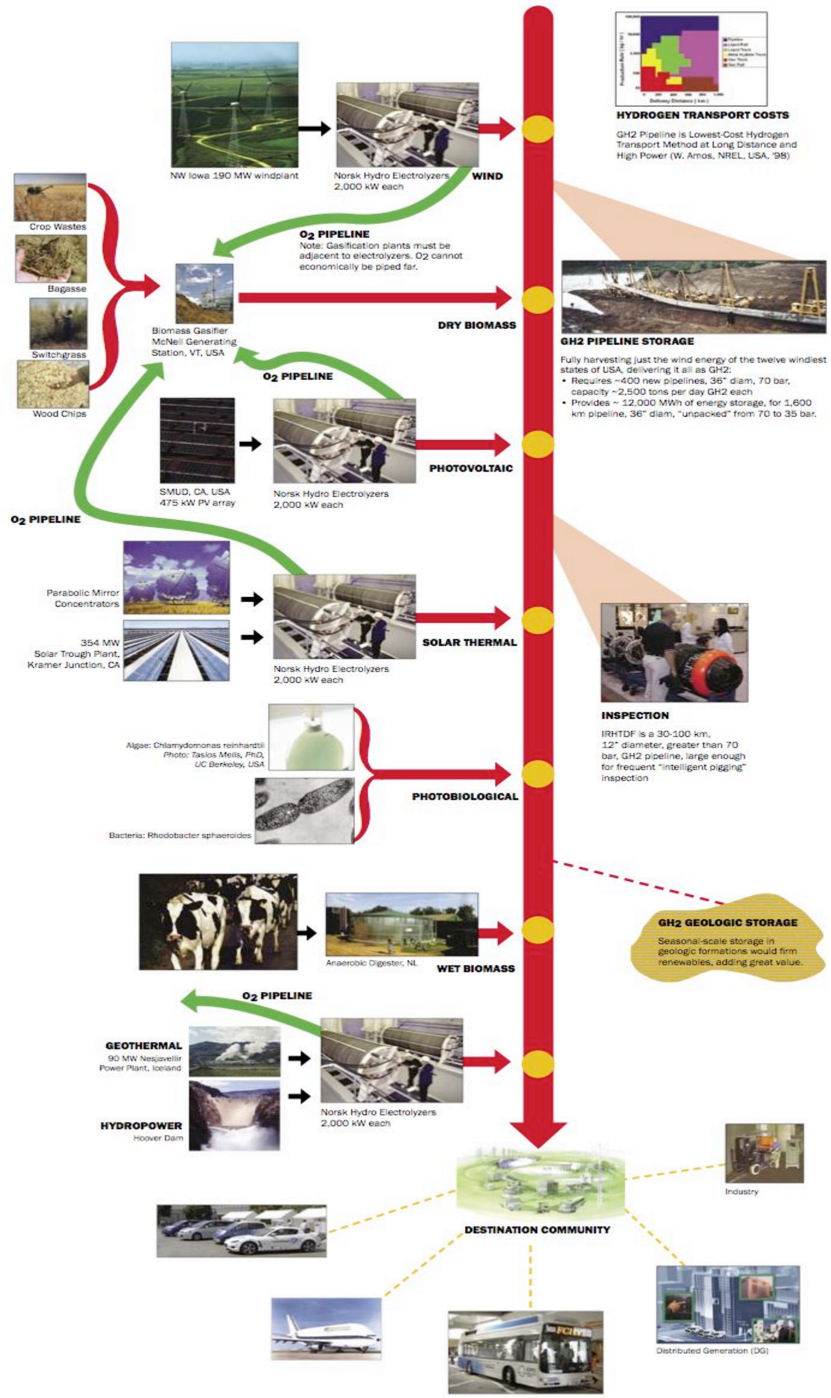
	No firming	**Firmed**
1: HVDC electricity	$ 0.54	----
2: GH2 pipeline	$ 1.94	$ 2.01
3: NH3 pipeline, deliver NH3	$ 2.57	$ 2.65
4: NH3 pipeline, deliver GH2	$ 3.20	$ 3.28

Conclusions

- Electricity costs less; no storage
- CF problem: size NH3 synthesis for peak windplant output? What do with excess?
- NH3 firming storage tanks cost less capital than GH2 caverns, per unit energy: both good investments.

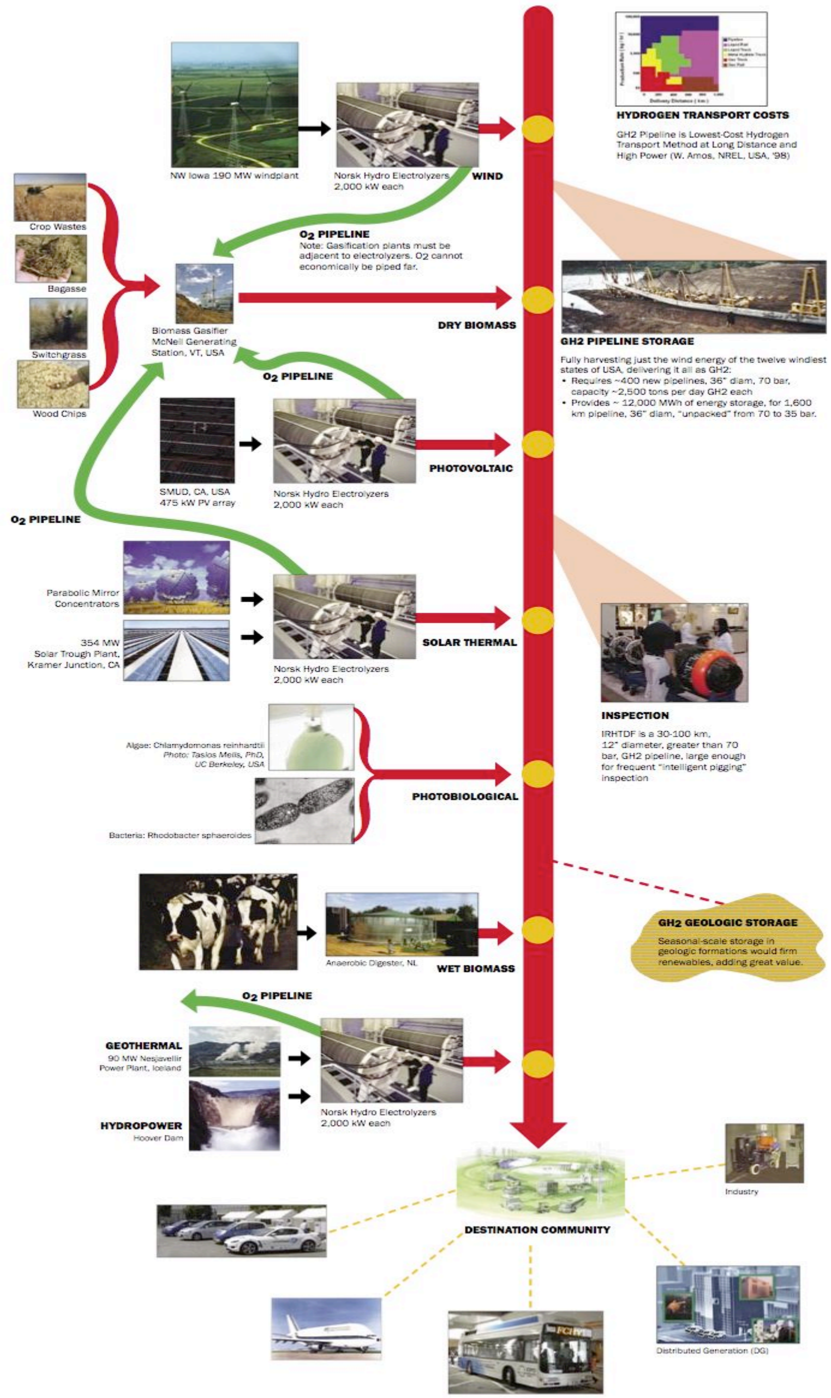
USDOE-EIA: Estimated 2050 energy use (H_2 fleet using wind electrolysis)





Pilot-scale Hydrogen Pipeline System: Renewables

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



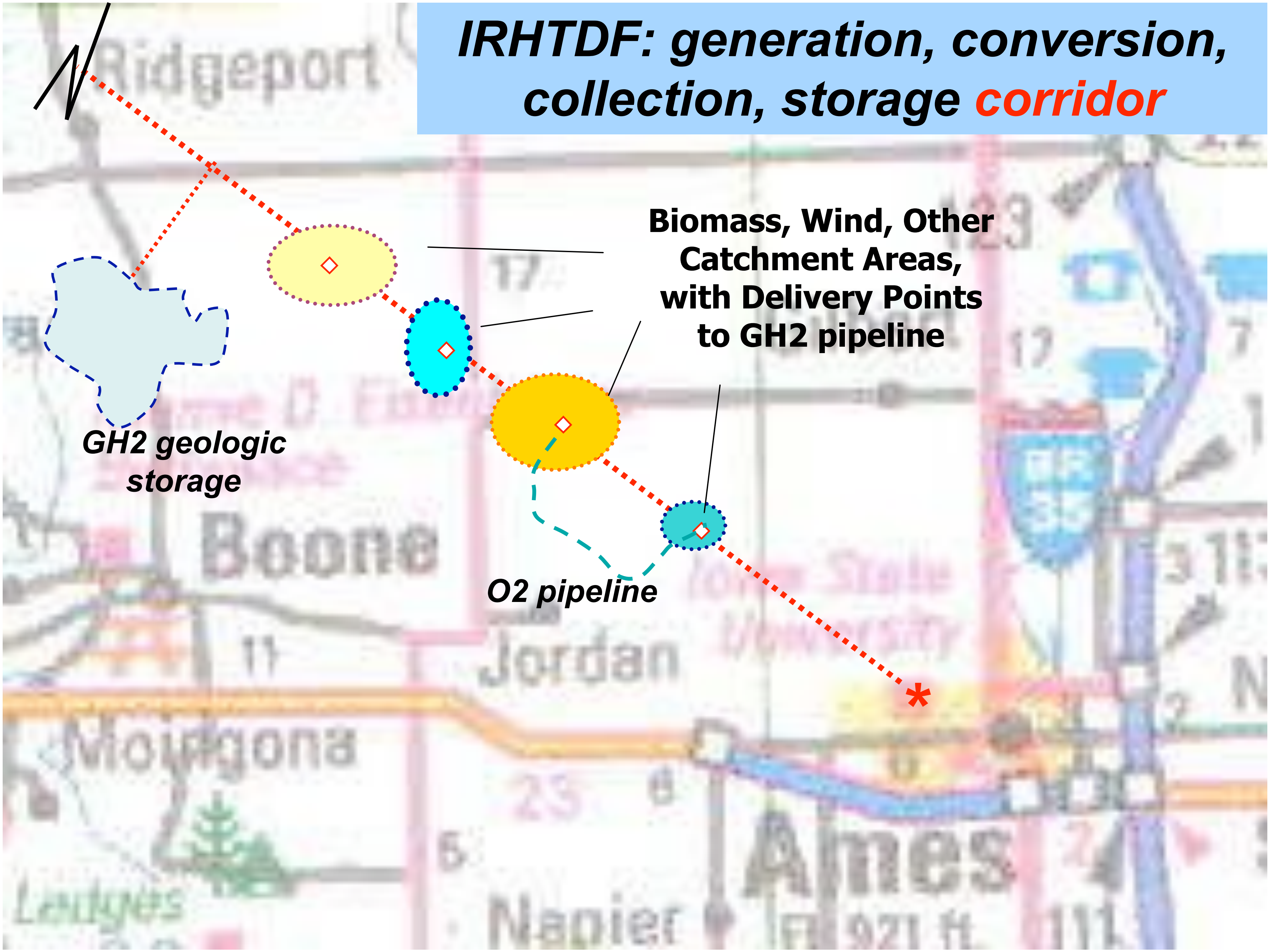
International Renewable Hydrogen Transmission Demonstration Facility

(IRHTDF)

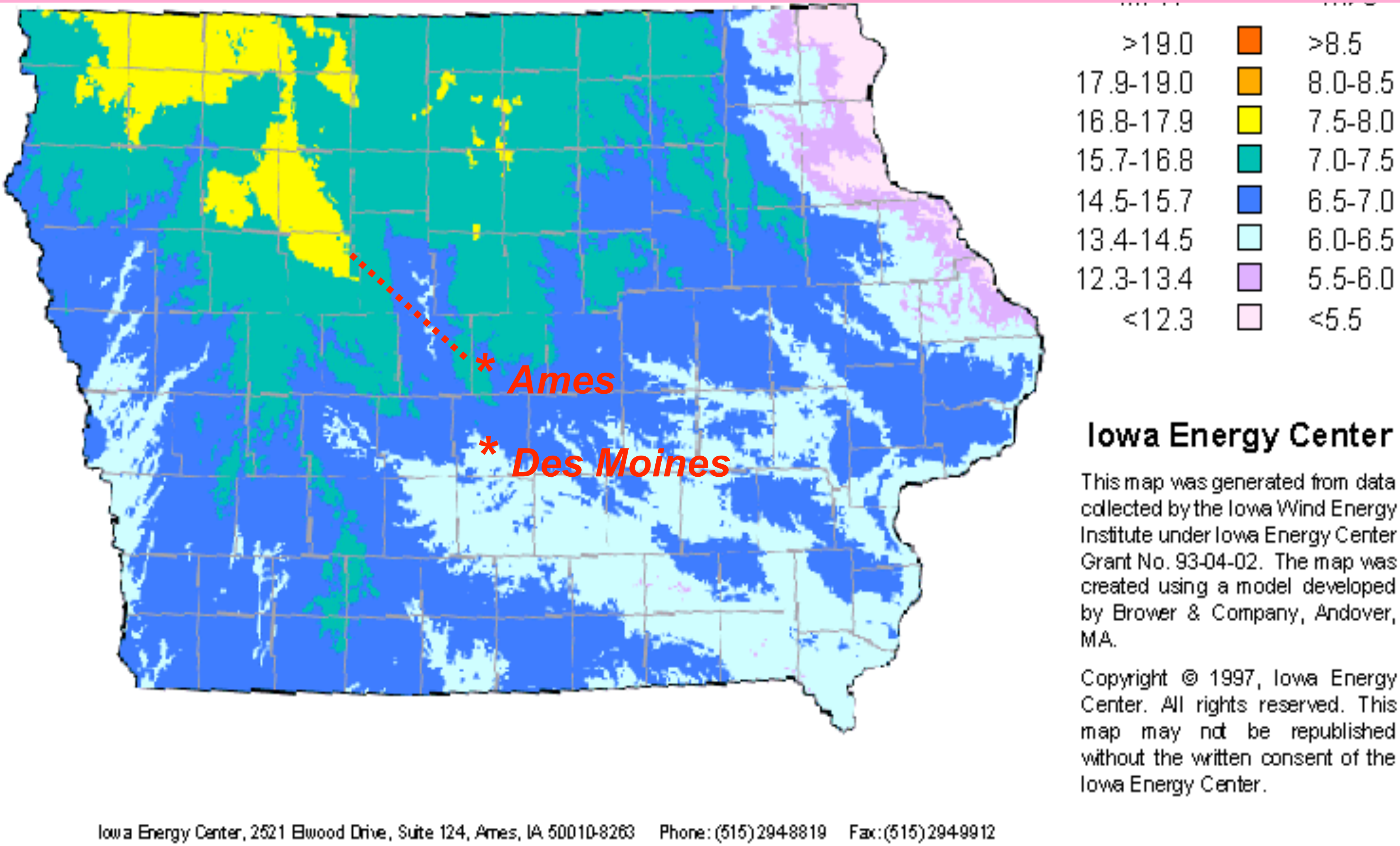
Pilot plant

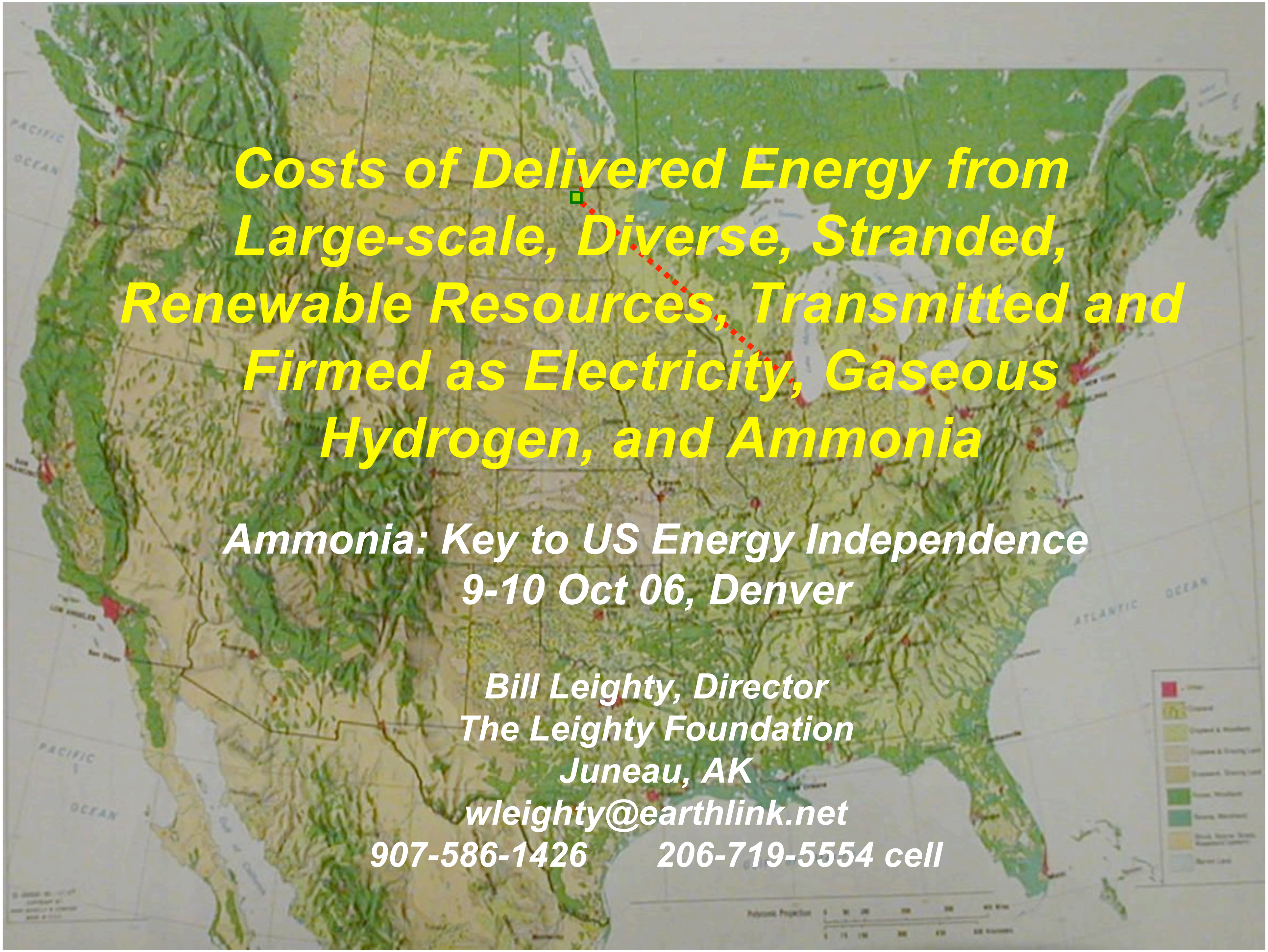
Global opportunity: IPHE project

IRHTDF: generation, conversion, collection, storage corridor



IRHTDF
International Renewable Hydrogen Transmission Demonstration Facility

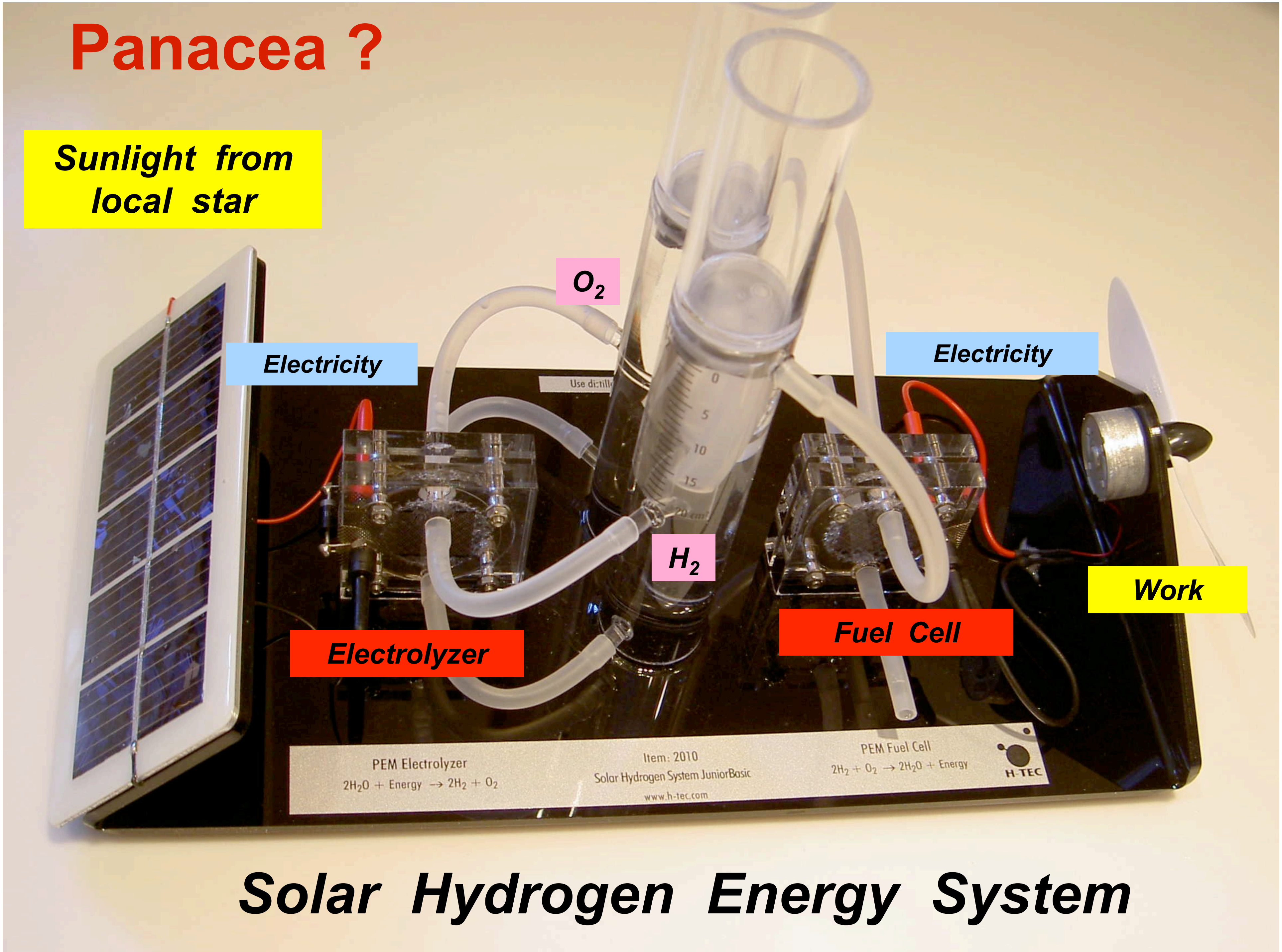




Costs of Delivered Energy from Large-scale, Diverse, Stranded, Renewable Resources, Transmitted and Firmed as Electricity, Gaseous Hydrogen, and Ammonia

Ammonia: Key to US Energy Independence
9-10 Oct 06, Denver

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


Panacea ?
Sunlight from local star
Electricity
O_2
H_2
Electricity
Work
Electrolyzer
Fuel Cell
PEM Electrolyzer
$2H_2O + Energy \rightarrow 2H_2 + O_2$
Item: 2010
Solar Hydrogen System JuniorBasic
www.h-tec.com
PEM Fuel Cell
$2H_2 + O_2 \rightarrow 2H_2O + Energy$
H-TEC
Solar Hydrogen Energy System

Hydrogen's principal value

- NOT fuel cell cars
- Gather, transmit, store:
  - Large-scale, diverse, stranded renewables
  - FIRM time-varying-output renewables
    - Pipeline transmission, storage
    - Geologic storage
- Benign, if from renewables
- Global opportunity
- Hydrogen "sector", not "economy"
  - Transportation fuel: ground, air
  - DG electricity, CHP, retail value

When we realize these as emergencies:

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

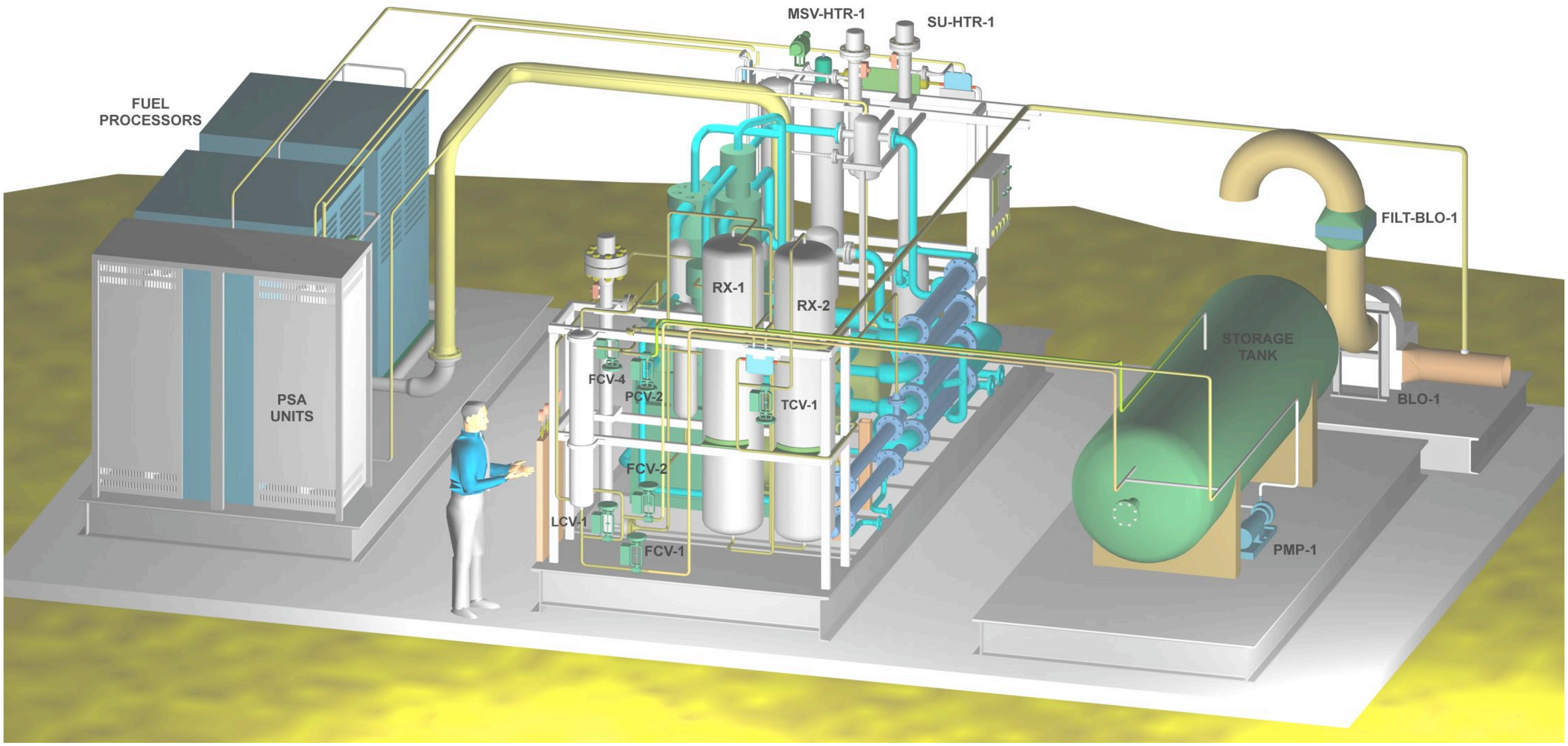
We must quickly invest in:

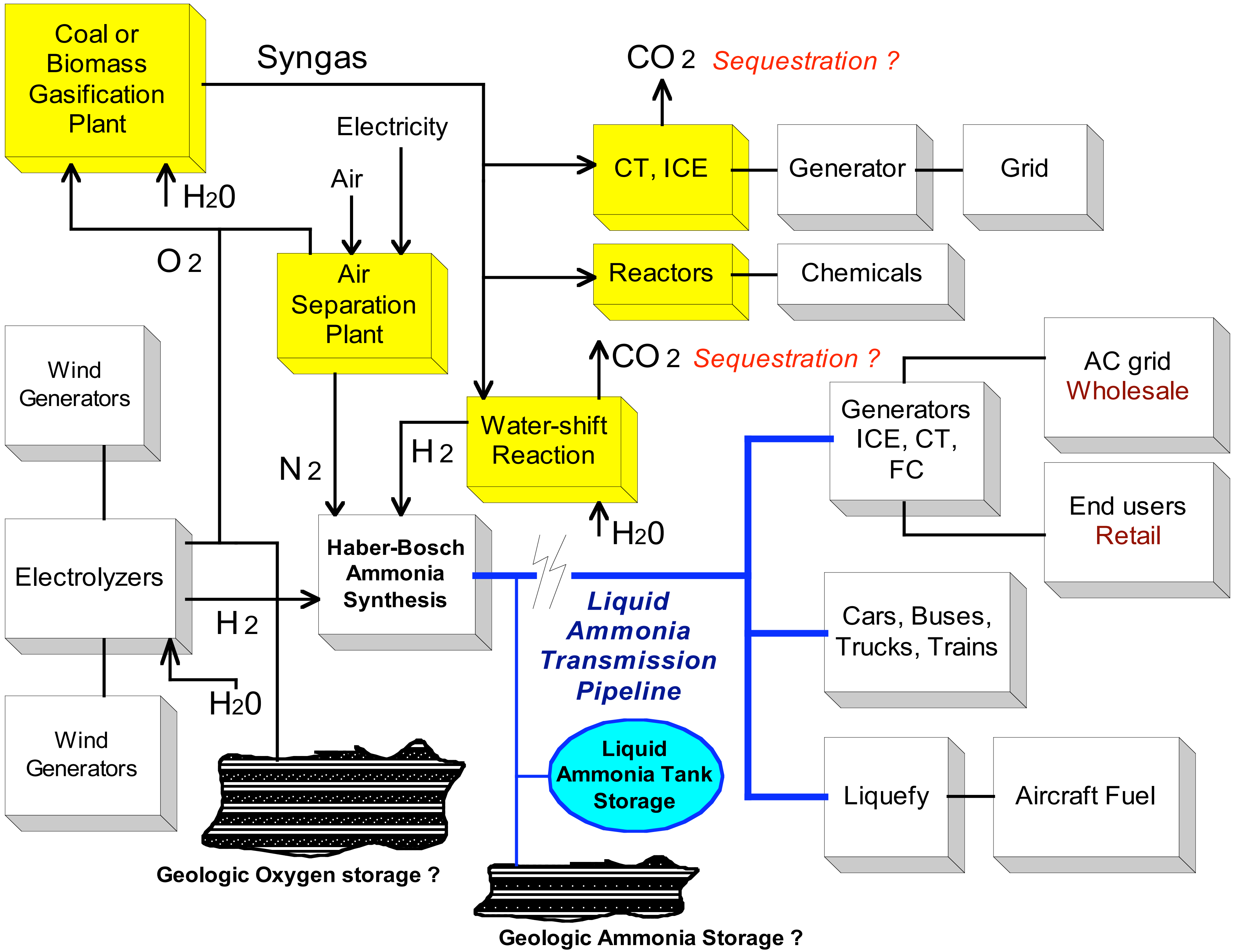
- ***Extant fleet***
- Energy conservation, efficiency
- Large, new energy supplies:
  - CO_2-emissions-free
  - Indigenous
  - Both Distributed, Centralized

GW-scale Transmission Storage Options

- Electricity
  - Vanadium Redox battery (VRB Power Systems)
- Gaseous Hydrogen (GH2) pipeline
  - Pipeline
  - Geologic: salt caverns (man-made)
  - Geologic: natural formations
- Liquid Hydrogen (LH2)
  - Pipeline, truck, rail car, ship
- Ammonia (NH3) liquid
  - Tank, refrigerated, 10K – 60K ton
  - Truck, rail car, ship
- Liquid synthetic HC’s – zero net C
  - Pipeline
  - Tank, truck, rail car, ship
  - Geologic: salt caverns (man made)
- “Energy Pipeline”, EPRI: LH2 in pipeline
- Chemicals
  - Hydrides
  - Al – Ga ← → Alumina

3 tpd Mini-NH3 Plant

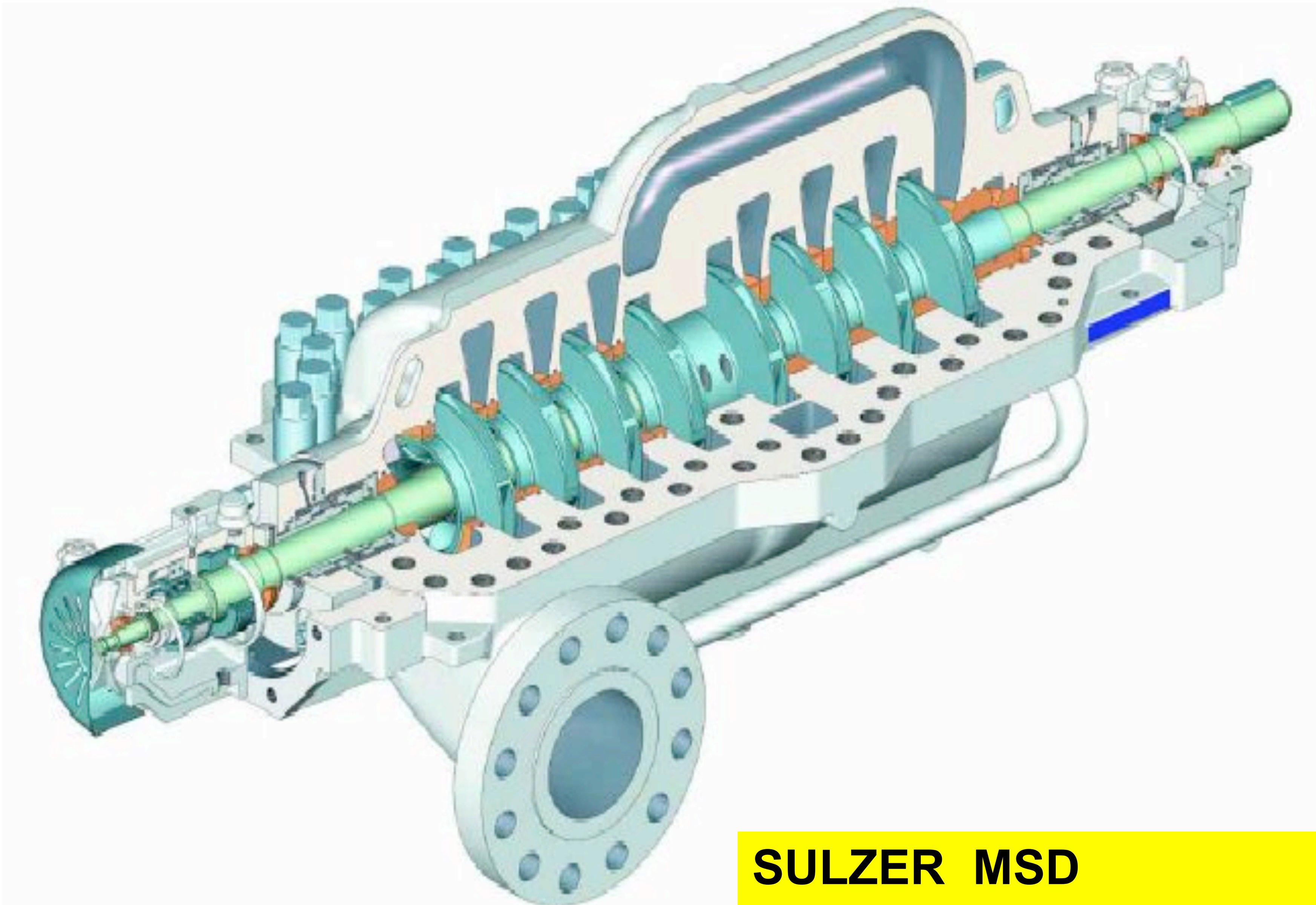




Coal or Biomass Gasification Plant
Syngas
CO 2 Sequestration ?
Electricity
Air
H2O
CT, ICE
Generator
Grid
O 2
Air Separation Plant
Reactors
Chemicals
Wind Generators
CO 2 Sequestration ?
AC grid Wholesale
Generators ICE, CT, FC
Water-shift Reaction
H 2
N 2
End users Retail
H2O
Electrolyzers
Haber-Bosch Ammonia Synthesis
Liquid Ammonia Transmission Pipeline
Cars, Buses, Trucks, Trains
H 2
H2O
Wind Generators
Liquid Ammonia Tank Storage
Liquefy
Aircraft Fuel
Geologic Oxygen storage ?
Geologic Ammonia Storage ?

Smith Positive Displacement liquid meters, by FMC Energy Systems. Integrated Systems. Up to 16”.

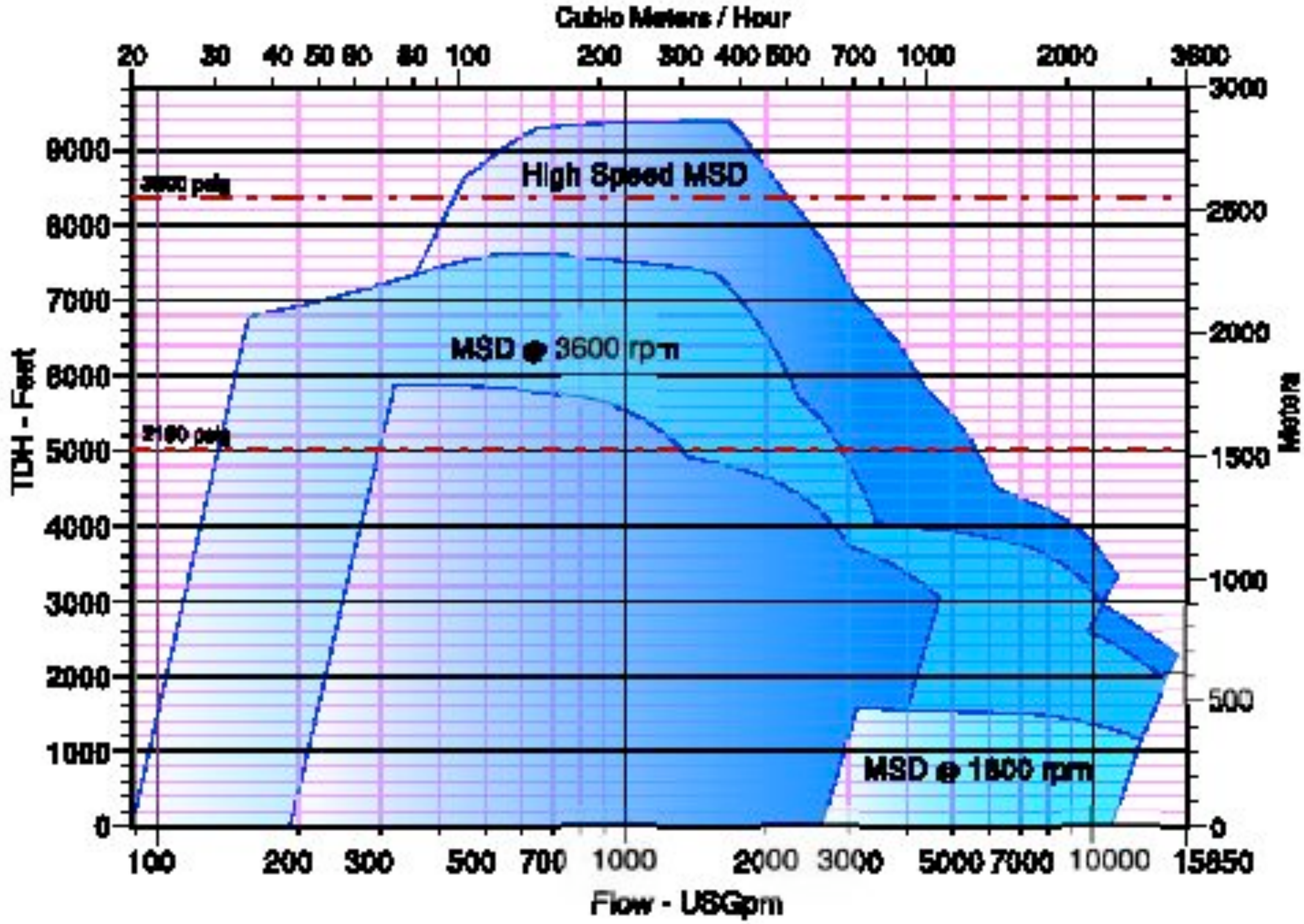
Integrated systems with Supervisory control capabilities



SULZER MSD

Axially Split Multistage Pump

60Hz Range Map



Sulzer Pump Hydraulic Range Map

NH3 Properties

- Density = 682 kg / m^3 = 1,500 lbs / m^3 = 5.68 lbs / gal
- 264 US gallons / m^3
- 18 % Hydrogen by weight
- Energy density ~ 1.5 LH2 (liquid hydrogen)
- Liquid at 70F for at > 8 bar (120 psi)
- Liquid/gas equivalent (1.013 bar and 15 °C (59 °F)) : 947 vol/vol
- Boiling point (1.013 bar) : -33.5 °C
- Latent heat of vaporization (1.013 bar at boiling point) : 1371.2 kJ/kg
- Vapor pressure (at 21 °C or 70 °F) : 8.88 bar
- Viscosity: at 70F viscosity is ~0.13 centipoise (about 1/10 of water)

Electricity: ***energy transmission and storage***

- Advantages

- Disadvantages

Hydrogen: ***energy transmission and storage***

- Advantages

- Disadvantages

Ammonia: ***energy transmission and storage***

- Advantages

- Disadvantages

Topology options

- SYSTEM: Gathering, transmission, storage, distribution
- Gathering:
  - generators, producers
  - nodes on transmission line
- Transmission:
  - security: overhead, underground
  - inherent storage
- Storage:
  - distributed, centralized
  - centralized: remote from end user; at sources
  - pipelines, geological, tanks
- Distribution:
  - safety
  - ubiquitous, as electricity and natural gas ?

Topology options

- Large NH_3 storage at sources

NH3 liquid pipeline pumps - A

- Assume: 10” line, 1,000 psi, 150 tons per hour
- Design: Recip or radial multistage split
- 3,600 rpm typical
- Estimated $500K / pump package: elec motor drive, skid
- Paired in pump stations
  - Split flow
  - Redundant: service one, other assumes full load
  - Doubles pump cost: ~ $1M per station
- NH3-fueled ICE: more costly
  - Speed increaser gear
  - ICE, gear cooling
- USA suppliers:
  - Textron: Union Pump
  - Flowserve
  - Sulzer: radial split only – not good for NH3

NH3 liquid pipeline pumps - B

- Proper liquid pipeline design requires assuming:
  - diameter; capacity (tons per hour)
  - inlet and delivery pressures
  - inlet temp
  - NH3 viscosity and density as *f* (temp)
  - ground temp (seasonal; worst cases)
  - elevation profile over length: pumping power = *f* (elev increase)
- Required pumping estimate: 500 mi, 10”, 400 hp pump, 250 psi delivery:
  - Inlet pump only: 75 tph — Total: 1 pump
  - Inlet + I midline: 112 tph — 2 pumps
  - Inlet + 2 midline: >150 tph — 3 pumps
- Required pumping estimate: 1,000 mi, 10”, 400 hp pump, 250 psi delivery:
  - Inlet + 4 midline: >150 tph — 5 pumps

500 mile, 10", NH3 transmission pipeline estimated capital costs

		$ million
• Pipeline only, X42 steel, including engrg + ROW		
– @ $ 175 / ft avg		460
• 3 pump stations:		
– 2 pumps @400 hp each @ $500 K	1	
– Building + infrastructure	1	
TOTAL pump stations		6
• Valves, meters, input / output nodes $ 10		

TOTAL		**476**

Capacity: 150 US tons / hour = 1.3 million tons / year

1,000 mile, 10", NH3 transmission pipeline estimated capital costs

		$ million
• Pipeline only, X42 steel, including engrg + ROW		
– @ $ 175 / ft avg		920
• 5 pump stations:		
– 2 pumps @400 hp each @ $ 500 K	1	
– Building + infrastructure	1	
TOTAL pump stations		10
• Valves, meters, input / output nodes		20

TOTAL		**950**

Capacity: 150 US tons / hour = 1.3 million tons / year

NH3 synthesis plant estimated capital costs

$ million

TOTAL

Capacity: 150 US tons / hour = 1.3 million tons / year

NH3 cracker plant estimated capital costs

$ million

TOTAL

Capacity: 150 US tons / hour = 1.3 million tons / year

Case 1: deliver renewables-source electricity as NH3 to city gate via 10” pipeline

$ million

CAPITAL COSTS

- Electrolyzers
- NH3 synthesis plant, 150 tph = 3,600 tpd = 1.3 M tpy
- Pipeline system, complete

TOTAL

ANNUAL COSTS

- Capital @ 15% CRF
- Conversion losses, 80% efficient * electrolyzers
- Conversion losses, 80% efficient * NH3 plant
- Pumping energy
- Other O&M

TOTAL

* large electrolyzers and plants may be 85% efficient

Total Installed Capital Cost

1,000 mile GH2 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

Total Installed Capital Cost

1,000 mile GH2 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

500 mile, 10", NH_3 Pipeline Costs

- **Capital (including "easy" design, ROW)**
  - **Pipeline**
  - **Pumps**
  - **Valves, meters, nodes (input, output)**
  - **TOTAL**
- **O+M**
  - **Energy conversion (to, from NH_3)**
  - **Pumping**
  - **Maintenance**
  - **Insurance**
  - **TOTAL**

500 mile, 3 GW, HVDC electric line

- **Capital (including design, “easy” ROW)**
  - **ROW**
  - **Converter stations (pair)**
  - **Line**
  - **TOTAL**
- **O+M**
  - **Energy conversion (to, from NH3)**
  - **Pumping**
  - **Maintenance**
  - **Insurance**
  - **TOTAL**

500 mile, 20” diam, GH2 pipeline

- Capital (including design, “easy” ROW)
  - ROW
  - TOTAL
- O+M
  - Maintenance
  - Insurance
  - TOTAL

Total Installed Capital Cost

1,000 mile NH3 pipeline, $US million

Windplant size	**1,000 MW**	**2,000 MW**
Wind generators	$ 1,000	$ 2,000
Electrolyzers	500	1,000
Pipeline, ??	??	??
TOTAL	$?	$?

Total Installed Capital Cost

1,000 mile NH3 Pipeline

"Firming" NH3 Tank 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 tanks	?	?
Tanks @ ? ea	?	?
TOTAL	$?	$?

Tank storage: ? % total capital cost

"Firming" NH3 Tank Storage
for ALL Great Plains Wind

~ ?? Tanks		
Construction:	$? M each	$? B
Annual O&M:	$? M each	$? B
Total		$? B

Adds VALUE: strategic, market

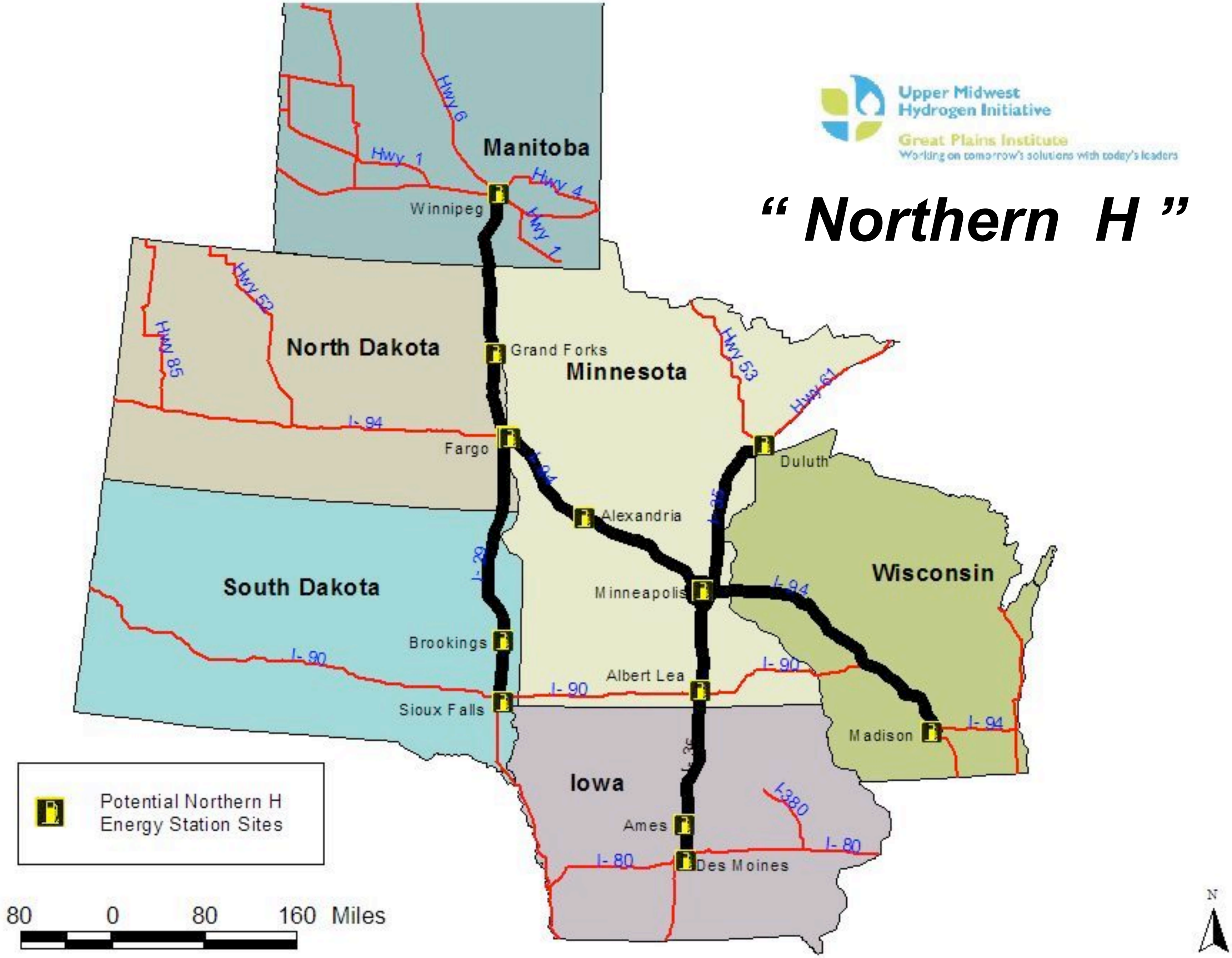
250 hydrogen "gas stations"

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 "



“Efficiency” and Cost of NH_3 Synthesis

- From CH_4 (natural gas) by SMR (steam methane reforming)
- From renewable-source H_2

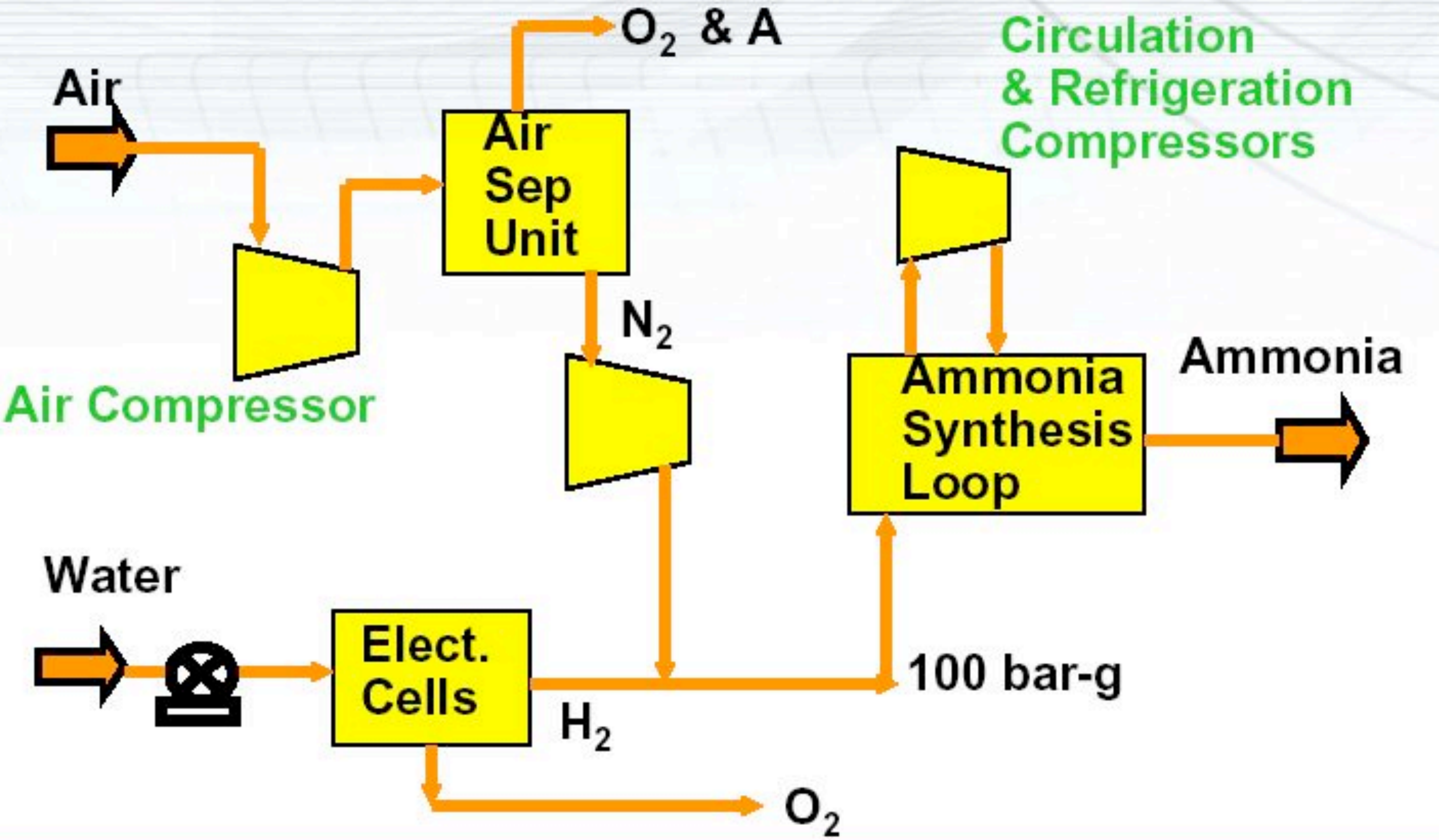
- Industry A: “90 % of cost of NH_3 is natural gas”
- Industry B:
  - “SMR is 60% of capital cost of NH_3 plant”
  - “But, must add N_2 source: air separation plant”
- Industry C:
  - “140 mmscfd SMR plant cost $210M for 2,000 tpd NH_3 plant”
- Industry D: “NH_3 plants are 80 - 85% efficient”
- So: NH_3 energy costs 1.15 times H_2 energy

Renewable-source Hydrogen Eliminates:

- Natural gas feed purification section
- SMR
- Secondary reformer (water-shift) (high + low temp)
- CO_2 removal system
- Methanator + dryers
- Cryogenic purification
- All associated heat exchangers for the above

Ammonia from Water Electrolysis

Conceptual Process Scheme



Electric Power Input to Process

	kWh/MT of NH_3
Compressors	390
Pump	8
Electrolytic cells	7000 – 9000 [(1)]
TOTAL	~7400 – 9400

(1) Based on 3.5 – 4.5 kWh/Nm^3 of H_2

Approx. Energy Consumption (Cont'd)

	Gcal/Metric Ton NH_3	
	860 kcal/kWh	2150 kcal/kWh[2]
Electricity [1]	6.4	16.0
Heat recovery	-0.6	-0.6
TOTAL	5.8	15.4

(1) Based on 3.5 kWh/Nm^3 of H_2

(2) Conversion of primary energy to electricity at 40% efficiency.

KBR
Energy and Chemicals

Approx. Variable Operating Cost

	$/MT of NH_3
Electricity @ $0.035/kWh	$259 (1)
Water @ $5/1000 gallons	2
By-product O_2 @ $25/t	-42
Heat recovery @ $40/Gcal	-24
TOTAL	$195

(1) Based on 3.5 kWh/Nm^3 of H_2

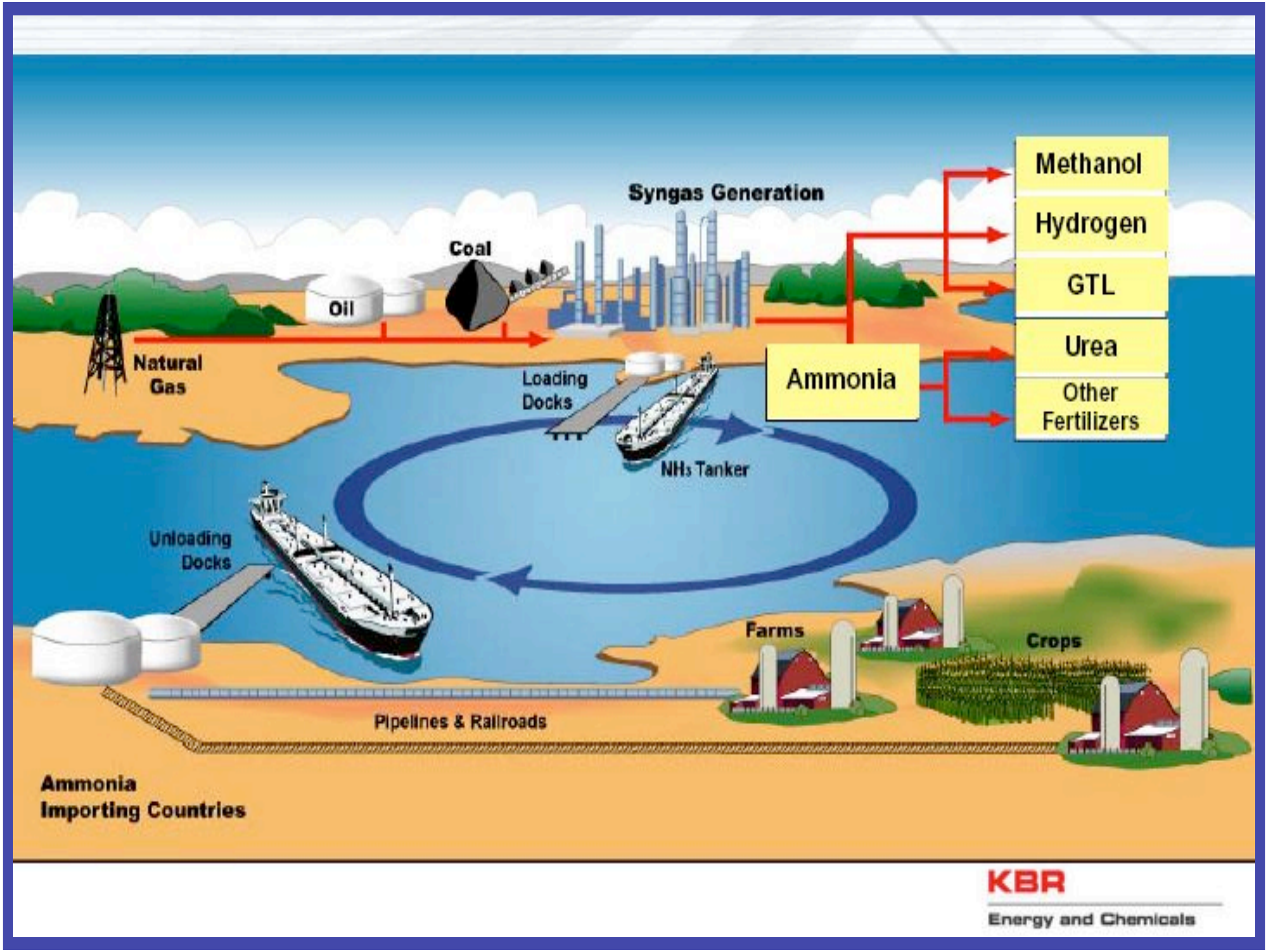
Approx. Energy Consumption of Process

	GCal/MT of NH_3
Electricity @ 860 kcal/kWh	6.4 – 8.1[(1)]
Heat recovery from loop	-0.6
TOTAL	5.8 – 7.5

(1) Based on 3.5 – 4.5 kWh/Nm^3 of H_2

NH3 Dissociators / Crackers

Manufacturer	H2 Output kg/Day	Electric Power Consumpt. kW	Efficiency %	Weight kg	Footprint cm X cm	Cost $K
Lindberg	273	140	63	5800	290 X 240	155
CI Hayes	228	140	55	2180	180 X 170	N/A
CI Hayes	136	64	66	2180	180 X 170	70
Koyo Thermo	96	59.5	55	N/A	280 X 100	N/A
Borel	11.2	7.5	51	N/A	85 X 56	N/A



Syngas Generation
Methanol
Hydrogen
GTL
Urea
Other Fertilizers
Coal
Oil
Natural Gas
Ammonia
Loading Docks
NH3 Tanker
Unloading Docks
Farms
Crops
Pipelines & Railroads
Ammonia Importing Countries
KBR
Energy and Chemicals


Ed Stein '90 Rocky Mtn. News NEA
U.S. OiL
$1001 29 REG.
$1001 39 UNLEAD.
The Gas is only $1.39. The aircraft carrier is $470, The Tank is $125, The Stealth Fighter is $330, The Gas Mask is $45 and The Gun adds $30 a Gallon.

“Distributed Collection”

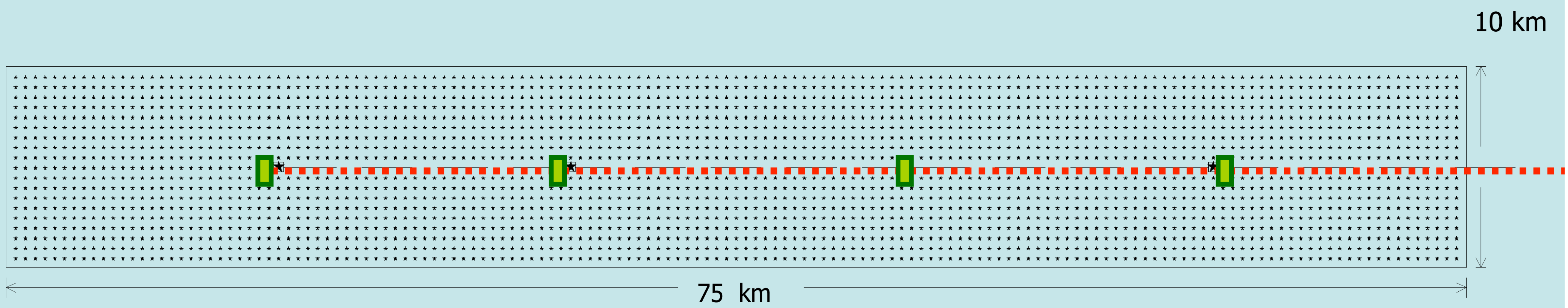
4,000 MW of Nameplate Wind Generation

150 x 19 grid
500 m spacing

2,850 wind generators at 1,400 kW each

~ 750 sq km

~ 300 sq mi



ITEM 130 LOCAL RATES - In Dollars per Ton

[I] Increase. All Local Rates On This Page Are Increased.

TO	FROM					
	Enid	Borger Agrium	Verdigris	Blair	Mocane Trk Unl	Port Neal
Farnsworth	28.21	26.66	28.92	29.14	26.66	29.42
Borger Agrium	28.53		29.24	29.46	26.97	29.75
Conway Koch	27.18	28.01	27.88	27.80	27.20	28.07
Beatrice Agrium	28.10	28.92	28.81	26.97	28.01	27.28
Early	29.14	29.98	29.85	27.00	29.36	26.84
Garner Agrium	29.69	30.52	30.41	27.54	29.89	27.38
Blair	28.64	29.46	29.35		28.84	26.74
Port Neal	28.91	29.75	29.62	26.74	29.11	
Sargeant Bluff	28.89	29.74	29.61	26.73	29.11	26.37
Garner Koch	29.69	30.52	30.41	27.54	29.89	27.38
Mankato Koch	30.15	30.99	30.84	27.98	30.32	27.84
Garner CF	29.69	30.52	30.41	27.49	29.89	27.38
Clay Center A Terminal	27.66	28.52	28.39	27.31	27.88	27.57
Greenwood A Terminal	28.31	29.14	29.01	26.68	28.50	26.95
Whiting A Terminal	28.81	29.62	29.52	26.65	29.00	26.50
Mankato A Terminal	30.15	30.99	30.84	27.95	30.32	27.84
Conway A Terminal	27.18	28.01	27.88	27.50	27.38	28.07
Mocane A Terminal	27.91	26.97	28.62	28.65		29.11

Magellan Tariff

NH3 Pipeline

Holbrook notes: 23 Sep 06 - A

- Valero system ~ 2,000 miles of anhydrous ammonia pipeline in Midwest.
- Magellan/Enterprise owns/operates ~ 1,500 miles of anhydrous ammonia pipeline in central Midwest.
- May be shorter pipelines Australia and Mexico: single supply lines from production to storage facilities ?
- Diameter: USA 6" – 10" transmission plus 4" – 6" laterals.
- Almost entirely underground.
- Typically X-42 or Grade B steel. Rated yield (SMYS) = 35,000 – 42,000 psi. Welded.
- Diameter / Wall: 10" / 0.250" , 8" / 0.203", 6" / 0.188", 4" / 0.188"
- Valero LP line operates 1,340 - 1,420 psi Liquid NH_3 is at ambient ground temperature at elevated pressures.
- Valero transmission line > 150 tons per hour (tph)
- Transmission pipeline needs intermediate pipeline pump stations.
- Transmission line continuous flow supplies industrial accounts and builds the terminal inventories in the Midwest for the short burst agricultural application seasons.
- Seasonal spikes of flow during the agricultural fertilizer seasons of spring, summer side-dress, and fall.
- Frequency of leaks, releases, failures, or shut-downs: rare, brief
- Leak detection: pipeline control centers use line balance methods and proven meters
- Lines are patrolled by air > 26 times per year
- Corrosion: Anhydrous ammonia is waterless, so a perfect preservative of carbon steel.
- External pipe coating defects are only potential corrosion areas.
- Cathodic protection and pipeline coating materials are used.
- In-line inspection tools are now being used.
- Construction cost estimate: $250,000 for a best case scenario, for a smaller diameter line.
- Production energy cost / ton, "modern Haber-Bosch" = ~40 GJ / ton
- The Magellan line is about 1000 miles and is still the 6-10 inch carbon steel type. Operates at ~800-900 psi and 400-500 barrels per hour (42 gals/barrel, density 0.68 kg/liter) I believe it has pumps about every 50 miles. Bill: 40-60 tph, less than Valero
- Not all ammonia is applied as anhydrous (only about 4-5 MMT out of 12-15 MMT total, the rest urea, and ammonium salts) and not all is delivered by pipeline. Much by train and truck.

Holbrook notes: 23 Sep 06 - B

- DOE: hydrogen fueling station can provide 1500 kg per day pressurized hydrogen gas to fuel-cell powered cars. 1500 kg of hydrogen = 8500 kg = 3,750 gallons anhydrous ammonia per day, not including the excess energy needed to power the reforming reaction. The volume of this amount of ammonia is quite small, and several day's supply can be stored at the fueling station in a standard 30,000 gallon ammonia tank, which is a low-cost nominal size routinely used at ammonia fueling stations in the United States.
- Annual world NH_3 = 100 million tons (includes urea and ammonium salts); 14-15 million tons in USA (Only 4-5 of that is anhydrous) . So, Valero + Magellan pipelines @ full capacity = 2.4 / (4 to 5) million tons / yr =~ 50%
- David Bloomfield, 2 Oct: The efficiency of modern ammonia synthesis plants is probably around 80% Check with (KBR). The biggest loss is compression.

Holbrook notes: 23 Sep 06 - C

- $30K / year total O&M, including refrig, for 60K ton storage tank (CF Industries) (what CF; average tank contents?)
- The current price for a 2,000 mtd gas-based ammonia export plant is about $500 million.This price includes everything: EPC price, IDC, financing, jetty, water supply and assumes a stand-alone greenfield site. A (coal) gasification-based plant costs much more depending on the feedstock. However, some (coal) gasification retrofits seem likely to happen in the next few years.   Keith Stokes
- Holbrook, on above: A "renewables" ammonia plant will probably cost less because it gets its hydrogen from electrolysis and doesn't need an NG reforming component. I'd guess 25% savings. Also, for plant size scaling, Keith says he always uses a 0.65 power law.

Other notes: 30 Sep 06 - A

At 02:12 PM 4/26/2006, Schainker, Robert wrote: rschaink@epri.com

Bill:

I assume your GH2 transmission pipeline paper was well received at the Las Vegas conference in early April.

Below are some of my thoughts which address the questions/topics you raised in your email and paper.

1. Yes, you can store GH2 in "bedded" salt. The issue is the depth of the bedded salt formation and the depth of the cavern within the bedded salt formation, since the pressure you store the GH2 at should be about the same pressure as the hydrostatic head of pressure at the depth the cavern is located in, within the bedded salt formation. This will insure the salt cavern does not slowly creep inward or outward from its original position when it was solution mined over its lifetime of yearly cycling.. Also, the temperature of the injected GH2 should not be greater than about 20C higher than the existing temperature of the walls of the cavern, which depends on the depth of the cavern. The people at ChevronPhilips Clemens Terminal GH2 storage cavern operation should be able to give you ample information on this topic, since they have valuable experience in this area.
2. I do think the GH2 pipeline system will need some recompression stations since the friction in a long pipeline will indeed be large enough to require recompression along the pipeline. The exact number of recompression stations depends, of course, on the pipeline throughput rate, pipe diameter and GH2 temperature. I suggest you get in contact with the Netherlanders on this topic since they have the longest H2 pipeline in the world right now, and they have been operating it for many years successfully.
3. The Netherlanders should also know more than anyone else regarding corrosion/embitterment.
4. Regarding the EPRI SuperGrid project which incorporates a H2 pipeline cooling a superconductor, yes, this project is still being funded, albeit at a low level. Currently, a scoping study is being performed and one of my energy storage colleagues, Steve Eckroad, is managing it.

Dr. Robert B. Schainker, Strategic Planning, EPRI Office of Innovation 650- 855-2549, - 996-6186, - 855-8997

Other notes: 30 Sep 06 - B

- Gary Koeppel, Praxair: In a wide open area, to design, engineer, buy materials, excavate, construct, test and clean, obtain ROWs, permits for a 10 inch pipe would cost $150-$175 per foot. In congested urban areas or environmentally sensitive areas, or areas with questionable ROW costs, the cost could go to $250-$350 per foot. Horizontal Directional Drills used to go under waterways or congested areas are costing about $400/ft.