

ASME Power, 31 July 13, Boston

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Mendenhall Glacier, Juneau, AK June '71



Mendenhall Glacier, Juneau, AK 10 October 10



Mendenhall Glacier, Juneau, AK 10 October 10

Rapid climate change



Spruce bark beetle kill, Alaska



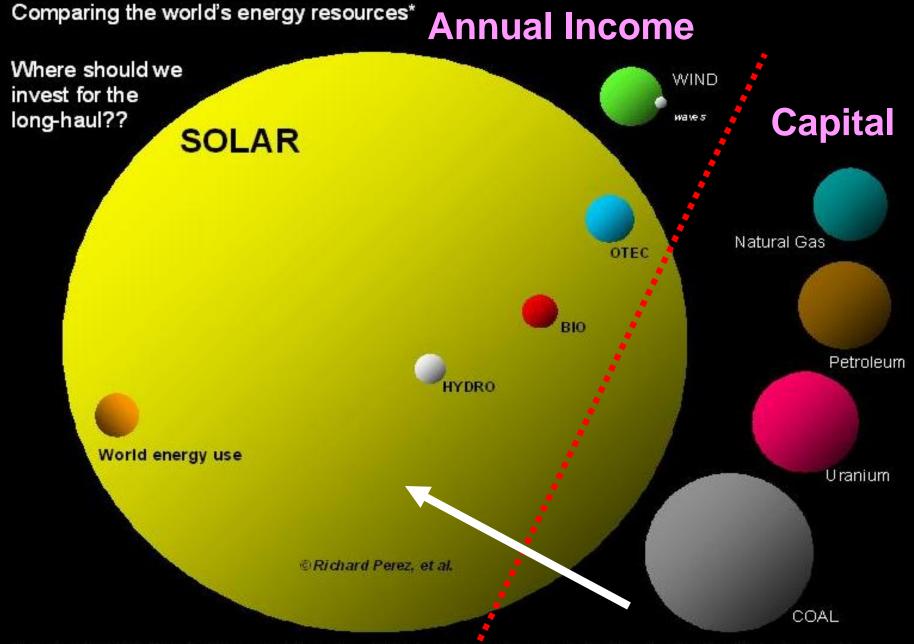


Shishmaref, Alaska Winter storms coastal erosion

MUST Run the World on Renewables – plus Nuclear?

- Climate Change
- Ocean acidification
- Sea level rise
- Demand growth
- Water for energy
- War
- Depletion of Oil and Gas
- Only 200 years of Coal left
- Only Source of Income:
 - Sunshine
 - Tides
 - Spending our capital

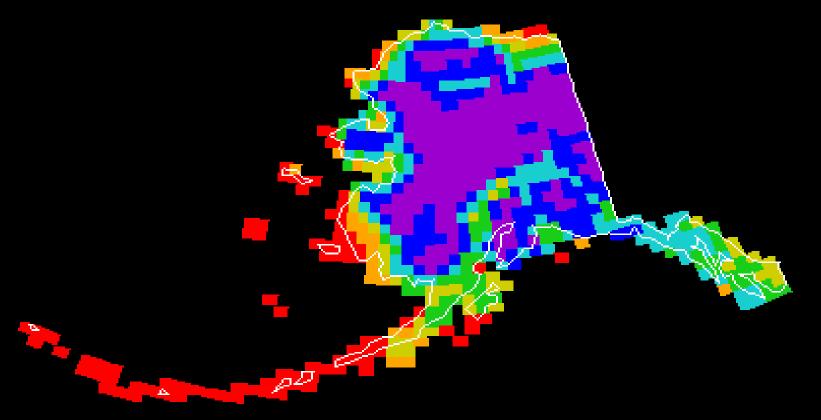




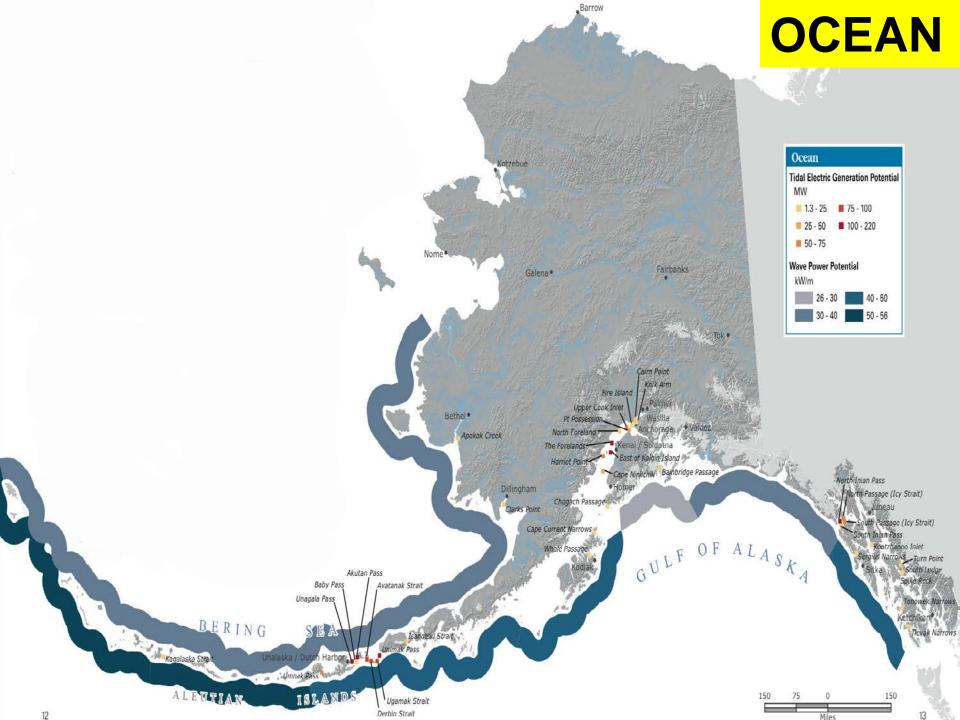
*yearly potential is shown for the renewable energies. Total reserves are shown for the fossil and nuclear "use-them, lose-them" resources. Word energy use is annual.

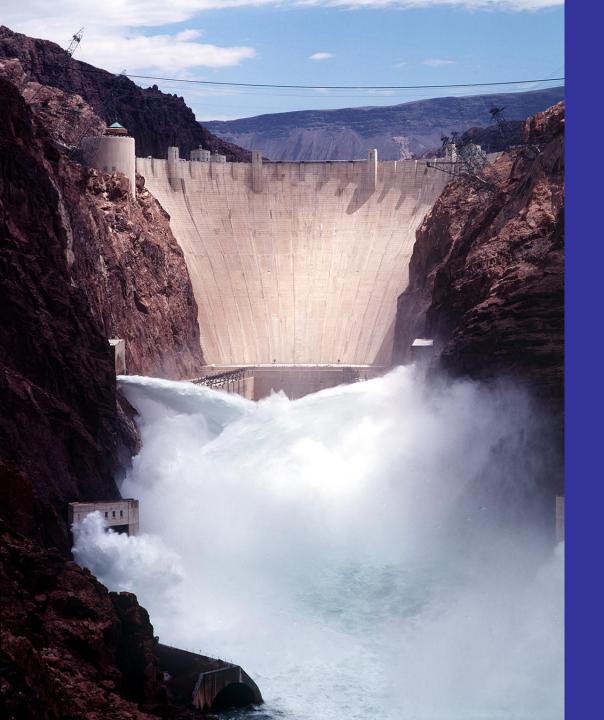


Wind Power Class

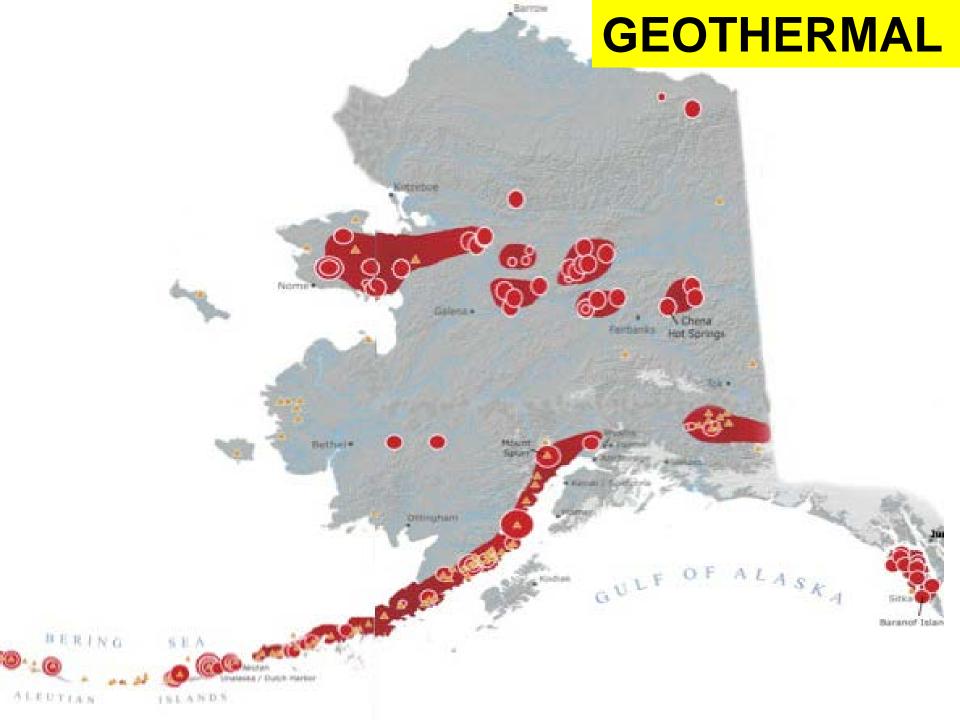


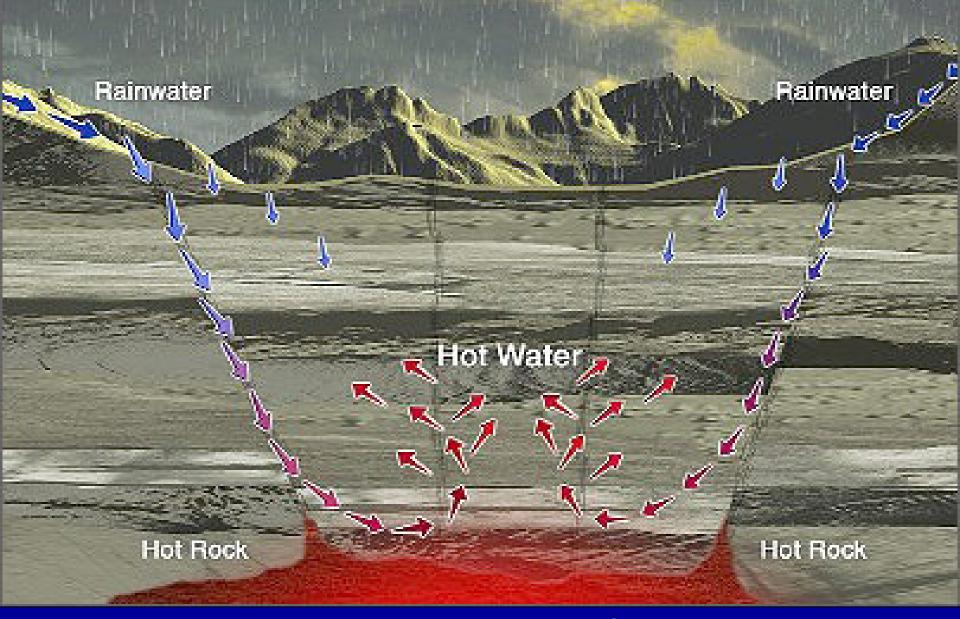
Power	Class	Speed	Power Density
	1	0.0-5.6m/s	0-200W/m2
	2		200-300W/m2
	3		300-400W/m2
	4	7.0-7.5m/s	400-500W/m2
	5	7.5-8.0m/s	500-600W/m2
	6	8.0-8.8m/s	500-800W/m2
	7	>8.8m/s	>800W/m2



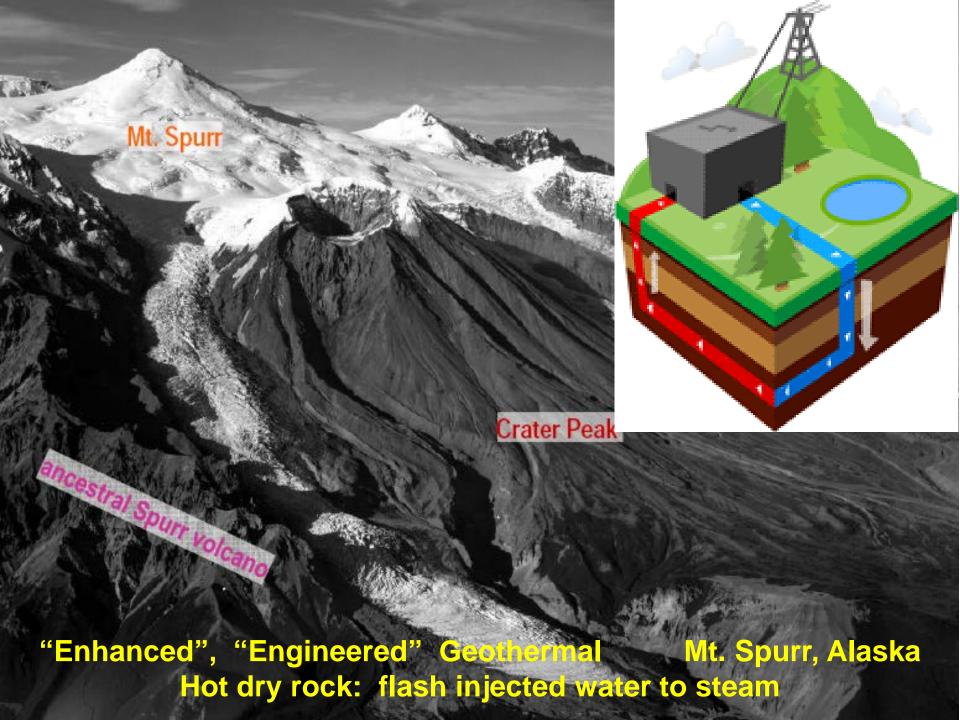


Hydro



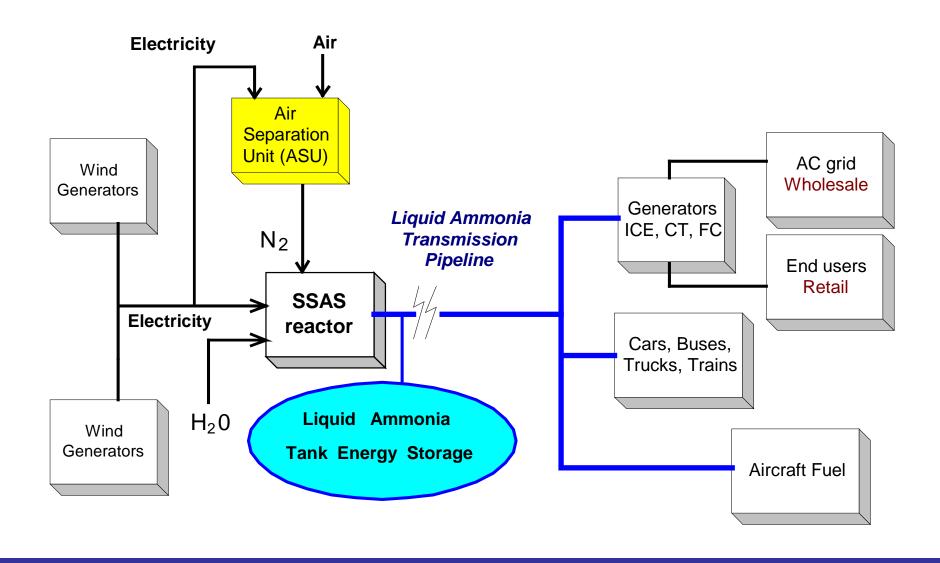


Geothermal: hot water, surface recharge



Opportunity: Alaska Applications

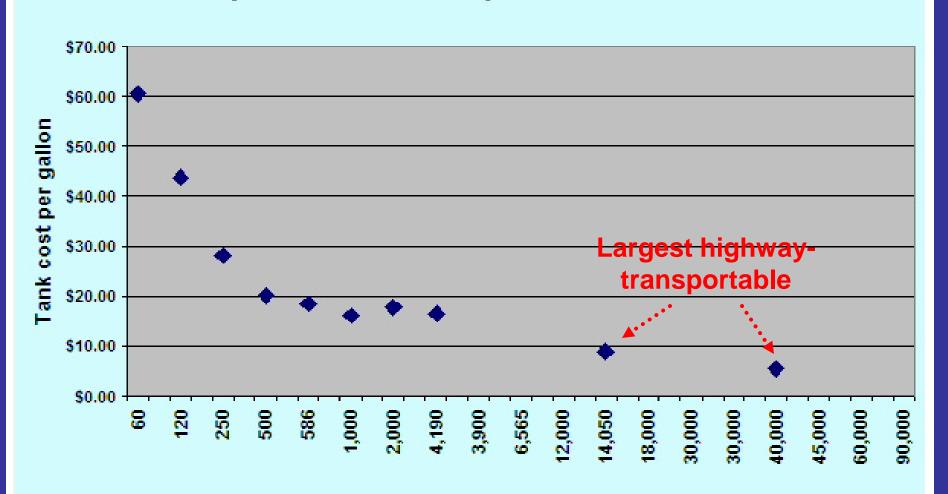
- 1. Village energy "independence": degree
 - a. Internal, external energy economies
 - b. Diverse renewable sources
 - c. Low-cost tank storage
 - d. CHP, transportation fuels
- 2. Firming storage: annual scale
 - a. Susitna hydro
 - b. Other
- 3. Export large, diverse, stranded renewables
 - a. Cryo tankers: global trade
 - b. "Green" NH3 premium? C-tax required?
 - c. SE AK "Cluster Industry"
 - d. Aleutians cargo ship fueling
- 4. Military fuel: ground, marine
 - a. USCG, Navy
 - b. Other services
 - c. DOD Assistant Secretary Sharon Burke visit 3-7 Aug 12



Solid State Ammonia Synthesis (SSAS)

Liquid Ammonia Tank Storage

Cost per Gallon: 250 psi Ammonia Tanks



Tank capacity, gallons



Alaska Energy Authority Emerging Energy Technology Fund Project Fundamentals

- 1. Does SSAS system "work"?
- 2. Competitive with EHB?
- 3. Useful in Alaska?

SSAS Proof-of-concept pilot plant Two-year project Alaska Applied Sciences, Inc.

EHB vs SSAS prelim estimates

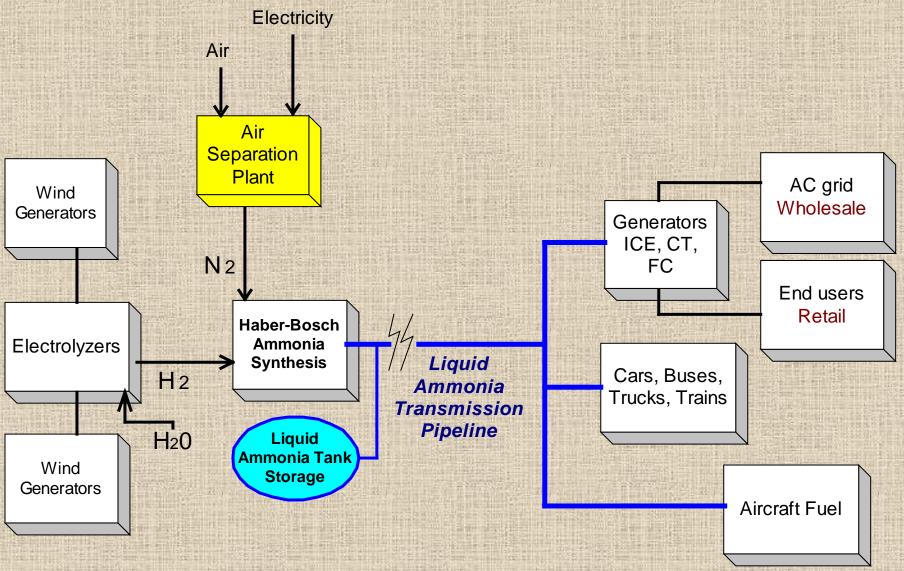
EHB:

```
11-12 kWh / kg
$1,000 / kWe input capital cost
```

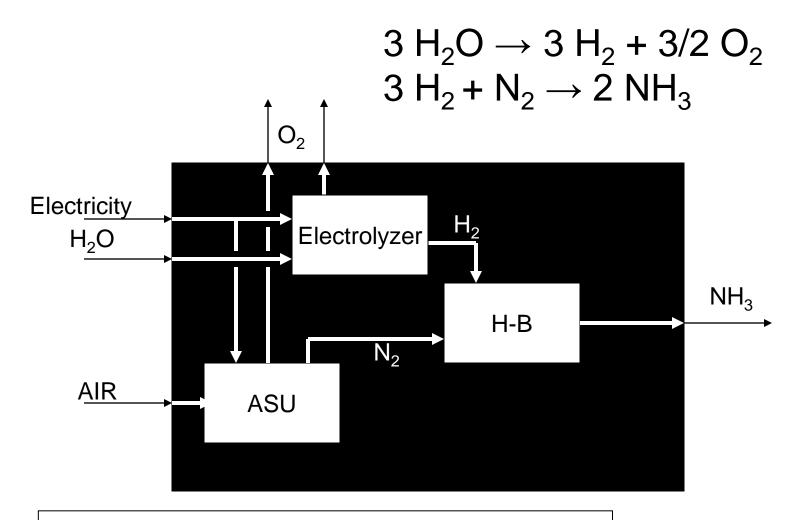
SSAS:

```
7-8 kWh / kg
$500 / kWe input capital cost
$200K / Mt / day capital cost
```

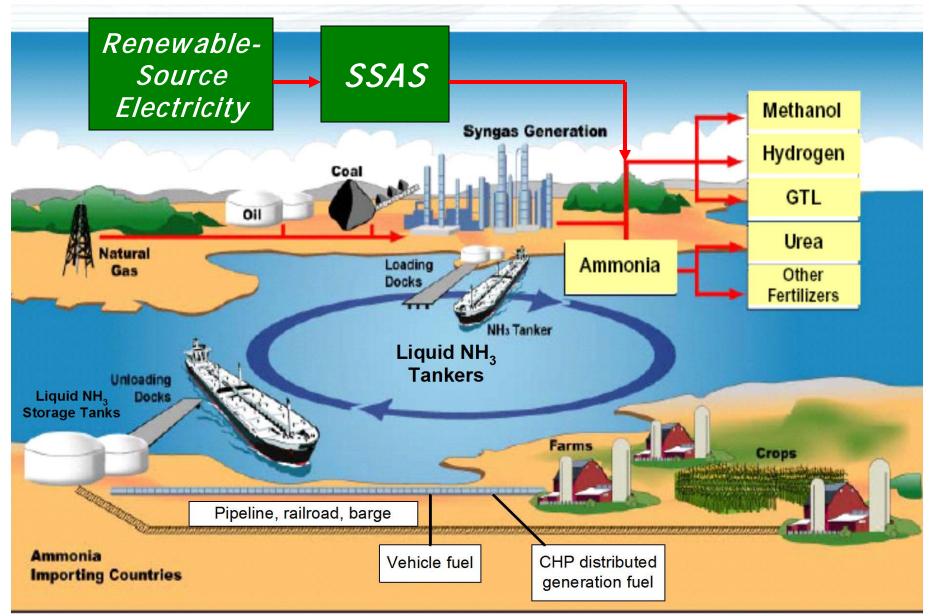
RE Ammonia Transmission + Storage Scenario: Electrolysis + Haber-Bosch (EHB)



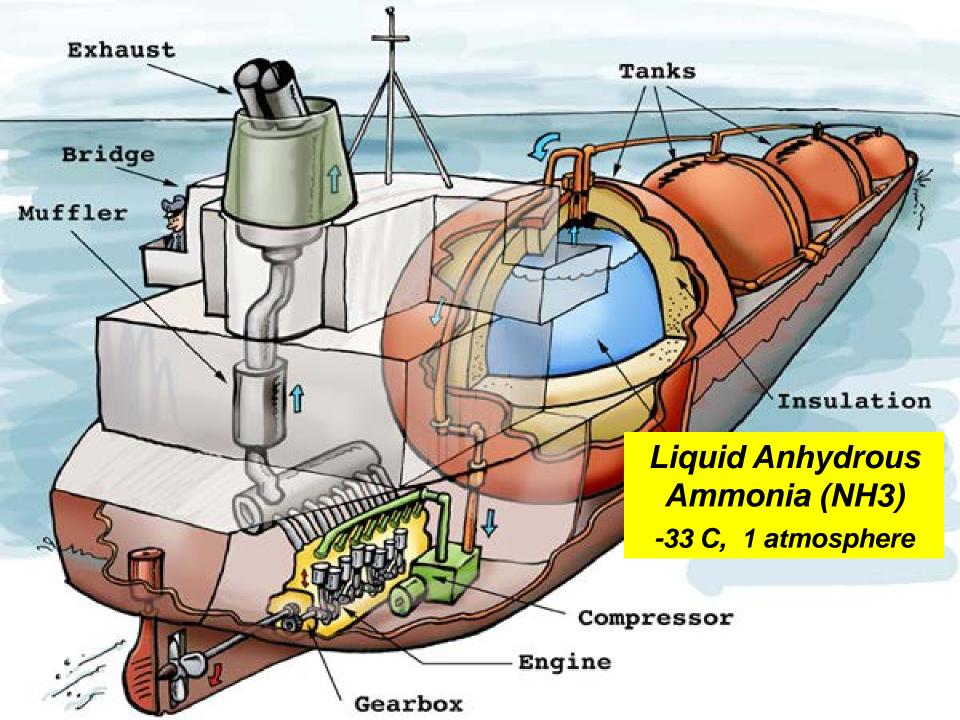
Inside the Black Box: HB Plus Electrolysis



Energy consumption ~12,000 kWh per ton NH₃



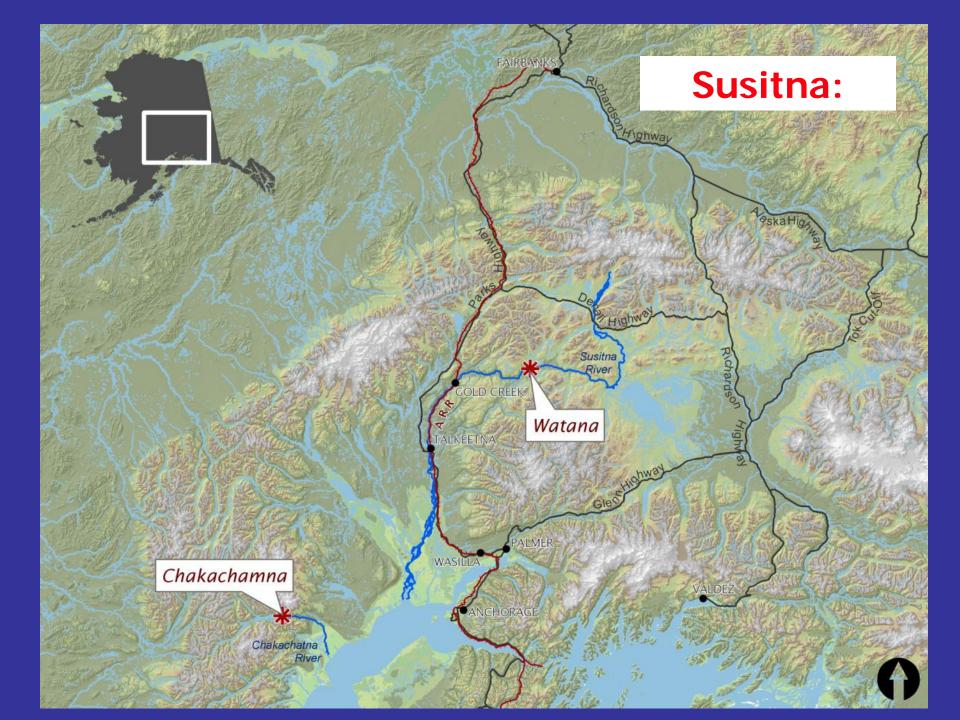




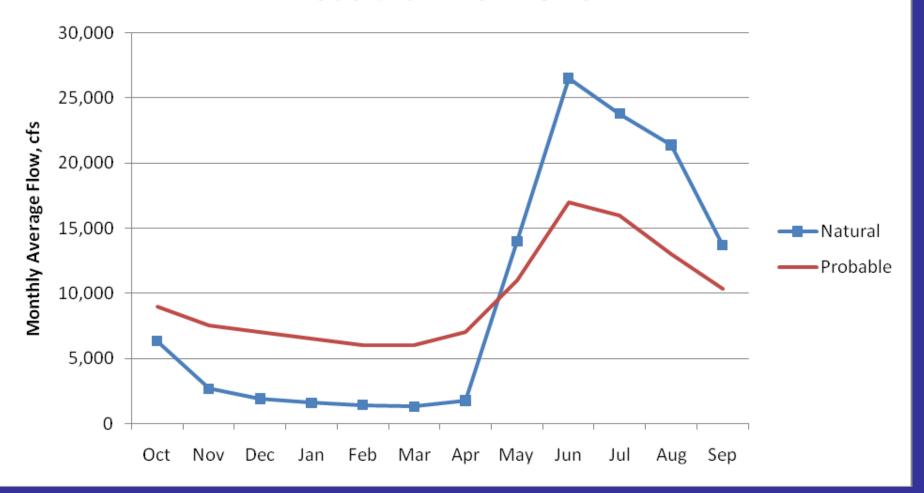
Military: Land + sea fuel

- USCG, Navy ships
- Land vehicles: road, rail
- Recip engines modify: multifuel, Sturman
- Mini + micro app's

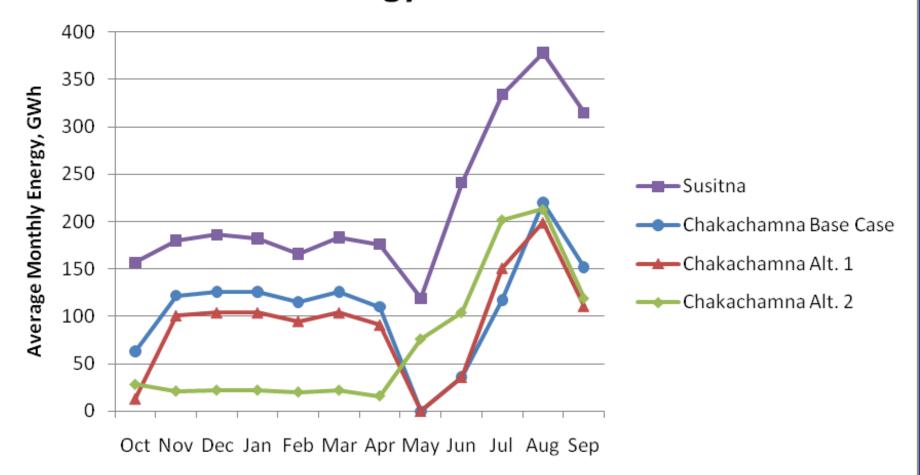




Susitna River Flows



Energy Production



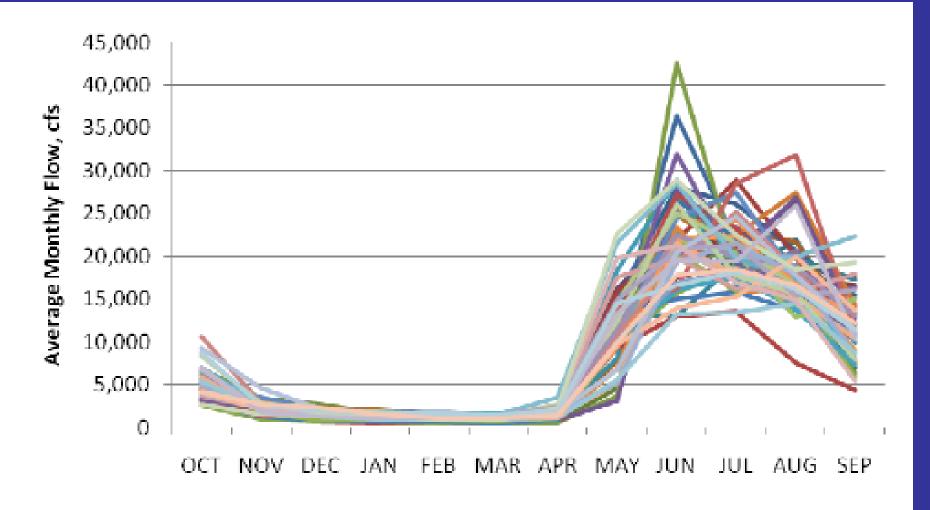


Figure 1 - Susitna River at Watana Hydrologic Variation

Annual Firming for Susitna: Liquid NH3 in "atmospheric" tanks

- 400 MW @ 50% CF = 1,752 GWh / year (AEA: 2,600)
- Store 40% = 700,800 MWh
- 3 tanks @ ~ \$20M each = \$60M
- SSAS plant:
 - 200 MW nameplate
 - \$300 / kWe input capital cost
 - \$600M capital cost
- Regeneration plant:
 - 200 MW nameplate
 - \$300 / kW output capital cost
 - \$600M capital cost
- Total NH3 storage system \$ 1,260 M

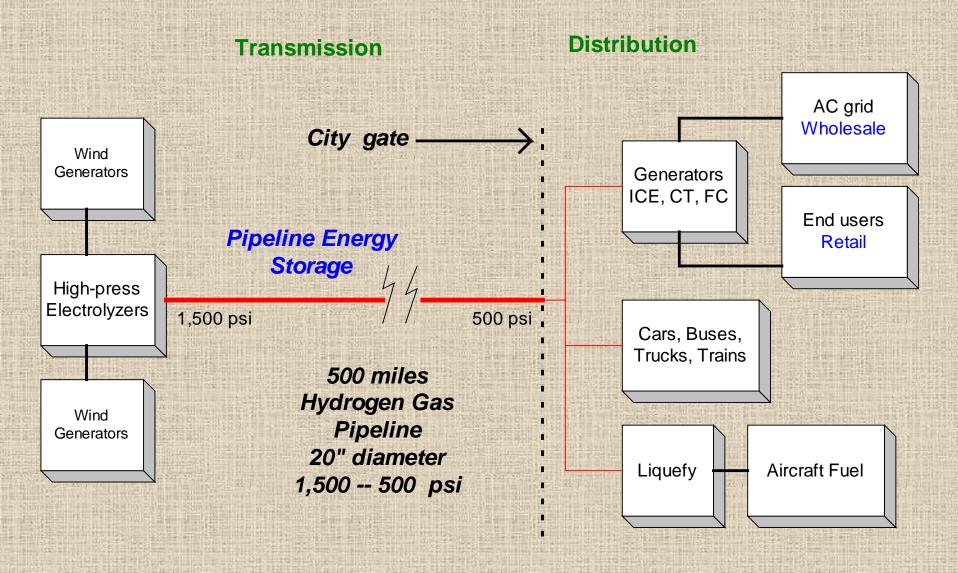


"Atmospheric"
Liquid
Ammonia
Storage Tank
(corn belt)

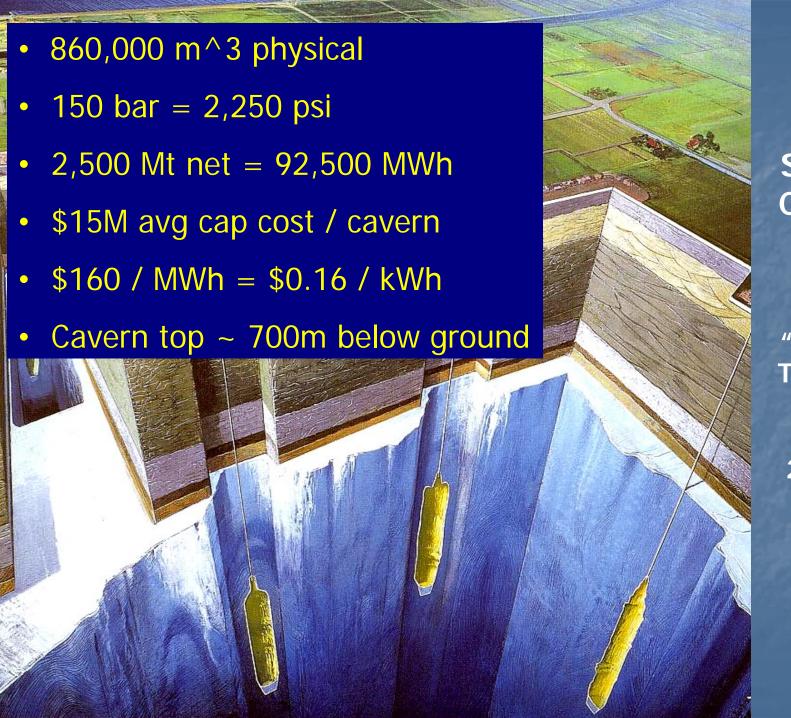
30,000 Tons
190 GWh
\$ 15M turnkey
\$ 80 / MWh
\$ 0.08 / kWh

-33 C 1 Atm

Compressorless system: No geologic storage



Hydrogen Energy Storage **Storage AC**grid Wholesale 1,000 miles Hydrogen Gas Wind Pipeline 36" diameter, 1,500 - 500 psi Generators Generators ICE, CT, FC Pipeline Storage = 120 GWh **Endusers** Retail Electrolyzers Cars, Buses, Trucks, Trains **Storage** Wind Generators Liquefy Aircraft Fuel Geologic Storage? **Storage**



Domal Salt Storage Caverns

Texas

"Clemens Terminal" Conoco Phillips 20 years

> Praxair '07

> > **PB ESS**

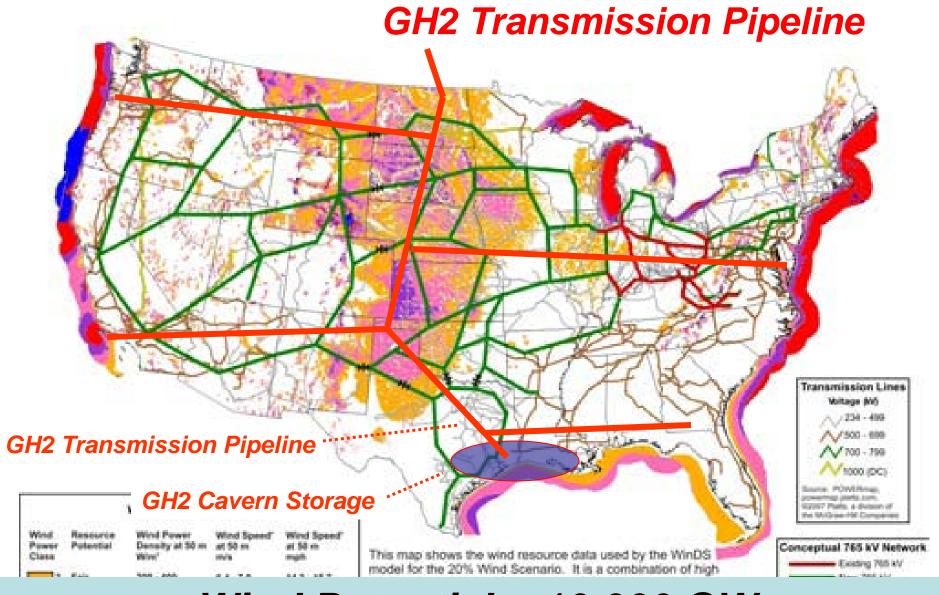


Renewable-source GH2 geologic storage potential.

Candidate formations for manmade, solution-mined, salt caverns

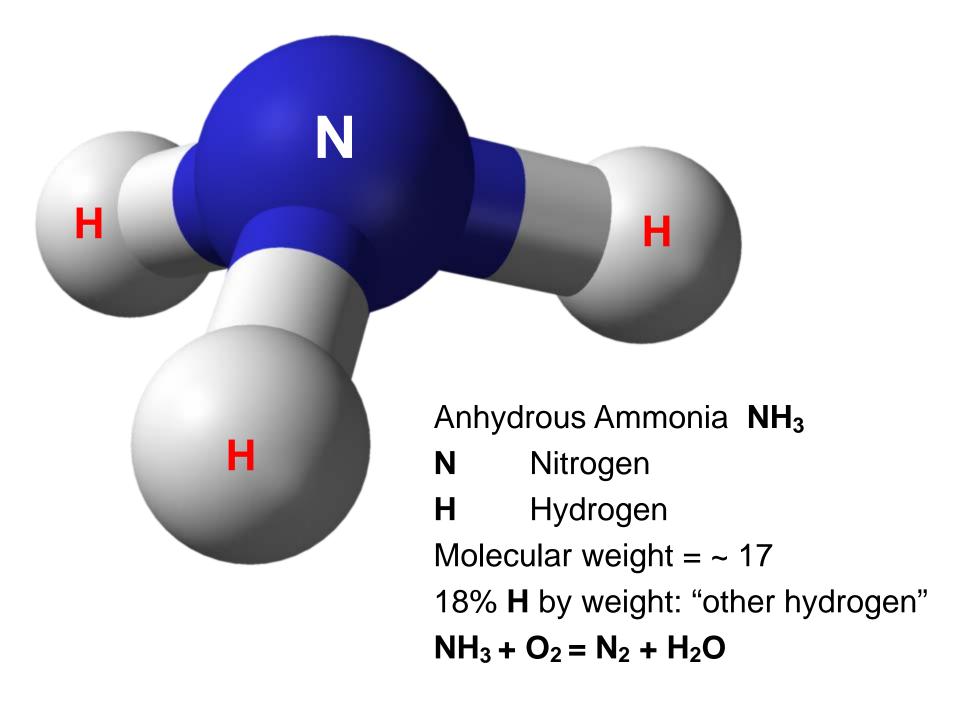


Hydrogen "sector" of a benign, sustainable, equitable, global energy economy



Wind Potential ~ 10,000 GW 12 Great Plains states





Why Ammonia? Fertilizer and Fuel

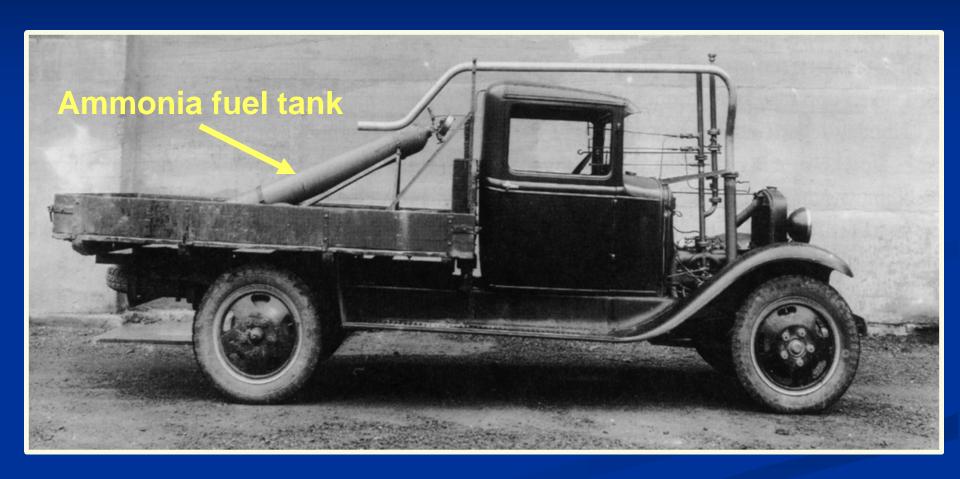
Only liquid fuel embracing all:

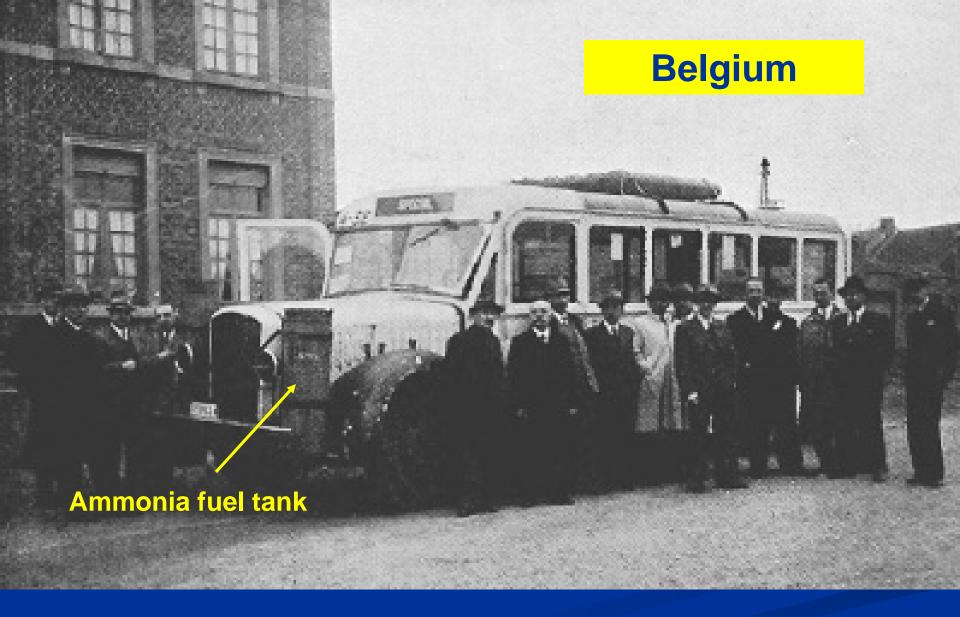
- Carbon-free: clean burn or conversion; no CO₂
 - Excellent hydrogen carrier
 - Easily "cracked" to H₂
- Reasonably high energy density
- Energy cycle inherently pollution free
 - Potentially all RE-source: elec + water + Nitrogen
 - Cost competitive with hydrocarbon fuels?
- Decades of global use, infrastructure
 - Practical to handle, store, and transport: "propane-like"
 - End-use in ICE, Combustion Turbine, fuel cell
 - Safety: self-odorizing; safety regs; hazard

Ammonia Fuel Uses

- 1. Internal Combustion Engine (ICE)
 - Diesel: NH₃ gas mixed with intake air
 - Spark-ignition: 70%+ NH₃ plus
 gasoline, ethanol, propane, NG, hydrogen
 - NOx ~ ¼ gasoline engines
- 2. Combustion Turbines
- 3. Direct Ammonia Fuel Cells:
 - Combined heat + power (CHP)
 - No NOx
- 4. Reform ("crack") to liberate hydrogen for fuel
 cells: 2NH₃ → 3H₂ + N₂

Ammonia fueled - Norway





Ammonia Fueled Bus: Thousands of Problem-free Miles 1943





Ammonia + Gasoline Powered

• Idle: gasoline

• Full power: 80% ammonia

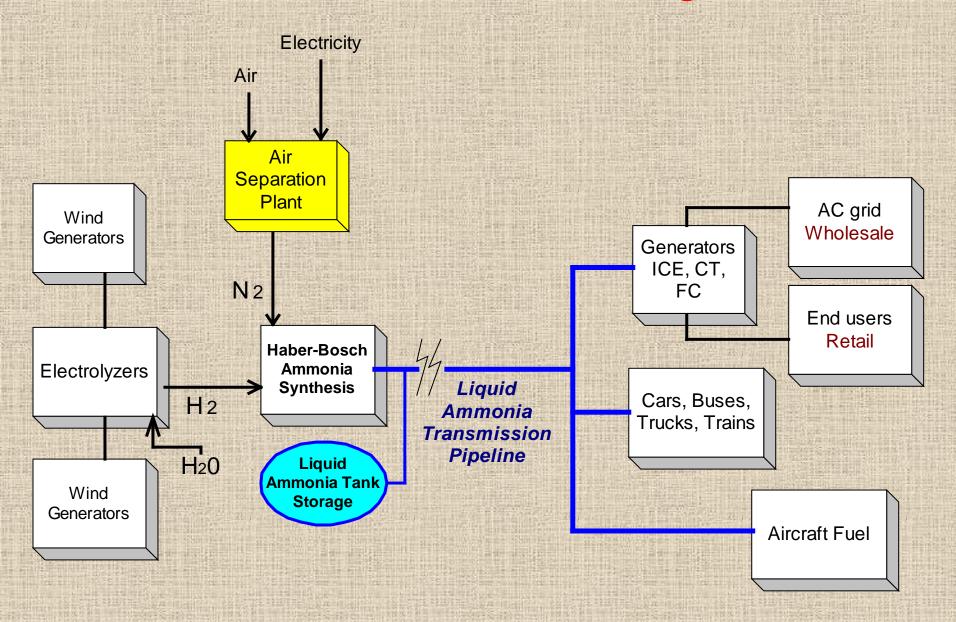
Summer '07 Detroit → San Francisco

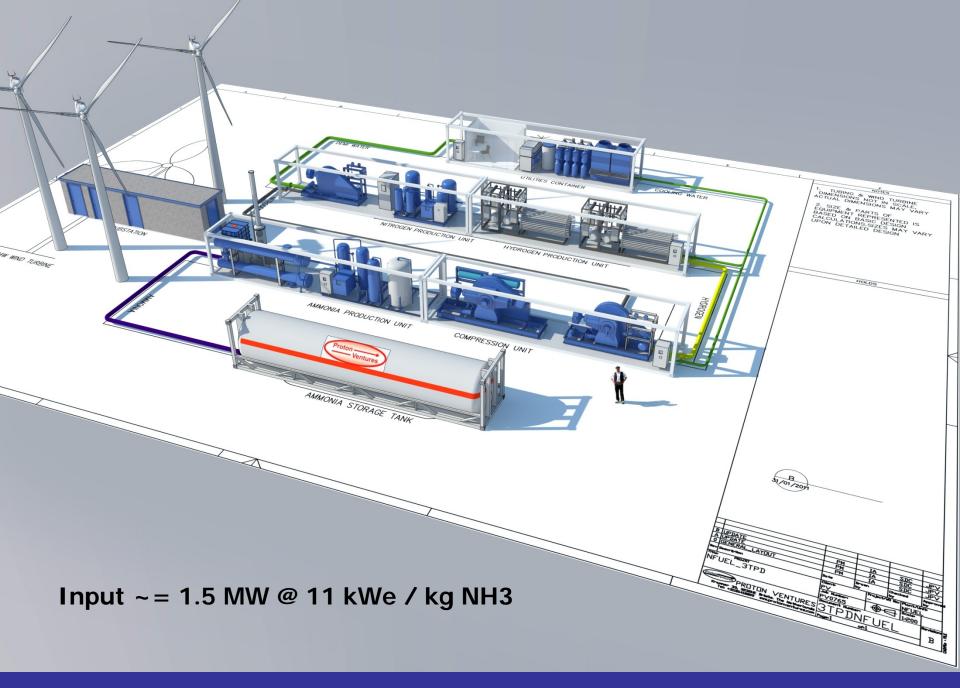
2007

State of the Art; Competition

- Electrolysis + "Haber-Bosch" = EHB
 - NH3 United, TX + Canada NH3
 - Proton Ventures
 - Freedom Fertilizer
- Other "SSAS"
 - Hydrogen Engine Center
 - Other?

RE Ammonia Transmission + Storage Scenario



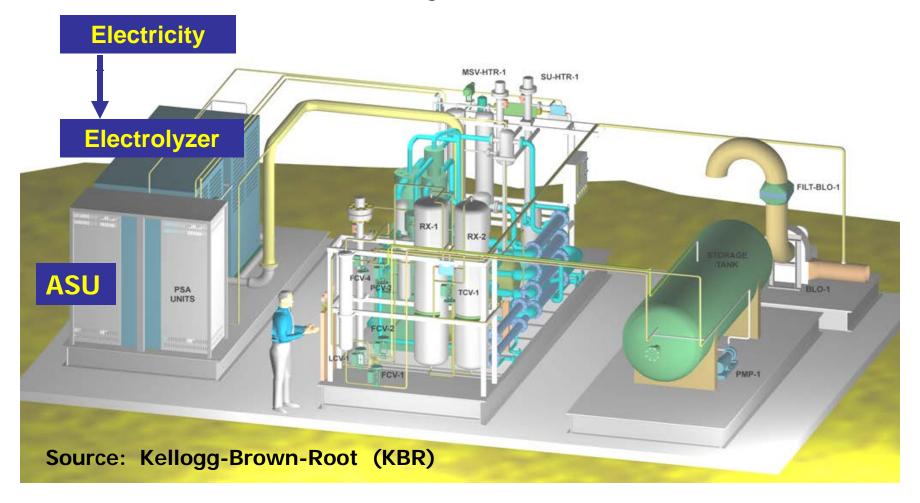


Quoted at \$4M. Delivered?

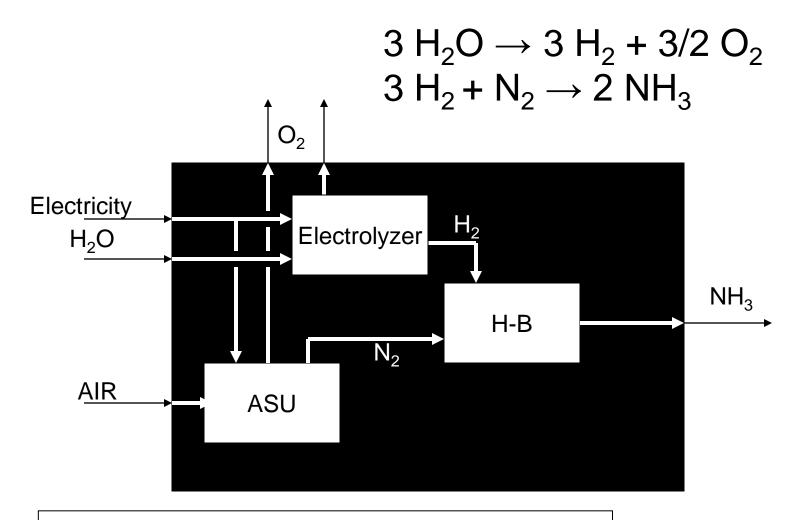
Contact: Steve Gruhn sgruhn@freedomfertilizer.com



Village-scale 3 Mt / day Mini-NH3 Plant RE Electricity Haber-Bosch

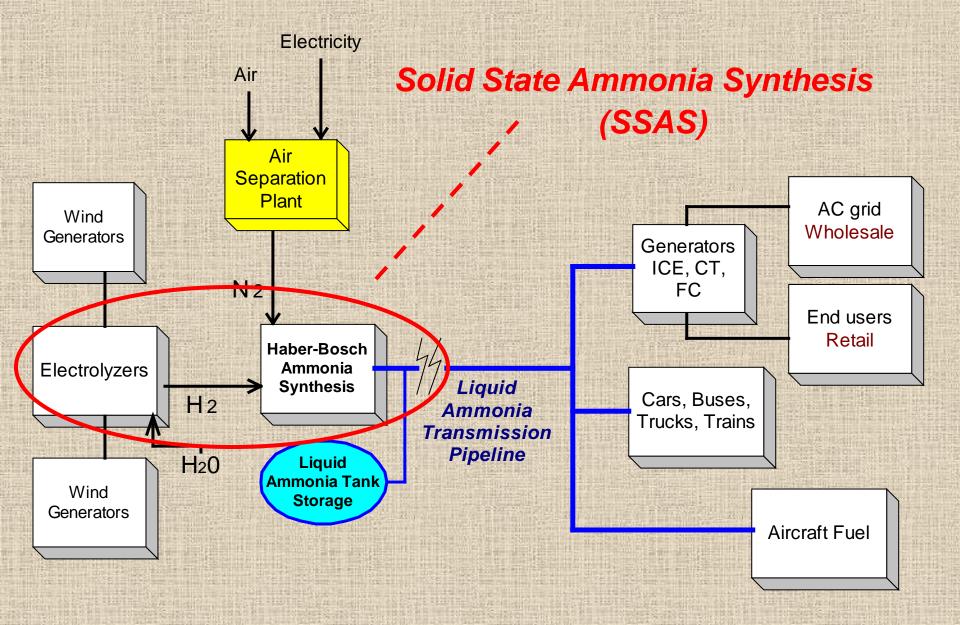


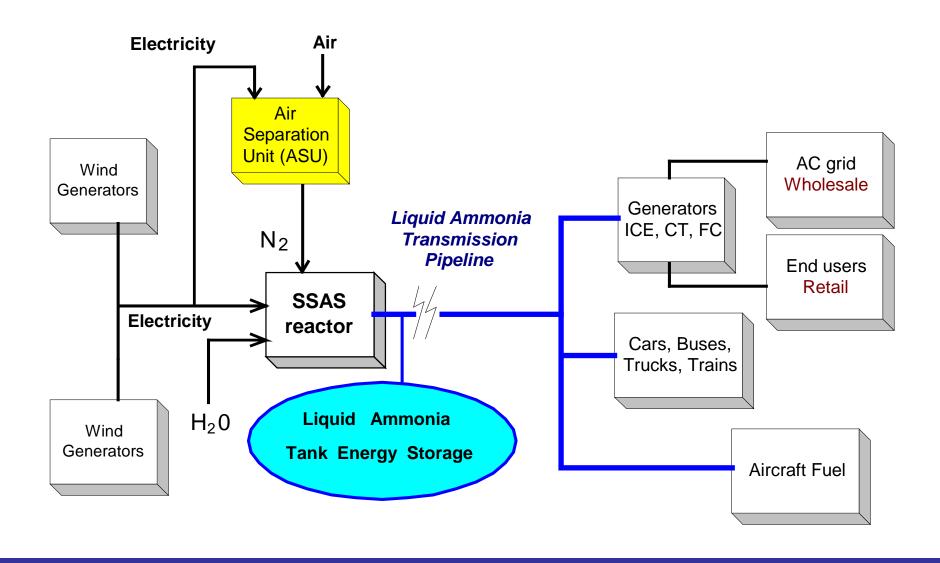
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Energy consumption ~12,000 kWh per ton NH₃

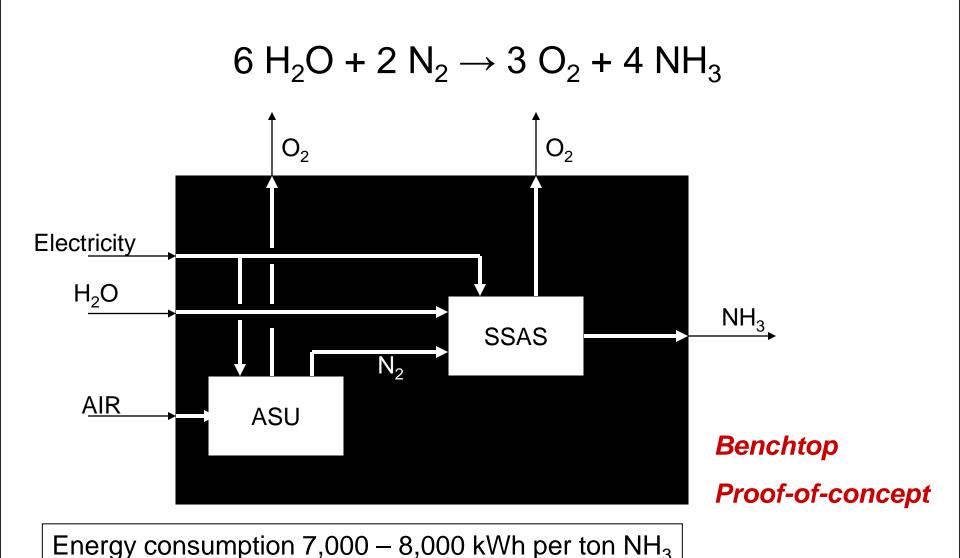
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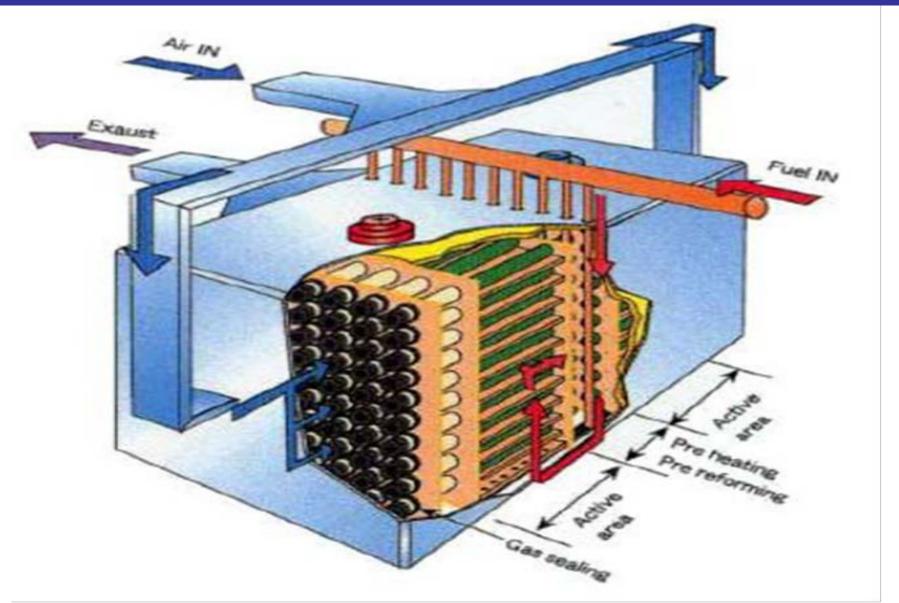


Solid State Ammonia Synthesis (SSAS)

Inside the Black Box: Solid State Ammonia Synthesis



Solid State Ammonia Synthesis (SSAS) NHThree LLC patent



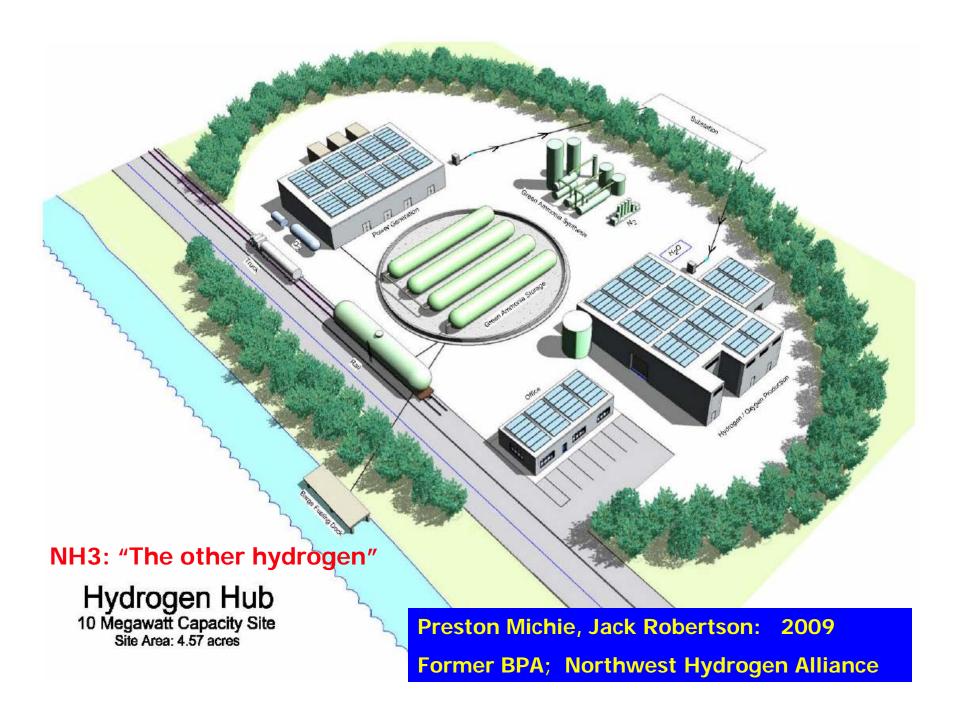
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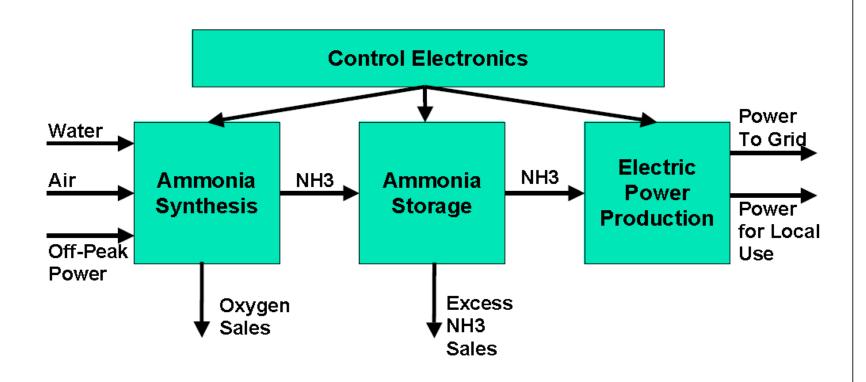
SSAS Proof-of-concept pilot plant Two-year project Alaska Applied Sciences, Inc.

NH₃ Ag Fertilizer Tanks, Wind Generators, NW Iowa





Hydrogen Hub Concept





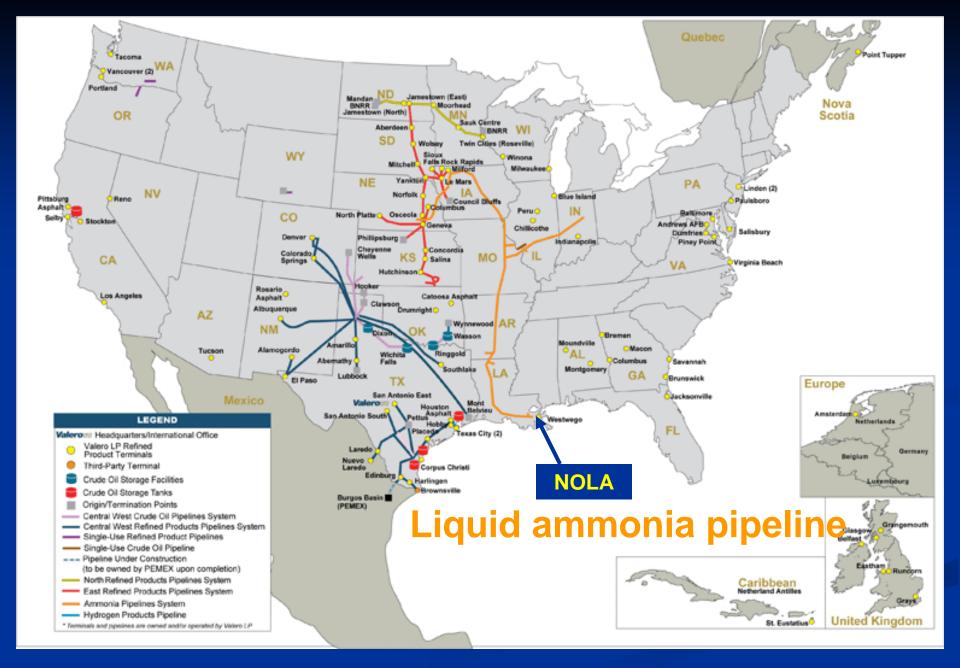
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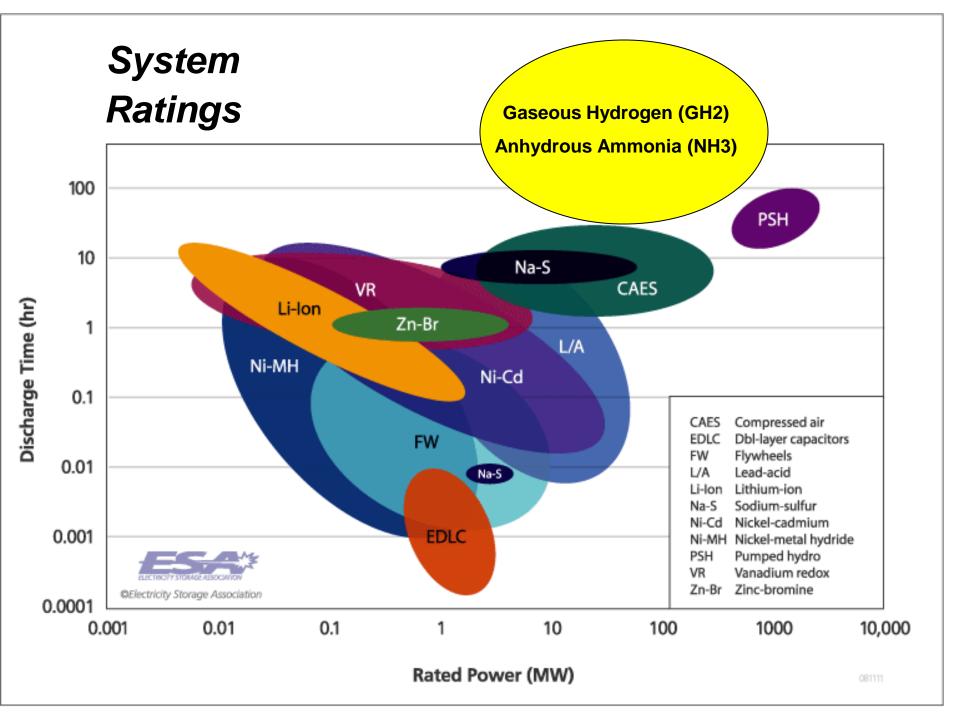
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190 GWh
\$ 15M turnkey
\$ 80 / MWh
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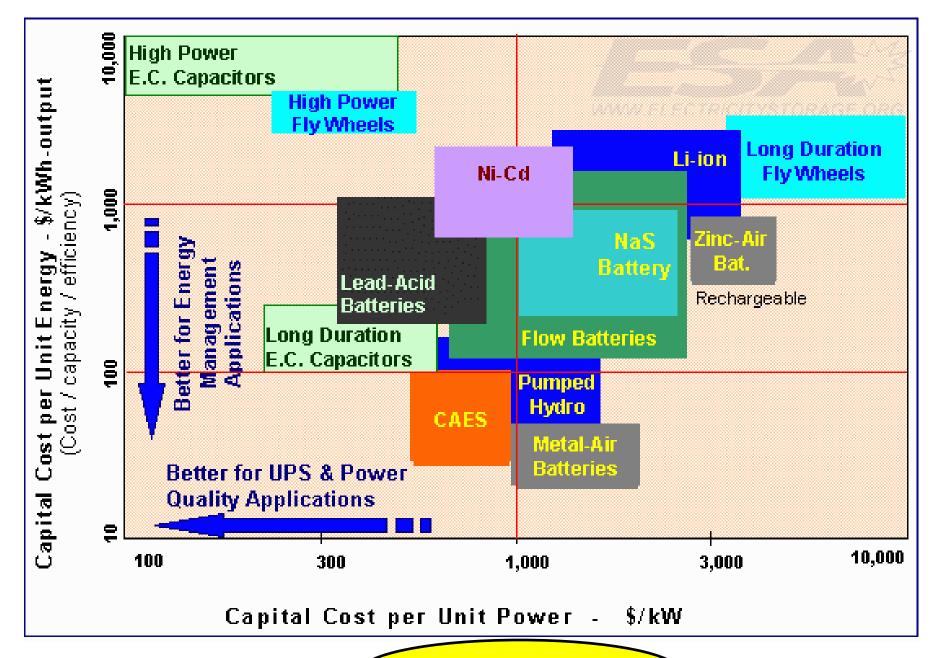
-33 C 1 Atm



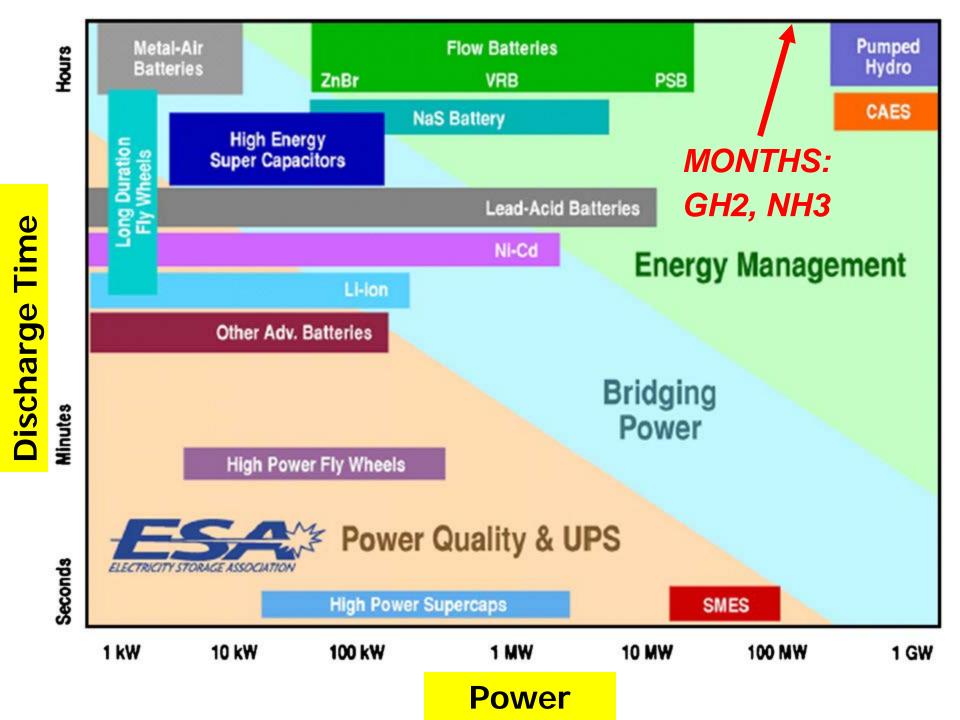
"Atmospheric" NH3 tank construction







GH2 and NH3



Energy Storage System Characteristics Hydrogen and Ammonia off the charts?

- Storage capacity (Mwh, scf, nM3, Mt, gallons)
- Power (MW, scfm) In / Out rate
- Costs
 - Capital
 - O&M
- Efficiency
- Response time
- Durability (cycling capacity)
- Reliability
- Autonomy
- Self-discharge
- Depth of discharge
- Adaptation to the generating source
- Mass and volume energy densities
- Monitoring and control equipment
- Operational constraints
- Feasibility
- Environmental
- Fresh water use

Annual Fresh Water for Energy

- USA today
- All energy = 100 Quads = 10^20 J
- 17,000 billion liters
 - "Withdrawn"
 - "Consumed"
 - Include all NG + oil "fracking"?
- If all via GH2 + NH3 feedstock:
 - Dissociated, disintegrated: H₂O → H₂ + O₂
 - 7,000 billion liters H2O
 - System efficiency vis-à-vis today's ?

Annual Fresh Water for Energy

- USA today
- All energy = 100 Quads = 10^20 J

If all via GH2 + NH3, feedstock water:

- Dissociated, disintegrated: H₂O → H₂ + O₂
- 7,000 billion liters fresh H₂O
- Gal / MWh = 63
- Liters / kWh = 0.24
- System efficiency vis-à-vis today's ?

Handout: GM 2014 panel



Exporting From 12 Windiest Great Plains States

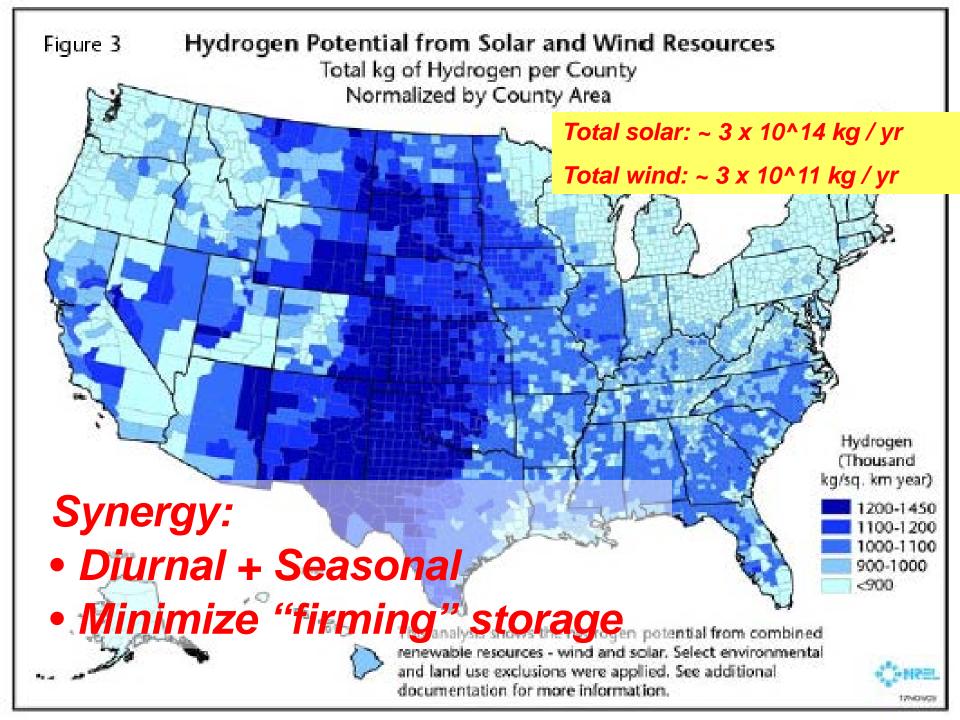
Number of GH2 pipelines or HVDC electric lines necessary to export total wind resource

Capacity at 500 miles length

Capacity Factor (CF) = 30%

						3 GW	
	Annual	Nameplate	Nameplate	6 GW	\$ Billion	500 KV	\$ Billion
	Energy	Installed	Installed	36" GH2	Total	HVDC	Total
	Production	Capacity	Capacity	Hydrogen	Capital	Electric	Capital
State	(TWh)	(MW)	(GW)	Pipelines	Cost	Lines	Cost
Texas	6,528	1,901,530	1,902	317		634	
Kansas	3,647	952,371	952	159		317	
Nebraska	3,540	917,999	918	153		306	
South Dakota	3,412	882,412	882	147		294	
Montana	3,229	944,004	944	157		315	
North Dakota	2,984	770,196	770	128		257	
Iowa	2,026	570,714	571	95		190	
Wyoming	1,944	552,073	552	92		184	
Oklahoma	1,789	516,822	517	86		172	
Minnesota	1,679	489,271	489	82		163	
New Mexico	1,645	492,083	492	82		164	
Colorado	1,288	387,220	387	65		129	
TOTALS	33,711	9,376,694	9,377	1,563	\$1,500	3,126	\$2,000

Wind energy source: Archer, Jacobson 2003





Ammonia "sector" of a benign, sustainable, equitable, global energy economy



Project Fundamentals

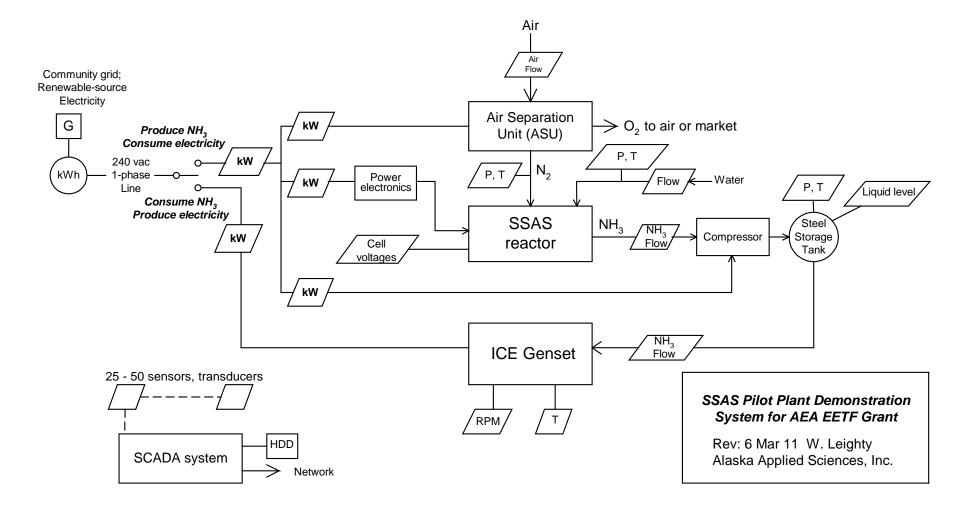
- Anhydrous ammonia (NH3) is a fuel and transmission and low-cost energy storage medium
- NH3 made from renewable energy (RE) electricity, water, and air (Nitrogen, N2) by:
 - a. Electrolysis + Haber-Bosch (EHB)
 - b. Solid State Ammonia Synthesis (SSAS)
- SSAS should best EHB in:
 - a. Capital cost per kWe in, kg NH3 out
 - b. Energy conversion efficiency
 - c. System simplicity, low O&M cost
 - d. AK value

Project Fundamentals

- 4. SSAS unproven: needs proof-of-concept, small pilot plant
- 5. Design and build pilot plant:
 - a. Complete
 - b. SCADA instrumented
 - c. Containerized & transportable
 - d. Upgradeable

6. Success:

- a. Great value to AK, beyond
- b. Next steps to commercial
- c. SA AK "RE Cluster Industry" via USFS, JEDC



PROJECT: Complete RE – NH₃ SSAS Storage System

- > NH3 synthesis from RE electricity, water, air (N₂)
- > Liquid NH₃ tank storage
- > Regeneration + grid feedback
- > SCADA instrumentation > UAF ACEP

Great Reward, and Risk

Project success: SSAS "works"

- Reactor, multi-tube
- Power electronics drive
- Regeneration from stored NH3
- SCADA: UAF ACEP download
- Complete system functions, efficient
- Complete system durable, reliable
- Cost estimates: capital, O&M

Next steps?

Great Reward, and Risk: Demonstration System for Renewable Energy (RE) Firming Storage, Transmission, and Export

AK renewable energy (RE) opportunities:

- 1. Village energy "independence"
- 2. Annual-scale firming storage
- 3. Transmission for:
 - a. Intrastate AK
 - b. RE export
- 4. Fuel for military land and sea

Scales: Village → Susitna → Global export

Project Objectives

- Run AK, world on RE: all energy, beyond electricity
- Discover and demo SSAS potential
- Demo complete RE storage system
- Begin commercialization
- Attract funding

Project Goals

- 1. Estimate efficiency
- 2. Estimate capital cost:
 - a. PCC tube area, tube
 - b. Reactor
 - c. Power electronics drive
- 3. Dynamics
- 4. TRL 5-6
- 5. Attract RE industry: AK, US, global, ARPA-E

1. Decrease Cash OUT: Village "Energy Independence" via RE Generation + Storage

- What's Annual Average RE Cost of Energy (COE) ?
- Competitive ?
- What degree of "energy independence"?
- Is SSAS required?

2. Increase Cash IN: Export AK GW-scale RE as "Green" Ammonia

- Can RE compete with "brown"?
- What would C-tax need to be ?
- What would global NG price need to be?

Opportunity: Alaska Applications

- 1. Village energy "independence": degree
 - a. Internal, external energy economies
 - b. Diverse renewable sources
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 - b. Other services
 - c. DOD Assistant Secretary Sharon Burke visit 3-7 Aug 12

Electrolysis plus Haber-Bosch (EHB) vs Solid State Ammonia Synthesis (SSAS) preliminary estimates

EHB:

11-12 kWh / kg \$1,000 / kWe input capital cost

SSAS:

7-8 kWh / kg \$500 / kWe input capital cost \$200K / Mt / day capital cost

Project Status: 30 Jul 13 AASI for AEA, for EETF program

- 1. Calculated perform: 46 m² per ton NH3 per day
- 2. AEA patience: 31 Aug 12 grant announce
- 3. NHThree LLC:
 - a. Procured cartridge for PNNL's reactor; launch AASI's TAP at PNNL, Richland, WA
 - a. Extant PCC tube inventory may be adequate for AEA project, if proven fit-for-purpose
- 4. WindToGreen LLC (W2G):
 - a. Default engineering + systems integration subcontractor
 - b. Holding lab space + personnel in Berkeley, CA incubator
 - c. Reactor design: CAD ready, options
 - d. Senior advisors group seeks <u>alternatives</u>
- 5. PNNL: Greg Coffey, PI
 - a. Technical Assistance Program (TAP)
 - b. SSAS-mode results August?

Project Status: 30 Jul 13 AASI for AEA, for EETF program

- 6. AASI: low profile, pending Milestone 1 and grant agreement. Weekly reports to AEA
- 7. UAS, Juneau test site available
- 8. AEL&P, Juneau ready to assist feedback
- 9. Collaboration potential:
 - a. KIER, Daejeon, Korea
 - b. Alaska Power & Telephone, SE Alaska
 - c. SE AK RE-CWG Action Initiative 3
 - d. Mining, data centers



W2G, Berkeley lab space, 19 Feb 13



L to R: Peter Swearengen

Jim Kennon Berkeley, CA 19 Feb 13 Jack Swearengen



Tube assembly installed in test fixture.

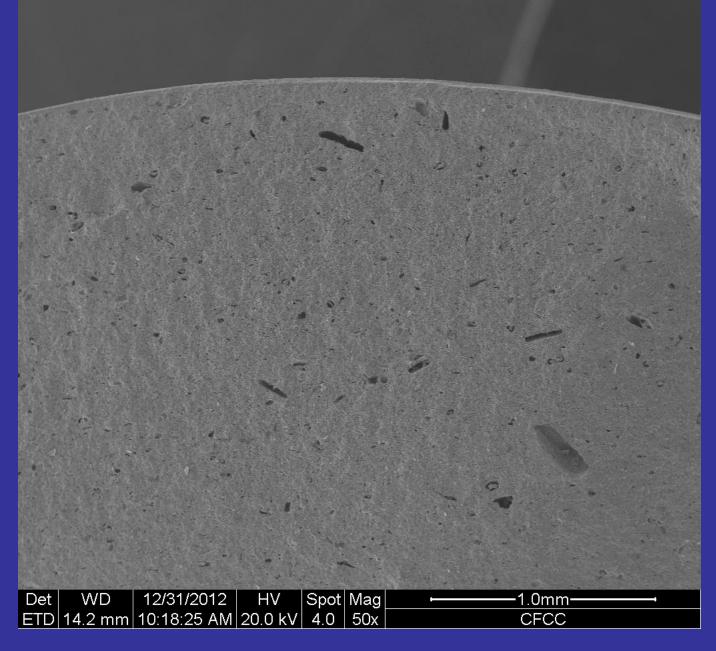
Nickel oxide cathode coating (tube interior) reduced by hydrogen to metallic nickel, ready for subsequent tests.



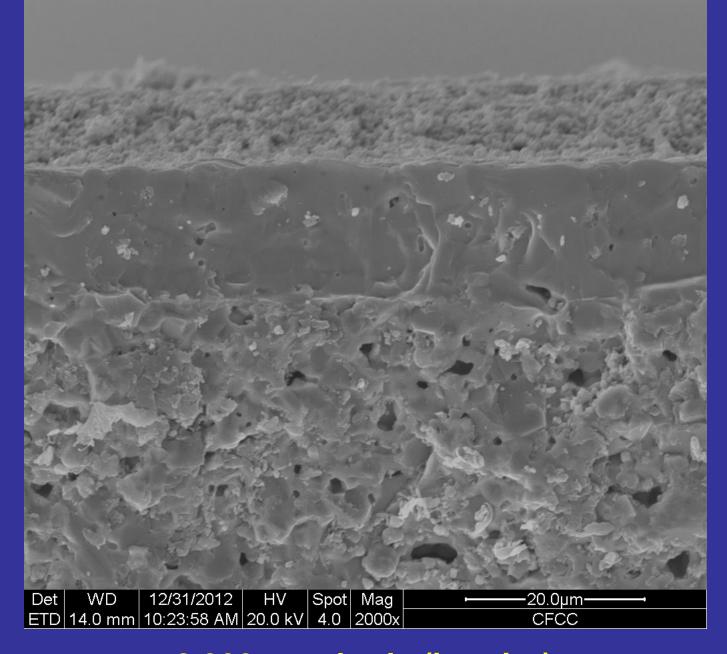
Center: PCC tube 33 cm² active area.

Current collectors installed.

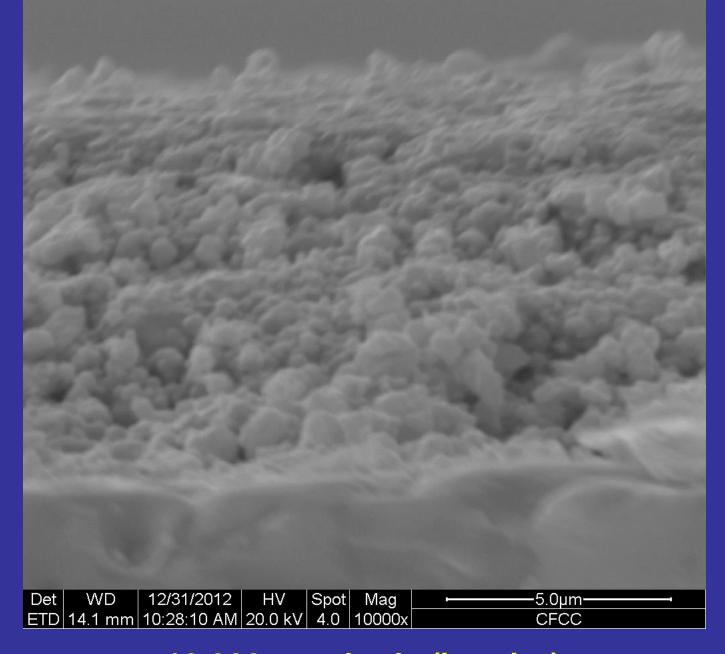
Sealed to alumina support tubes. Setup is leak-free.



50x PCC tube cross-section, anode layer (exterior)



2,000x cathode (interior)



10,000x cathode (interior)



PNNL, Richland, WA 25 Feb 13

L to R: John Holbrook, NHThree Bill Leighty, AASI Greg Coffey, PNNL

Test reactor is above Bill's left shoulder

Opportunity: Global Applications Alaska pioneers

- 1. Diverse, stranded RE
- 2. Solves Big Three problems:
 - a. Transmission
 - b. Storage
 - c. Integration
- 3. Regional, continental pipeline systems
 - a. Gathering
 - b. Transmission
 - c. Distribution
- 4. Low-cost storage: \$ 0.10 / kWh capital
- 5. End-use fuel
 - a. CHP, stationary
 - b. Transport fuel, ground + sea
 - c. Need NH3-ready equipment

Project Risks

1. Technical

- a. PCC tubes: catalysis, fragile
- b. SSAS reactor design: thermal, gas manage
- c. Electric drive: low-Z tube load
- d. Scalability: MW

2. Business

- a. Three small companies
- b. Small capital, small staff, low overhead
- c. Senior management
- d. \$750K adequate?

3. Economic, market

- a. RE-source NH3 cost / kg
- b. Competition from NG, coal NH3 plants
- c. No NH3-fueled equipment; no demand for "green" NH3
- d. Need C-tax or subsidy
- e. AK exception: energy islands, stranded RE, high prices
- f. NH3 not a "fuel"
- g. NH3 "inhalation hazard", toxic

Risk mitigation

- 1. Technical: select the best
 - a. PCC tube suppliers
 - b. Designers and consultants
 - c. Fabricators
- 2. Technical: extensive testing, upgradeable
- 3. Business:
 - a. Frequent milestones, reviews, go-nogo
 - b. Seek other funding for similar workplans
- 4. Market:
 - a. Demand: Encourage NH3-fueled equipment
 - b. Supply: Attract RE gen industry
 - c. Demonstrations
 - d. Conference papers: RE Industry
 - e. ARPA-E: Dane Boysen (REAP BCEA 2012)
 - f. SE "RE Cluster Industry" action initiatives

CONCLUDE: Great Reward / Risk

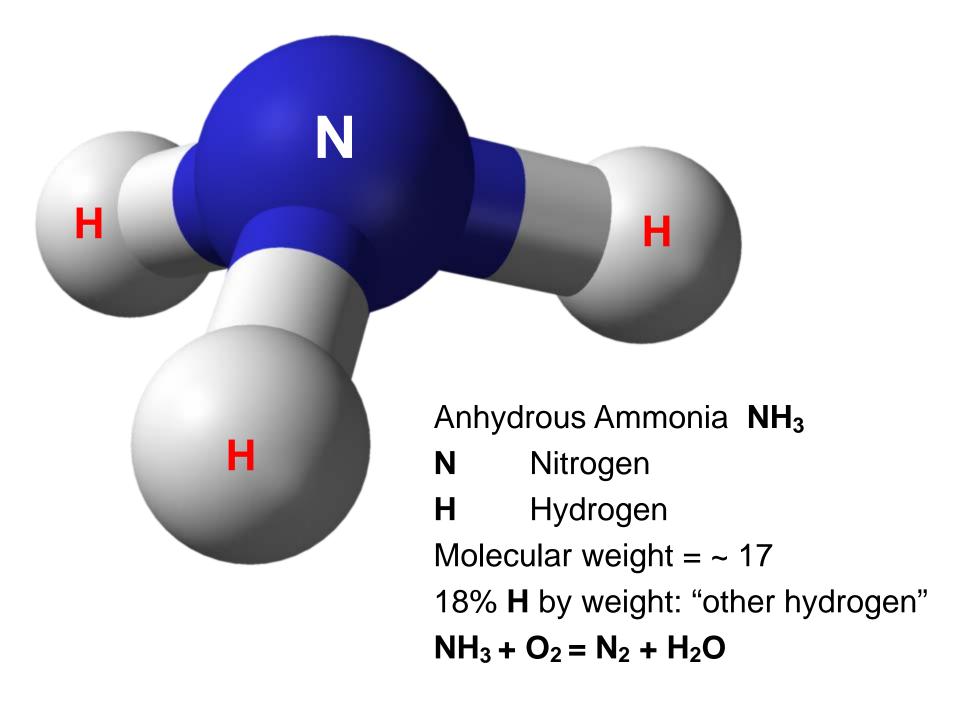
AK RE opportunities:

- 1. Village energy "independence"
- 2. Annual-scale firming storage
- 3. Transmission for:
 - a. Intrastate AK
 - b. RE export
- 4. Fuel for military land and sea

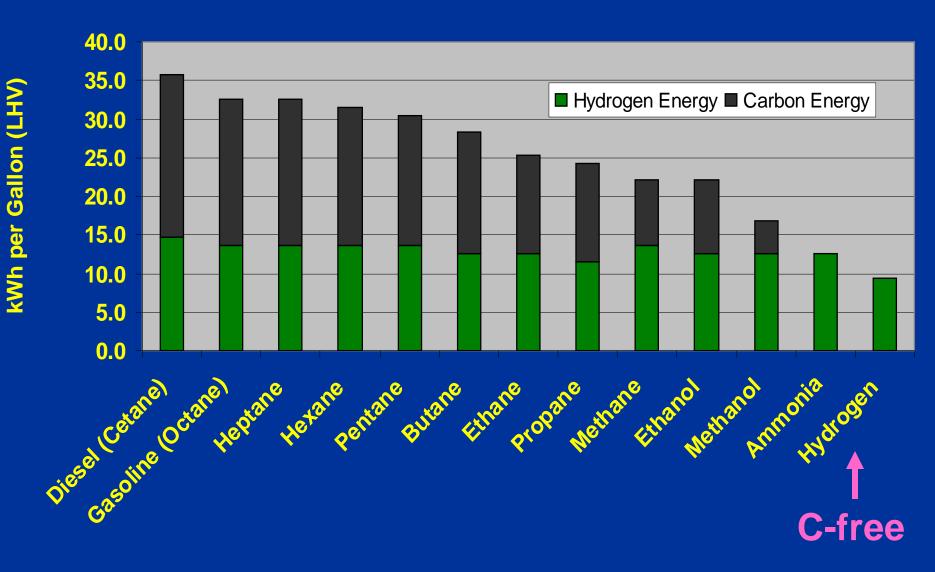
Alternatives? RE transmission, storage, integration

Need SSAS discovery and demo, now

Senior Partner Team: Run World on Renewables



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





ASME Power, 31 July 13, Boston

Bill Leighty, Principal
Alaska Applied Sciences, Inc.
Box 20993, Juneau, AK 99802
wleighty@earthlink.net
907-586-1426 206-719-5554 cell

End of 31 July presentation

ASME Power 2013

Following slides are supplemental



- 180 C at 6,000 m depth
- Closed loop hot water
- Single borehole well
- "Electro Pulse Boring" lowers cost

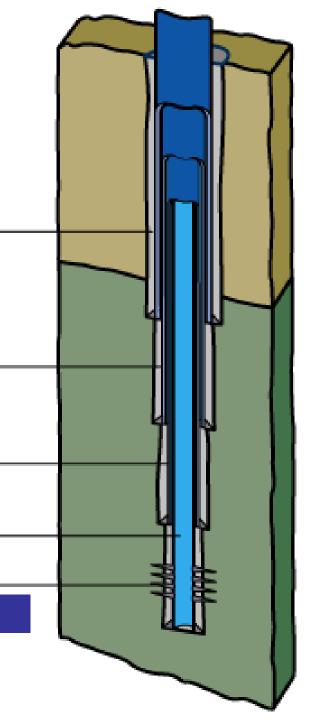
Surface casing

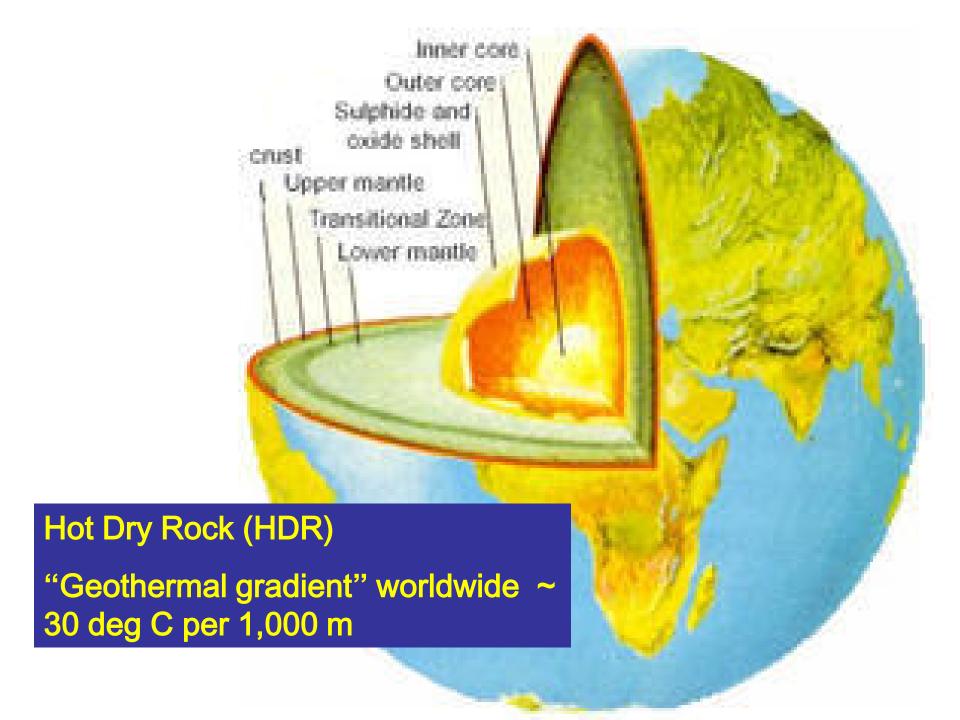
Intermediate casing

Production casing

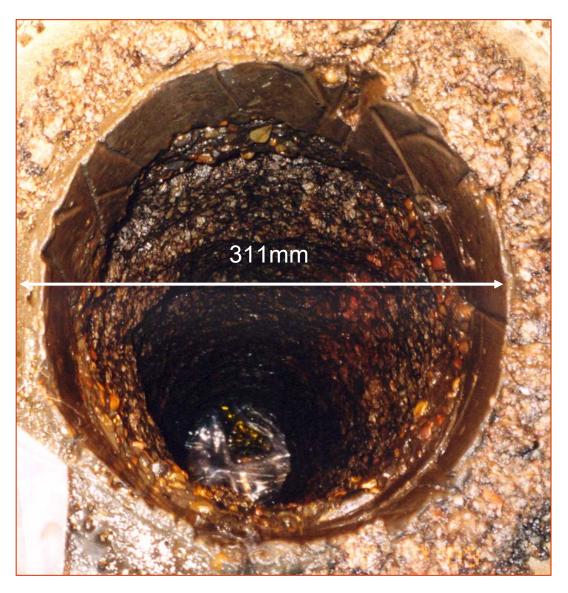
Perforated interval ____

6,000 m depth in HDR



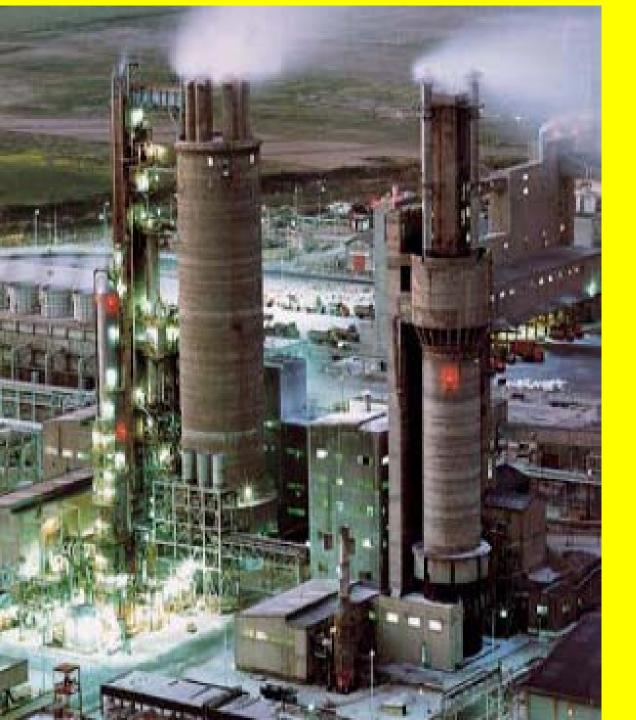


2003 : EPB Drilling Full Scale in Granite 311 mm = 12.25 "



2006 BIT DESIGN

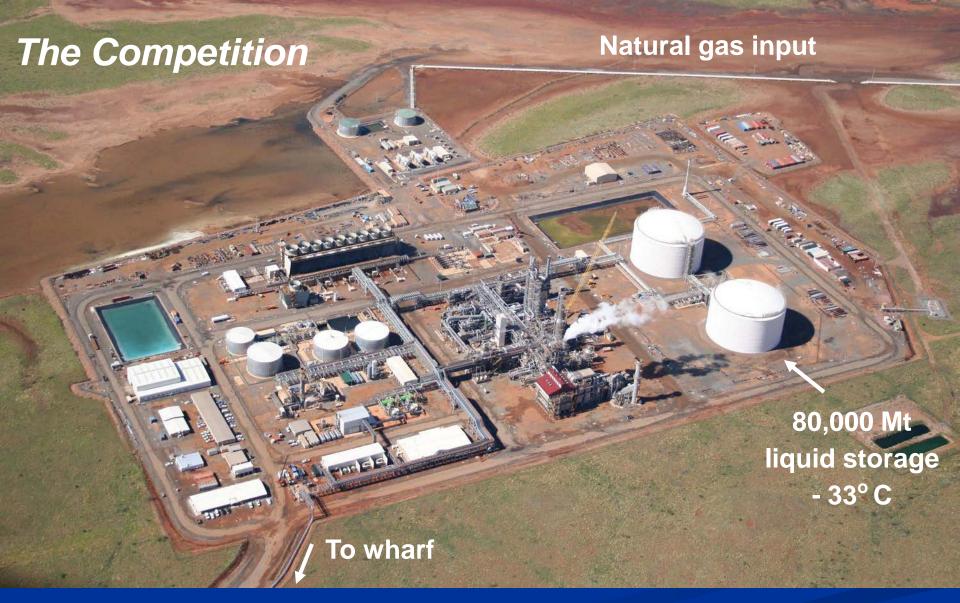




95% Global Ammonia

Synthesis
Plant
Natural Gas
1 – 3,000 tpd

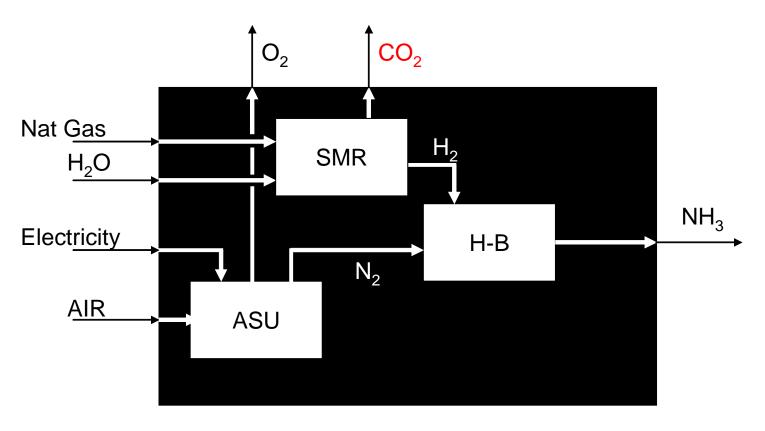
Haber-Bosch process



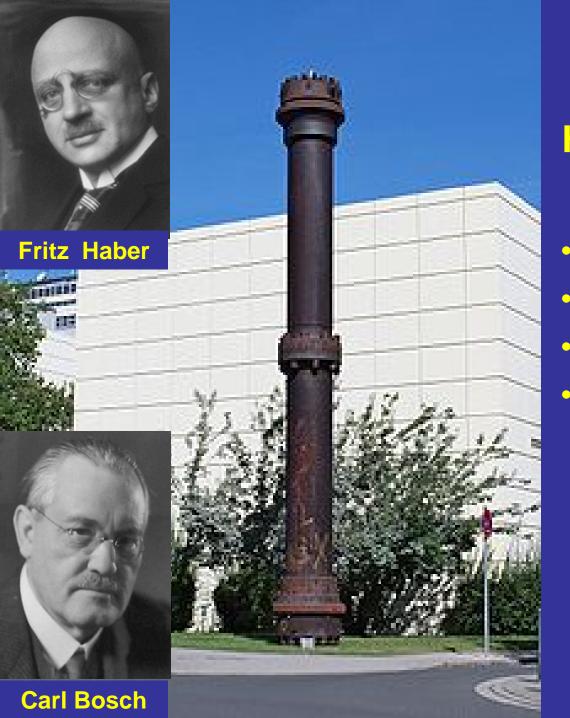
Burrup Peninsula, NW Australia, Natural Gas to Ammonia Plant 760,000 Mt / year \$US 650 million capital cost '06

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

$$3 \text{ CH}_4 + 6 \text{ H}_2\text{O} + 4 \text{ N}_2 \rightarrow 3 \text{ CO}_2 + 8 \text{ NH}_3$$



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

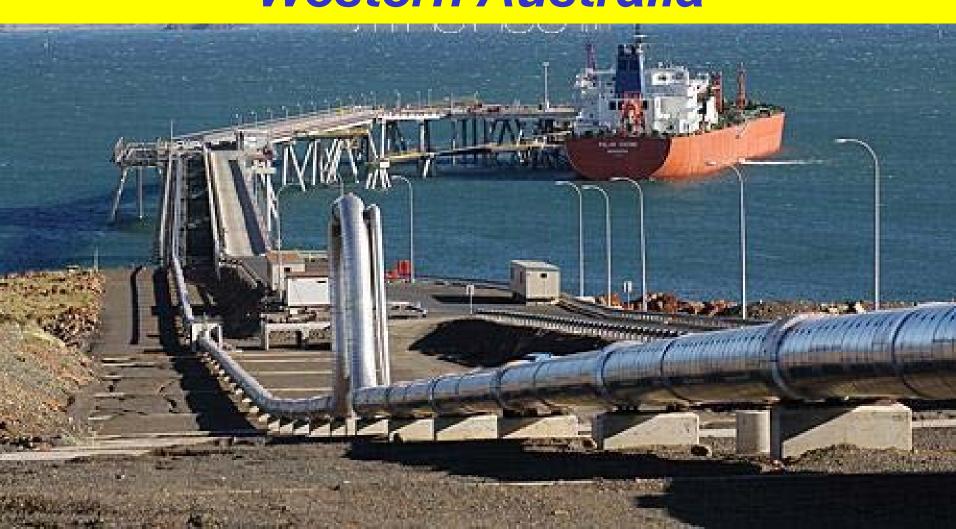


Haber-Bosch Process 1909 – 1913 BASF

- NH₃ synthesis
- Coal gasification → H2
- WW I explosives
- 40% humanity: N fertilizer

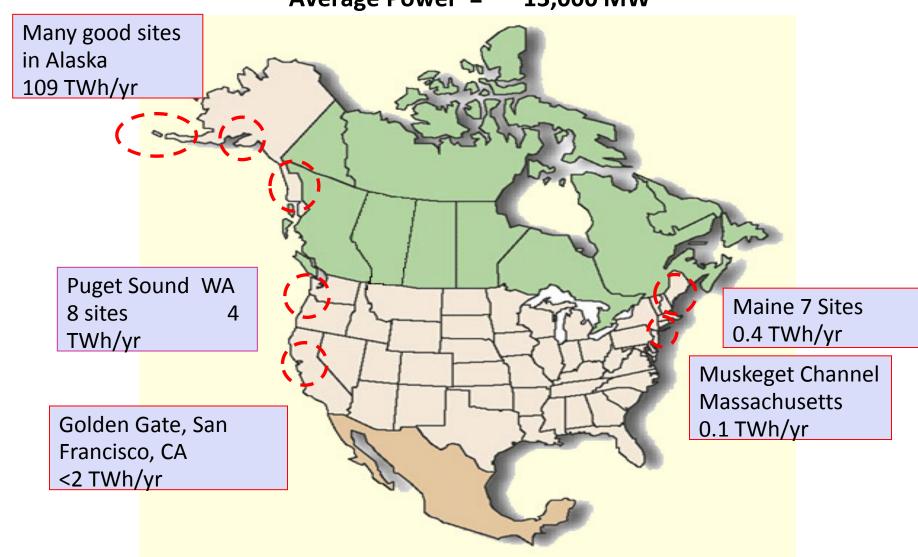
Haber-Bosch Reactor 1921 Ludwigshafen, Germany

Ammonia Tanker Burrup Peninsula Western Australia

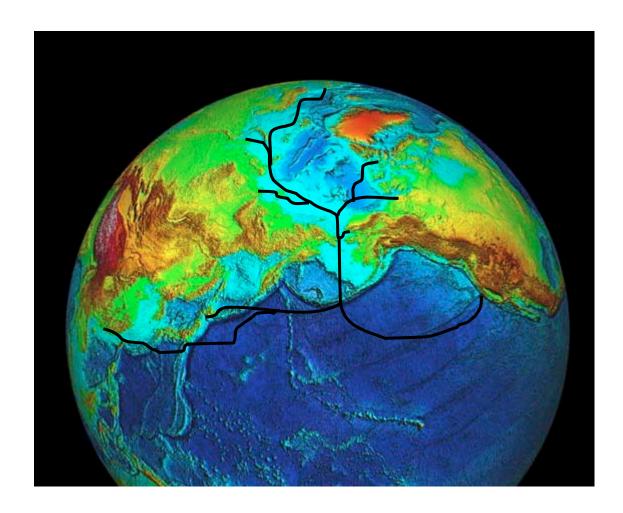


Tidal Current Energy: USA TOTAL

Primary Energy = 115 Twh/yr Average Power = 13,000 MW



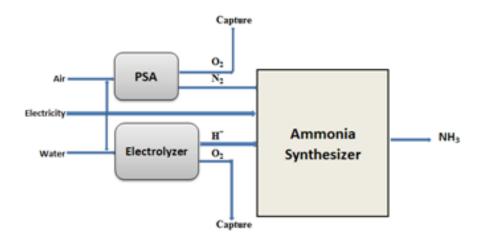
Alaska in the future global energy economy







Ammonia Production Process



The NH₃ United equipment "cracks" steam into oxygen and hydrogen and extracts nitrogen from the air in separate process steps. These elements are combined in a pressure chamber in the presence of a catalyst to form anhydrous ammonia (NH₃).

Patent pending: US 2011 / 0243828



Commercial

- 310 kg/day unit available for delivery o/a April 2013
- Currently requires ~11kWh/kg; projected to be reduced to <9.7 kWh/kg within 24 months
- Unit price US\$459,200
- Development warranty
- FOB, Fredericton, New Brunswick
- Site prep, engineering & installation to be quoted separately, if needed

AASI note: 310 kg / day = 142 kWe input

459K / 142 kW = 3,200 / kWe input

Why SSAS?

- Electrolysis + Haber-Bosch too costly
 - From RE electricity
 - Capital components at low capacity factor (CF)
 - Energy conversion losses
- Proton conducting ceramics (PCC) now
- Solid oxide fuel cell (SOFC) success
- Need stranded RE transmission
- Need RE storage

2,000 MW (nameplate) Great Plains Windplant Output

Energy production at windplant 40 % Capacity Factor:

As electricity: 19,200 MWh / day

7,000,000 MWh / year

	tons/hr	tons/day	tons/yr
As H2 @ 80% electrolysis efficiency	16	390	142,350
As NH3 @ 70% conversion efficiency	97	2,321	847,321
10" NH3 pipeline capacity as H2	11	264	96,360
10" NH3 pipeline capacity as NH3	60	1,440	525,600

Case 4a: Capital costs, no firming 2,000 MW Great Plains windplant

Elec → GH2 → NH3 → Liquid Pipeline → "Terminal" or "City gate"

Capital costs:

_	Wind generators, 1.5 MW @ \$1,500 / kW	\$ 3,000 M
-	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
Tot	al, without firming storage	\$ 5,270 M

Case 4a: Annual costs, no firming

Elec → GH2 → NH3 → Liquid Pipeline → "Terminal" or "City gate"

Unsubsidized 1

² Annual Energy Production @ \$US 0.057 / kWh

Produc	ction capital costs @ 15% CRF @ \$ 5,270 M	\$	790 M
Conve	rsion and transmission losses		
_	Electrolyzer conversion loss @ 20% AEP 2	\$	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	\$	954 M
	Total cost per mt NH3 = \$ 1,126		
	Total cost per kg NH3 = \$ 1.13		
	¹ Subsidies, value-adders: PTC, O ₂ s	ale	s, REC

Case 4b: Capital costs, Firming storage tanks 2,000 MW Great Plains windplant

Elec → GH2 → NH3 → Liquid Pipeline → Firming tanks → "Terminal" or "City gate"

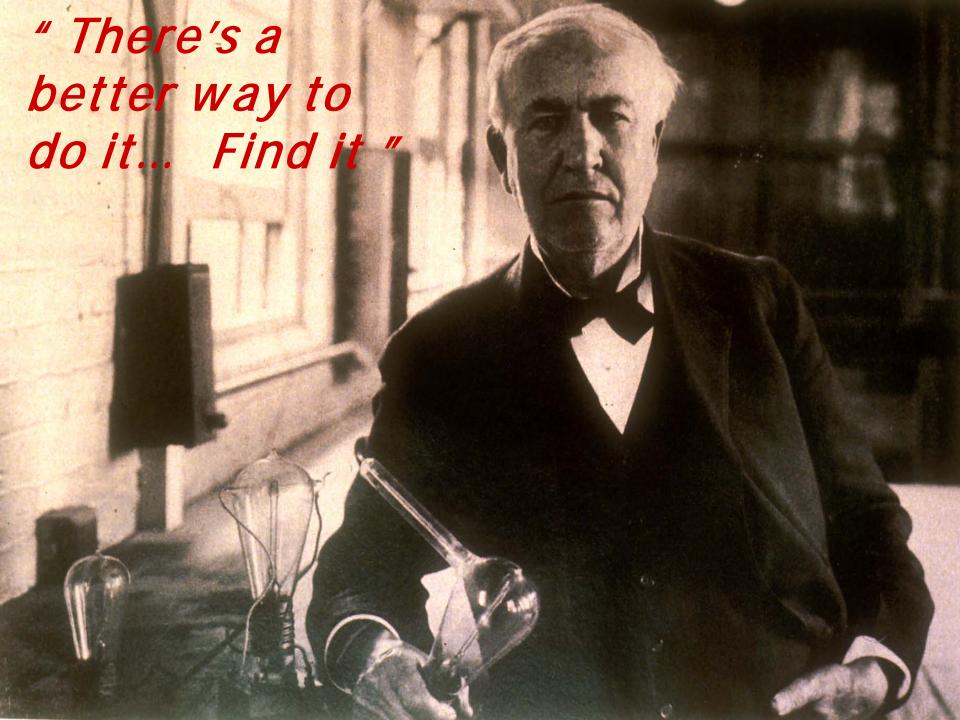
Capital costs

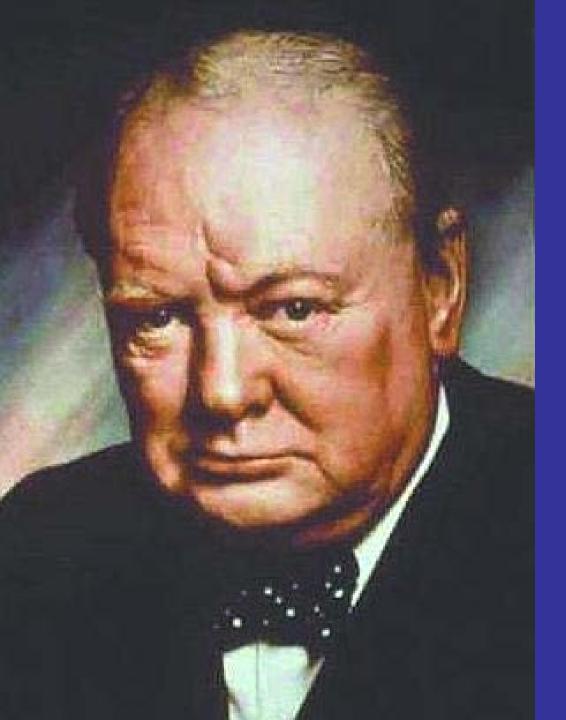
 Wind generators, 1.5 MW @ \$1,500 / kW 	\$ 3,000 M
 Electrolyzers, 450 psi out @ \$350 / kWe 	\$ 700 M
 Electrolyzer power electronics saving 	\$ 0 M
 H2 compressors 	\$ 10 M
 NH3 synthesis plant 	\$ 750 M
Pipeline	\$ 800 M
 Pipeline pumping 	\$ 8 M
 Pipeline infrastructure 	\$ 2 M
- Tanks: 4 tanks @ \$ 25 M	\$ 100 M
Total, with firming storage	\$ 5,370 M

Incremental capital cost of NH3 tanks = \$100 / 5,370 = ~ 0.2 %

Case 4b: Annual costs, Firming storage tanks 2,000 MW Great Plains windplant Elec → GH2 → NH3 → Liquid Pipeline + tanks → City gate

•	Capital costs @ 15% CRF @ \$ 5,370	\$	805 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	<u>\$</u>	<u>0 M</u>
	Total annual costs	\$	969 M
	Total cost per Mt NH3 = \$ 1,144		





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

but only after they have tried everything else "

Winston Churchill

Trouble with Renewables

- Diffuse, dispersed: gathering cost
- Richest are remote: "stranded"
 - High intensity
 - Large geographic extent
- Time-varying output:
 - "Intermittent"
 - "Firming" integration + storage required
- Distributed AND centralized

"Firm" Energy Essential

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

Trouble with Renewables: Electricity Transmission

- Grid nearly full
 - New must pay for transmission
 - Costly: AC or DC
- Integration
 - Continental energy system
 - Quality
 - Generation O+M: fatigue, wear, low efficiency
- Low capacity factor (CF) or curtailment
- Costly "firming" storage: CAES, VRB
- Overhead vulnerable: God or man
- Underground: Only HVDC, 6x cost
- FERC no interstate jurisdiction
- Wide ROW
- NIMBY: site, ROW delay + cost

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



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 costs \$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

USA NH3 Infrastructure

- USA imports ~60% of 14 MMt / year
- 3,000 miles pipelines
 - ~ 250 psi liquid
 - Smaller diameter than NG or hydrogen
- ~ 4.5 MMt large "atmospheric" tank storage
- Mild steel construction
 - Low cost
 - No corrosion or embrittlement

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" = \$ 400M
- Capacity 2 GW
- Capital cost = \$200K / GW-mile

Capital Cost per GW-mile

Electricity:		Capacity		
	<u>KV</u>	<u>MW</u>	\$M / GW-mile	
• SEIA:	765	5,000	1.3	
	345	1,000	2.6	
• AEP-AWEA	765	5,000	3.2	
Consens	us?		2.5	

Hydrogen pipeline:

36", 100 bar, 500 miles, no compress 0.3

Ammonia pipeline:

10", liquid, 500 miles, with pumping 0.2

320,000 MWh storage Annual firming 1,000 MW wind

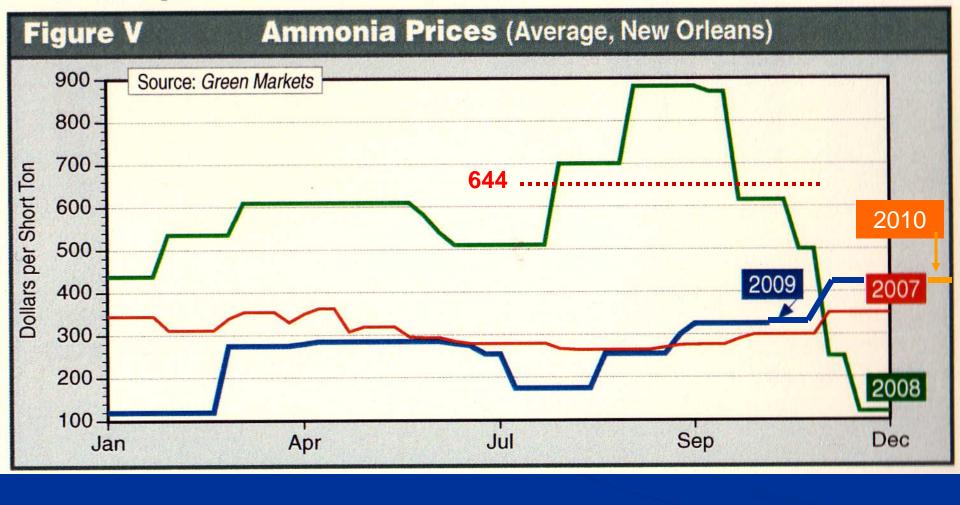
- Electricity
 - VRB (Vanadium Redox Battery)
 - O&M: 80% efficiency round-trip
 - Capital: \$500 / kWh = \$ 160 Billion
 - CAES (Compressed Air Energy Storage)
 - O&M: \$46 / MWh typical
 - Iowa Stored Energy Park:
 - Power = 268 MW
 - Energy capacity = 5,360 MWh
 - Capital: 268 MW @ \$ 1,450 / kW = \$ 390 M
 - @\$ 40 / kWh = \$ 13 Billion

\$70 Million

- @ \$1 / kWh = \$ 325M
- GH2 (3 hydrogen caverns) Capital
- NH3 (2 ammonia tanks) Capital \$30 Million

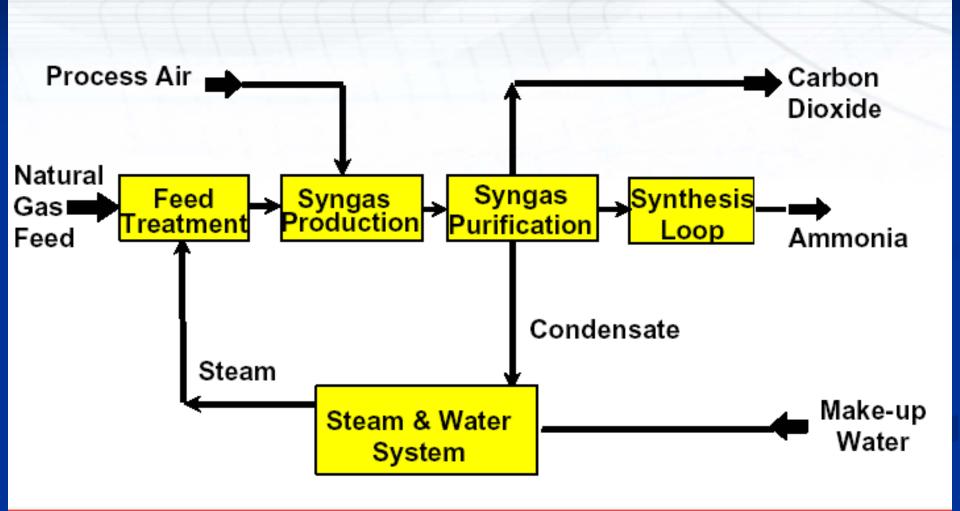
Opportunities

- Collaboration
 - International: "Run world on renewables"
 - RE systems: sources to end uses, firm and dispatchable
 - USA lead ? Korea ?
 - R&D
 - Demonstrations & pilot plants
- Solid State Ammonia Synthesis (SSAS)
 - RE electricity + water + N₂ → NH₃
 - Proof-of-concept pilot plant
 - Technical + economic promise?
 - Several processes ?
 - NHThree LLC patented PCC
 - Hydrogen Engine Center lithium
 - Other?
- End use: stationary, transportation, fertilizer
- Commercialization



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

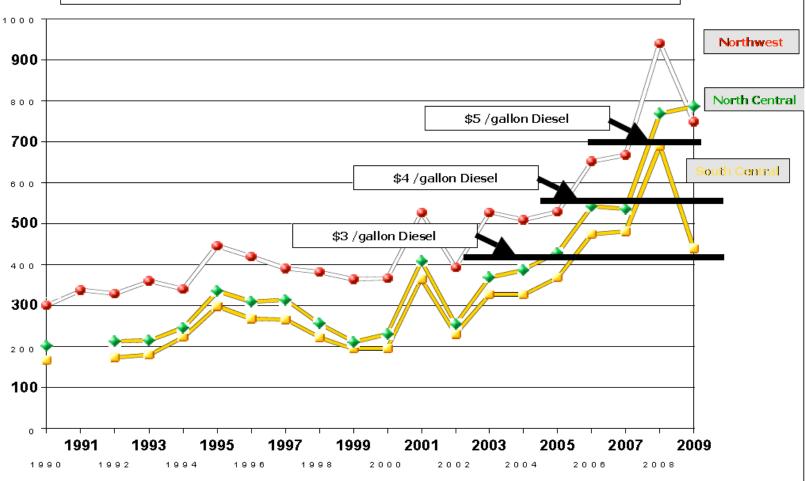
Sections in an Ammonia Plant





Ammonia Can Be Cheaper Than Diesel





Year

Humanity's Goal

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

- CANNOT with only electricity transmission
- "Transmission" must include GH2, NH3, other

Beyond "Smart Grid"

- Primarily DSM
- More vulnerable to cyberattack?
- Adds no physical:
 - Transmission, gathering, distribution
 - Storage
- Next big thing; panacea
- Running the world on renewables?
- Must think:
 - Beyond electricity
 - Complete energy systems

