The Alaska Renewable-Source Ammonia Fuel Pilot Plant: Village Energy Independence, Firming Storage, and Renewables Export

Renewable Energy World

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ARCTIC OCEAN
CHUKCHI SEA
BEAUFORT SEA
GULF OF ANADYR
CHUKOTK
RUSSIA UNITED STATES
BERING SEA
GULF OF ALASKA
PACIFIC OCEAN
FAR NORTH
INTERIOR
SOUTHWEST
SOUTHCENTRAL
INSIDE PASSAGE
Barrow
Wainwright
Point Hope
Prudhoe Bay
Deadhorse
Umiat
Noatak
Kotzebue
Noorvik
Selawik
Shishmaref
Wales
Little Diomede
Uelen
Lavrentiya
Provideniya
Gambell
Savoonga
ST. LAWRENCE ISLAND
Teller
Taylor
Pilgrim Springs
Nome
Council
White Mountain
GATES OF THE ARCTIC NAT'L PARK & PRESERVE
Anaktuvuk Pass
BROOKS RANGE
ARCTIC NATIONAL WILDLIFE REFUGE
Arctic Village
ARCTIC CIRCLE
Bettles
Coldfoot
Huslia
U.S.A. ALASKA
CANADA YUKON
Fort Yukon
Stevens Village
Nulato
Galena
Tanana
Rampart
Unalakleet
St. Michael
Emmonak
ST. MATTHEW ISLAND
Manley Hot Springs
Central
Circle
Chena Hot Springs
Fairbanks
North Pole
Nenana
YUKON-CHARLEY RIVERS NAT'L PRESERVE
Scammon Bay
Hooper Bay
Saint Marys
Holy Cross
DENALI NAT'L PARK & PRESERVE
Kantishna
MT. McKINLEY
Healy
Cantwell
Delta Jct.
Eagle
Chicken
Boundary
Dawson City
Mekoryuk
NUNIVAK ISLAND
McGrath
KUSKOKWIM MTNS
Bethel
Aniak
Kuskokwim River
ALASKA RANGE
Paxson
Tok
Northway
Talkeetna
Willow
Houston
Big Lake
Wasilla
Sutton
Lake Louise
Gakona Jct.
Glennallen
Nabesna
Beaver Creek
PRIBILOF ISLANDS
ST. PAUL ISLAND
ST. GEORGE ISLAND
KISKA ISLAND
Quinhagak
Goodnews Bay
TOGIAK NAT'L WILDLIFE REFUGE
Dillingham
LK. CLARK NAT'L PARK & PRESERVE
Lake Clark
Iliamna
Iliamna Lake
Anchorage
Palmer
Copper Center
CHUGACH MTNS
Chitina
Kennicott
McCarthy
Kenai
Soldotna
Whittier
Valdez
PRINCE WILLIAM SOUND
Cordova
Ninilchik
Anchor Pt.
Homer
Seldovia
Seward
COOK INLET
KENAI FJORDS NAT'L PARK
Naknek
King Salmon
KATMAI NAT'L PARK & PRESERVE
WRANGELL-ST. ELIAS NAT'L PARK & PRESERVE
Carmacks
Ross River
N.W. TERRITORY
YUKON
Kluane Lake
Destruction Bay
Haines Junction
KLUANE NAT'L PARK
Lake Laberge
Whitehorse
ALEUTIAN ISLANDS
ANIAKCHAK NAT'L MONUMENT & PRESERVE
Port Lions
Kodiak
KODIAK ISLAND
Old Harbor
KODIAK NATIONAL WILDLIFE REFUGE
Dutch Harbor
Unalaska
Akutan
False Pass
Cold Bay
King Cove
Chignik
Sand Point
Yakutat
White Pass Summit
Carcross
Watson Lake
BRITISH COLUMBIA
Haines
Skagway
GLACIER BAY NAT'L PARK & PRESERVE
Gustavus
Auke Bay
Juneau
Elfin Cove
Pelican
Hoonah
Tenakee
Tracy Arm
Angoon
Stikine River
Sitka
Kake
Petersburg
Wrangell
Hyder
Stewart
MISTY FIORDS NAT'L MONUMENT WILDERNESS
Hollis
Ketchikan
Metlakatla
Prince Rupert

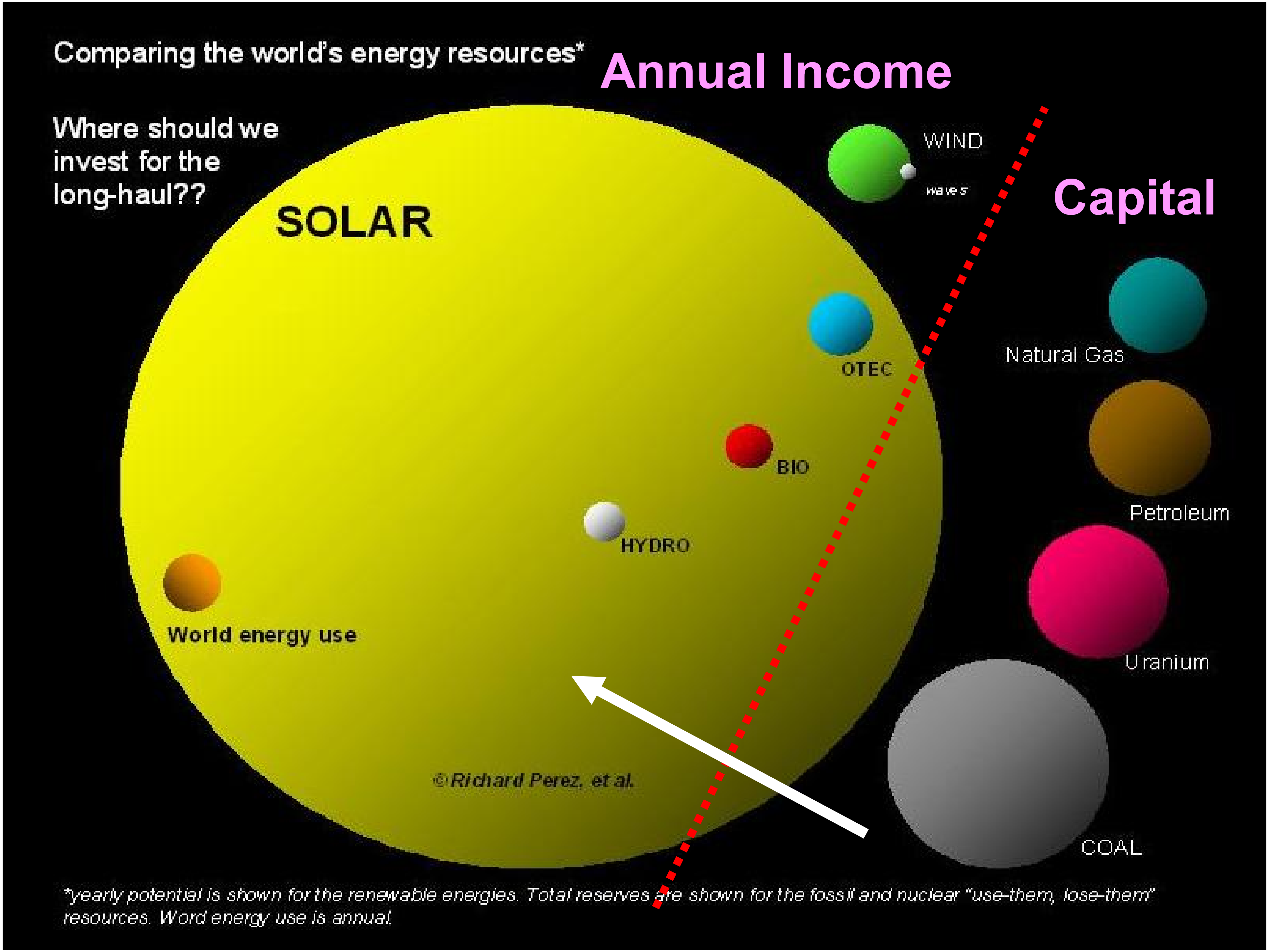
Mendenhall Glacier, Juneau, AK

June '71

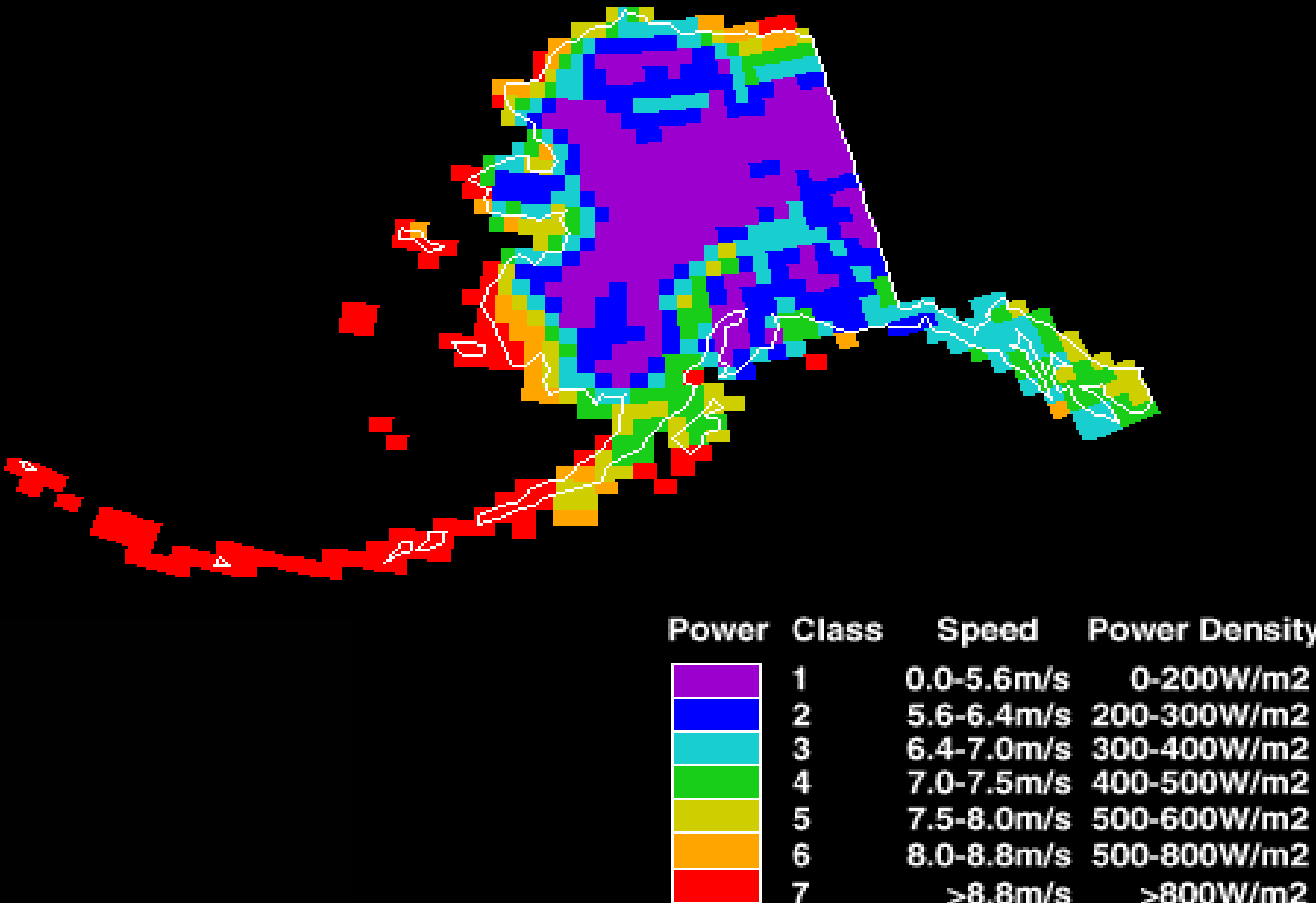
Mendenhall Glacier, Juneau, AK

10 October 10

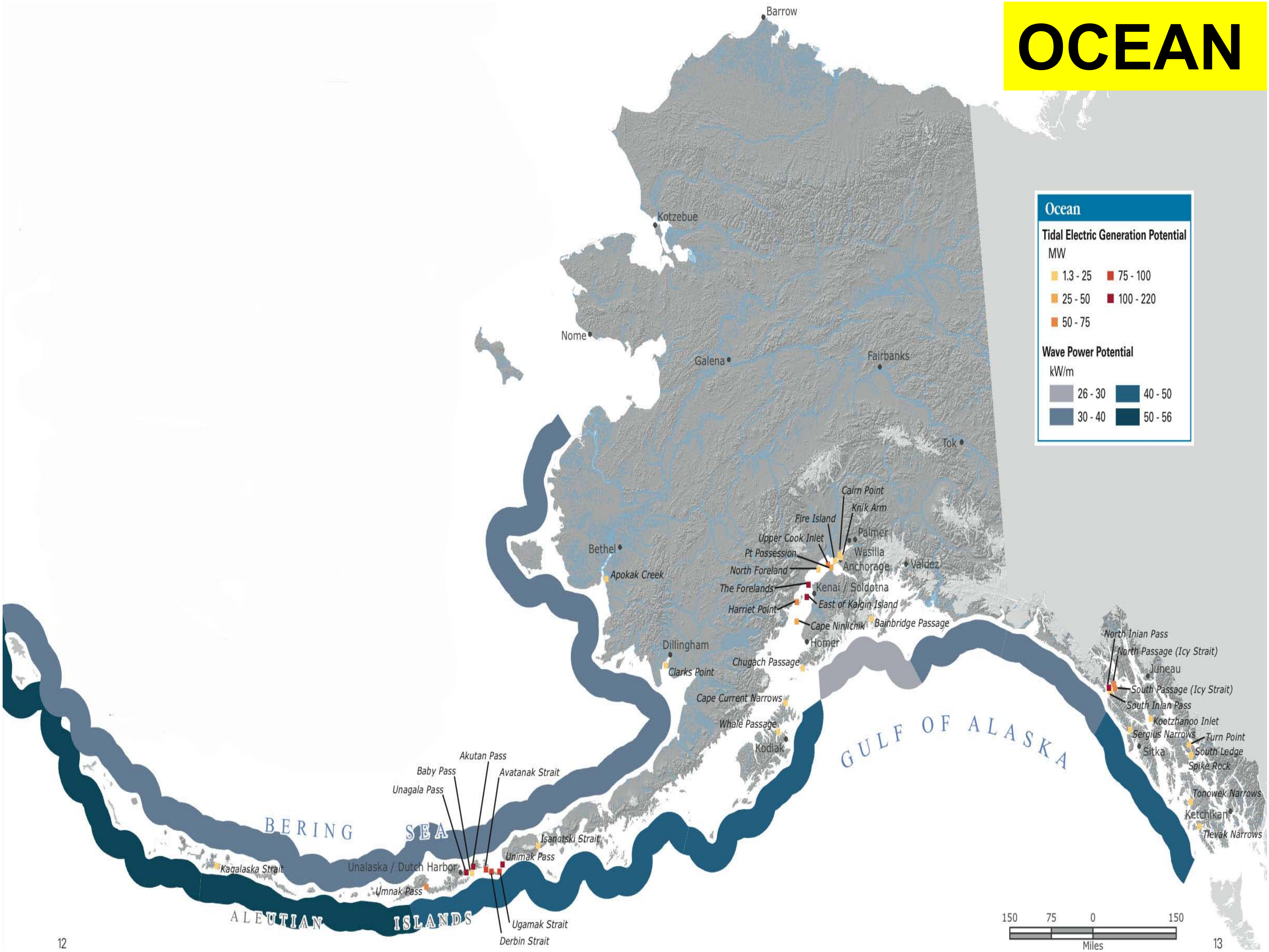
Mendenhall Glacier, Juneau, AK
10 October 10


Comparing the world's energy resources*
Annual Income
Where should we invest for the long-haul??
SOLAR
WIND
waves
Capital
Natural Gas
OTEC
BIO
Petroleum
HYDRO
World energy use
Uranium
© Richard Perez, et al.
COAL
*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

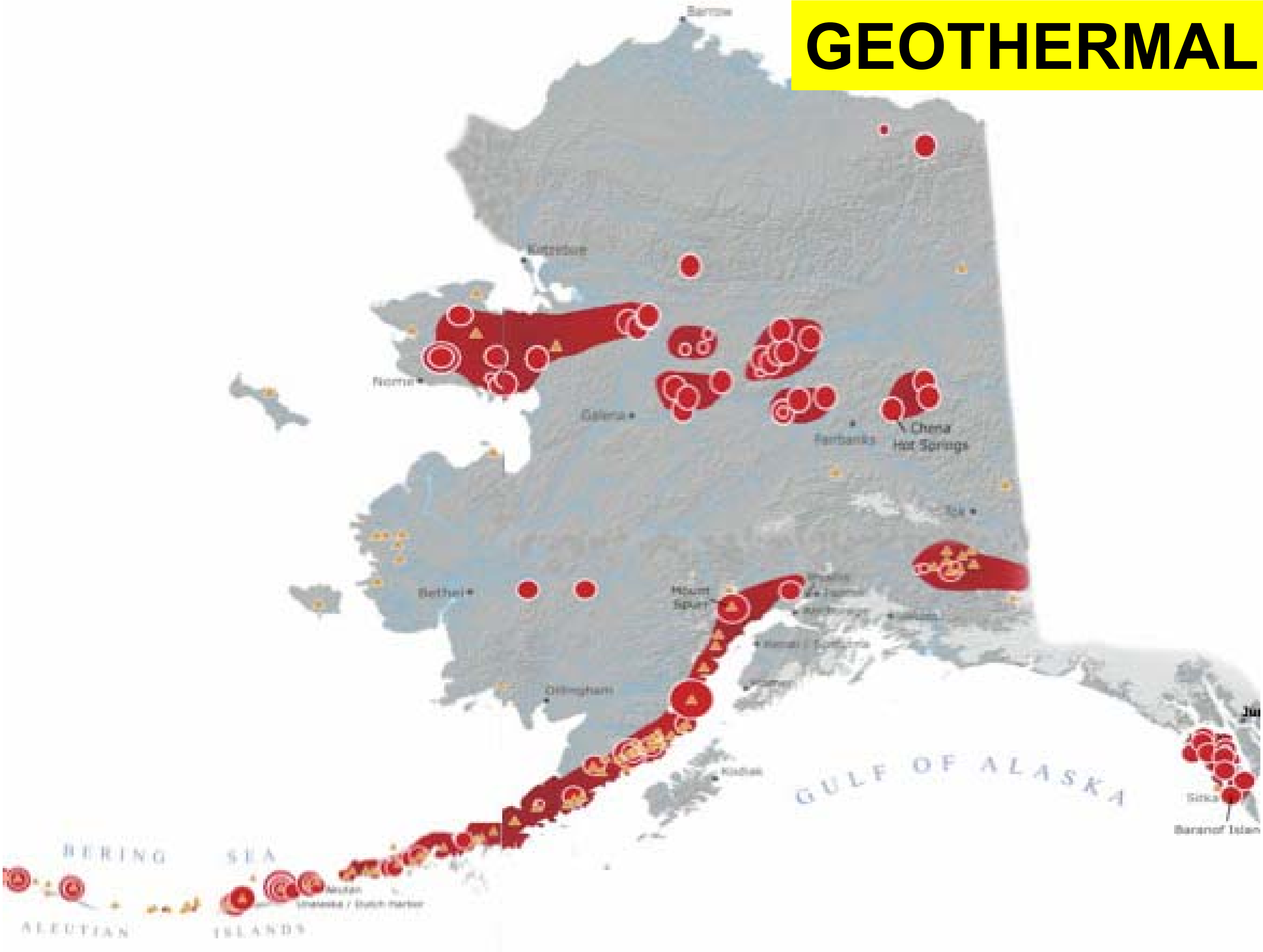


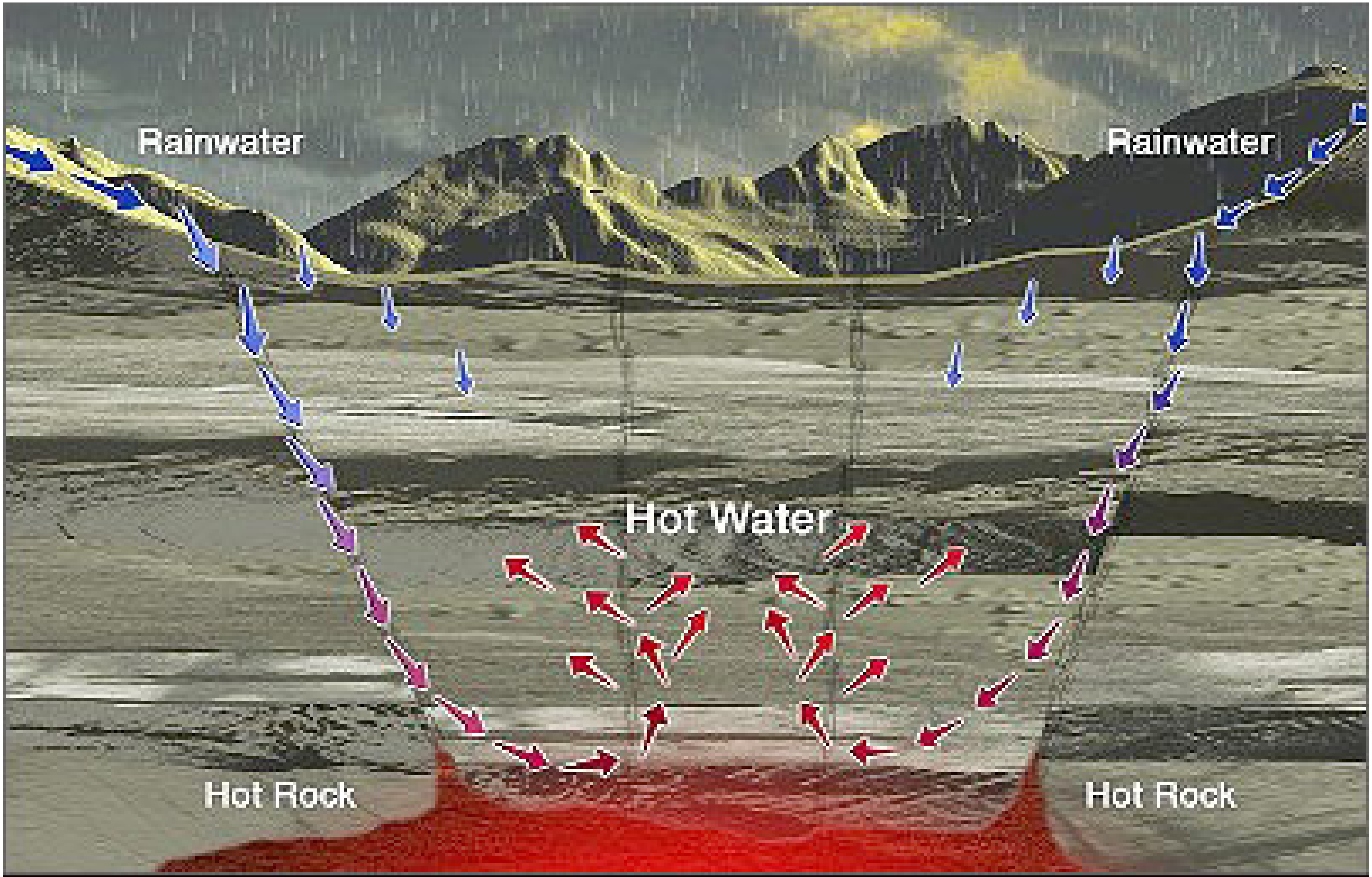
OCEAN



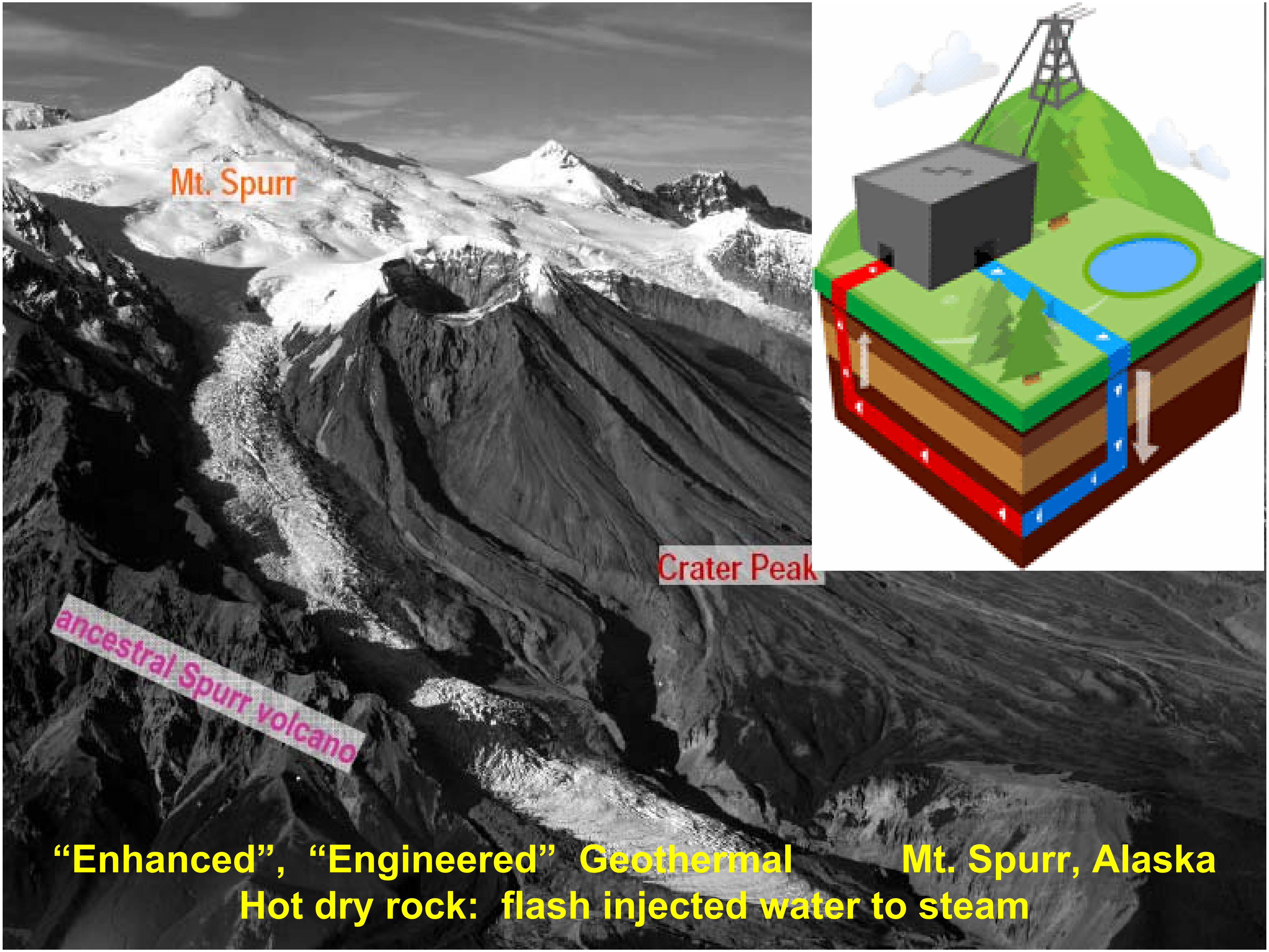
Ocean
Tidal Electric Generation Potential
MW
1.3 - 25
25 - 50
50 - 75
75 - 100
100 - 220
Wave Power Potential
kW/m
26 - 30
30 - 40
40 - 50
50 - 56
Barrow
Kotzebue
Nome
Galena
Fairbanks
Tok
Bethel
Apokak Creek
Dillingham
Clarks Point
Cairn Point
Knik Arm
Fire Island
Upper Cook Inlet
Pt Possession
North Foreland
The Forelands
Harriet Point
Palmer
Wasilla
Anchorage
Valdez
Kenai / Soldotna
East of Kalgin Island
Cape Ninilchik
Bainbridge Passage
Homer
Chugach Passage
Cape Current Narrows
Whale Passage
Kodiak
GULF OF ALASKA
BERING SEA
ALEUTIAN ISLANDS
Akutan Pass
Baby Pass
Avatanak Strait
Unagala Pass
Unalaska / Dutch Harbor
Isanotski Strait
Unimak Pass
Kagalaska Strait
Umnak Pass
Ugamak Strait
Derbin Strait
North Inian Pass
North Passage (Icy Strait)
Juneau
South Passage (Icy Strait)
South Inian Pass
Kootzhanoo Inlet
Sergius Narrows
Turn Point
Sitka
South Ledge
Spike Rock
Tonowek Narrows
Ketchikan
Tlevak Narrows
150 75 0 150
Miles

GEOTHERMAL


Barrow
Kotzebue
Nome
Galena
Chena
Hot Springs
Fairbanks
Tok
Bethel
Mount
Spurr
Dillingham
Kodiak
GULF OF ALASKA
Sitka
Baranof Islan
BERING SEA
ALEUTIAN ISLANDS
Akutan
Unalaska / Dutch Harbor



Geothermal: hot water, surface recharge


Mt. Spurr
Crater Peak
ancestral Spurr volcano
"Enhanced", "Engineered" Geothermal Mt. Spurr, Alaska
Hot dry rock: flash injected water to steam

Hydro

Alaska's Renewable Energy (RE) Goals

- 150+ community "energy islands":
  - Affordable
  - Indigenous; independence
  - Survival: outmigration
  - All energy, all uses: elec, heat, transport
  - Annual-scale, low-cost storage
- "Firm" large RE: Susitna Dam electricity
- Export large RE: "green" ammonia fuel
- Cluster industry: employment
- Prevent:

1. Rapid climate change: warming
2. Ocean acidification
3. Sea level rise
4. Species extinction

Trouble with Renewables

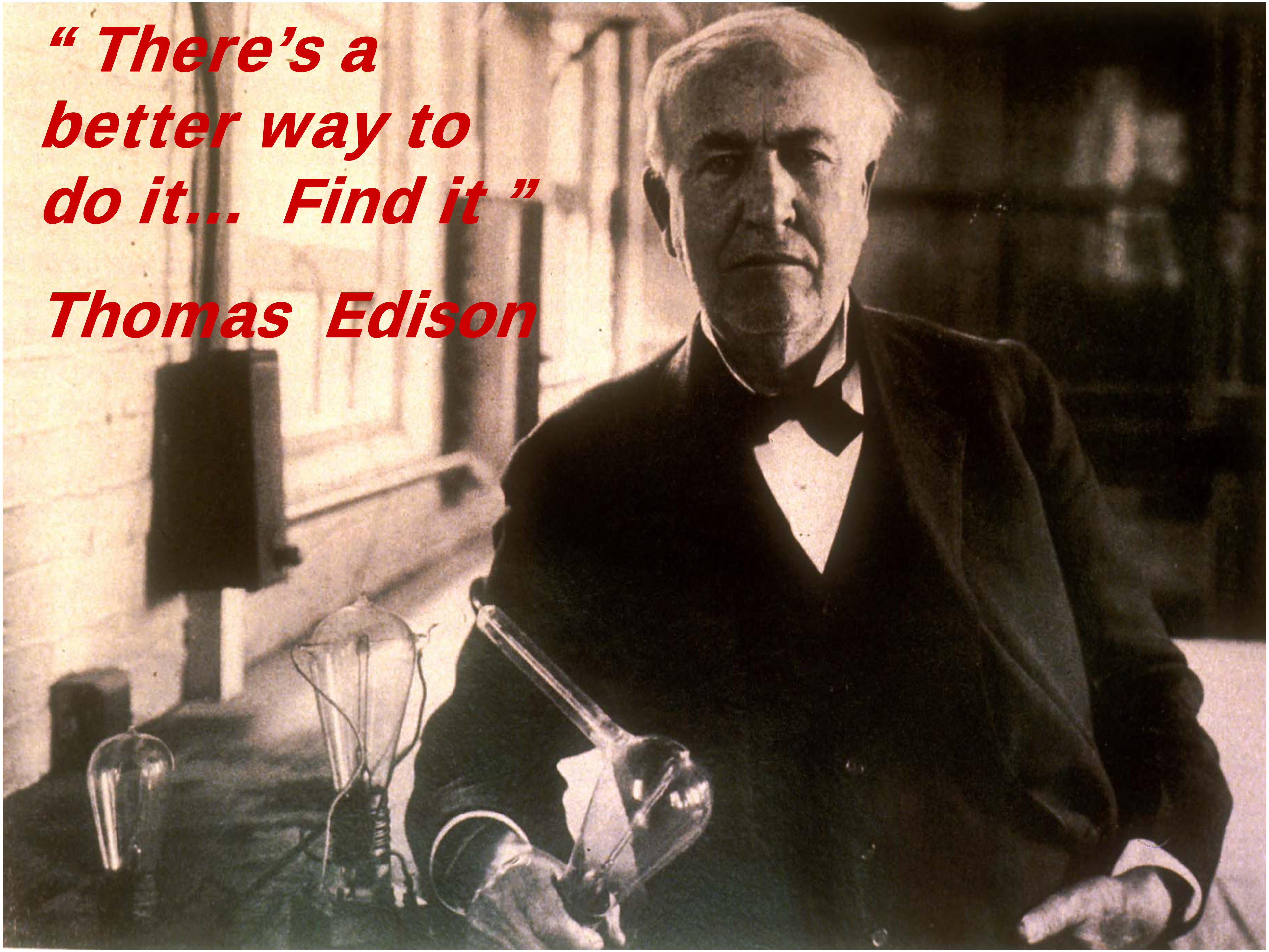
- Diffuse, dispersed: gathering cost
- Richest are remote: “stranded”
  - High intensity
  - Large geographic extent
- Time-varying output:
  - “Intermittent”
  - “Firming” integration + storage required
- “Energy island” communities, Alaska

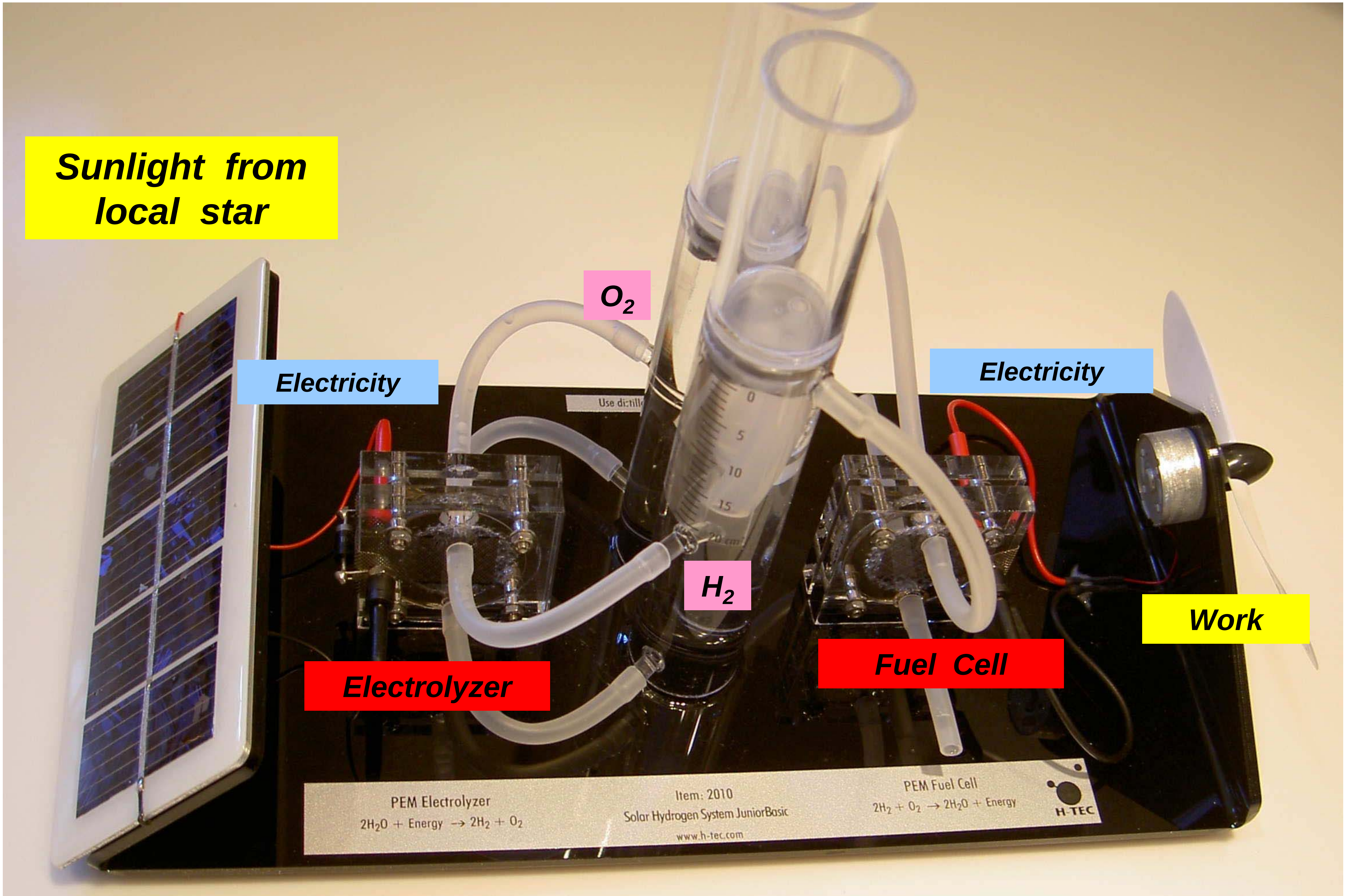
Trouble with Renewables: Big Three

1. Transmission and gathering
2. Storage: Annual-scale firming
3. Integration
   - Extant energy systems
   - Electricity grid
   - Fuels: CHP, transportation
   - Macro: “centralized plants”
   - Micro: distributed gen (DG), microgrids

Trouble with Renewables: Electricity Transmission

- Grid nearly full: who pays?
- Integration
  - Distributed AND centralized: utilities squeezed
  - Continental energy system
  - Quality
  - Time-varying
- Costly “firming” storage: CAES, VRB, pump hydro
- Low capacity factor (CF) or curtailment
- Overhead vulnerable: God or man
- Underground: only HVDC, 6x cost
- Wide ROW
- NIMBY: delay + cost,   site + ROW


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



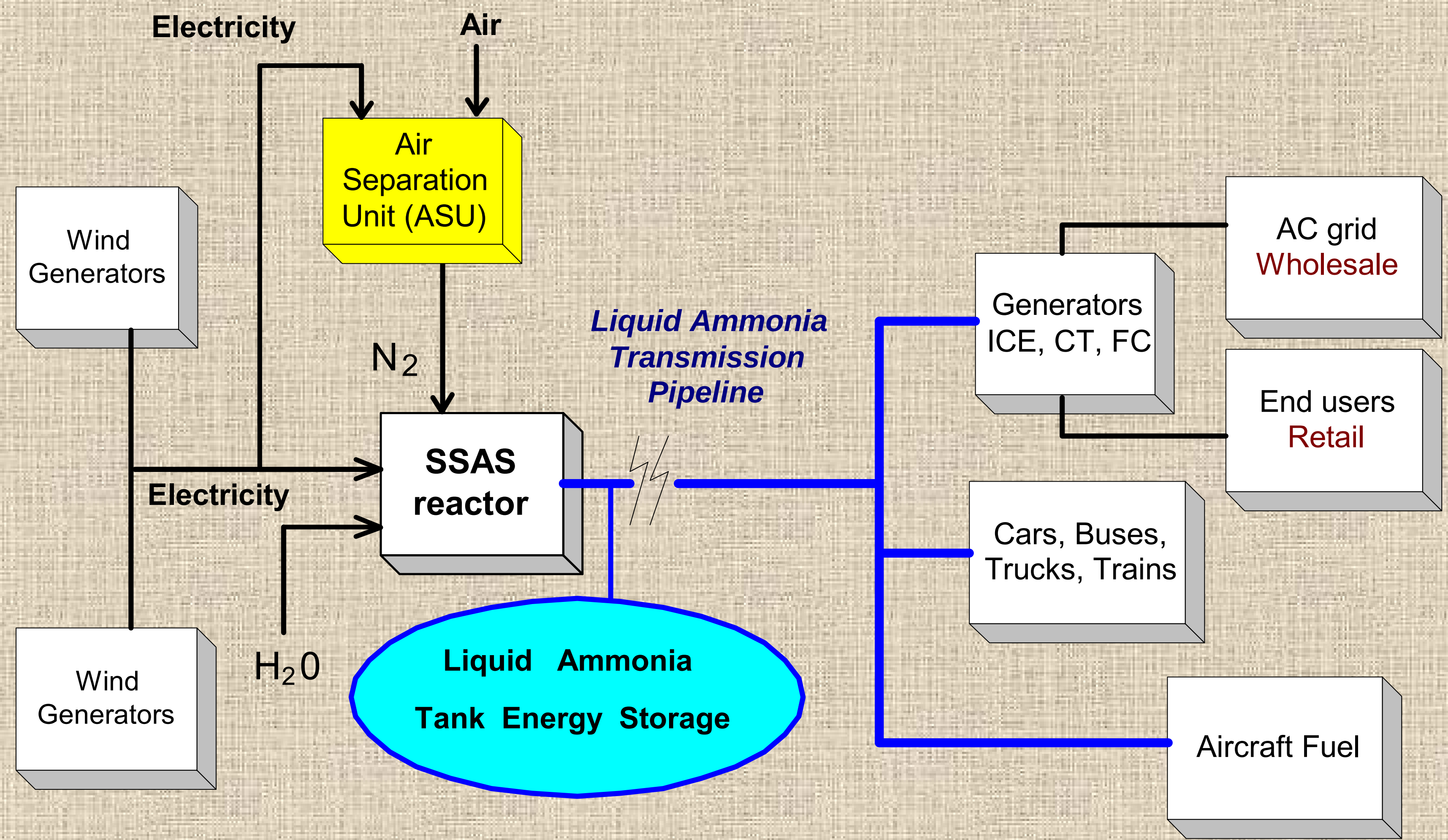
Solar Hydrogen Energy System

AEA EETF AASI Project

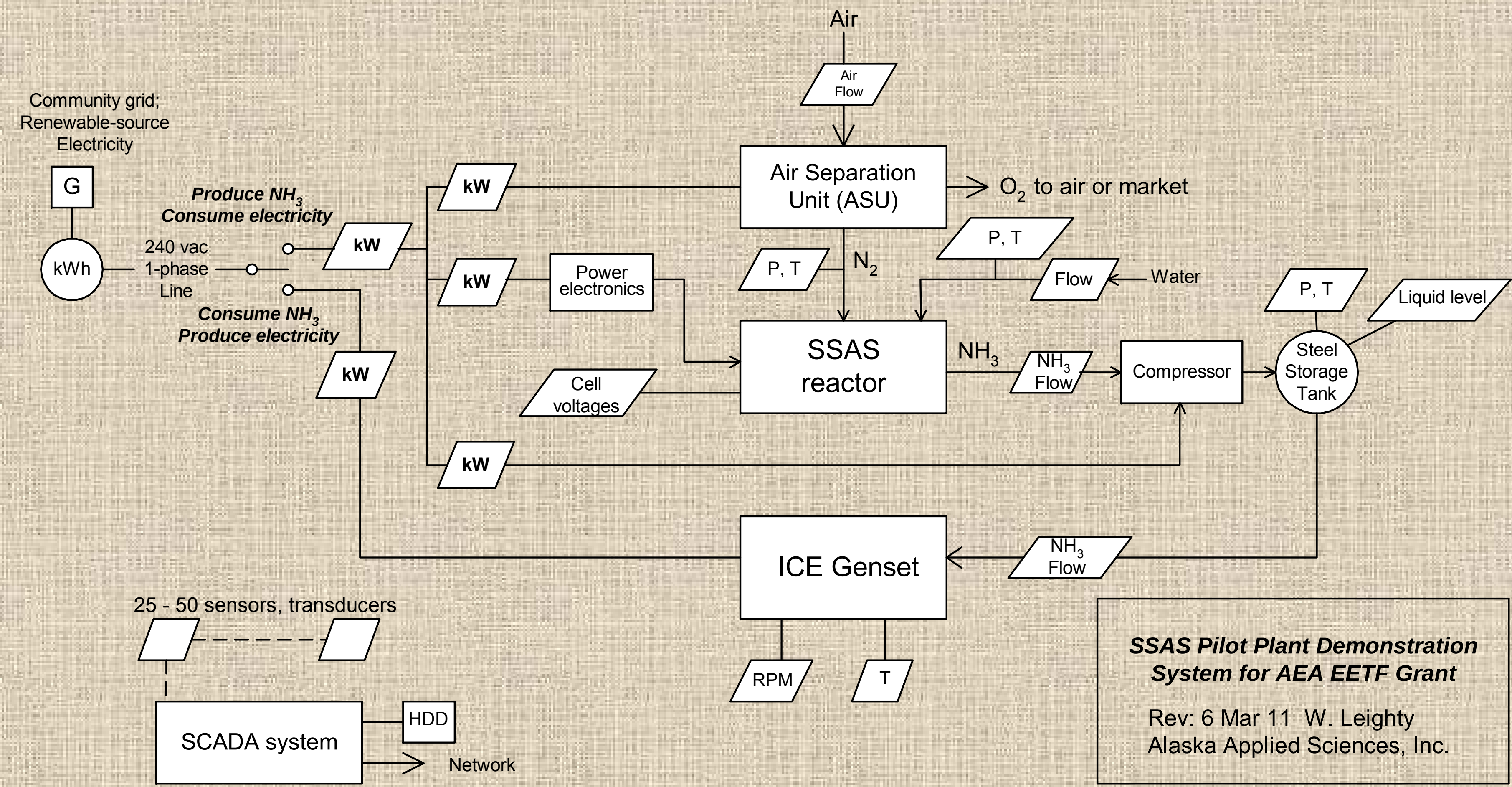
- AEA: Alaska Energy Authority, State of Alaska
- EETF: Emerging Energy Technology Fund
- AASI: Alaska Applied Sciences, Inc.
- Anhydrous ammonia (NH3) fuel from RE
- SSAS: Solid State Ammonia Synthesis
- PCC: Proton Conducting Ceramic
- AEA grants $750K from EETF to AASI: Aug ‘12
- AASI in-kind $250K
- Total $1M

AEA EETF AASI Project

- Deliver: Containerized, transportable, SSAS pilot plant “ammonia microgrid” system
- Produce NH_3 from RE-electricity, water, air
- Store NH_3 in small tank
- Recover via CHP in ICE genset
- SCADA data export for public
- Demo around Alaska

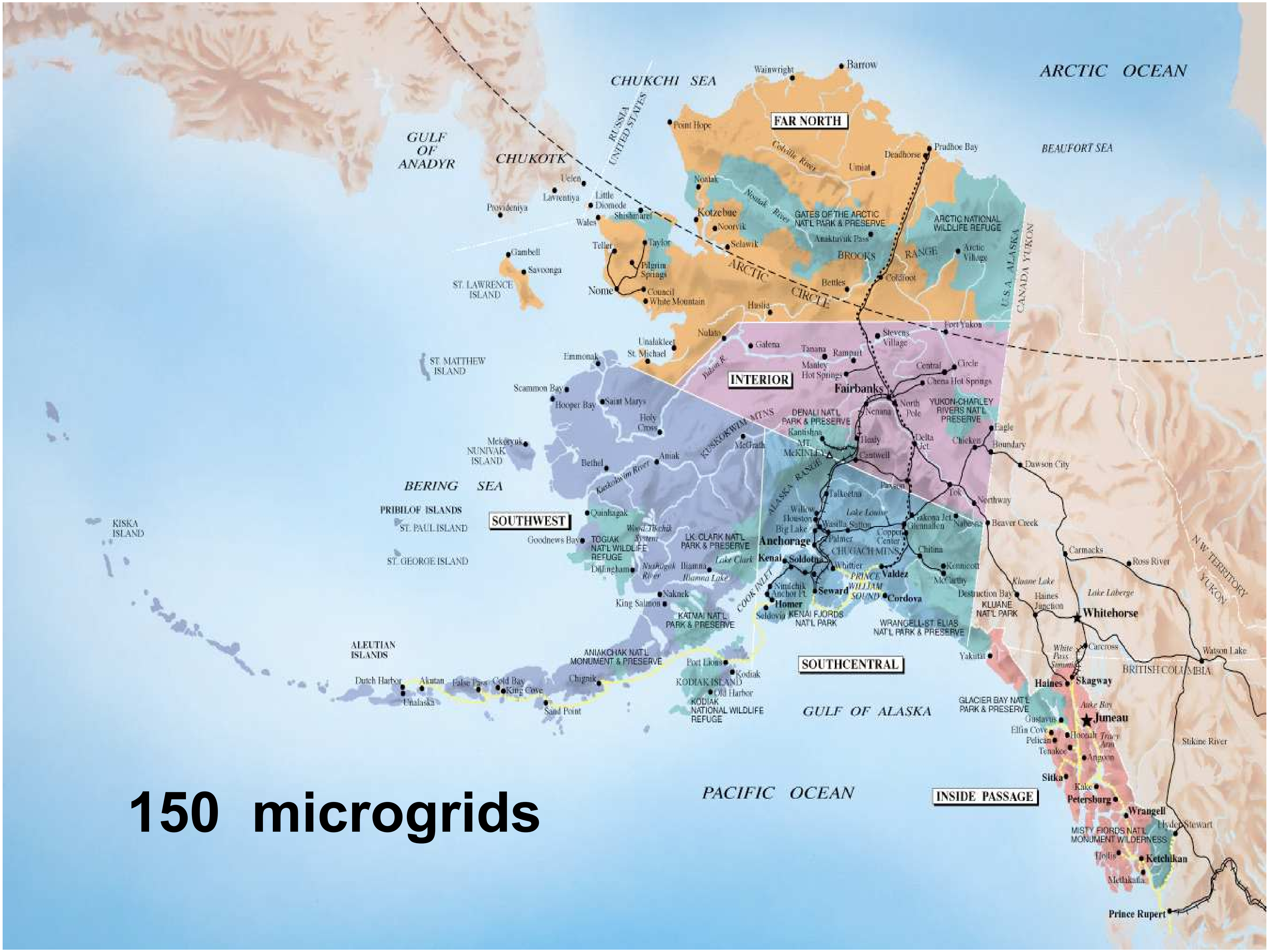


Solid State Ammonia Synthesis (SSAS)



PROJECT: Complete RE – NH_3 SSAS Storage System

- **> NH3 synthesis from RE electricity, water, air (N_2)**
- **> Liquid NH_3 tank storage**
- **> Regeneration + grid feedback**
- **> SCADA instrumentation → UAF - ACEP**



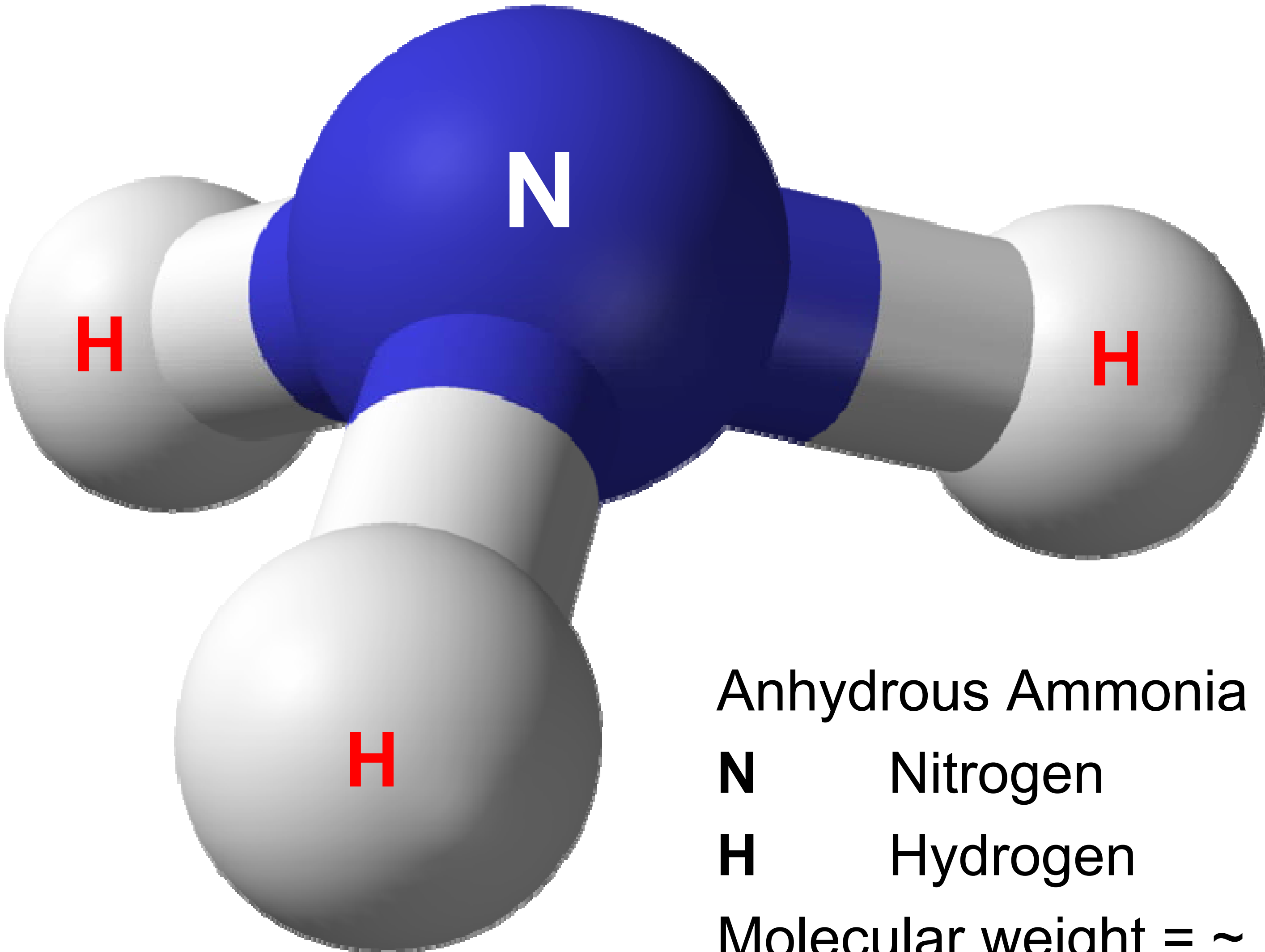
150 microgrids

Opportunity: Alaska Microgrid Applications

1. Village energy “independence”
   a. Diverse renewable sources
   b. Low-cost tank storage
   c. 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” NH_3 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

Military: *Land + sea fuel*

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



Anhydrous Ammonia **NH_3**

N Nitrogen

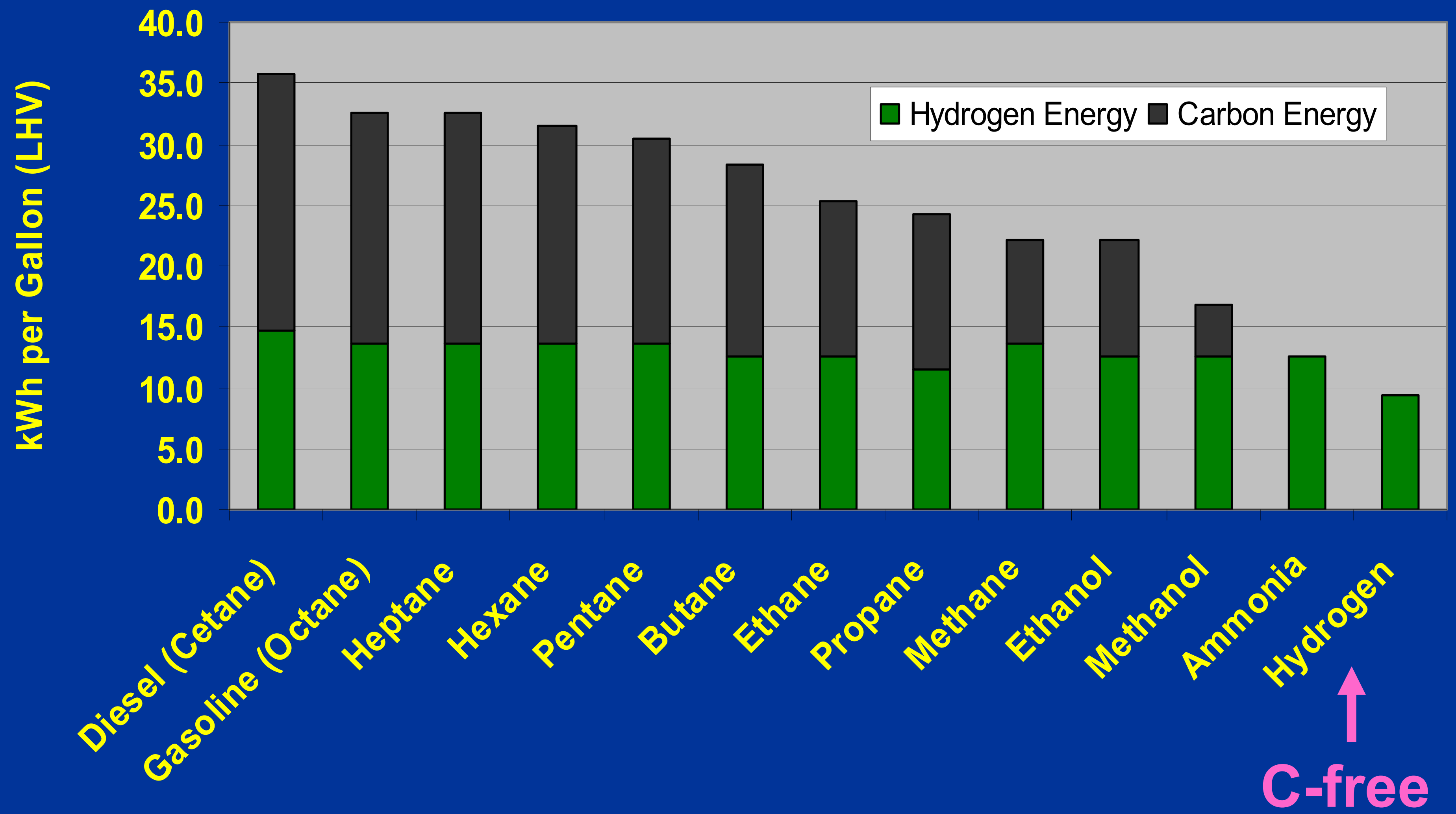
H Hydrogen

Molecular weight = ~ 17

18% **H** by weight: “other hydrogen”

$NH_3 + O_2 = N_2 + H_2O$

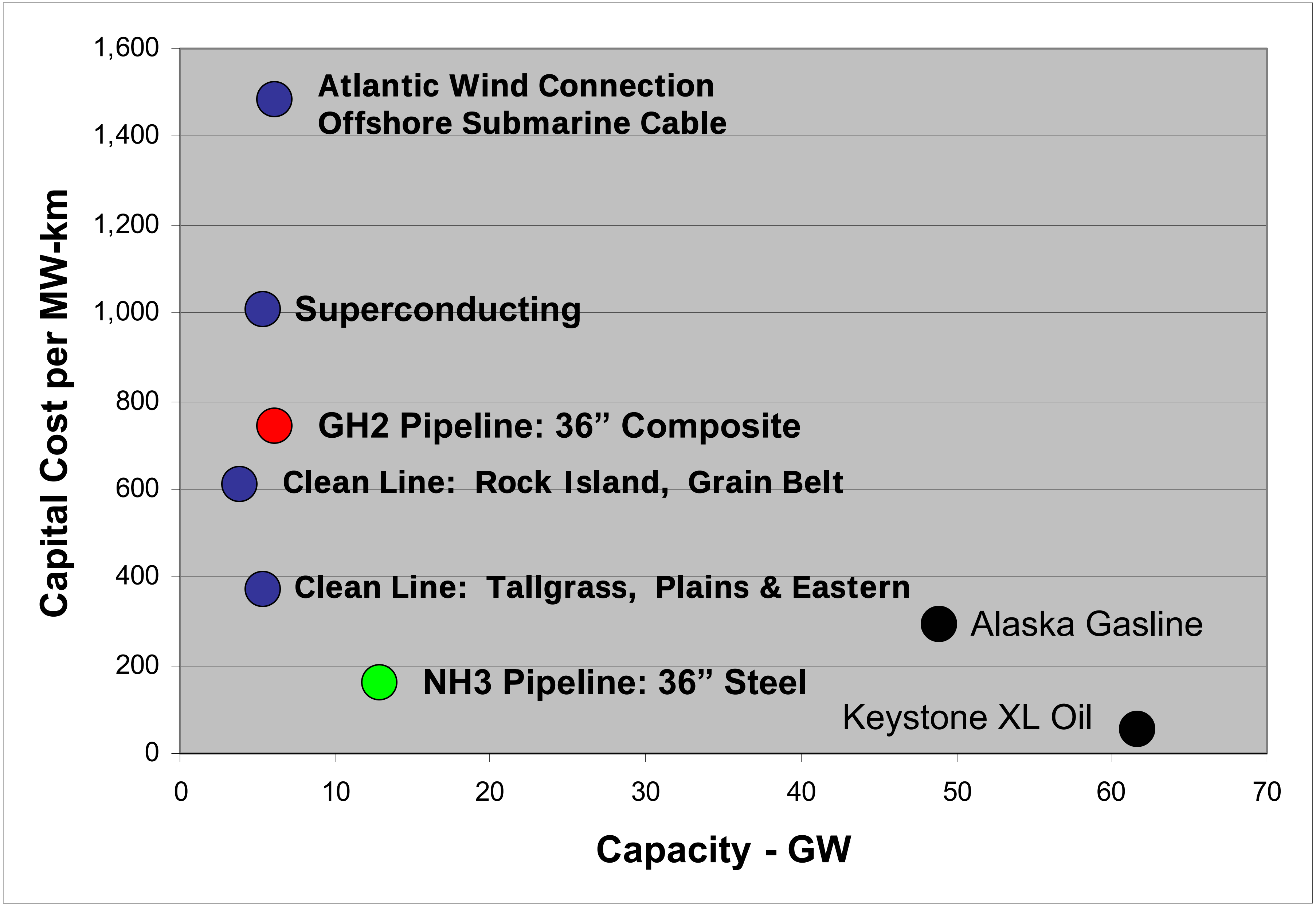
Volumetric Energy Density of Fuels
(Fuels in their Liquid State)



Why Ammonia ?
Fertilizer and Fuel

Only liquid fuel embracing:

- Carbon-free: clean burn or conversion; no CO_2
  - Excellent hydrogen carrier
  - Easily "cracked" to H_2
- Reasonably high energy density
- Energy cycle inherently pollution free
  - Potentially all RE-source: elec + water + Nitrogen
  - Cost competitive with hydrocarbon fuels ?
- Decades of global use, infrastructure
  - Practical to handle, store, and transport: fertilizer
  - End-use in ICE, CT, fuel cell
  - Safety: self-odorizing; safety regs; hazard; toxic

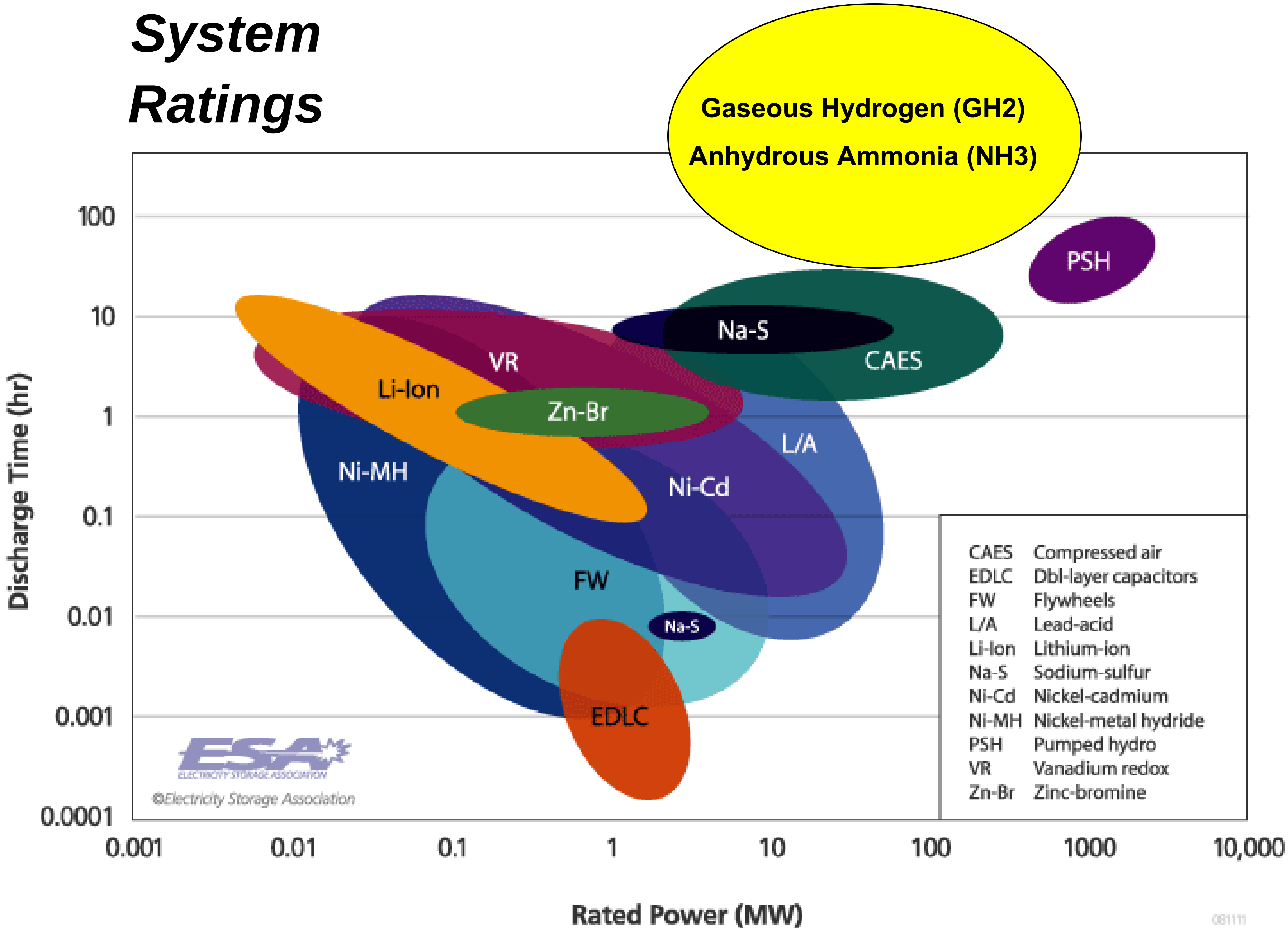


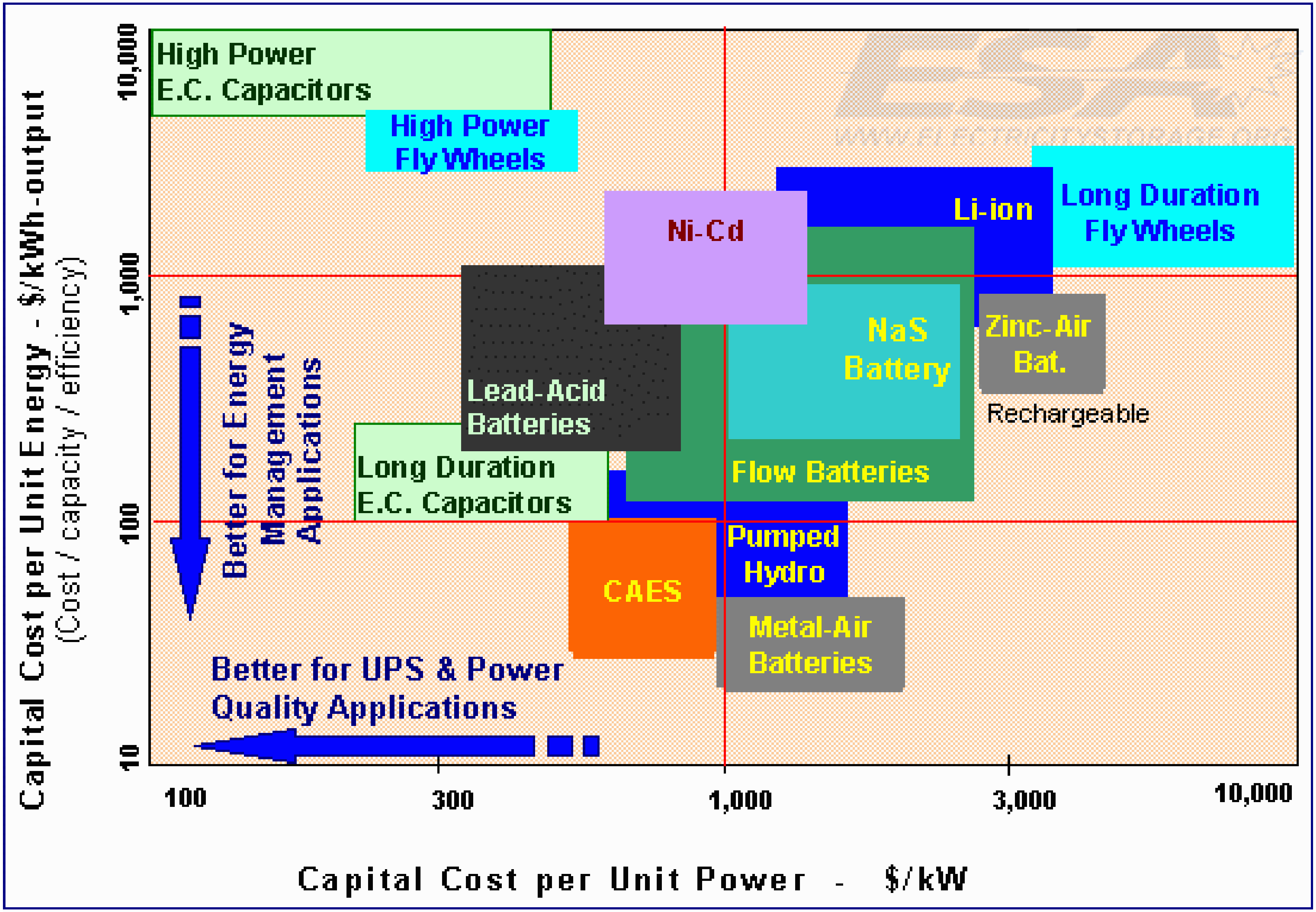
Capital Cost per MW-km
1,600
1,400
1,200
1,000
800
600
400
200
0
Atlantic Wind Connection
Offshore Submarine Cable
Superconducting
GH2 Pipeline: 36” Composite
Clean Line: Rock Island, Grain Belt
Clean Line: Tallgrass, Plains & Eastern
Alaska Gasline
NH3 Pipeline: 36” Steel
Keystone XL Oil
0
10
20
30
40
50
60
70
Capacity - GW

Energy Storage System Characteristics
Hydrogen and Ammonia off the charts ?

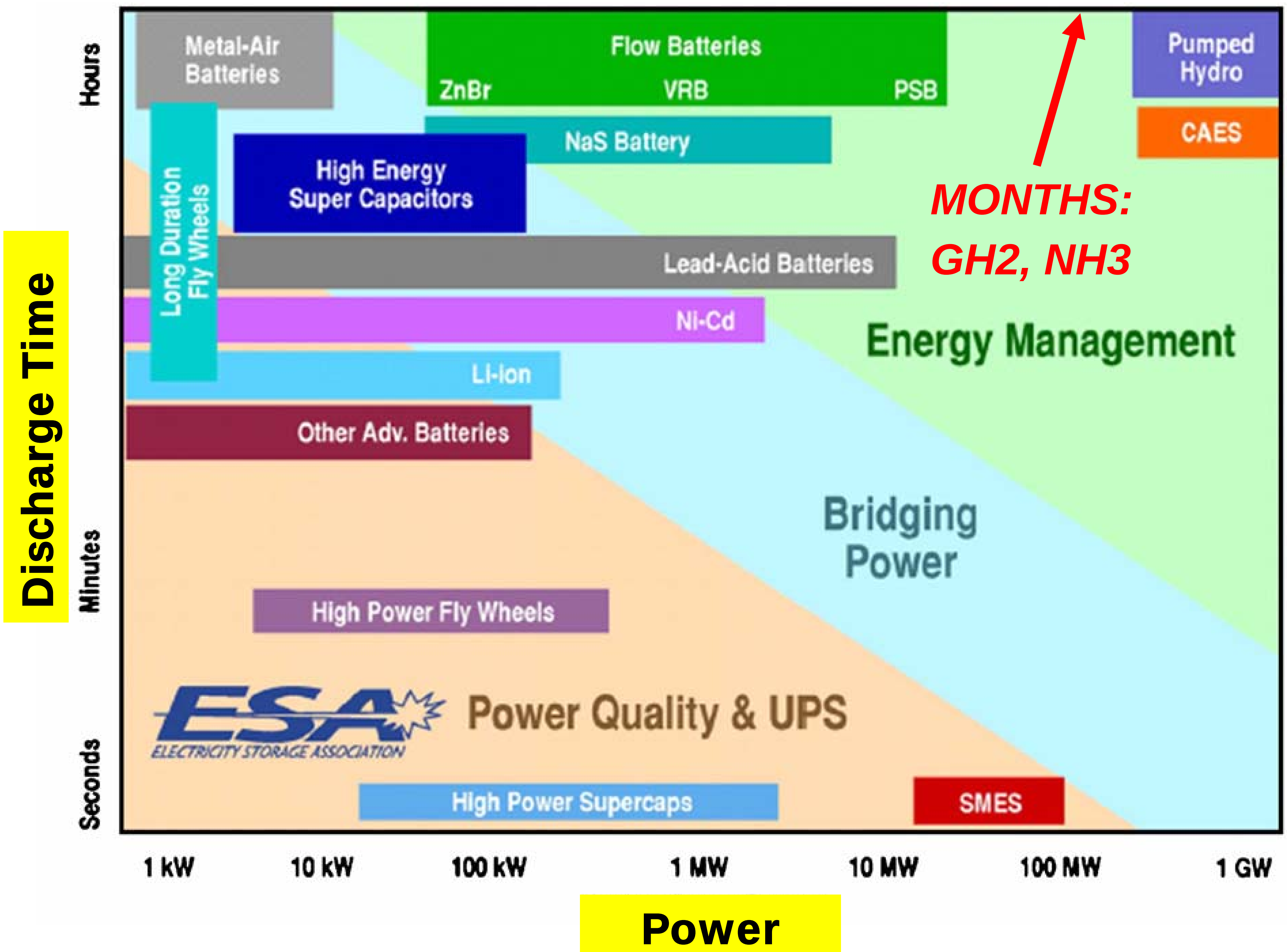
- *Storage capacity (Mwh, scf, nM3, Mt, gallons ….)*
- *Power (MW, scfm ….)   In / Out rate*
- *Costs*
  - *Capital*
  - *O&M*
- **Efficiency**
- **Response time**
- **Durability (cycling capacity)**
- **Reliability**
- **Autonomy**
- **Self-discharge**
- **Depth of discharge**
- **Adaptation to the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

System Ratings



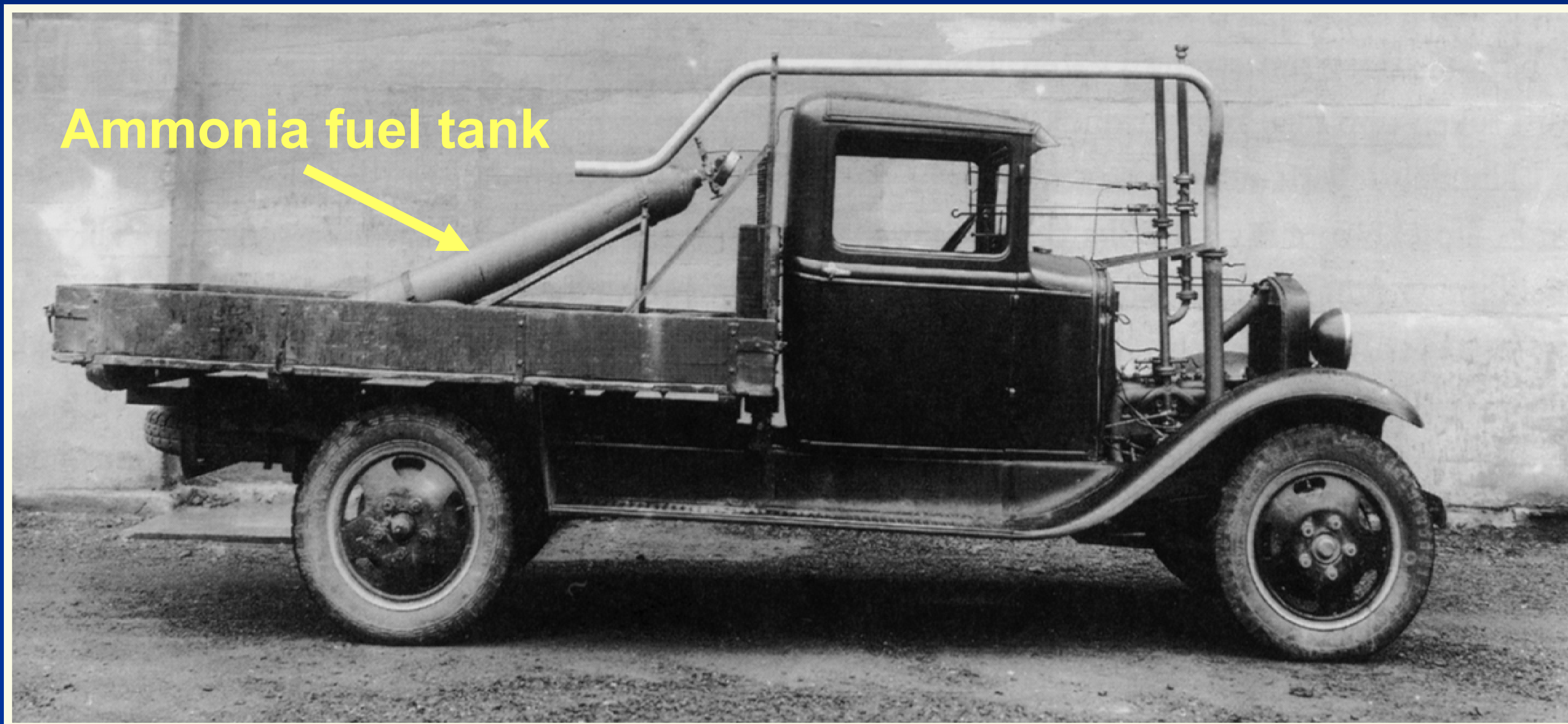

High Power
E.C. Capacitors
High Power
Fly Wheels
Li-ion
Long Duration
Fly Wheels
Ni-Cd
NaS
Battery
Zinc-Air
Bat.
Rechargeable
Lead-Acid
Batteries
Long Duration
E.C. Capacitors
Flow Batteries
Pumped
Hydro
CAES
Metal-Air
Batteries
Better for Energy
Management
Applications
Better for UPS & Power
Quality Applications
Capital Cost per Unit Energy - $/kWh-output
(Cost / capacity / efficiency)
10,000
1,000
100
10
100
300
1,000
3,000
10,000
Capital Cost per Unit Power - $/kW

GH2 and NH3

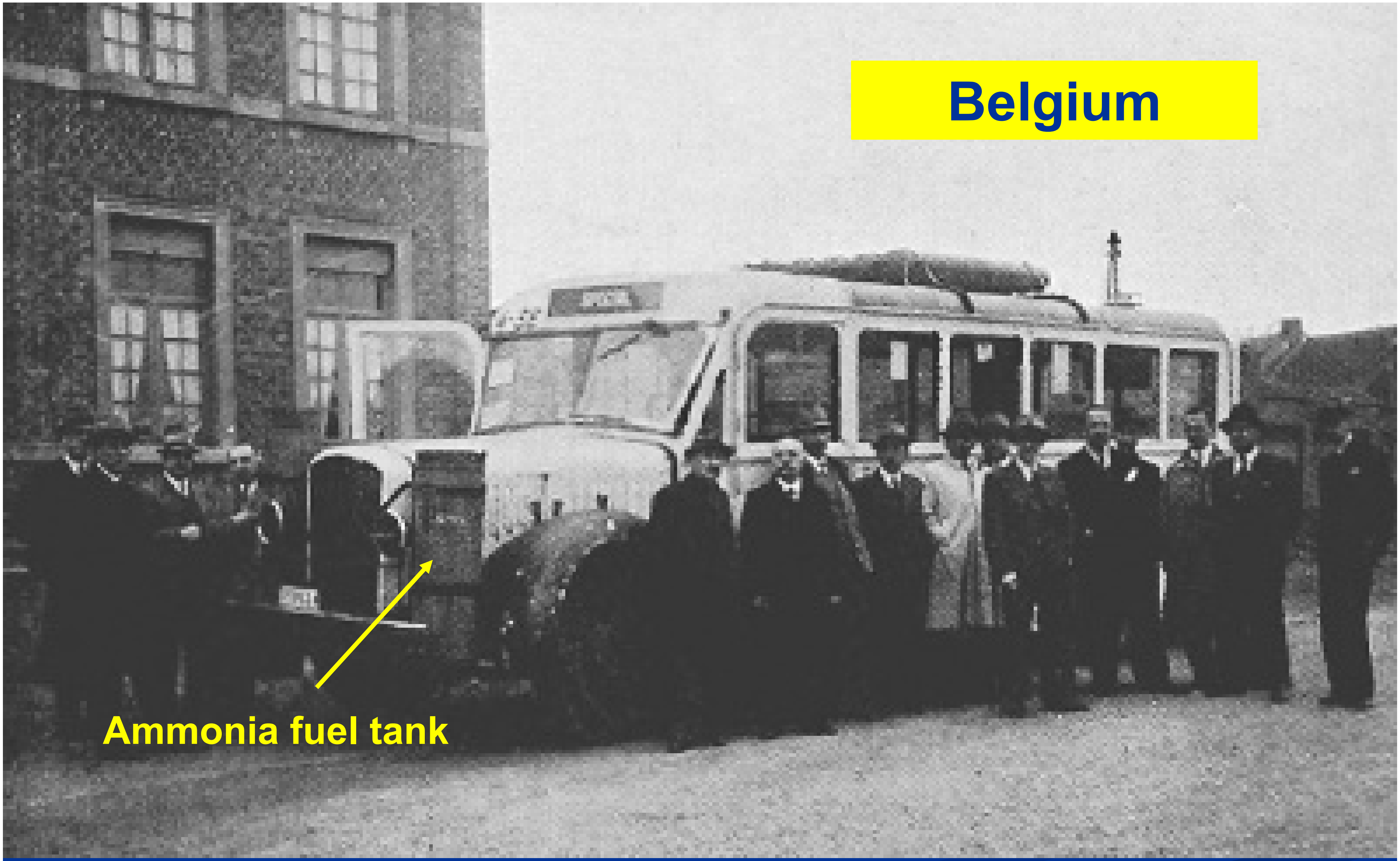


Discharge Time
Hours
Minutes
Seconds
Metal-Air Batteries
Flow Batteries
ZnBr
VRB
PSB
Pumped Hydro
CAES
NaS Battery
Long Duration Fly Wheels
High Energy Super Capacitors
MONTHS:
GH2, NH3
Lead-Acid Batteries
Ni-Cd
Energy Management
Li-Ion
Other Adv. Batteries
Bridging Power
High Power Fly Wheels
ESA
ELECTRICITY STORAGE ASSOCIATION
Power Quality & UPS
High Power Supercaps
SMES
1 kW
10 kW
100 kW
1 MW
10 MW
100 MW
1 GW
Power

Ammonia fueled – Norway



1933



Ammonia Fueled Bus: Thousands of Problem-free Miles

1943

University of Michigan

Ammonia + Gasoline Powered

- **Idle: gasoline**
- **Full power: 80% ammonia**

Summer ’07 Detroit → San Francisco

2007

X-15 rocket plane: NH3 + LOX fuel

Mach 6.7 on 3 Oct 67

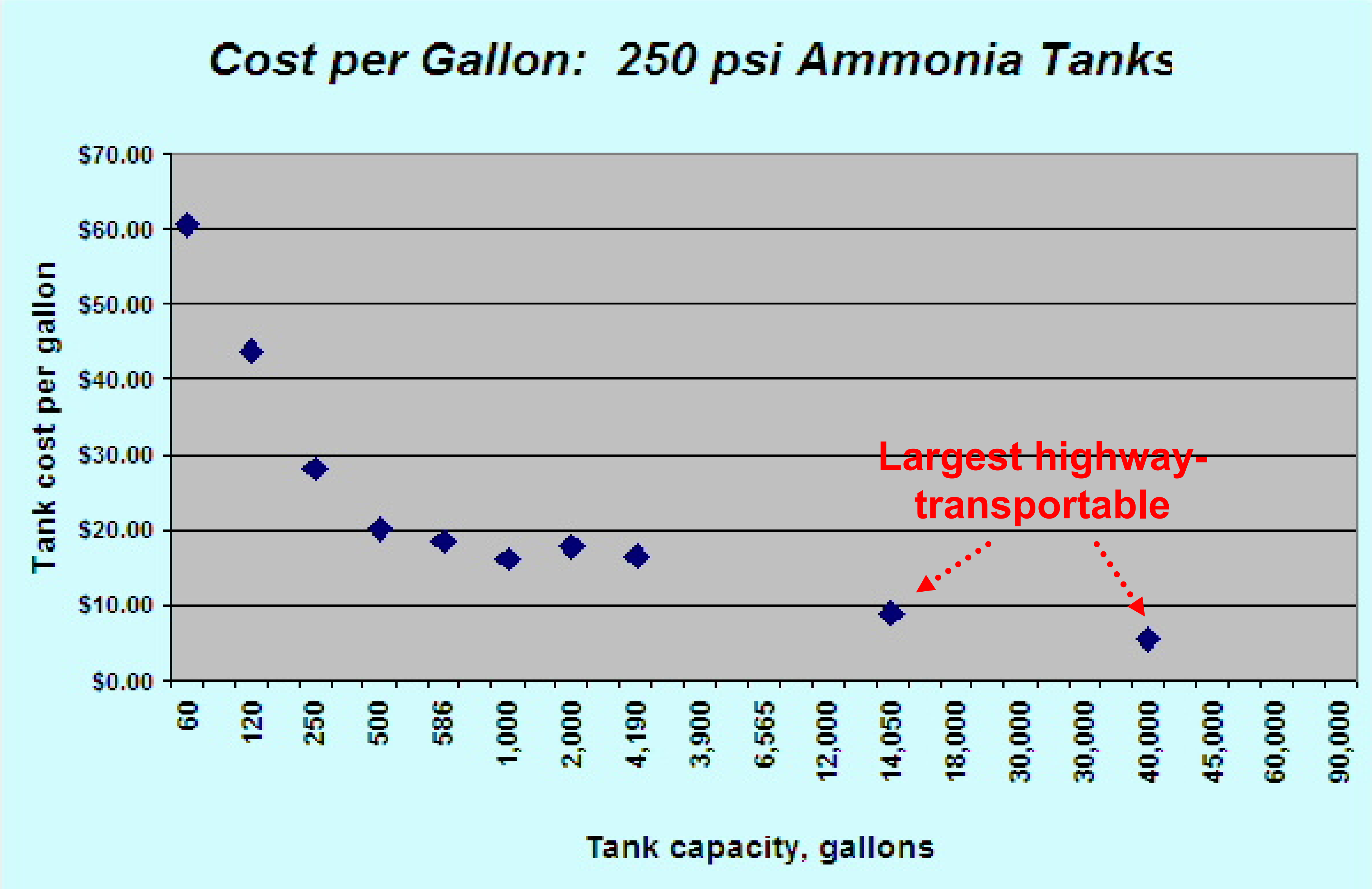
199 missions

1959 - 68

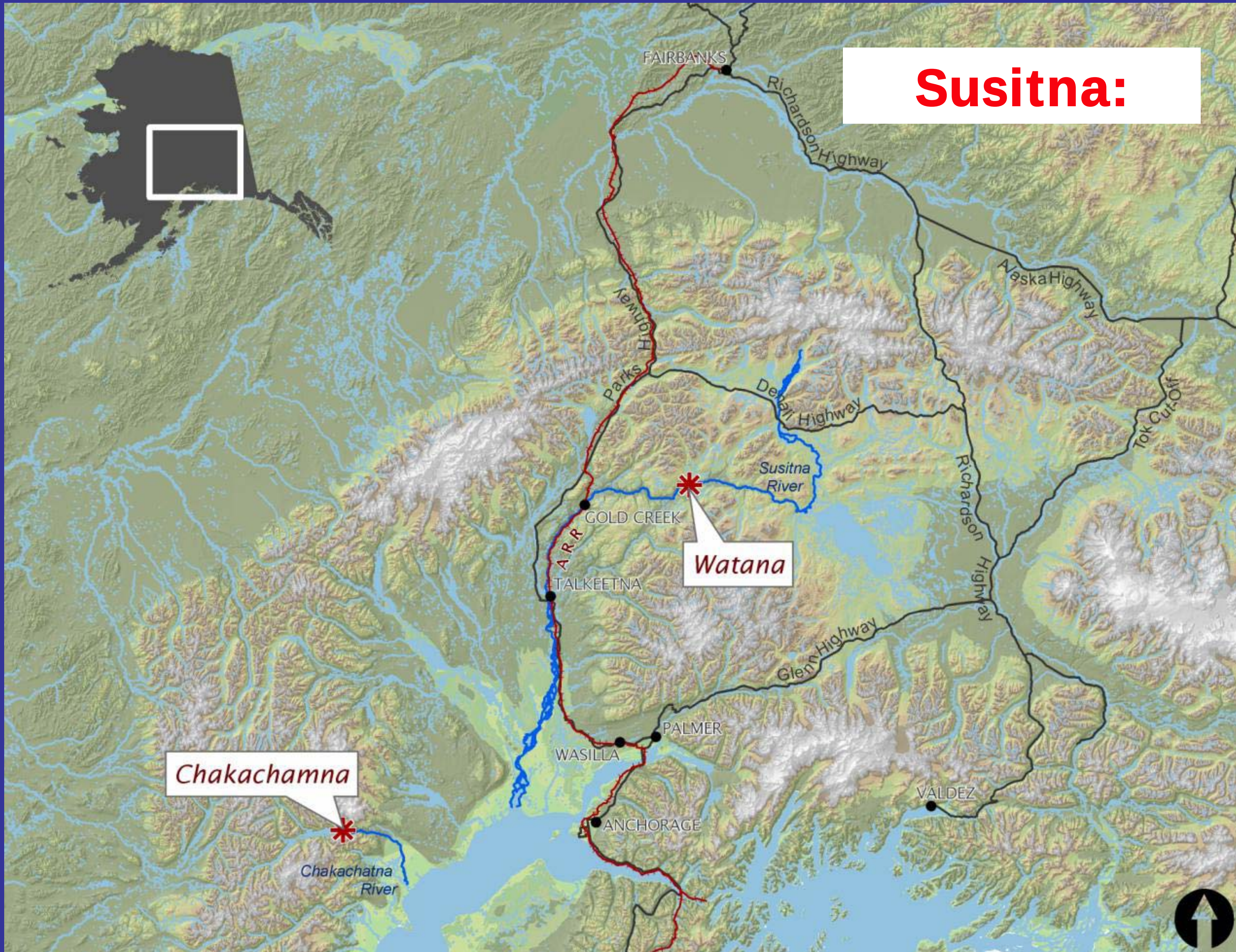
1,000 hours, ICE, 6 cyl, 100 hp
75% ammonia, 25% propane

NH_3 Ag Fertilizer Tanks, Wind Generators, NW Iowa

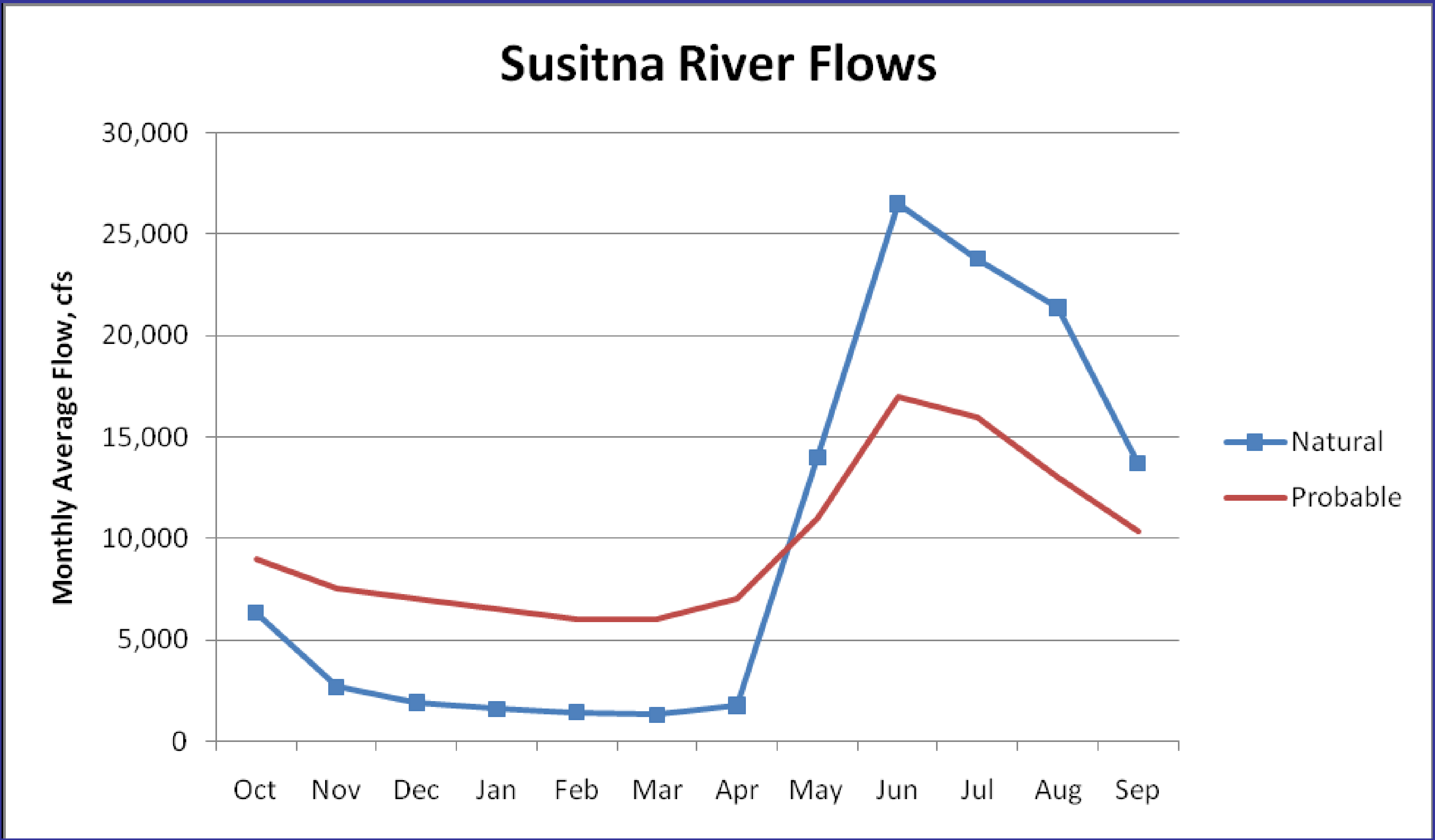
Liquid Ammonia Tank Storage



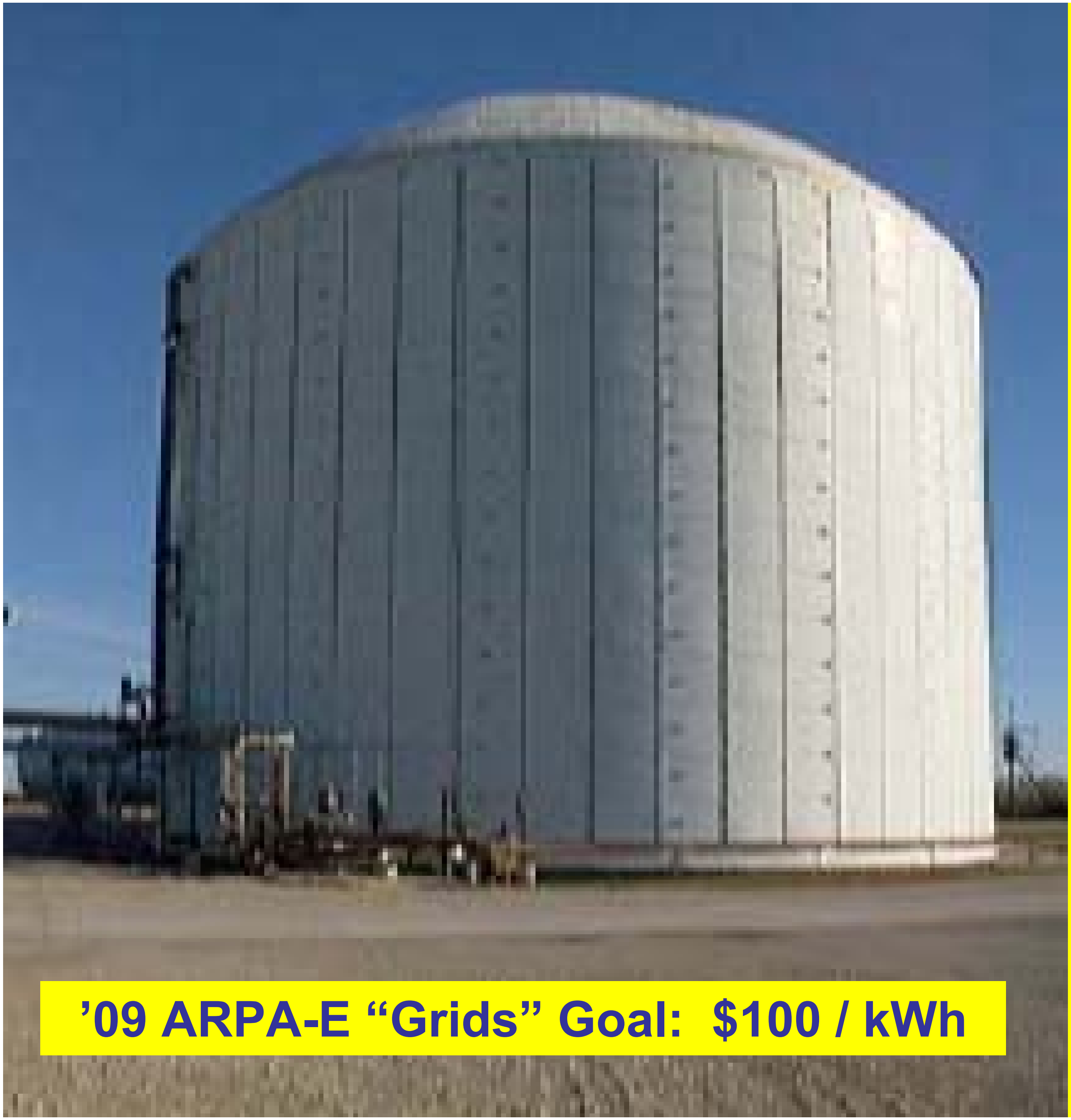
Susitna:



FAIRBANKS
Richardson Highway
Alaska Highway
Parks Highway
Denali Highway
Tok Cut-Off
Susitna River
GOLD CREEK
A.R.R.
Watana
TALKEETNA
Richardson Highway
Glenn Highway
PALMER
WASILLA
VALDEZ
ANCHORAGE
Chakachamna
Chakachatna River



Hydro “Dispatchable” with NH3 storage



’09 ARPA-E “Grids” Goal: $100 / kWh

“Atmospheric” Liquid Ammonia Storage Tank (corn belt)

30,000 Tons

190 GWh

$ 15M turnkey

$ 80 / MWh

$ 0.08 / kWh

-33 C

1 Atm

Haber-Bosch Process

1909 – 1913 BASF

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

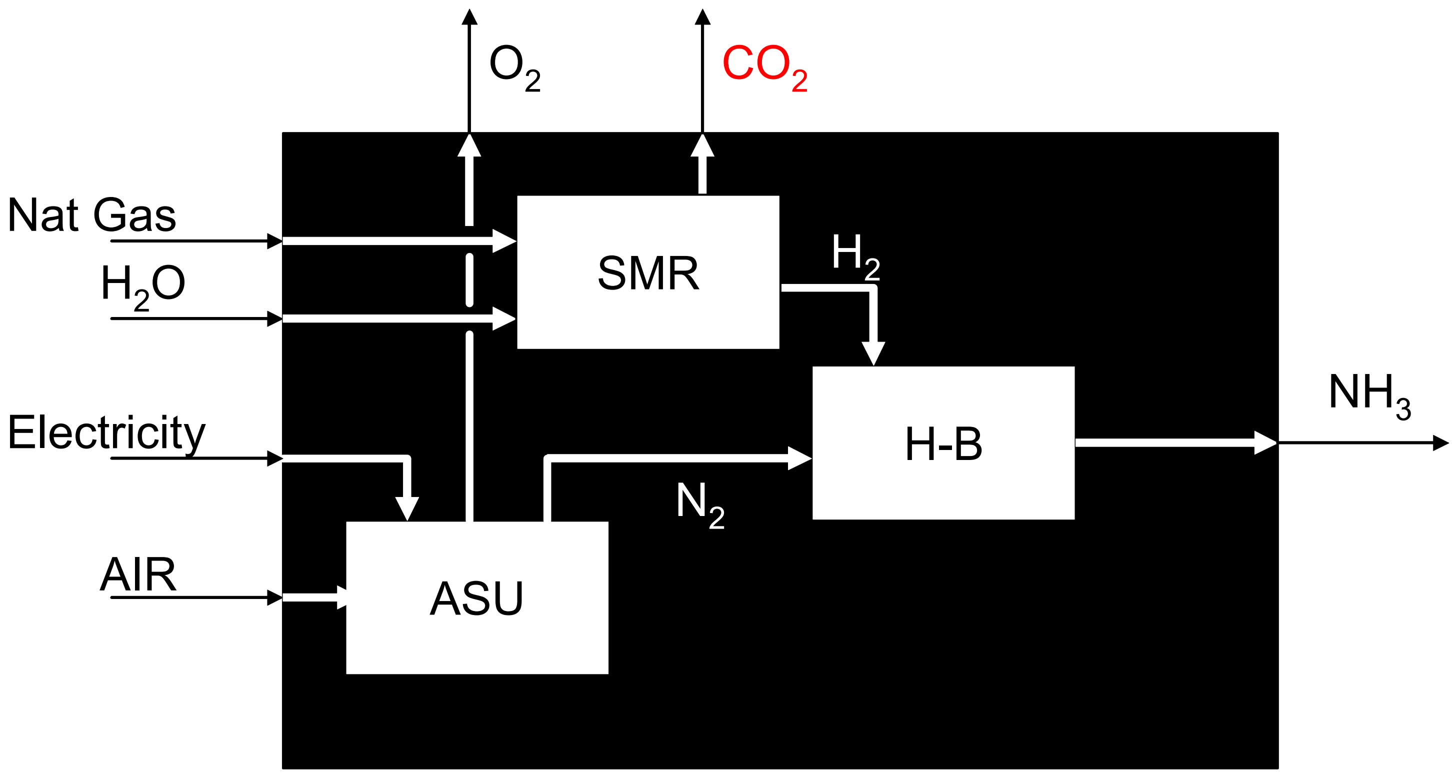
Haber-Bosch Reactor

1921

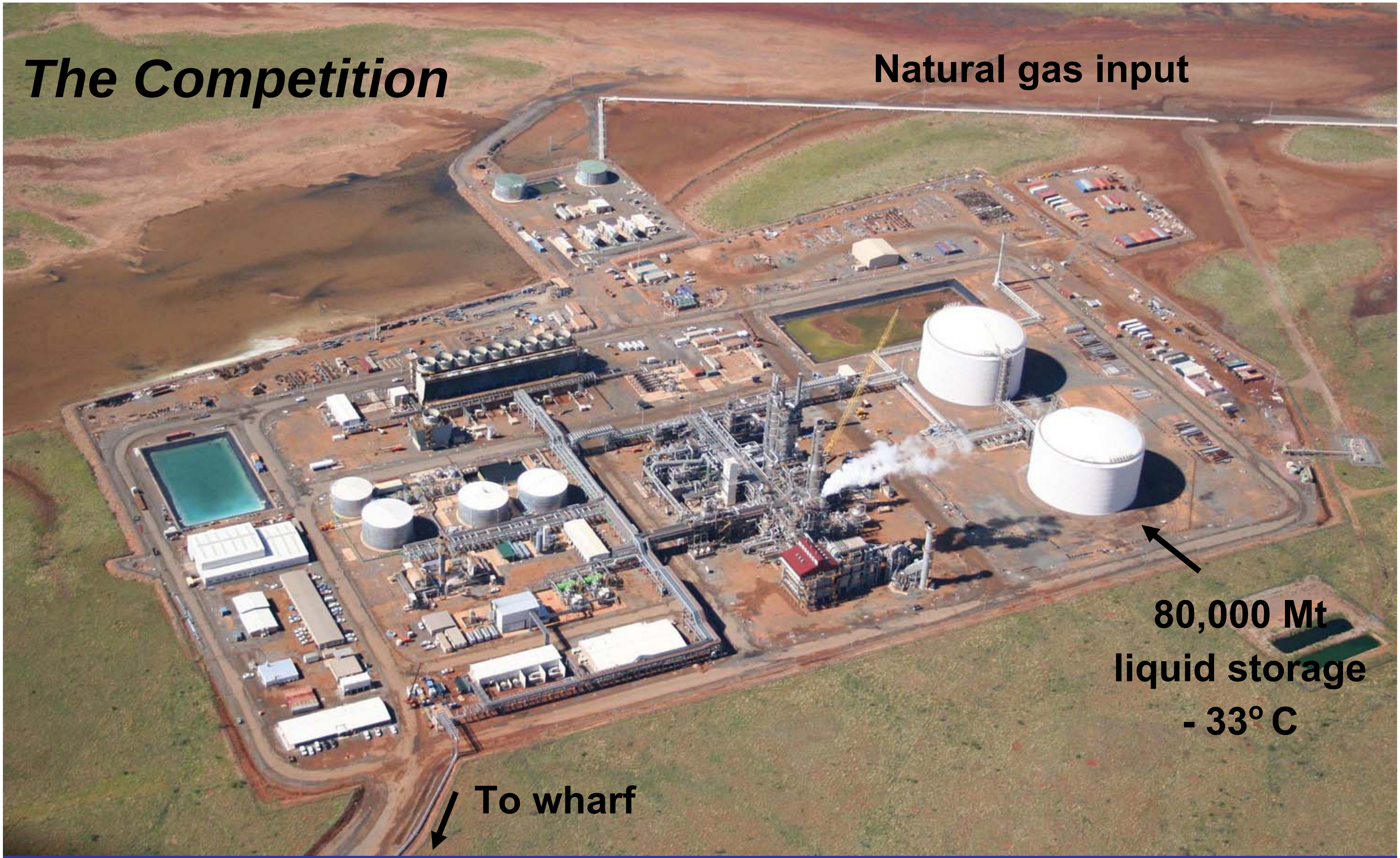
Ludwigshafen, Germany

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

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



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



Burrup Peninsula, NW Australia, Natural Gas to Ammonia Plant

760,000 Mt / year

$US 650 million capital cost '06

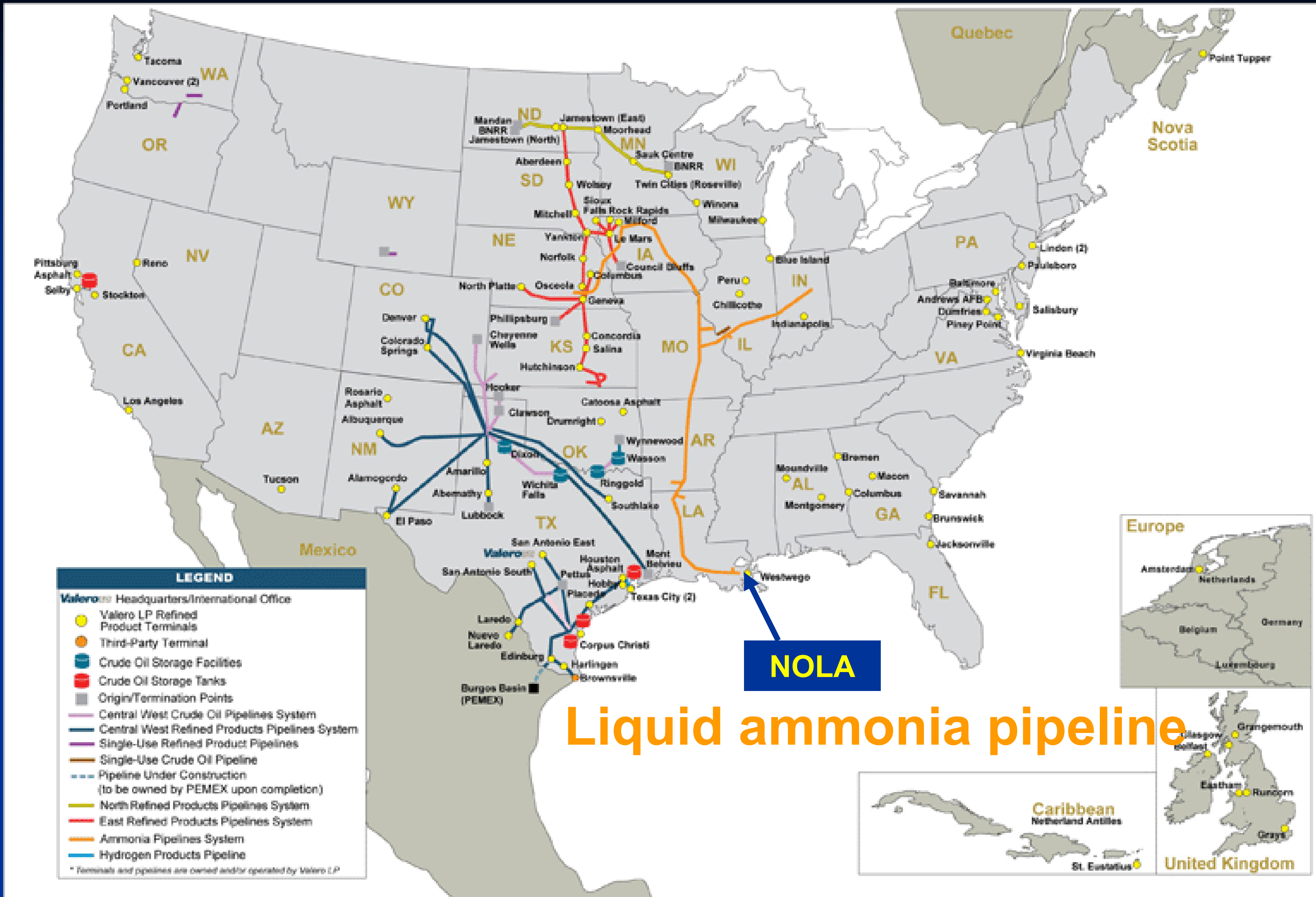
Ammonia or LPG Tanker

To 35,000 Mt

Refrigerated

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



Valero LP Operations

Capital Cost per GW-mile

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

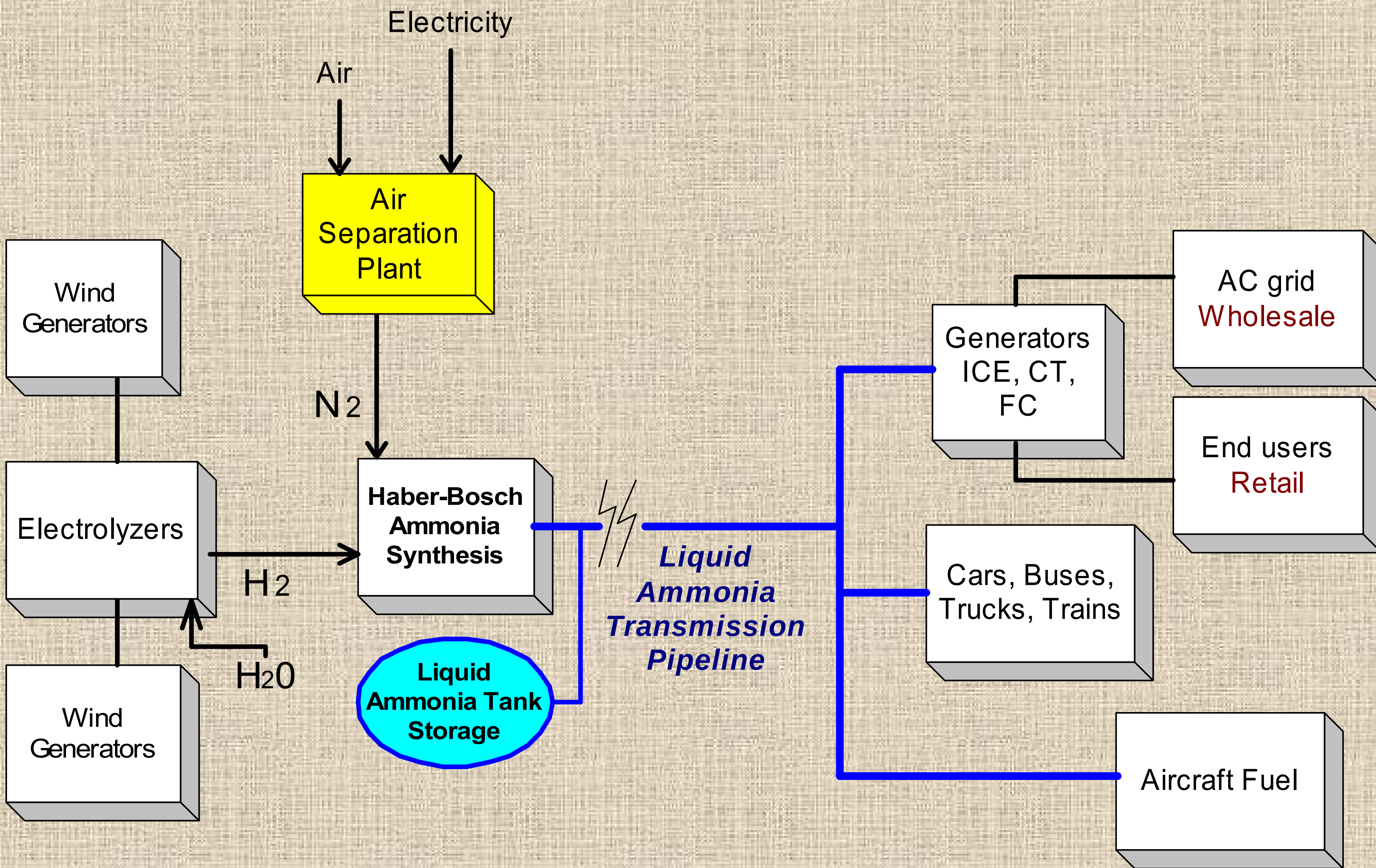
Hydrogen pipeline:

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

Ammonia pipeline:

10” , liquid, 500 miles, with pumping 0.2

RE Ammonia Transmission + Storage Scenario

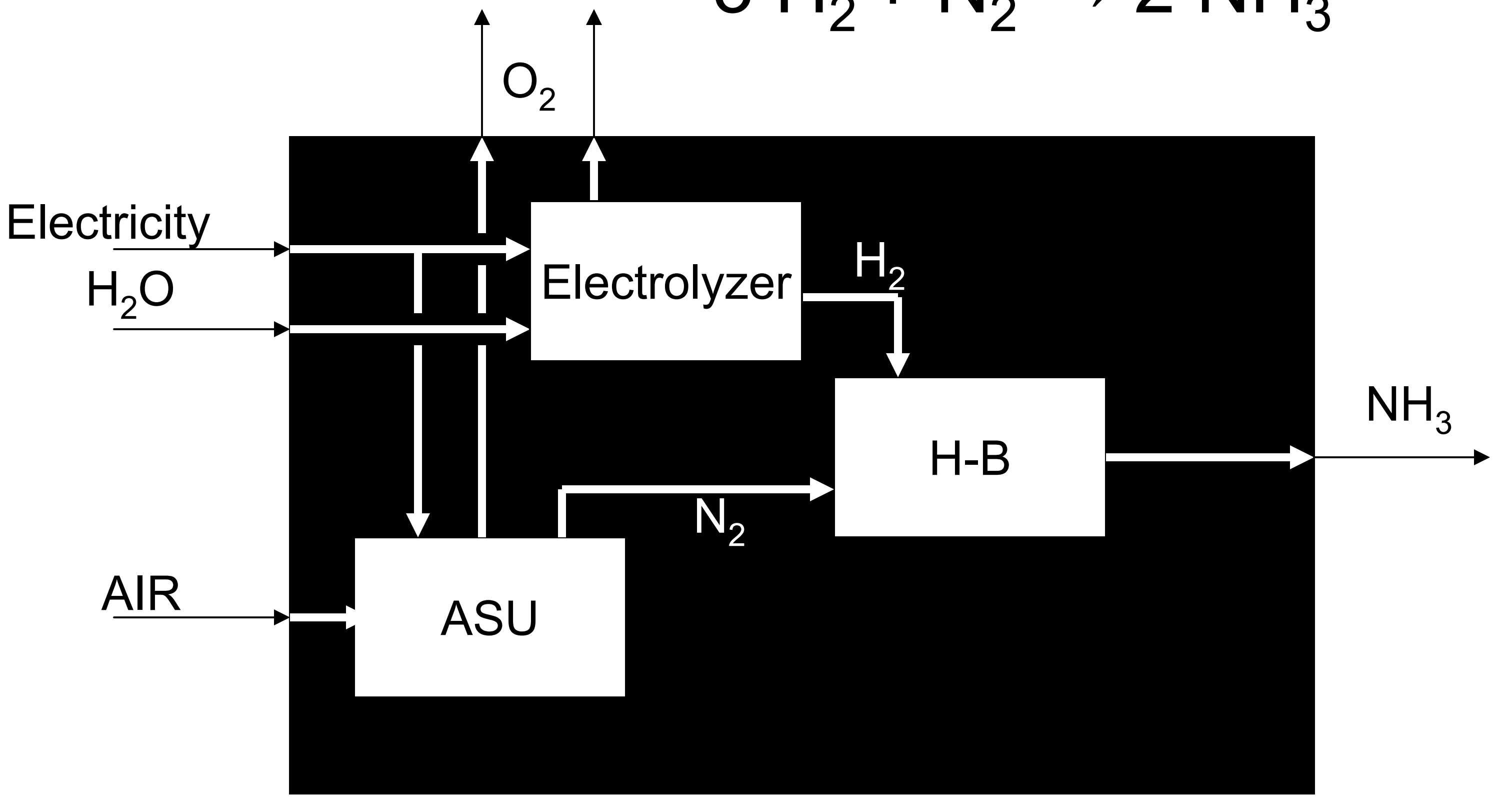


Norsk Hydro Electrolyzers 2 MW each

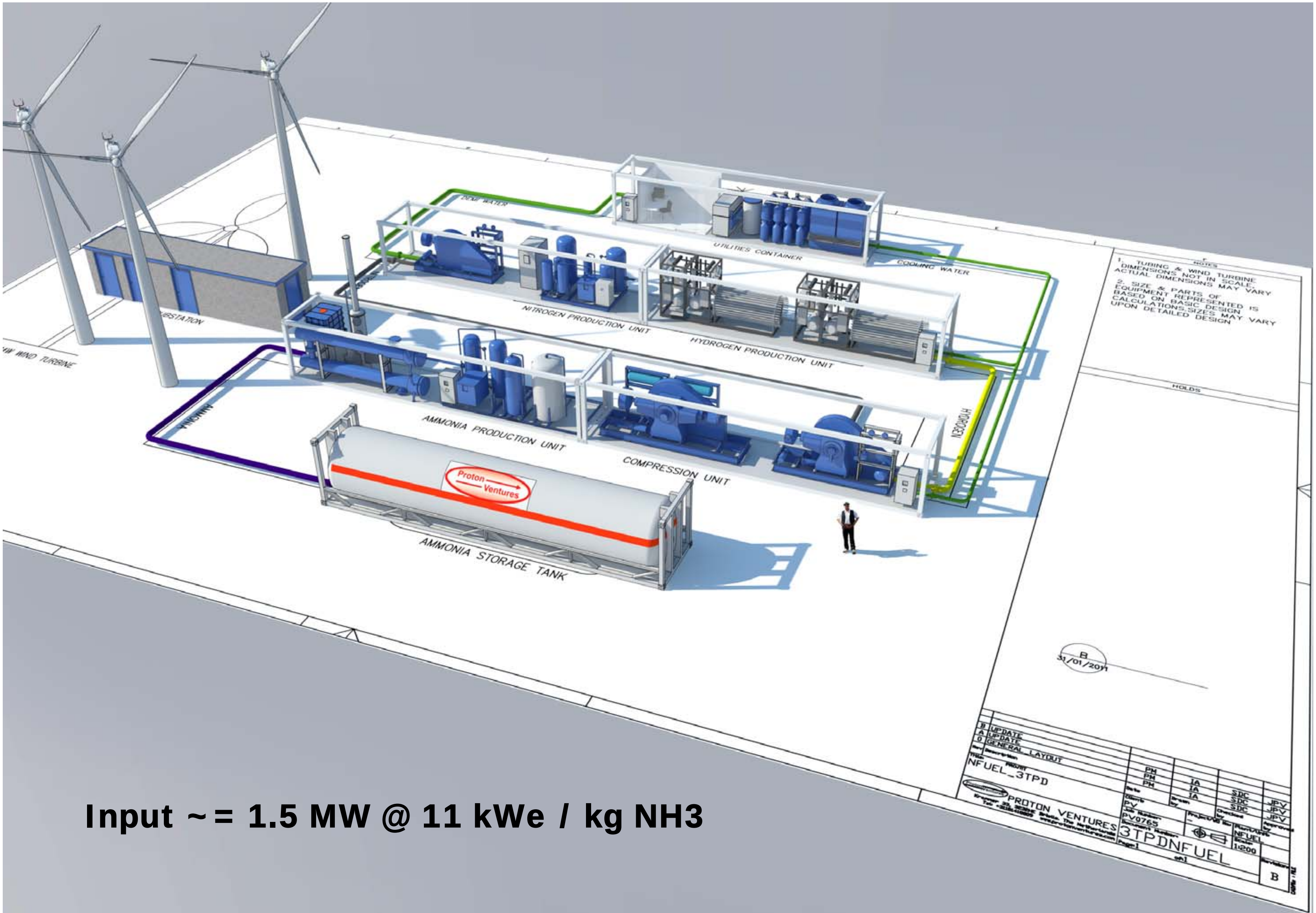
Ammonia from hydrogen from zero-cost off-peak hydro

Inside the Black Box: HB Plus Electrolysis

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



Energy consumption ~12,000 kWh per ton NH_3

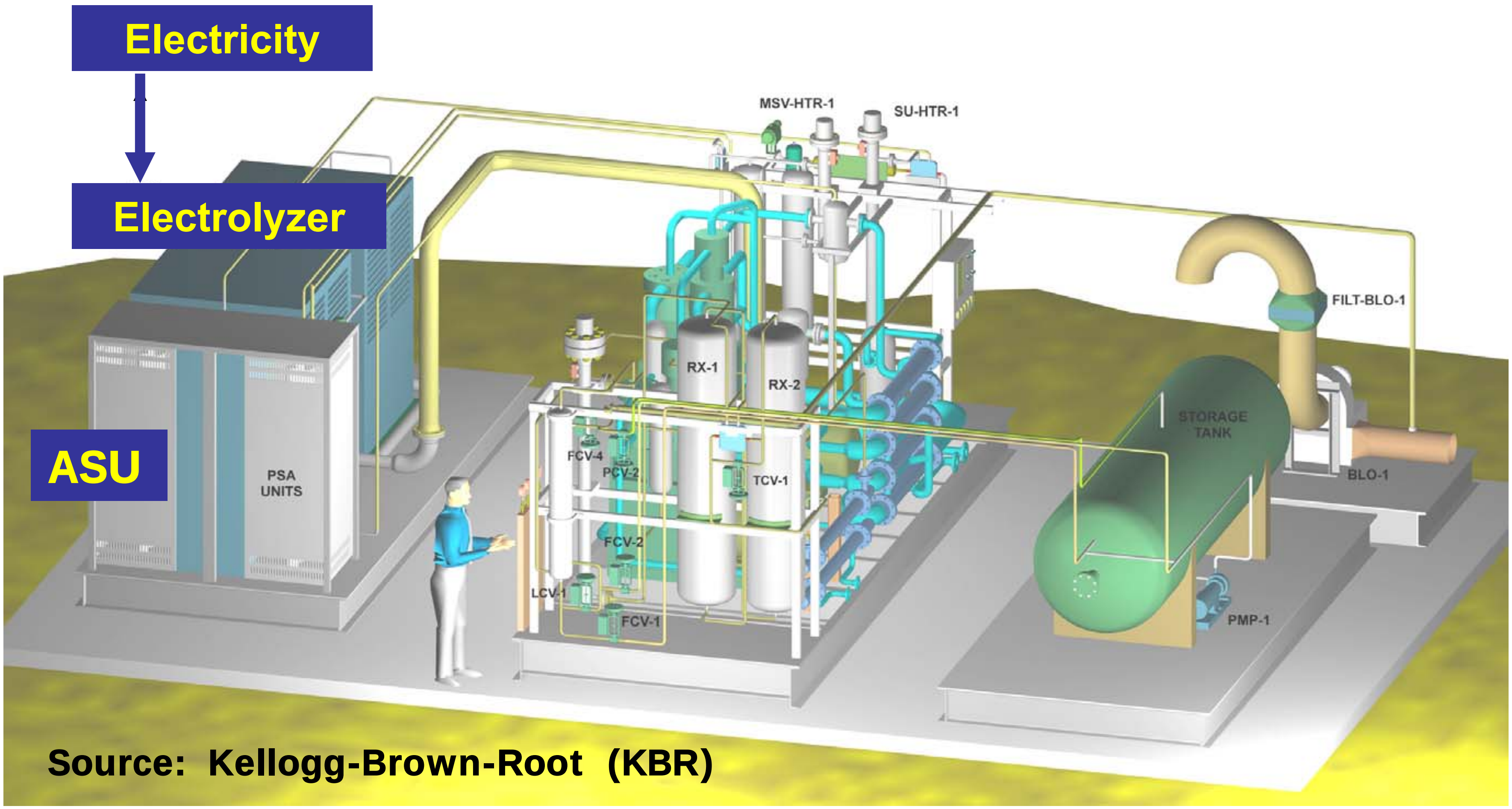


Input ~= 1.5 MW @ 11 kWe / kg NH3

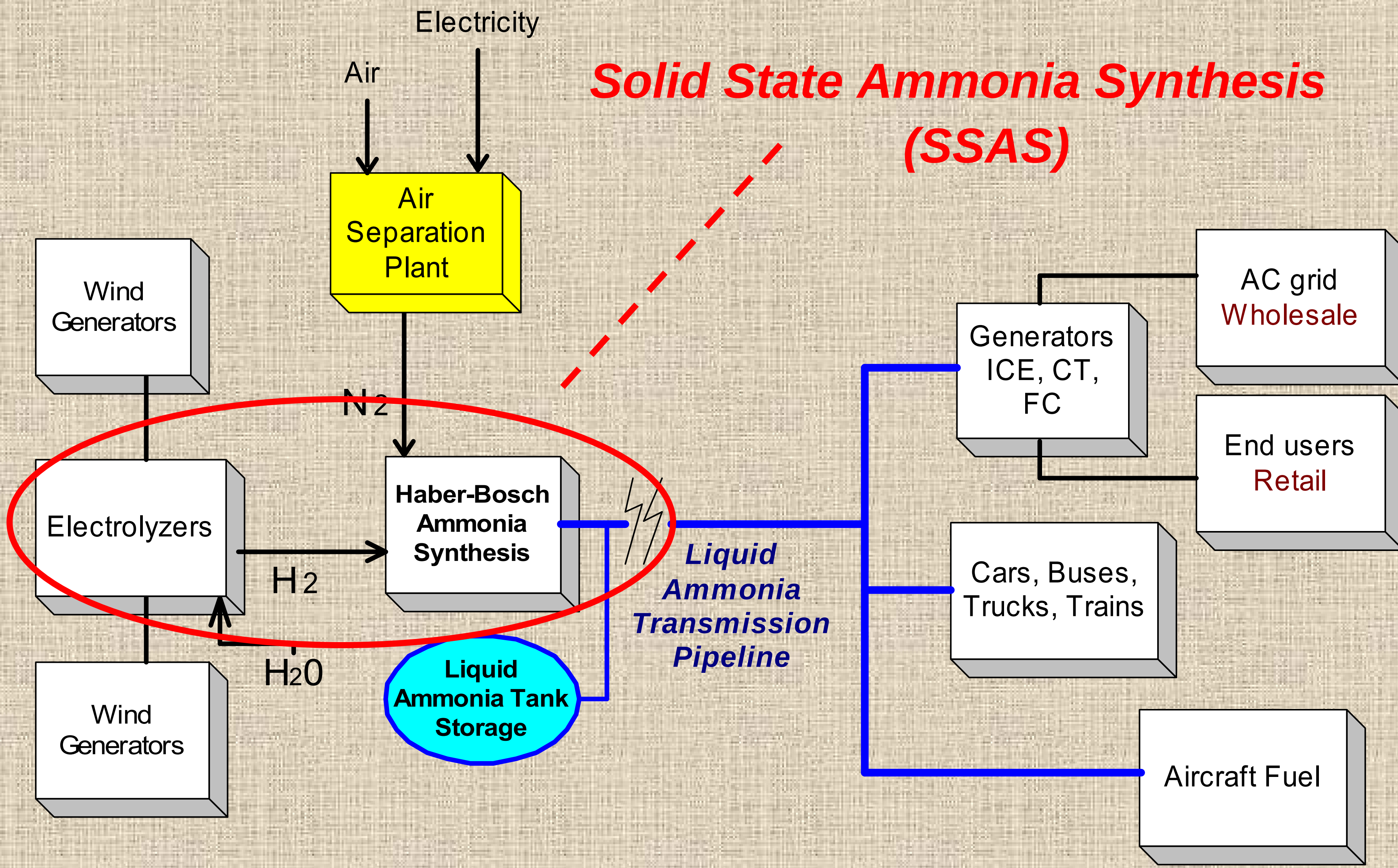
3 Mt / day Electrolysis + Haber-Bosch (EHB) NH3 plant by Proton Ventures

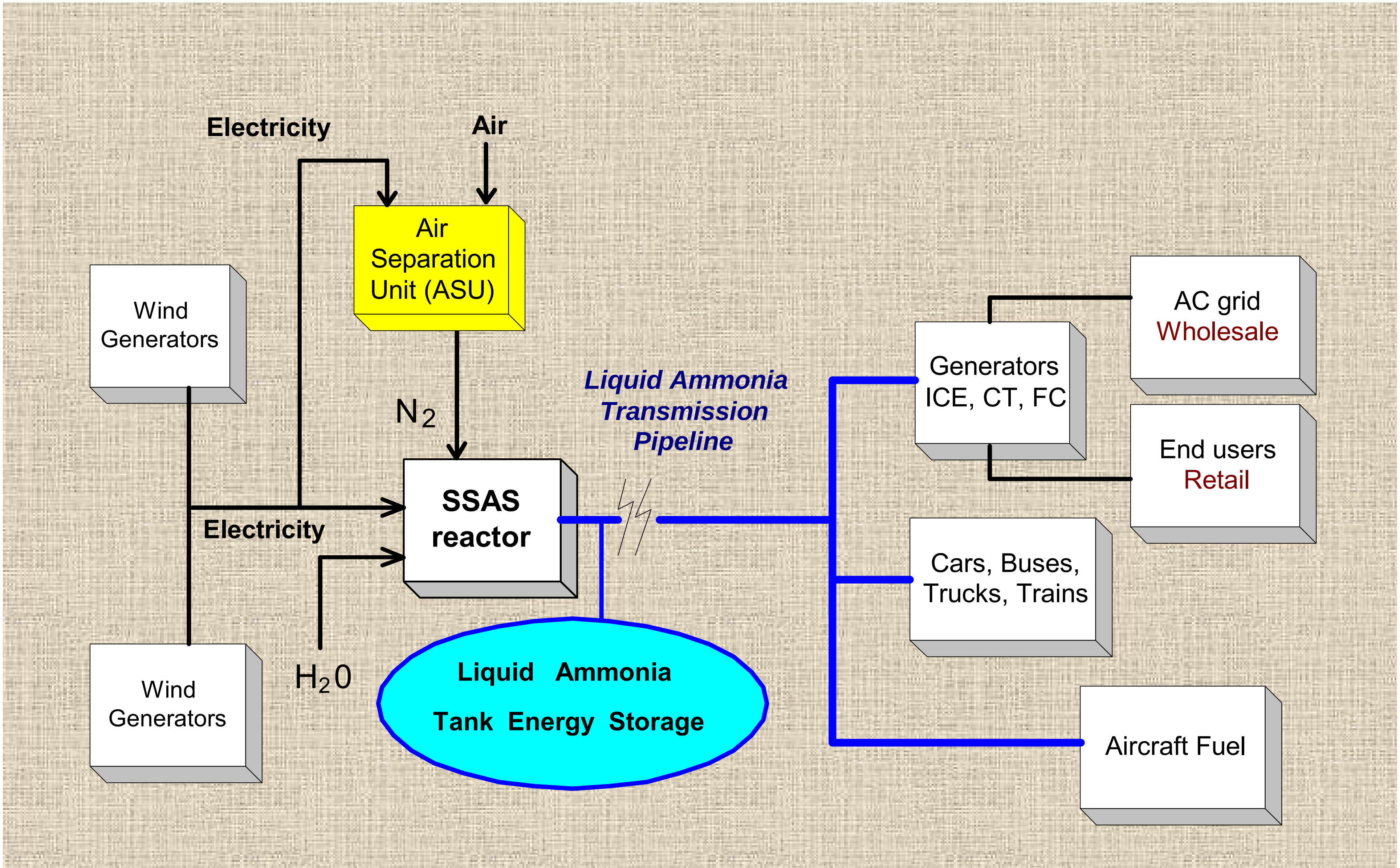

Quoted at $4M. Delivered ?
Contact: Steve Gruhn sgruhn@freedomfertilizer.com
Freedom Fertilizer
1.5MW Nitrefinery

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



RE Ammonia Transmission + Storage Scenario

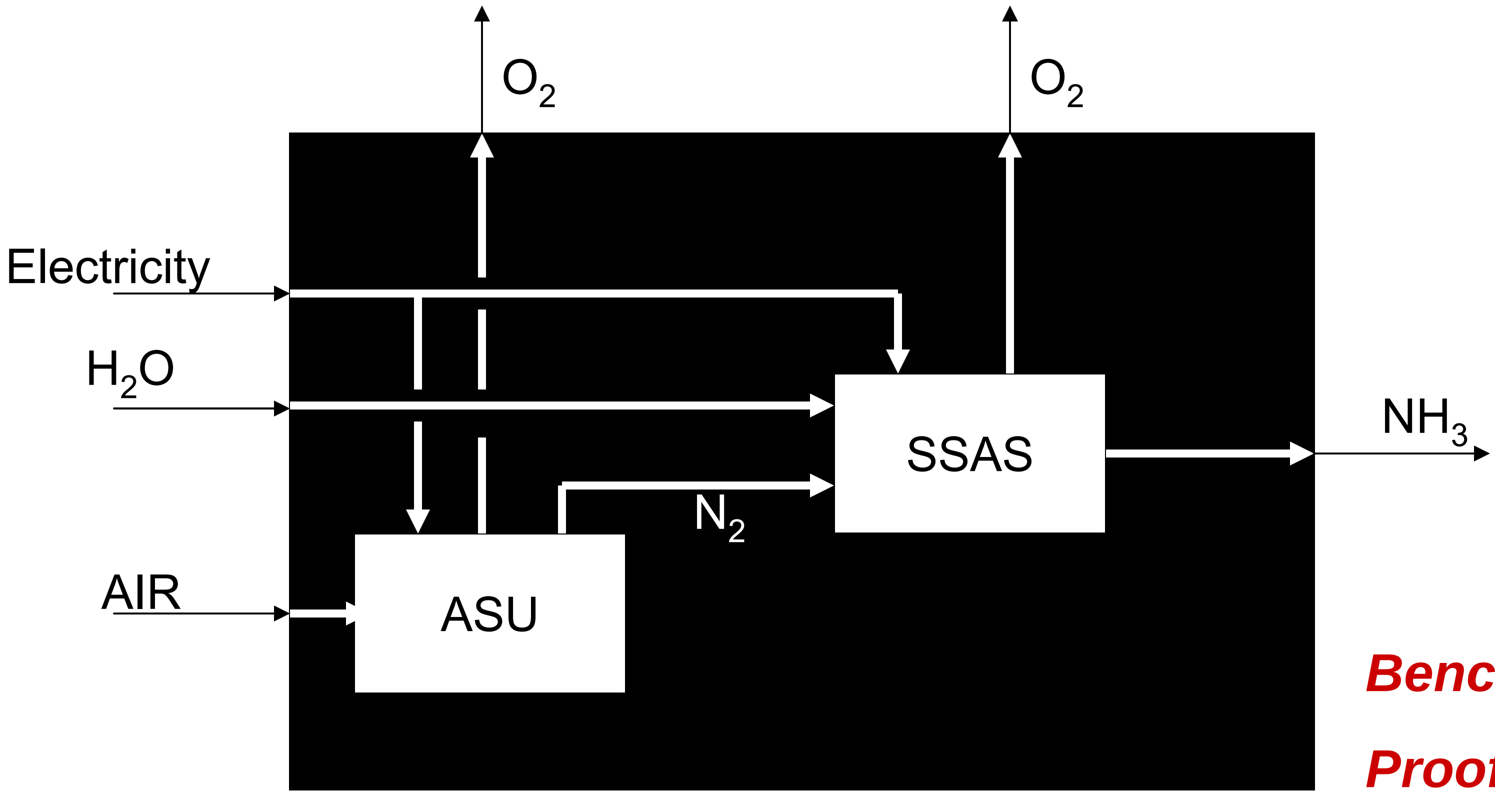




Solid State Ammonia Synthesis (SSAS)

Inside the Black Box:
Solid State Ammonia Synthesis

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

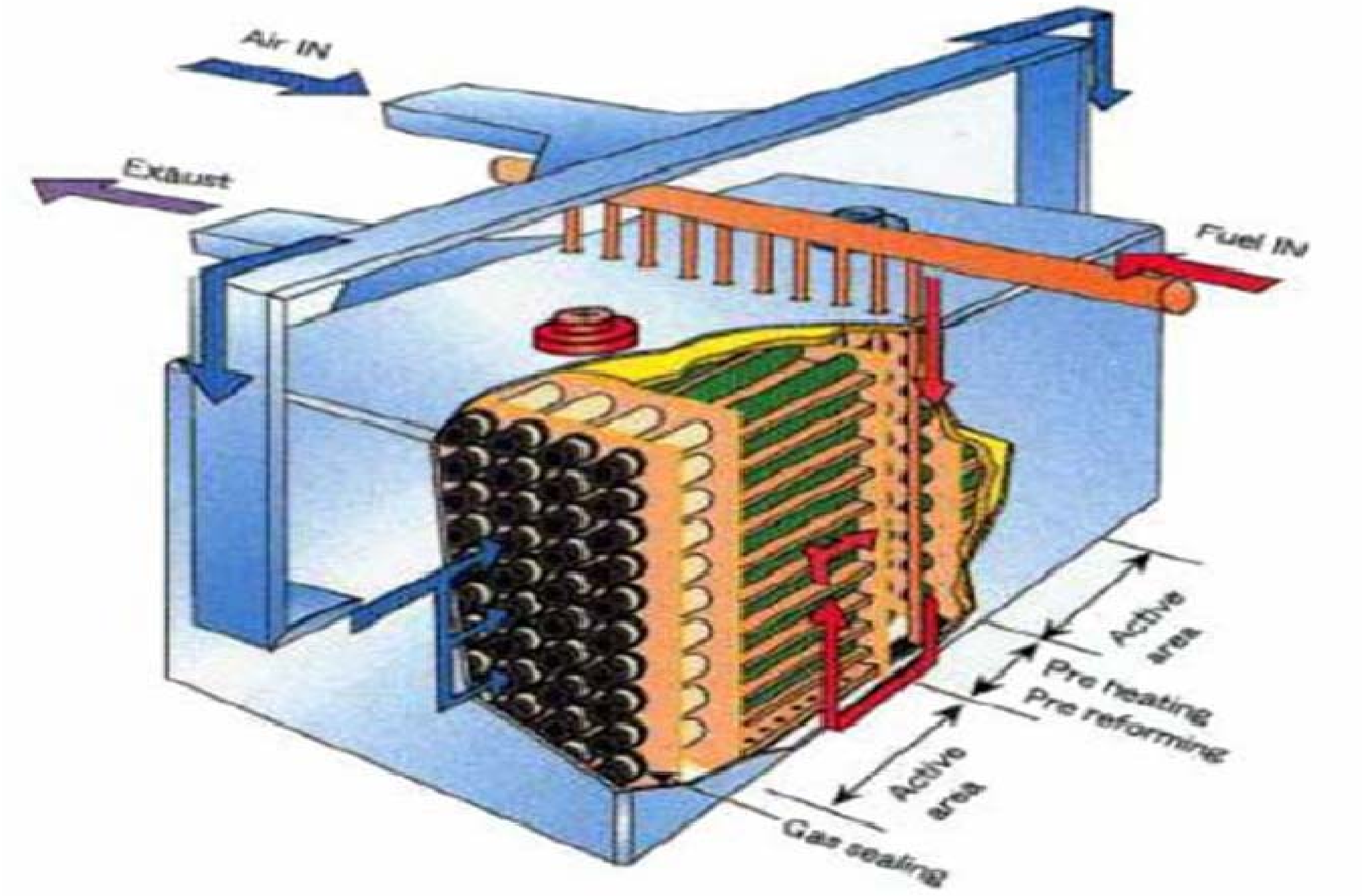


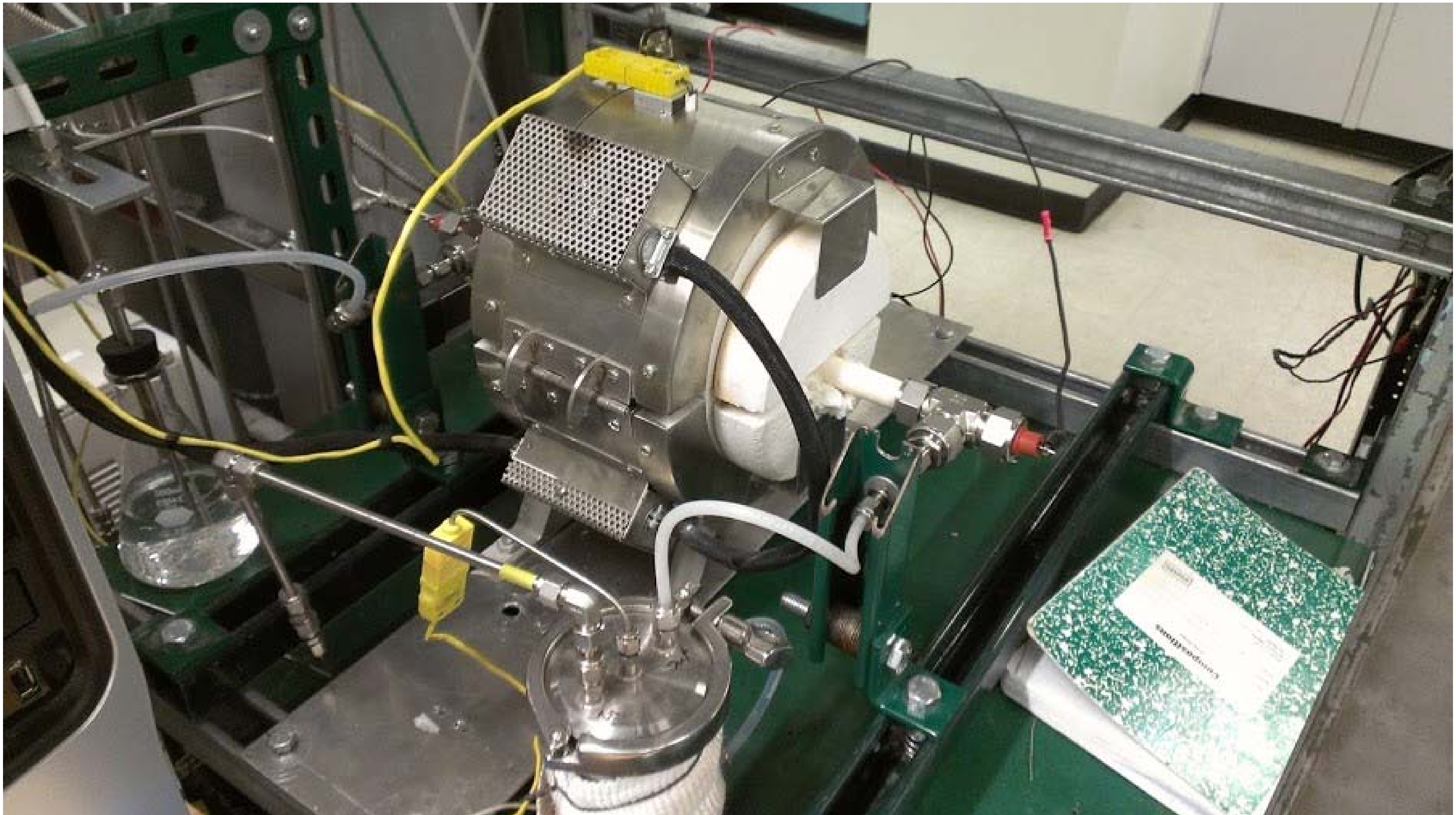
Benchtop

Proof-of-concept

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

Solid State Ammonia Synthesis (SSAS)
NHThree LLC patent

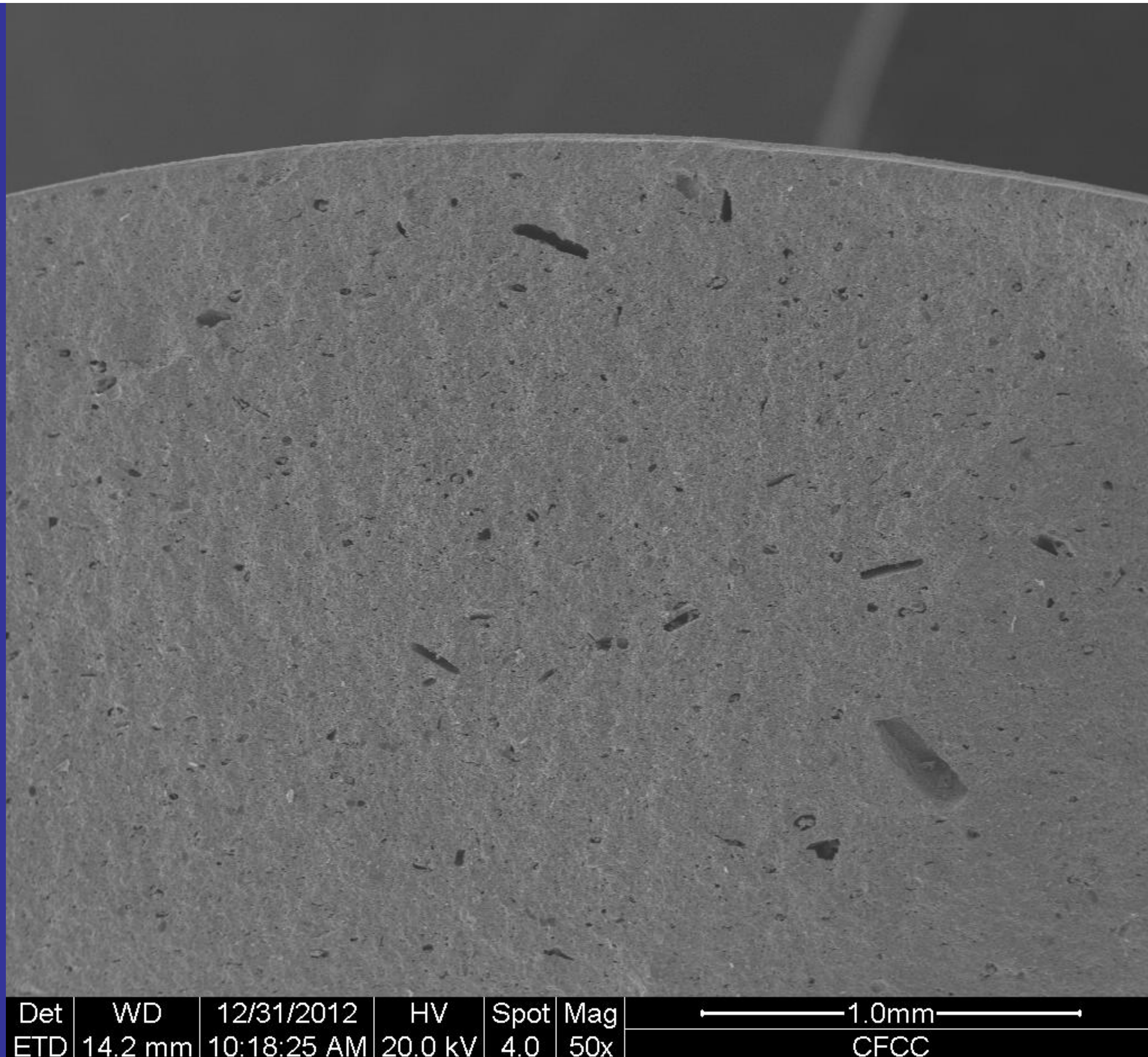




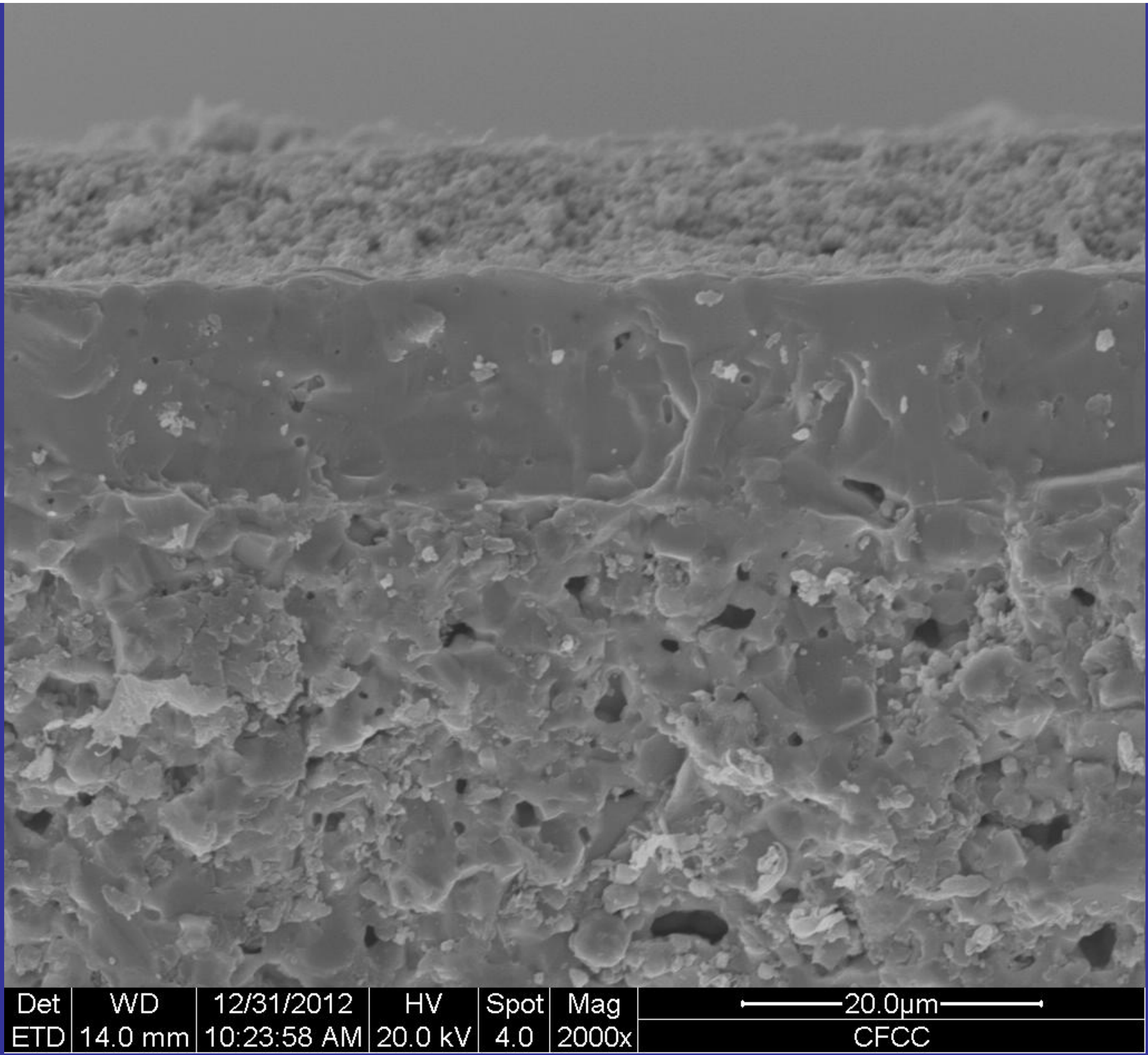
Tube assembly installed in test fixture.

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

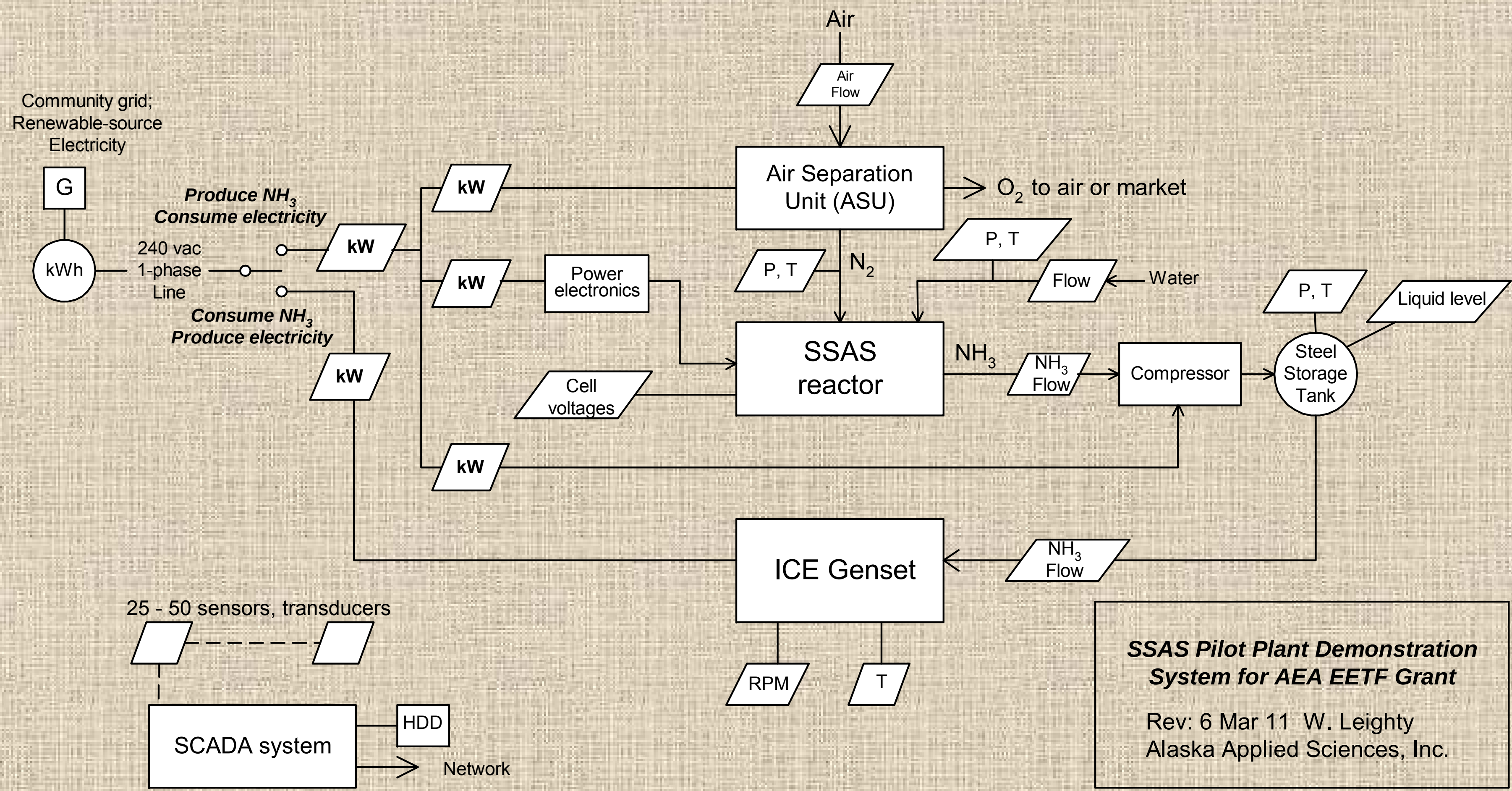
Center: PCC tube 33 cm^2 active area.
Current collectors installed.
Sealed to alumina support tubes. Setup is leak-free.



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



2,000x cathode (interior)



PROJECT: Complete RE – NH_3 SSAS Storage System

> NH3 synthesis from RE electricity, water, air (N_2)

> Liquid NH_3 tank storage

> Regeneration + grid feedback

> SCADA instrumentation → UAF - ACEP

Beyond Alaska Microgrids

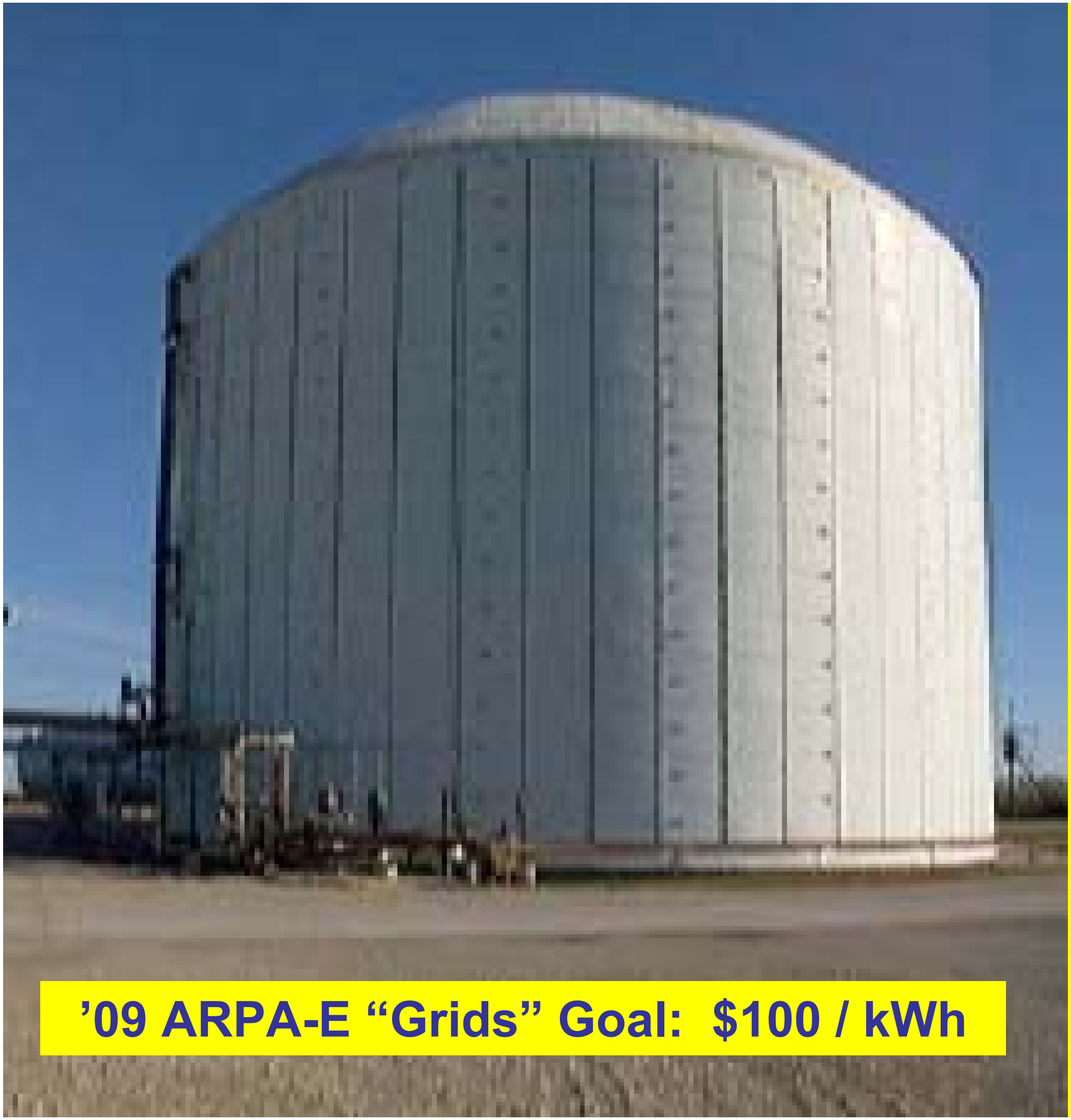
- Success: global application
- "Electrofuels" microgrids
- Merging RE microgrids
  - Ammonia microgrid → macrogrid
- Continental scale RE systems
- RE for all energy, all purposes
- "Run world on renewables"
- "Green" ammonia compete? C-tax?

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

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

        @$ 40 / kWh = $ 13 Billion

        @ $1 / kWh = $ 325M
- GH2 (3 hydrogen caverns) Capital $70 Million
- NH3 (2 ammonia tanks) Capital $30 Million



’09 ARPA-E “Grids” Goal: $100 / kWh

“Atmospheric” Liquid Ammonia Storage Tank (corn belt)

30,000 Tons

190 GWh

$ 15M turnkey

$ 80 / MWh

$ 0.08 / kWh

-33 C

1 Atm

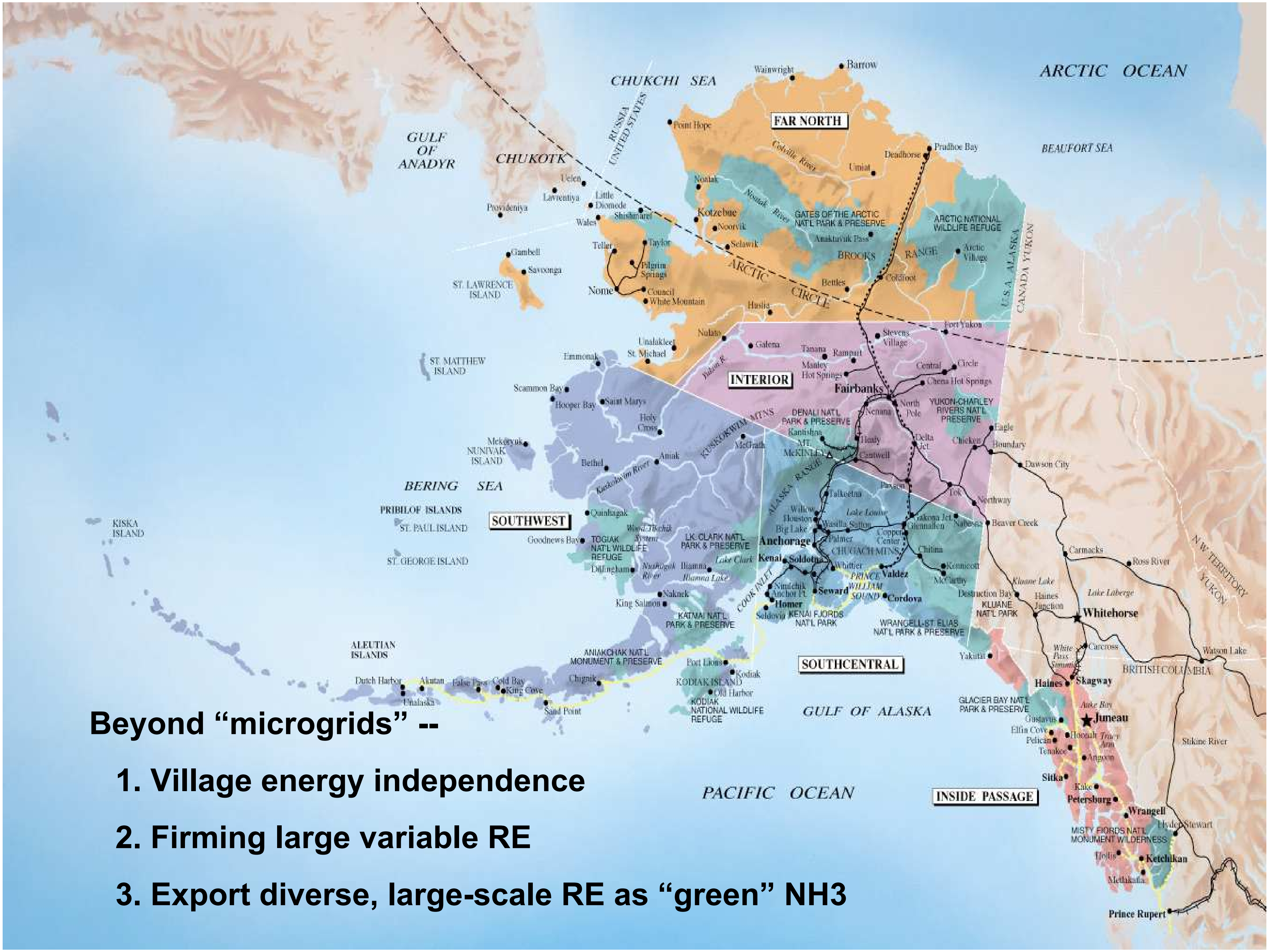
“ Americans can be counted on to always do the right thing –

but only after they have tried everything else ”

Winston Churchill

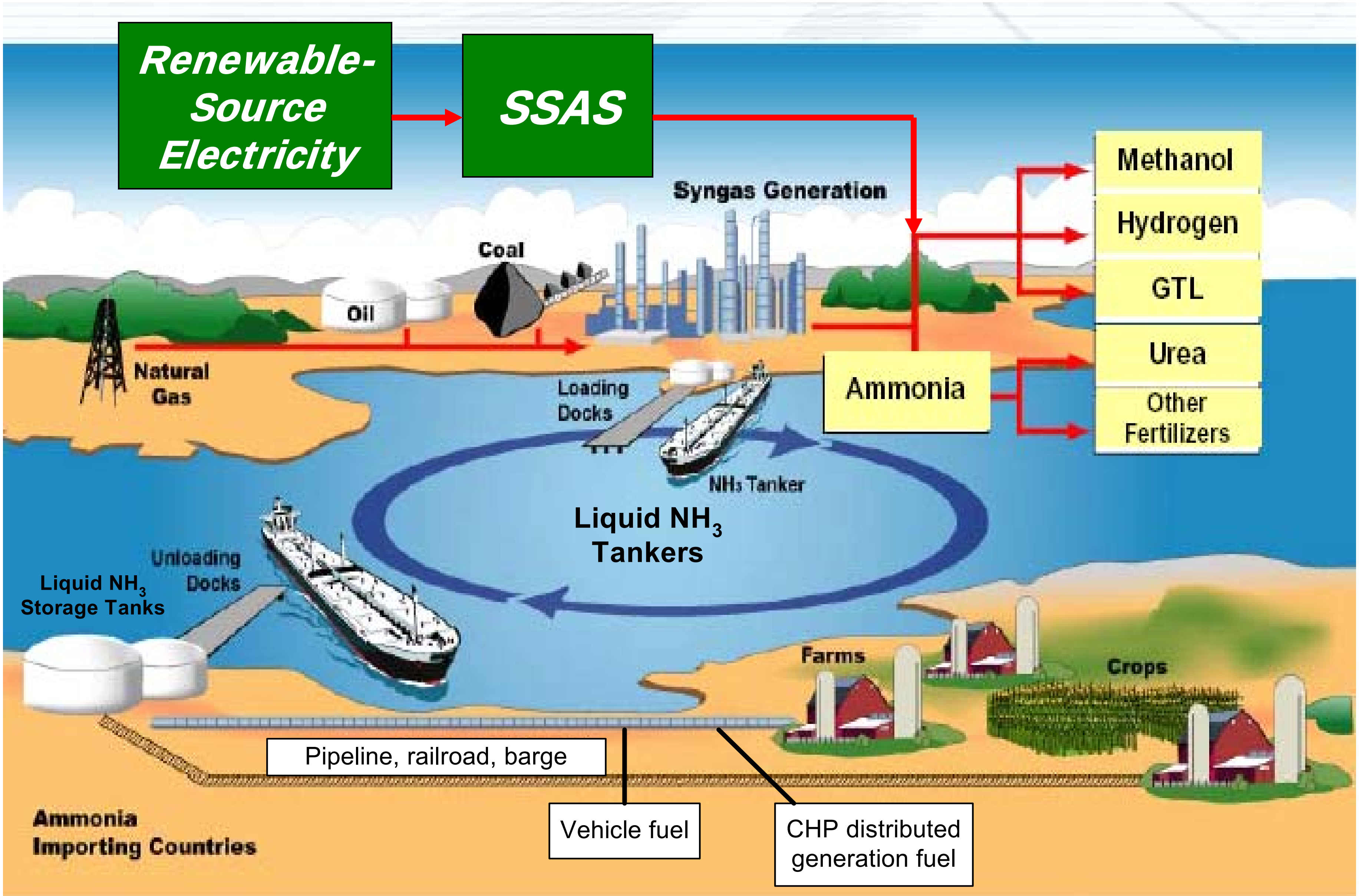
The dog caught the car.

Dan Reicher



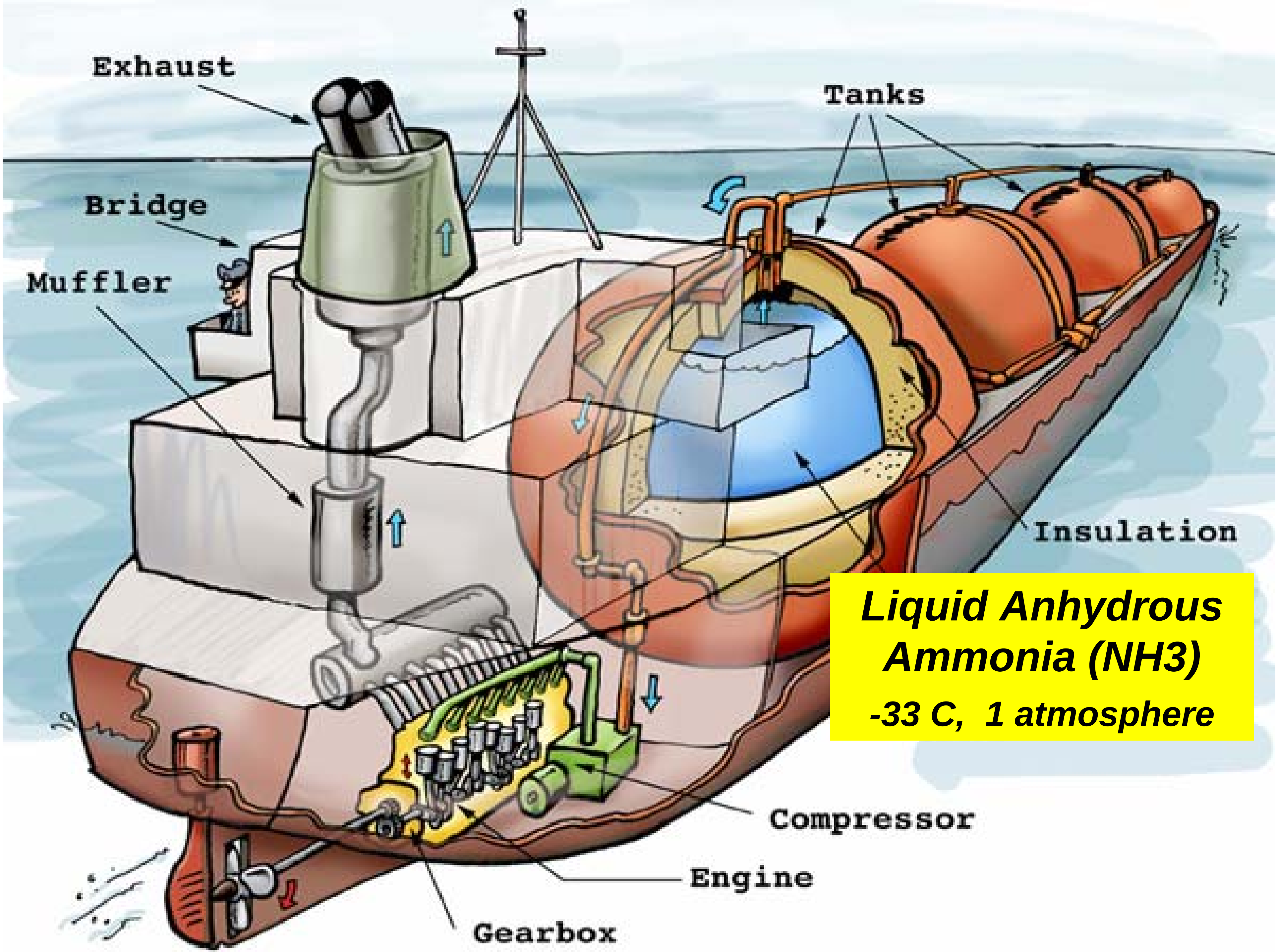
Beyond "microgrids" --

1. **Village energy independence**
2. **Firming large variable RE**
3. **Export diverse, large-scale RE as "green" NH3**



KBR
Energy and Chemicals

Merging microgrids



Liquid Anhydrous Ammonia (NH3)

-33 C, 1 atmosphere

Alaska Energy Authority
Emerging Energy Technology Fund
Project Fundamentals

1. Does SSAS system “work” ?
2. Competitive with EHB ?
3. Useful in Alaska ?

SSAS: Solid State Ammonia Synthesis

Alaska Energy Authority Emerging Energy Technology Fund $750K grant to Alaska Applied Sciences, Inc.

- SSAS Proof-of-concept pilot plant
- Alaska applications
  - Village energy independence
  - Hydro firming, annual-scale
  - RE export as NH3 fuel
  - ALL energy: elec, heat, transport
- 2-year project

Project Fundamentals

1. Anhydrous ammonia (NH_3) is a:
   a. Fuel: ICE, CT, fuel cell
   b. Transmission medium
   c. Low-cost energy storage medium: liquid, 15 bar
2. NH_3 made from RE electricity, water, and air (nitrogen, N_2) by:
   a. Electrolysis + Haber-Bosch (EHB)
   b. Solid State Ammonia Synthesis (SSAS)
3. SSAS should best EHB in:
   a. Capital cost per kWe in, kg NH_3 out
   b. Energy conversion efficiency
   c. System simplicity, low O&M cost
   d. Alaska value

Project Fundamentals

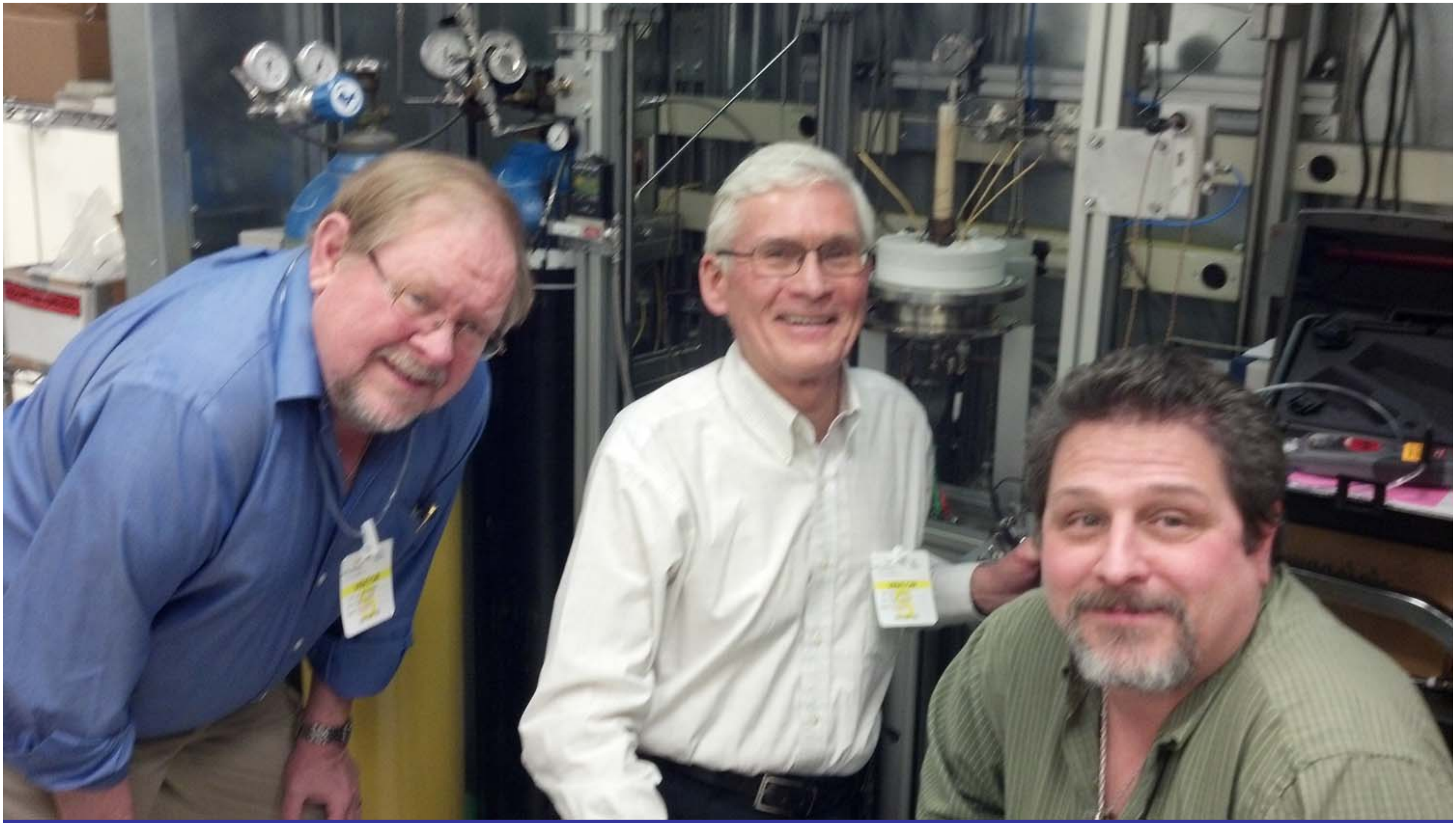
4. SSAS unproven: needs proof-of-concept, kW-scale pilot plant
5. Design and build pilot plant:
   a. Complete system: convert, store, regenerate
   b. SCADA instrumented: public
   c. Containerized & transportable
   d. Upgradeable
6. Success:
   a. Great value to Alaska, beyond
   b. Scaleup to commercial
   c. SE Alaska “RE Cluster Industry” via USFS, JEDC

Project Status

- PCC tube section in test at PNNL, Richland, WA
- AEA 1 Dec deadline: “use or lose” $750K grant
- Alternative technology propose?

  “Nafion” membrane reactor: TRL = 0
- Fundamentals persist:

  Alaska, global need



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

The Alaska Renewable-Source Ammonia Fuel Pilot Plant: Village Energy Independence, Firming Storage, and Renewables Export

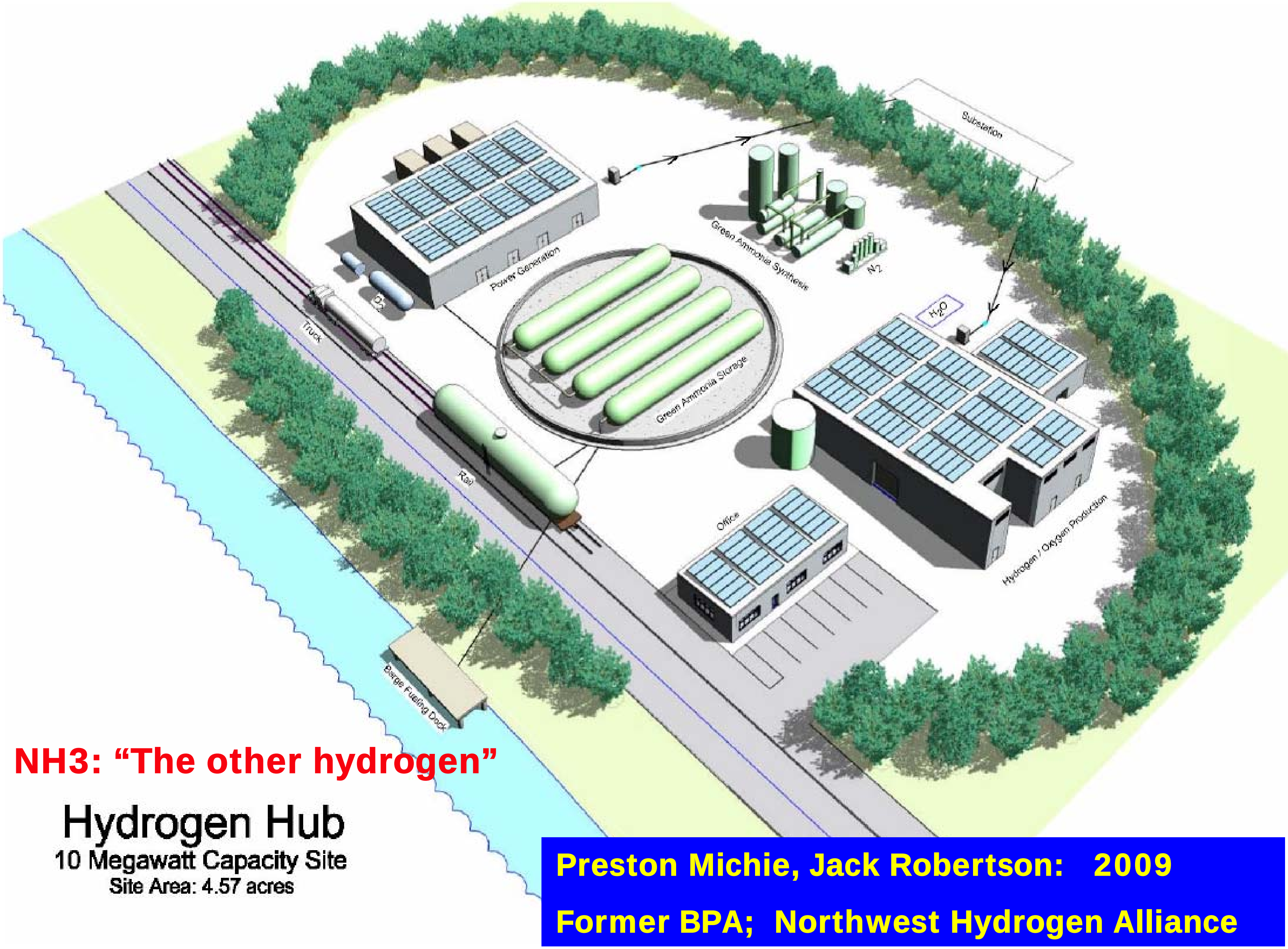
Handouts + DVD's

Renewable Energy World

12-14 November 2013 Orlando

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

NH3: "The other hydrogen"



Preston Michie, Jack Robertson: 2009

Former BPA; Northwest Hydrogen Alliance

Hydrogen Hub Concept