Making Ammonia Fuel From Alaska's Vast Stranded Renewable Energy Resources

Business of Clean Energy in Alaska
Anchorage, AK
18 June 10

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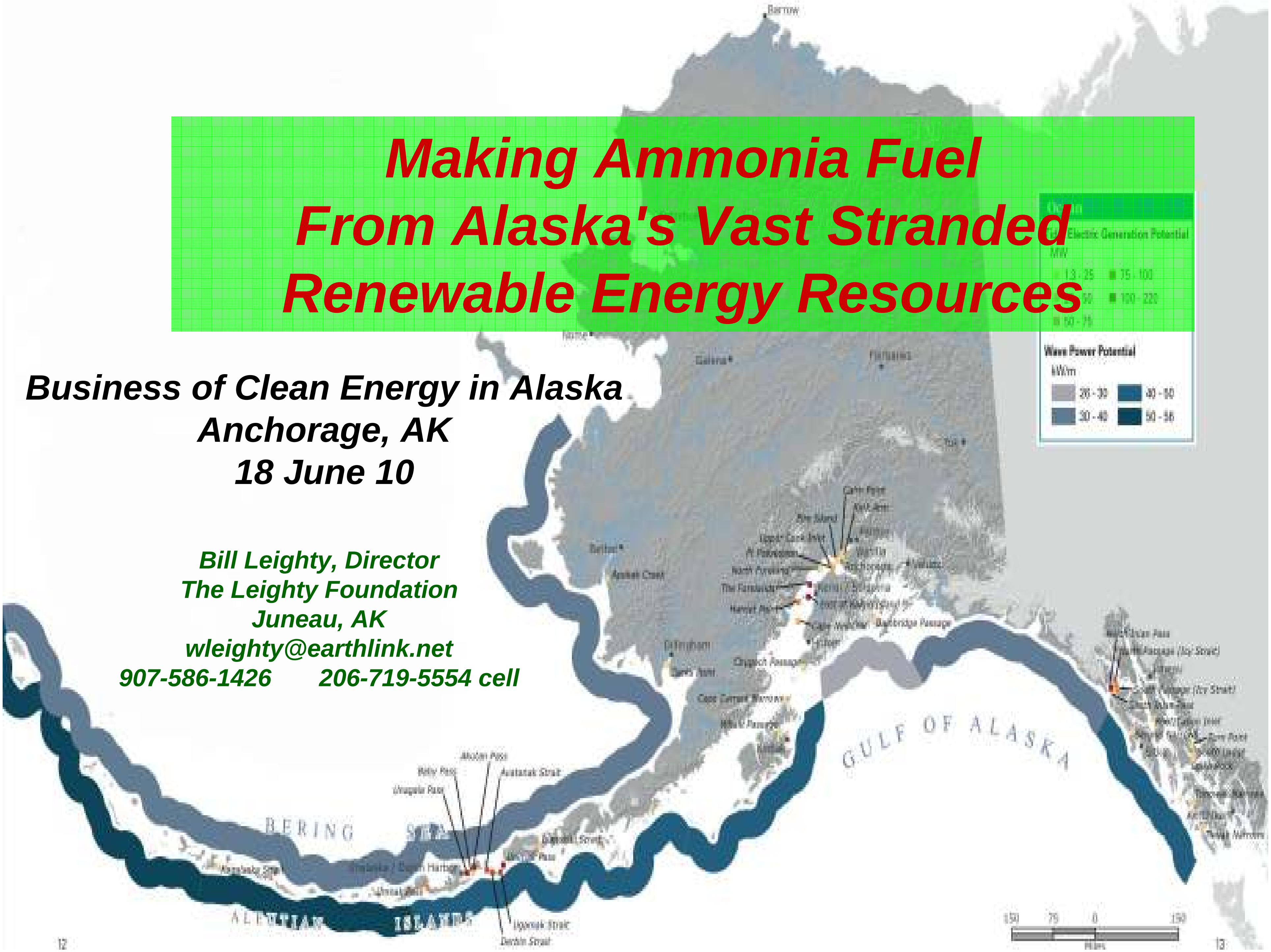

OCEAN

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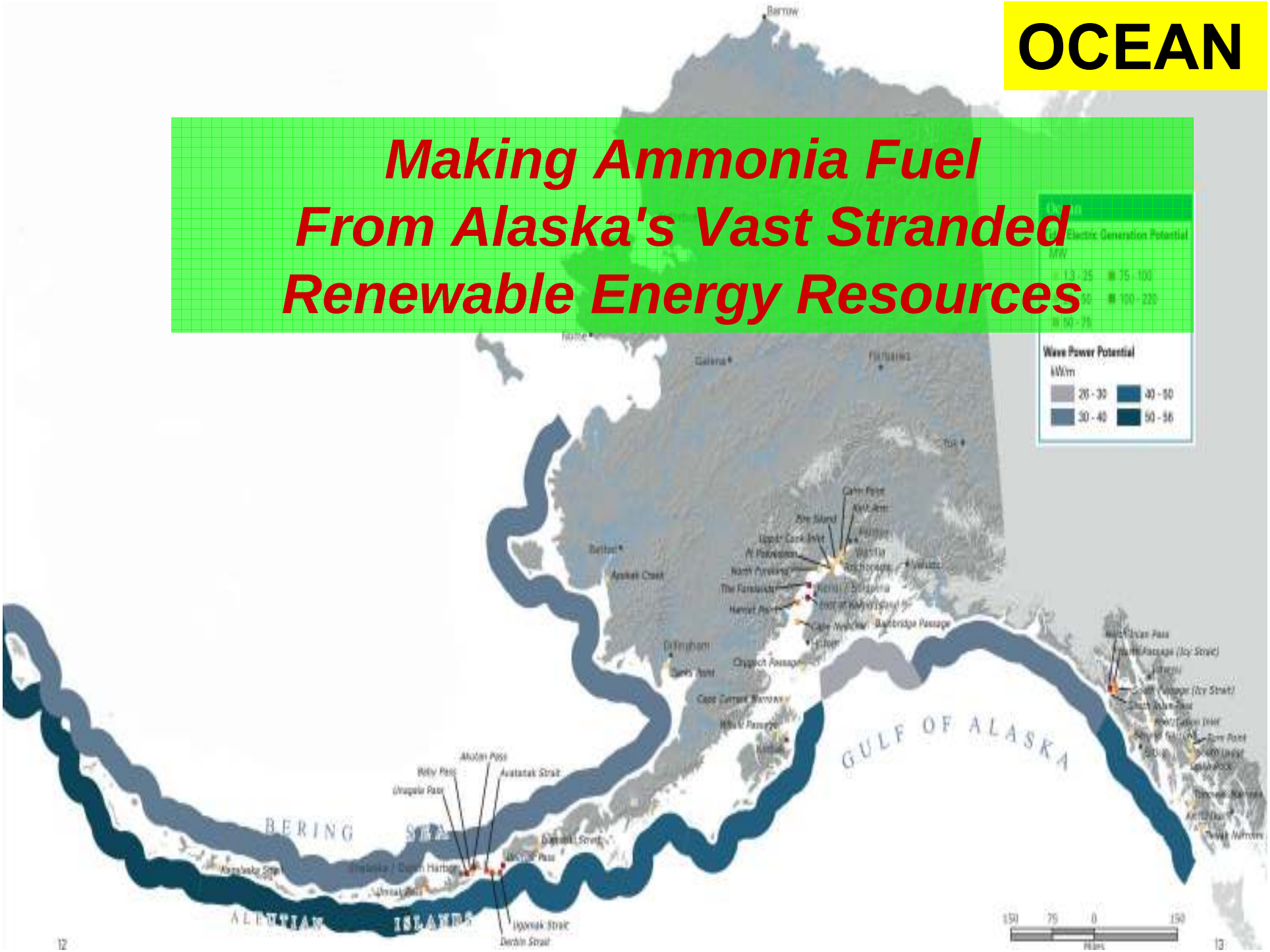
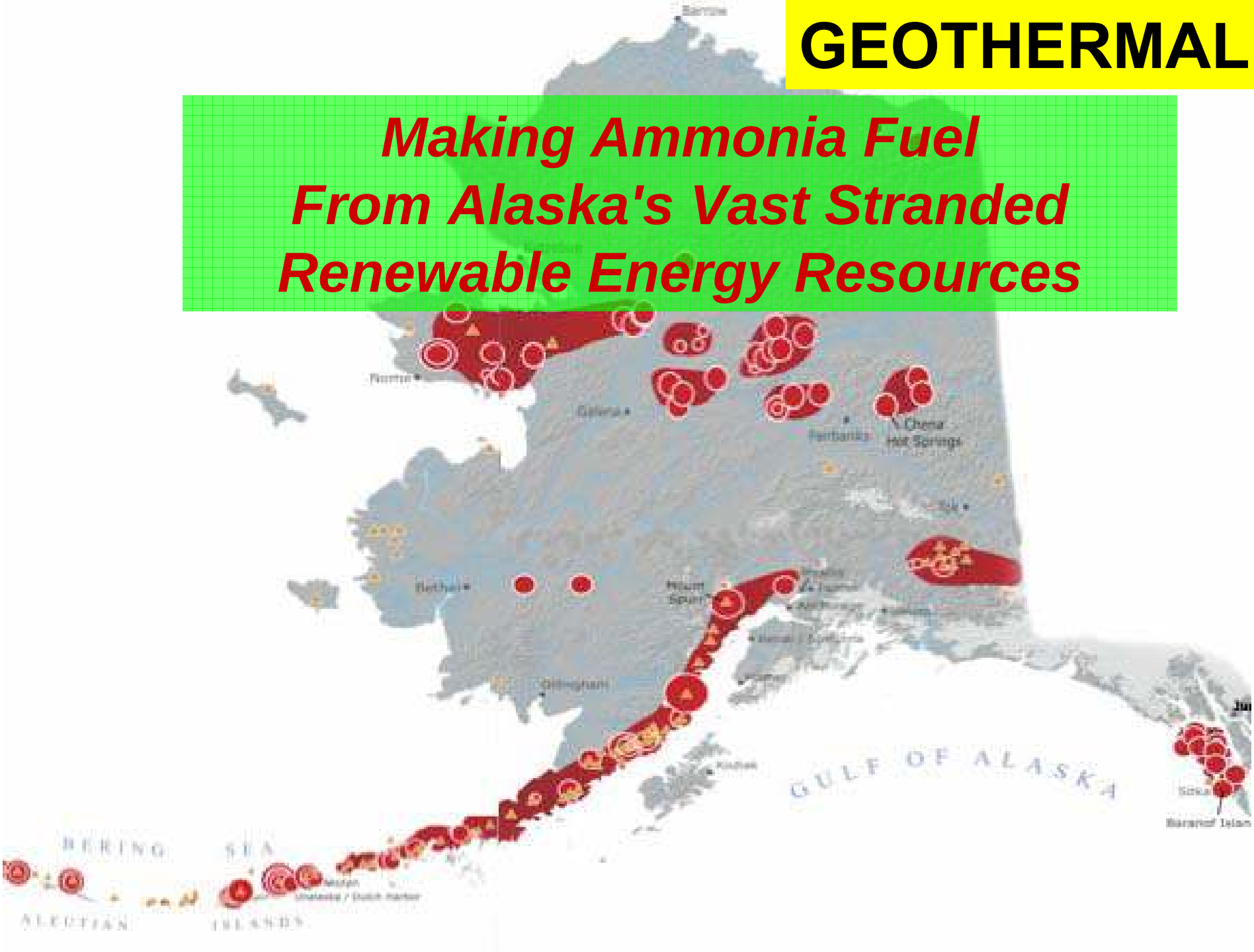


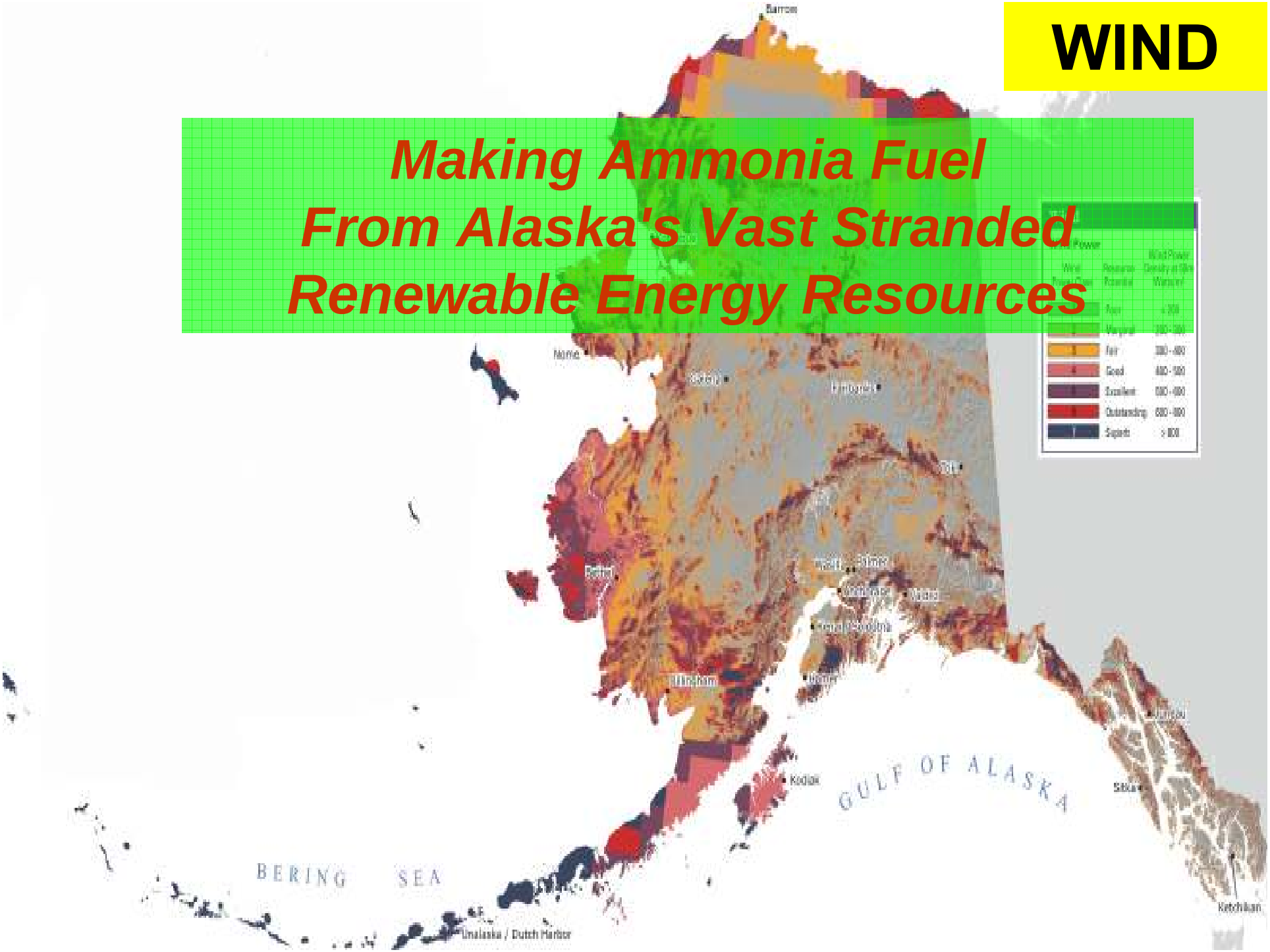
GEOTHERMAL

Making Ammonia Fuel From Alaska's Vast Stranded Renewable Energy Resources

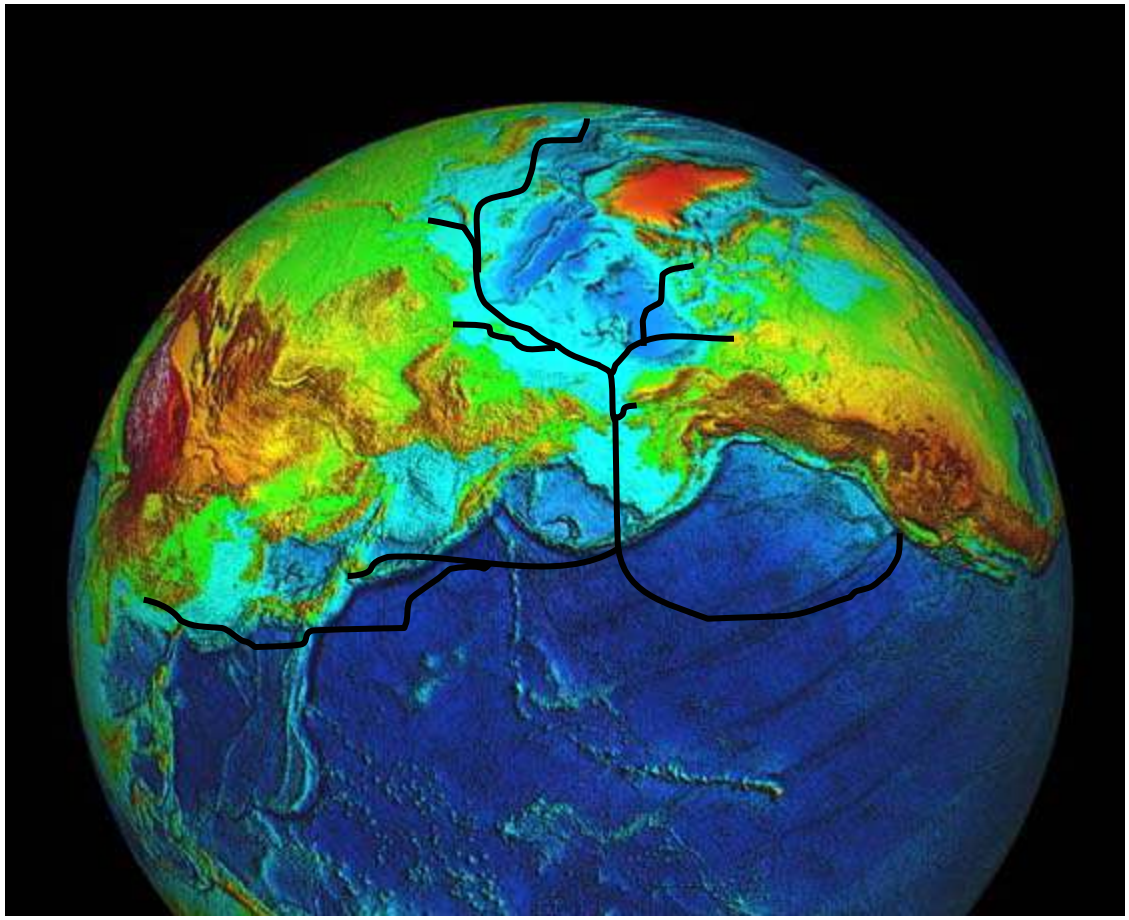


WIND

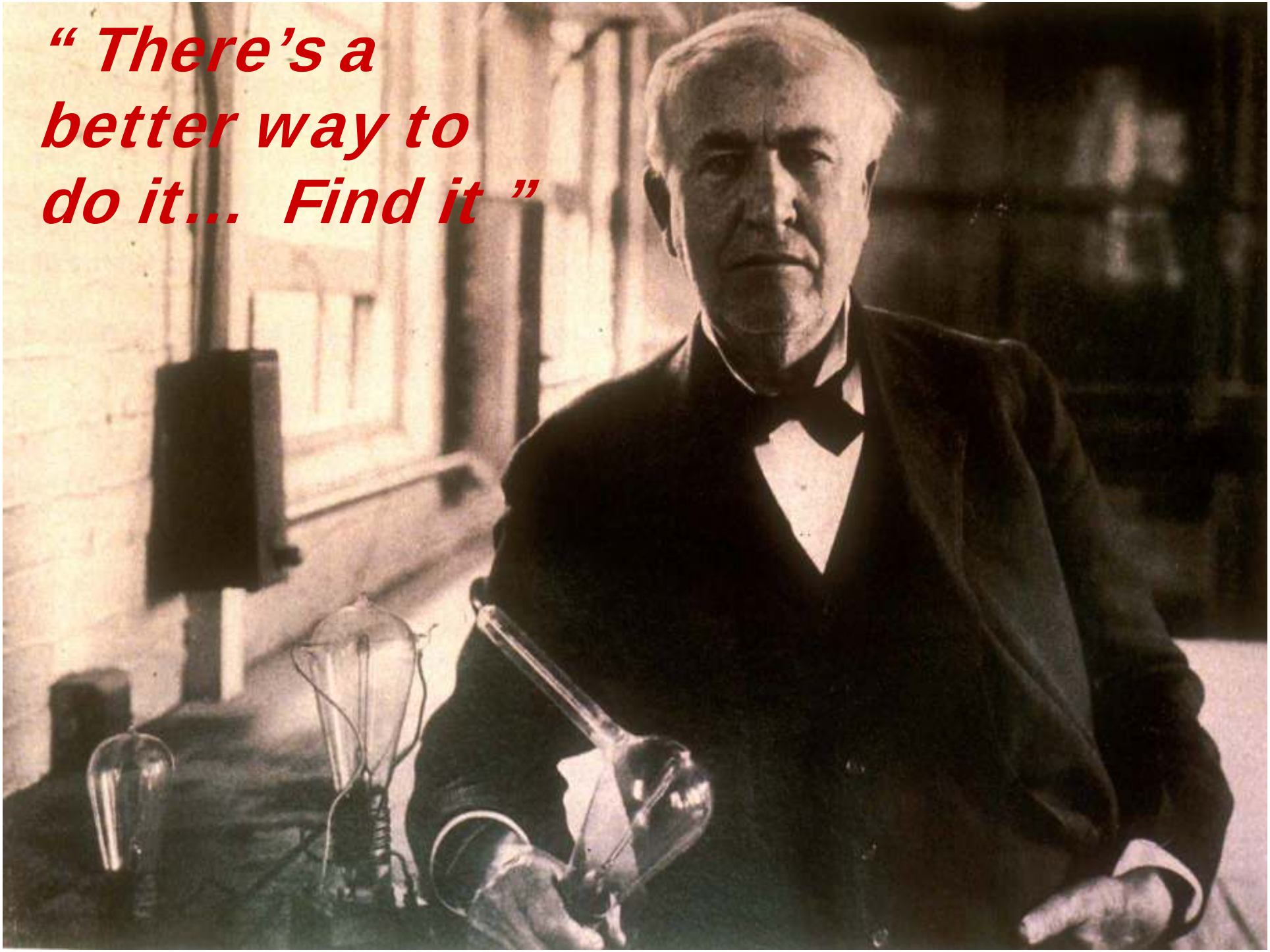
Making Ammonia Fuel From Alaska's Vast Stranded Renewable Energy Resources

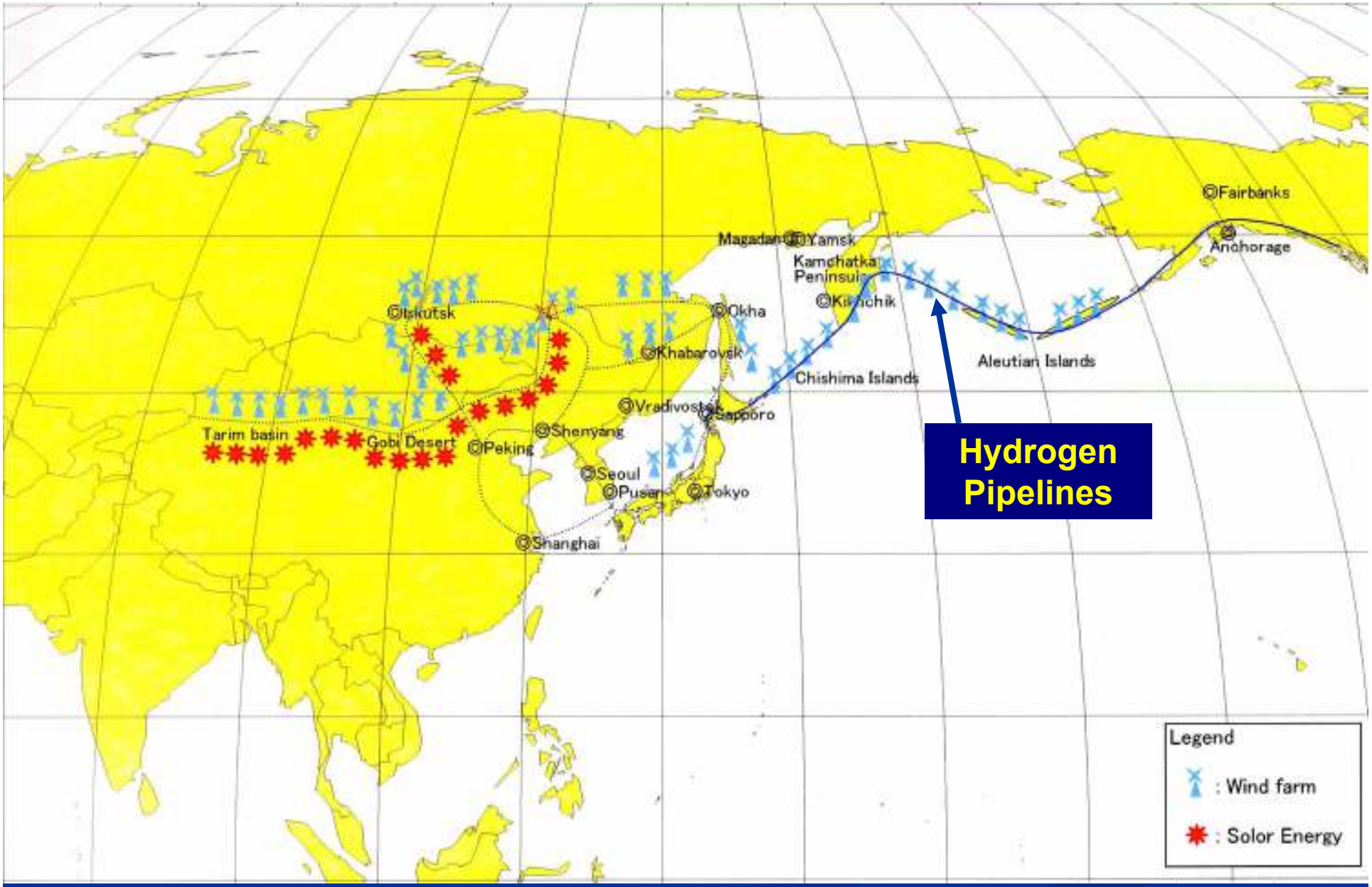


Alaska in the future global energy economy



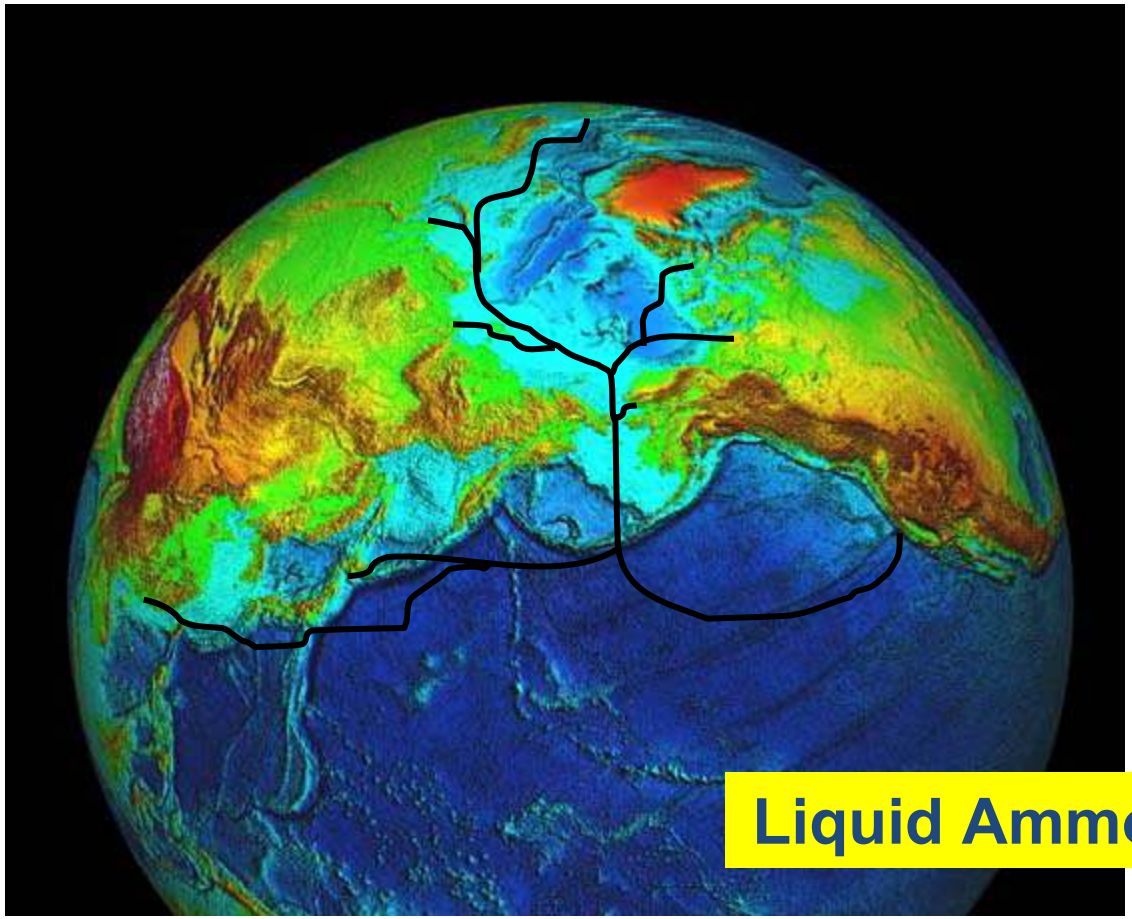
ACEP
Alaska Center for Energy and Power


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

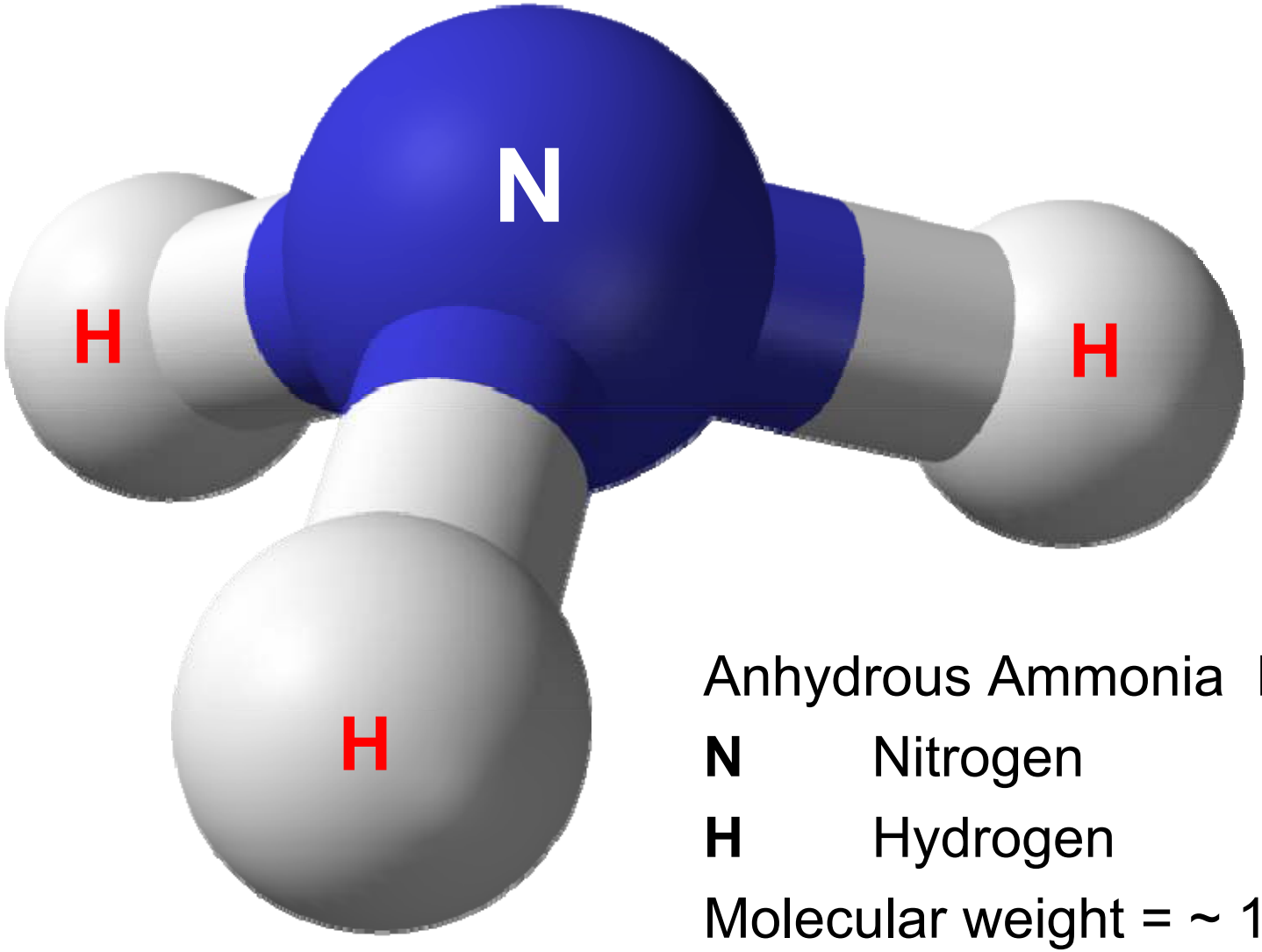


Map by K. O'Hashi, Nippon Steel

Alaska in the future global energy economy



ACEP



Anhydrous Ammonia **NH_3**

N Nitrogen

H Hydrogen

Molecular weight = ~ 17

18% **H** by weight: “other hydrogen”

$NH_3 + O_2 = N_2 + H_2O$

Why Ammonia ?
Fertilizer and Fuel

Only liquid fuel embracing:

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

Ammonia
534 kg H2
EACH

Hydrogen gas
350 kg H2

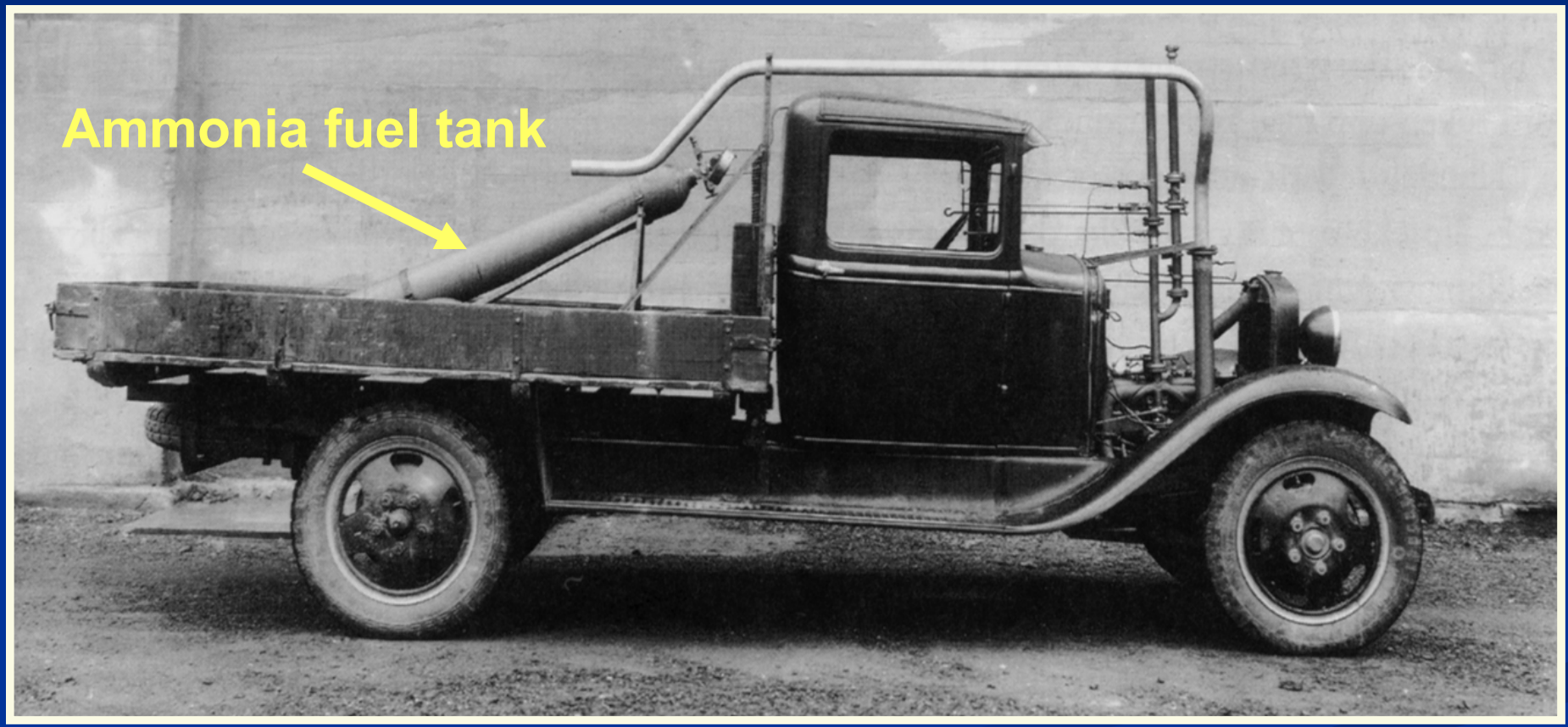
Streetcar

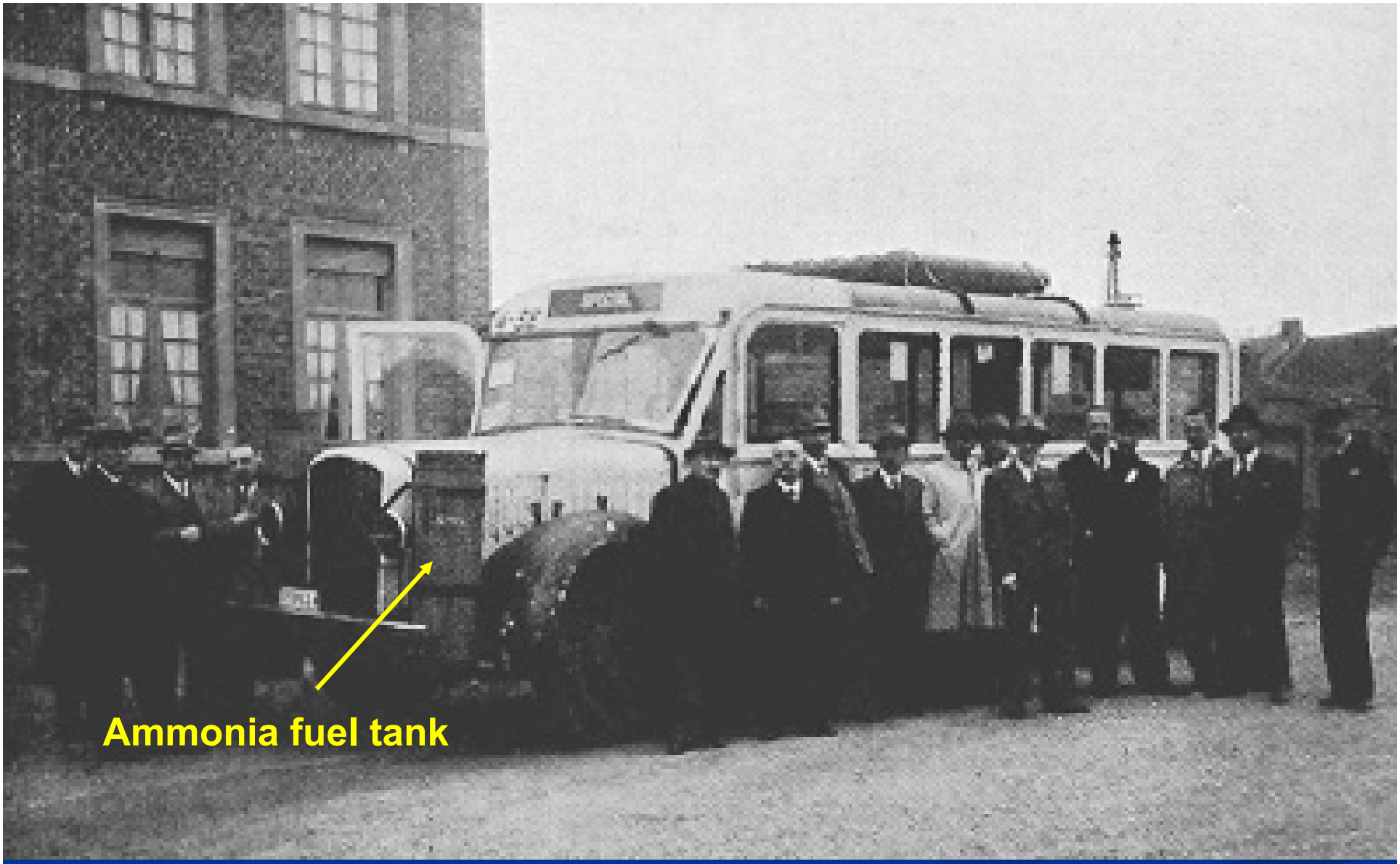
New Orleans

1871

“Ammoniacal Gas Engine”

Ammonia fueled – Norway 1933





Belgium, 1943

Ammonia Fueled Bus: Thousands of Problem-free Miles

X-15 rocket plane: NH3 + LOX fuel

Mach 6.7 on 3 Oct 67

199 missions between 1959 and 1968

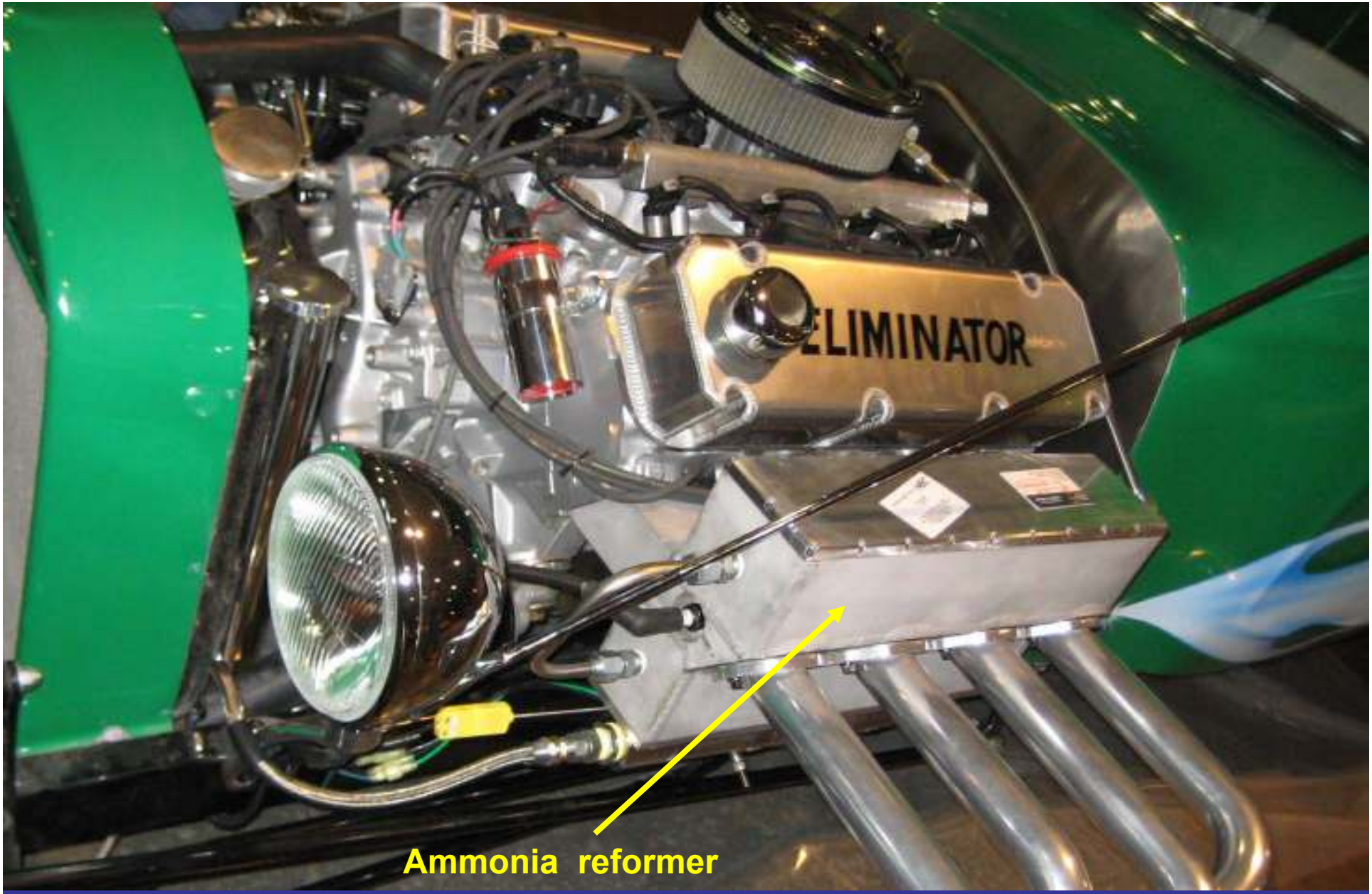
University of Michigan

Ammonia + Gasoline Powered

- Idle: gasoline
- Full power: 80% ammonia

Summer ’07 Detroit → San Francisco

'08: 1,000 hours, ICE, 6 cyl, 100 hp
75% ammonia, 25% propane

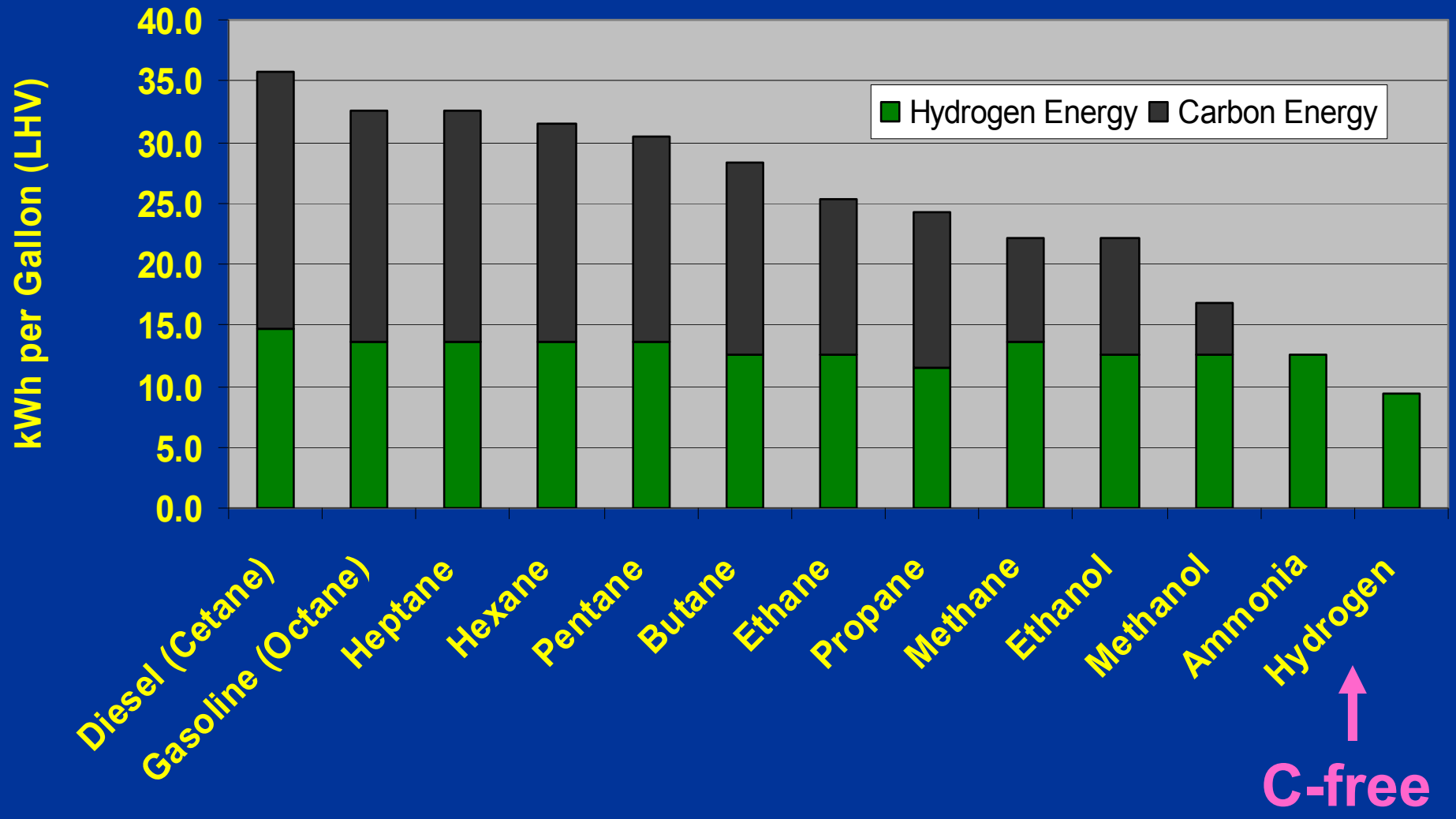


Oct ’09 Ammonia Fueled V-8 with Hydrogen Injection: Reformed from NH_3
Hydrogen Engine Center, Algona, IA

Ammonia Fuel Uses

- Internal Combustion Engine (ICE)
  - Diesel: NH_3 gas mixed with intake air
  - Spark-ignition: 70%+ NH_3 plus – gasoline, ethanol, propane, NG, hydrogen
  - NOx ~ ¼ gasoline engines
- Combustion Turbines
- Direct Ammonia Fuel Cells:
  - Combined heat + power (CHP)
  - No NOx
- Reform ("crack") to liberate hydrogen for fuel cells: $2NH_3 \rightarrow 3H_2 + N_2$

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



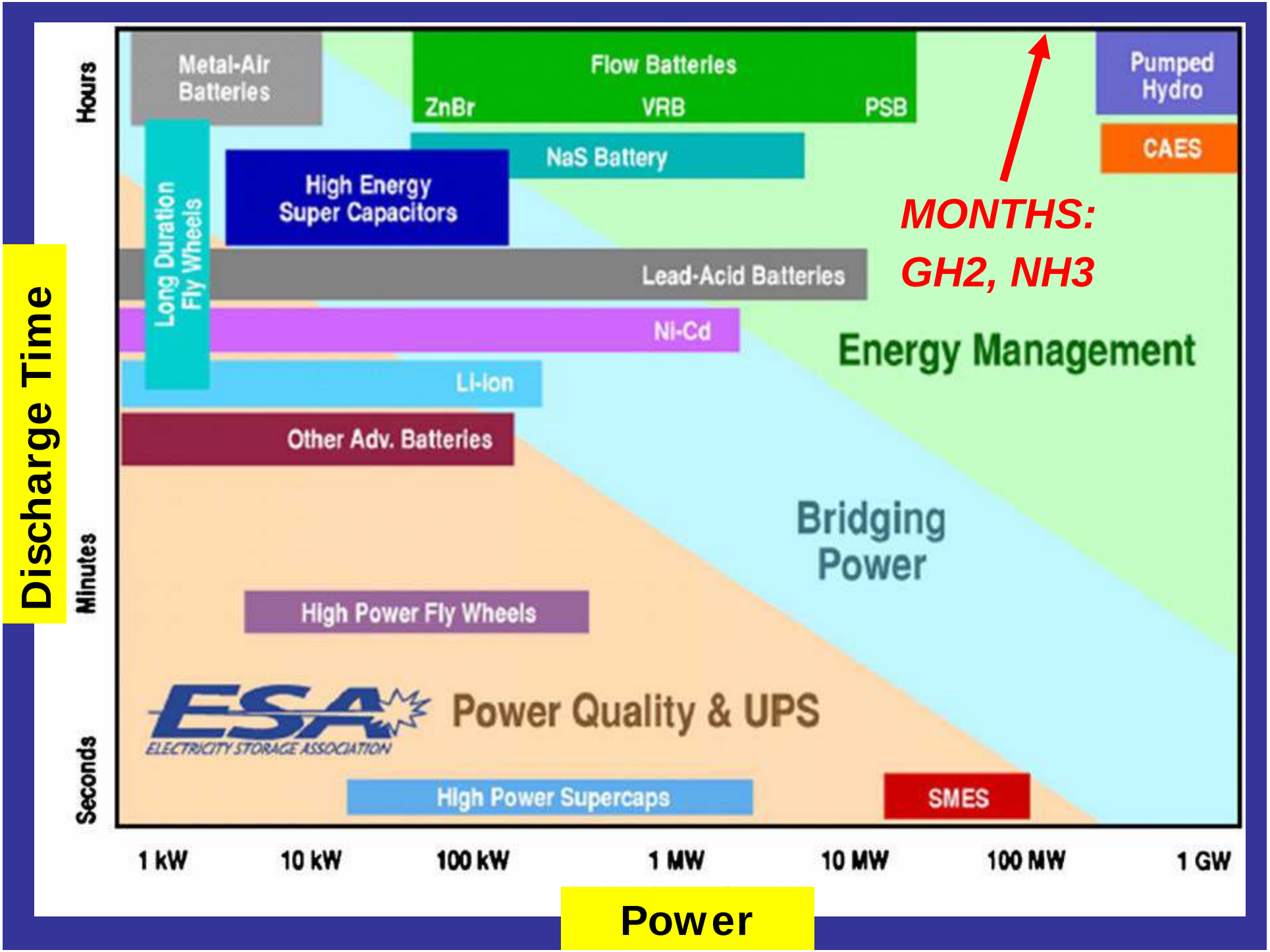
Ammonia Properties

- C-free fuel: unique physical, chemical properties
- Carbon-free energy cycle, system
- # 2 global industrial chemical trade
- 95%+ from stranded natural gas
  - ~ $1.00 / MMbtu
  - Trinidad, Australia, Quatar, Algeria, Russia
  - Other from coal gasification → hydrogen + Haber-Bosch
- Liquid at >125 psi at room temperature
- ~ Half energy density gasoline or diesel,
  volume or weight
- Easily "cracked" to H_2 + N_2 at end-use
- Low flammability, flame spread

Ammonia Properties

- Forms:
  - "Anhydrous" NH_3 : useful as fuel
  - Urea: (2) NH_3 + CO_2
  - Ammonium nitrate: NH_4NO_3
  - UAN: aqueous urea + ammonium nitrate
- Decades infrastructure + safety record

  ~14 MMt / year in USA, mostly fertilizer
  - Inhalation hazard; detected @ 5 ppm
  - OSHA, NIOSH regs + exposure limits
  - Toxic to aquatic life


Discharge Time
Hours
Minutes
Seconds
Metal-Air Batteries
Flow Batteries
ZnBr
VRB
PSB
Pumped Hydro
CAES
NaS Battery
High Energy Super Capacitors
Long Duration Fly Wheels
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

"Firm" Energy Essential

- **Rural Alaska, Islands, Humanity**
- **Every hour, every year**
- **Dispatchable**
- **Strategically: indigenous, secure**
- **Market price: worth more**
- **Bankable large projects**
- **Risk avoidance:**
  - **Rapid climate change**
  - **Death**

Alaska Business Opportunities: Business is About Cash Flow

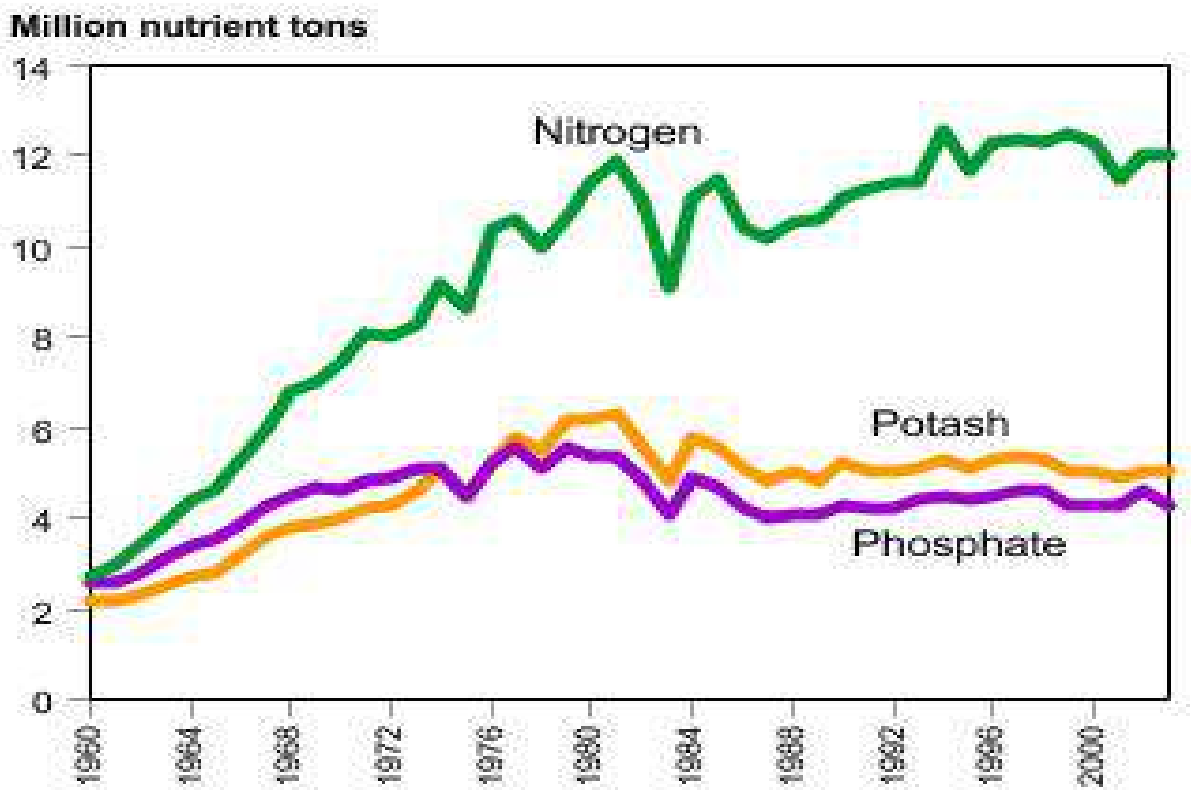
- **Maximize cash IN**
- **Minimize cash OUT**
- **Short, long term NCF, IRR, NPV**
- **Enterprises:**
  - **State, Communities**
  - **People of Alaska**
  - **Capital Investors**

Alaska Business Opportunities: RE – NH3 = "Green" Ammonia

1. **Export GW-scale RE: Increase cash IN**
2. **Energy "independence": Reduce cash OUT**
   - **Villages, communities**
   - **Indigenous renewables; diverse**
   - **Seasonal, diurnal variability**
   - **Storage as NH3 in pressurized tanks**
   - **"Firm" energy**

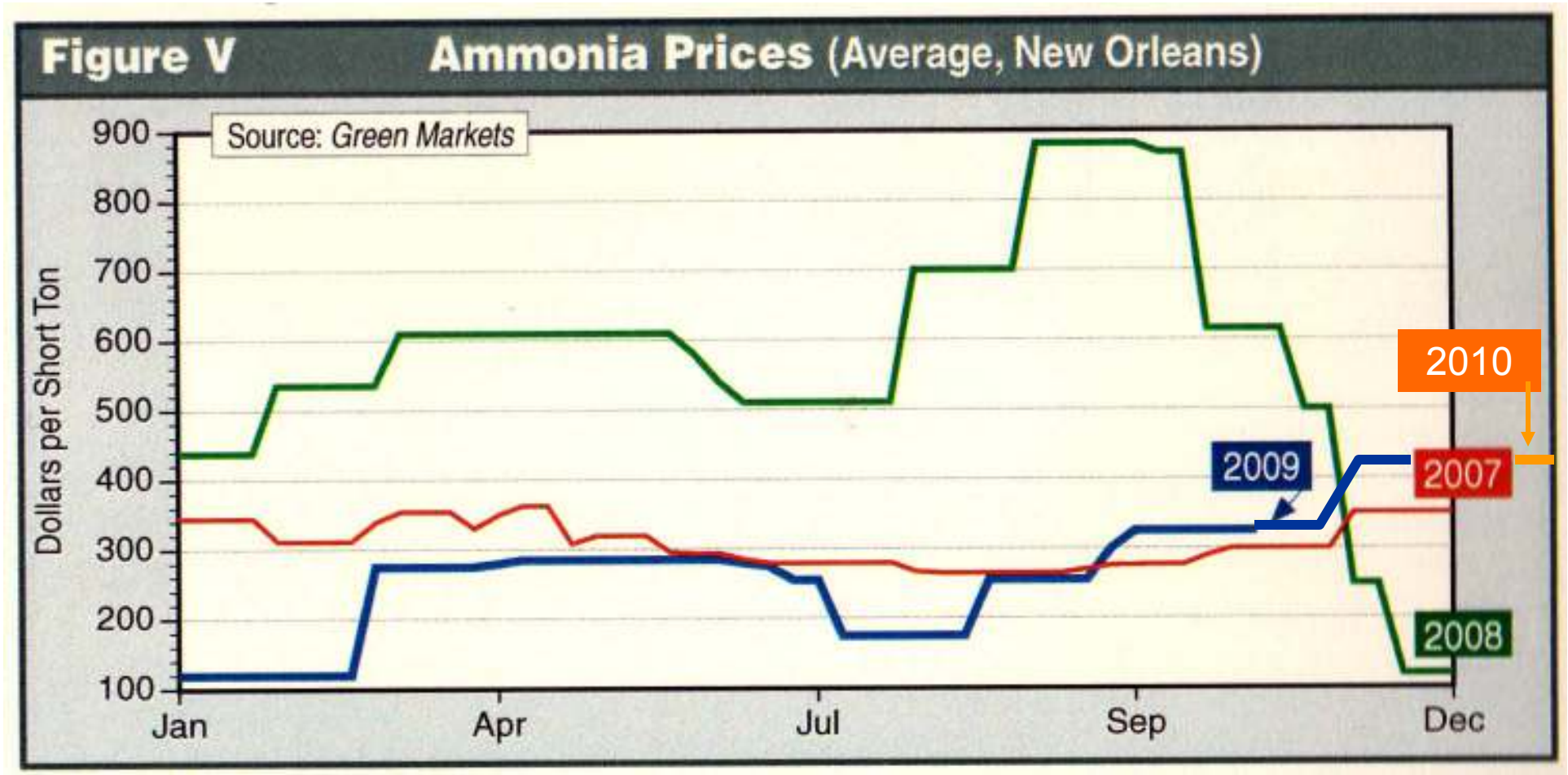
Expect N-Fertilizer Consumption to Rise:
World Food Supply

Figure 4.4.2--Consumption of primary plant nutrients, 1960-2003



40% of humanity requires Haber-Bosch synthetic N-fertilizers

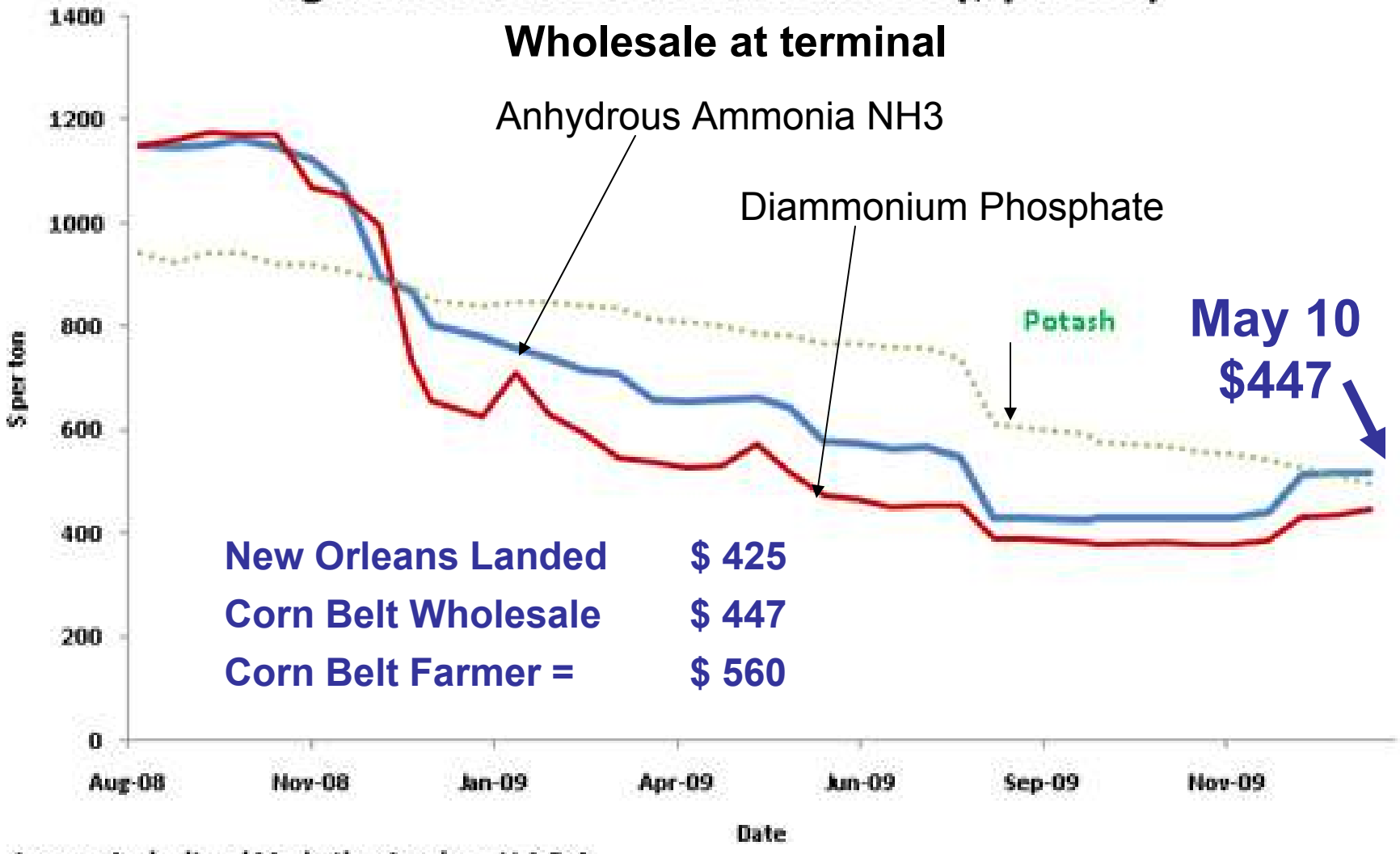
ERS



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

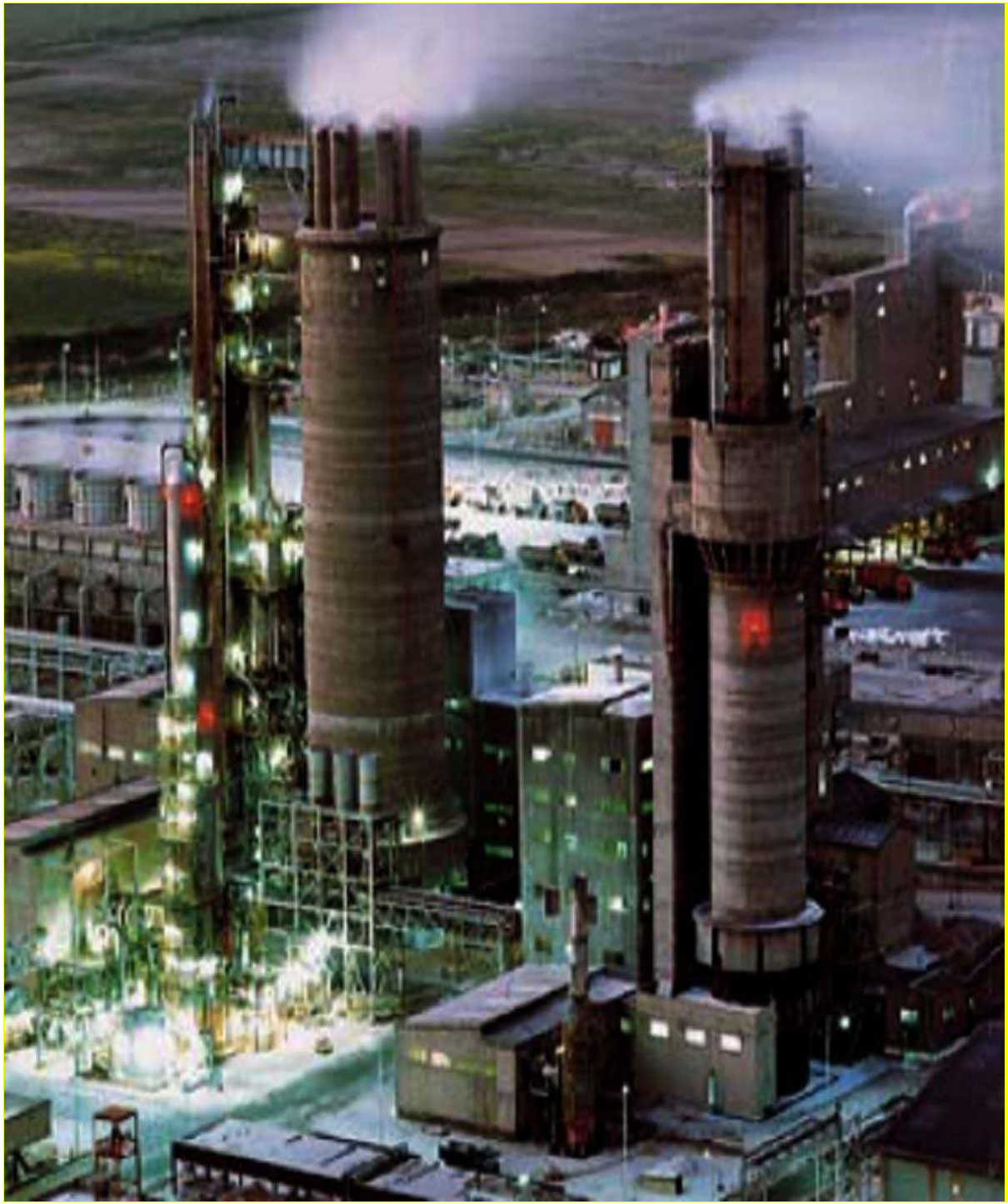
Figure 1. Fertilizer Prices in Illinois ($ per ton)

Wholesale at terminal



New Orleans Landed	$ 425
Corn Belt Wholesale	$ 447
Corn Belt Farmer =	$ 560

Source: Agricultural Marketing Services, U.S.D.A.



95% Global Ammonia

Synthesis Plant

Natural Gas

1 – 3,000 tpd

Haber-Bosch process

Fritz Haber

Haber-Bosch Process

1909 – 1913 BASF

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

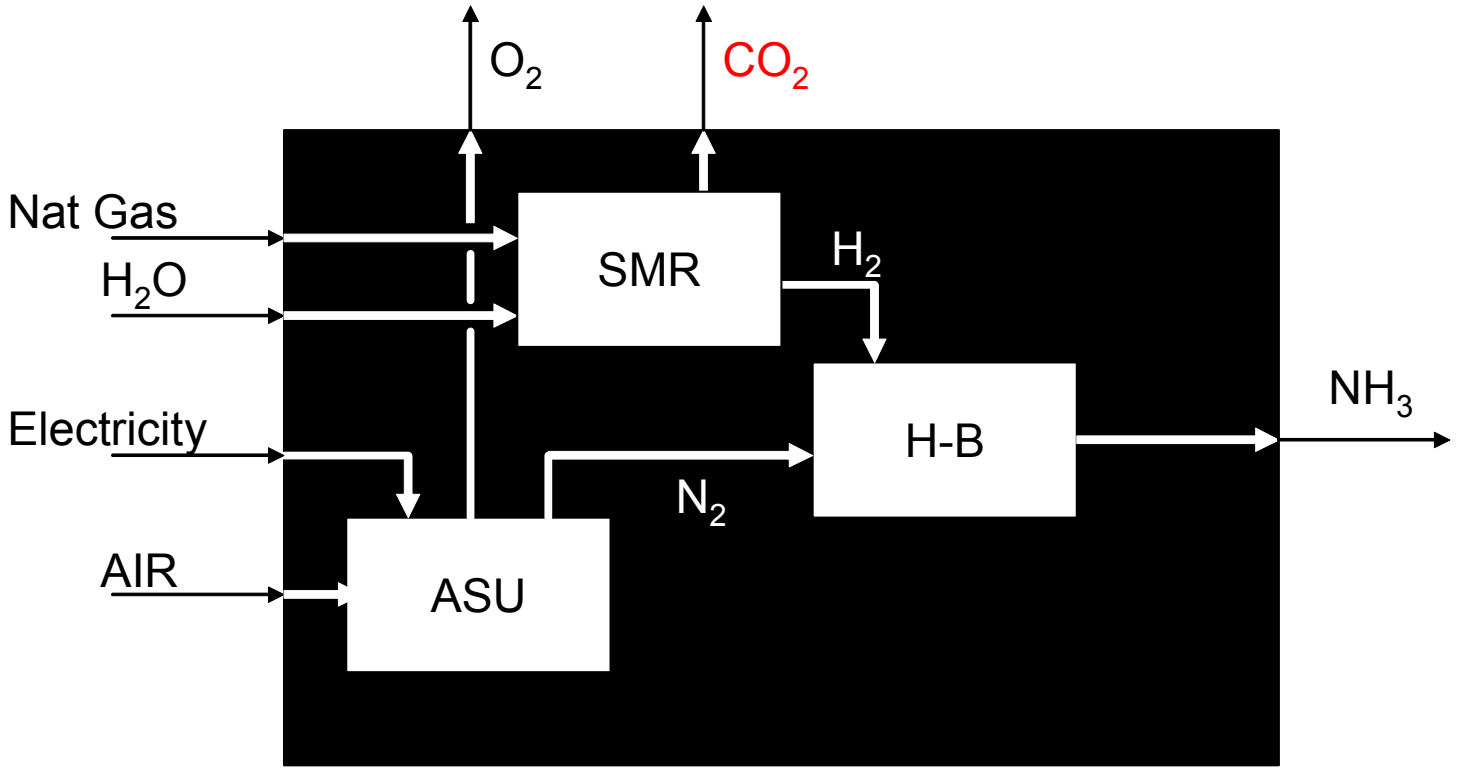
Haber-Bosch Reactor

1921

Ludwigshafen, Germany

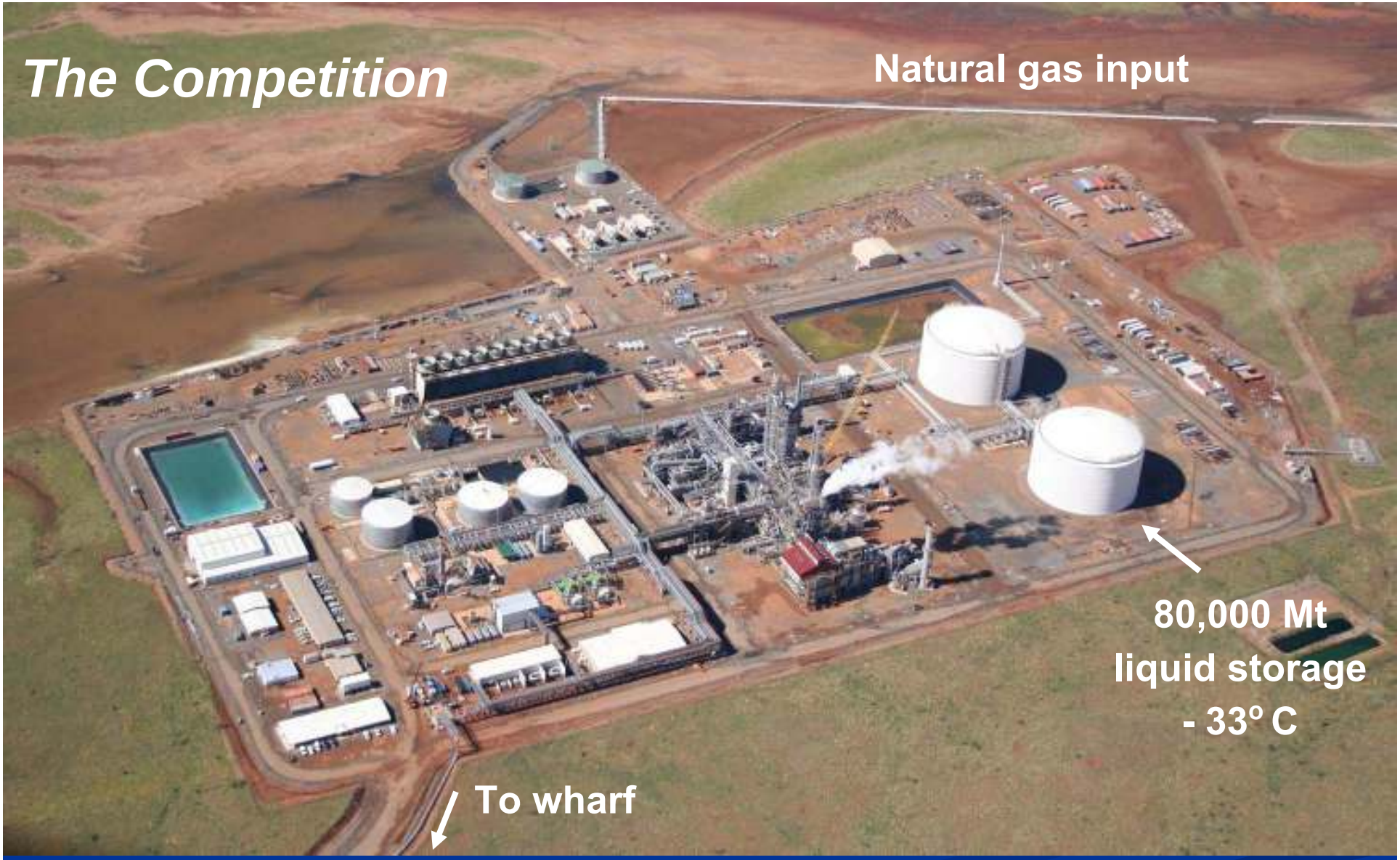
Inside the Black Box: Steam Reforming + Haber-Bosch

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



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

The Competition



Burrup Peninsula, NW Australia, Natural Gas to Ammonia Plant

760,000 Mt / year

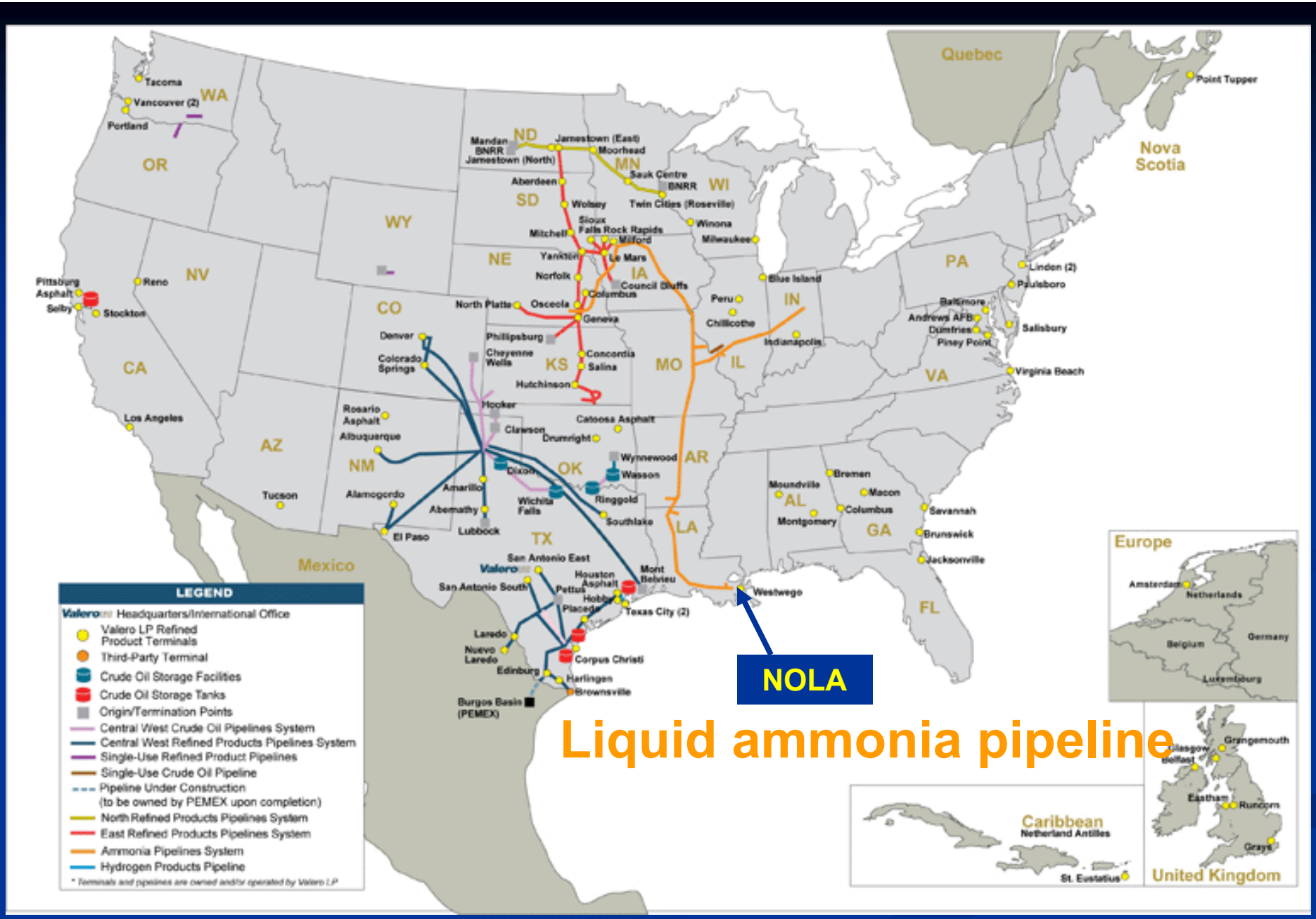
$US 650 million capital cost ‘06

Ammonia Tanker
Burrup Peninsula
Western Australia

Ammonia or LPG Tanker

9,000 – 35,000 Mt

Refrigerated



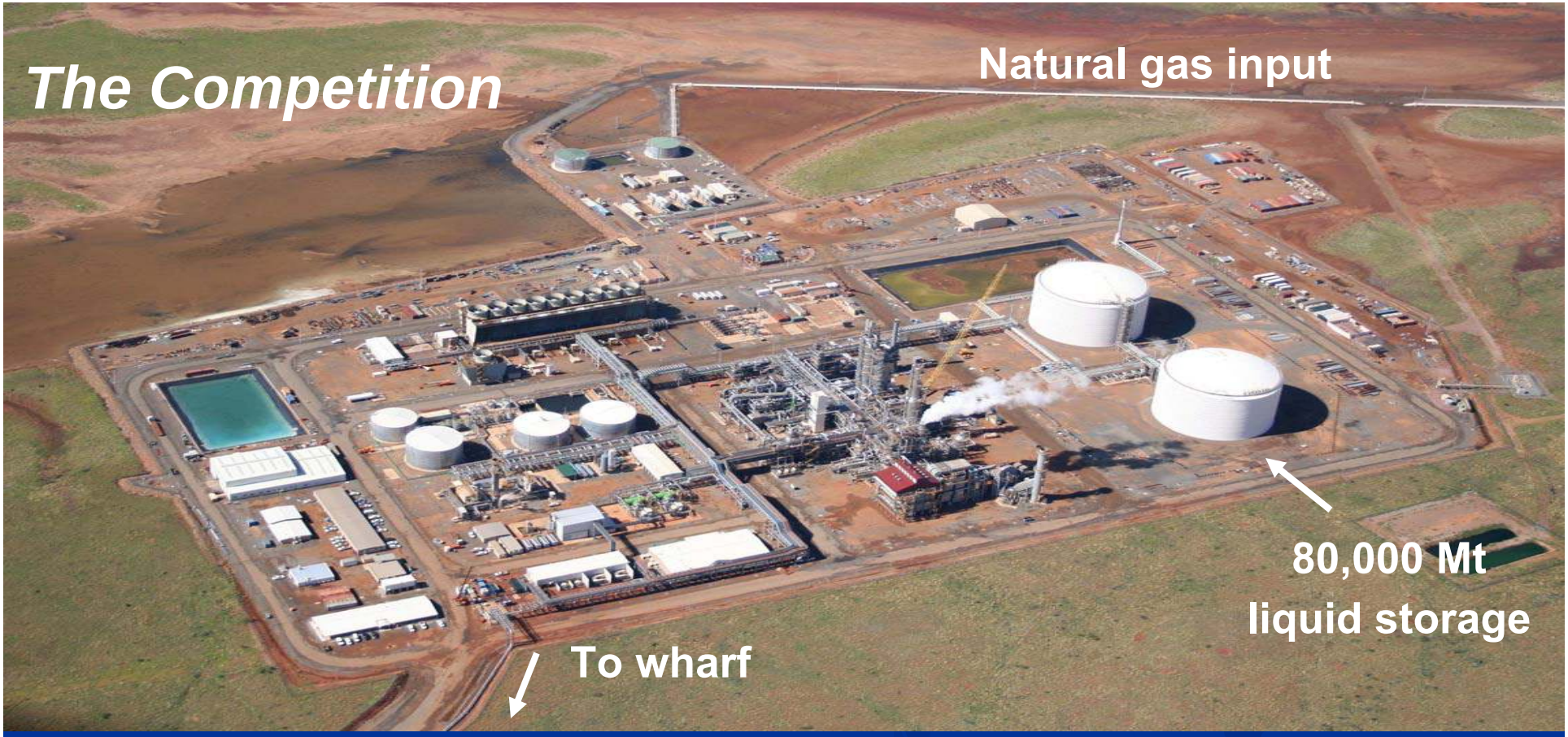
Valero LP Operations


Ammonia Storage Terminal
Mississippi River
Winona, MN

USA NH3 Infrastructure

- ~ 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

The Competition



Global Ammonia = 140 million Mt / year

- **#2 chemical**
- **200 plants, nat gas + coal**
- **~ 500 Million Bbl oil**
- **~ 2% oil**
- **~ 0.5% energy**

14 million Mt / yr USA; 60% imported; corn ethanol

Cost: Ammonia from Stranded Natural Gas (NG)

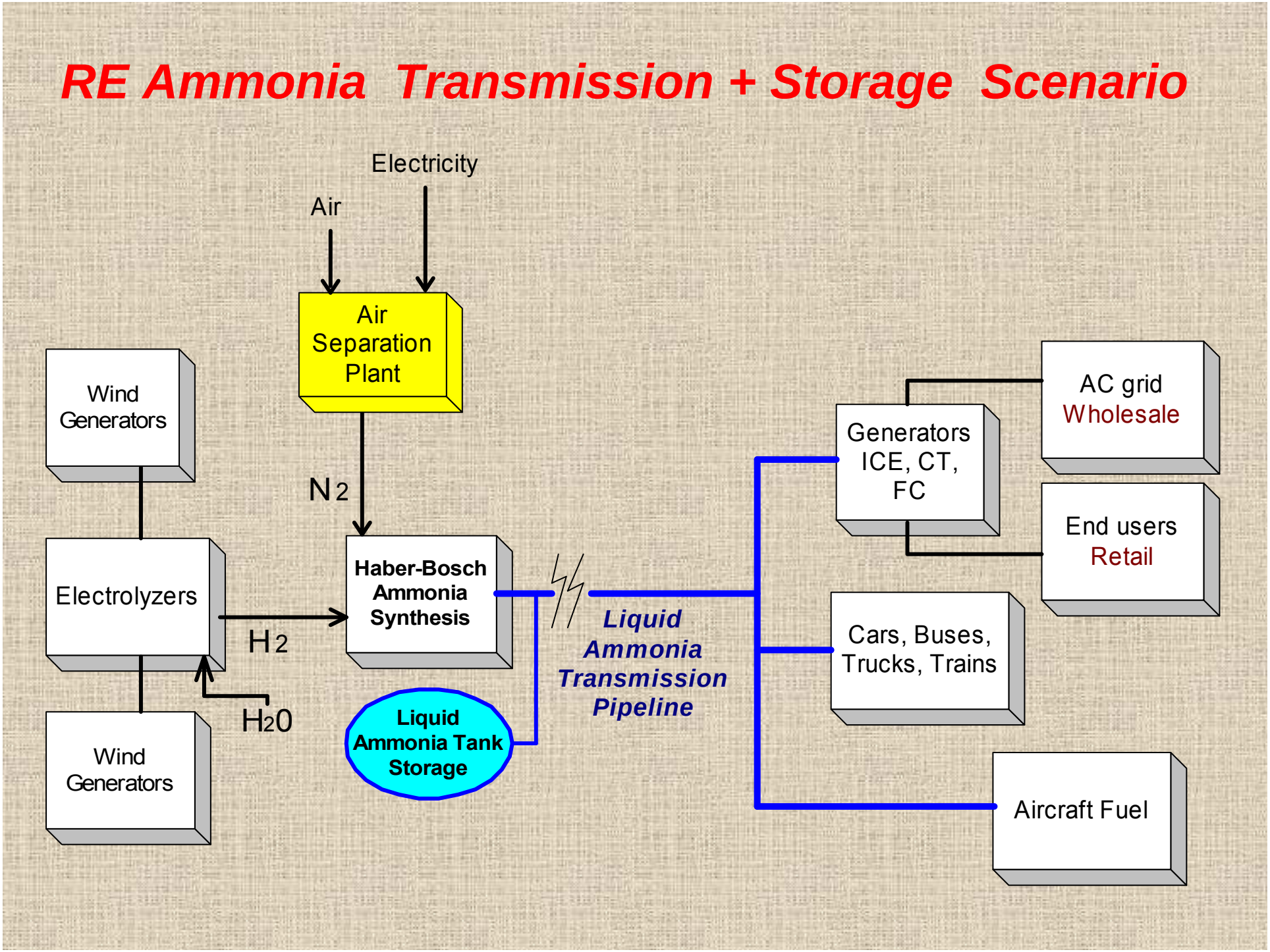
> Burrup, Australia Plant: 750,000 Mt / year
> $650M capital @ 15% capital recovery factor (CRF)
> 34 MMBtu NG / Mt NH3
> NG cost $1.20 / MMBtu long-term
> Tanker shipping to New Orleans, LA (NOLA) $50 / Mt
> CO2 emission 1.8 Mt / Mt NH3

	C-tax 0	C-tax $50 / Mt CO2	C-tax $100 / Mt CO2
Capital	98	98	98
NG	41	41	41
Shipping	50	50	50
C-tax	0	90	180
Plant O&M	2	2	2
Total NOLA / Mt	**$191**	**$281**	**$371**

1. 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?**

RE Ammonia Transmission + Storage Scenario

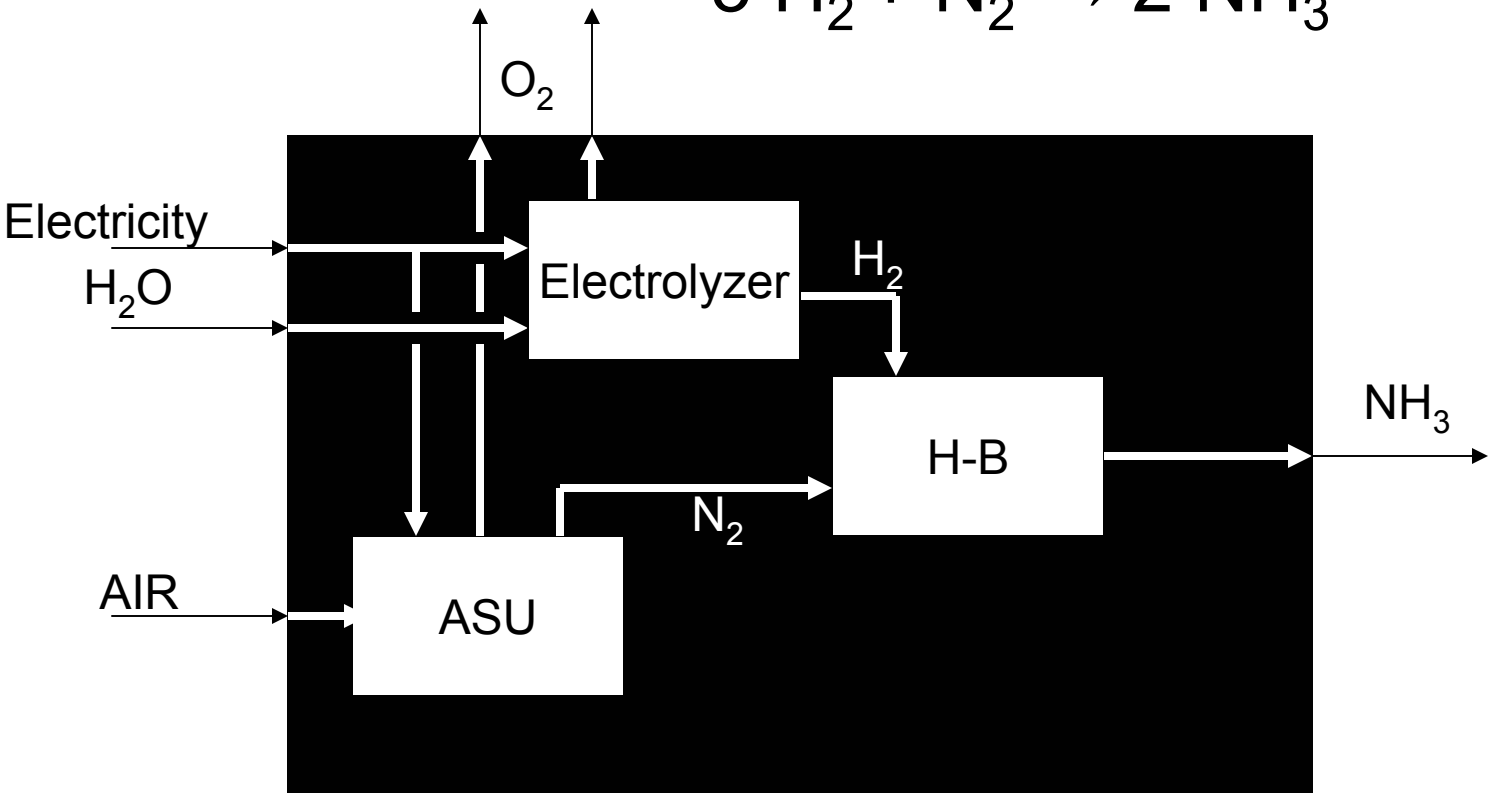


Wind – to – Ammonia Potential, NW Iowa


Norsk Hydro
Electrolyzers
2 MW each
Ammonia from
hydrogen
from zero-cost
off-peak hydro

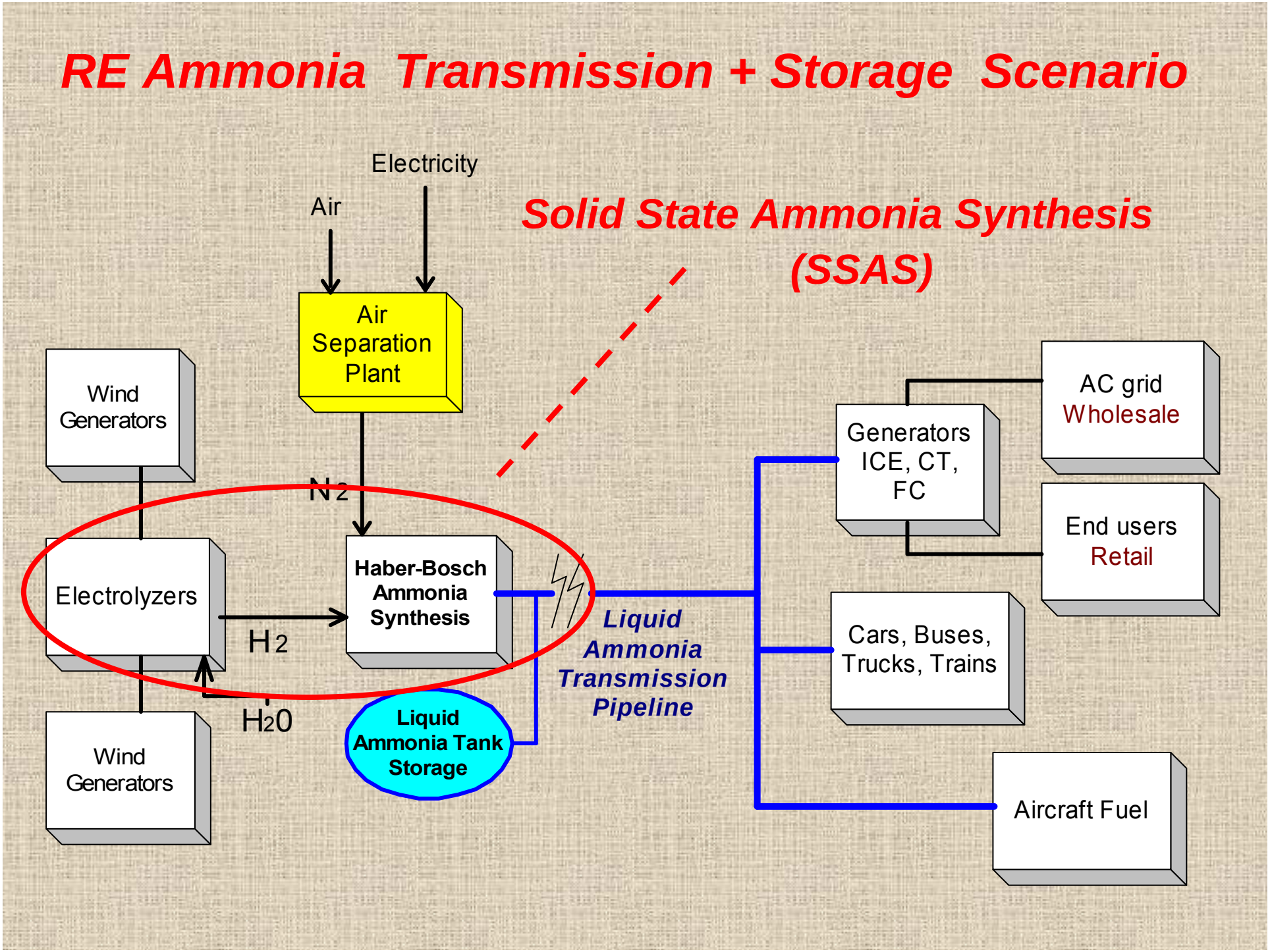
Inside the Black Box: HB Plus Electrolysis

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



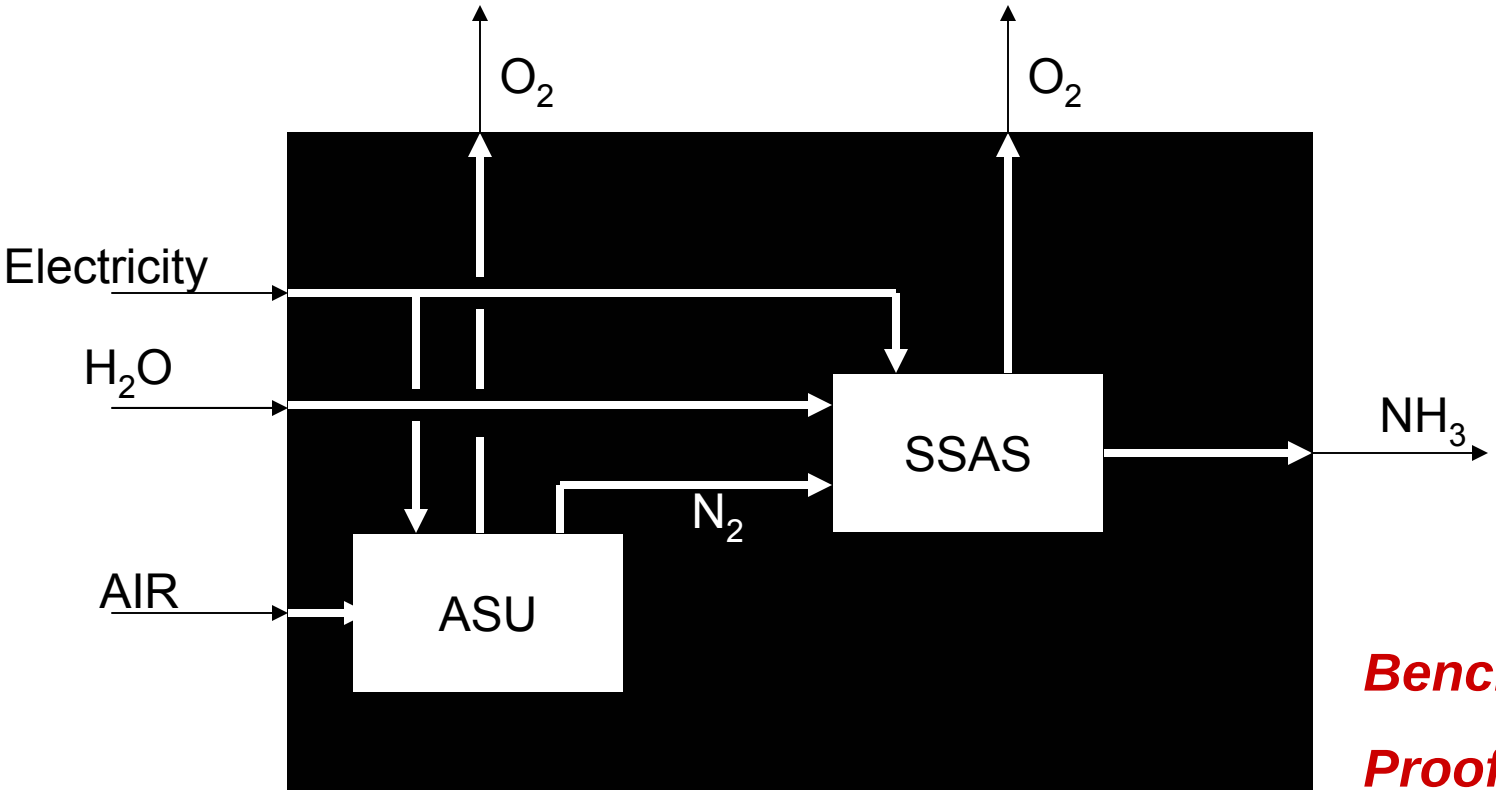
Energy consumption ~12,000 kWh per ton NH_3

RE Ammonia Transmission + Storage Scenario



Inside the Black Box: Solid State Ammonia Synthesis

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

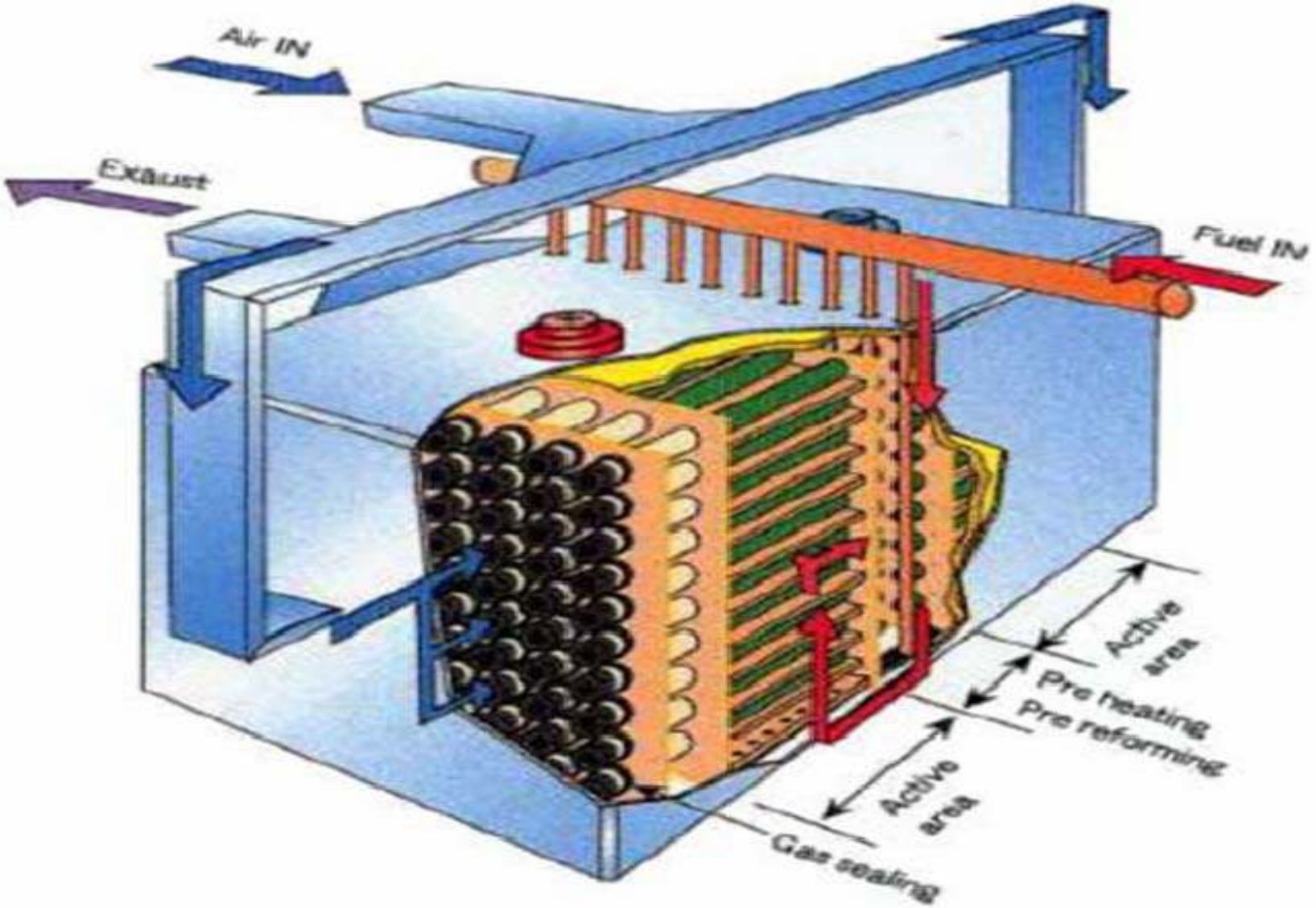


Benchtop

Proof-of-concept

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

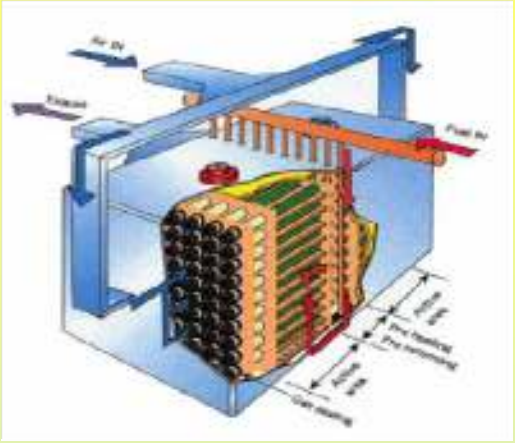
Solid State Ammonia Synthesis (SSAS)
NHThree LLC patent



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

Solid State Ammonia Synthesis (SSAS)



- Goals:
  - Renewables-source ammonia (NH3)
  - Compete with natural gas source NH3
- High energy conversion efficiency
  - ~50% better than electrolysis → hydrogen + H-B
  - No hydrogen production
- Electricity + water + nitrogen → ammonia
- ~ 50% lower capital cost
- SSAS reactor: SOFC * in reverse

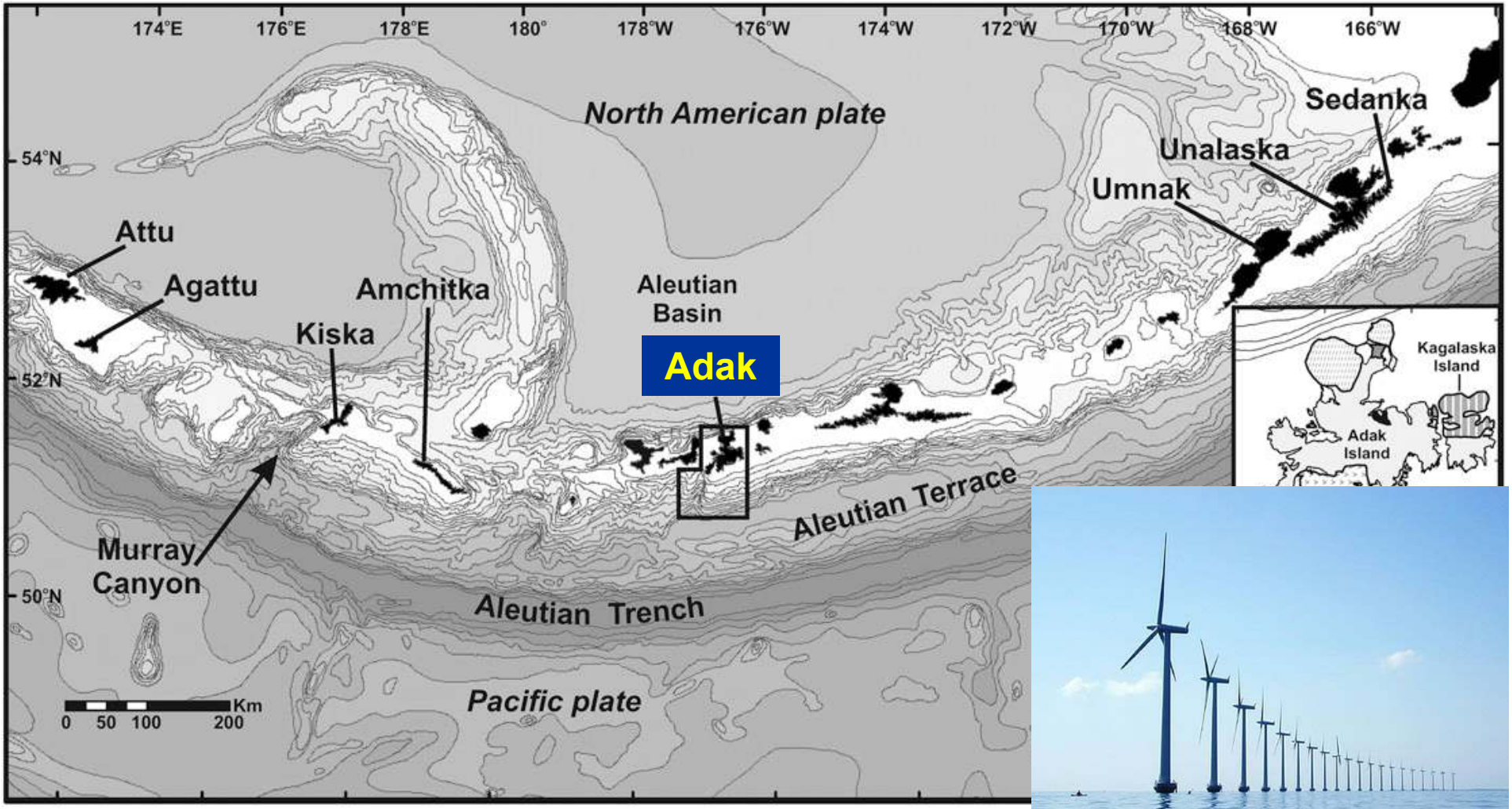
*** SOFC: Solid oxide Fuel Cell**

SSAS vs H-B NH3 Synthesis

Solid State Ammonia Synthesis vs Haber – Bosch

Renewable-source electricity input

- **H-B per MW input**
  - **Capital $1.5 M**
  - **2 tons / day output**
- **SSAS per MW input**
  - **Capital $650 K**
  - **3.2 tons / day output**



Adak, Alaska
Aleutian Islands
Class 7 Wind: Capacity Factor (CF) >45% ?


Sea of
Okhotsk
KAMCHATKA
Bering Strait
Monday
Sunday
Komandorskis Ostrova
(Commander Islands)
Date Line
N
ALASKA
Bering Sea
SHEMYA
ATTU
DUTCH HARBOR
Aleutian Islands
AGATTU
KISKA
AMCHITKA
Adak
0 100 200 300
MILES
Pacific Ocean

"Green" Ammonia (NH3) Output

> 2,000 MW Adak Wind-to-ammonia Plant

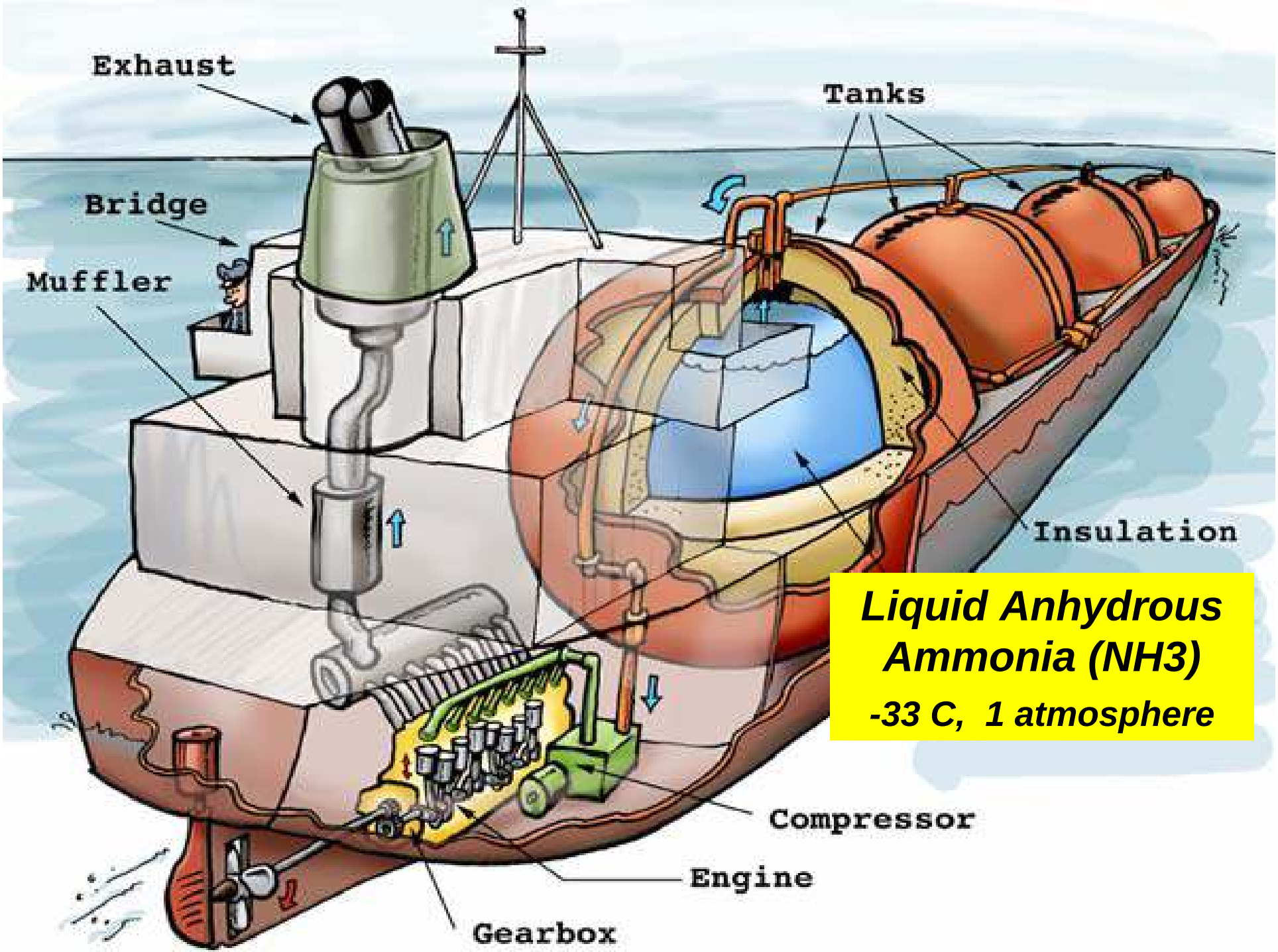
> $5 B total capital @ $2,500 / kW

> 45% Capacity Factor (CF)

Windplant Annual Energy Production

As electricity:	**21,600**	**MWh / day**
	7,884,000	**MWh / year**

Convert to NH3 by:	**Electrolysis + H-B @ 12 MWh / Mt**	**SSAS @ 7.5 MWh / Mt**
Mt (tons) / year	**657,000**	**1,050,000**
Sales @ $300 / Mt (plant gate)	**$197 M**	**$315 M**
Simple ROI	**4%**	**6%**


Exhaust
Tanks
Bridge
Muffler
Insulation
Liquid Anhydrous Ammonia (NH3)
-33 C, 1 atmosphere
Compressor
Engine
Gearbox

"Green" Ammonia (NH3) Output

- *> 2,000 MW Adak Wind- to- ammonia plant*
- *> $5 B total capital @ $2,500 / kW*
- *> 45% Capacity Factor (CF)*
- *> 15% Capital Recovery Factor (CRF)*

Windplant Annual Energy Production
As electricity: 7,884,000 MWh / year

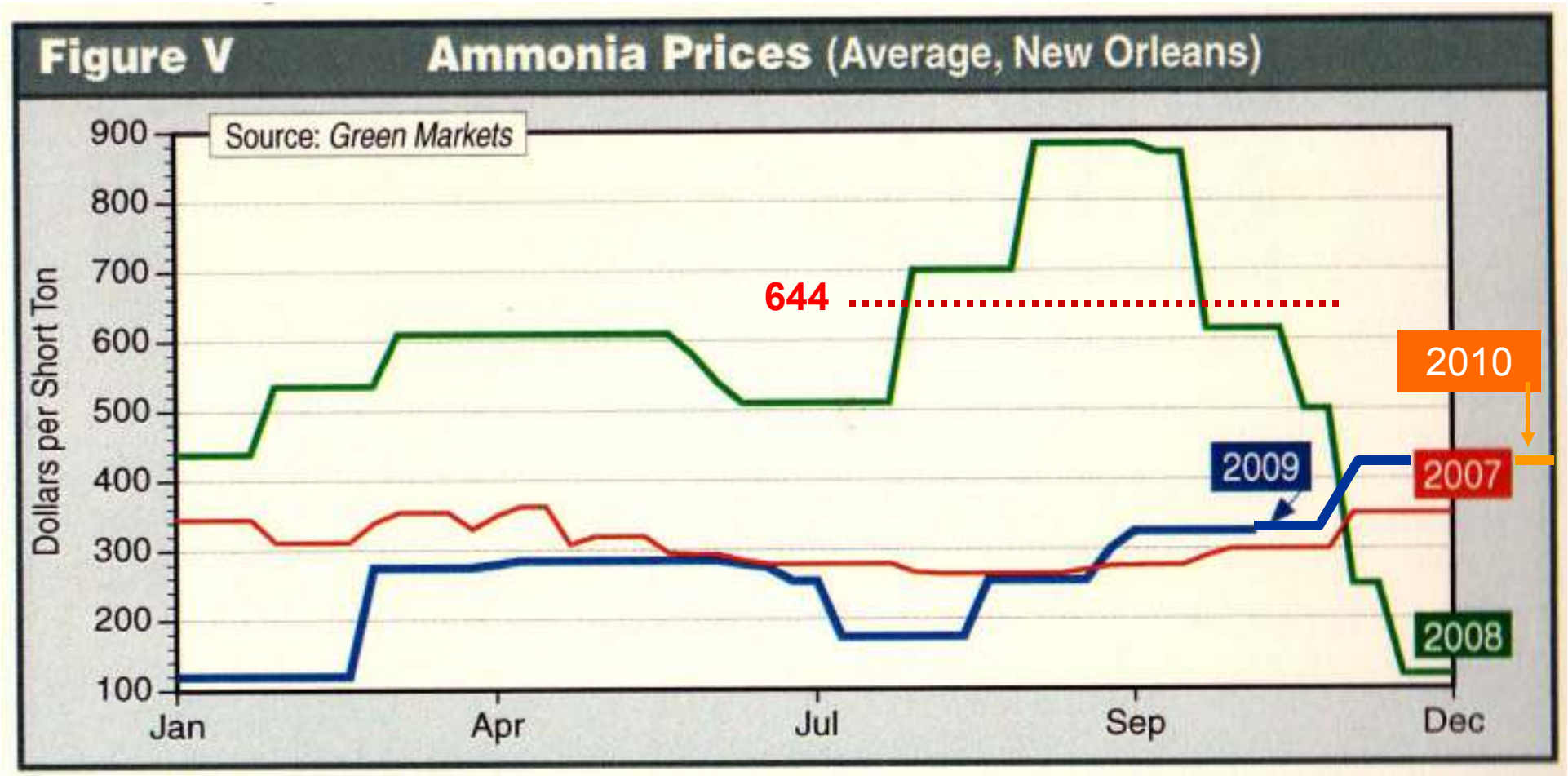
	Electrolysis + H-B	SSAS
Sales: Mt (tons) / year	657,000	1,050,000
Total Cost of Sales:		
Capital @ 15% CRF	$750M	$750M
Plant O&M @ $0.03 / kWh	24M	24M
Input energy	0	0
TOTAL	$774M	$774M
Cost / Mt NH3	$1,178	$ 737
Shipping @ $50 / Mt	50	50
Total NOLA / Mt	$1,228	$ 787

"Green" Ammonia (NH3) Output

- *> 2,000 MW Adak Wind- to- ammonia plant*
- *> $5 B total capital @ $2,500 / kW*
- *> 45% Capacity Factor (CF)*
- *> 12% Capital Recovery Factor (CRF)*

Windplant Annual Energy Production
As electricity: 7,884,000 MWh / year

	Electrolysis + H-B	SSAS
Sales: Mt (tons) / year	657,000	1,050,000
Total Cost of Sales:		
Capital @ 12% CRF	$600M	$600M
Plant O&M @ $0.03 / kWh	24M	24M
Input energy	0	0
TOTAL	$624M	$624M
Cost / Mt NH3	$ 949	$ 594
Shipping @ $50 / Mt	50	50
Total NOLA / Mt	$ 999	$ 644



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

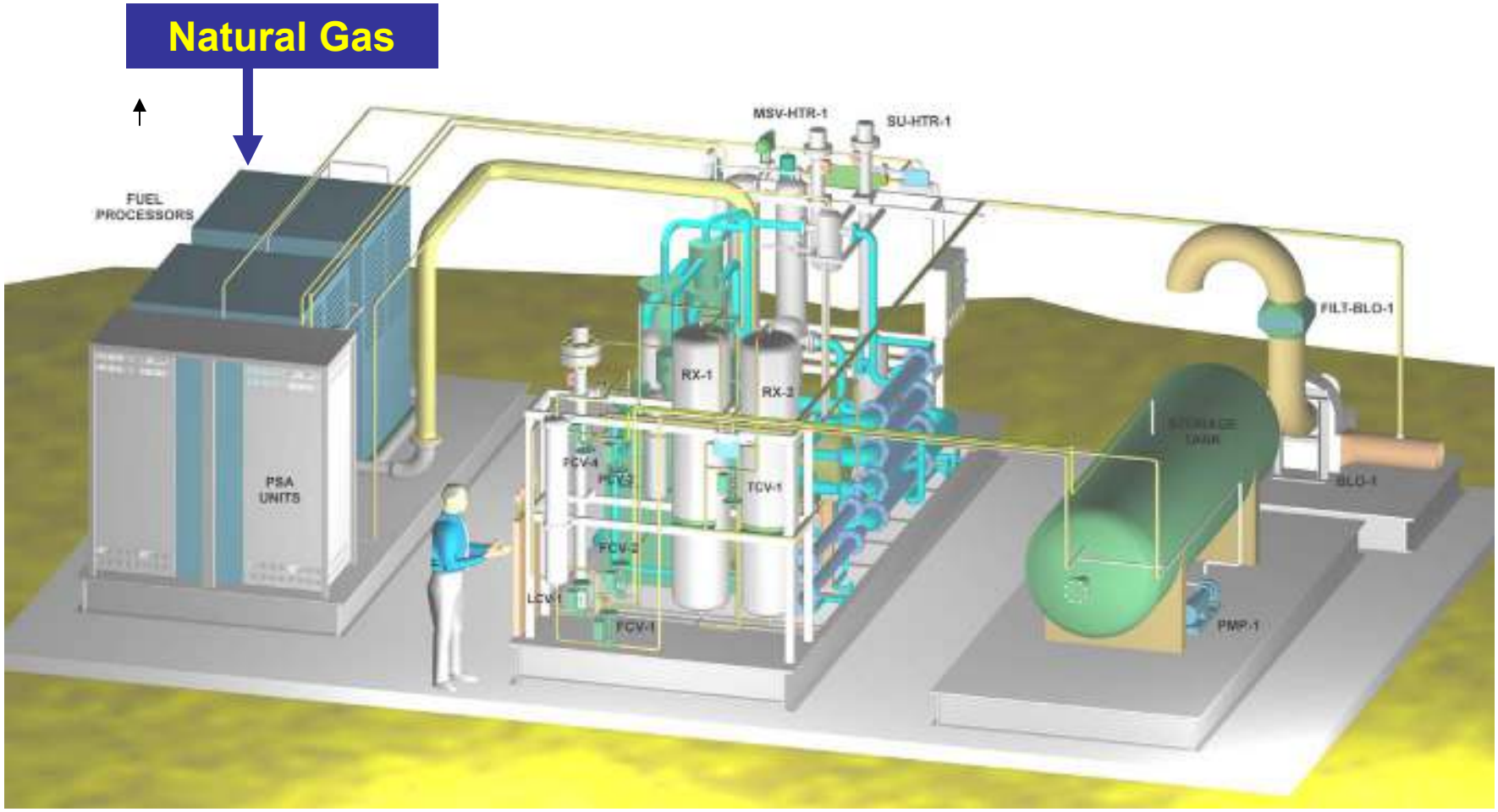
Other Alaska GW-scale Stranded RE

- Higher capacity factor (CF) → 100%
- Lower cost of energy (COE)
- Tanker transport affordable
    - Geothermal
    - Wave, tidal
    - Instream kinetic
    - Solar
    - Biomass

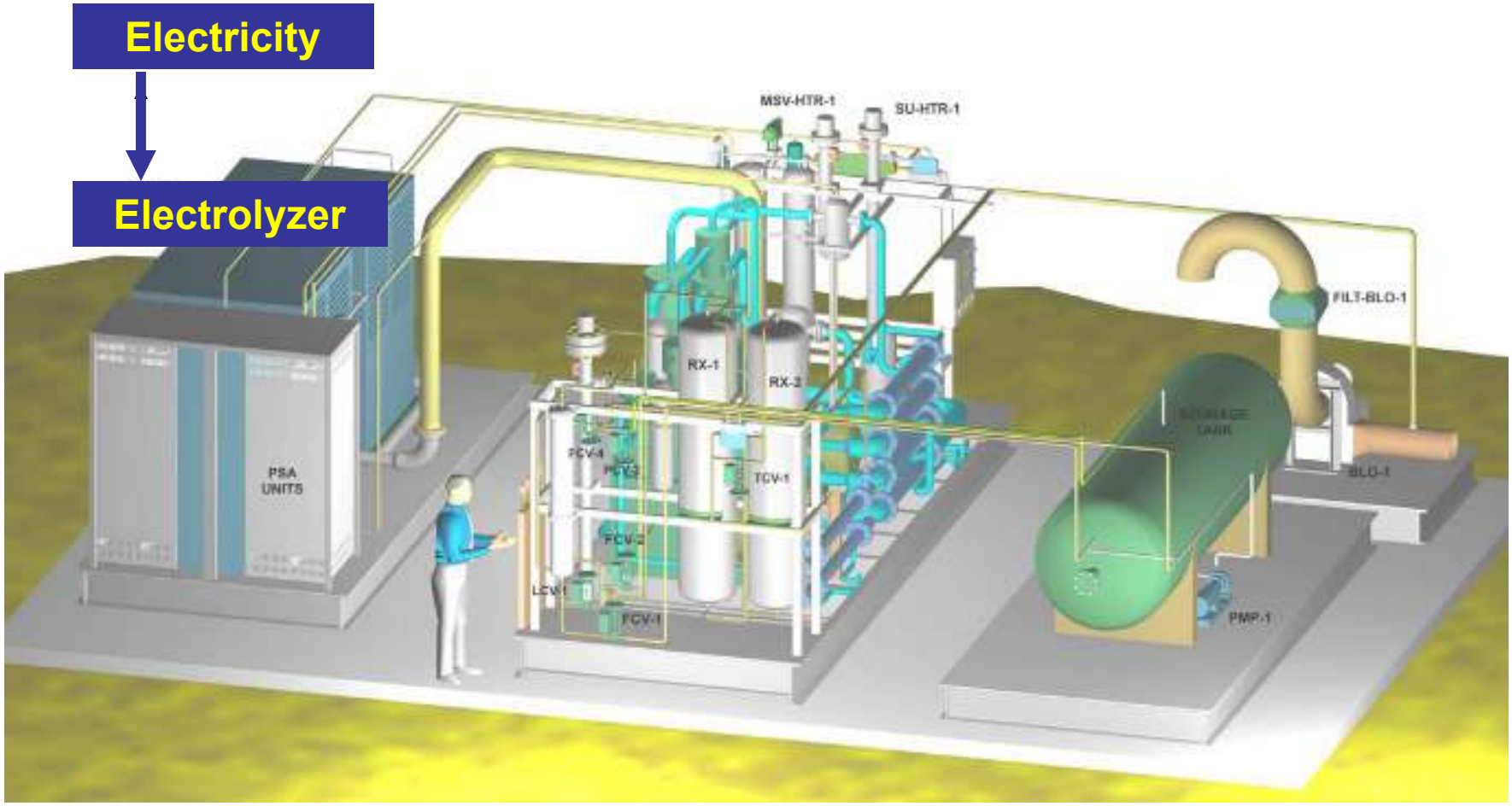
2. Decrease Cash OUT: Village "Energy Independence" via RE Generation + Storage

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

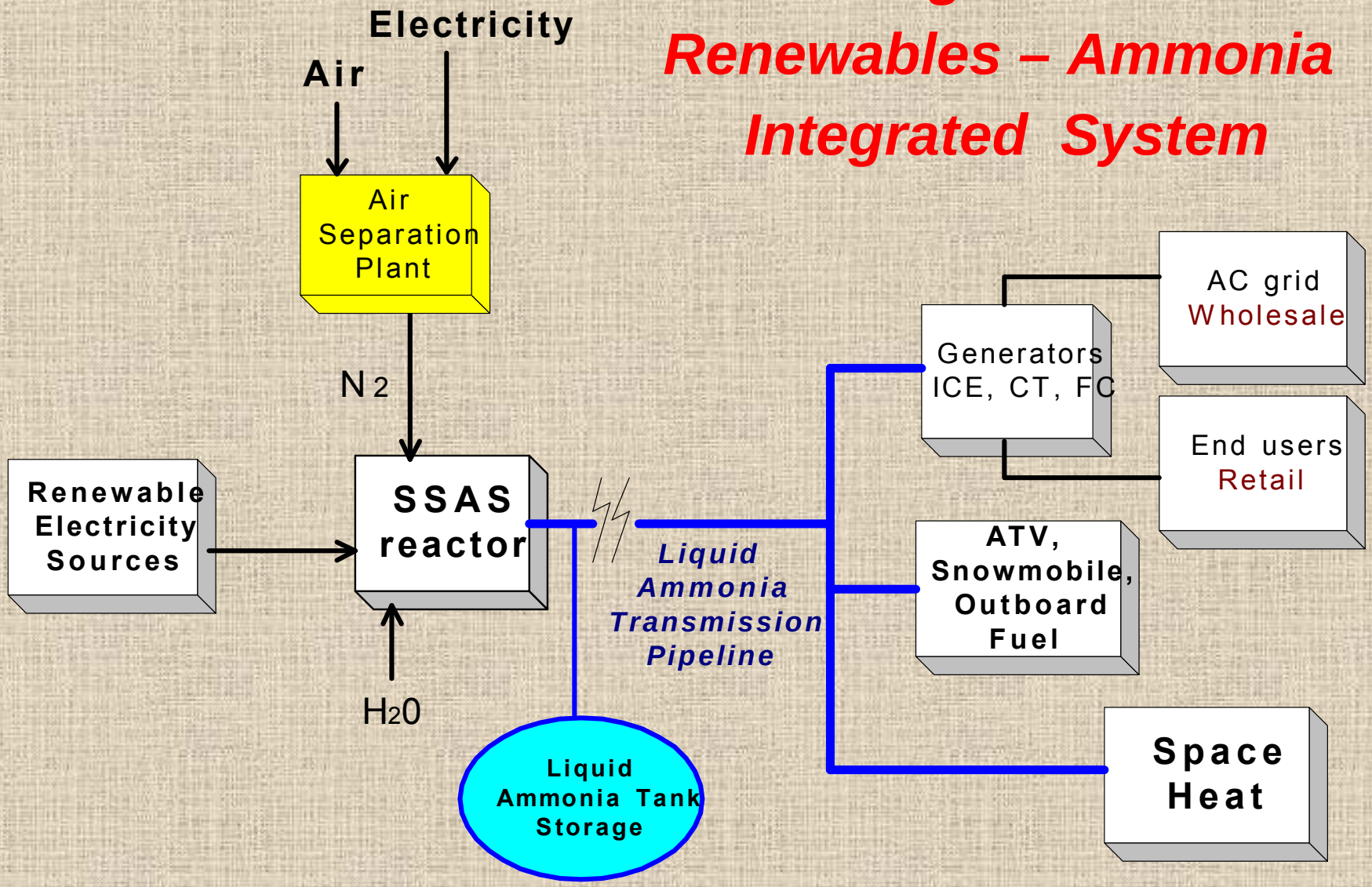
Village-scale
3 Mt / day Mini-NH3 Plant
Natural Gas Fueled Haber-Bosch



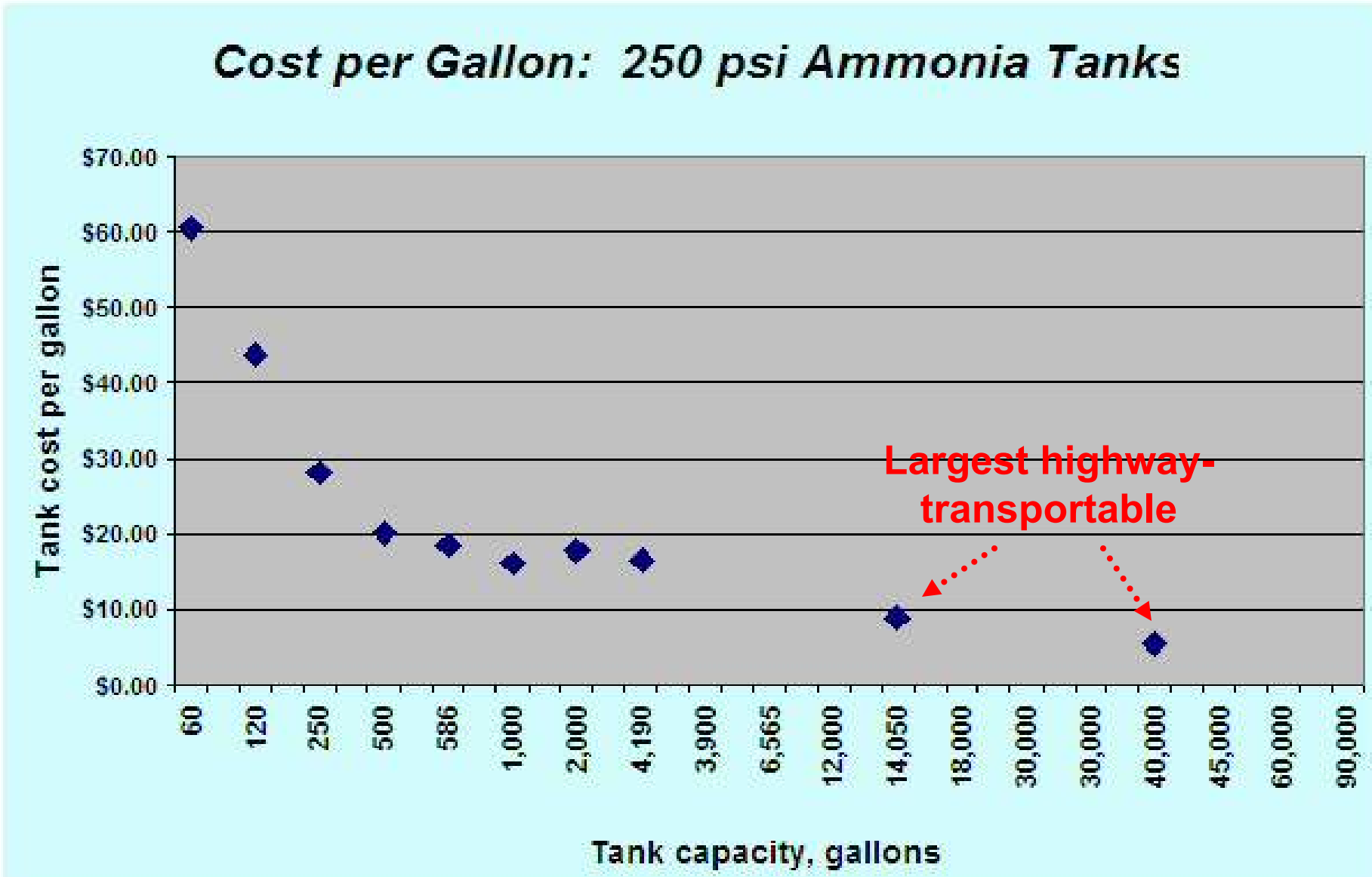
Village-scale
3 Mt / day Mini-NH3 Plant
RE Electricity Haber-Bosch



"Village" SSAS Renewables – Ammonia Integrated System

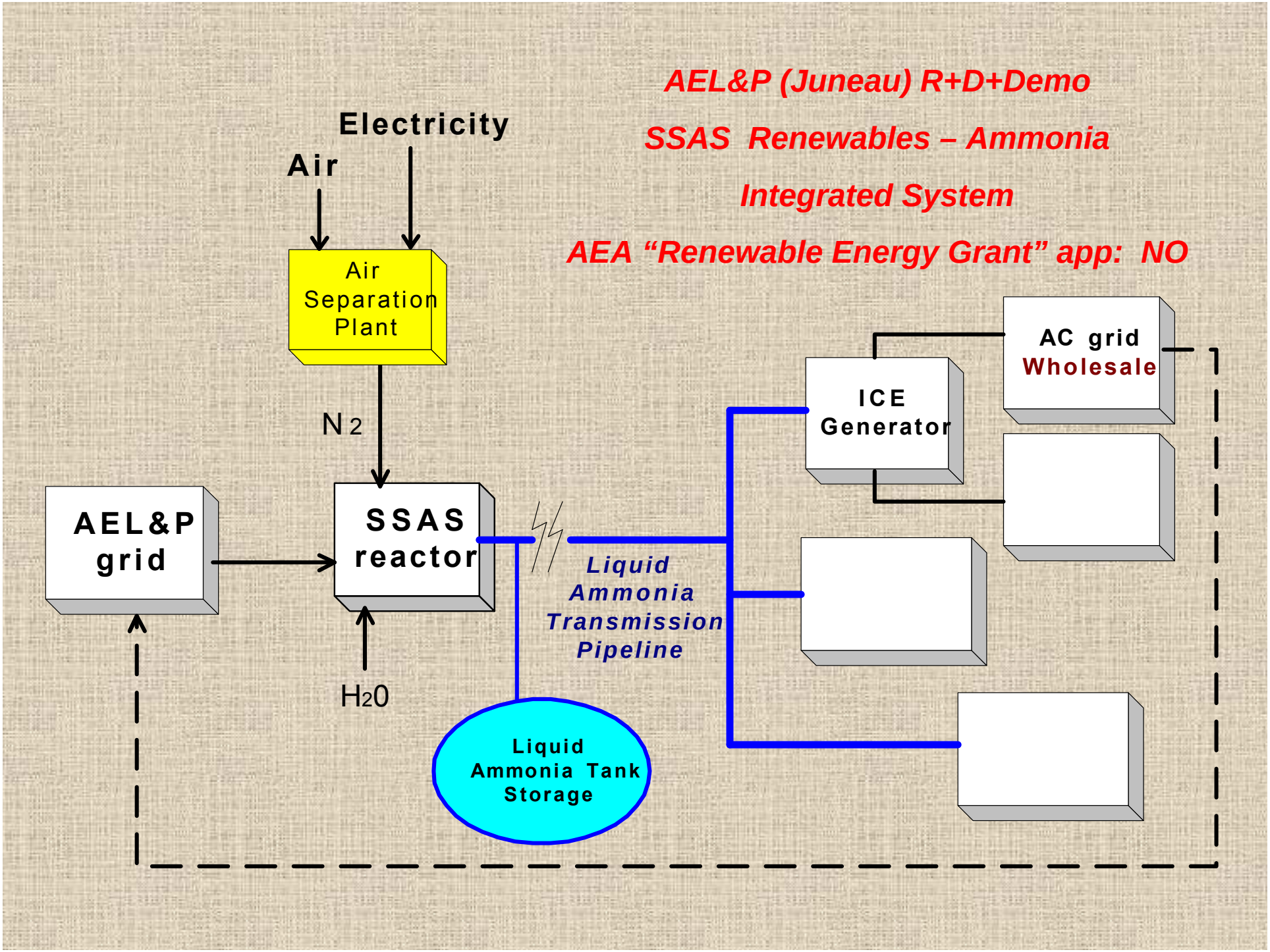


Liquid Ammonia Tank Storage



'08 AEL&P Grant Application: Renewable Energy, AEA, HB152

- Alaska Electric Light & Power (AEL&P) Juneau
- R+D+Demonstration of SSAS system
- $800K, round one, HB152 grants
- Advance SSAS from lab scale: tech + econ feasible
- Statewide application:
  - "Energy Islands"
  - "Energy Independence"
  - Village survival: imported energy cost, delivery
  - Scaleup: export NH3, tanker
- Demonstrate in major AK city, first: Juneau
- Redeployed to remote community
- Not funded by AEA: no R&D


AEL&P (Juneau) R+D+Demo
SSAS Renewables – Ammonia
Integrated System
AEA "Renewable Energy Grant" app: NO
Electricity
Air
Air Separation Plant
N2
AEL&P grid
SSAS reactor
H20
Liquid Ammonia Transmission Pipeline
Liquid Ammonia Tank Storage
ICE Generator
AC grid Wholesale

Sept '09 AASI Grant Application: Denali Commission (Alaska) EETG (Emerging Energy Technology Grant program)

- **Alaska Applied Sciences, Inc., Juneau (AASI)**
- **$800K: SSAS R+D+Demonstration (same as AEL+P)**
- **Not funded by Denali:**
  - **Timing mismatch**
  - **NHThree LLC prime subcontractor: single-source**
  - **NHThree LLC ARPA-E application pending: mfg plant**
- **Statewide application:**
  - **"Energy Islands"**
  - **"Energy Independence"**
  - **Village survival: imported energy cost, delivery**
- **Demonstrate in major AK city, first: Juneau**
- **Close loop to AEL+P hydro grid**
- **Redeploy to village if successful**
- **Eight support letters**

SSAS R+D+Demo Concept

- $4 – 5 M total program
- Simulate Alaska community energy island
- SSAS offer RE-source internal energy independence ?
  - Discover, demonstrate tech & econ advantages
  - Conversions efficiency; byproduct heat used
  - Economic: capital, O&M costs
- R&D plus demo pilot plant:
  - NHThree LLC patented IP
  - PCC tube mfg pilot plant

SSAS R+D+Demo Concept

- Deploy at UAS Tech Center, Juneau
- Operate in two modes on AEL&P grid:
  - Hydroelectricity-to-NH3
  - NH3-to-AEL&P grid
- SCADA data collect, analyze
- Modify system hardware + software
- Relocate to smaller community
- Implications for export of large-scale, stranded AK RE

TDX Power, Inc., St. Paul Island

Candidate SSAS Pilot Plant Advanced Test Site

Alaska Business Opportunities: RE – NH3 "Green" Ammonia

Monetizing Alaska's vast RE

1. **Export from GW-scale RE: Increase cash IN**
2. **Village energy "independence"**
   - **Indigenous renewables; diverse**
   - **Seasonal, diurnal variability**
   - **Storage as NH3: pressurized tanks**
   - **Reduce cash OUT**

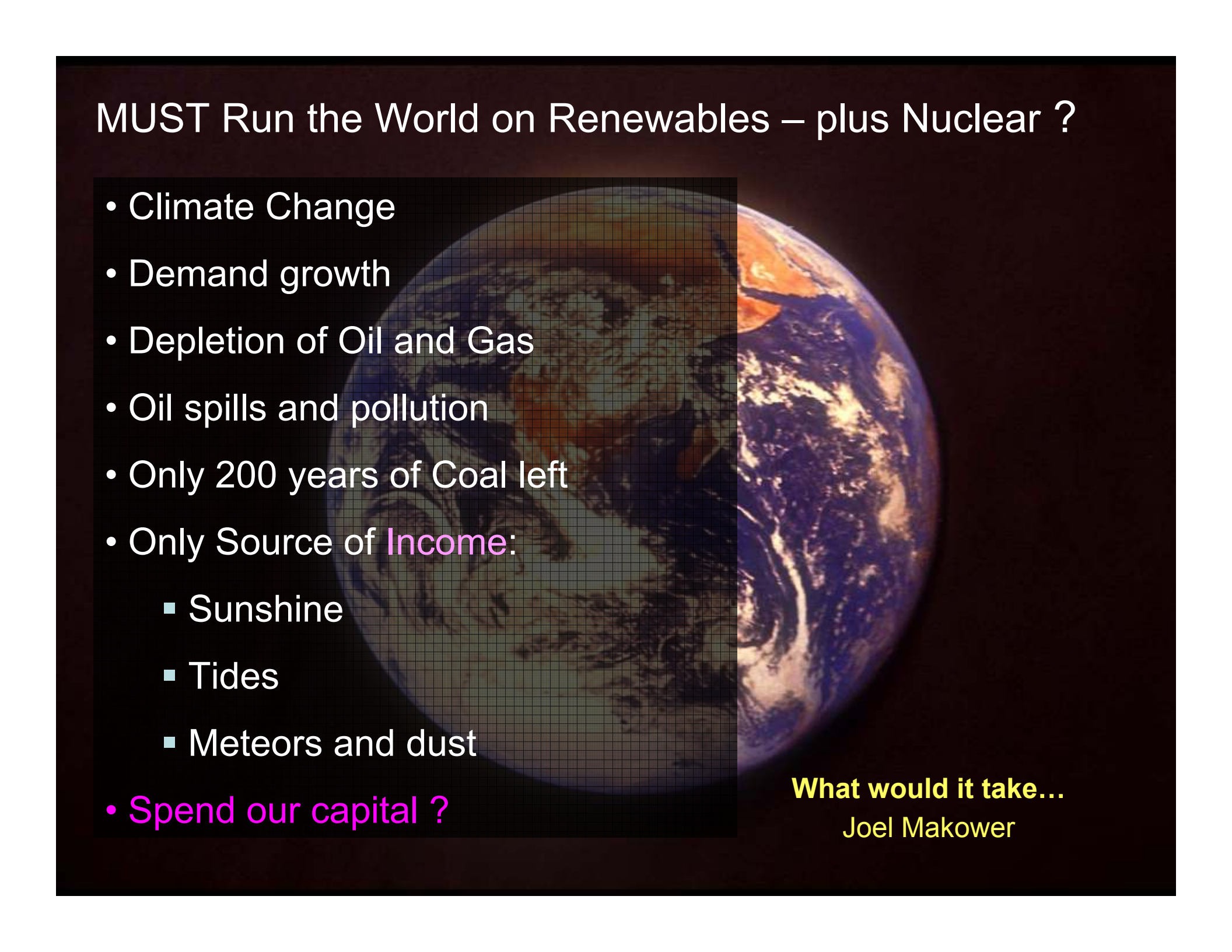
Alaska's Immediate Opportunity: SSAS

- Village energy "independence" - degree
  - Diverse, indigenous RE sources
  - Convert % to NH_3
  - Storage as NH_3 in steel tanks: annually-firm
  - Deliver energy services: CHP, heat, transport,
  - Competitive price: $6-8 / gallon diesel + heat fuel
- SSAS R&D and Demonstration
  - NHThree LLC owns SSAS IP patent
  - PCC tube mfg pilot plant
  - RE – SSAS pilot plant → AK village(s)

Alaska's Immediate Opportunity: SSAS

- Funding Collaboration: State of AK, Denali, Fed, Industry
  - $4-5M total R&D&Demo
  - EETG funds
    - SB220 State $2.5M
    - Denali Commission $2.5M
    - USDA: '08 Farm Bill Sec 9003 "RE Fertilizer Research"
- Set stage for GW-scale NH_3 export via SSAS
  - Diverse RE
  - Capital cost; CF; lower cost of energy (COE) ?
- Barriers
  - EPA: Ammonia not a fuel
  - DOE: Currently not interested; "toxic"; electricity transmis
  - Industry: too risky, no fuel market, hazardous

MUST Run the World on Renewables – plus Nuclear ?



- Climate Change
- Demand growth
- Depletion of Oil and Gas
- Oil spills and pollution
- Only 200 years of Coal left
- Only Source of Income:
  - Sunshine
  - Tides
  - Meteors and dust
- Spend our capital ?

What would it take…
Joel Makower

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

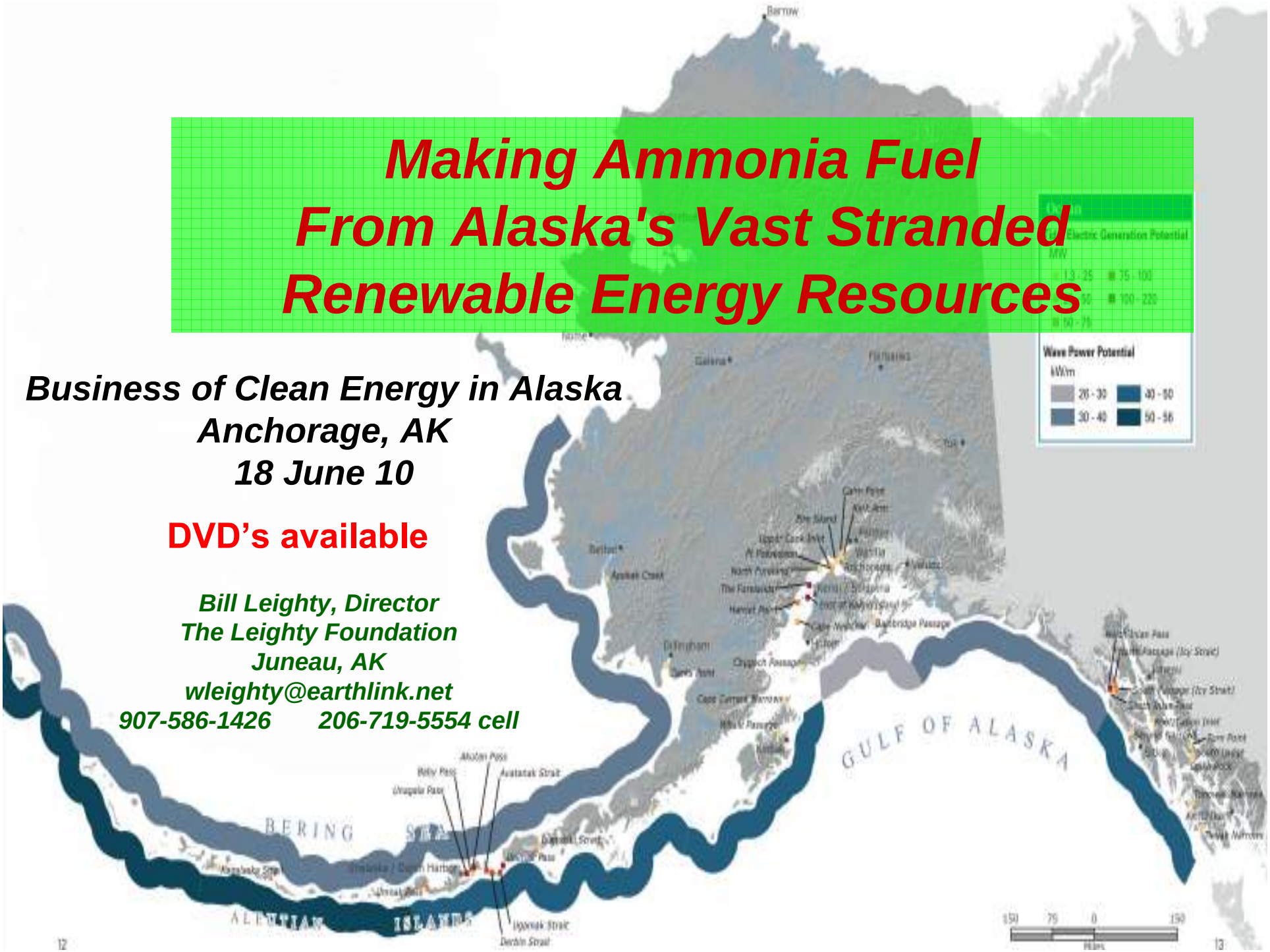
but only after they have tried everything else ”

Winston Churchill

The dog caught the car.

Dan Reicher

Making Ammonia Fuel From Alaska's Vast Stranded Renewable Energy Resources



Business of Clean Energy in Alaska
Anchorage, AK
18 June 10

DVD's available

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

End of 18 June 10 presentation

About 24 minutes, without Q+A

The following slides are for Q+A discussion, immediately following the presentation:

- If the PowerPoint file is still active on the projector;
- If needed;
- If program format includes immediate Q+A.

These are the most complex slides, likely to need explanation or discussion.

Cost: Ammonia from Stranded Natural Gas (NG)

> Burrup, Australia Plant: 750,000 Mt / year
> $650M capital @ 15% capital recovery factor (CRF)
> 34 MMBtu NG / Mt NH3
> NG cost $1.20 / MMBtu long-term
> Tanker shipping to New Orleans, LA (NOLA) $50 / Mt
> CO2 emission 1.8 Mt / Mt NH3

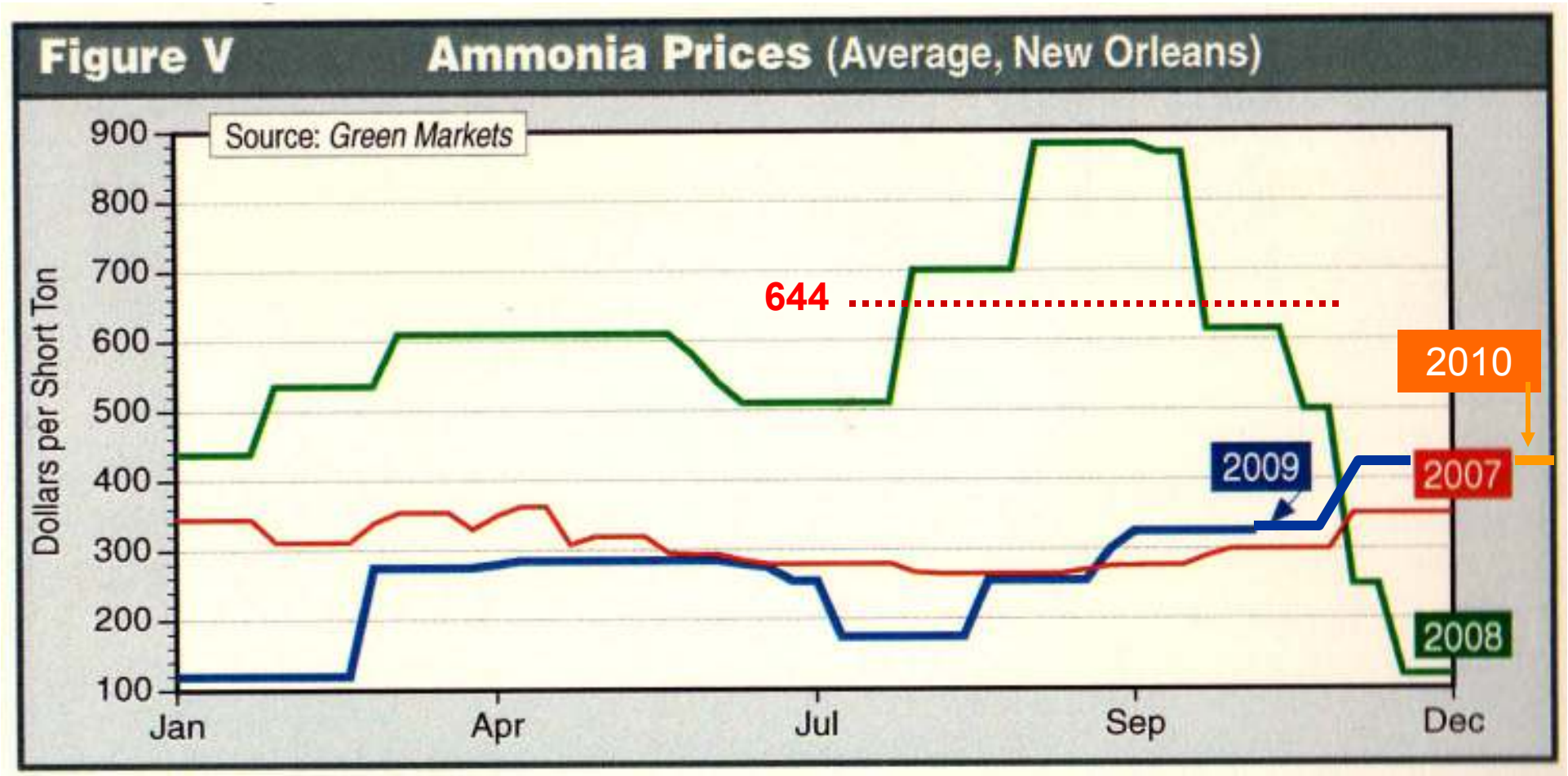
	C-tax 0	C-tax $50 / Mt CO2	C-tax $100 / Mt CO2
Capital	98	98	98
NG	41	41	41
Shipping	50	50	50
C-tax	0	90	180
Plant O&M	2	2	2
Total NOLA / Mt	**$191**	**$281**	**$371**

"Green" Ammonia (NH3) Output

- *> 2,000 MW Adak Wind- to- ammonia plant*
- *> $5 B total capital @ $2,500 / kW*
- *> 45% Capacity Factor (CF)*
- *> 12% Capital Recovery Factor (CRF)*

Windplant Annual Energy Production
As electricity: 7,884,000 MWh / year

	Electrolysis + H-B	SSAS
Sales: Mt (tons) / year	657,000	1,050,000
Total Cost of Sales:		
Capital @ 12% CRF	$600M	$600M
Plant O&M @ $0.03 / kWh	24M	24M
Input energy	0	0
TOTAL	$624M	$624M
Cost / Mt NH3	$ 949	$ 594
Shipping @ $50 / Mt	50	50
Total NOLA / Mt	$ 999	$ 644



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