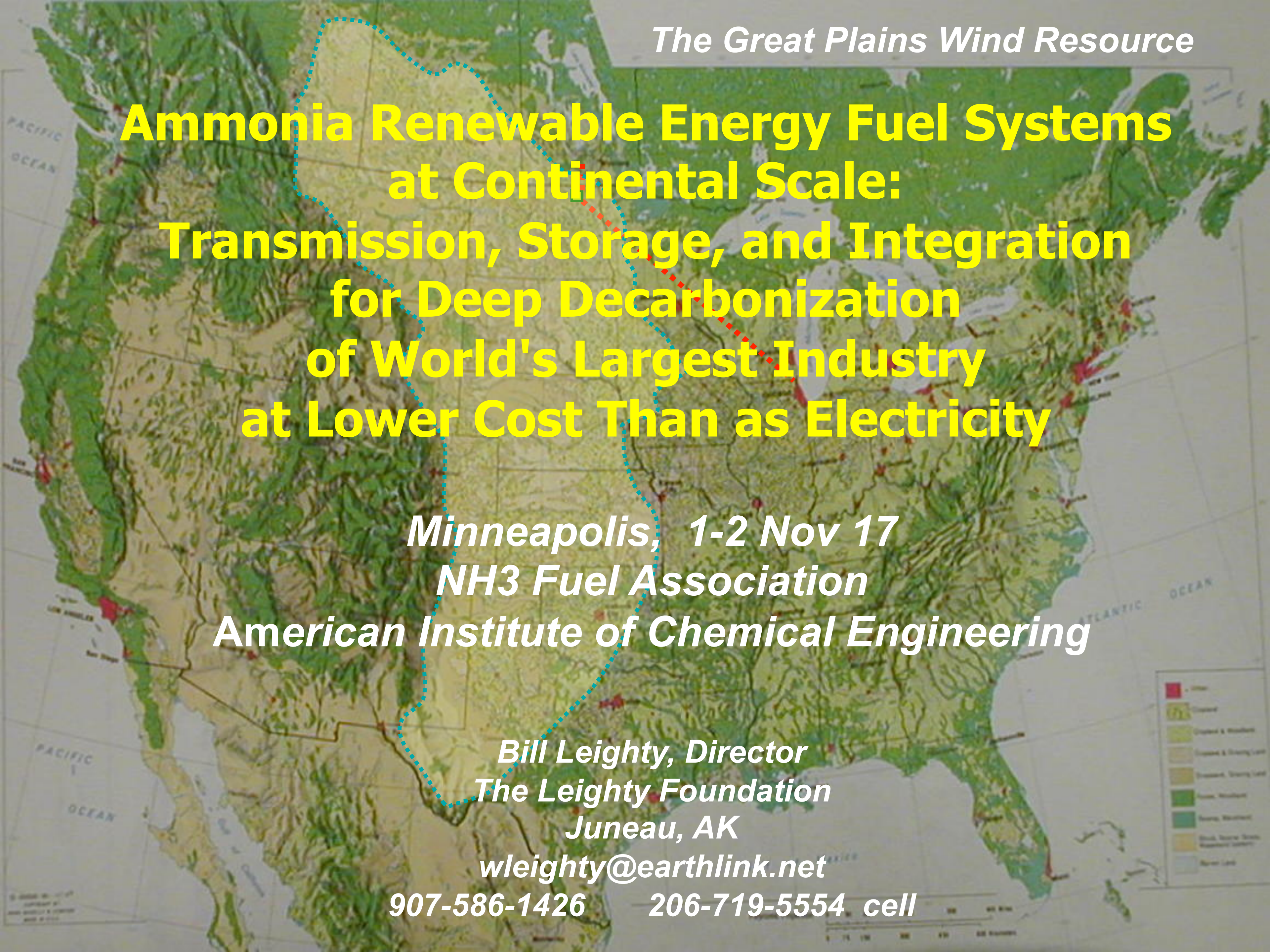


Ammonia Renewable Energy Fuel Systems at Continental Scale: Transmission, Storage, and Integration for Deep Decarbonization of World's Largest Industry at Lower Cost Than as Electricity

Minneapolis, 1-2 Nov 17
NH3 Fuel Association
American Institute of Chemical Engineering

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

Transform World's Largest Industry

Run the World on Renewables --

Including some nuclear ?

Transform World's Largest Industry

- ~ 85% fossil → 100% renewables
- Quickly
- Prudently
- Profitably
- Post – COP21, Paris
- Beyond electricity: H_2 and NH_3
- Nuclear ?

Transform World's Largest Industry

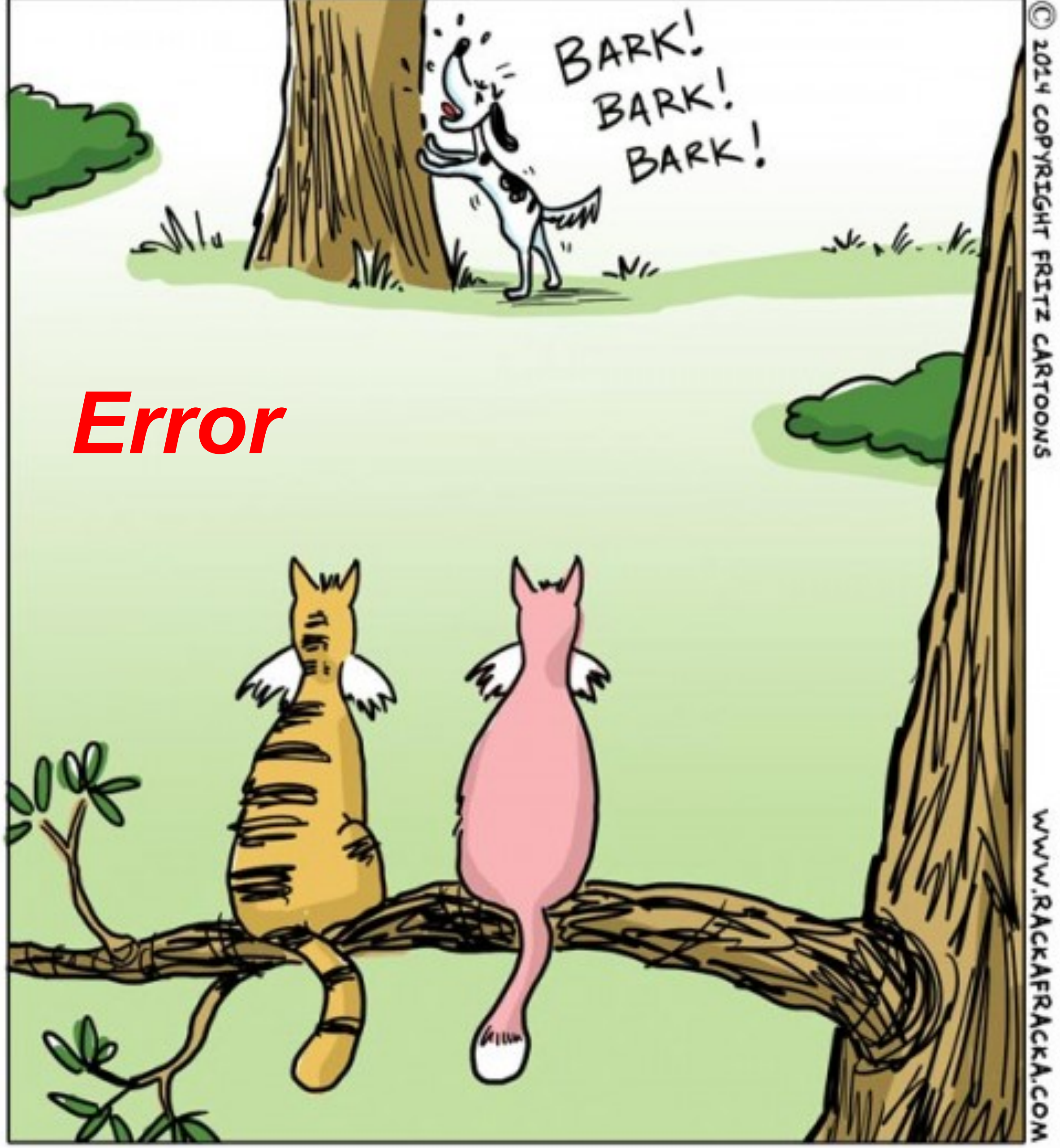
- Entirely via electricity systems ?
- Complete energy systems:
  - Renewable energy (RE)
  - CO2-emission-free (CEF)
  - Multiple sources
  - Time-varying output: variable generation (VG)
  - Integrated, synergistic
  - Harvest as electricity or as water-split Hydrogen ?
    - Photochemical: catalyst
    - Biochemical: photosynthesis
    - Thermochemical: High-T solar, nuclear

Tech, econ suboptimal ?
Opportunity cost

Global $ 45 trillion new infrastructure by 2030

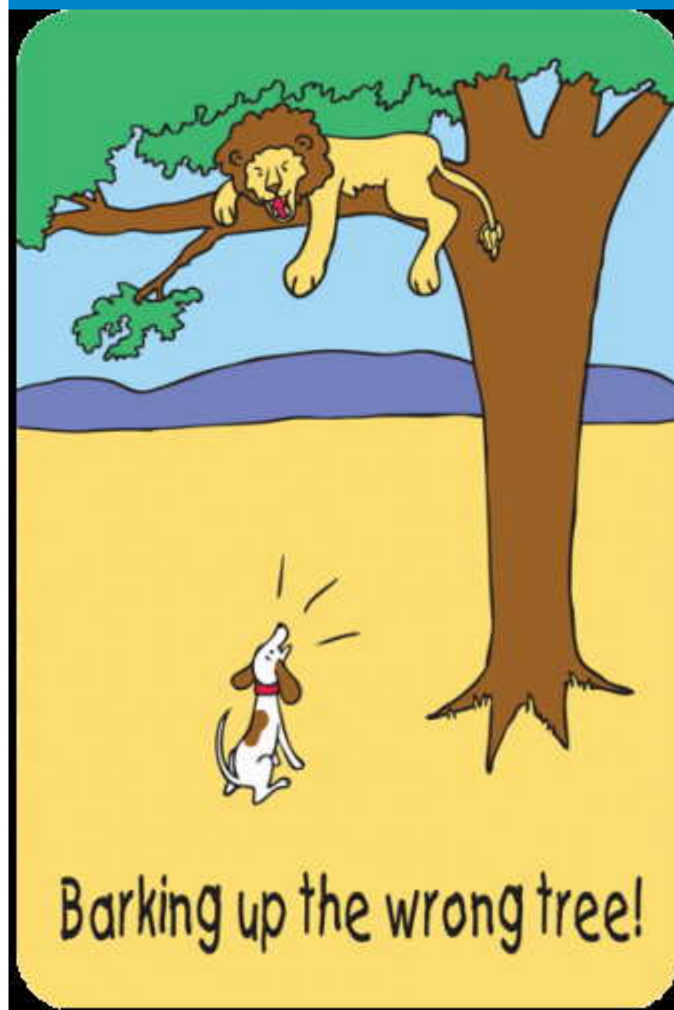
Electricity share ? NH_3 ? H_2 ?

Error



BUSTER WAS CAUGHT BARKING UP THE WRONG TREE AGAIN.

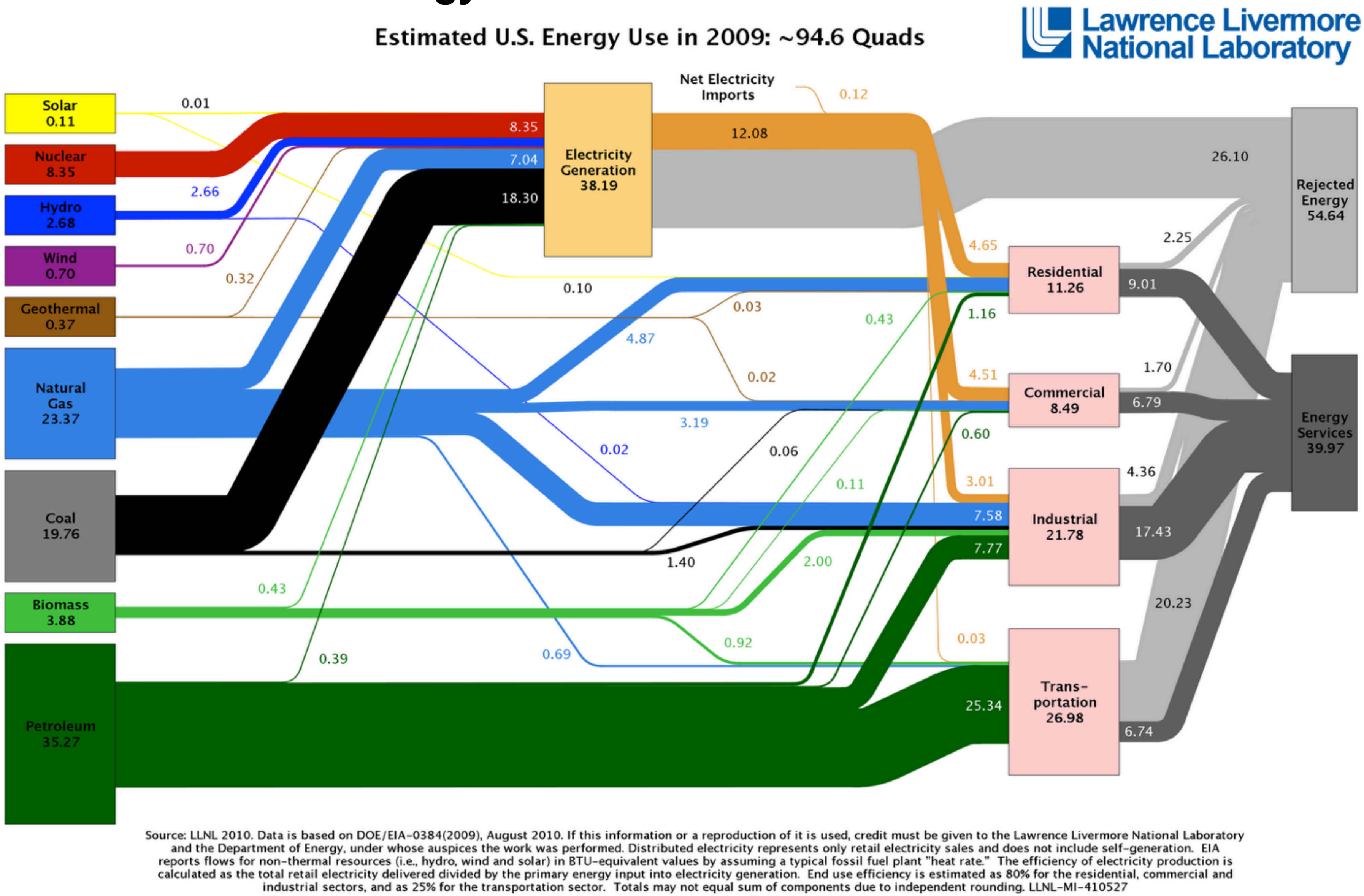
Danger



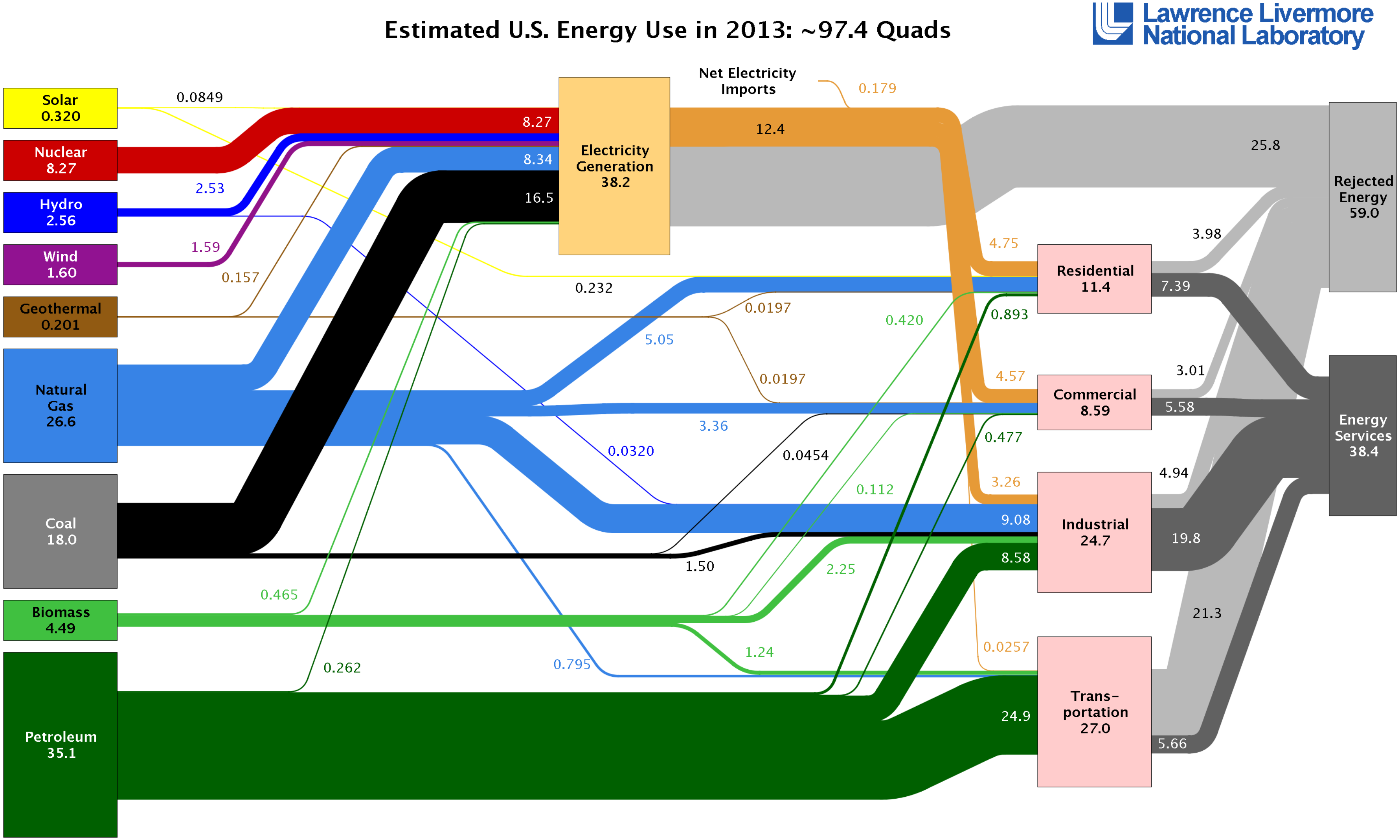
Transform World's Largest Industry

- **Think "Beyond Electricity"**
  - **"Smart", "Resilient", expanded Grid**
  - **Sunk costs**
  - **Stranded assets**
  - **Light speed**
  - **High-cost storage**
  - **NIMBY**
- **Carbon-free fuels, optimized systems**
  - **Hydrogen (H_2)**
  - **Anhydrous Ammonia (NH_3)**
  - **Low-cost storage ~ $ 0.10 – 0.20 / kWh**
  - **Underground pipelines**
  - **Transmission: ~ capex same, O&M lower**

Estimated U.S. Energy Use in 2009: ~ 95 Quads



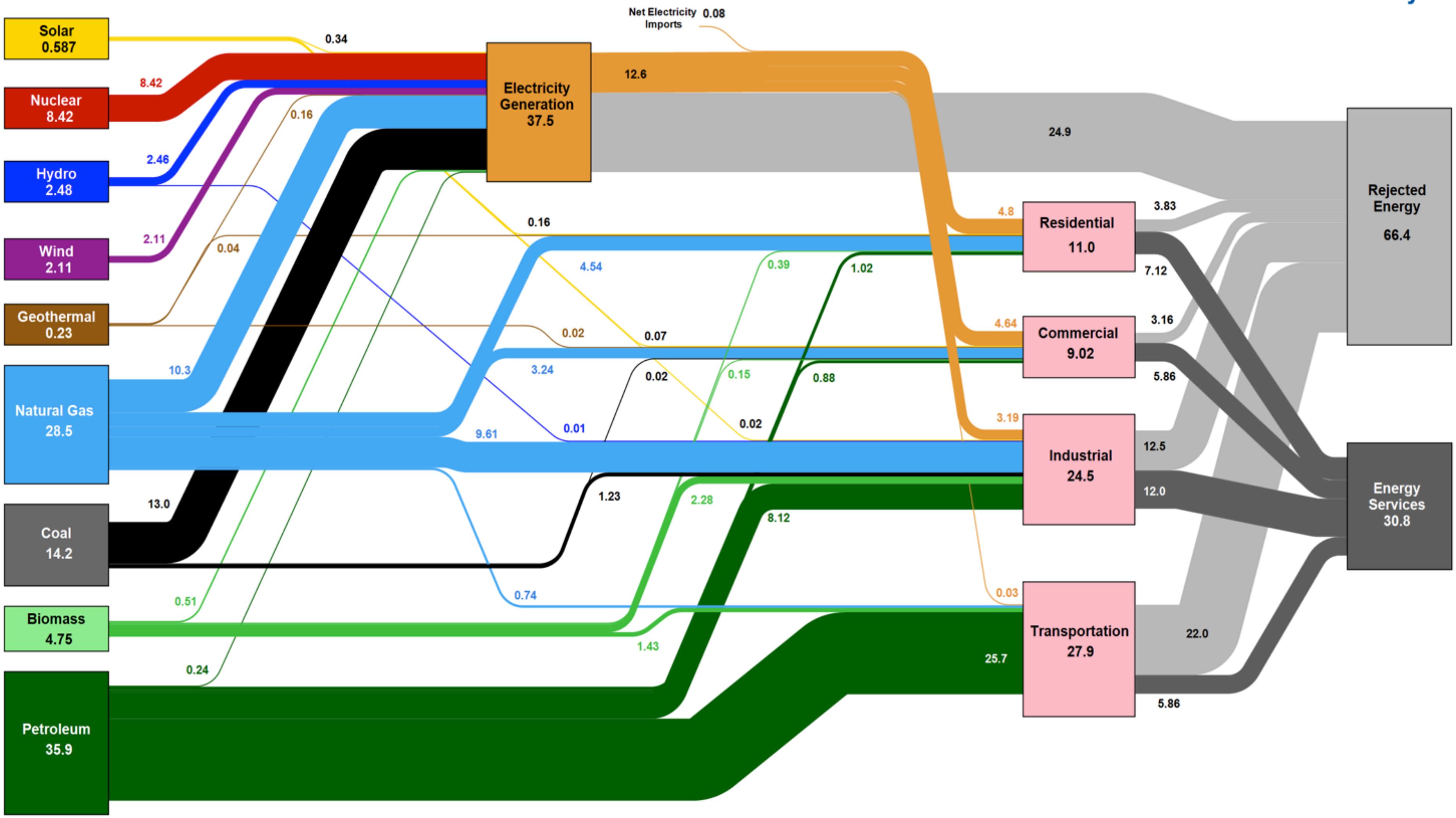
Estimated U.S. Energy Use in 2013: ~ 97 Quads



Source: LLNL 2014. Data is based on DOE/EIA-0035(2014-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

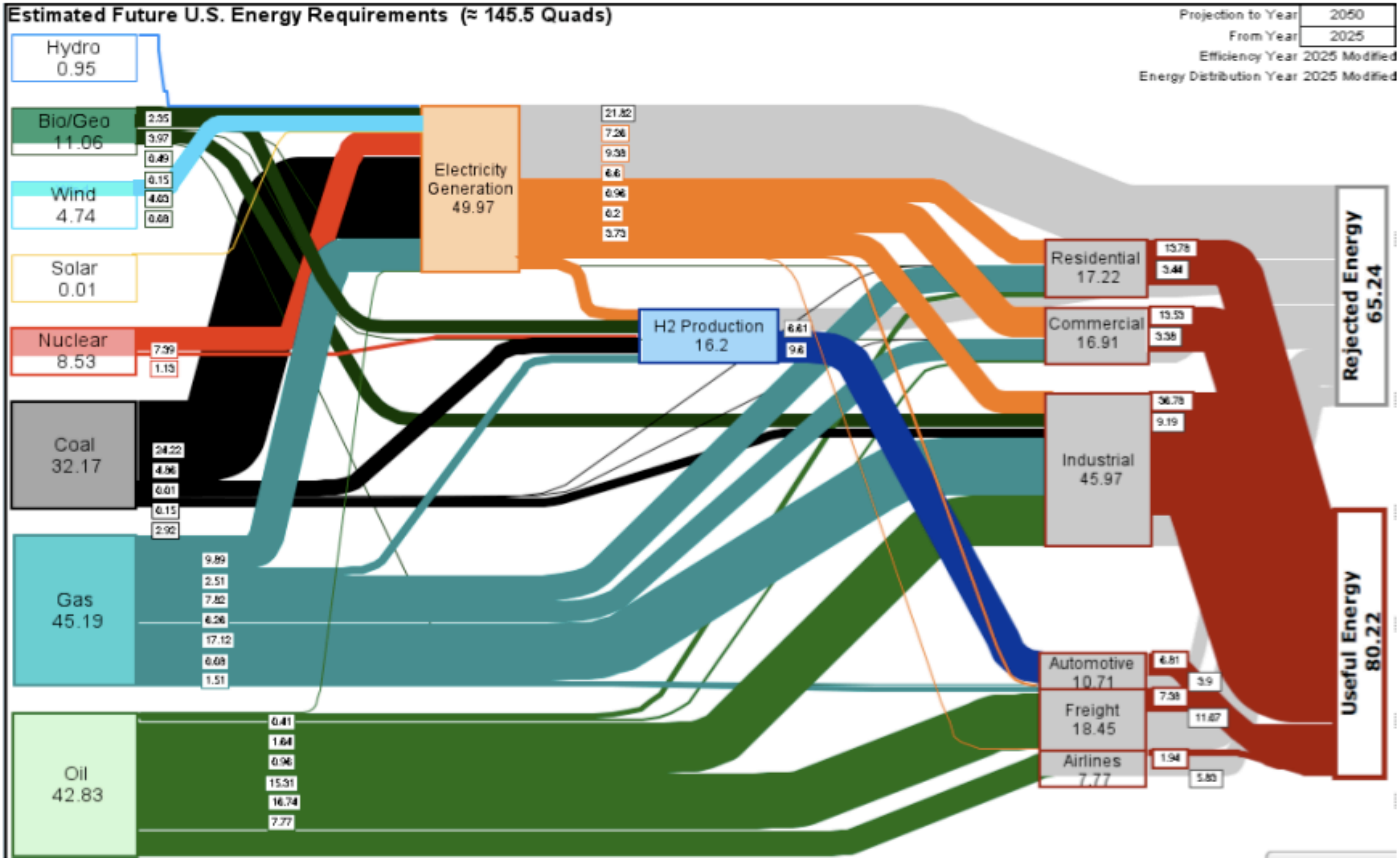
Estimated U.S. Energy Consumption in 2016: 97.3 Quads

Lawrence Livermore National Laboratory



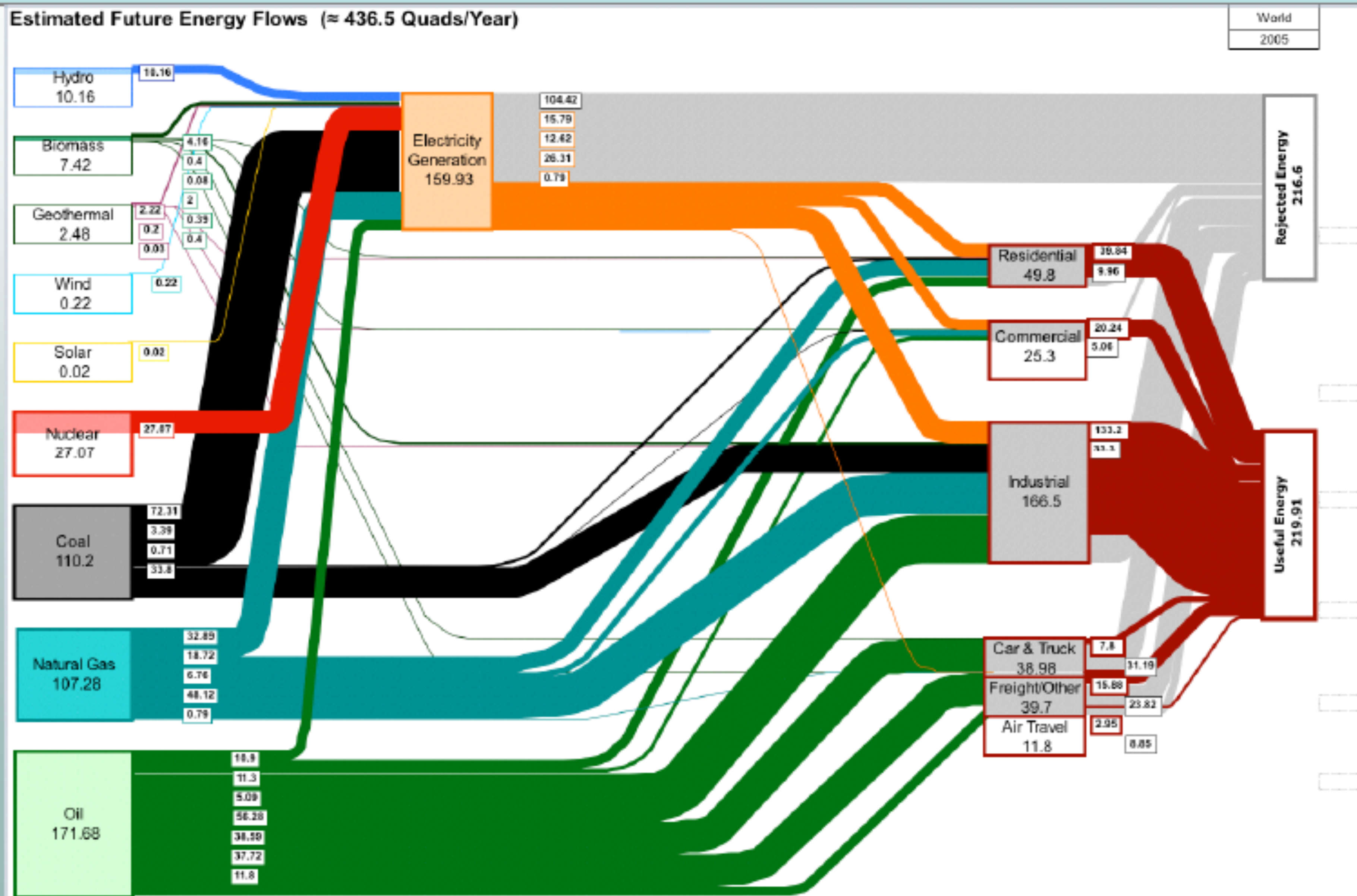
Source: LLNL March, 2017. Data is based on DOE/EIA MER (2016). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. This chart was revised in 2017 to reflect changes made in mid-2016 to the Energy Information Administration's analysis methodology and reporting. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector, and 49% for the industrial sector which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Estimated U.S. Energy Use in 2050: 145 Quads



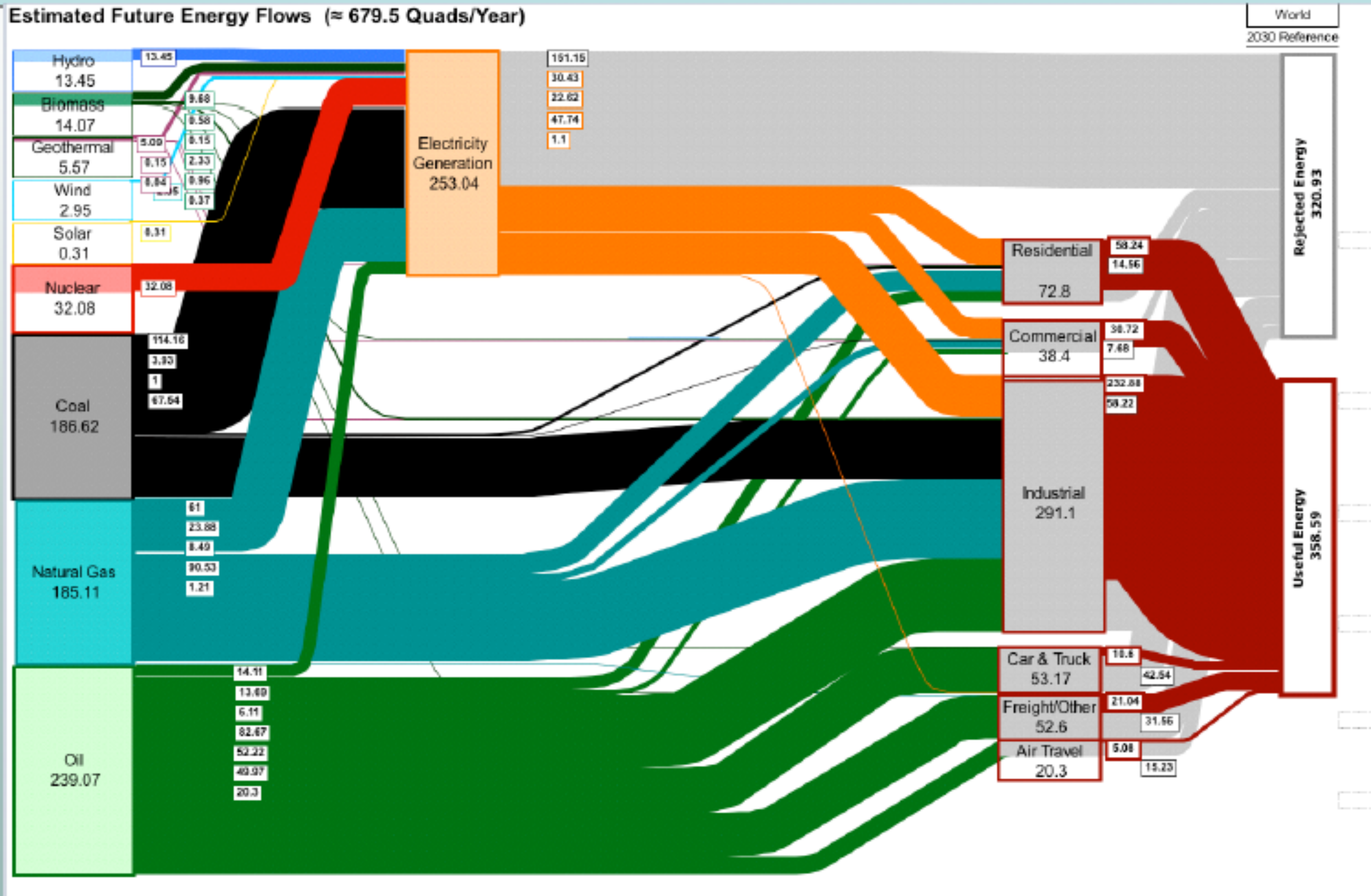
2005 World Energy ~ 436 Quads/yr

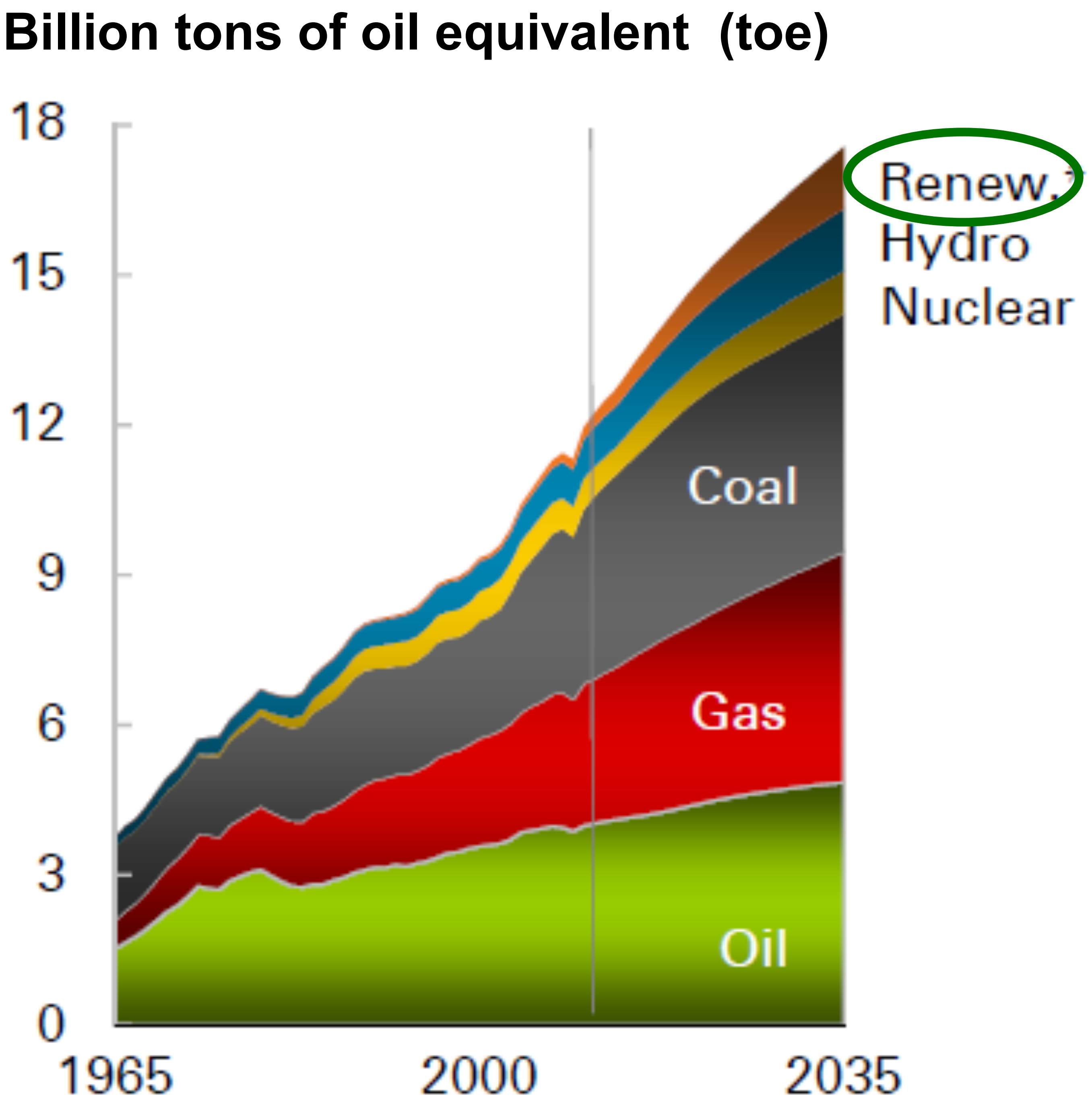
(International Energy Outlook 2006)



Projected World Energy ~ 680 Quads/yr

2030 Reference Case (IEO 2006)

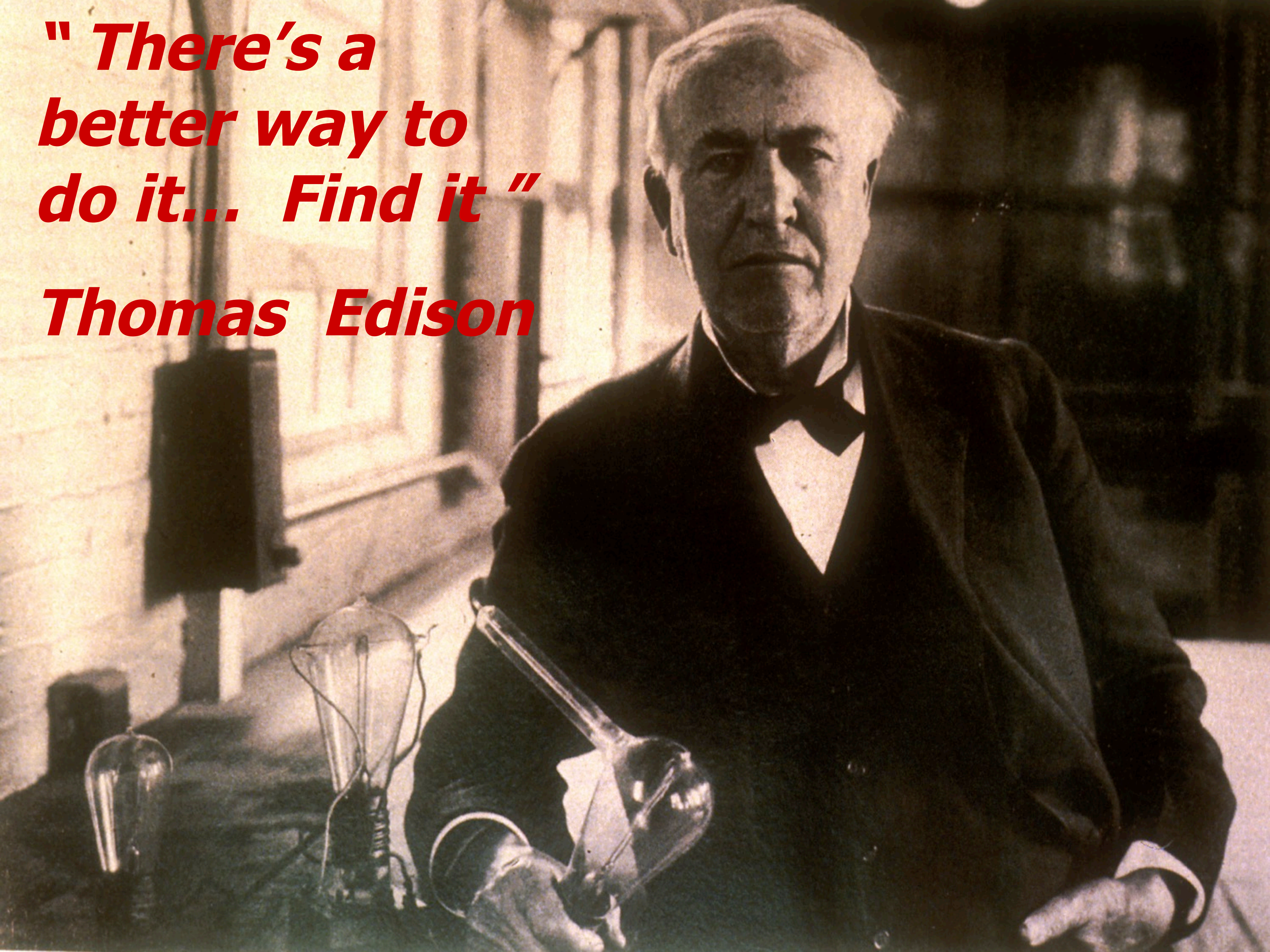




World Primary Energy Consumption

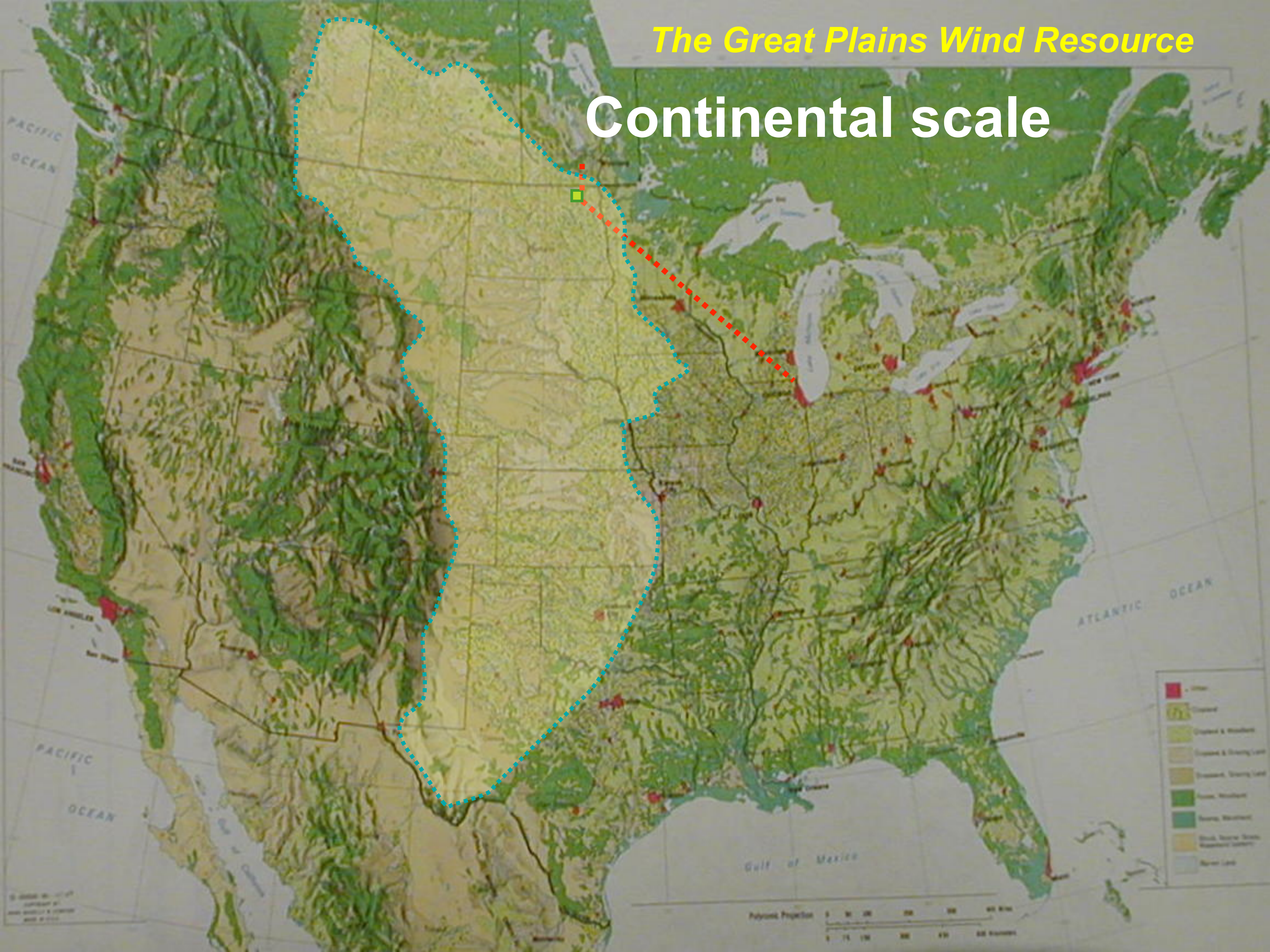
BP Energy Outlook 2035

January ‘14


" There's a better way to do it… Find it "
Thomas Edison

The Great Plains Wind Resource

Continental scale



Exporting From 12 Windiest Great Plains States

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

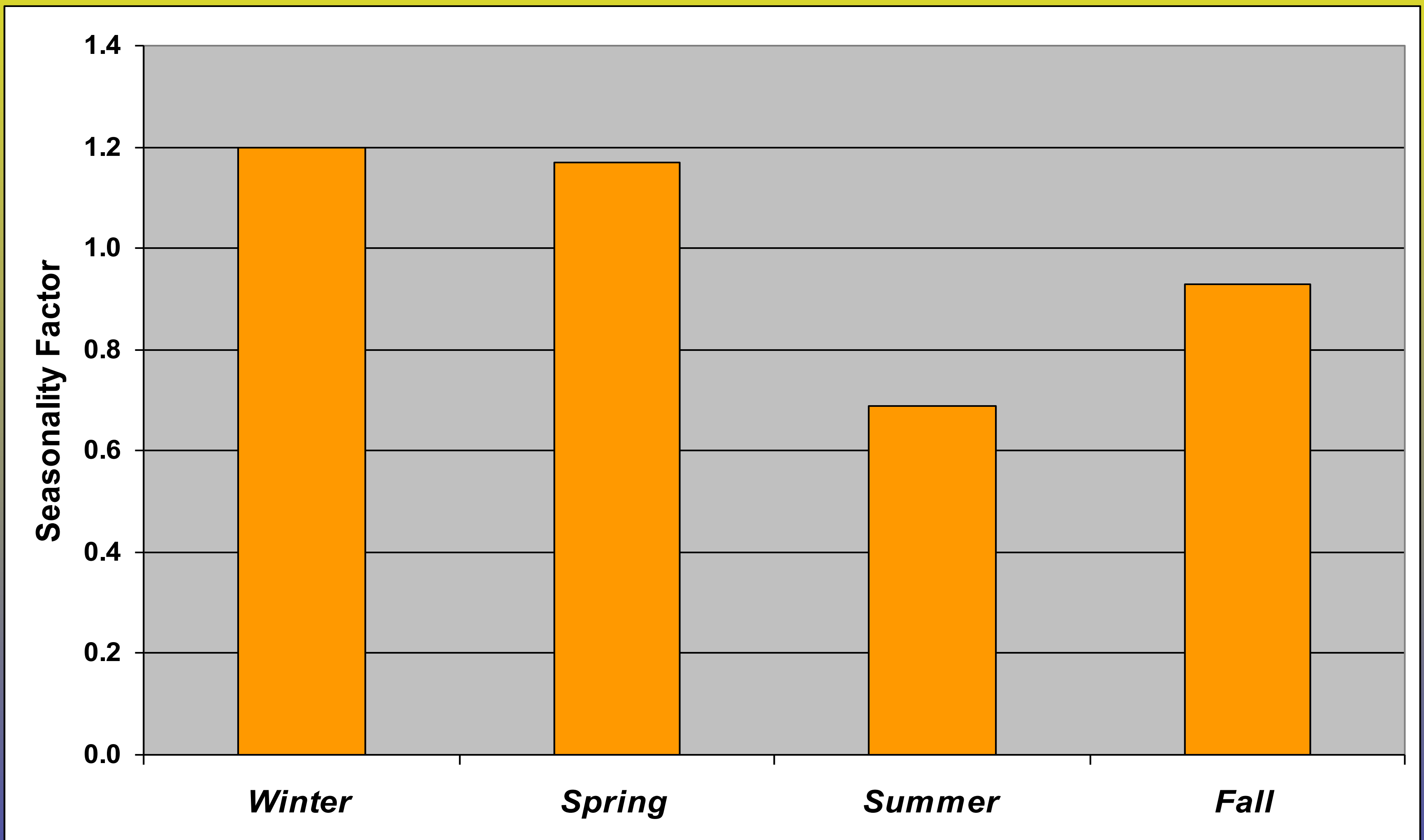
Capacity at 500 miles length **Capacity Factor (CF) = 30%**

State	Annual Energy Production (TWh)	Nameplate Installed Capacity (MW)	Nameplate Installed Capacity (GW)	6 GW 36" GH2 Hydrogen Pipelines	$ Billion Total Capital Cost	3 GW 500 KV HVDC Electric Lines	$ Billion Total Capital 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

Wind Seasonality, Northern Great Plains

Normalized to 1.0 per season



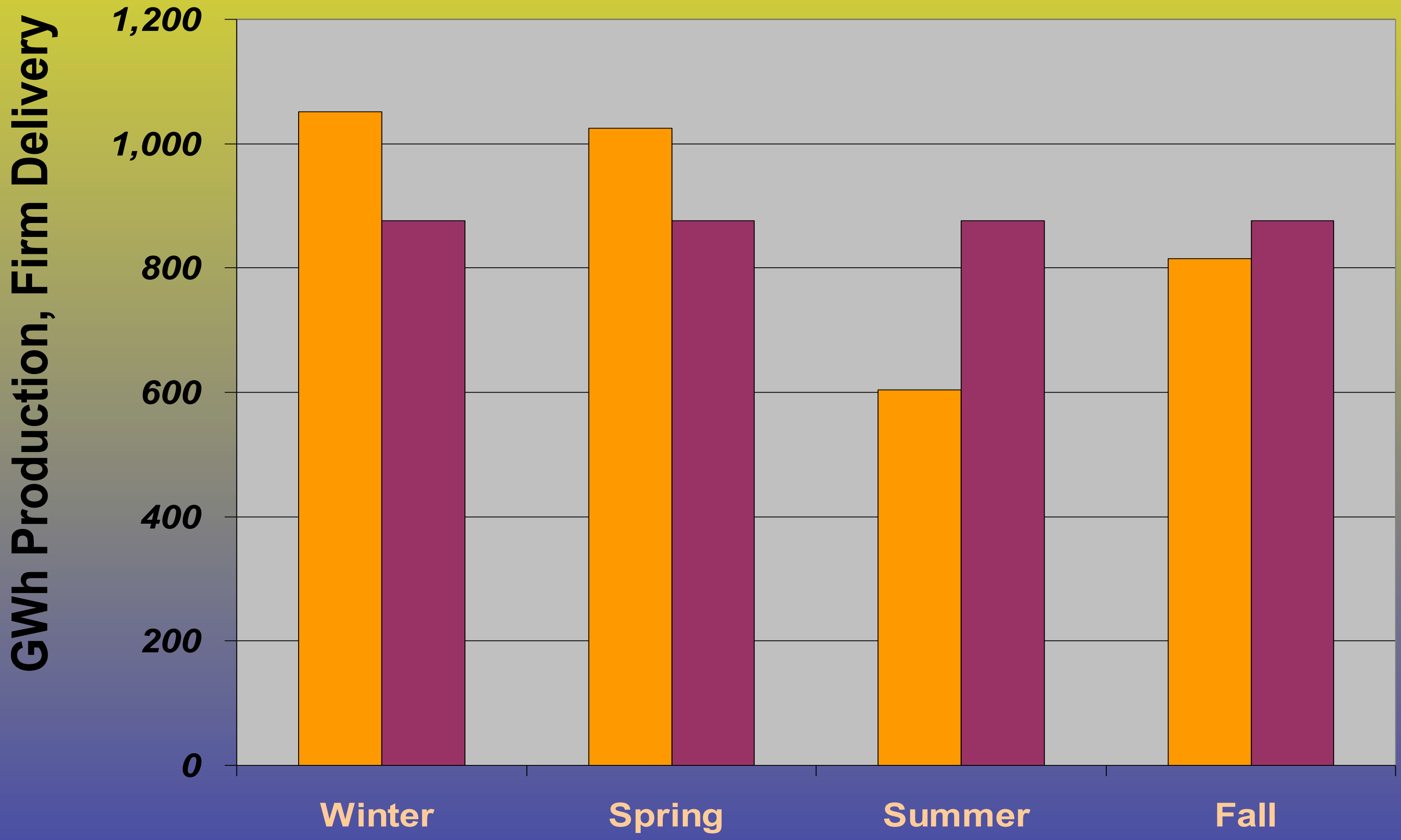
Wind Seasonality, Northern Great Plains

1,000 MW windplant: AEP = 3,500 GWh / yr

"Firm" goal = 875 GWh / season

Storage: 320 GWh per 1,000 MW wind

Source: NREL, D. Elliott



320 GWh

Annual firming, 1,000 MW wind nameplate

- **Battery**
  - **O&M: 90% efficiency round-trip**
  - **Capex: $500 / kWh = $ 160 Billion**
  - **Capex: $100 / kWh = $ 32 Billion**
- **CAES (compressed air energy storage)**
  - **O&M: $46 / MWh typical**
  - **Iowa, proposed: Power = 268 MW**
    - **Energy capacity = 5,360 MWh**
    - **Plant capex: 268 MW @$800 / kW = $ 214 Million**
    - **Storage @ $40 / kWh = $ 13 Billion**

Hydrogen Transportation Fuel Demand
California, year 2050
Million metric tons per year:

IF:

- **CA meets RPS and “80 in 50” goals**
- **Hydrogen-fueled FCVEV’s displace BEV’s**
- **CA builds new, underground, H2 pipeline system**
- **Transport modal mix same as 2016**

Then:

Source:
Interpret and extrapolate from several papers by ITS-STEPS, UC Davis

Year 2050 Electricity + Hydrogen Transportation Fuel, California will need :

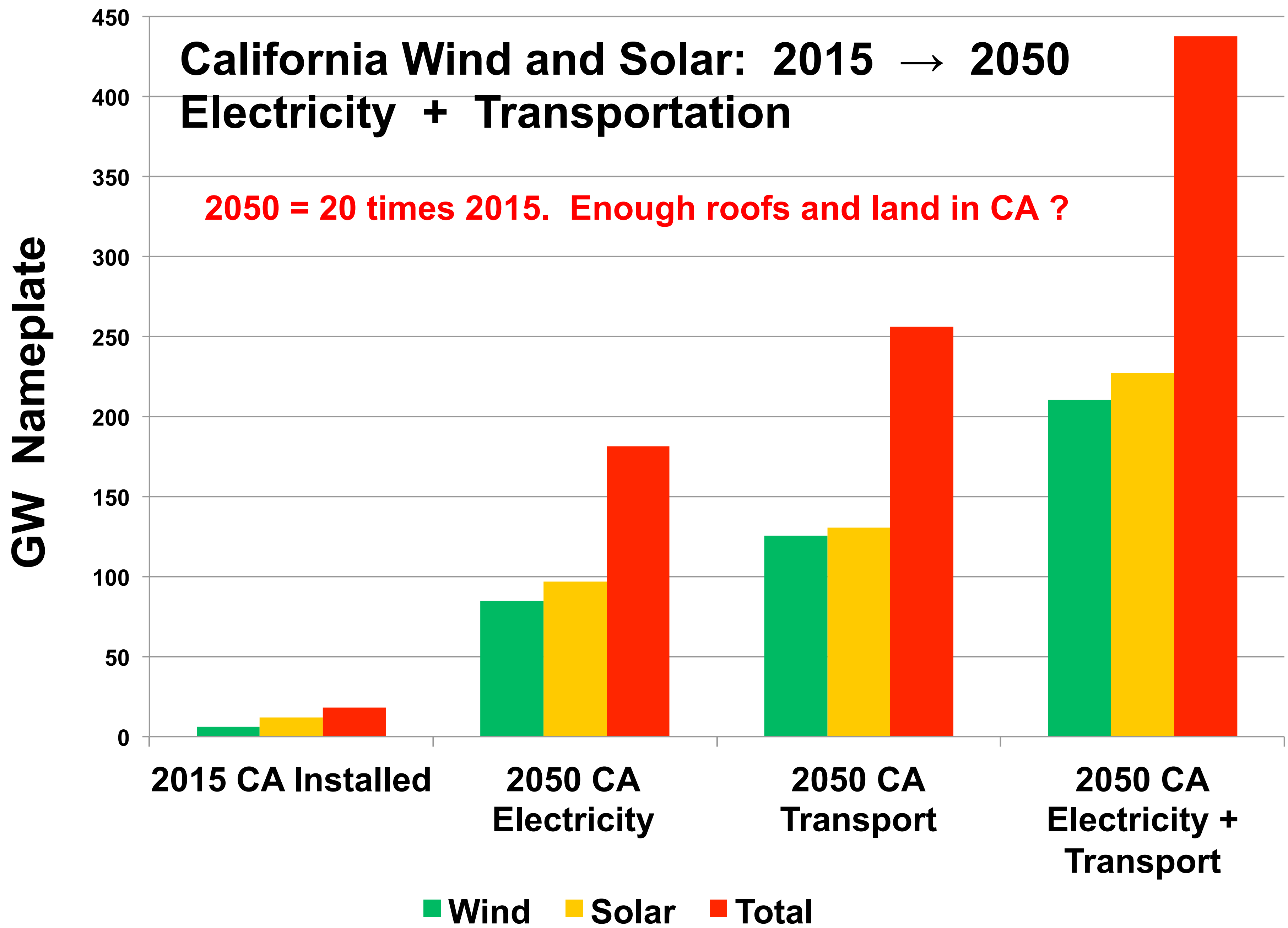
Reference: Year 2015	**GW**
Total installed nameplate wind generation in California (CA)	6
Total installed nameplate solar generation in California (CA)	12
ELECTRICITY: CA "Power Mix"	**GWh**
2014: Total electricity consumed	296,843
2050: Total electricity demand "Power Mix" is 130 % of 2014	385,896
ELECTRICITY in Year 2050: CA renewables	**GW**
Equivalent nameplate wind generation capacity @ 40 % CF	85
Equivalent nameplate solar generation capacity @ 35 % CF	97
TRANSPORTATION Hydrogen Fuel in Year 2050: CA renewables	**GW**
Equivalent nameplate wind generation capacity @ 40 % CF	126
Equivalent nameplate solar generation capacity @ 35 % CF	130
TOTAL CA RENEWABLE ELECTRICITY + TRANSPORT ENERGY in Year 2050	**GW**
Equivalent nameplate wind + solar + other @ CF (varies)	438

Hydrogen Transportation Fuel Demand California, year 2050 Million metric tons per year:

Light Duty Vehicles (LDV)	3.6	
Trucking	1.6	
Bus	1.4	
Aviation and Other	0.8	
Total	**7.4**	**Hydrogen**
	66.5	**Ammonia**

Source:

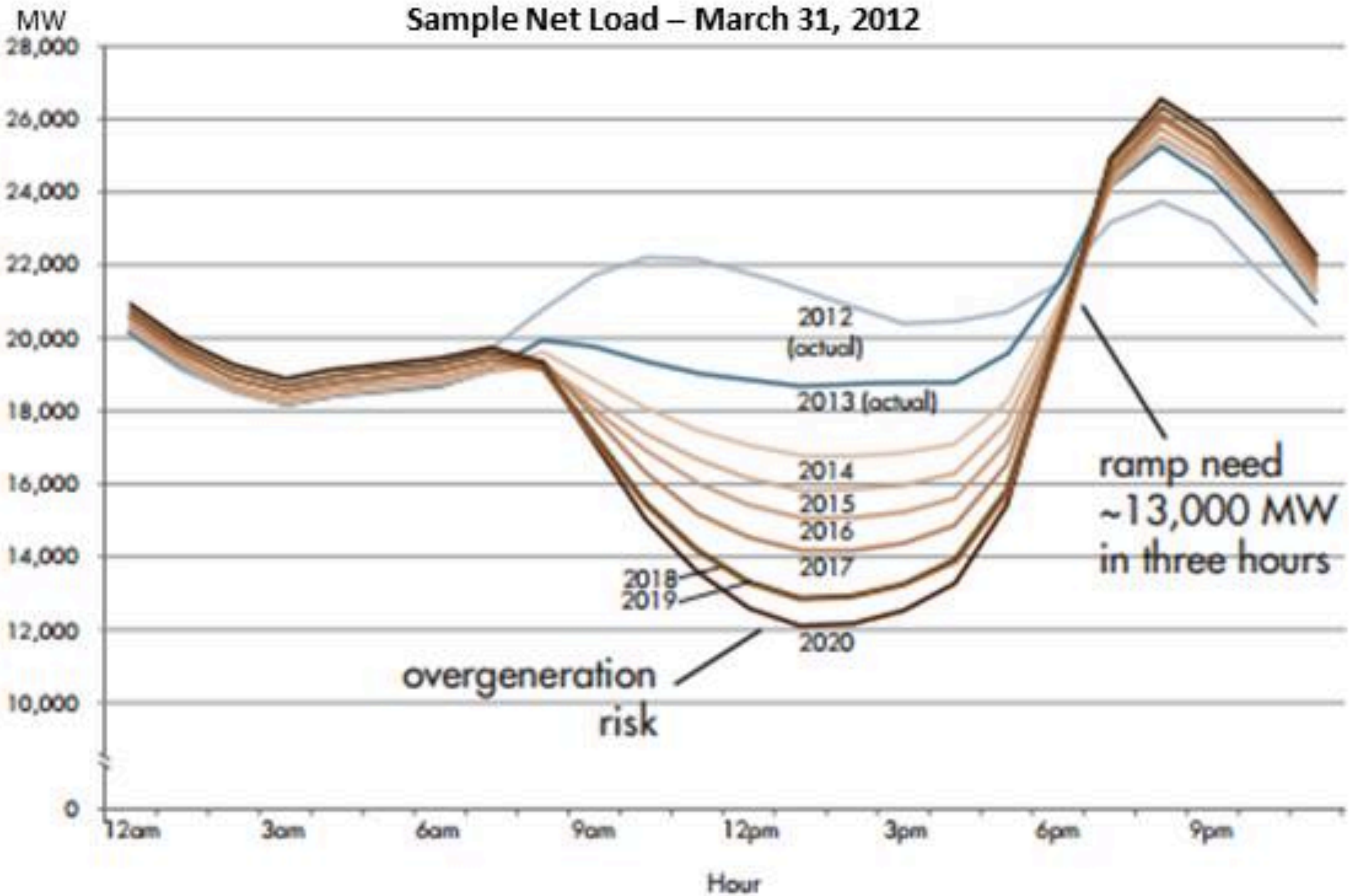
Interpret and extrapolate from several papers by ITS-STEPS, UC Davis



California Wind and Solar: 2015 → 2050
Electricity + Transportation
2050 = 20 times 2015. Enough roofs and land in CA ?
GW Nameplate
450
400
350
300
250
200
150
100
50
0
2015 CA Installed
2050 CA Electricity
2050 CA Transport
2050 CA Electricity + Transport
Wind
Solar
Total

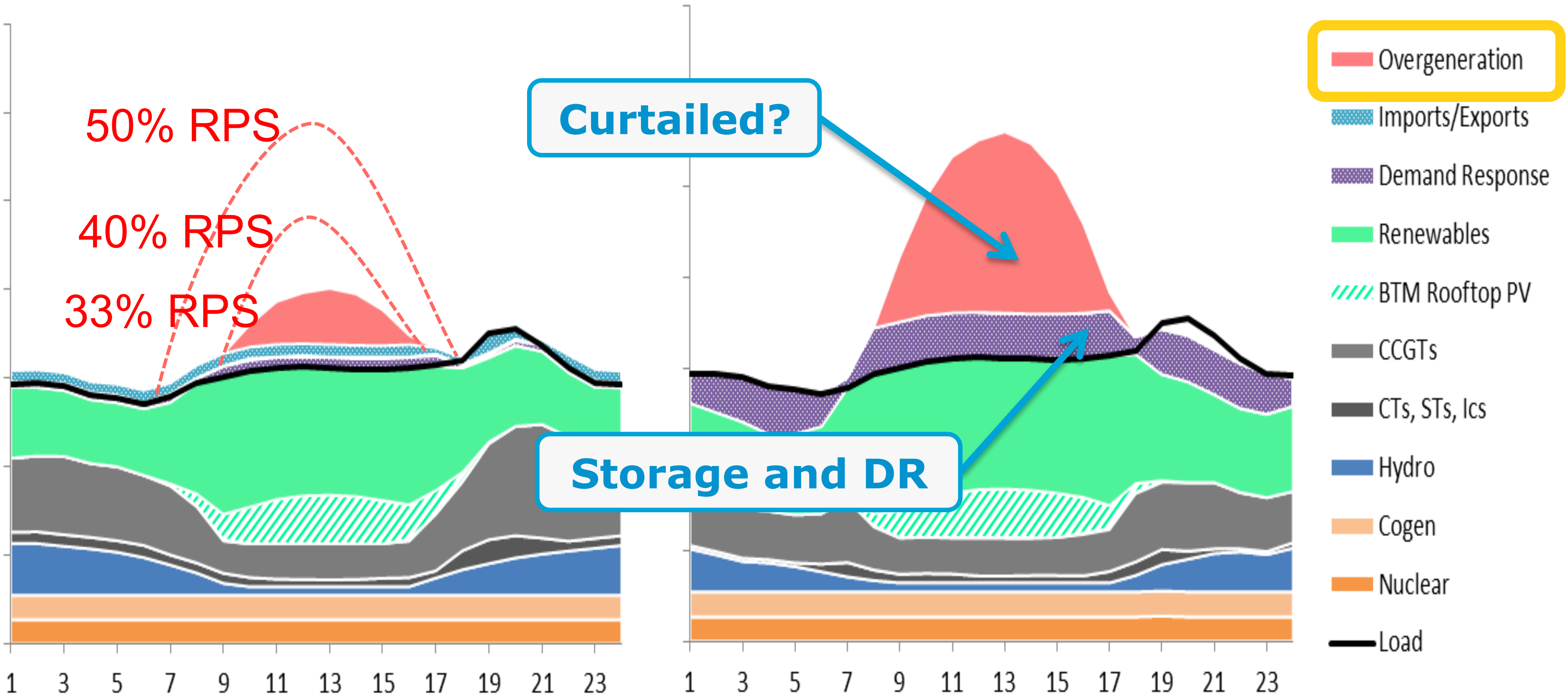
CA "Duck Curve": solar overgeneration, steep ramp

Electric utilities NET load



CA Independent System Operator - CAISO

California's surplus renewable generation

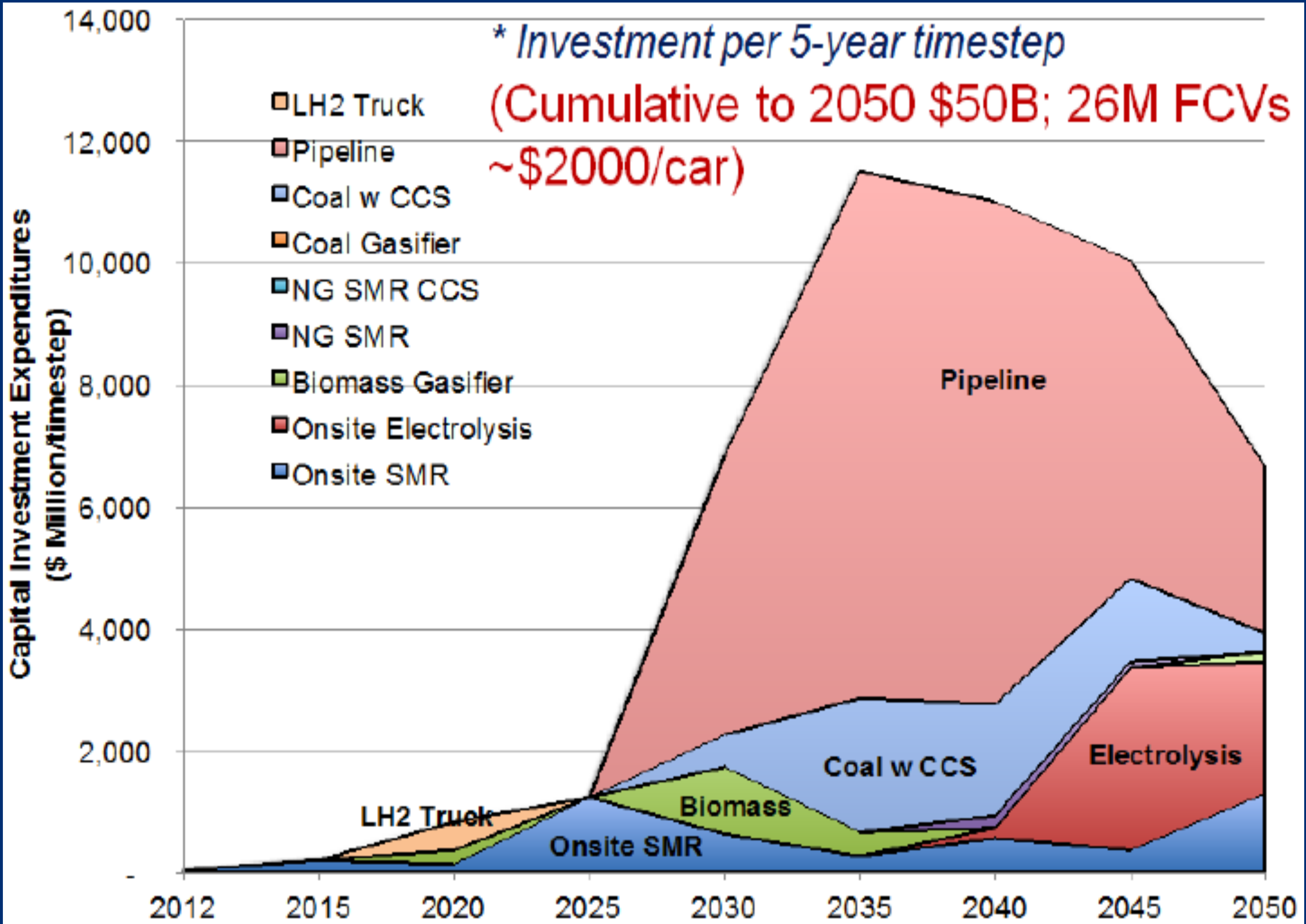


Do Not Cite
For Illustrative Purposes Only

Energy+Environmental Economics

Source: Adapted from + *Valuing Storage,* Eric Cutter, Energy + Environmental Economics – October 2013

"Hydrogen Transition" UC Davis, ITS "NEXTSteps"



January Week: Electricity

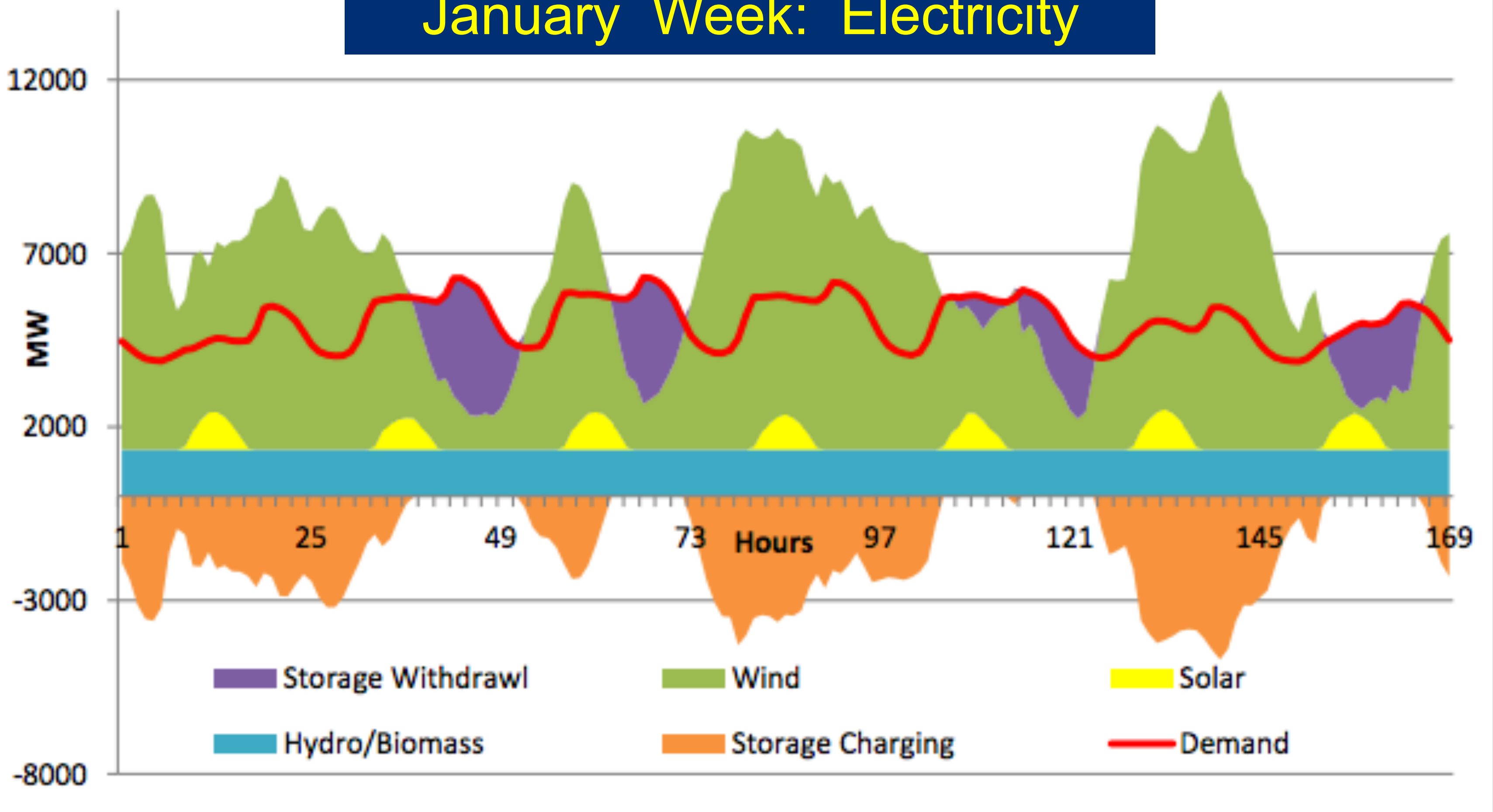
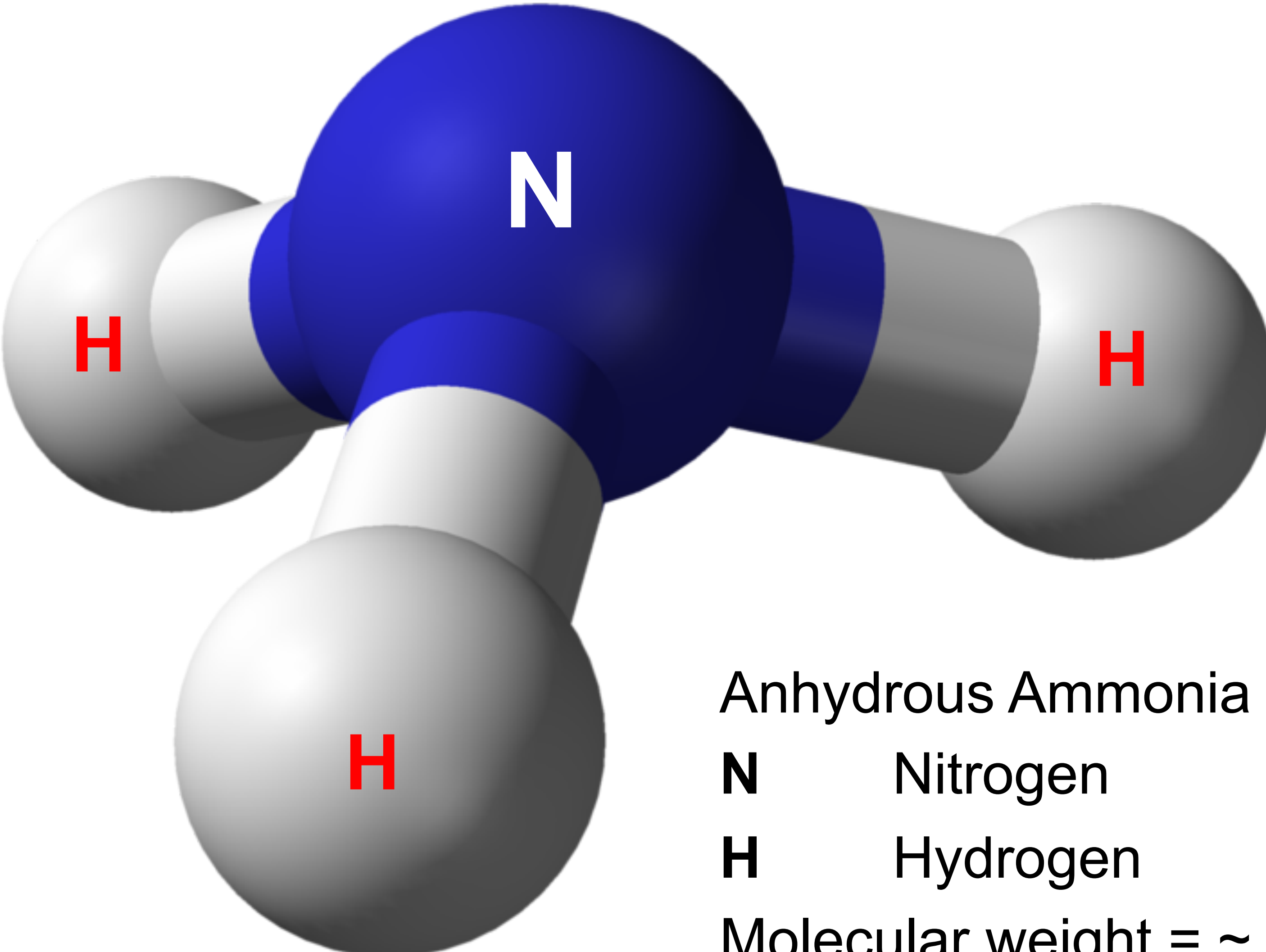


Figure III-6: Hourly supply and demand with storage, January 1-7, 2007. *Source: IEER.*

Hypothetical:
100 % Renewable Electricity System in Minnesota



Anhydrous Ammonia **NH_3**

N Nitrogen

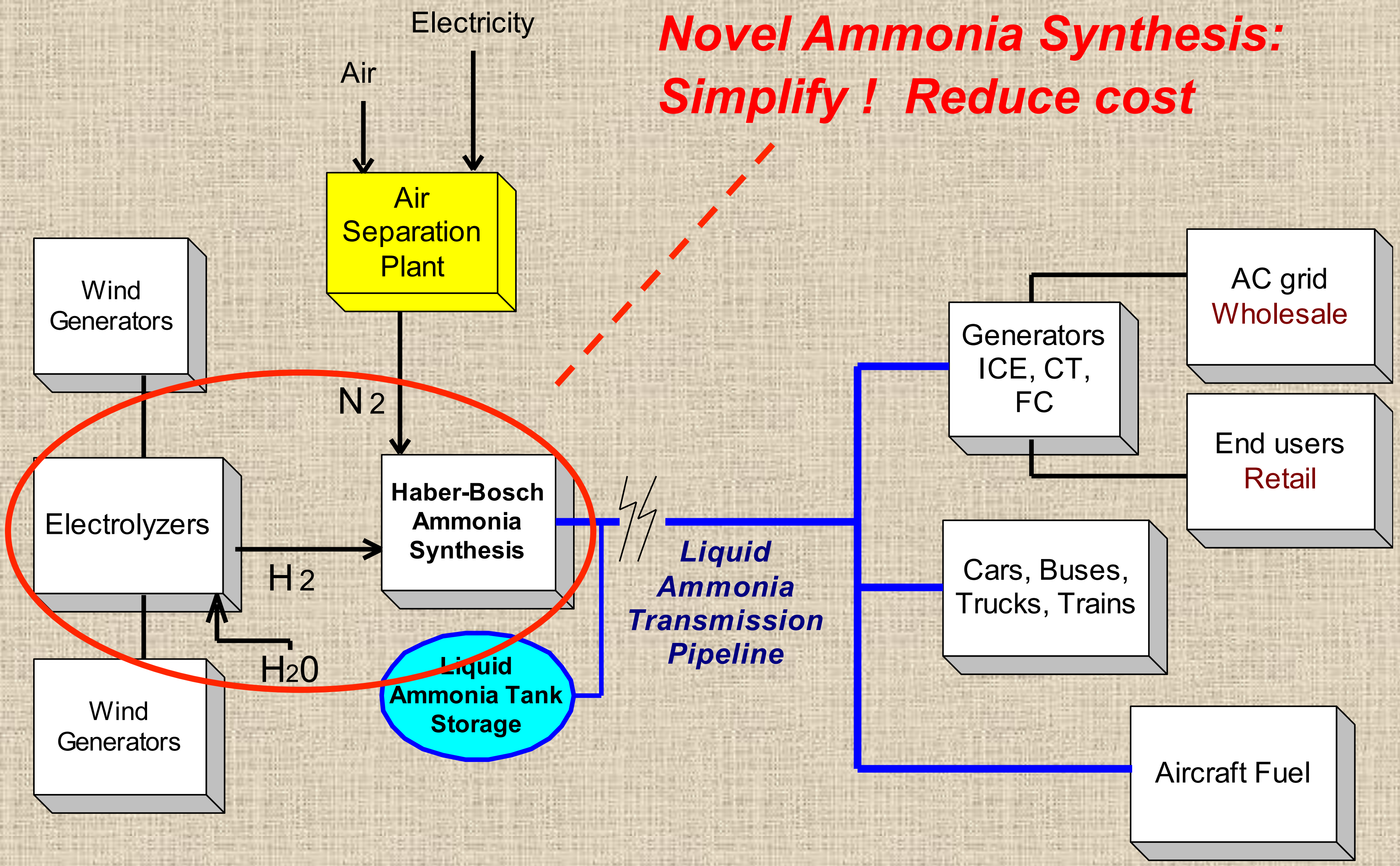
H Hydrogen

Molecular weight = ~ 17

18% **H** by weight: "other hydrogen"

$NH_3 + O_2 = N_2 + H_2O$

RE Ammonia Transmission + Storage Scenario



’09 ARPA-E “Grids” Goal: $100 / kWh

Total storage = 380 GWh

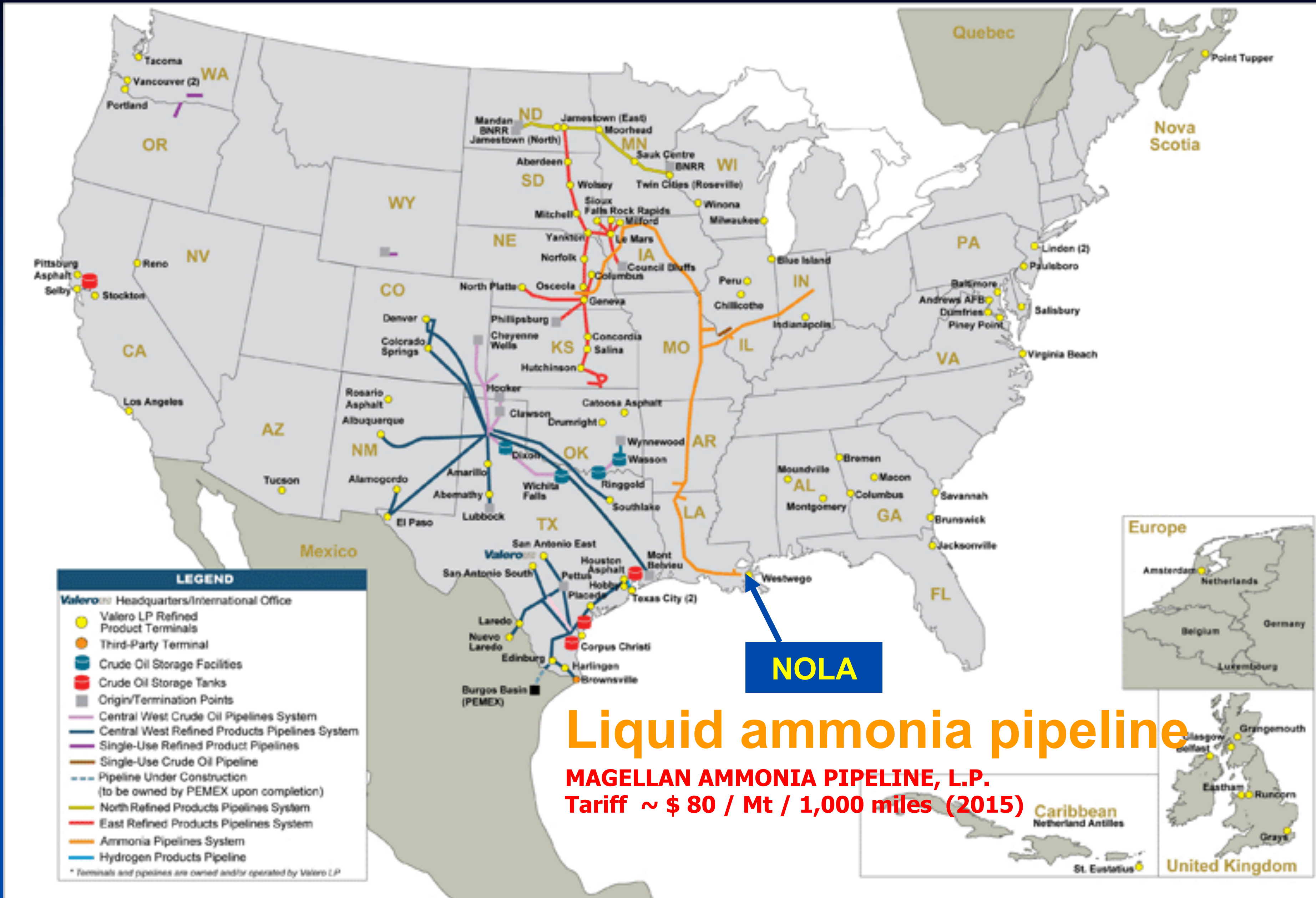
“Atmospheric” Liquid Ammonia Storage Tank (Corn Belt)

-33 C   1 Atm

Each: 30,000 Tons, 190 GWh $ 15M turnkey

$ 80 / MWh = $ 0.08 / kWh   capital cost


200 Ton “propane” tanks for liquid ammonia
~ 10 bar pressure



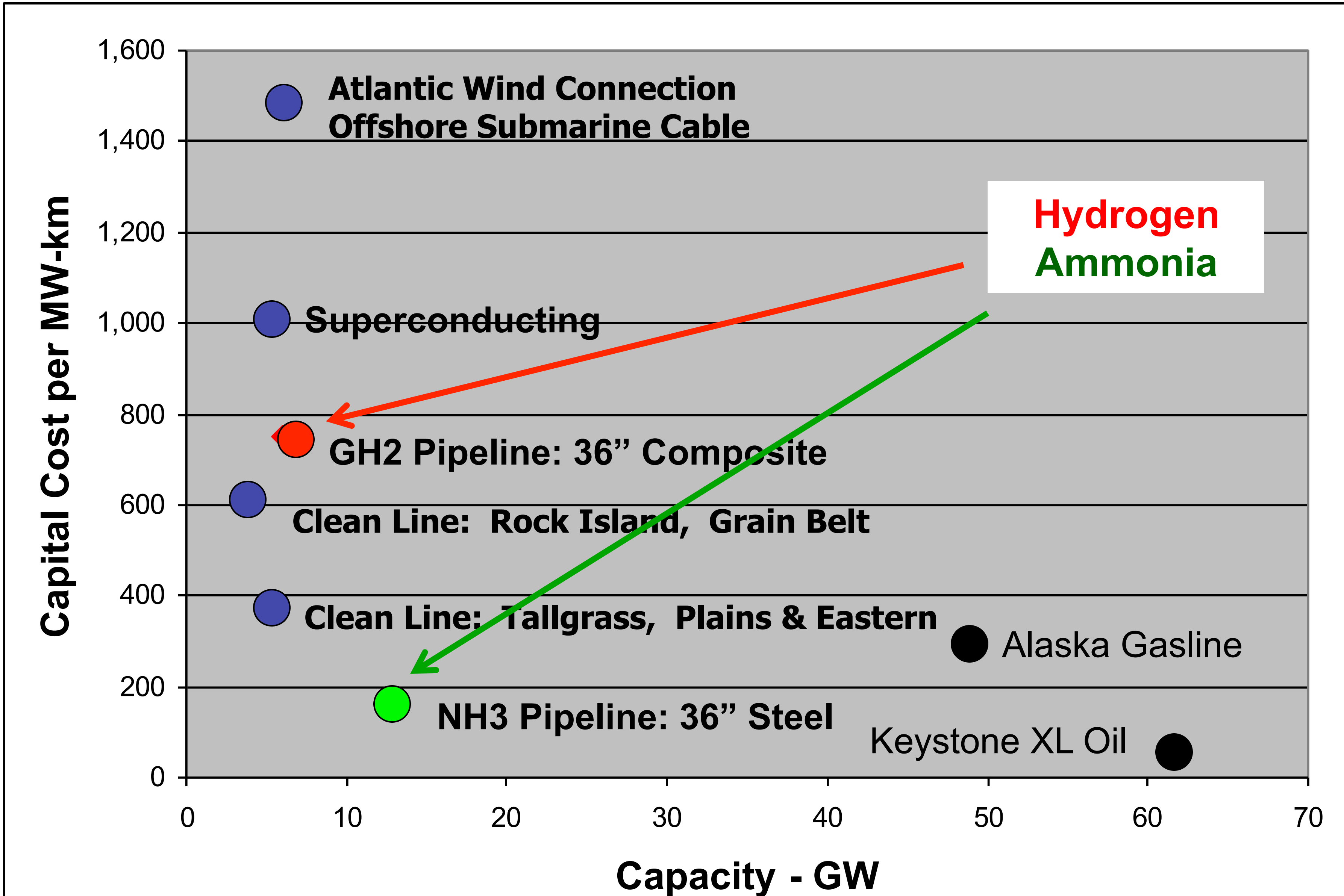
NOLA

Liquid ammonia pipeline

MAGELLAN AMMONIA PIPELINE, L.P.

Tariff ~ $ 80 / Mt / 1,000 miles (2015)

Valero LP Operations



Transmission capital costs per MW-km compared

Pipelines have large capacity and provide large storage

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

320 GWh
Annual firming, 1,000 MW wind

- CAES (compressed air energy storage)
  - O&M: $46 / MWh typical
  - Iowa: Power = 268 MW

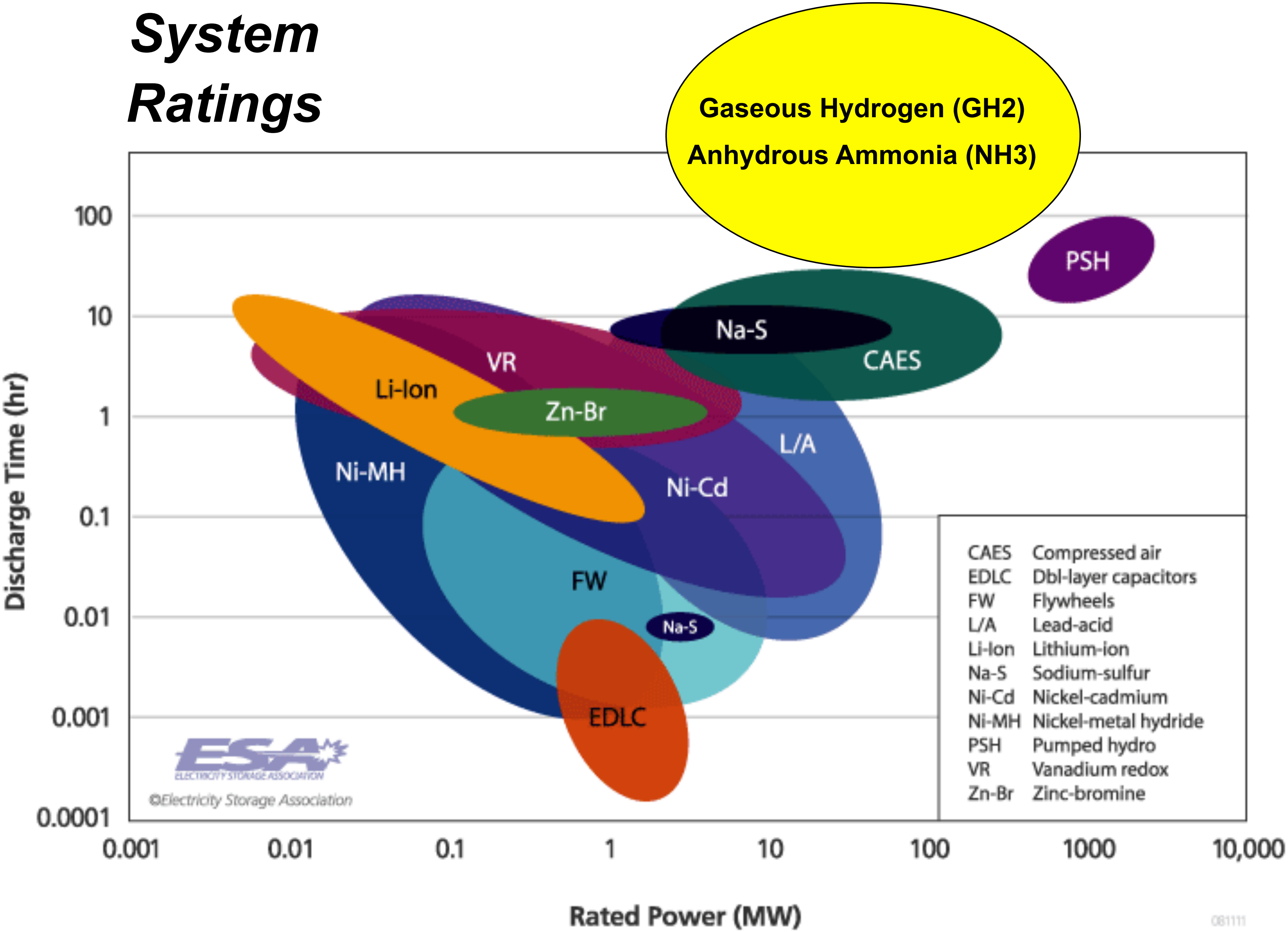
    Energy capacity = 5,360 MWh

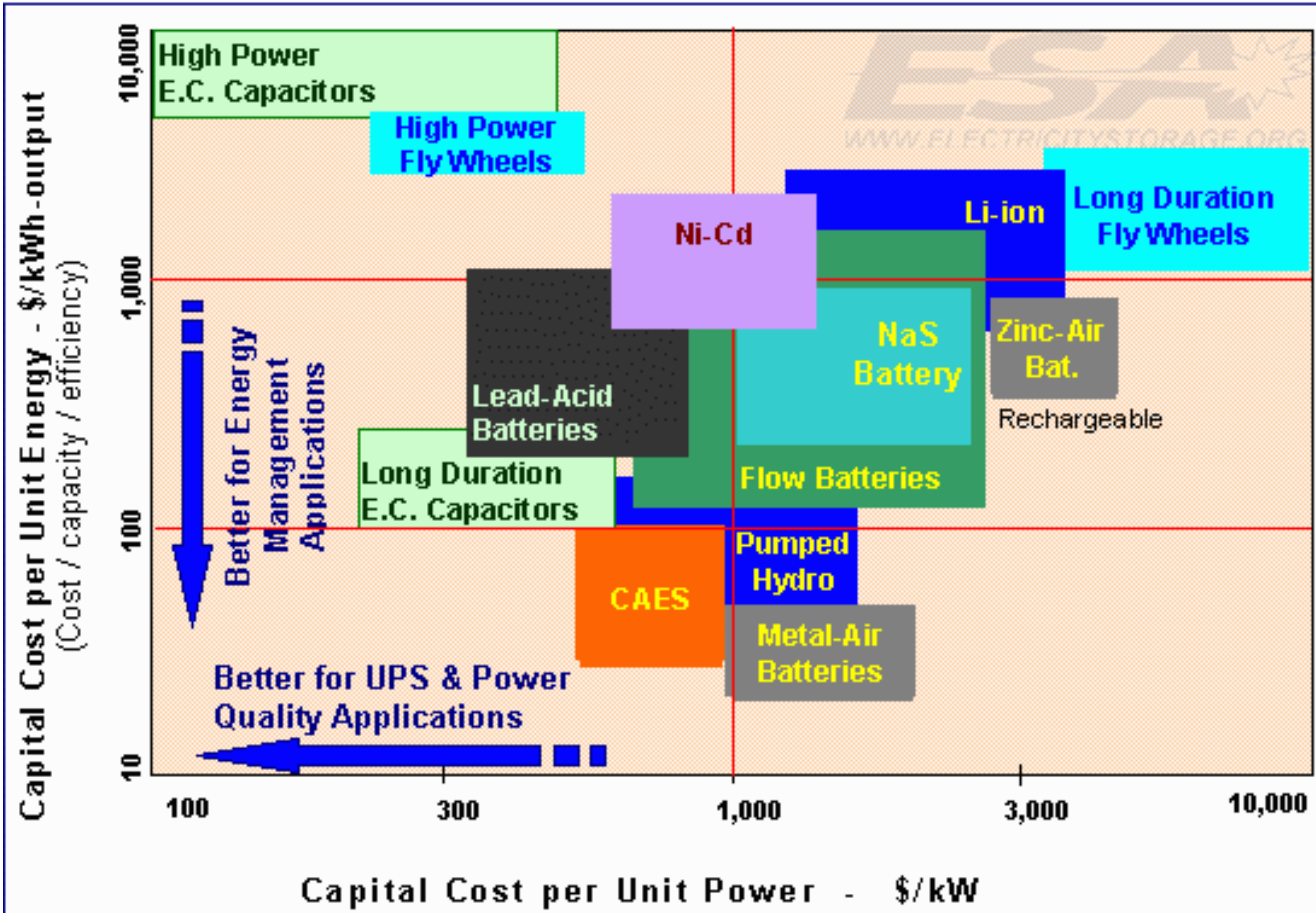
    Capital: 268 MW @$800 / kW = $214 M

    Storage @ $40 / kWh = $ 13 Billion

    Storage @ $1 / kWh = $ 325 Million
- Battery
  - O&M: 90% efficiency round-trip
  - Capital: $500 / kWh = $ 160 Billion
  - Capital: $300 / kWh = $ 96 Billion
- GH2 (3 hydrogen caverns)   Capital $70 Million
- NH3 (2 ammonia tanks)   Capital $30 Million

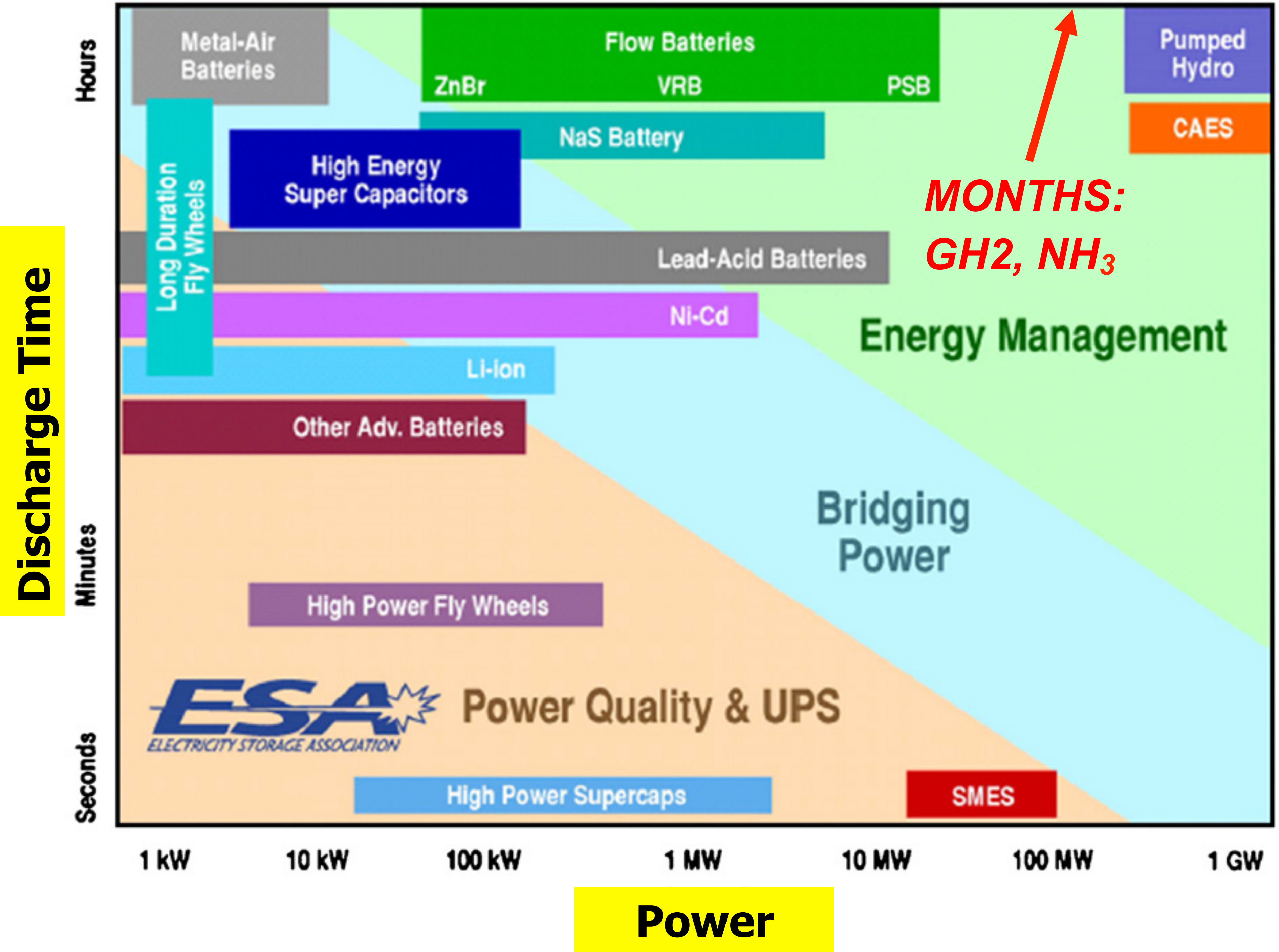
System Ratings



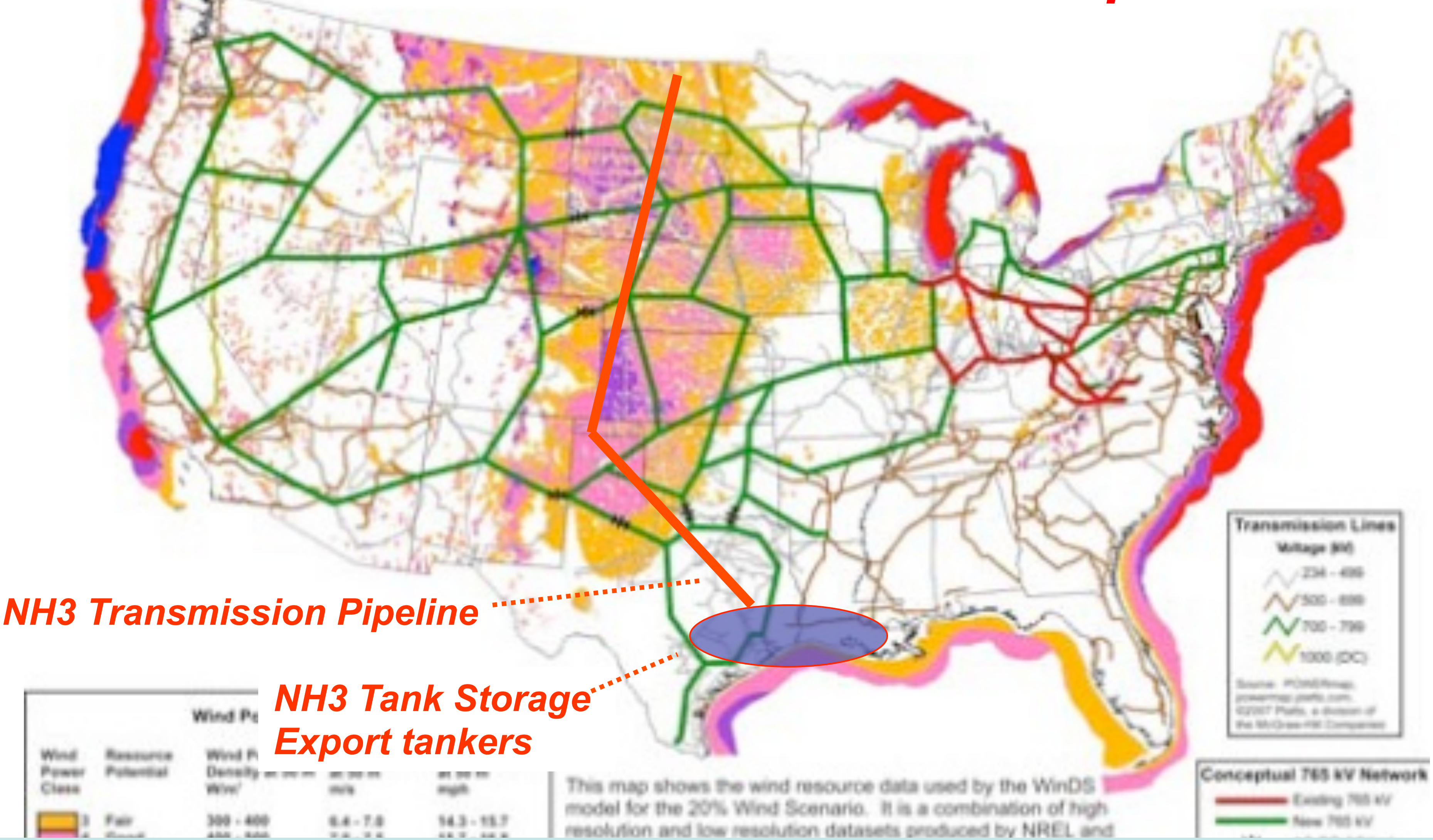


High Power
E.C. Capacitors
High Power
Fly Wheels
WWW.ELECTRICITYSTORAGE.ORG
Li-ion
Long Duration
Fly Wheels
Ni-Cd
NaS
Battery
Zinc-Air
Bat.
Rechargeable
Lead-Acid
Batteries
Flow Batteries
Long Duration
E.C. Capacitors
Pumped
Hydro
CAES
Metal-Air
Batteries
Better for Energy
Management
Applications
Better 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 NH_3


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
Lead-Acid Batteries
Ni-Cd
Li-ion
Other Adv. Batteries
MONTHS:
GH2, NH_3
Energy Management
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

NH3 Transmission Pipeline



Wind Potential ~ 10,000 GW

12 Great Plains states

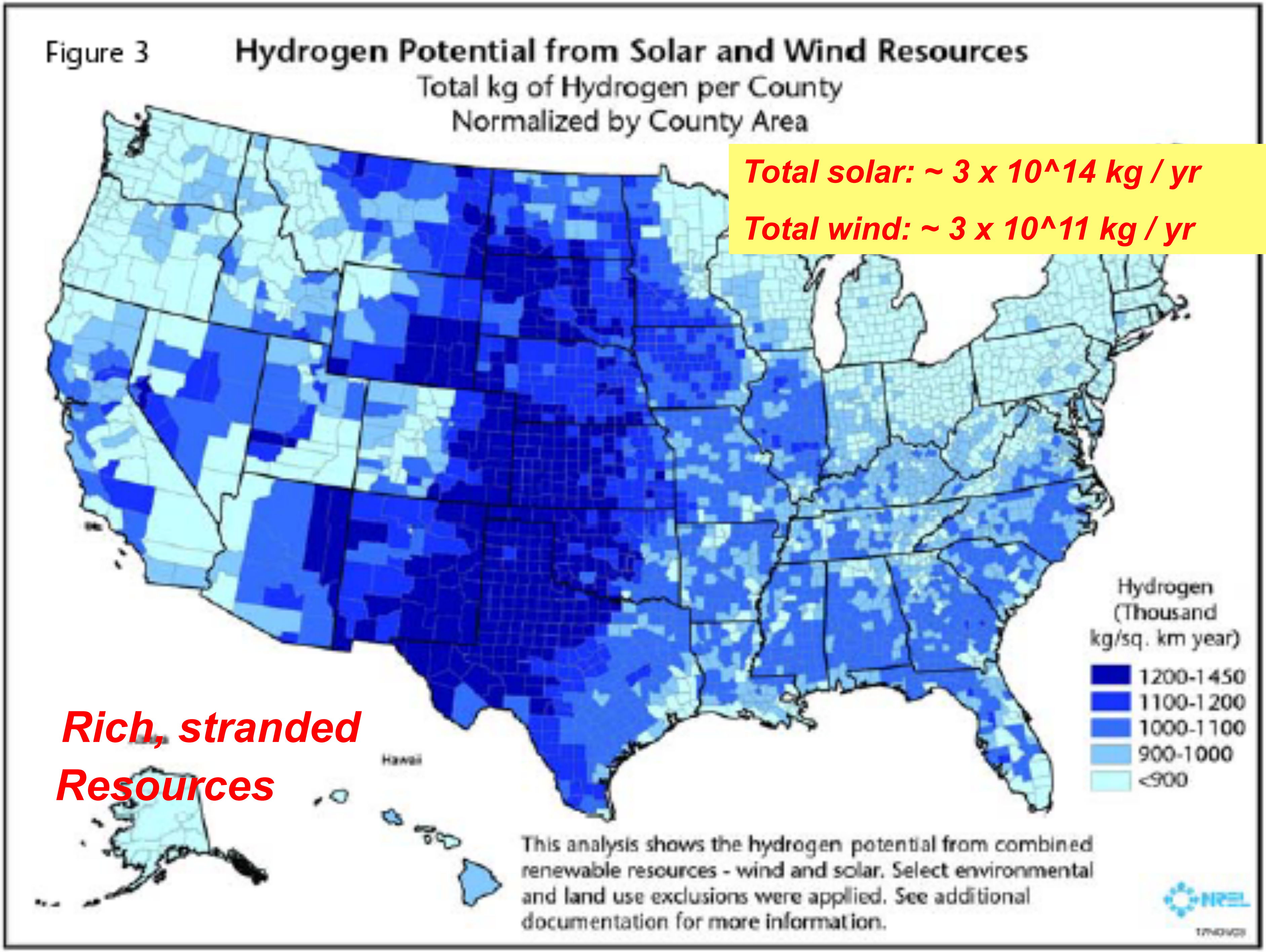
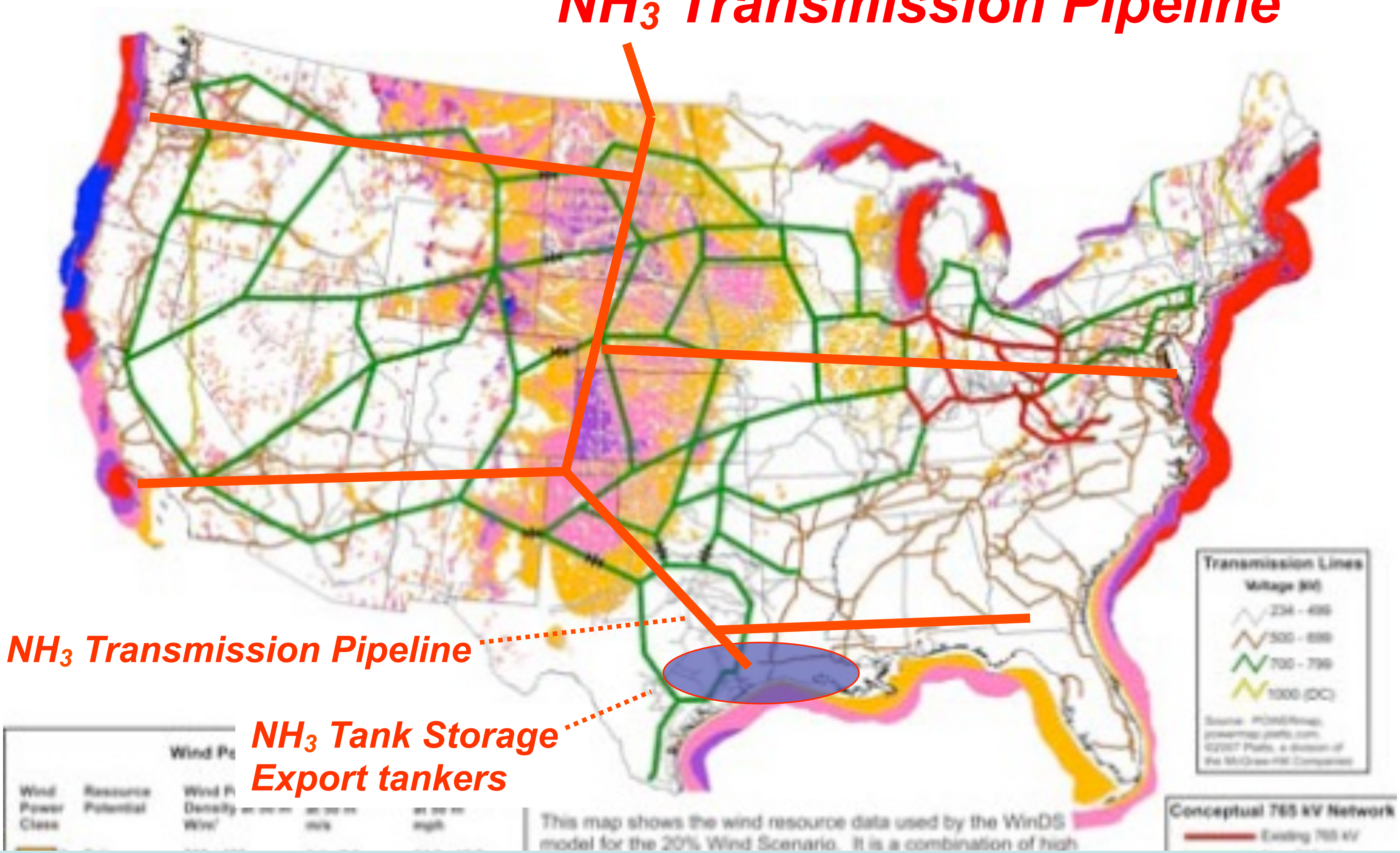


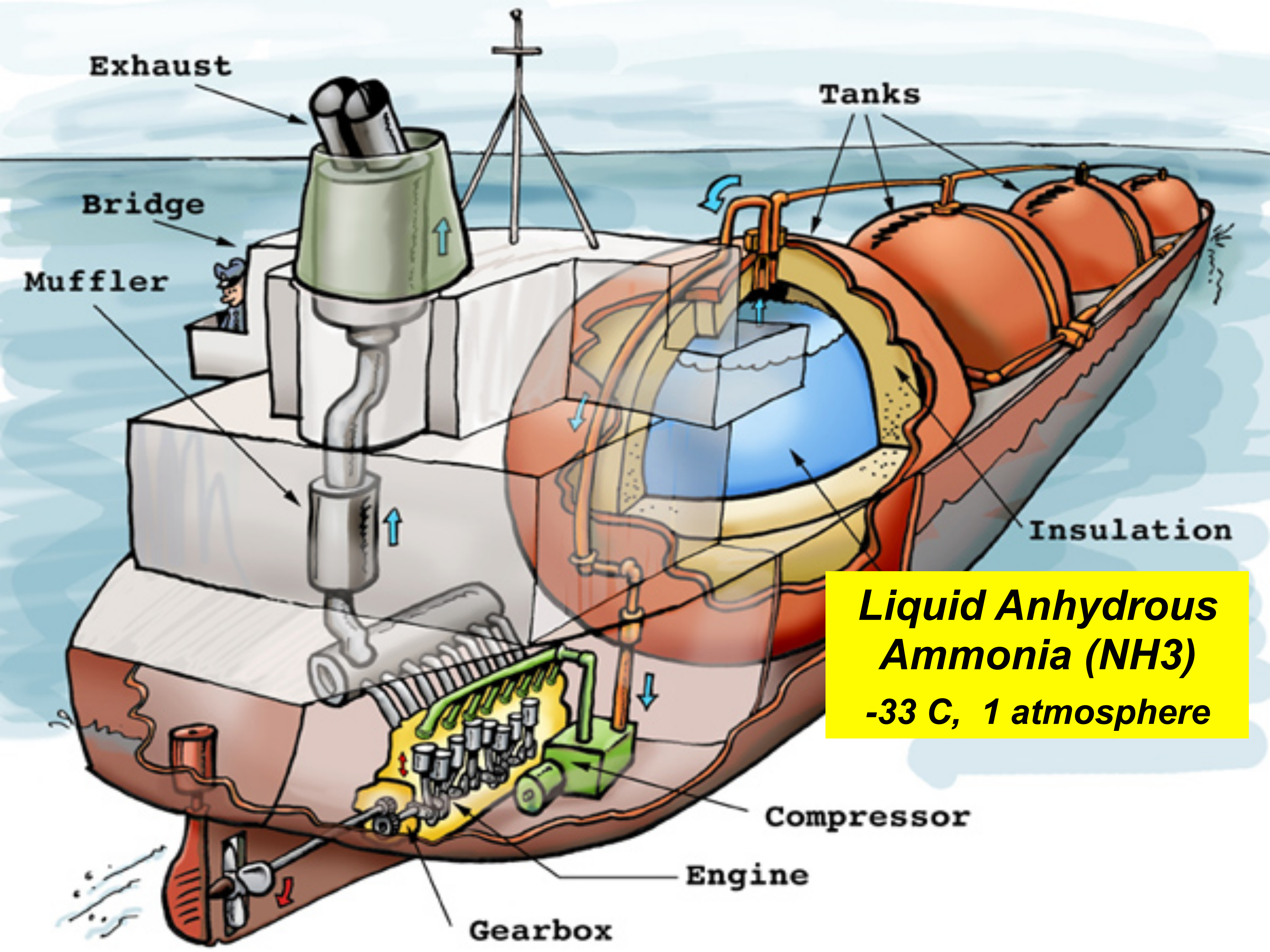
Figure 3
Hydrogen Potential from Solar and Wind Resources
Total kg of Hydrogen per County
Normalized by County Area
Total solar: ~ 3 x 10^14 kg / yr
Total wind: ~ 3 x 10^11 kg / yr
Hydrogen (Thousand kg/sq. km year)
1200-1450
1100-1200
1000-1100
900-1000
<900
Rich, stranded Resources
Hawaii
This analysis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

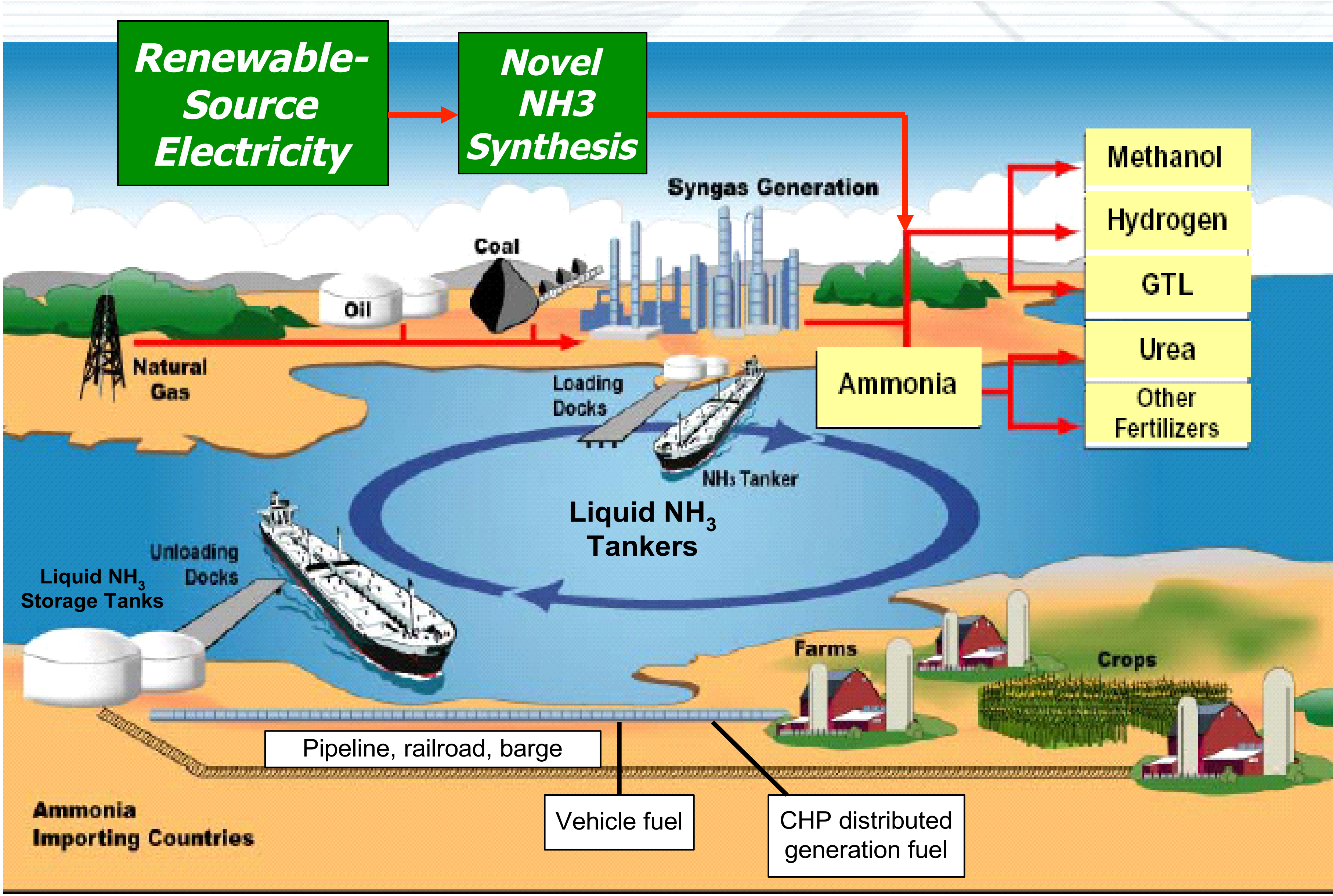
NH_3 Transmission Pipeline



Wind Potential ~ 10,000 GW

12 Great Plains states


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



KBR
Energy and Chemicals

2016

Japan Science and Technology Agency

Strategic Innovation Promotion Program

SIP

2016

Strategic Innovation Promotion Program

SIP

- **Liquid Hydrogen (LH2)**
  Kawasaki
- **Ammonia (NH_3)**
  Sumitomo
- **Organic Hydride (MCH)**
  Chiyoda

Kawasaki LH2 ocean tanker, truck

World Smart Energy Week

Tokyo, 26 Feb 14

Japan
Chiyoda Chemical

CHIYODA CORPORATION

Hydrogen transportation and storage as Methylcyclohexane (MCH) (C_7H_{14})

"Spera": Latin for "hope"

Spera Hydrogen

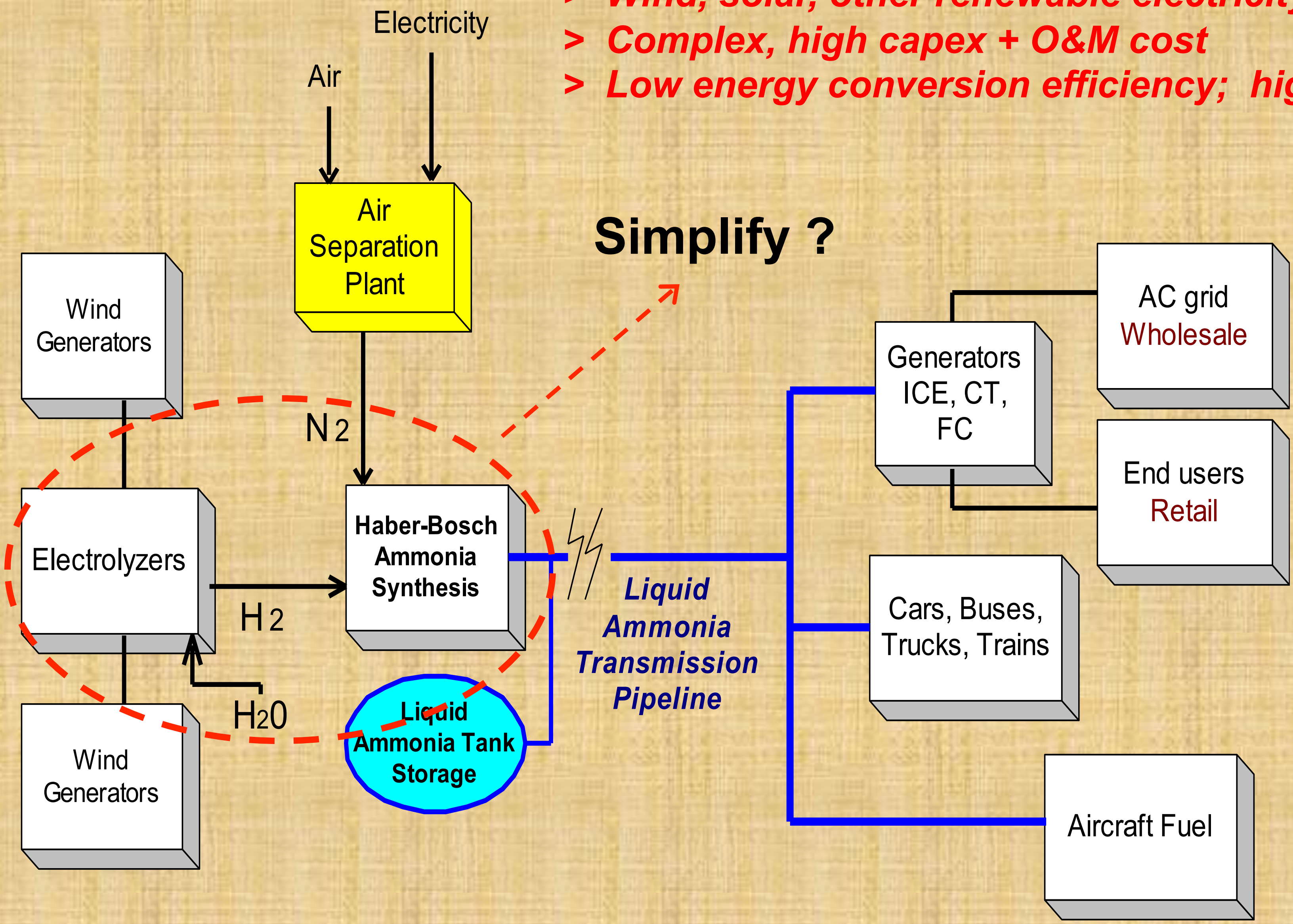
Chiyoda Chemical

Floating Offshore
Deep water, multi - MW

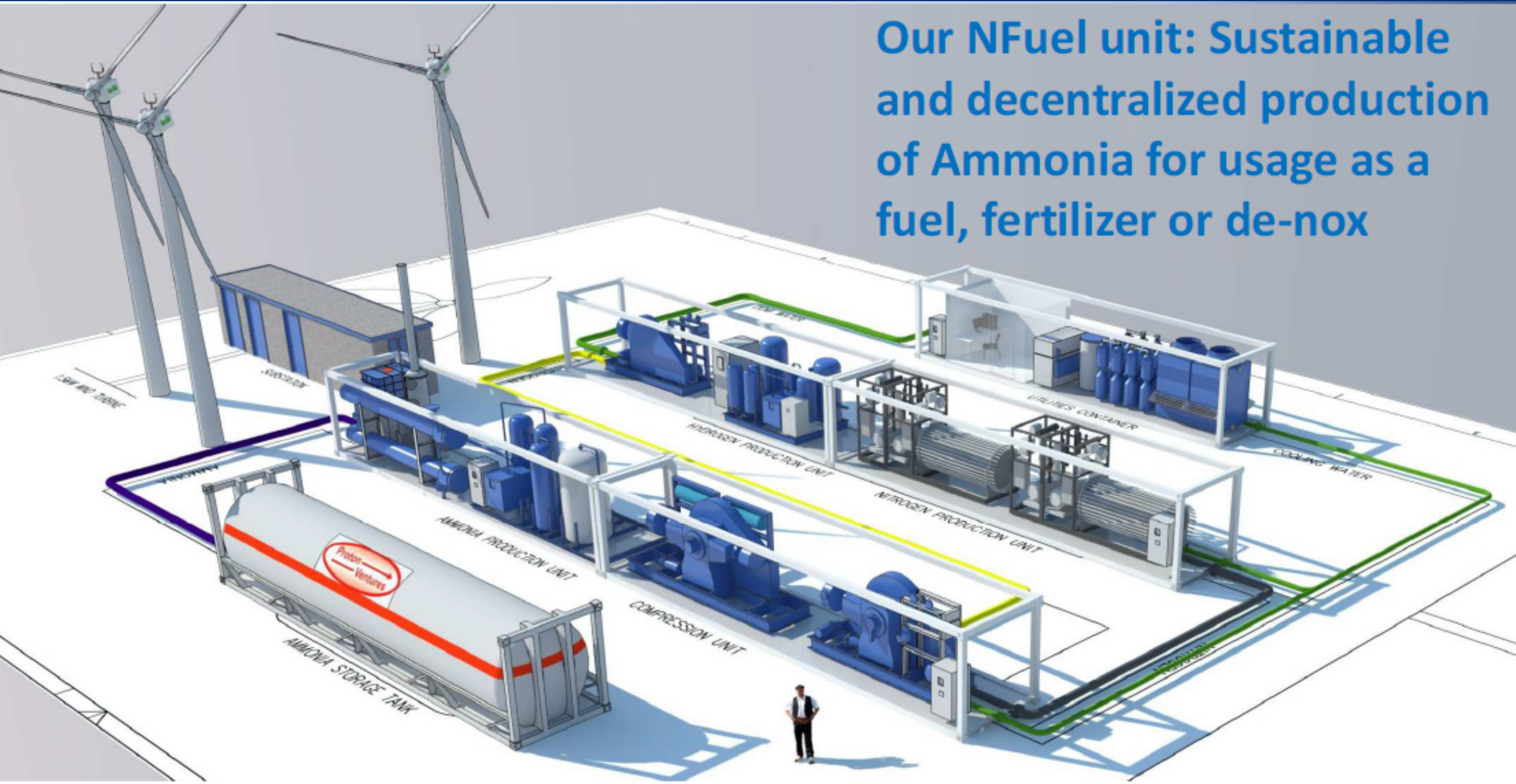
Aleutians wind to Japan via liquid fuel(s) tankers

Now: Electrolysis + Haber – Bosch (EHB)

- **> Wind, solar, other renewable electricity**
- **> Complex, high capex + O&M cost**
- **> Low energy conversion efficiency; high T, P**



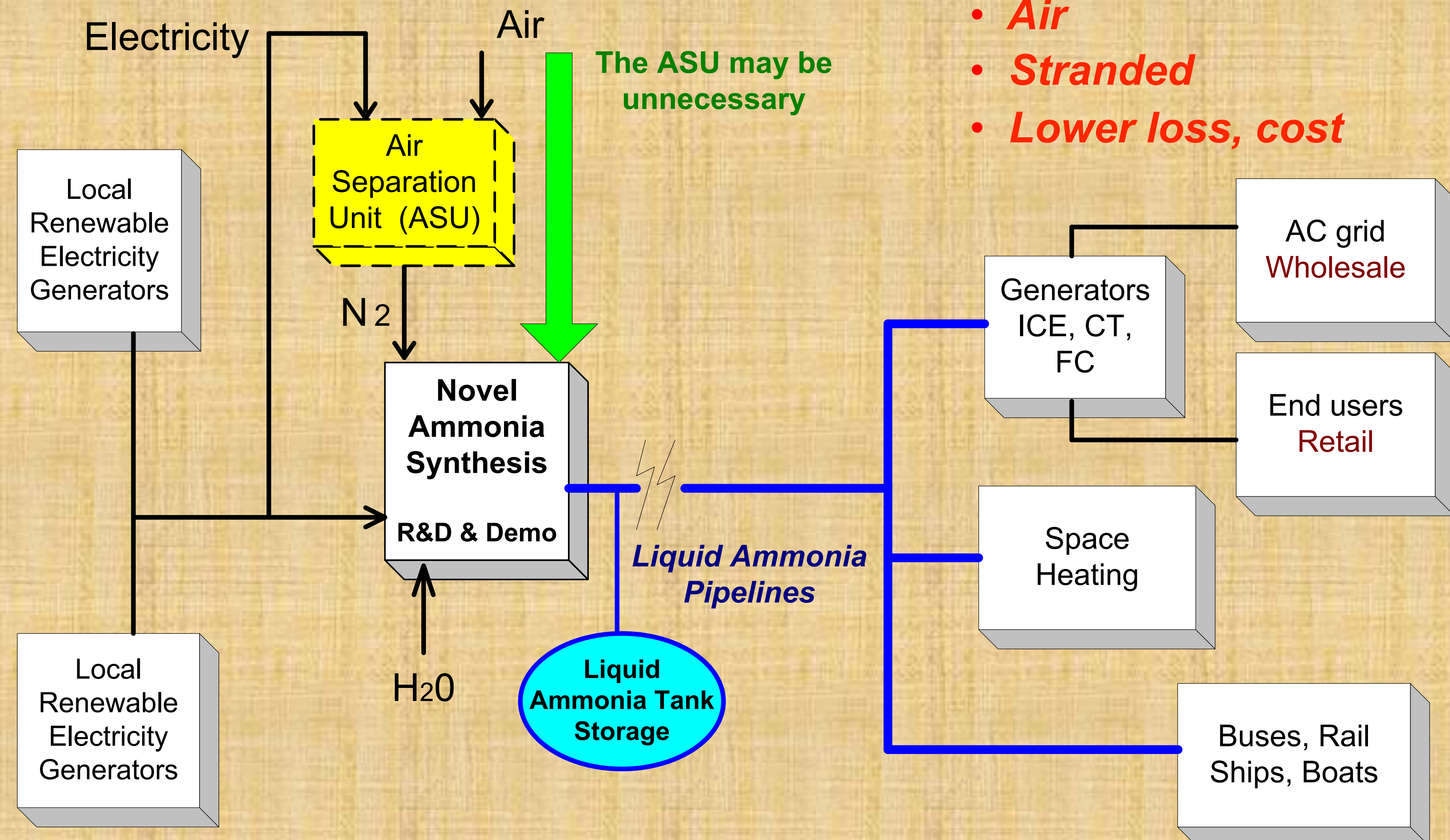
Our NFuel unit: Sustainable and decentralized production of Ammonia for usage as a fuel, fertilizer or de-nox



Proton Ventures BV, Netherlands
www.protonventures.com

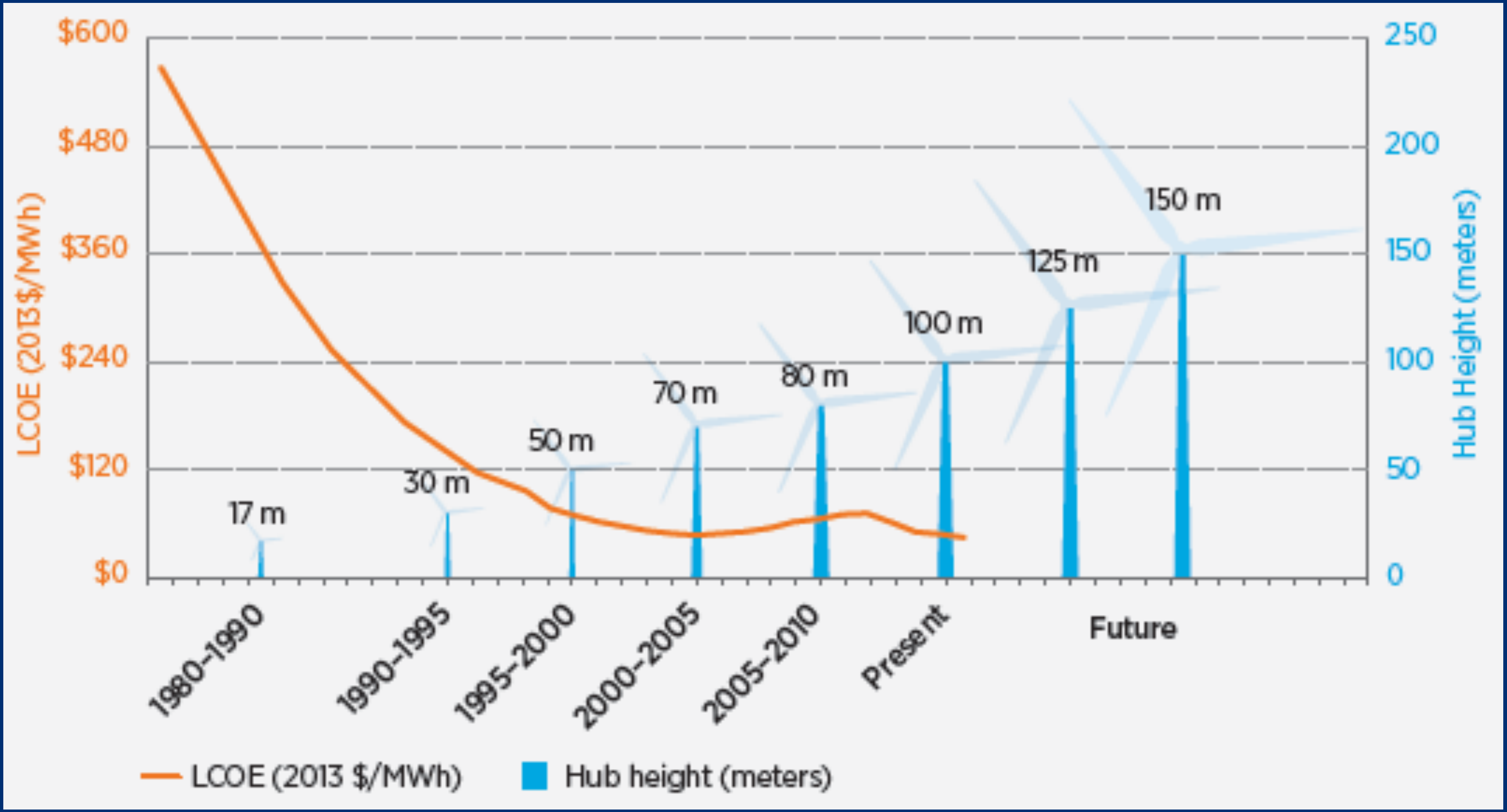
Novel Ammonia Synthesis

- ***Electricity***
- ***Water***
- ***Air***
- ***Stranded***
- ***Lower loss, cost***



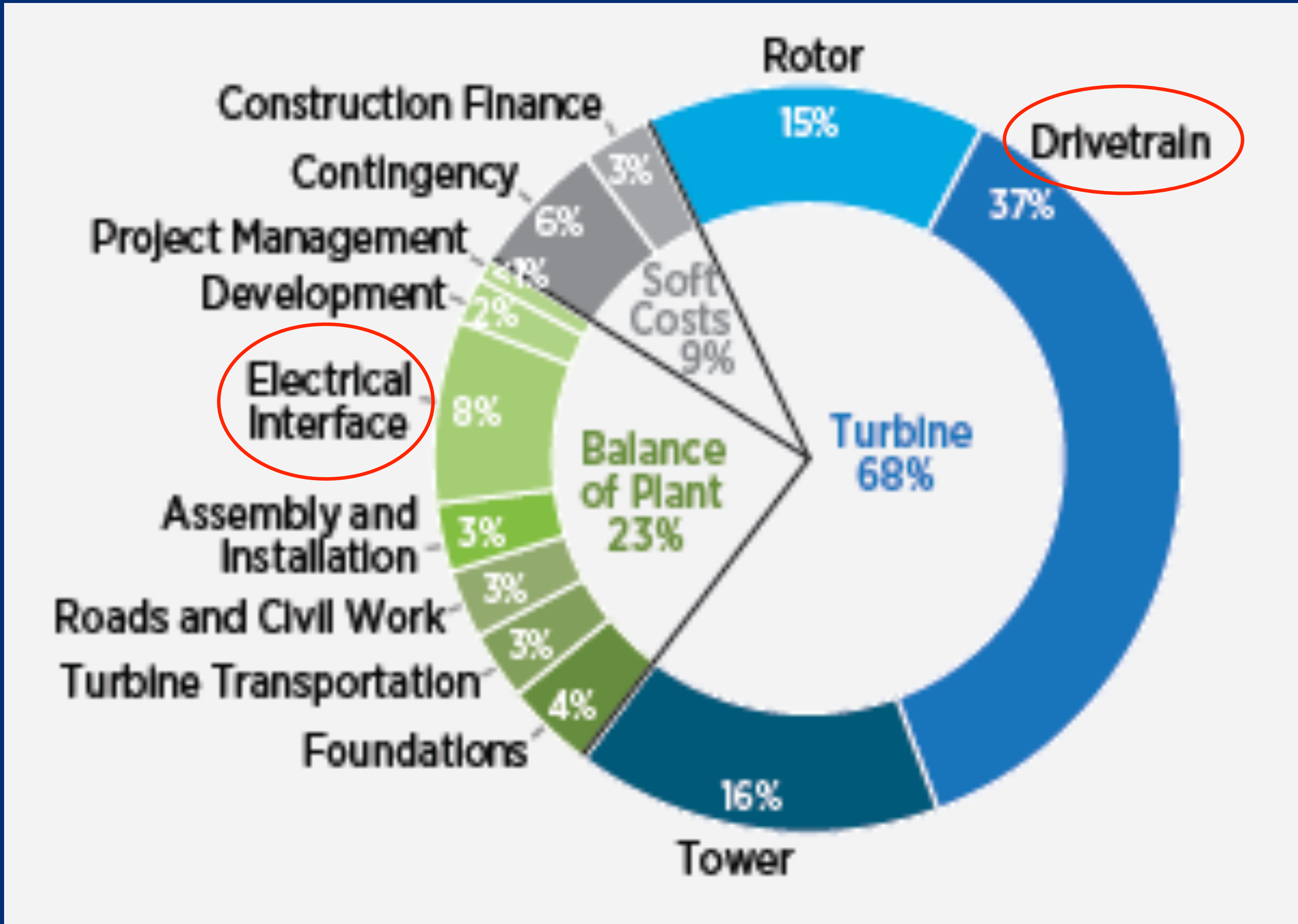
USDOE ARPA-E "REFUEL" R&D

- > Eliminate electrolyzer and Haber-Bosch reactor
- > NH3 synthesis directly from electricity, water, air
- > Lower capex + O&M costs, higher efficiency
- > Four USDOE-funded projects
- > KIER, WA State Univ

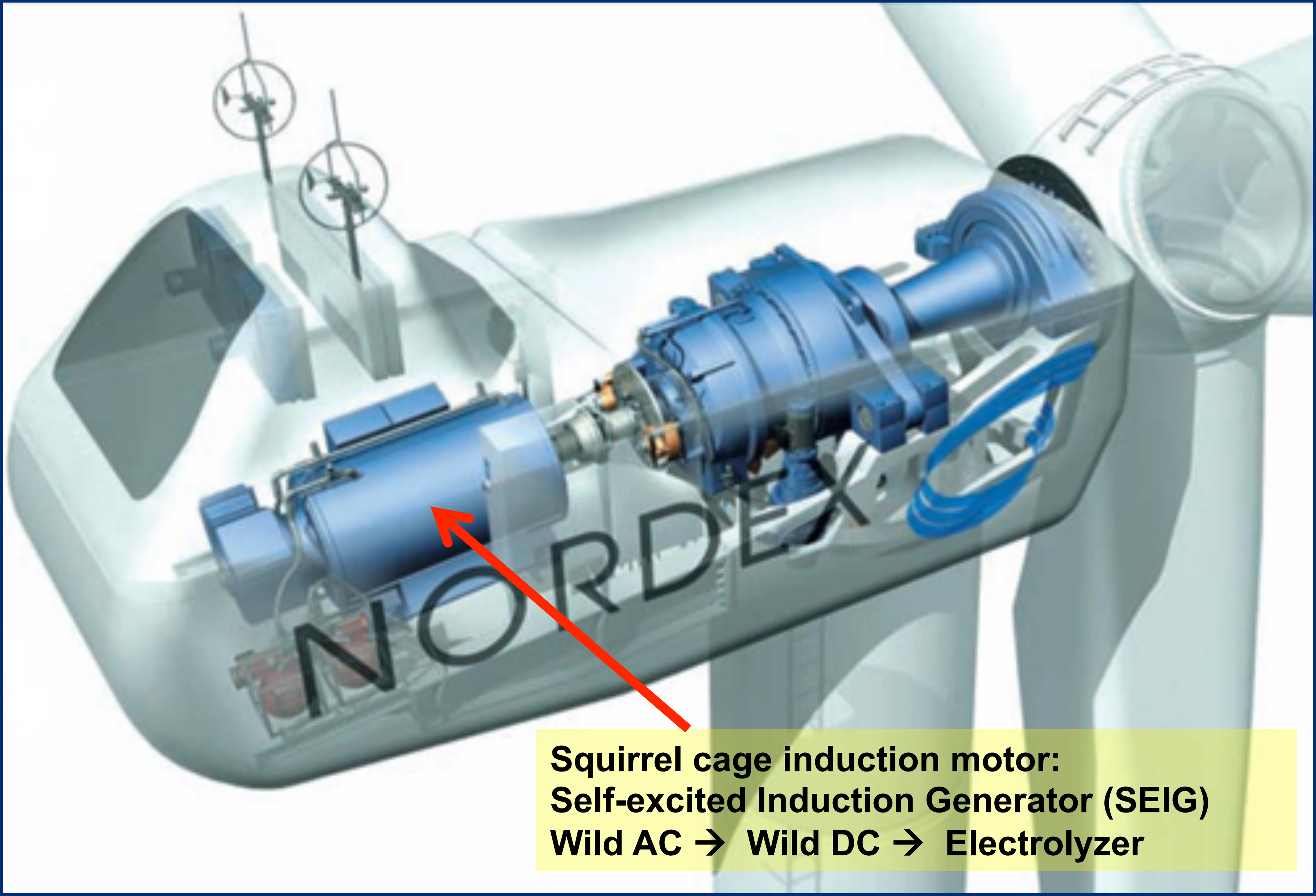


Wind LCOE reduction

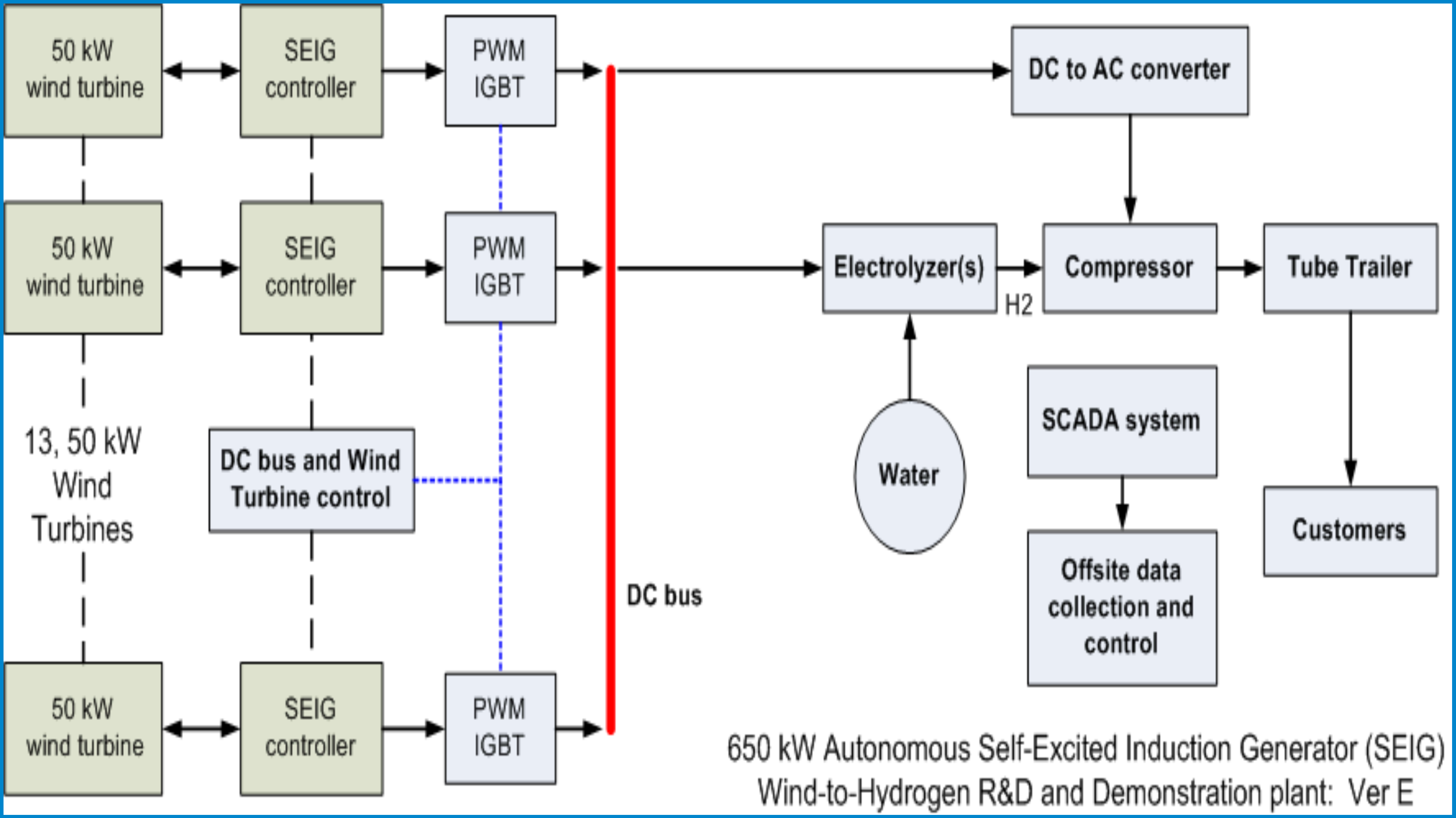
“ Wind Vision ” Executive Summary



Installed CAPEX: land-based, utility-scale

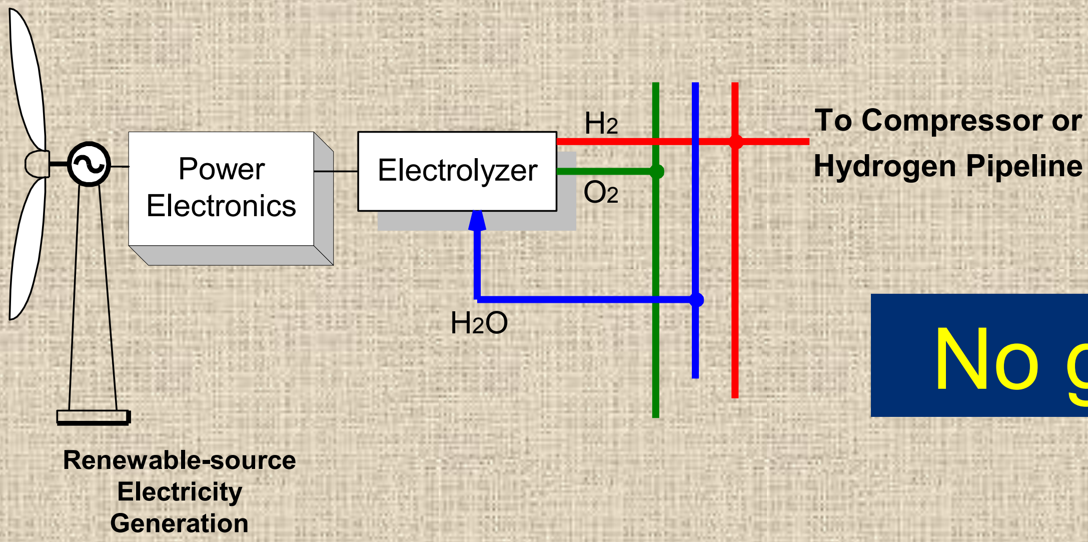


Dedicated Hydrogen Production: No Grid Connection

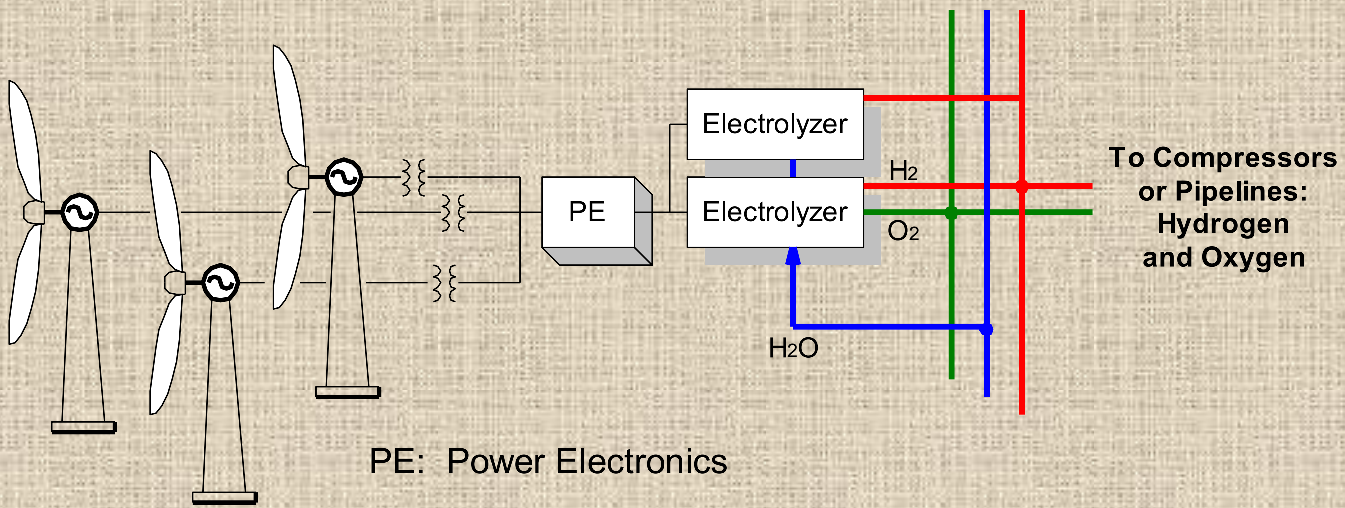


Self-Excited Induction Generator (SEIG)
Reduce Hydrogen cost
ARPA-E, SBV, CRADA apps: NREL, et al, 2015

ABB ACS800 low voltage wind turbine converter

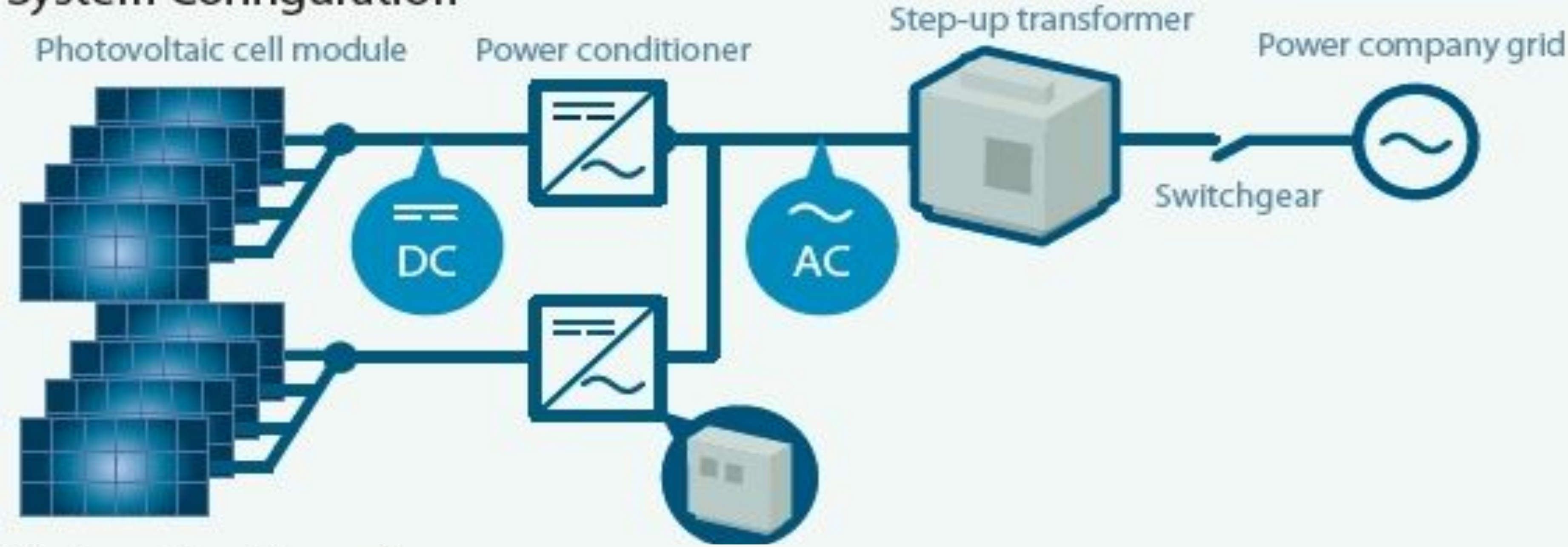


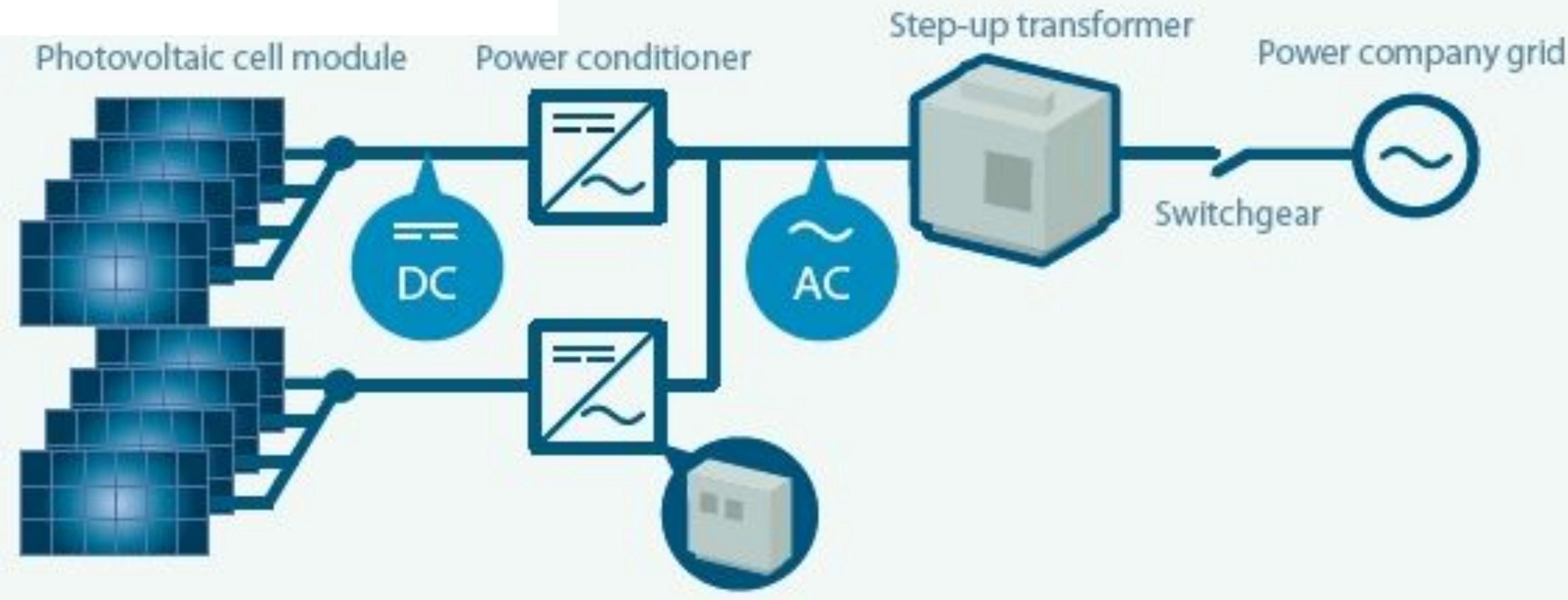
No grid connection



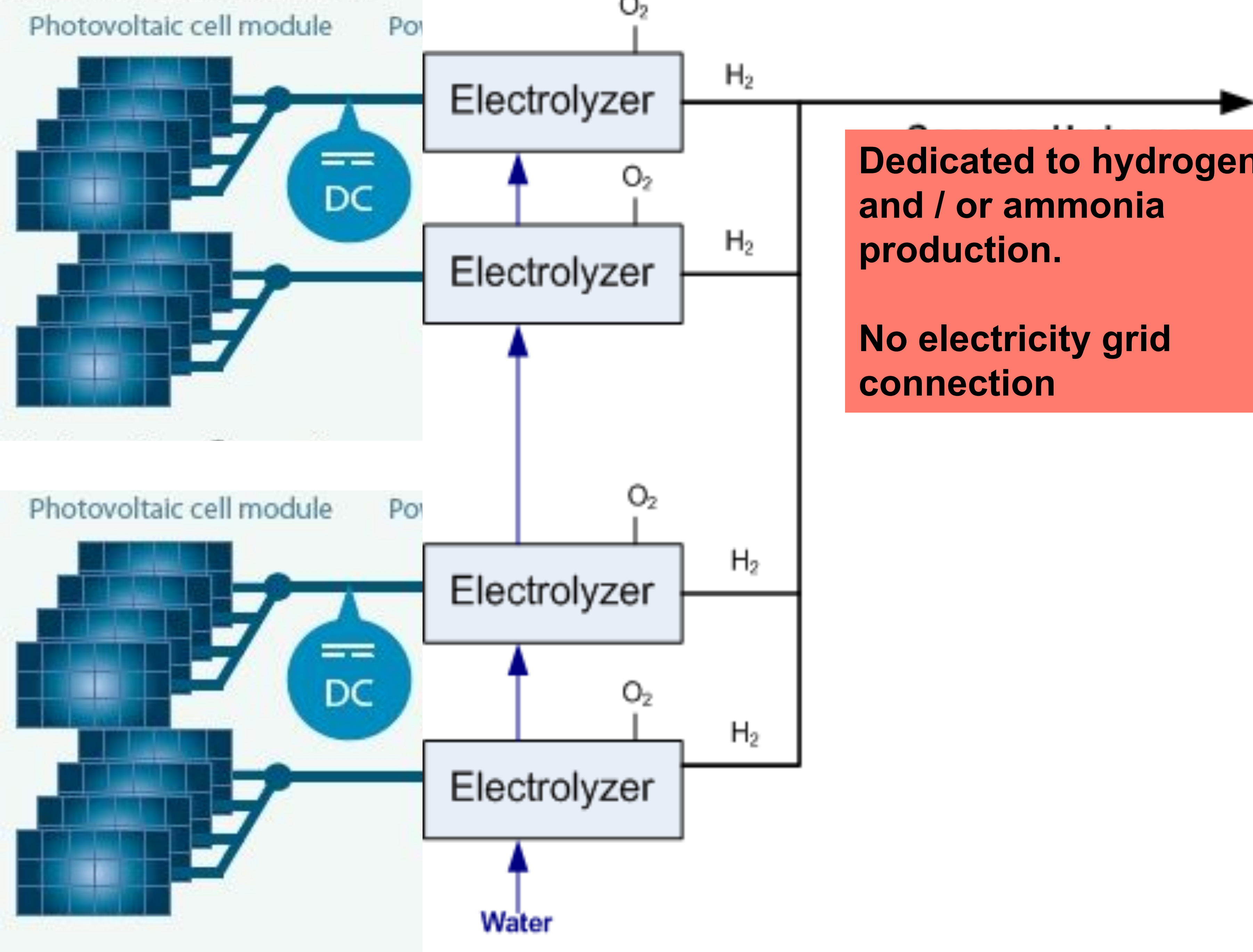
Topology Options: H_2 and O_2 Production and Gathering from Renewable Energy Generation

System Configuration



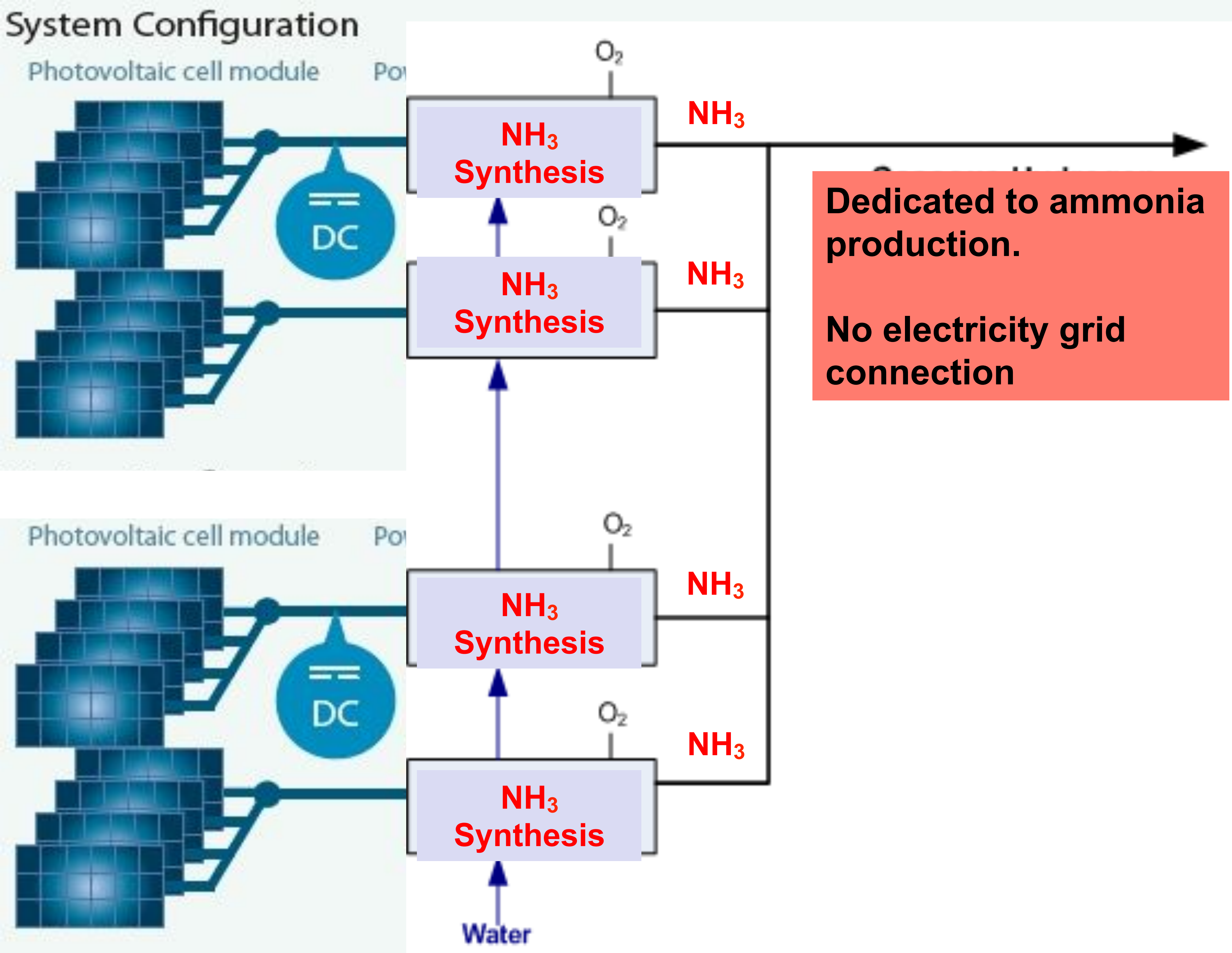


System Configuration



Dedicated to hydrogen and / or ammonia production.

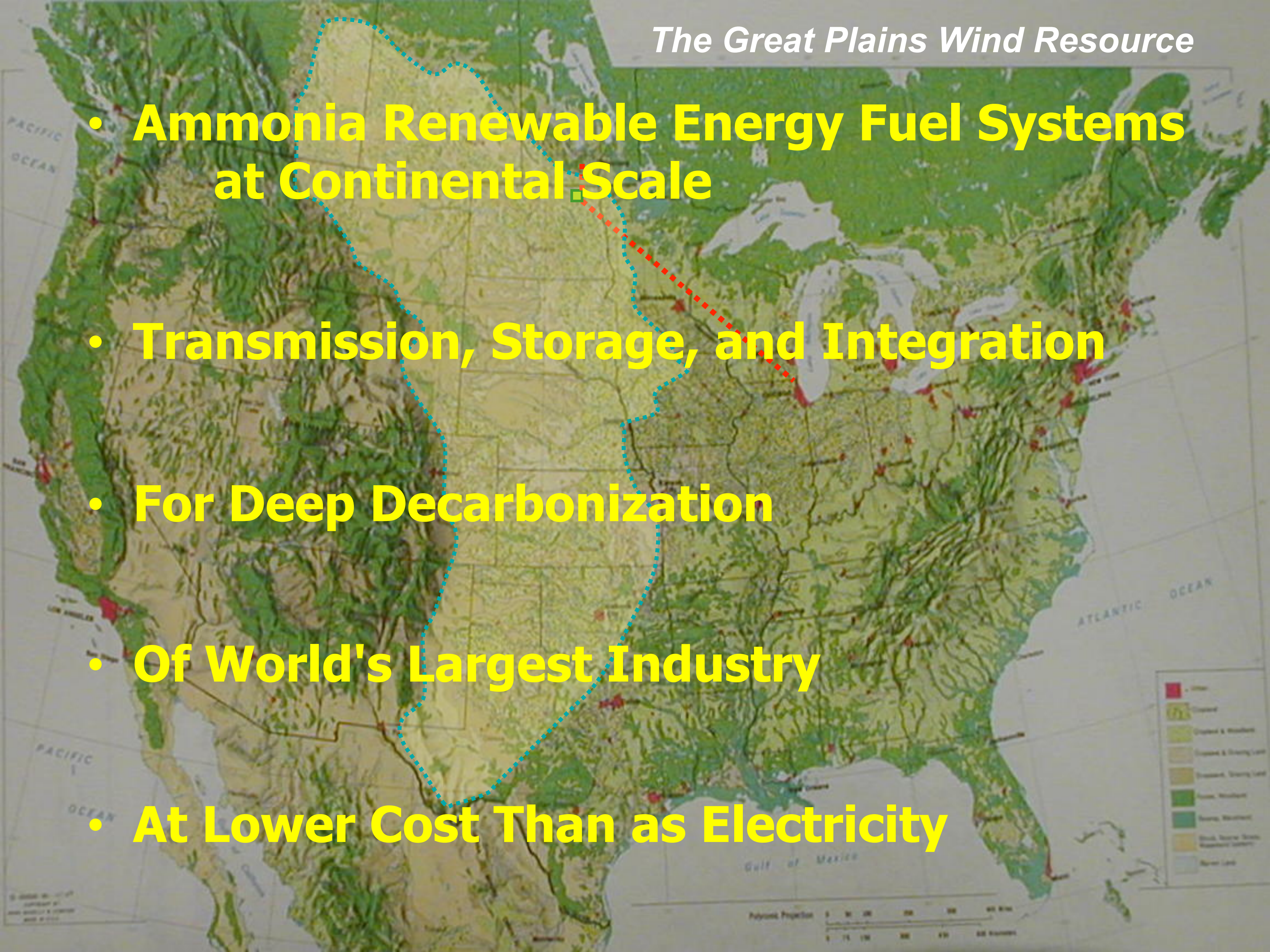
No electricity grid connection



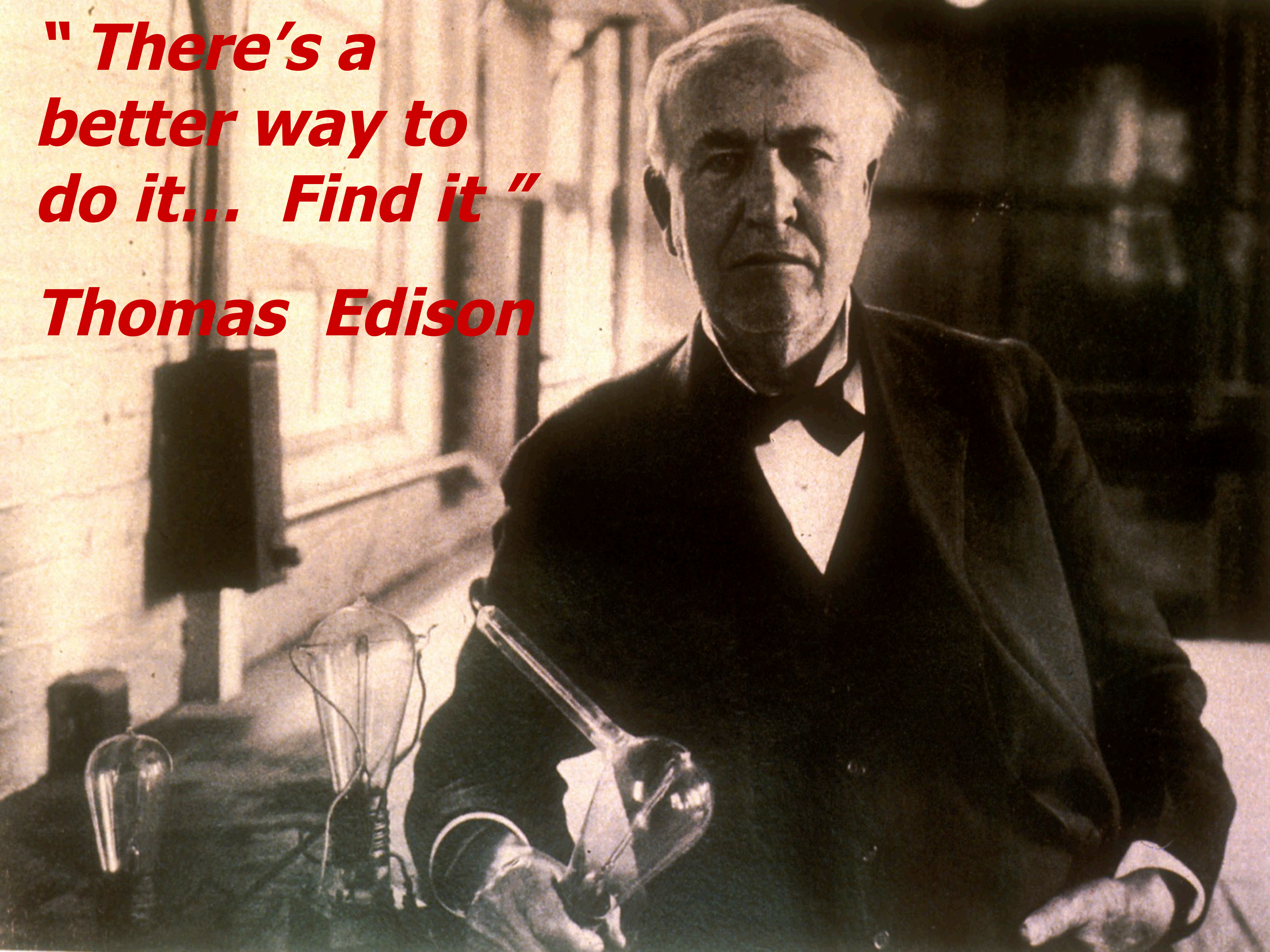
Dedicated to ammonia production.

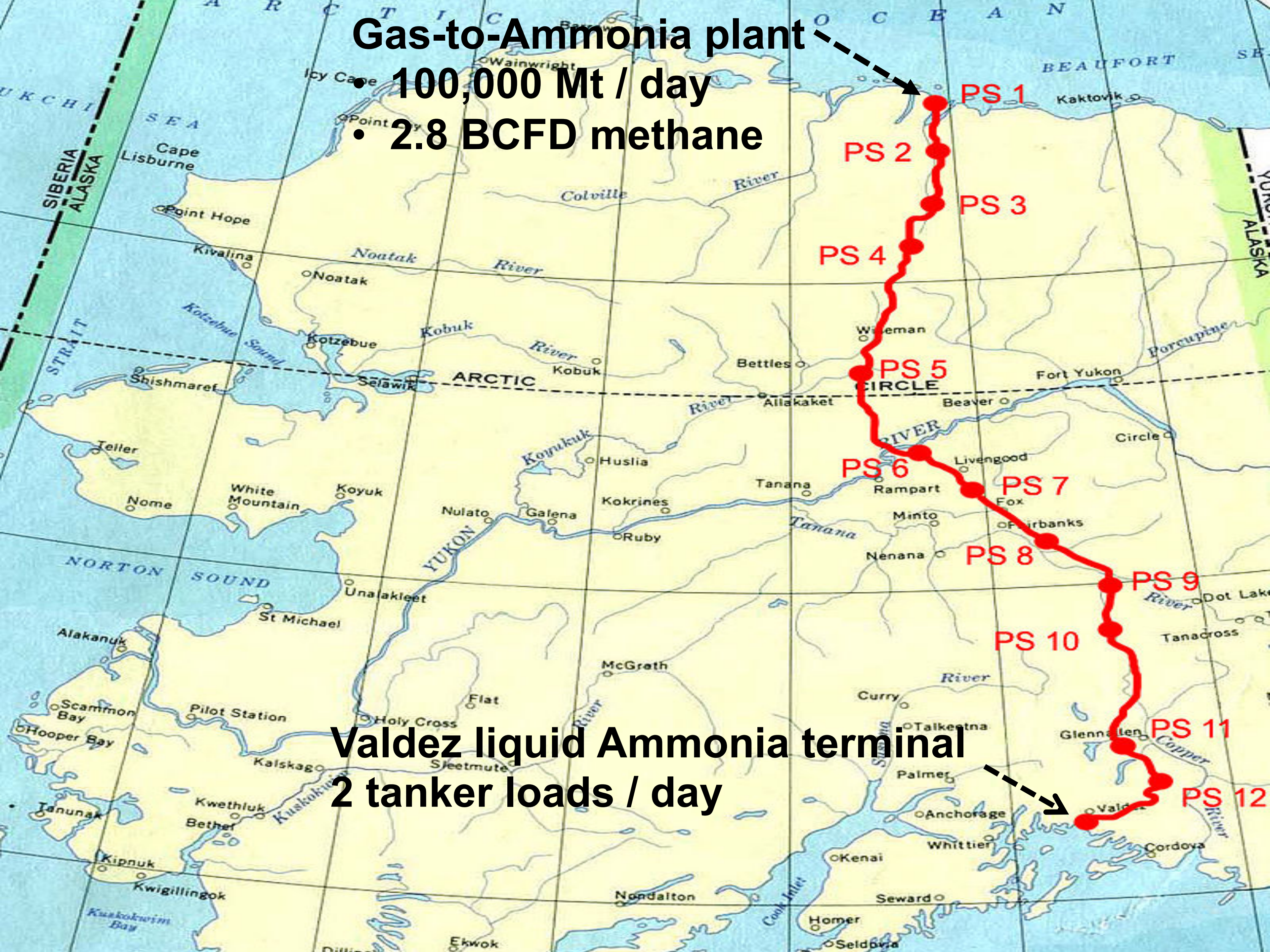
No electricity grid connection

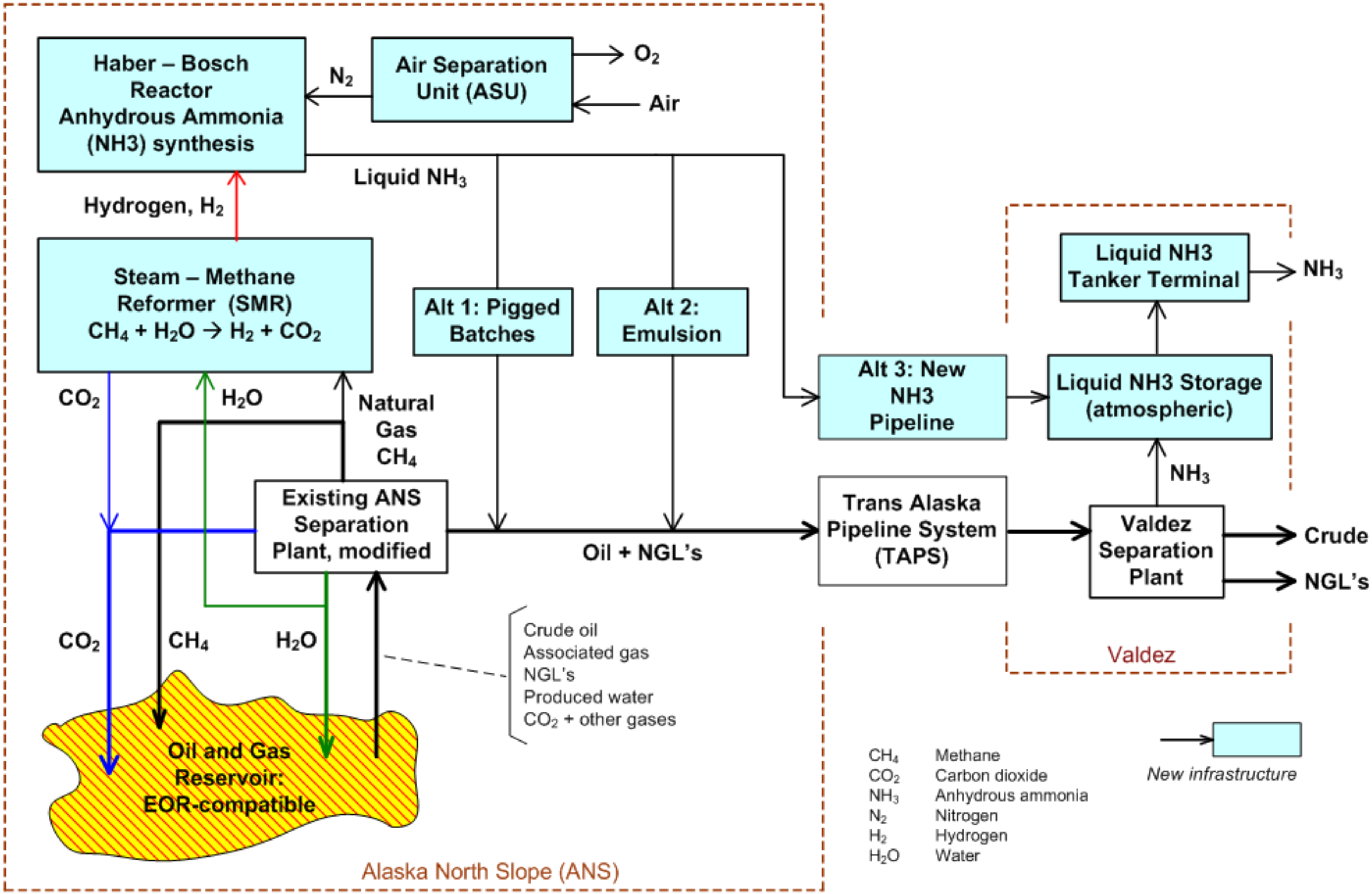
The Great Plains Wind Resource



- **Ammonia Renewable Energy Fuel Systems at Continental Scale**
- **Transmission, Storage, and Integration**
- **For Deep Decarbonization**
- **Of World's Largest Industry**
- **At Lower Cost Than as Electricity**


" There's a better way to do it... Find it "
Thomas Edison


Gas-to-Ammonia plant
• 100,000 Mt / day
• 2.8 BCFD methane
PS 1
PS 2
PS 3
PS 4
PS 5
PS 6
PS 7
PS 8
PS 9
PS 10
PS 11
PS 12
Valdez liquid Ammonia terminal
2 tanker loads / day
BEAUFORT
Kaktovik
Wainwright
Icy Cape
Point Lay
Cape Lisburne
Point Hope
Kivalina
Noatak
Colville River
Noatak River
Kotzebue Sound
Kotzebue
Kobuk River
Kobuk
Selawik
Shishmaref
ARCTIC CIRCLE
Bettles
Allakaket
Fort Yukon
Porcupine
Beaver
Circle
Livengood
Rampart
Tanana
Huslia
Koyukuk
Fox
Minto
Nenana
Kokrines
Galena
Nulato
Ruby
Koyuk
White Mountain
Nome
Teller
NORTON SOUND
Unalakleet
St Michael
Alakanuk
YUKON
Tanana
Dot Lake
Tanacross
McGrath
Curry
Talkeetna
Flat
Holy Cross
Pilot Station
Scammon Bay
Hooper Bay
Kalskag
Sleetmute
Palmer
Anchorage
Kwethluk
Bethel
Tanunak
Kipnuk
Kwigillingok
Kuskokwim Bay
Kenai
Whittier
Cordova
Seward
Nondalton
Cook Inlet
Homer
Seldovia
Ekwok
Glennallen
Copper River
SIBERIA
ALASKA
STRAIT



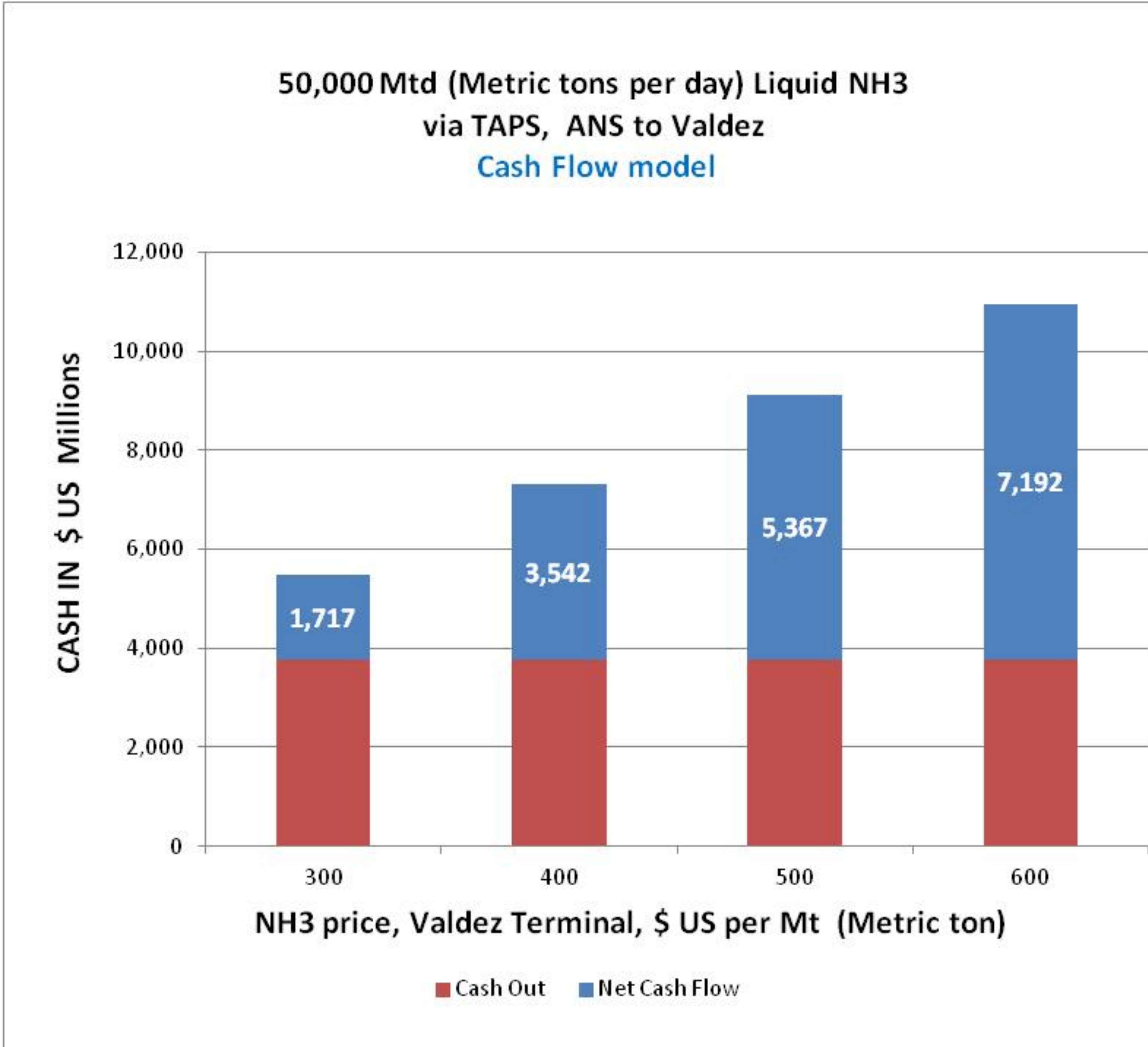
Haber – Bosch Reactor Anhydrous Ammonia (NH3) synthesis
N_2
Air Separation Unit (ASU)
O_2
Air
Liquid NH_3
Hydrogen, H_2
Steam – Methane Reformer (SMR) $CH_4 + H_2O \rightarrow H_2 + CO_2$
Alt 1: Pigged Batches
Alt 2: Emulsion
Alt 3: New NH3 Pipeline
Liquid NH3 Tanker Terminal
NH_3
Liquid NH3 Storage (atmospheric)
CO_2
H_2O
Natural Gas CH_4
NH_3
Existing ANS Separation Plant, modified
Oil + NGL's
Trans Alaska Pipeline System (TAPS)
Valdez Separation Plant
Crude
NGL's
CO_2
CH_4
H_2O
Crude oil
Associated gas
NGL's
Produced water
CO_2 + other gases
Valdez
Oil and Gas Reservoir: EOR-compatible
CH_4 Methane
CO_2 Carbon dioxide
NH_3 Anhydrous ammonia
N_2 Nitrogen
H_2 Hydrogen
H_2O Water
New infrastructure
Alaska North Slope (ANS)

Fundamentals - A

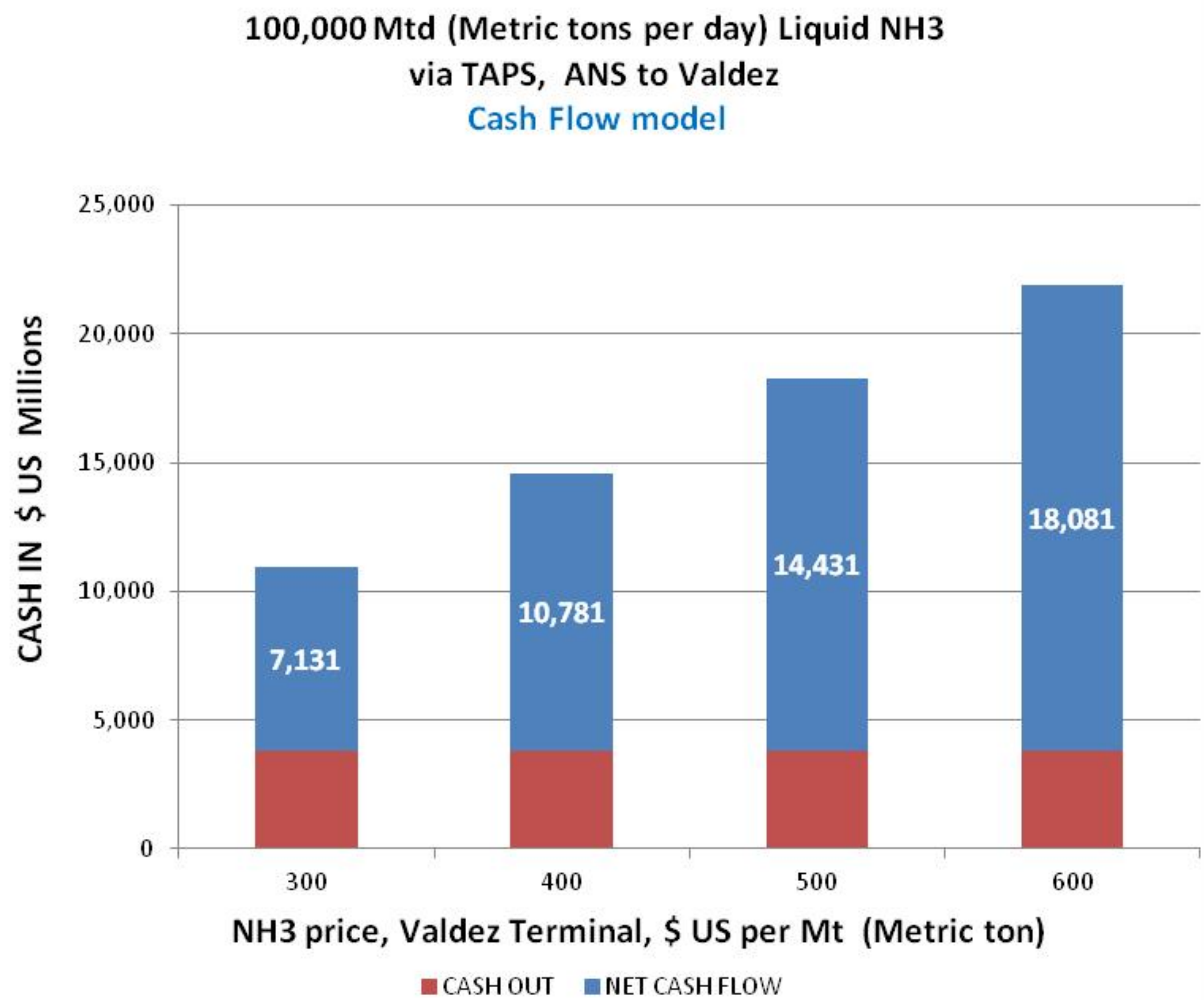
1. Convert natural gas (NG) (methane, CH_4) to liquid anhydrous ammonia (NH_3) at ANS
2. Capture all byproduct CO_2; inject for EOR at ANS
3. Transport liquid NH_3 to new Valdez Terminal via:
   a. TAPS: Emulsion with crude oil: phase separation at Valdez
   b. TAPS: Pigged batches
   c. TAPS: Annular flow NH_3, core flow crude
   d. New NH_3 pipeline paralleling TAPS
4. Ship CO_2-emissions-free “green” NH_3
   a. From new Valdez NH_3 tanker terminal
   b. 100,000 Mtd (metric tons per day) = 2 tankers per day
   c. Japan is apparent first market: is ANS gas-to-NH_3 with CCS for EOR “green” ?
   d. Requires doubling world tanker fleet

Trans Alaska Pipeline System

Valdez oil terminal



50,000 Mtd (Metric tons per day) Liquid NH3
via TAPS, ANS to Valdez
Cash Flow model
12,000
10,000
8,000
6,000
4,000
2,000
0
CASH IN $ US Millions
1,717
3,542
5,367
7,192
300
400
500
600
NH3 price, Valdez Terminal, $ US per Mt (Metric ton)
Cash Out
Net Cash Flow



100,000 Mtd =

36 MMtpa =

36 million Mt per year

= 25% world production

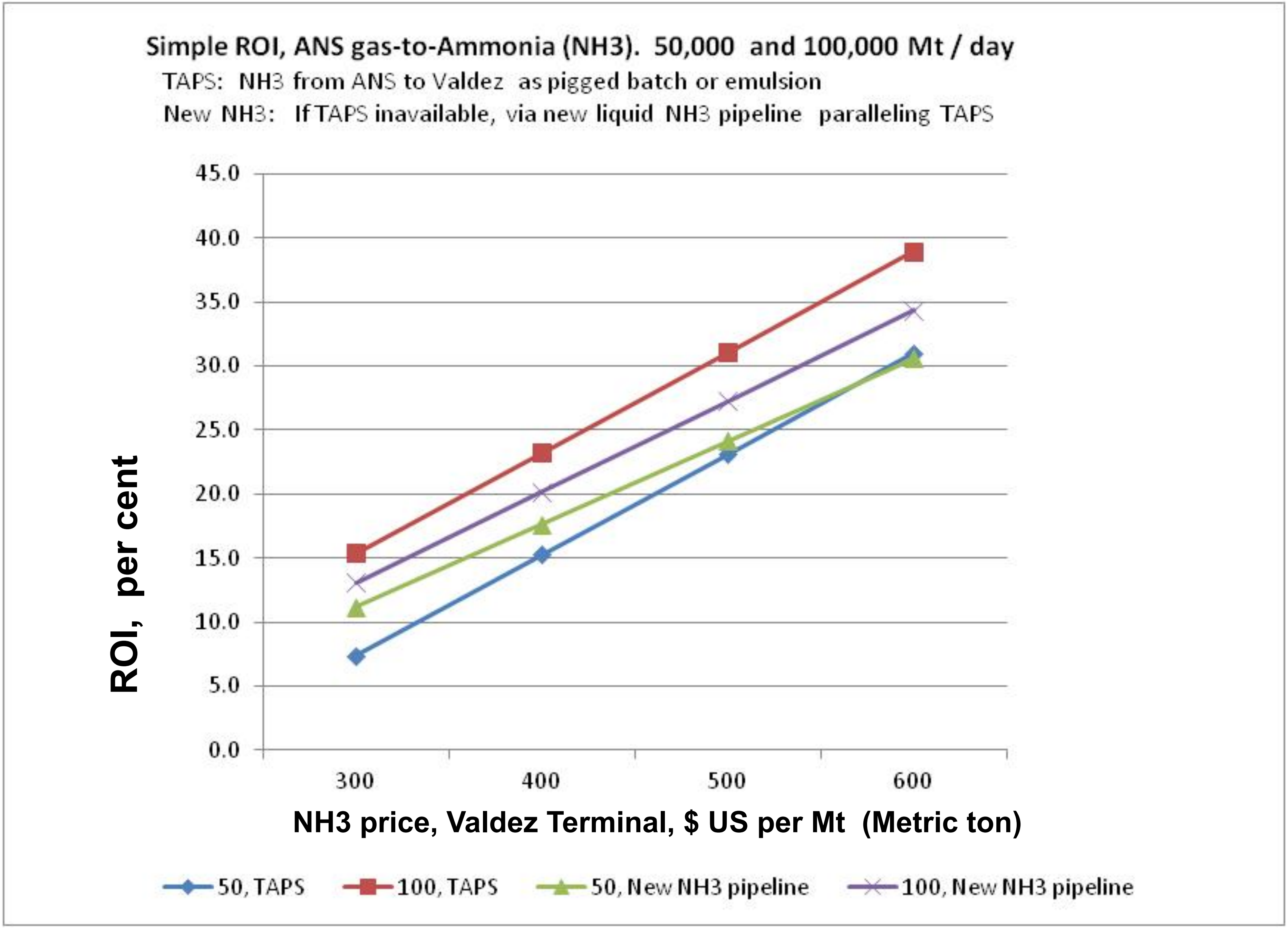
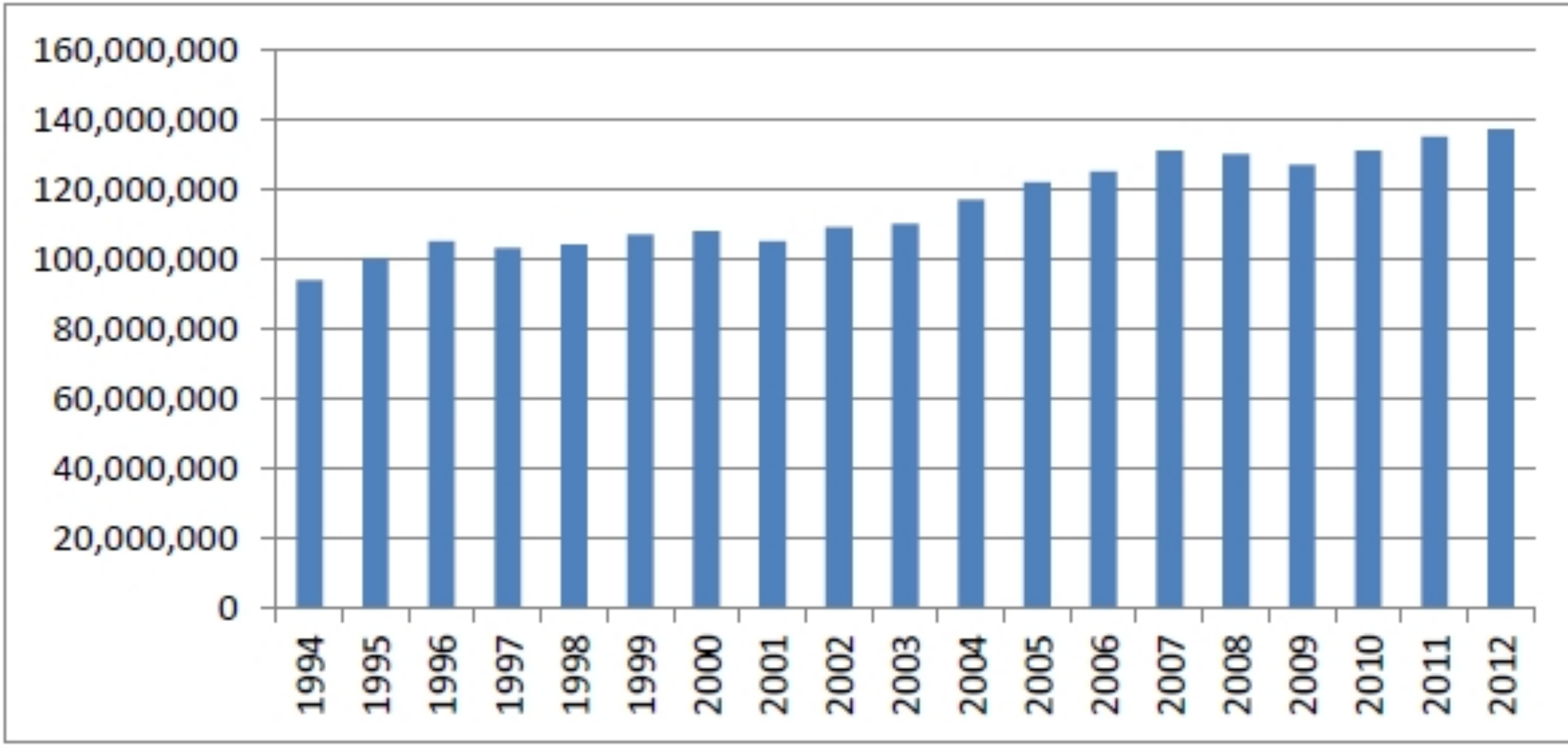
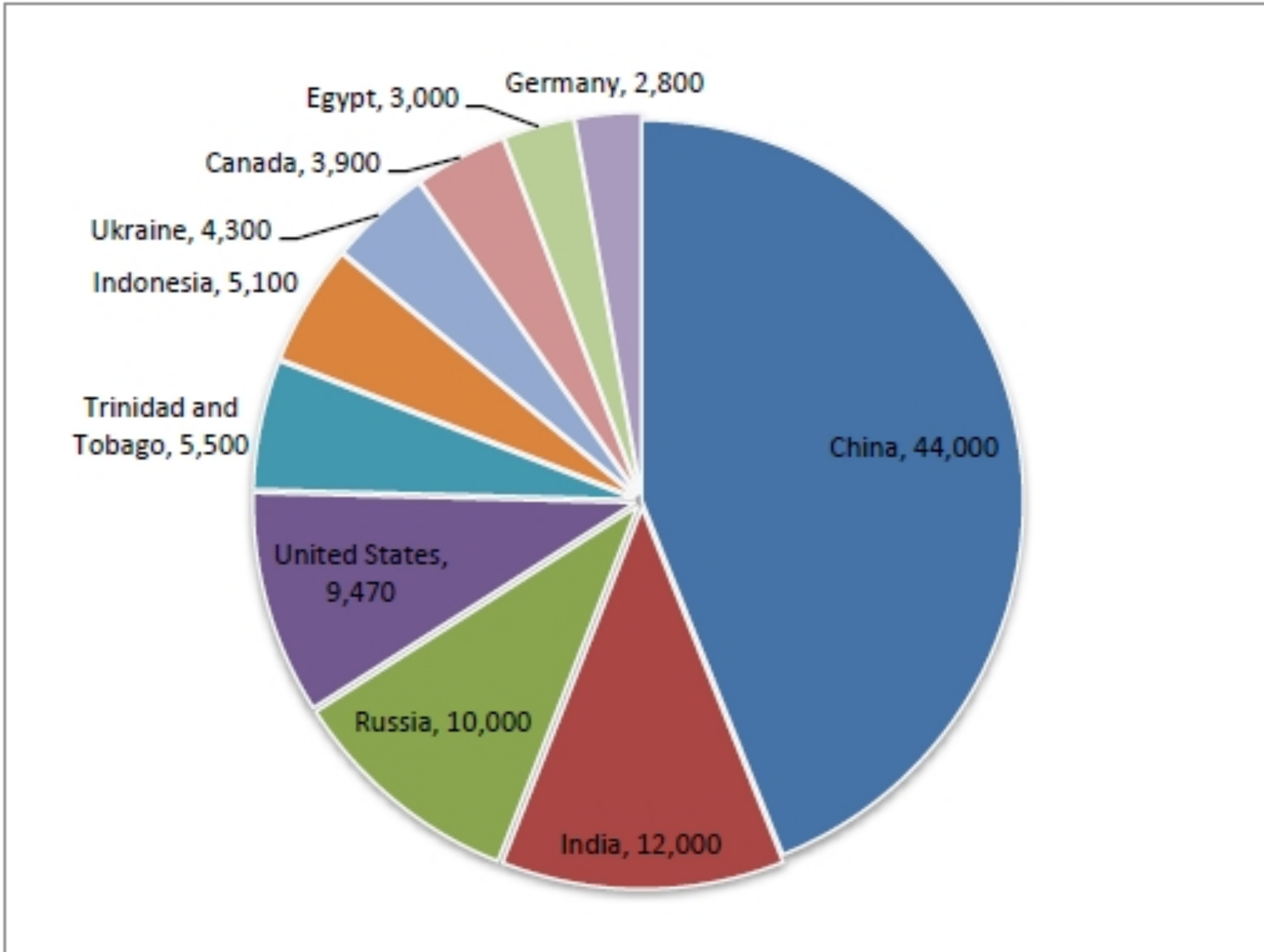

Simple ROI, ANS gas-to-Ammonia (NH3). 50,000 and 100,000 Mt / day
TAPS: NH3 from ANS to Valdez as pigged batch or emulsion
New NH3: If TAPS inavailable, via new liquid NH3 pipeline paralleling TAPS
ROI, per cent
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
300
400
500
600
NH3 price, Valdez Terminal, $ US per Mt (Metric ton)
50, TAPS
100, TAPS
50, New NH3 pipeline
100, New NH3 pipeline

Figure 1. Global ammonia production (tonnes)

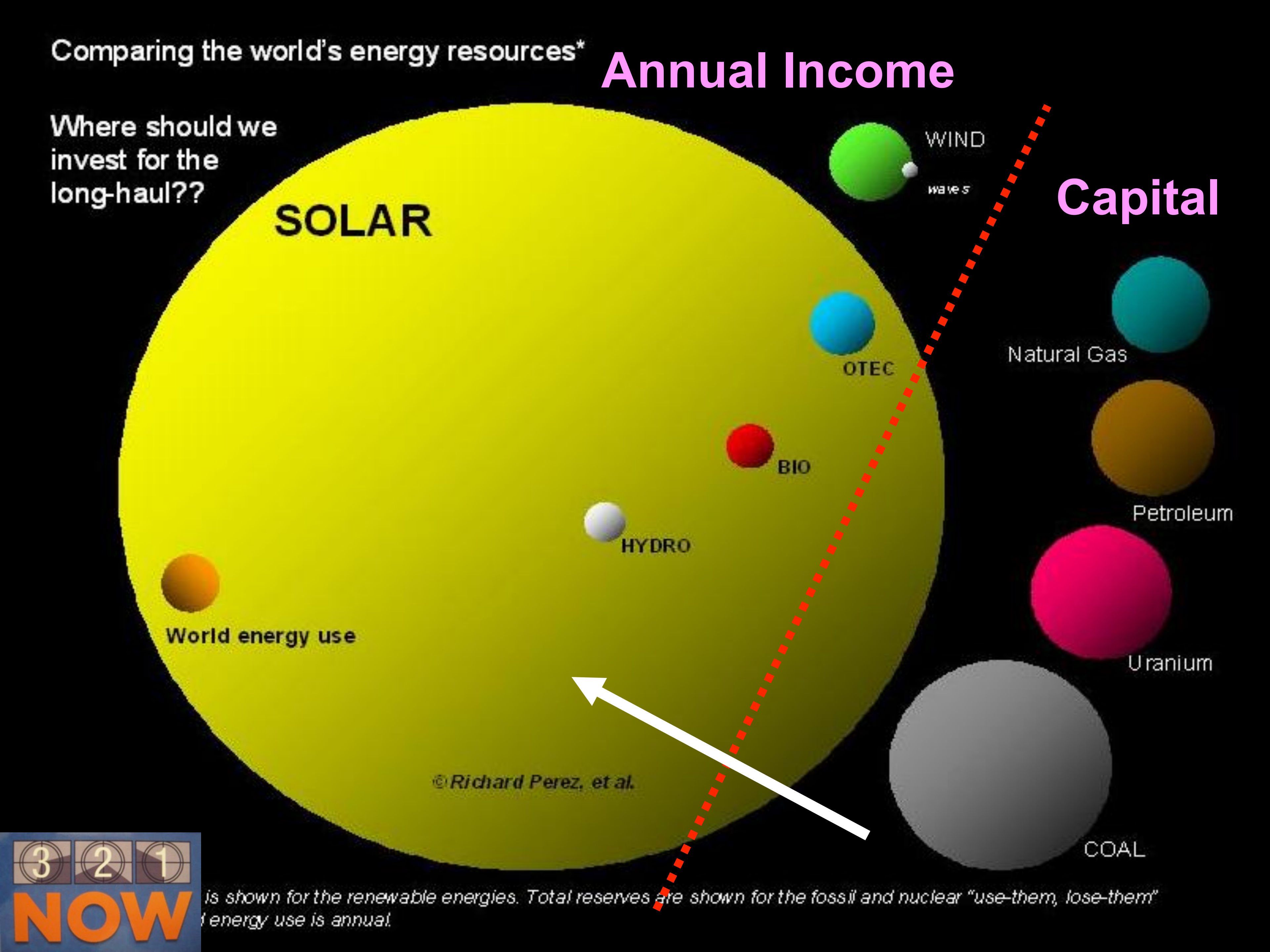


Source: Authors' elaboration on USGS (2013).

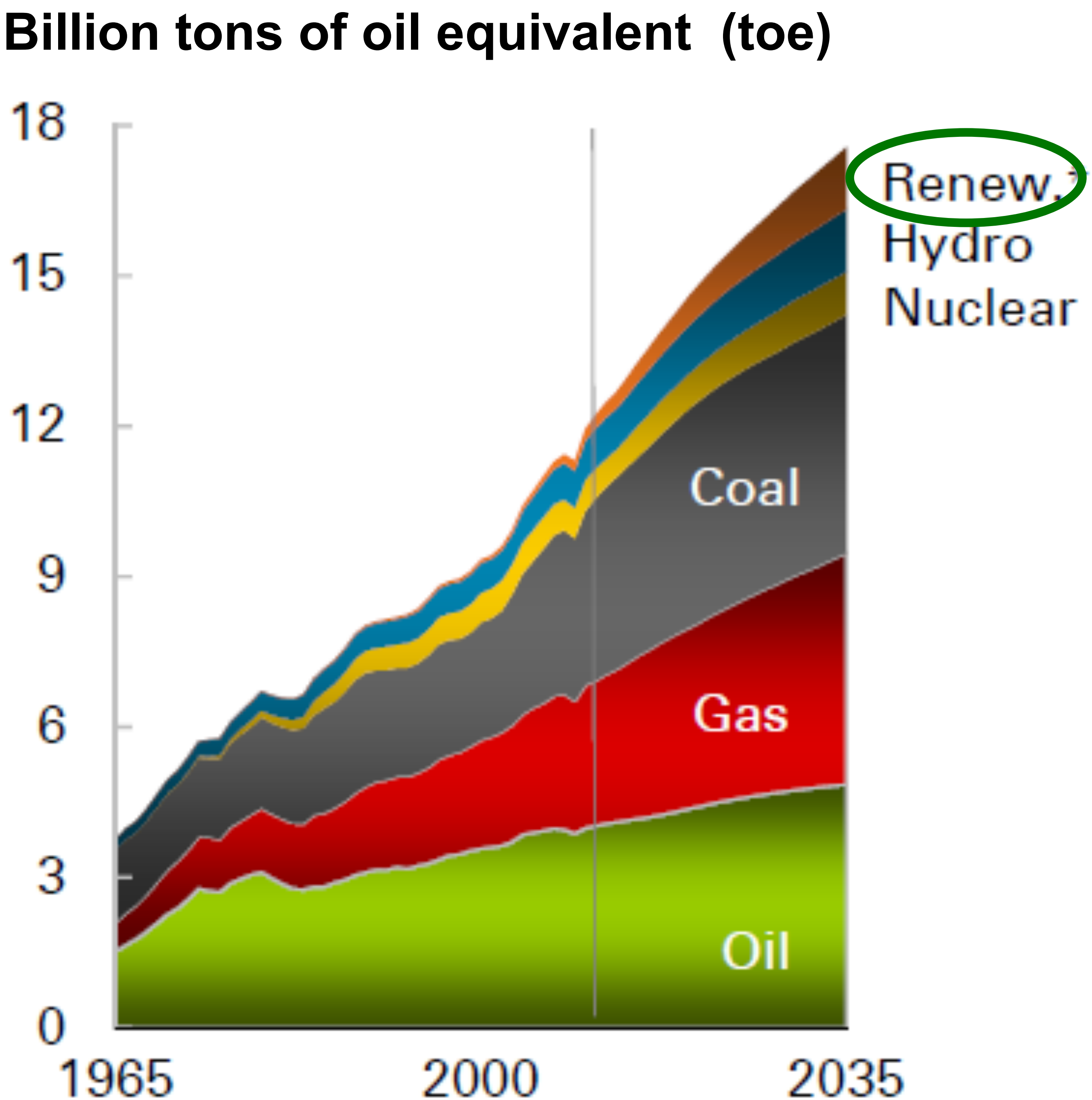
Figure 2. Top ten global ammonia producers, 2012 (k tonnes)



Source: Authors' elaboration on USGS (2013).



Comparing the world's energy resources*
Annual Income
Capital
Where should we invest for the long-haul??
SOLAR
WIND
waves
OTEC
BIO
HYDRO
World energy use
Natural Gas
Petroleum
Uranium
COAL
© Richard Perez, et al.
is shown for the renewable energies. Total reserves are shown for the fossil and nuclear "use-them, lose-them"
energy use is annual.



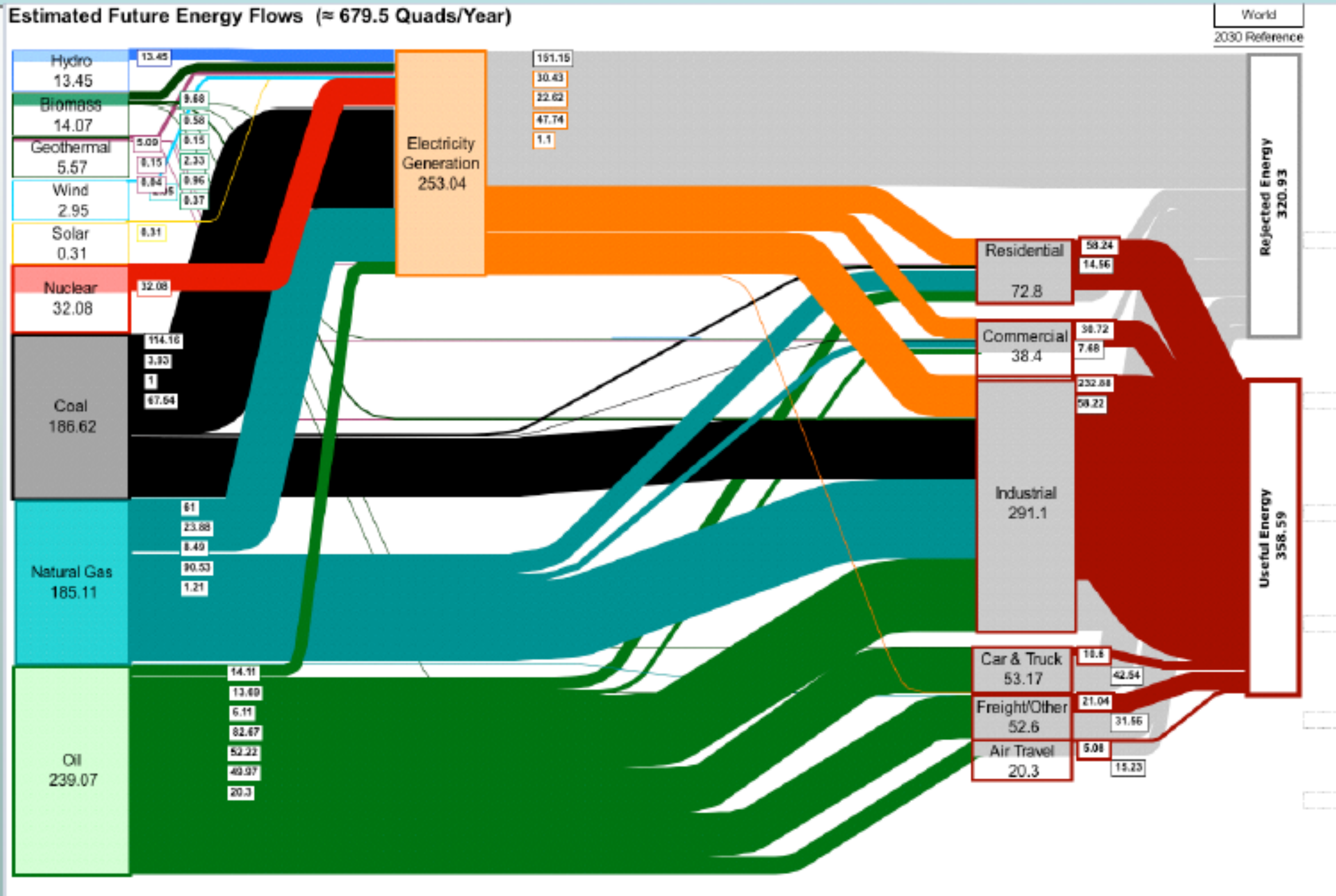
World Primary Energy Consumption

BP Energy Outlook 2035

January ‘14

Projected World Energy ~ 680 Quads/yr

2030 Reference Case (IEO 2006)



The Great Plains Wind Resource

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Minneapolis, 1-2 Nov 17
NH3 Fuel Association
American Institute of Chemical Engineering

Bill Leighty, Director
The Leighty Foundation
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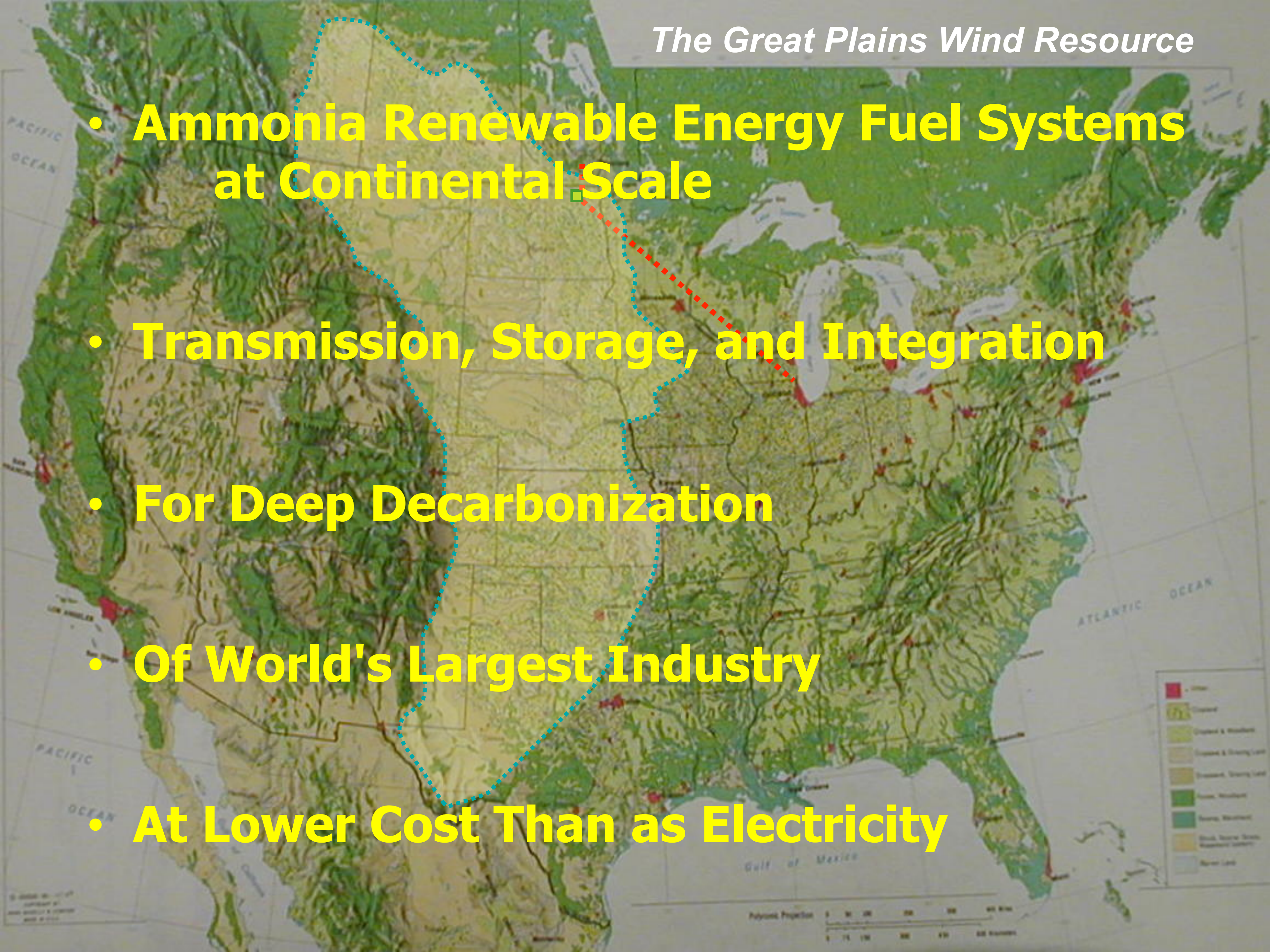
The Great Plains Wind Resource



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