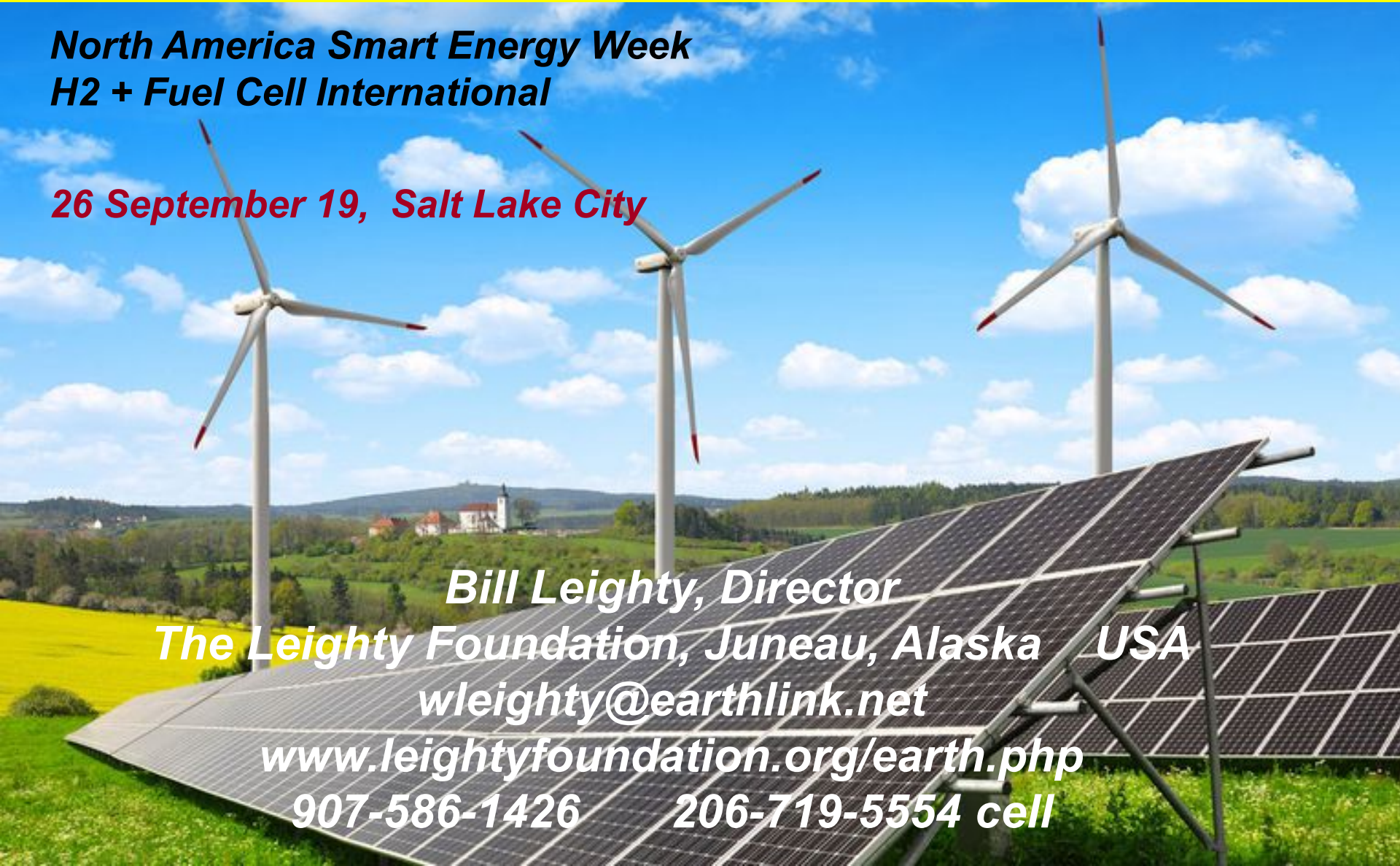
Deep Decarbonization of Total Global Energy: Hydrogen and Ammonia C-free Fuels versus Electricity as Integrated CO2-emission-free Energy Systems



North America Smart Energy Week
H2 + Fuel Cell International

26 September 19, Salt Lake City

Bill Leighty, Director
The Leighty Foundation, Juneau, Alaska USA
wleighty@earthlink.net
www.leightyfoundation.org/earth.php
907-586-1426 206-719-5554 cell

Transform Entire Human Enterprise

- **Our responsibility, obligation**
- **“Climate Change” emergency**
- **All human activity**
- **Near-total de-carbonization (CO_2)**
- **Near-total de-GHG-emission**
- **Enormous business opportunity**

FOCUS: Transform world’s largest industry

Transform World's Largest Industry

From ~ 85% fossil → ~ 100% CO_2-emiss-free

- **Quickly**
- **Prudently**
- **Profitably**

Via electricity systems, "Grid" ?

- **Default, obvious**
- **Entirely ? Try to ?**
- **Suboptimal -- tech & econ ? Waste of resources ?**
- **Obsolete ?**
- **Limit elec to " first & last km, m " of energy system ?**

Or: C-free fuels systems ? Entirely ?

- **Hydrogen**
- **Anhydrous ammonia (NH_3)**

Transform World's Largest Industry

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- **Default, obvious**
- **Entirely ? Try to ? Obsolete ?**
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Or: C-free fuels systems ? Entirely ?

- **Hydrogen**
- **Anhydrous ammonia (NH_3)**

Hypothesis:

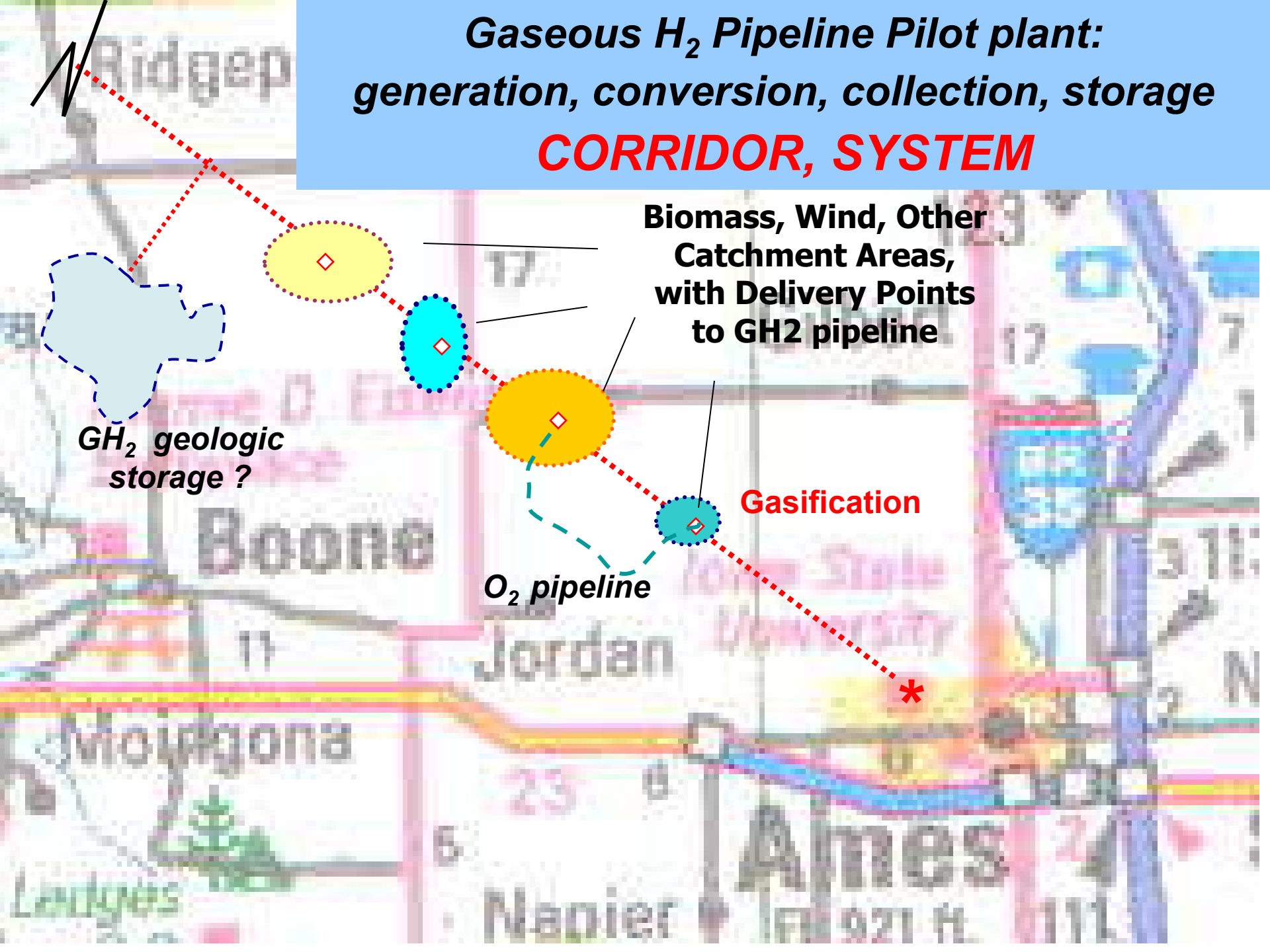
- **Limit elec to "first & last km, m" of energy system**
- **C-free fuels between: pipelines, low-cost bulk storage**

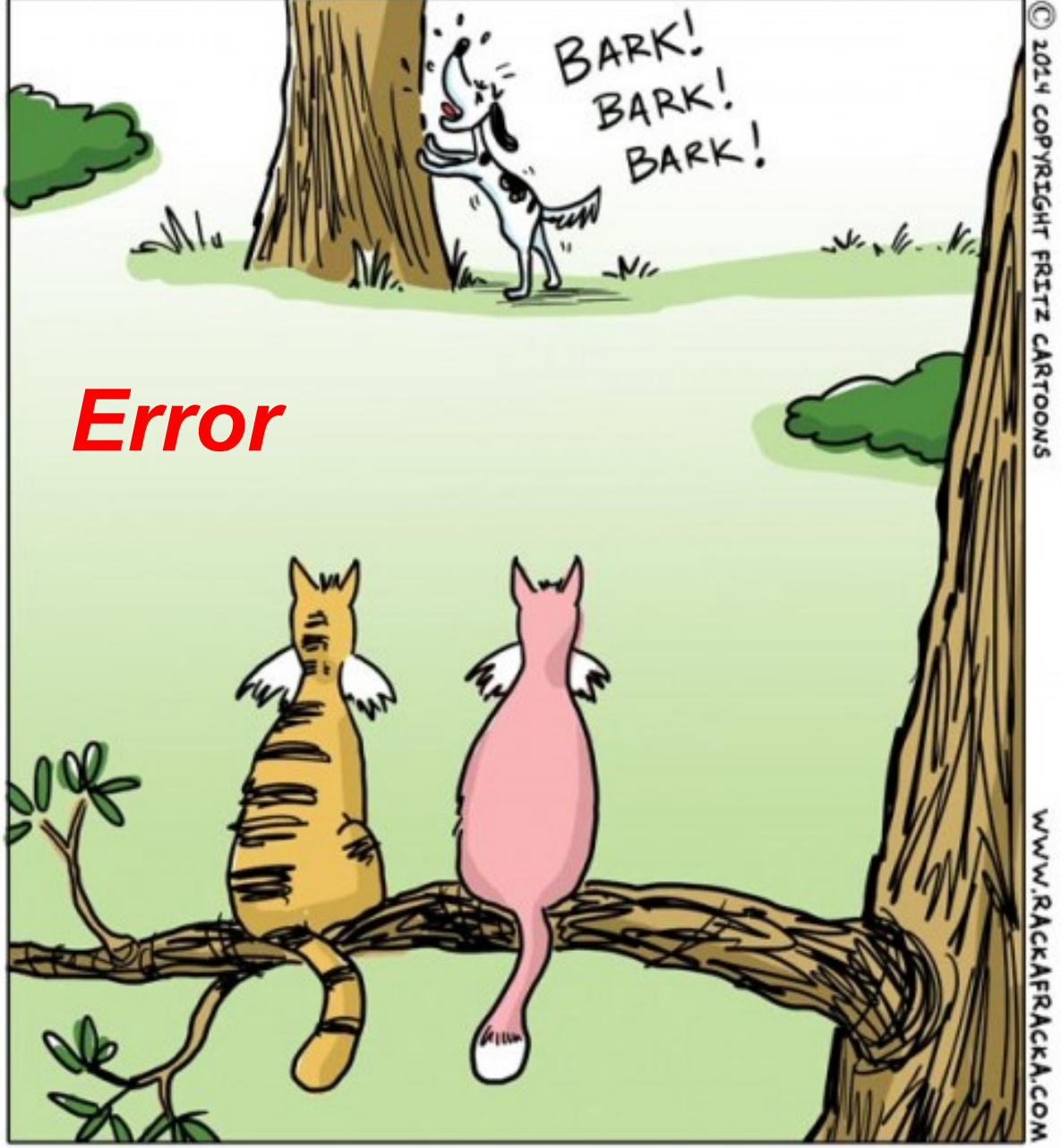
How to know ? Who will model, study, propose ? Urgent !

- **Collaborative; funding**
- **Optimum mix, strategy**
- **Prevent opportunity costs: wasted capital**

Gaseous H_2 Pipeline Pilot plant: generation, conversion, collection, storage

CORRIDOR, SYSTEM

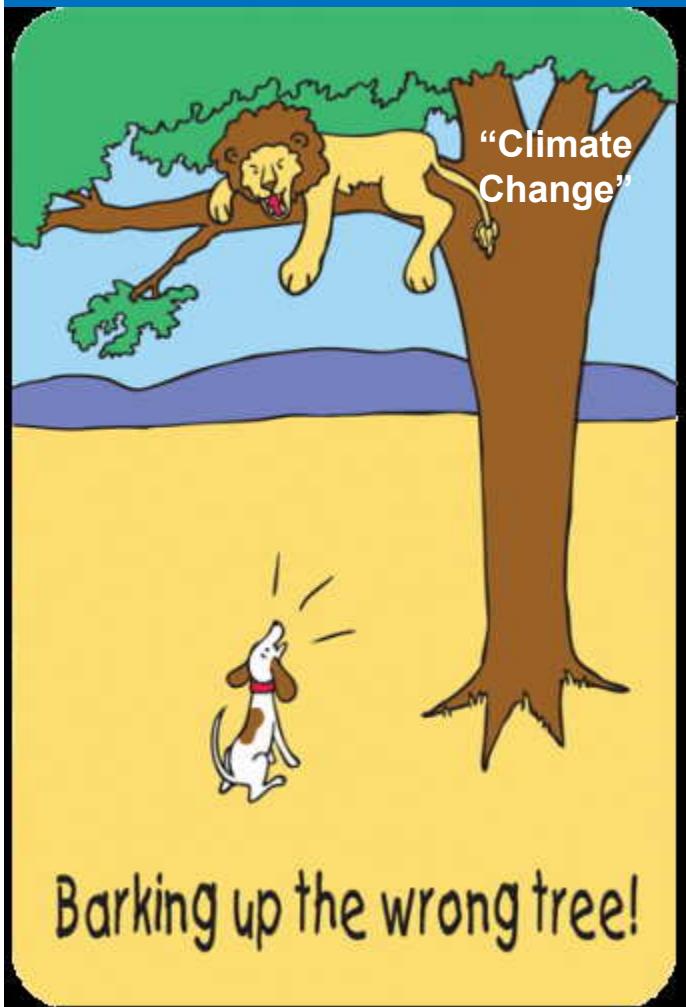




BUSTER WAS CAUGHT BARKING UP THE WRONG TREE AGAIN.

Danger:

All eggs in electricity basket ?



“Grid”

Technically, Economically Suboptimal ?

Obsolete ?

Opportunity cost to persist ?

Global $ 45 trillion new infrastructure by 2030

- **Shares: Electricity, H_2, NH_3 ?**
- **Stranded assets ?**

Transform World's Largest Industry

Perfect storm: danger + opportunity

- **Climate, sea level rise, ocean acidification, species loss**
- **Declining costs: renewables, storage**
- **Business opportunity huge: "Green New Deal"**
- **Systems optimization: DER → continental → global scales**

" Run the World on Renewables "

- **Inexhaustible: solar, geothermal Nuclear ?**
- **GHG-emission-free: CO_2 , CH_4 , other**

Near-total de-carb, de-GHG, human enterprise

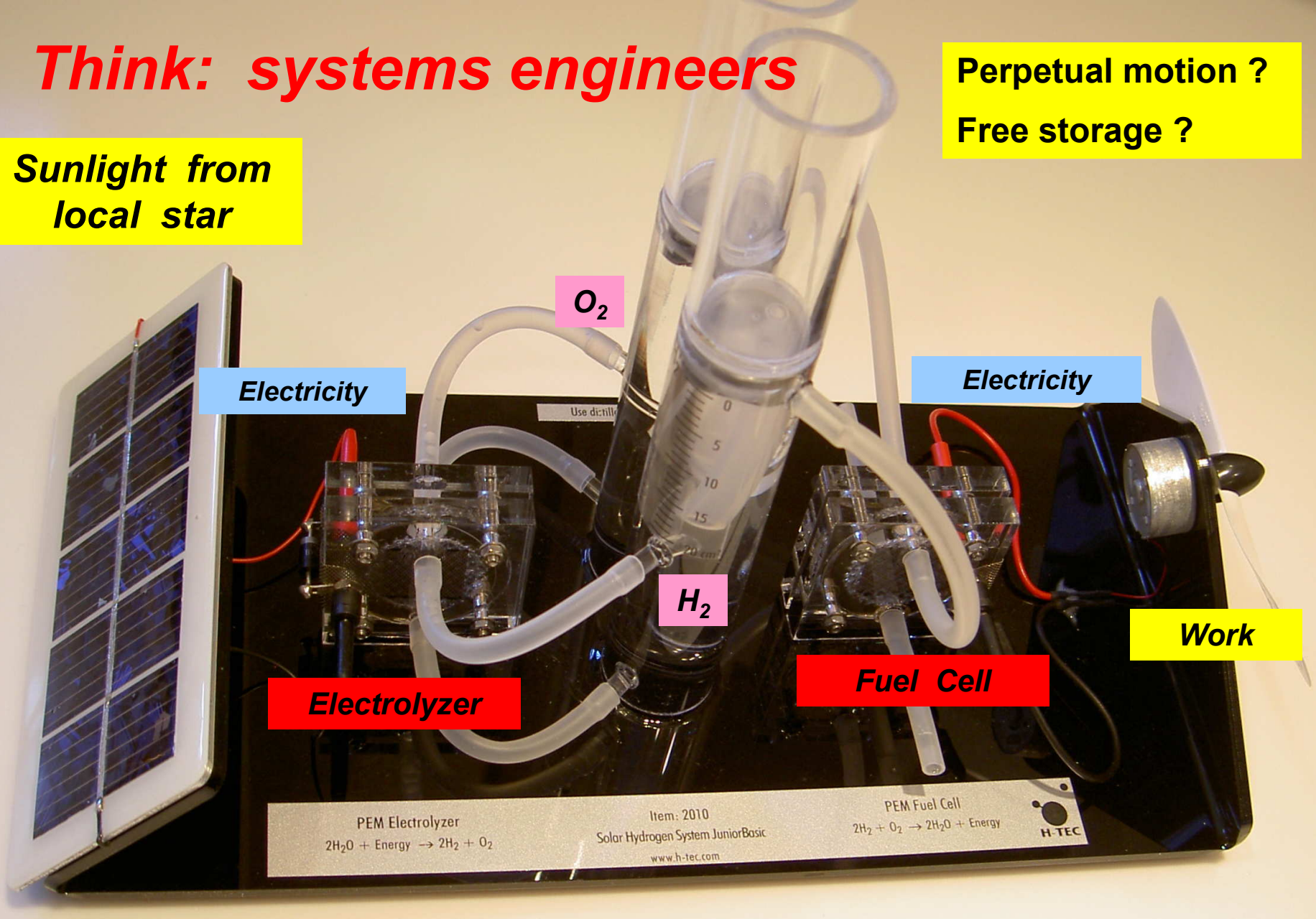
- **All sources, all uses**
- **Global, affordable, equitable**
- **Including some nuclear ?**

Think: systems engineers

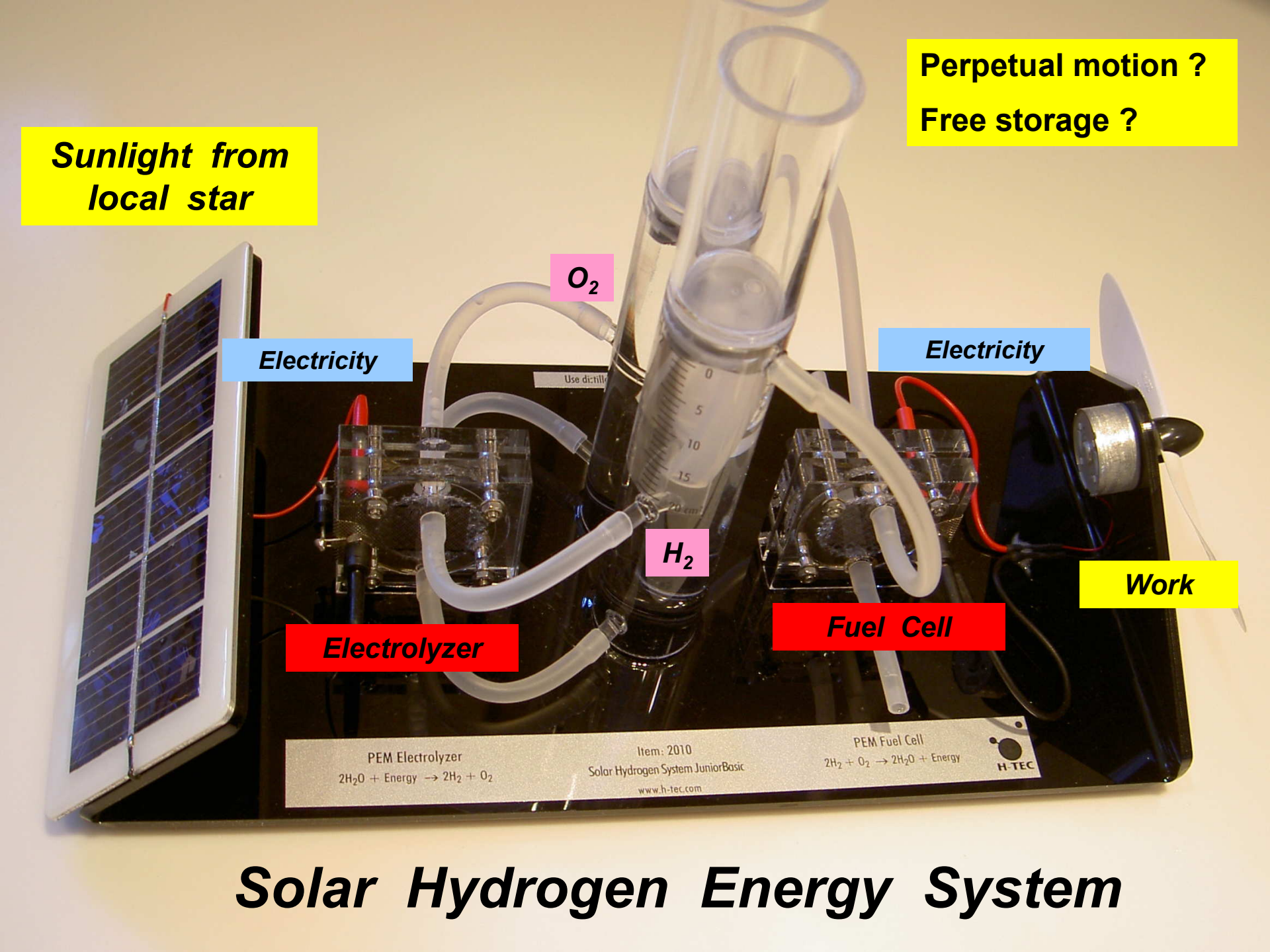
Perpetual motion ?

Free storage ?

Sunlight from local star

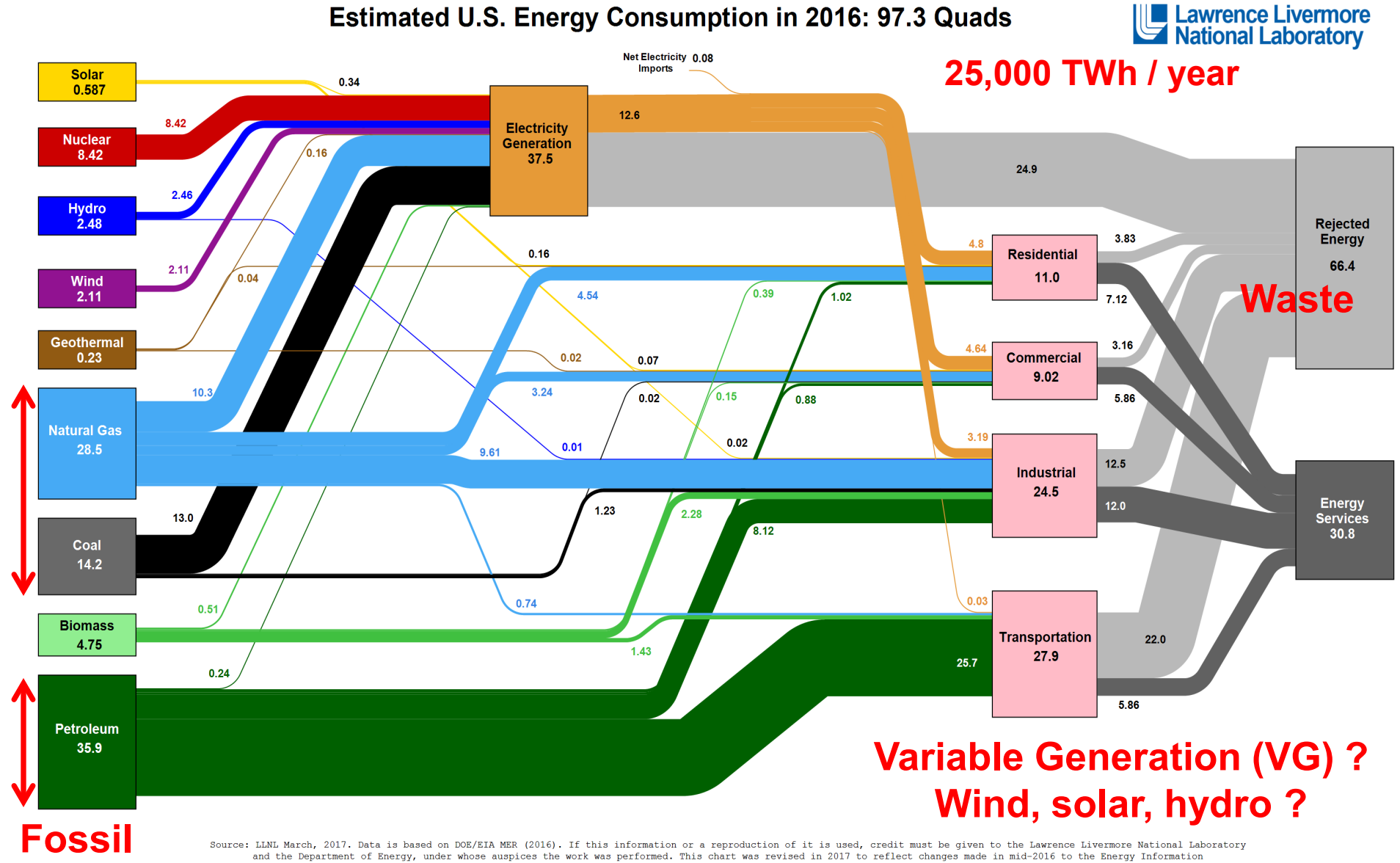


Solar Hydrogen Energy System



Solar Hydrogen Energy System

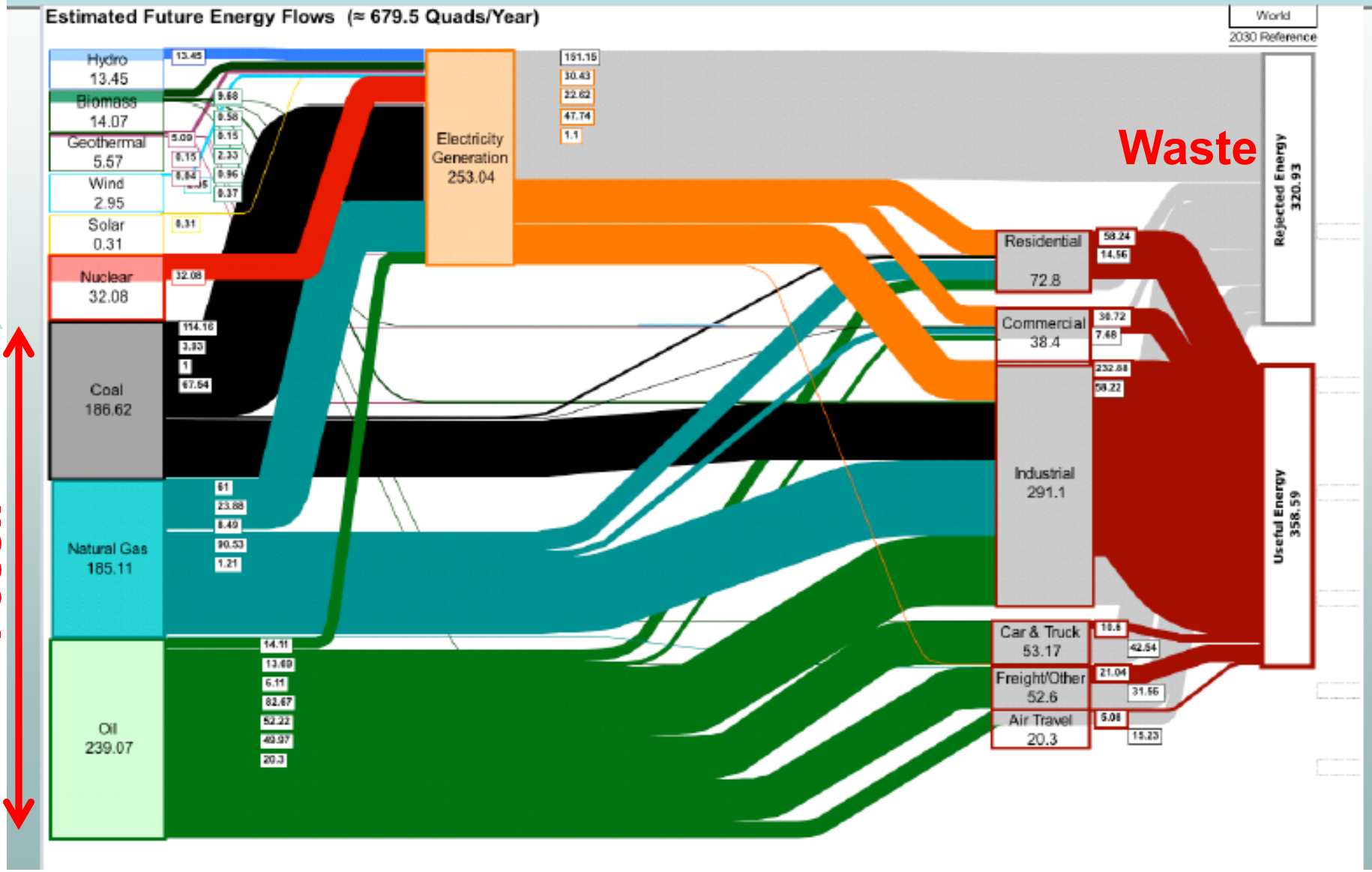
Estimated U.S. Total Energy Consumption 2016 = 25,000 TWh



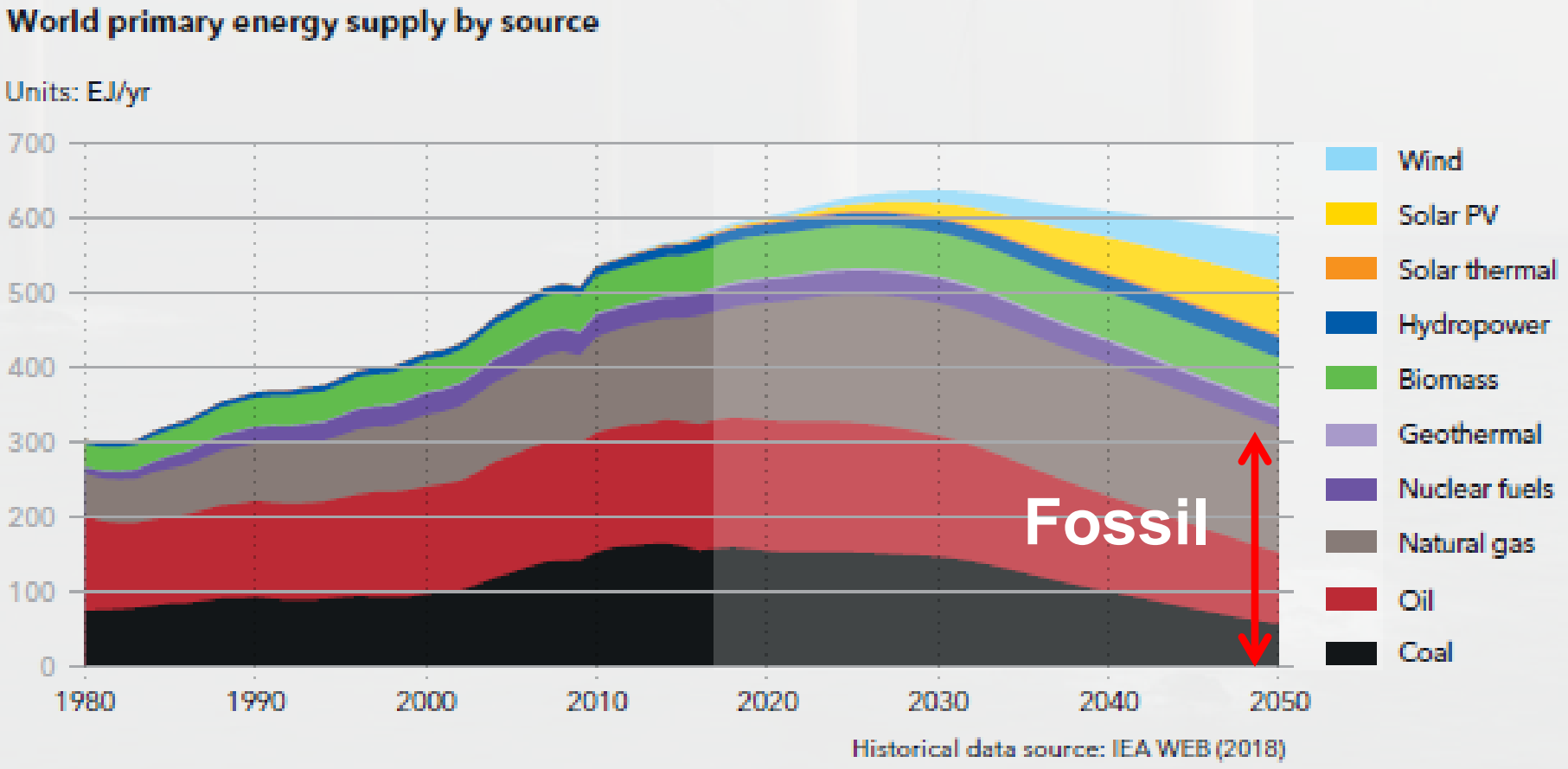
Source: LLNL March, 2017. Data is based on DOE/EIA MER (2016). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. This chart was revised in 2017 to reflect changes 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

Projected World Energy ~ 680 Quads/yr

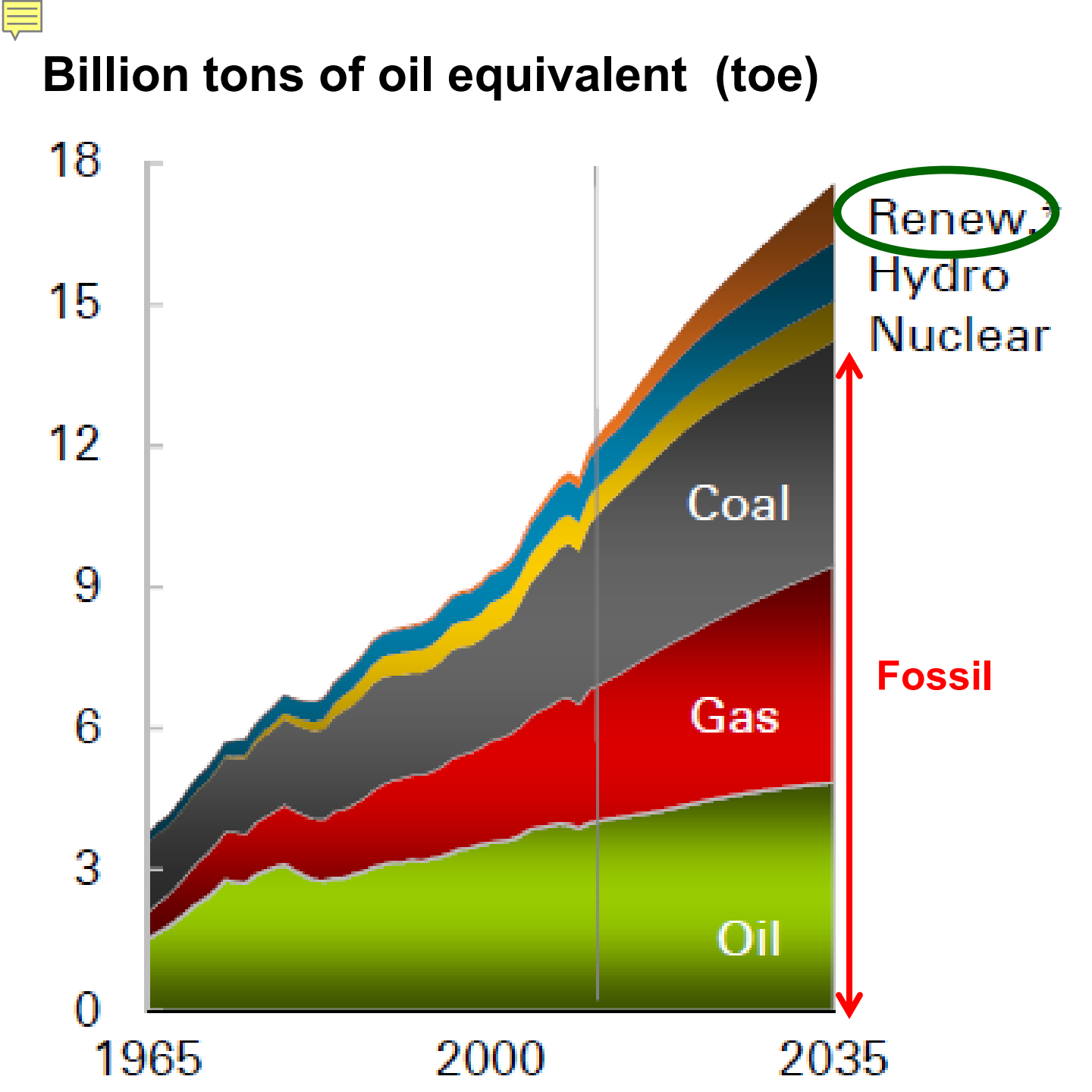
2030 Reference Case (IEO 2006)



IEA: International Energy Agency, 2018



- Peak energy ~ 2030 640 EJ =
- Efficiency up
- Fossil fuels: 81 % → 56 % 2050

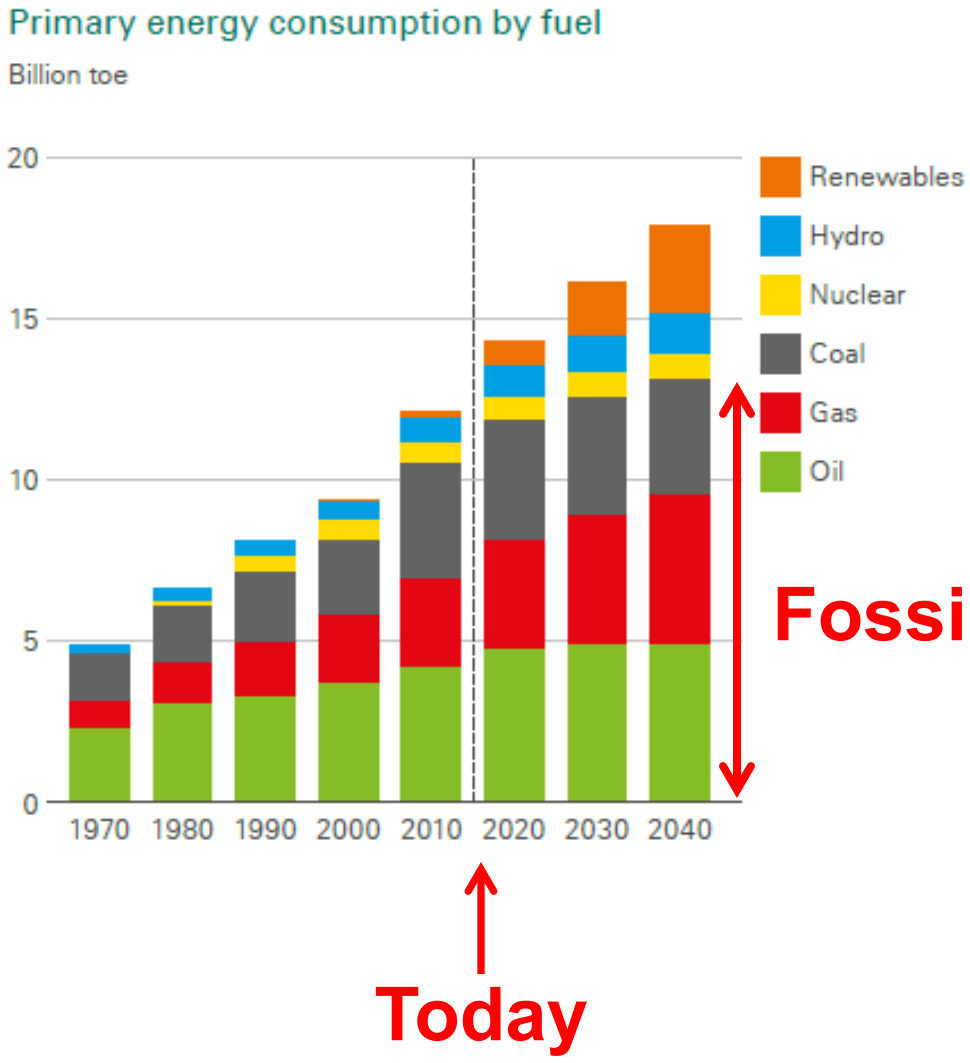


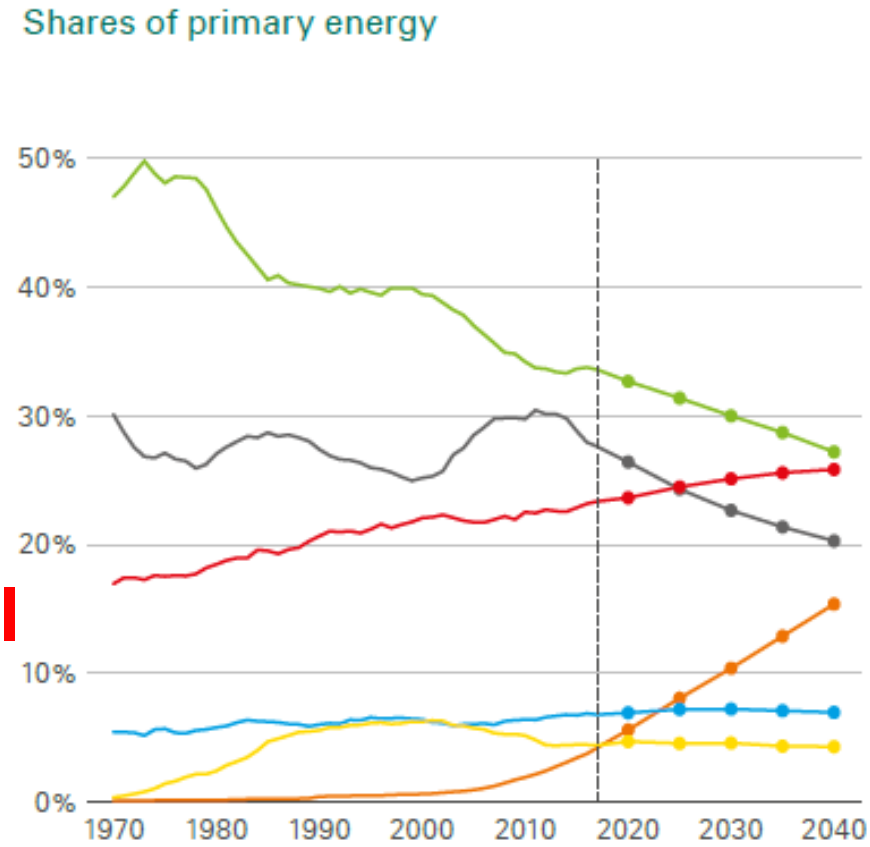
World Primary Energy Consumption

BP
Energy
Outlook
To 2035

January ‘14

BP Energy Outlook 2019 to 2040





IPCC Special Report 15

7 October 2018

- 1.5° C limit, or else … tipping ?
- *likely* reach 1.5°C between 2030 and 2052 at current rate
- ~ 2050 achieve net-zero global anthropogenic CO_2

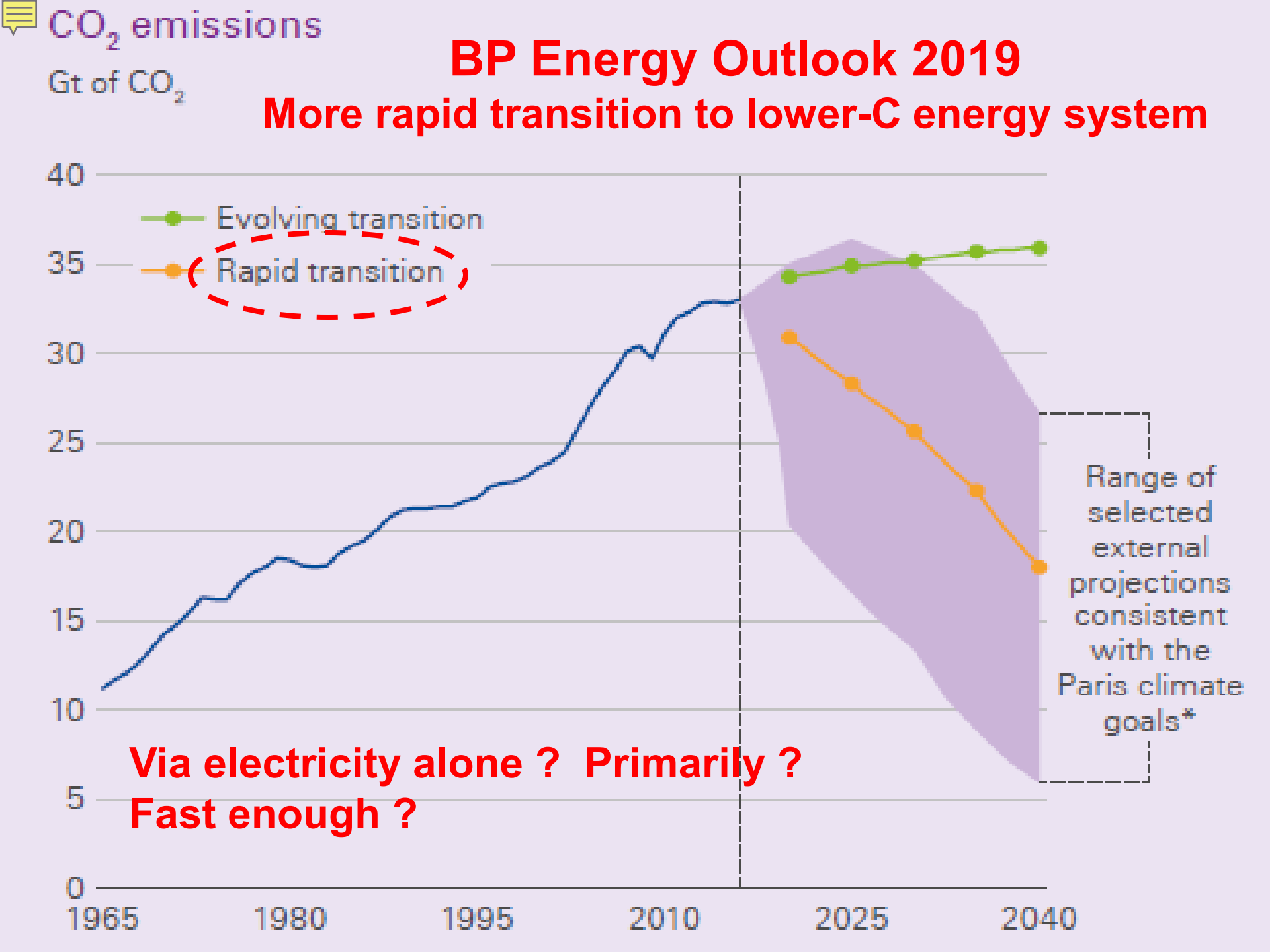
- DNV-GL "Energy Transition Outlook 2019"
  - Technology ready; policy not
  - Not fast enough

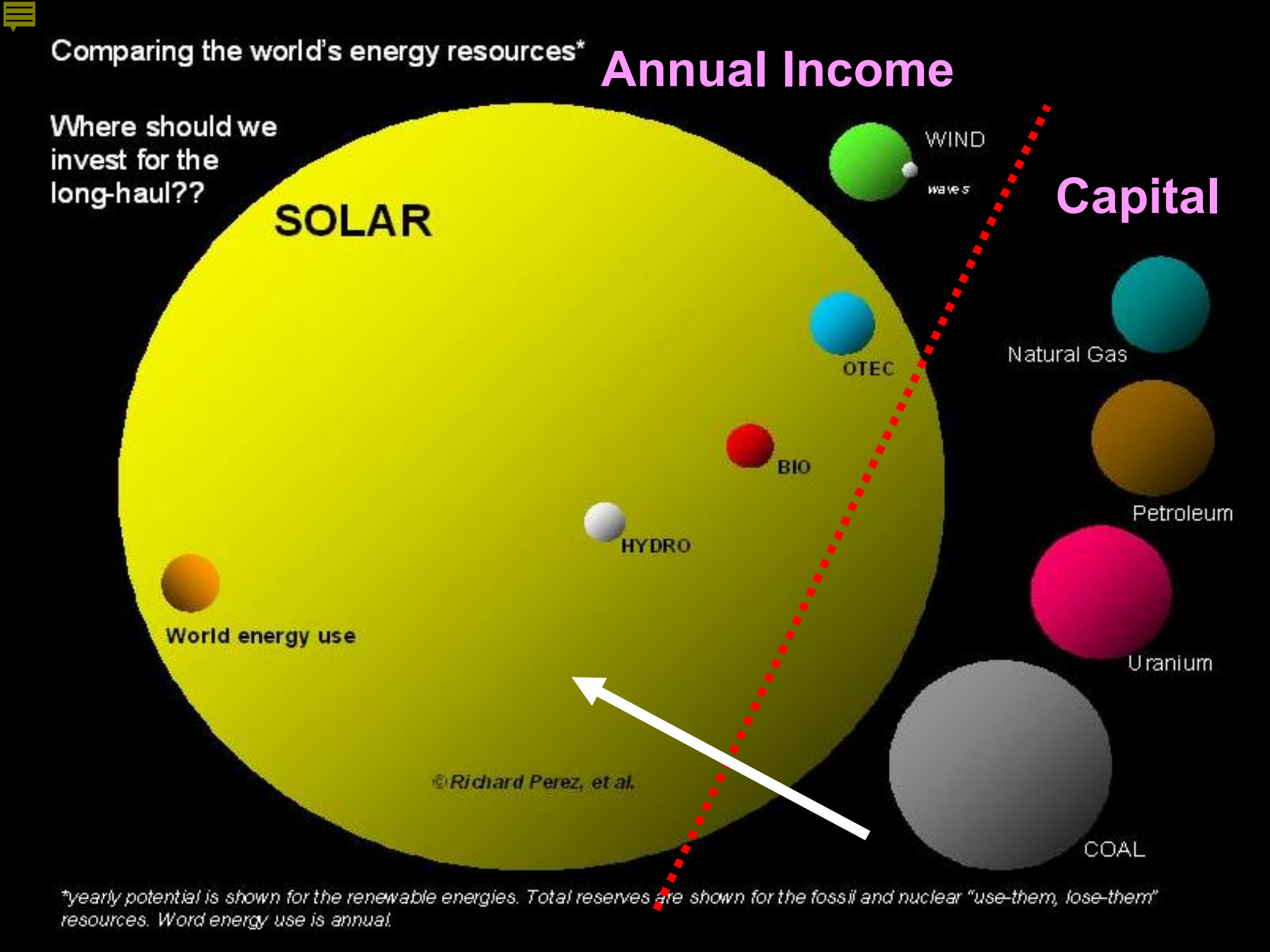
“Climate Change”

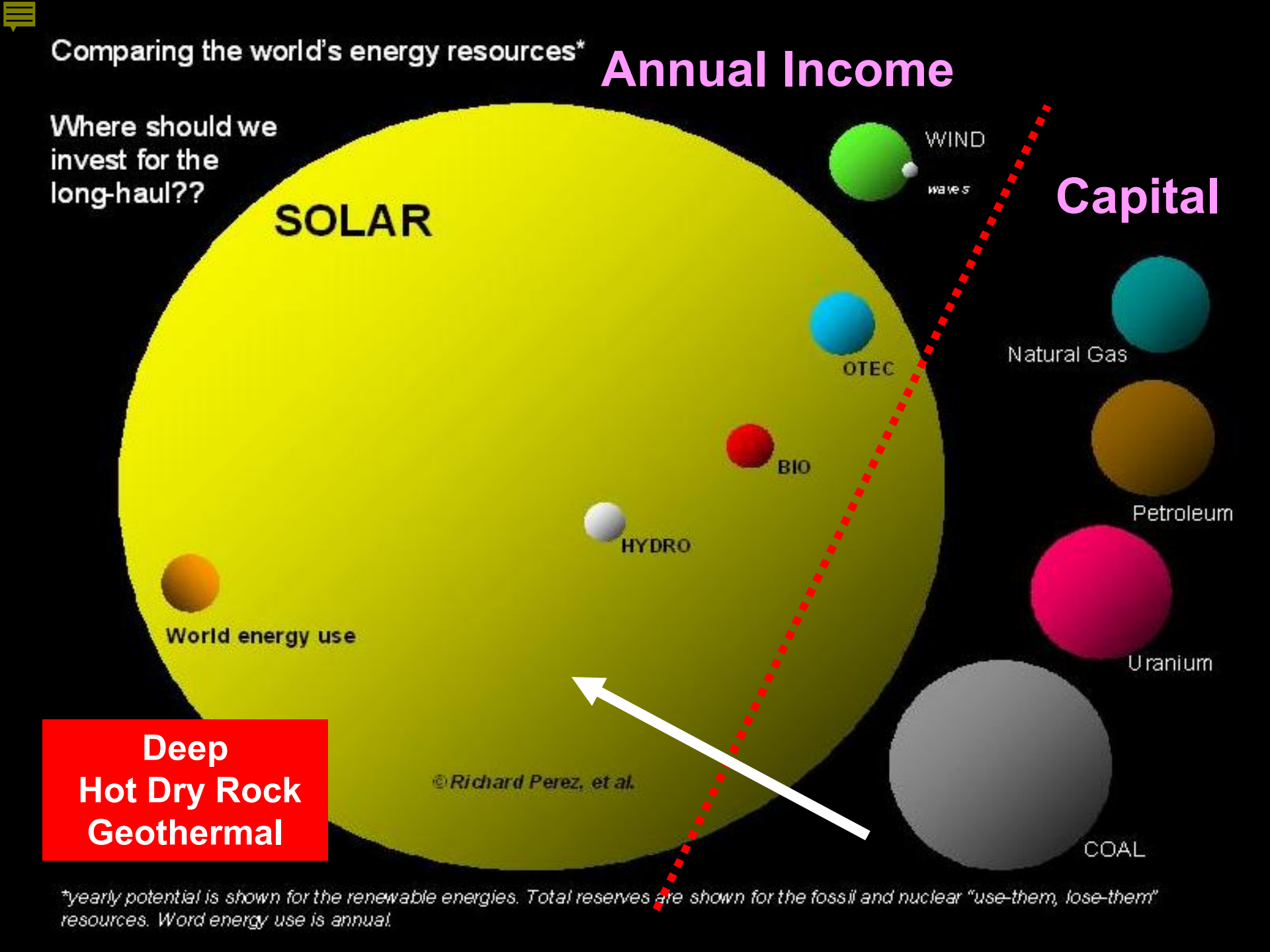
- Warming
- Severe weather
- Sea level rise
- Ocean acidification
- Species extinction
- Human conflict

BP Energy Outlook 2019

More rapid transition to lower-C energy system




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.
*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.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Transform World's Largest Industry

Complete energy systems:

- Renewable energy (RE)
- CO2-emission-free (CEF)
- Multiple sources
- Variable generation (VG): Time-varying output
- Integrated, synergistic
- Move, store, as electricity or as water-split Hydrogen ?
  - Electrochemical: " electrolyzer " proven
  - Photochemical: catalyst
  - Biochemical: photosynthesis
  - Thermochemical: High-T solar, nuclear
- Lower Dispensed Cost: Wind-source Hydrogen Fuel

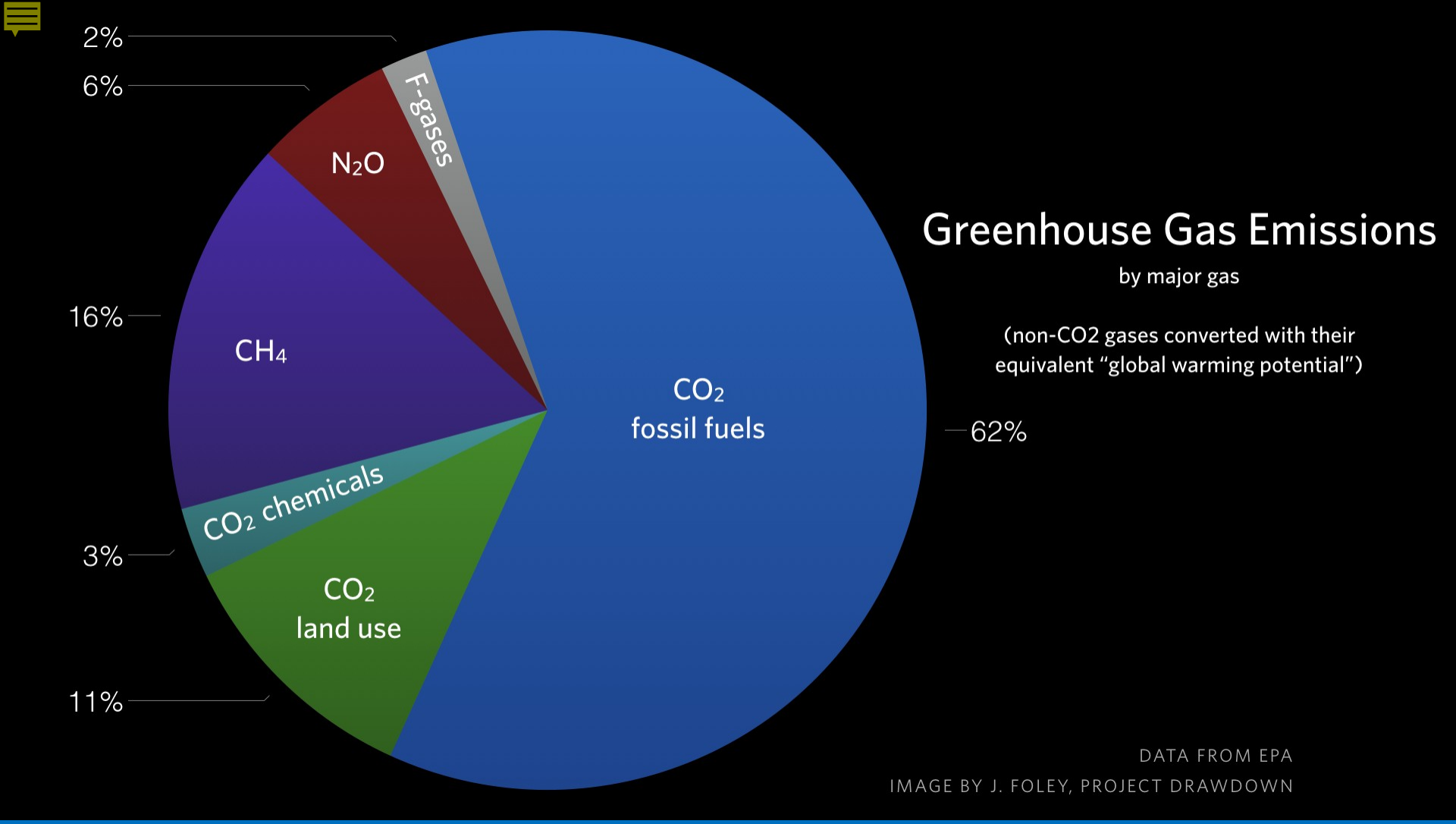
Entirely via electricity systems ?

- **Entirely with electricity systems, "Grid" ?**
- **Obvious, default**
- **Assume primarily variable generation (VG) ?**
- **Possible, but tech & econ suboptimal ?**
- **Optimum mix: electricity, C-free fuels -- H_2 , NH_3**

Need diverse collaboration to roadmap: neglected, urgent !

Hypotheses:

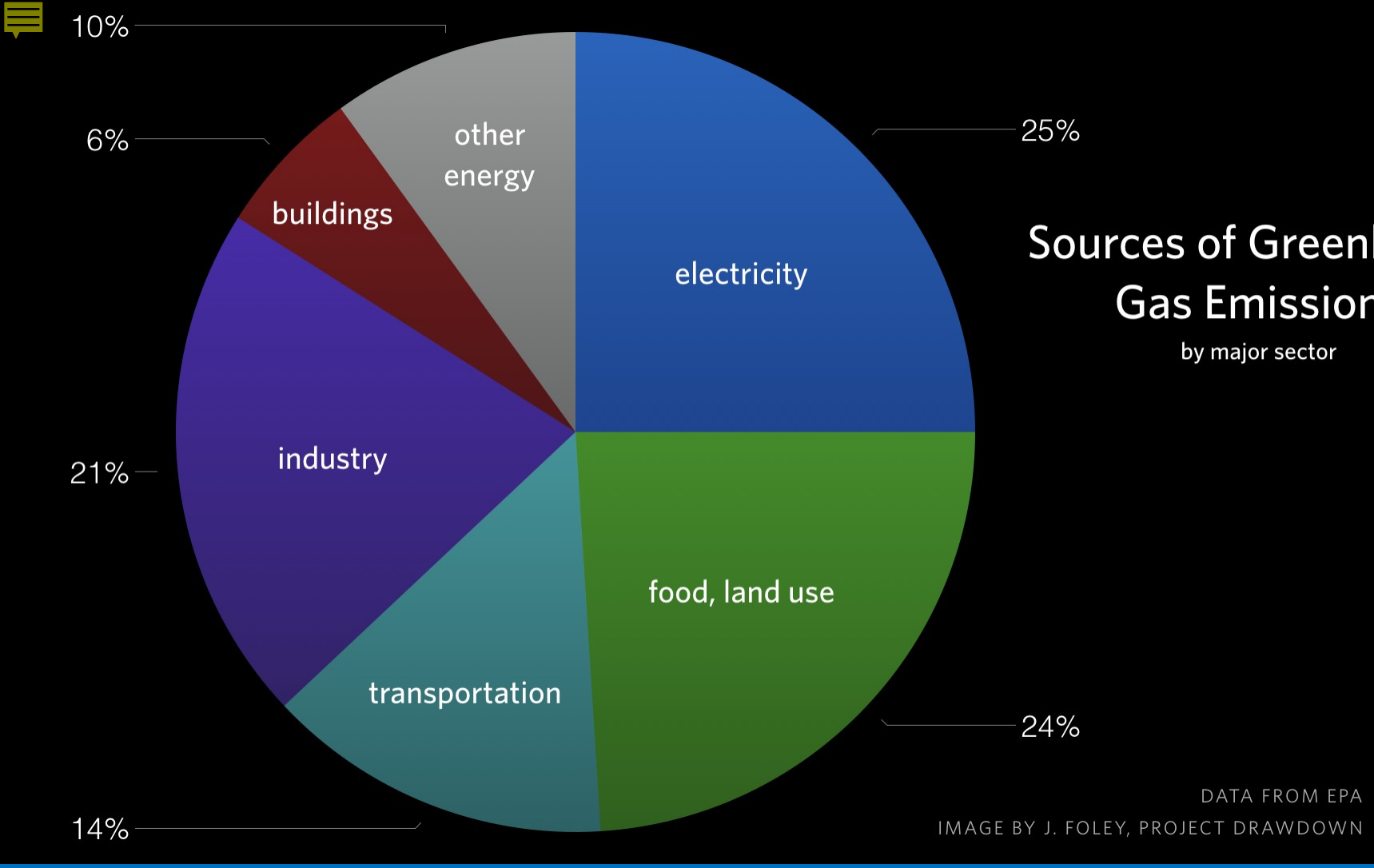
- **Electricity confined to " first & last km, or m "**
- **Between is C-free fuels via pipelines, low-cost storage**
- **"Grid" supports the C-free fuel systems, not reverse**
- **Cannot afford suboptimal: time, capital, "climate change"**
- **Scales: DER → global**
- **Need diverse collaboration to roadmap: neglected, urgent !**



Urgent Goals: Near-total

- De-carbonization of energy
- De-GHG of total human enterprise

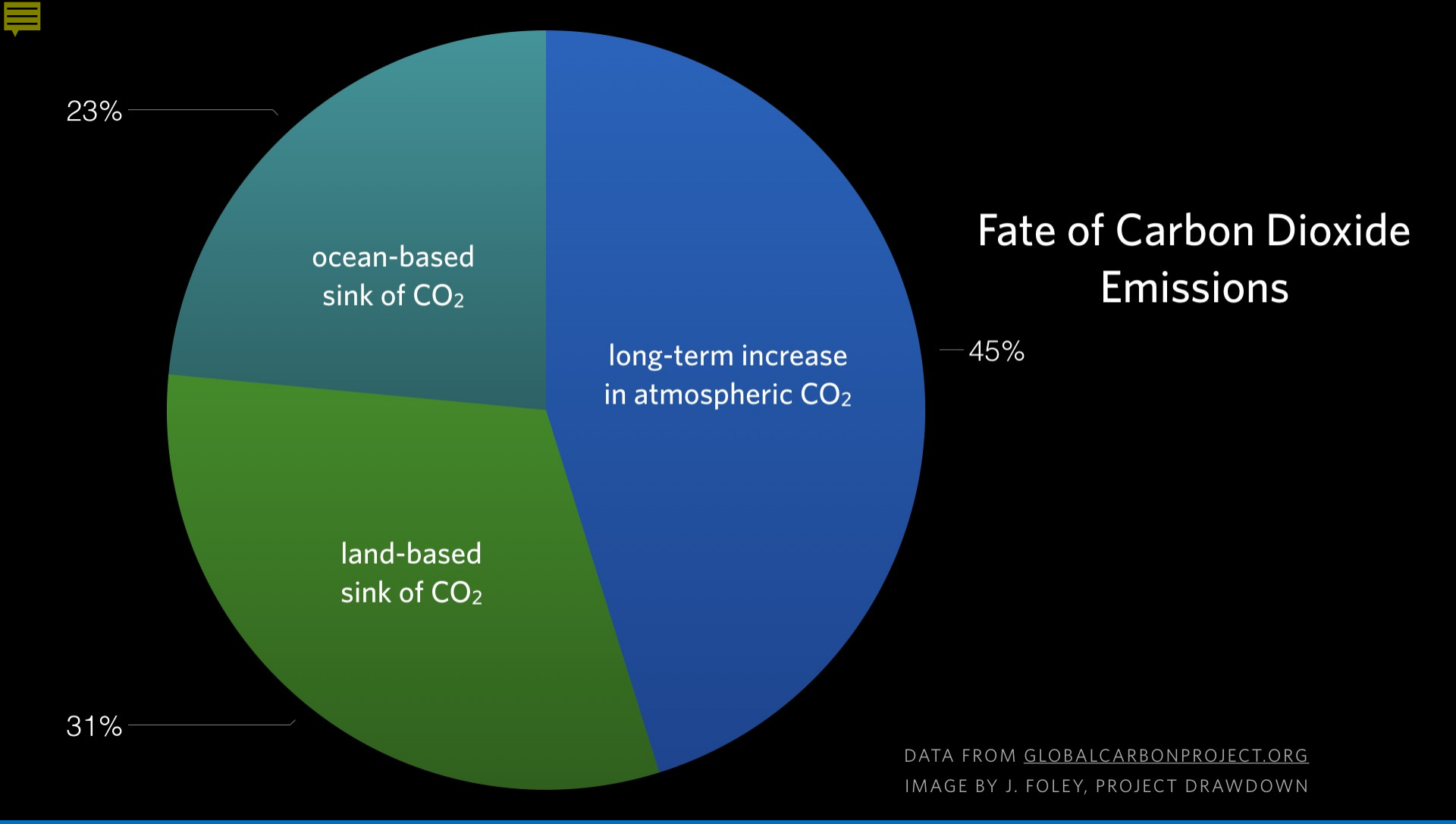
H_2 roles ?



Urgent Goals: Near-total

- De-carbonization of energy
- De-GHG-emission of human enterprise

H_2 roles ?



Urgent Goals: Near-total

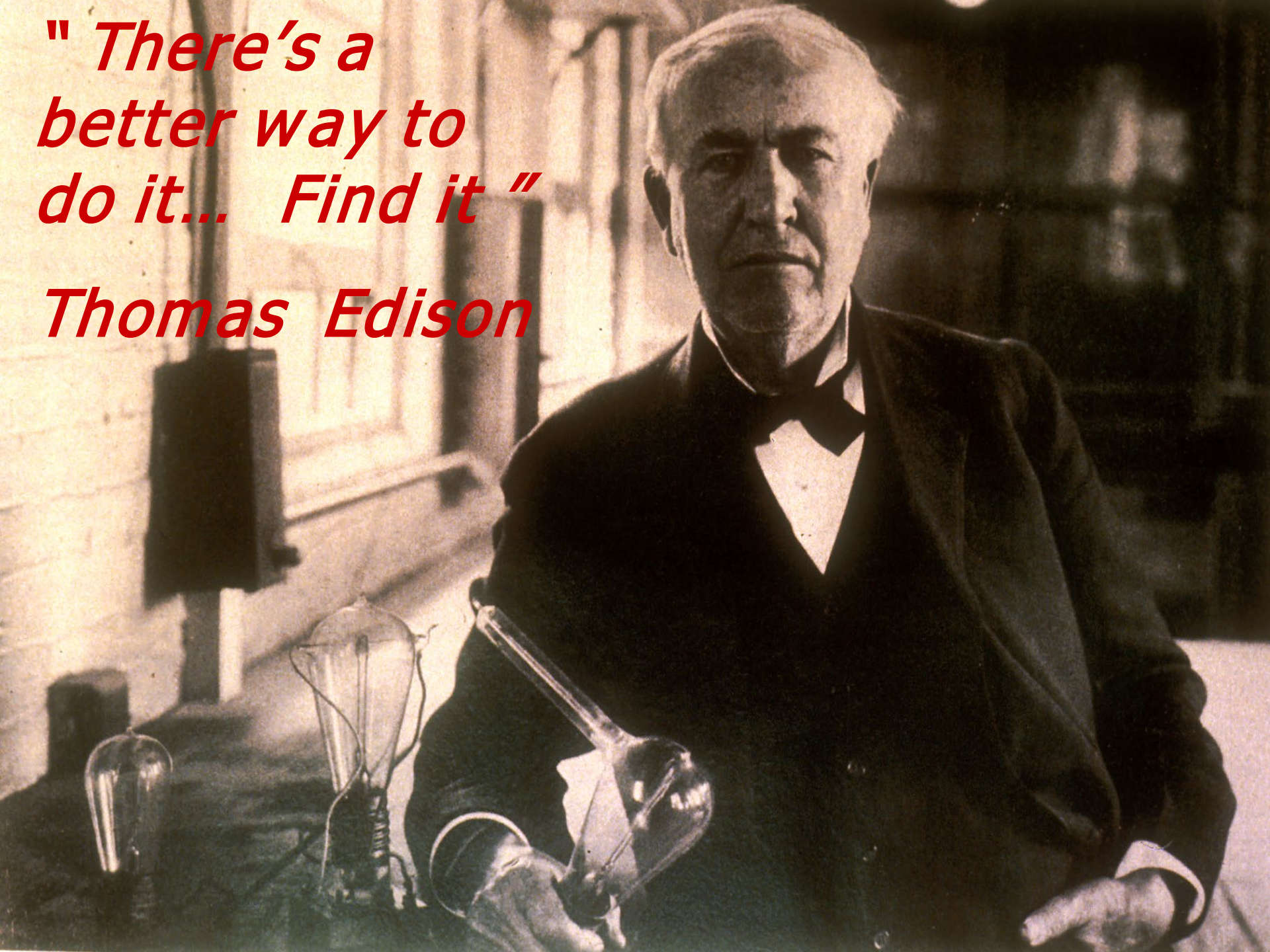
- De-carbonization of energy
- De-GHG of human enterprise

H_2 roles ?

Transform Human Enterprise

Goal: Global Energy System achieves all:

- **Benign**
- **Relatively safe**
- **Inexhaustible**
- **Affordable**
- **Baseload**
- **Firm and dispatchable**
- **Storage inherently free**
- **Resilient, robust: acts of God and man**
- **Cyberattack resistant**
- **Unobtrusive infrastructure**
- **Equitable: no monopoly**
- **Distributed, autonomous**
- **Ubiquitous on Earth**


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

Major new markets for H_2, NH_3

Transportation fuel

- **Highway: LDV, bus, truck**
- **Rail: Alstom, UK trains**
- **Marine: ammonia fuel (NH_3)**
- **Aviation: 6 – 20 pax, Airbus "Cryoliner" A320**

CHP stationary fuel: Combined Heat and Power

Iron ore reduction: $FeO_x + H_2 \rightarrow Fe + H_2O$

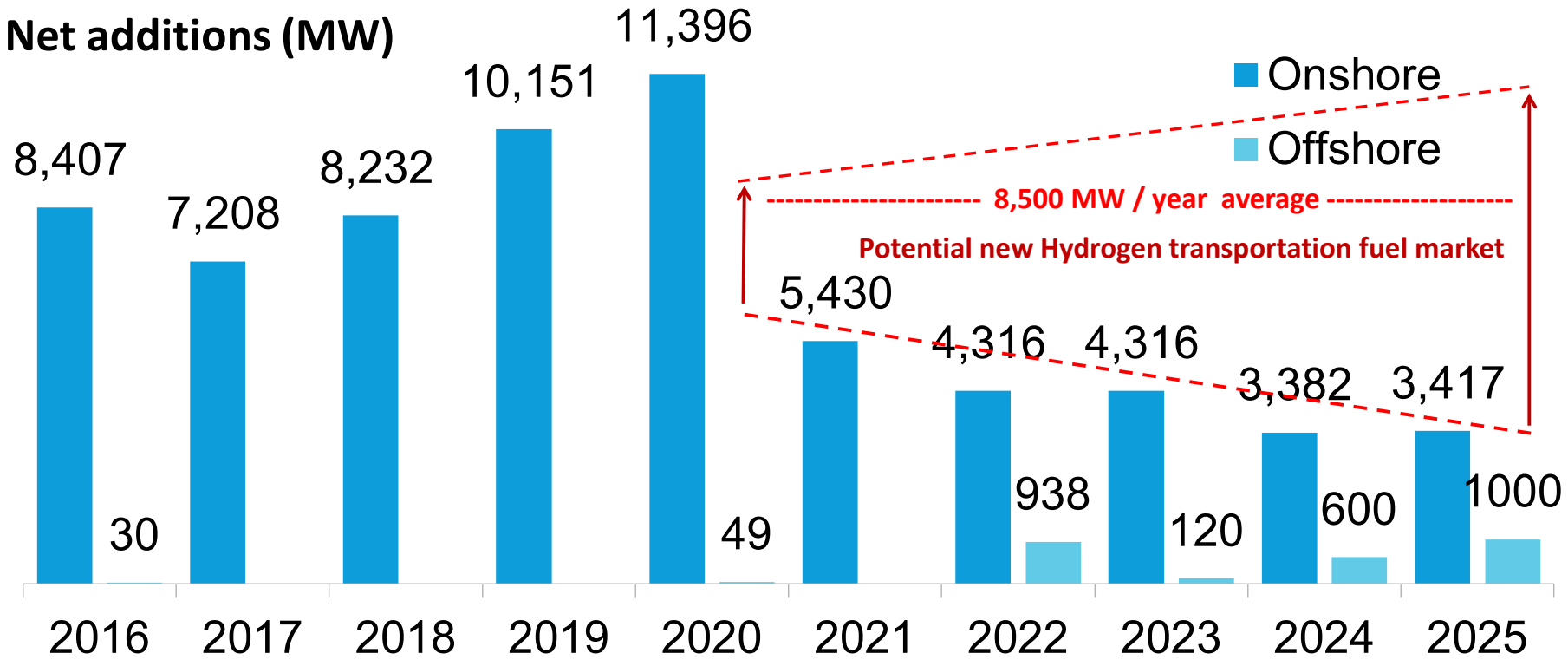
N-fertilizer production: $N_2 + H_2 \rightarrow NH_3 \rightarrow$

Oil refining

- ***Pipeline networks required ? GH_2, liquid NH_3***
- ***Possible with electricity ?***
- ***Curtailed wind + solar: 440,000 MWh, CA, 2018***
- ***Wind beyond 2020: PTC ends → cliff***

Potential new hydrogen fuel market

U.S. Wind Forecast



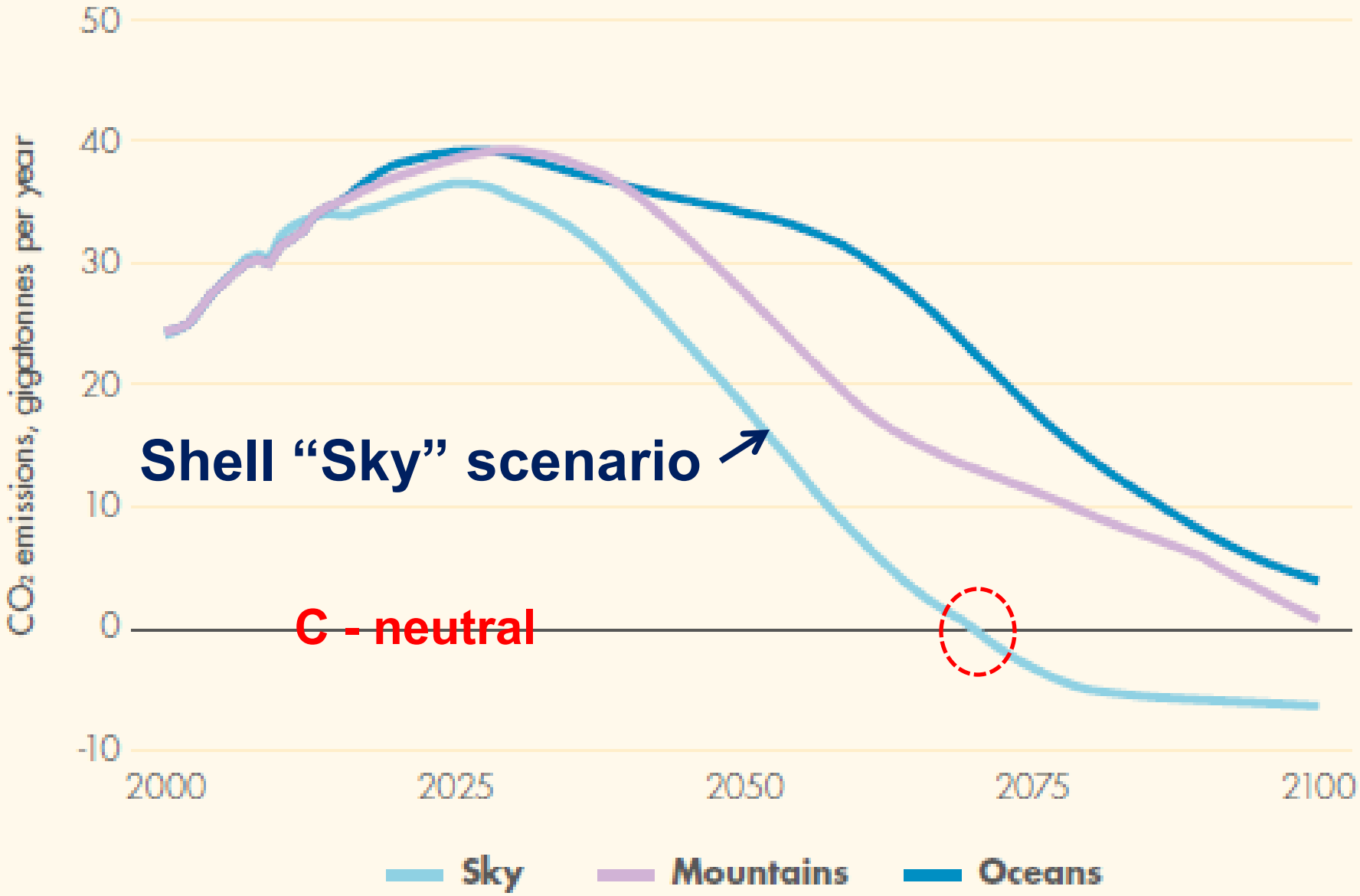
Source: Bloomberg New Energy Finance, Outlook for U.S. Wind Build
Presentation at Windpower 2018, Chicago, 08 May 18, by David Hostert, Head of Wind Research, London
"Potential new Hydrogen transportation fuel market" added by Bill Leighty, The Leighty Foundation, 22 May 18

Transform World's Largest Industry

~ 85 % fossil →→
~ 100% renewable,
CO2-emissions-free

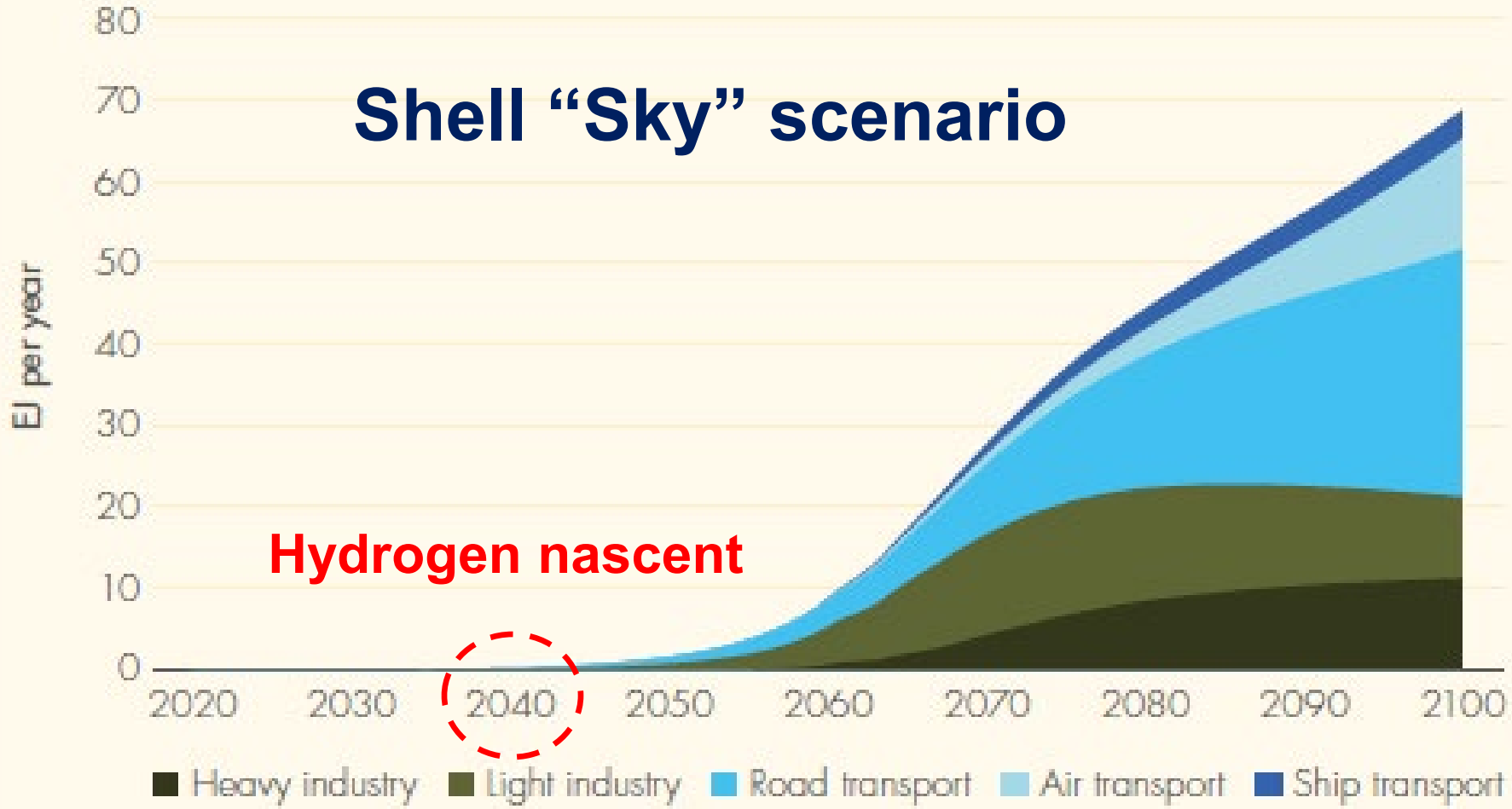
- ***Quickly***
- ***Prudently***
- ***Profitably***
- ***Beyond electricity:***
  - ***ALL sources, purposes, global***
  - ***Hydrogen + Ammonia fuel systems***

SHELL SCENARIOS COMPARED – WORLD ENERGY-RELATED CO_2 EMISSIONS



Source: Shell analysis

IN **SKY**, HYDROGEN EMERGES AS A MATERIAL ENERGY CARRIER AFTER 2040, PRIMARILY FOR INDUSTRY AND TRANSPORT



Note: By 2100, hydrogen supplies a quarter of all transport energy demand and over 10% of industrial energy

Source: Shell analysis

Far more Ambitious:

- Unacceptable scenarios
- Renewables industry
- Beyond electricity systems
- Transportation + CHP fuels
- Hydrogen + ammonia fuels
- Run the World on Renewables
- ~ 100 % GHG-emission-free energy
- ~ 100 % GHG-emission-free enterprise

A Bigger Renewable Energy Market than the Electricity Grid: Hydrogen Fuel for Transportation and CHP California 2050

California 2050

IF California:

1. Achieves RPS for electricity: 100 % in 2045
2. Achieves "80 in 50" for transportation CO_2
3. Fuel Cell Vehicles (FCV's):
   - Displace Battery Electric Vehicles (BEV's)
   - Trucks + buses first
   - Light Duty Vehicles (LDV's) BEV's + FCV's
4. Installs 100's of hydrogen fueling stations
5. Builds a new, high-purity, gaseous hydrogen pipeline network, renewables-dedicated – gather, transmit, store, deliver, integrate H_2 → $ 50 – 60 B
6. Transport modal mix remains same
7. **Relies on Variable Generation (VG) wind + solar**

THEN, California will need →

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

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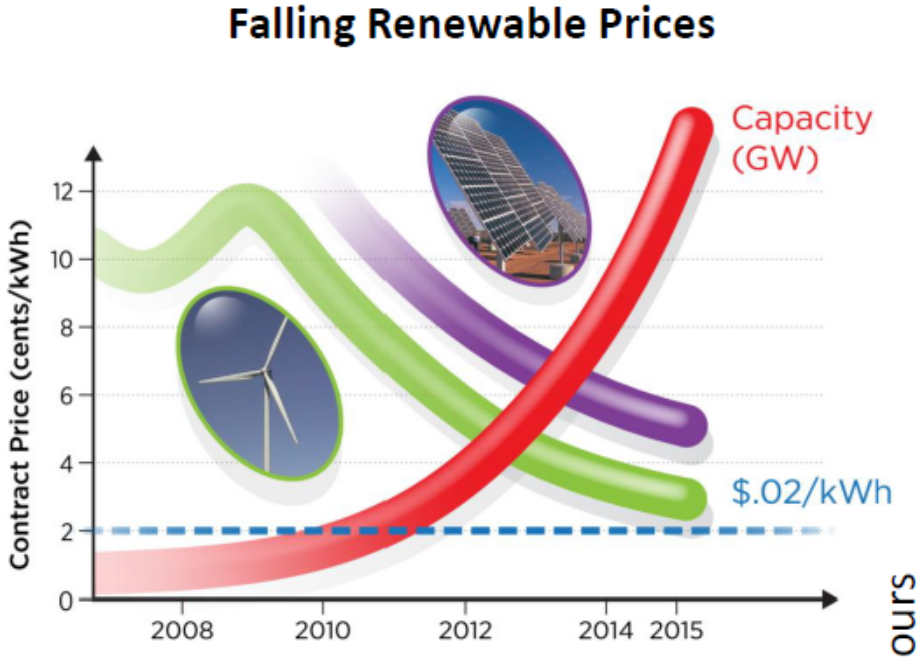
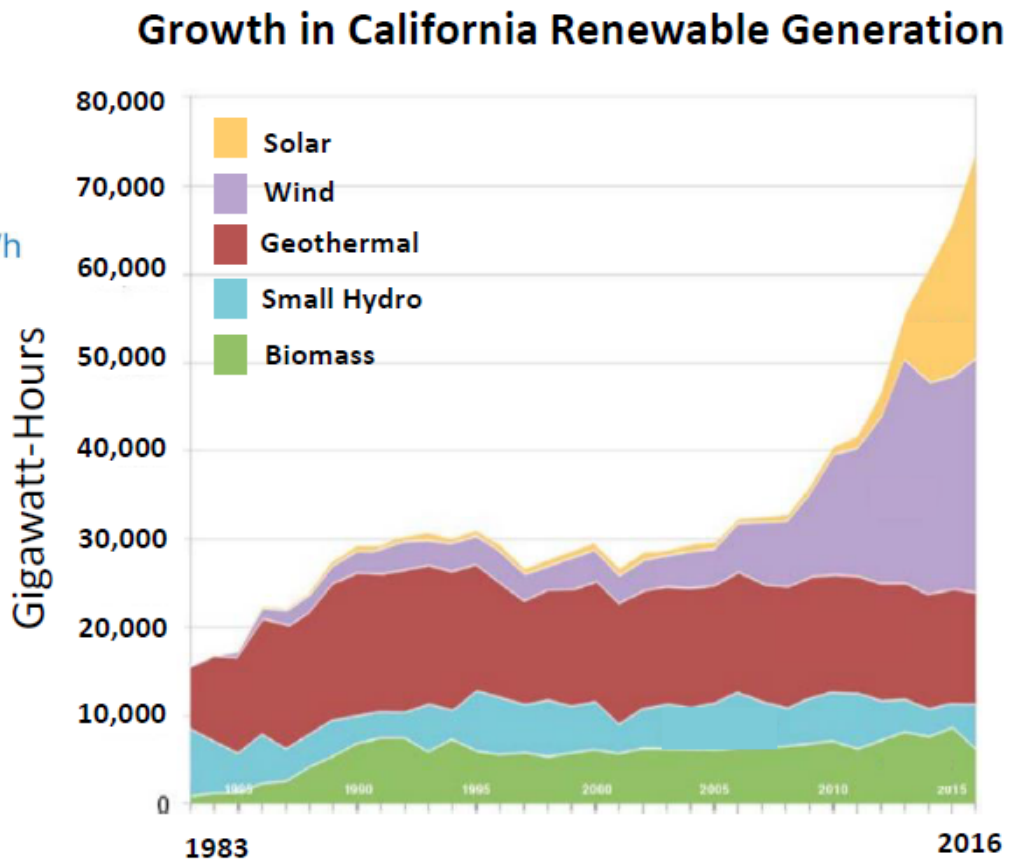
Changing Economics: Intermittent Electricity



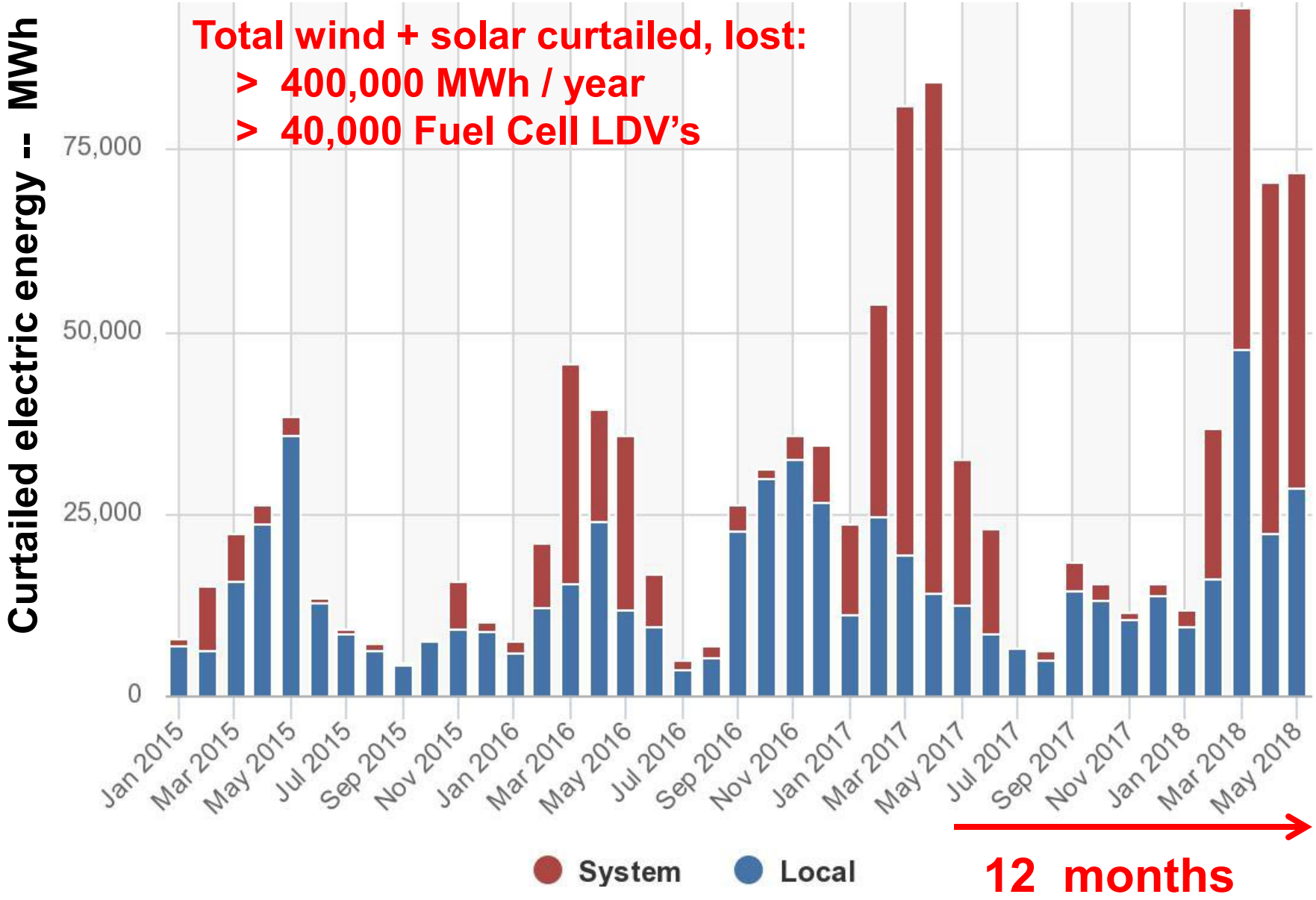
Source: (Arun Majumdar)
1. DOE EERE Sunshot Q1'15 Report,
2. DOE EERE Wind Report, 2015

California Renewable Energy



Source: California Energy Commission
http://www.energy.ca.gov/renewables/tracking_progress/documents/ renewable.pdf

California, CAISO: Curtailed wind + solar electric energy by "system condition"



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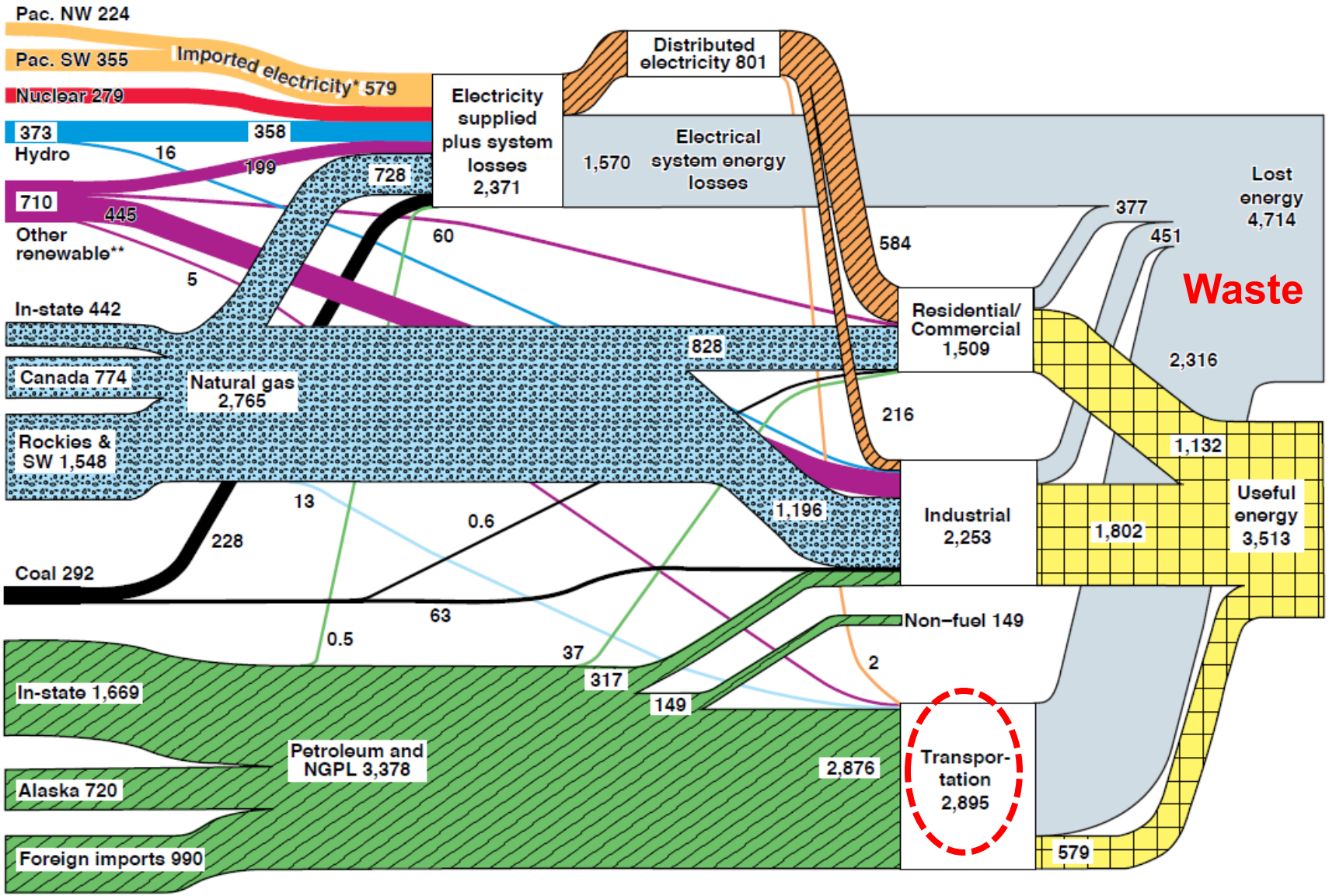
THEN, California will need →

California Energy Flow Trends– 1999

Net Primary Resource Consumption ~8375 Trillion Btu (8.375 Quads)



Sources: U.S. Department of Energy's Energy Information Administration and California Energy Commission.
*Electricity flowing into the California control areas: CAISO, LADWP, and IID.
**Other renewable includes geothermal, wood and waste, solar, and wind.

May 2003
Lawrence Livermore
National Laboratory
http://en-env.llnl.gov/flow

California, Year 2050, both:

- **Electricity RPS**
- **" 80 in 50 " Transport fuel**

- 210 GW wind = 35 times Year 2015 installed wind - electricity capacity in CA

PLUS

- 230 GW solar = 19 times Year 2015 installed solar - electricity capacity in CA

Total = 440 GW nameplate = 20 x 2015

- **wind + solar + other**
- **CO_2-emission-free energy**

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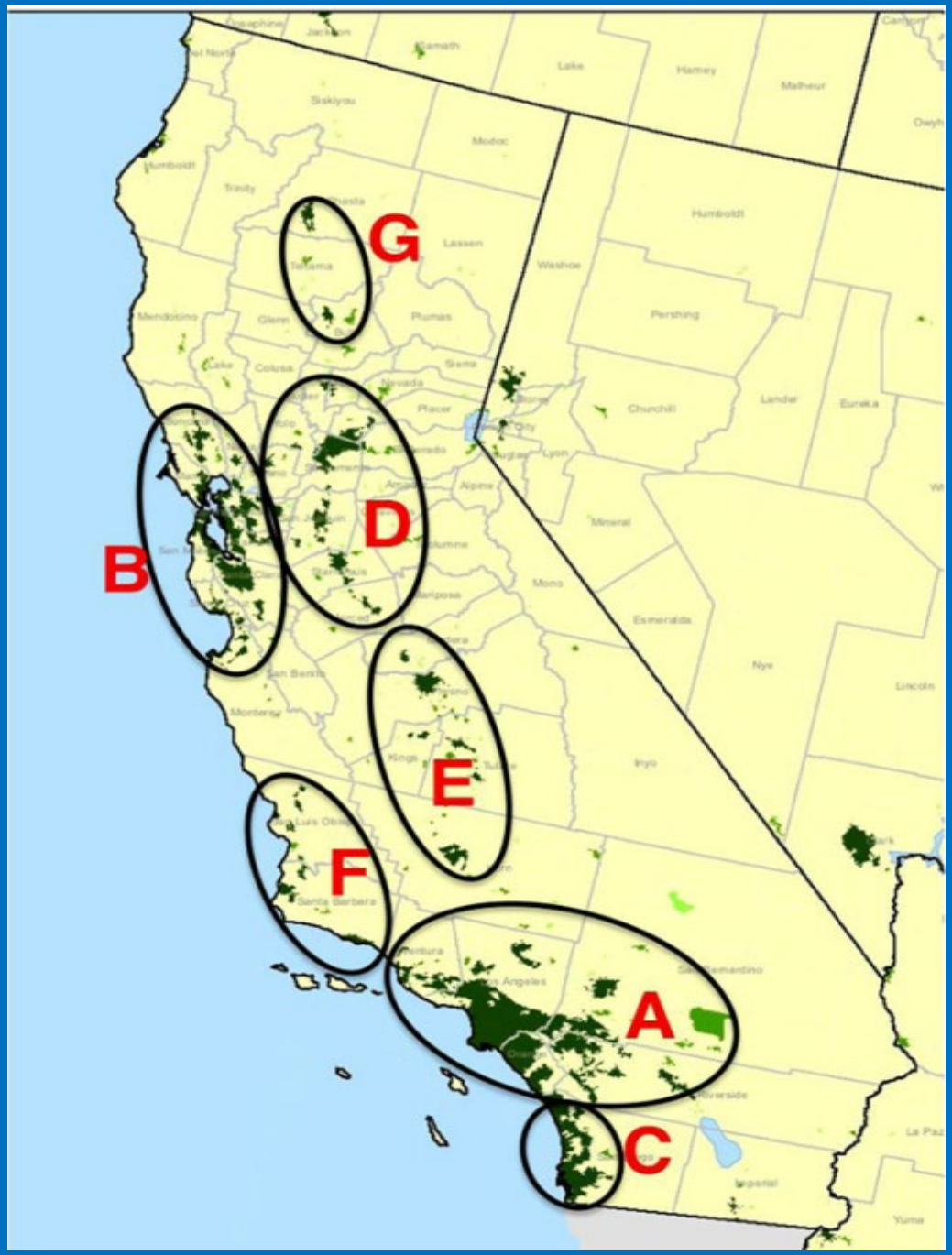
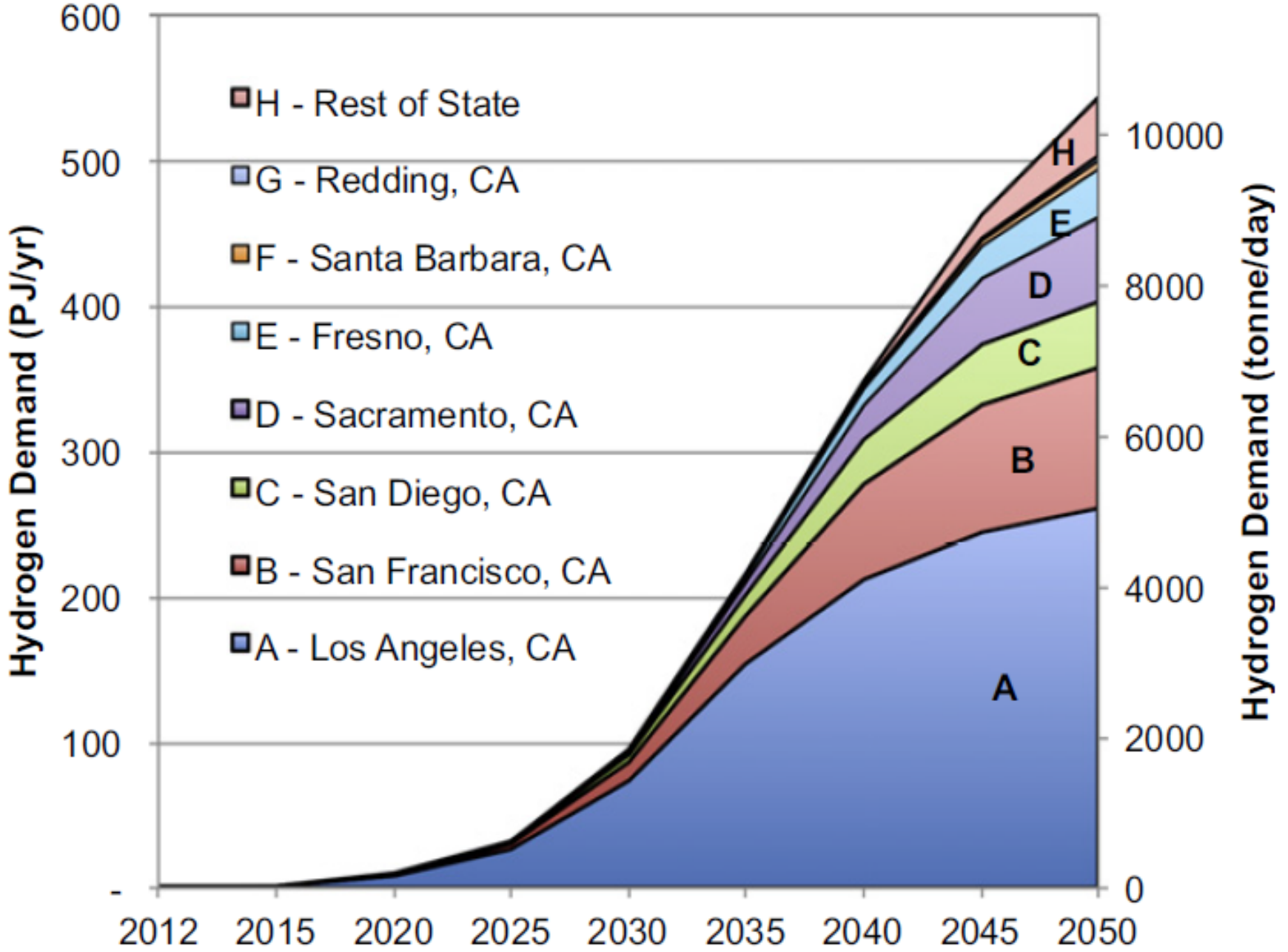


California Major Markets

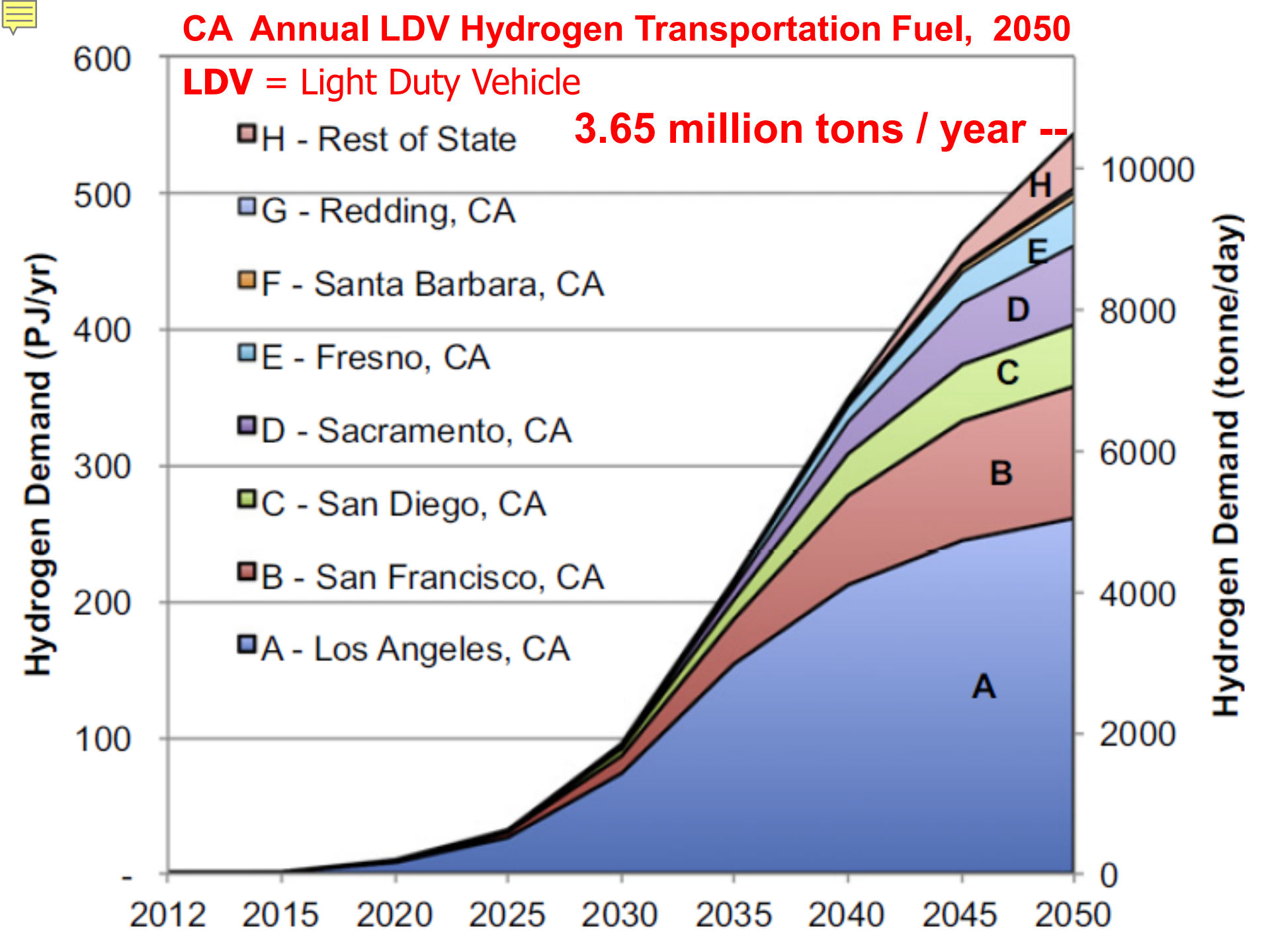
Hydrogen Transportation Fuel Light Duty Vehicles (LDV's)

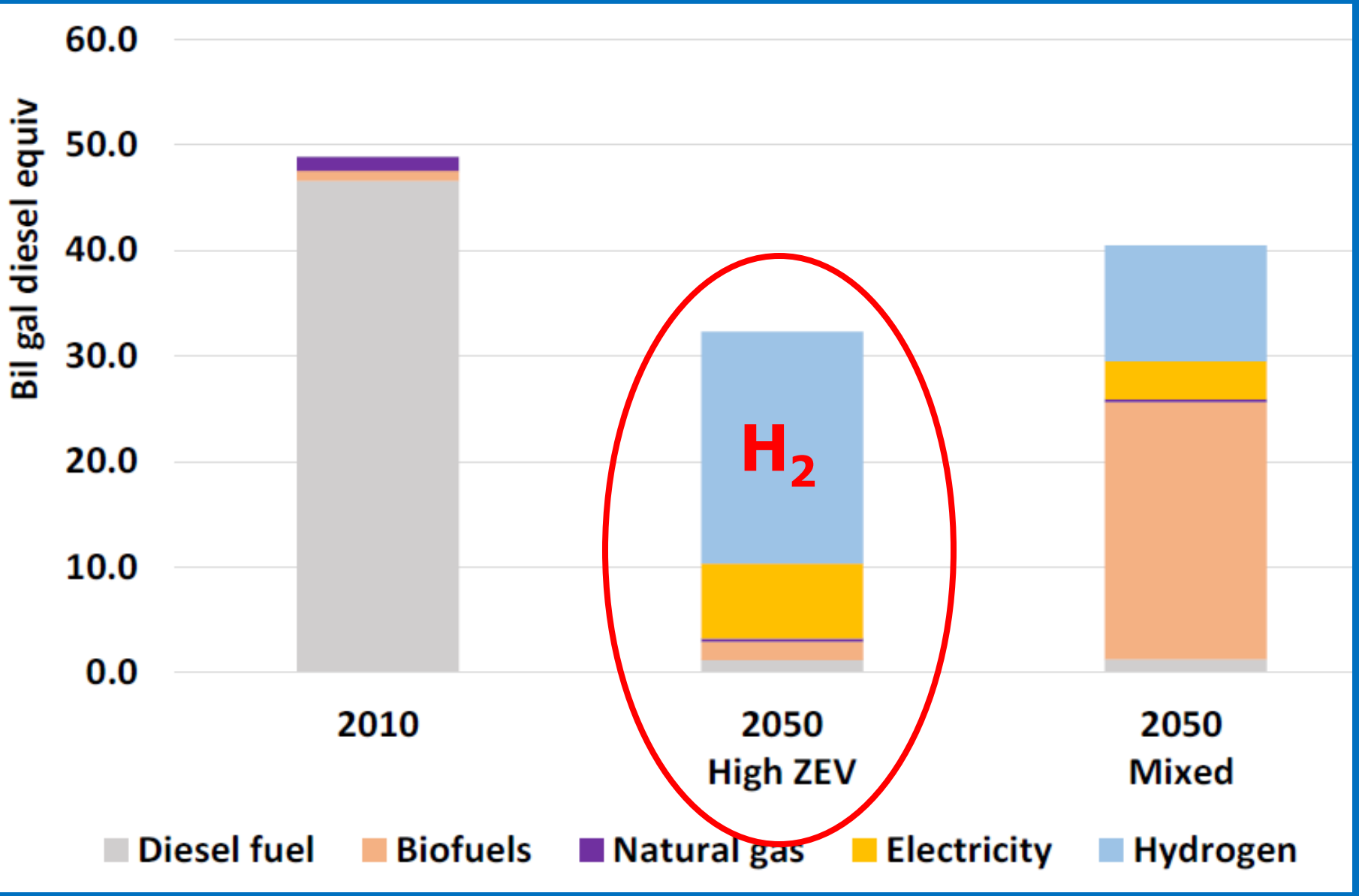
~ 7 million MT (metric ton = 1,000 kg) per year in 2050

California LDV Hydrogen Fuel Demand, MT / day



MT = metric ton = 1,000 kg per day


CA Annual LDV Hydrogen Transportation Fuel, 2050
LDV = Light Duty Vehicle
3.65 million tons / year --
H - Rest of State
G - Redding, CA
F - Santa Barbara, CA
E - Fresno, CA
D - Sacramento, CA
C - San Diego, CA
B - San Francisco, CA
A - Los Angeles, CA
Hydrogen Demand (PJ/yr)
Hydrogen Demand (tonne/day)
600
500
400
300
200
100
-
10000
8000
6000
4000
2000
0
2012
2015
2020
2025
2030
2035
2040
2045
2050



California trucking: "Goods movement"

~ 1.6 billion kg Hydrogen to replace diesel = ~ 1.6 MMt / year

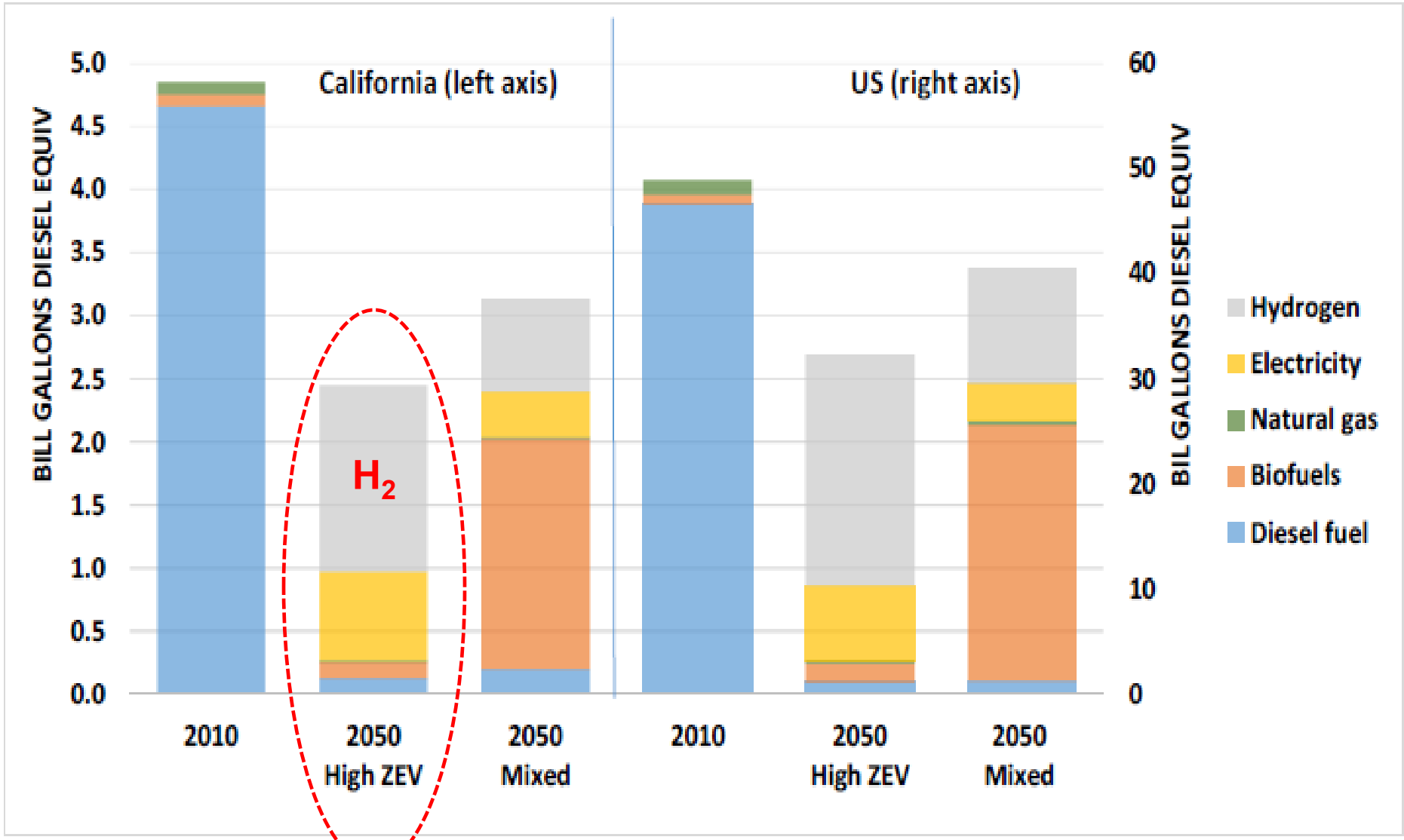


Figure ES-2. Energy use by fuel type, year and scenario, California and U.S. results

California and USA Trucking -- Year 2050

CA: ~ 1.6 billion kg Hydrogen to replace diesel = ~ 1.6 MMt / year

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**

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

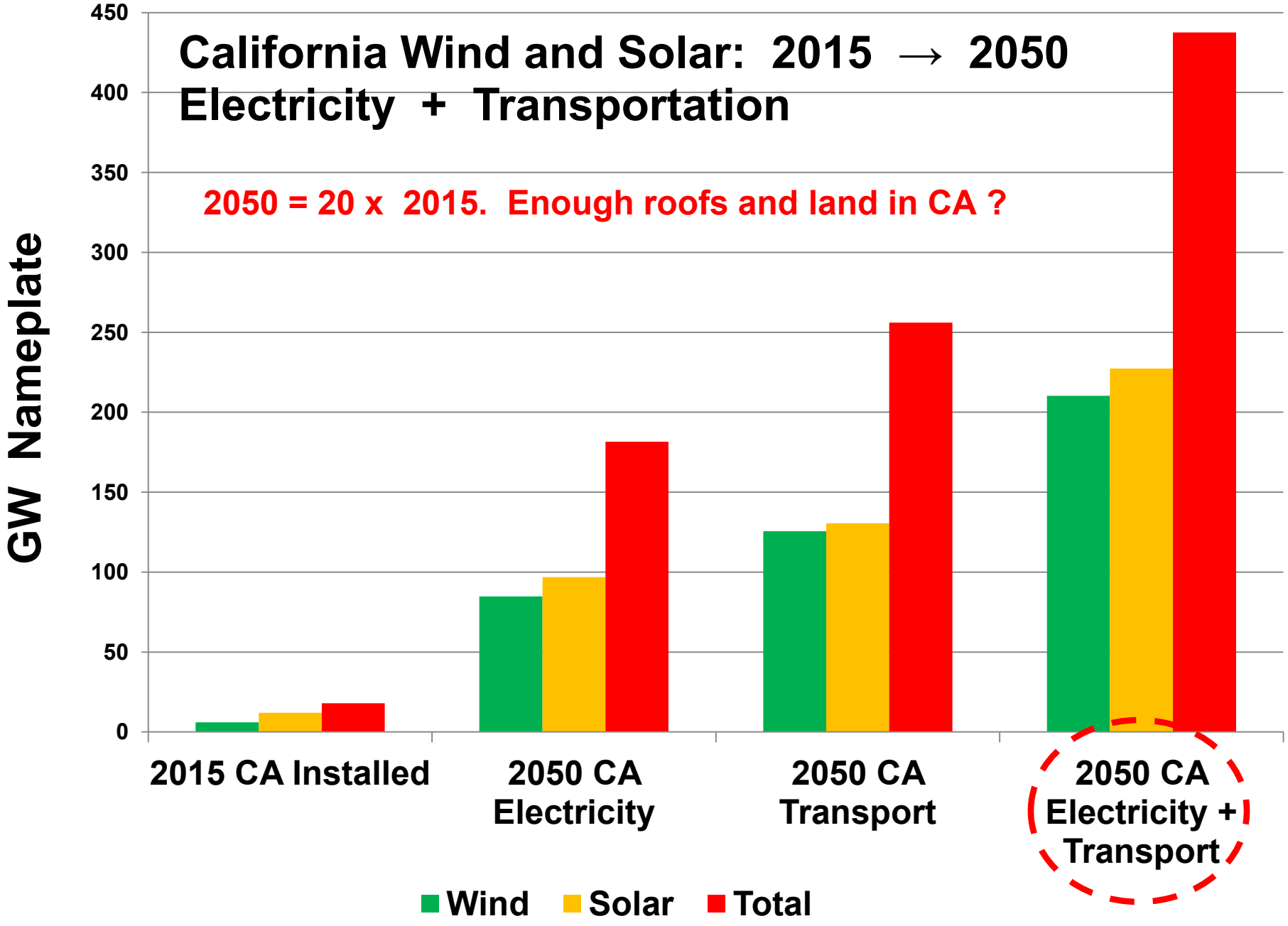
Hydrogen Transportation Fuel Demand
California, year 2050
Million metric tons per year:

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

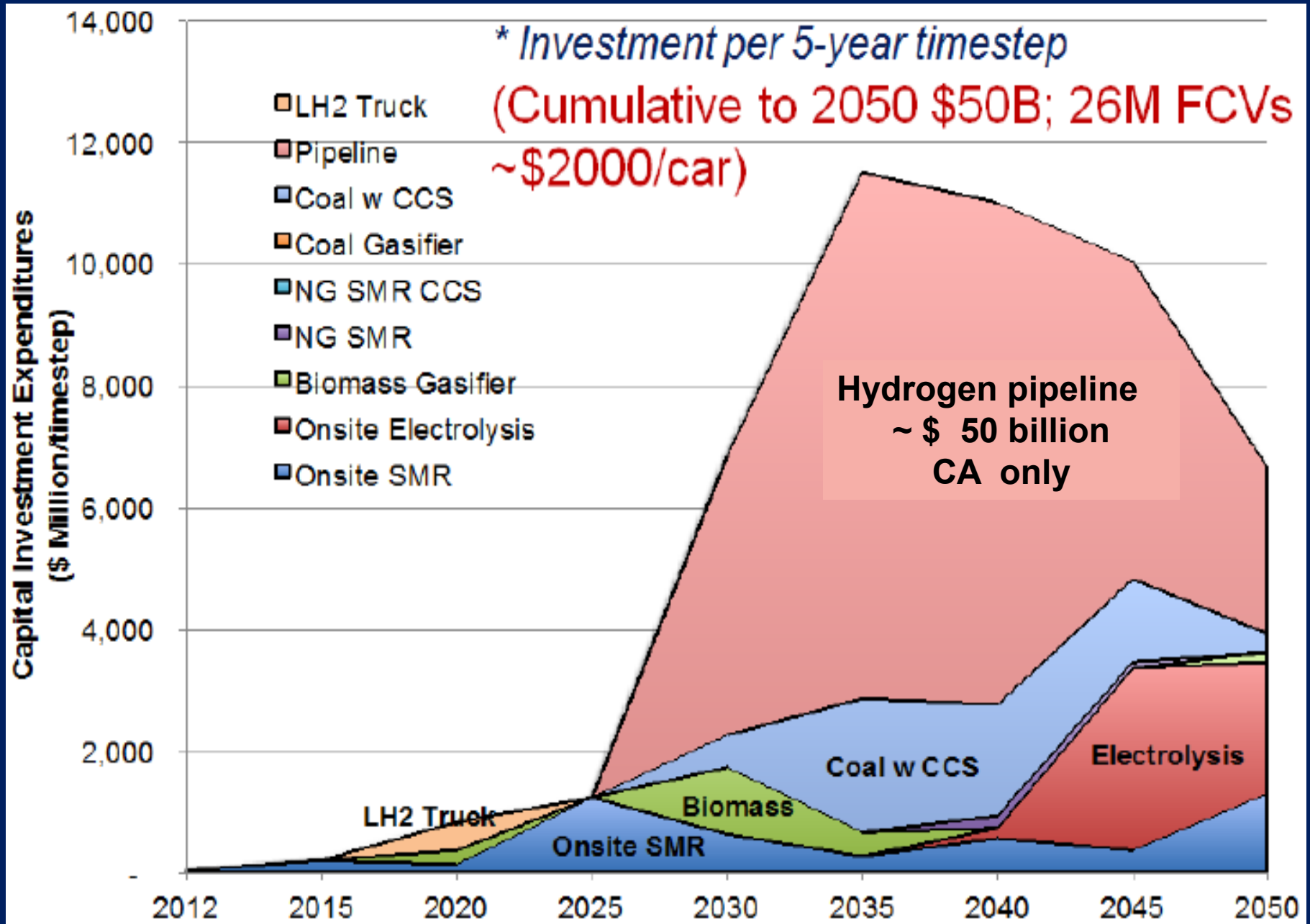
Source:
Interpret and extrapolate from several papers by
ITS-STEPS, UC Davis

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


California Wind and Solar: 2015 → 2050
Electricity + Transportation
2050 = 20 x 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

"Hydrogen Transition" UC Davis, ITS "NEXTSteps"



Major new markets for H_2, NH_3

Transportation fuel

- **Highway: LDV, bus, truck**
- **Rail: Alstom, UK trains**
- **Marine: ammonia fuel (NH_3)**
- **Aviation: 6 – 20 pax, Airbus "Cryoliner" A320**

CHP stationary fuel: Combined Heat and Power

Iron ore reduction: $FeO_x + H_2 \rightarrow Fe + H_2O$

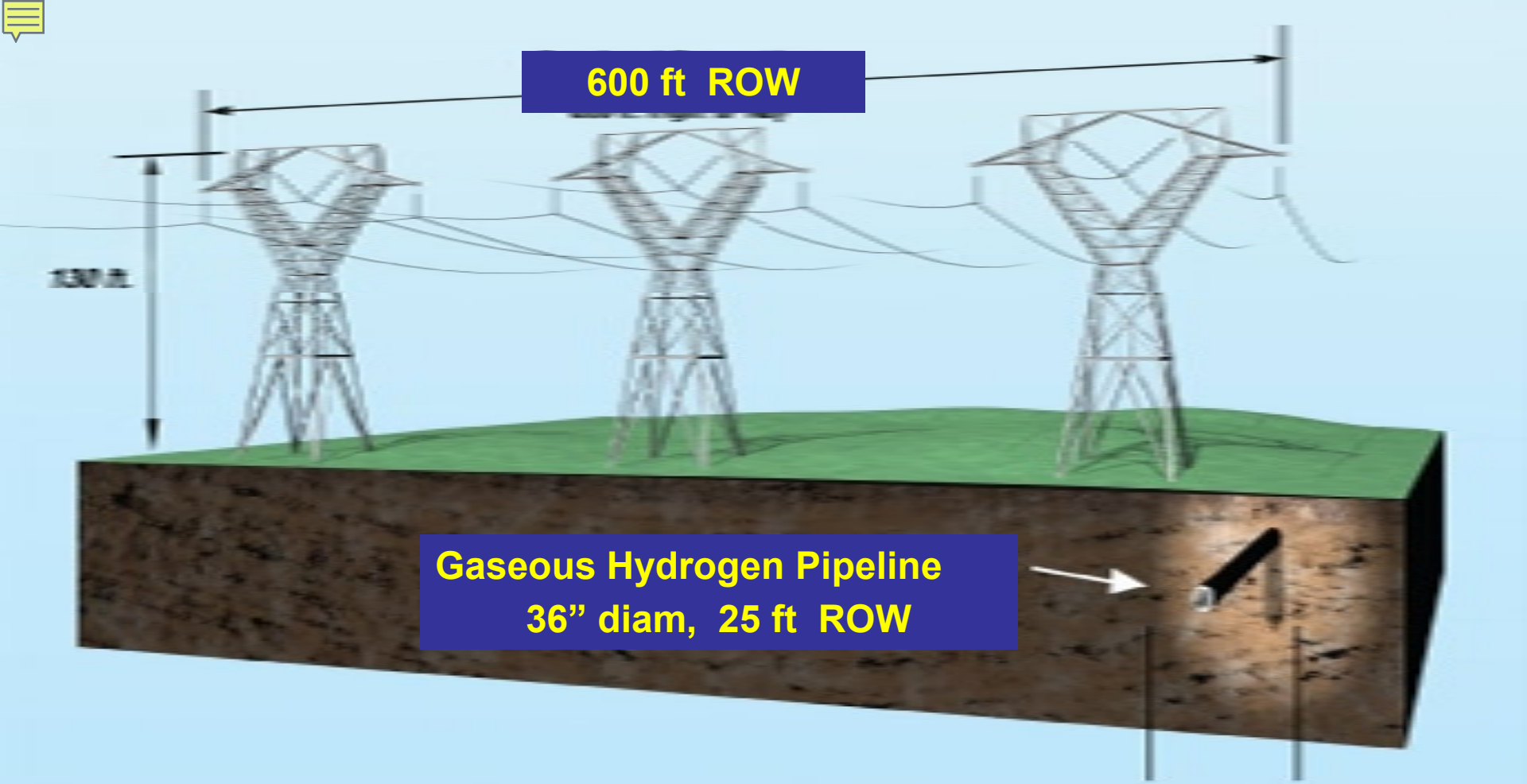
N-fertilizer production: $N_2 + H_2 \rightarrow NH_3 \rightarrow$

Oil refining

- ***Pipeline networks required ? GH_2, liquid NH_3***
- ***Possible with electricity ?***
- ***Curtailed wind + solar: 440,000 MWh, CA, 2018***
- ***Wind beyond 2020: PTC ends → cliff***

Trouble with Electricity

- "Grid quality" AC, DC
- Light speed
- Storage expensive: annual-scale, dispatchable ?
- Markets, regs, ISO's, RTO's → manipulate
- Infrastructure:
  - Costly: build, maintain Capex, Opex
  - Obtrusive, offensive, NIMBY
  - Wide ROW
  - Vulnerable to acts of God and man
  - Vulnerable to Cyberattack
  - Fire danger, liability: PG&E
- Extant USA "Grid" :
  - Old, end of service life
  - Repair, Replace, Renew ?
  - Expand, "smart" ? How much ? CF ? Cost ?
- Need comparative study: now, avoid misallocation

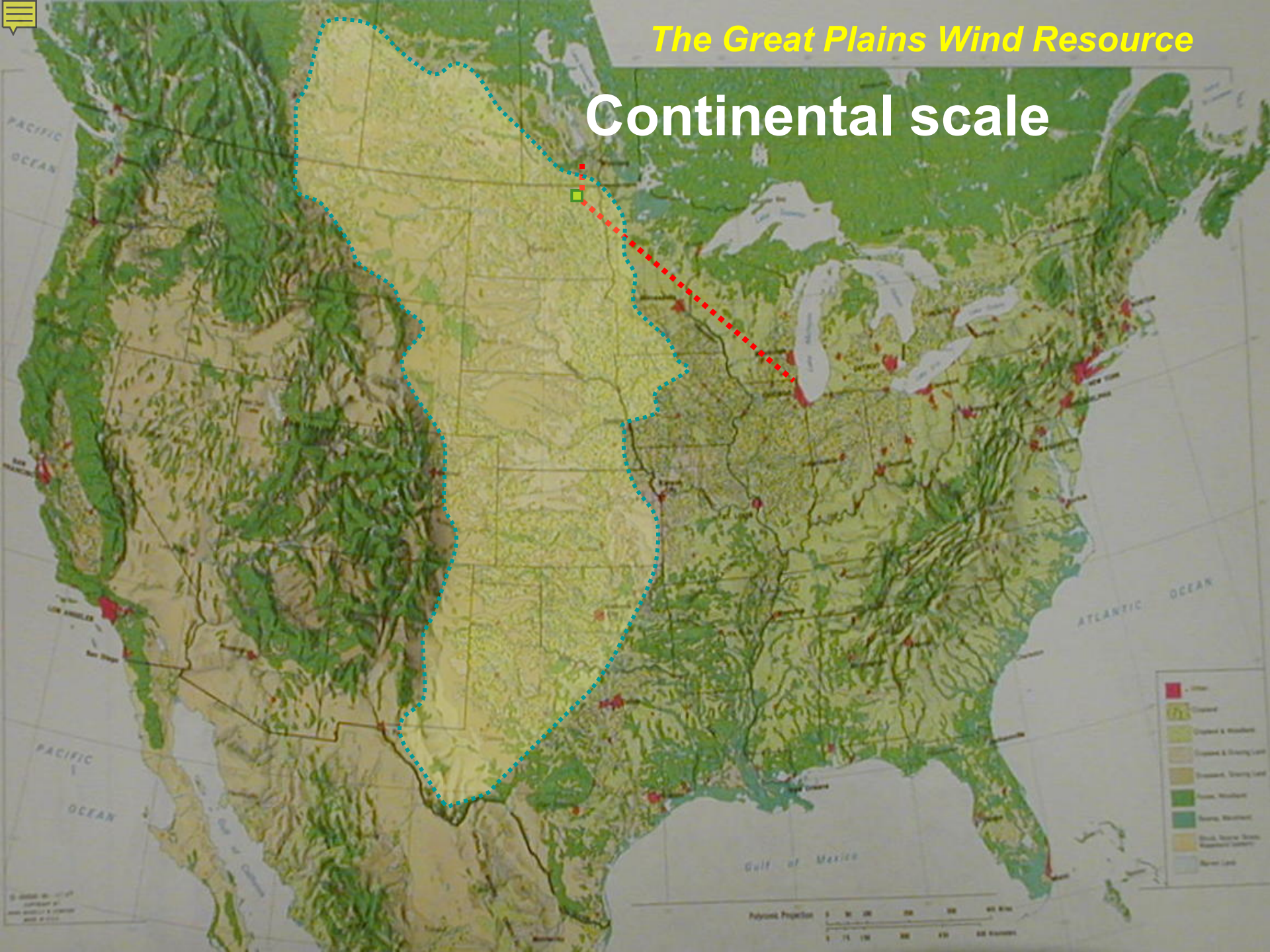


Out of Sight, Out of Harm’s Way

8,000 MW alternatives: HVAC vs Hydrogen Pipeline


Zion, IL
Near Zion nuclear plant, Oct 02

Vulnerable to acts of God and man


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

Exporting From 12 Windiest Great Plains States

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

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

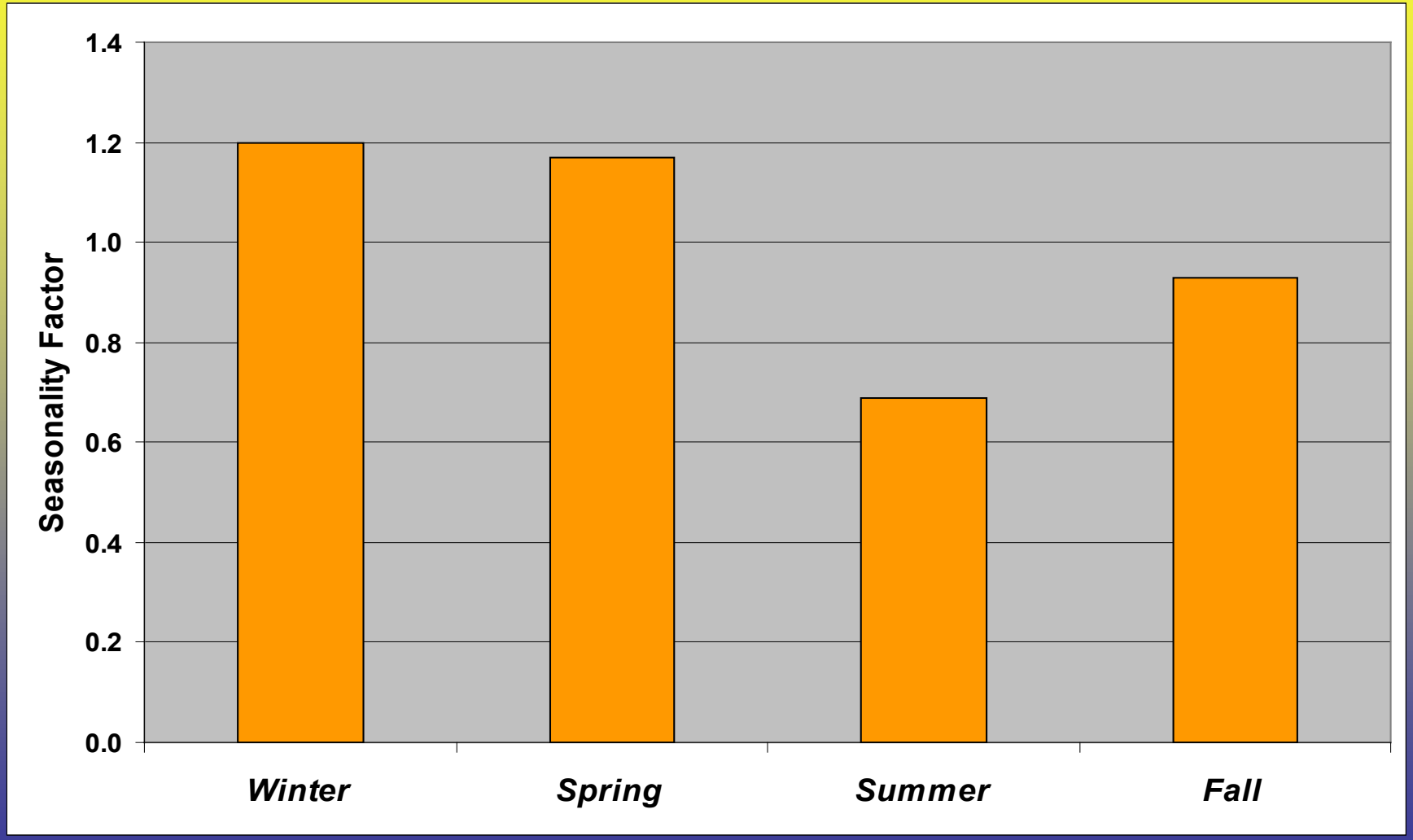
Wind energy source: Archer, Jacobson 2003

Michael Skelly

- Clean Line Energy Partners: HVDC transmission lines for wind, solar
- Lazard Senior Advisor

Wind Seasonality, Northern Great Plains

Normalized to 1.0 per season



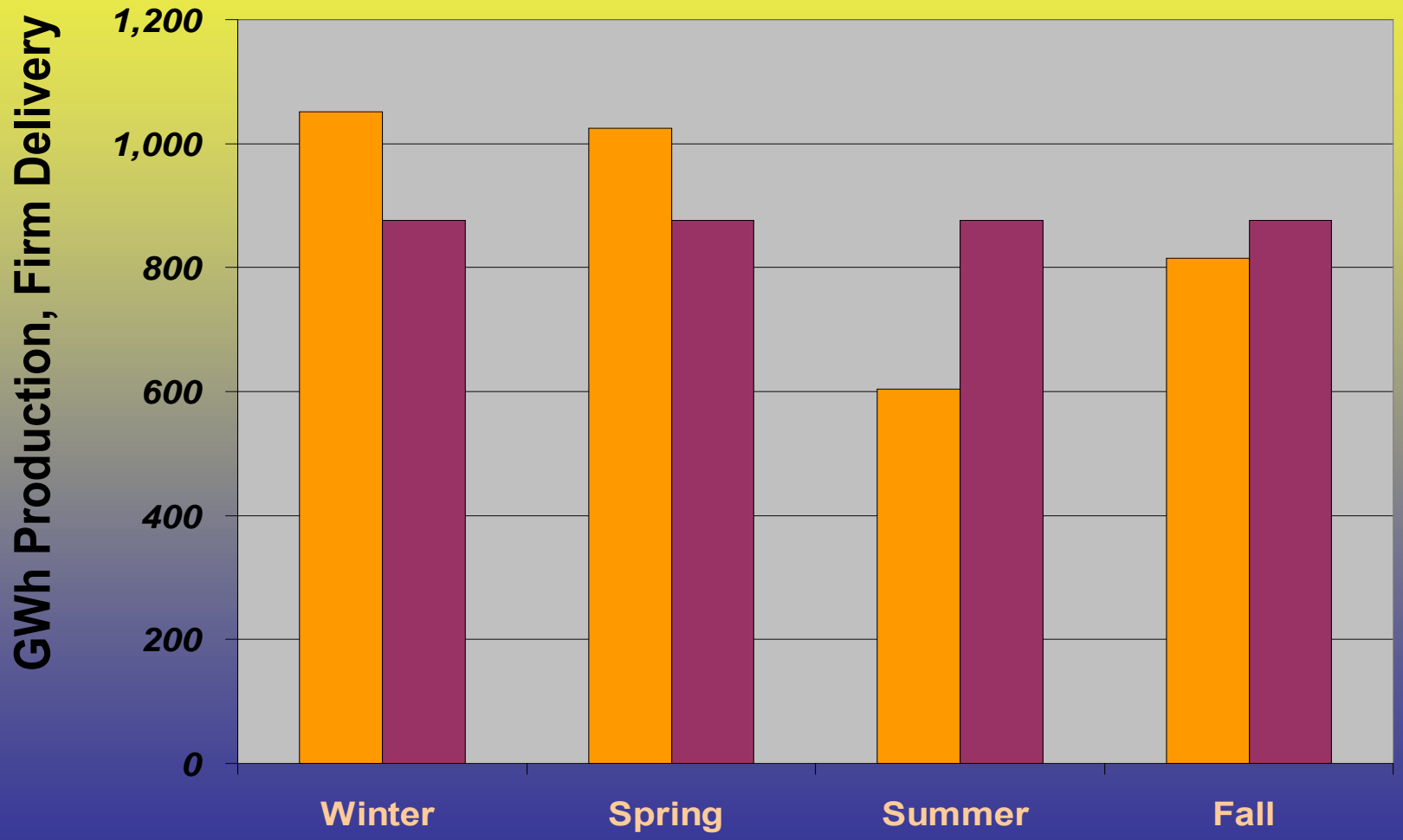
Wind Seasonality, Northern Great Plains

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**

TESLA 20 MW / 80 MWh battery
SCE Mira Loma Battery Storage Facility, Ontario, CA
Cost: undisclosed. @ $ 400 / kWh = $ 32 Million

TESLA 100 MW / 129 MWh battery
South Australia
“Cost me over $ 50 million” (if failed) -- Elon Musk
129 MWh @ $ 50 million = $ 390 / kWh capex

TESLA "Gigafactory", Nevada: Li-Ion

Annual capacity 35 GWh :

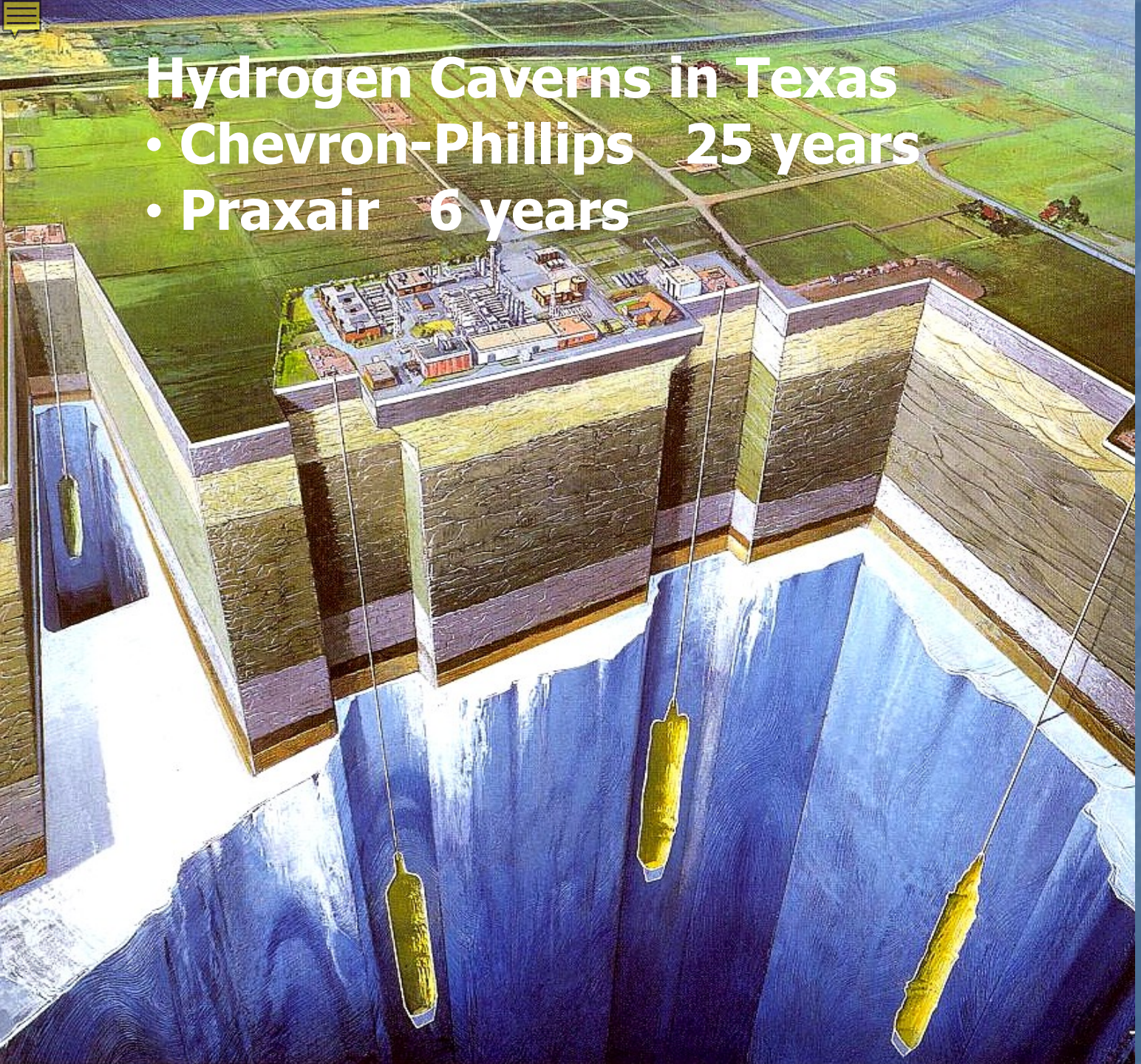
- Hydrogen: 1 salt cavern @ $ 15-20 million = 90 GWh
- Ammonia: 1 liquid tank @ $ 15-20 million = 200 GWh

Li-Ion battery production (Bloomberg)

Global total 2017 = 103 GWh / year

Global total 2021 = 278 GWh / year

- Hydrogen: 1 salt cavern @ $ 15-20 million = 90 GWh
- Ammonia: 1 liquid tank @ $ 15-20 million = 200 GWh



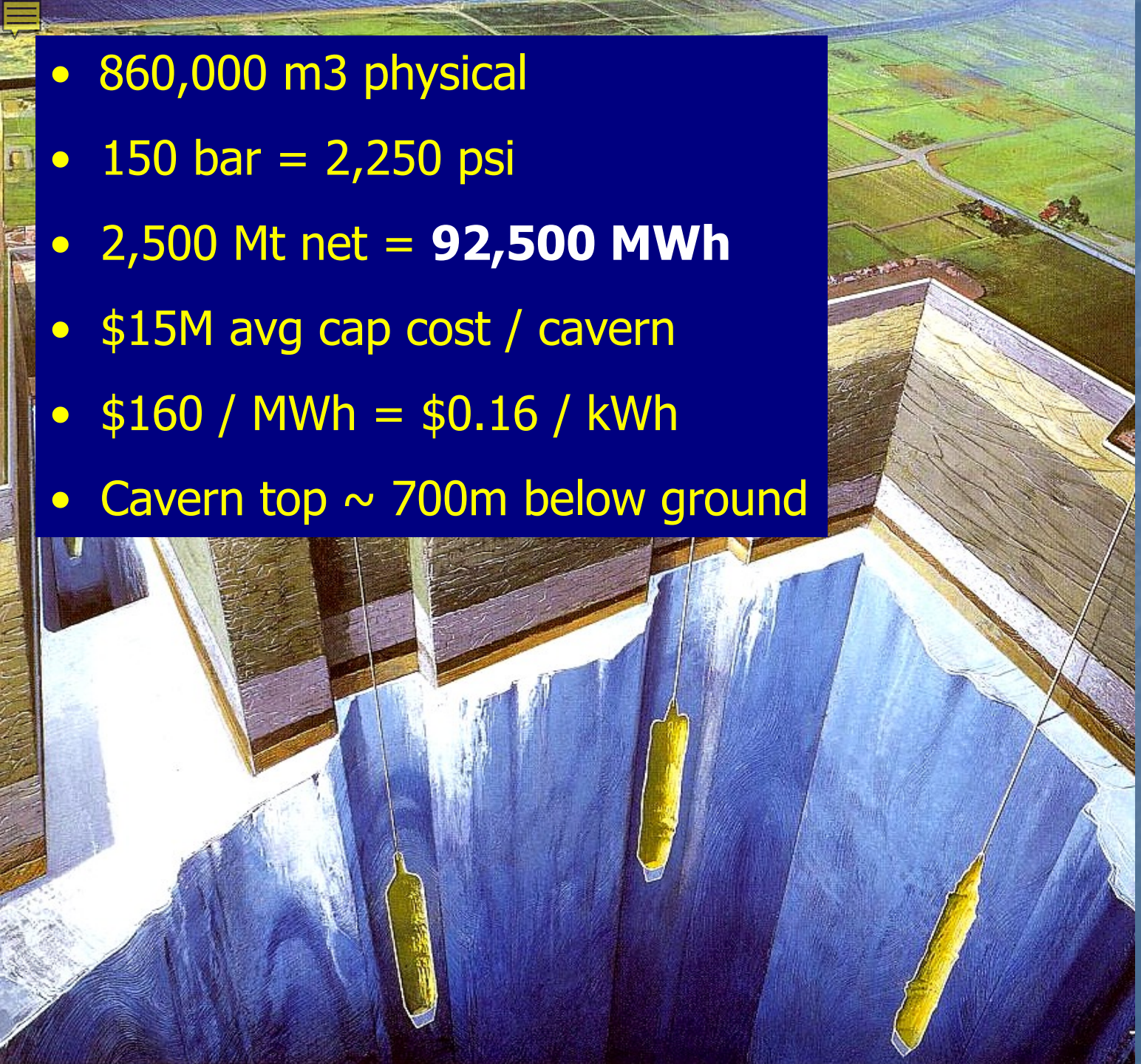
Domal Salt Storage Caverns

Each:

90 GWh

$ 15 million capex

$ 0.20 / kWh



- 860,000 m3 physical
- 150 bar = 2,250 psi
- 2,500 Mt net = **92,500 MWh**
- $15M avg cap cost / cavern
- $160 / MWh = $0.16 / kWh
- Cavern top ~ 700m below ground

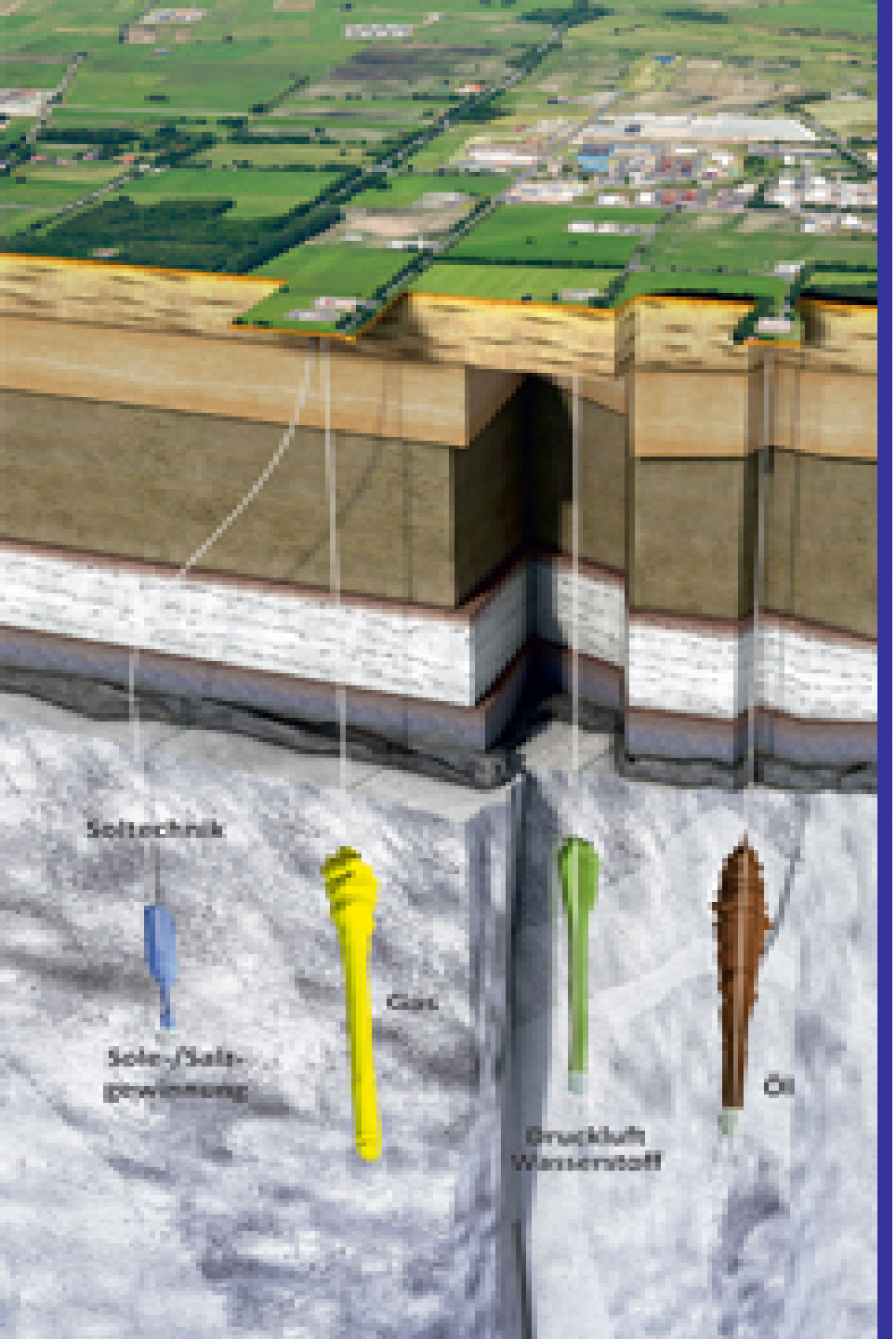
Domal Salt Storage Caverns

Texas

"Clemens Terminal" Conoco Phillips 20 years

Praxair '07

PB ESS



Erdgas

Porenspeicher
- in Betrieb
- in Planung oder Bau

Kavernenspeicher
- in Betrieb
- in Planung oder Bau

Rohöl, Mineralprodukte, Flüssiggas

Kavernenspeicher
- in Betrieb

(Quelle: LBEG, 2010)

Renewable-source GH2 geologic storage potential

Candidate formations for manmade, solution-mined, salt caverns

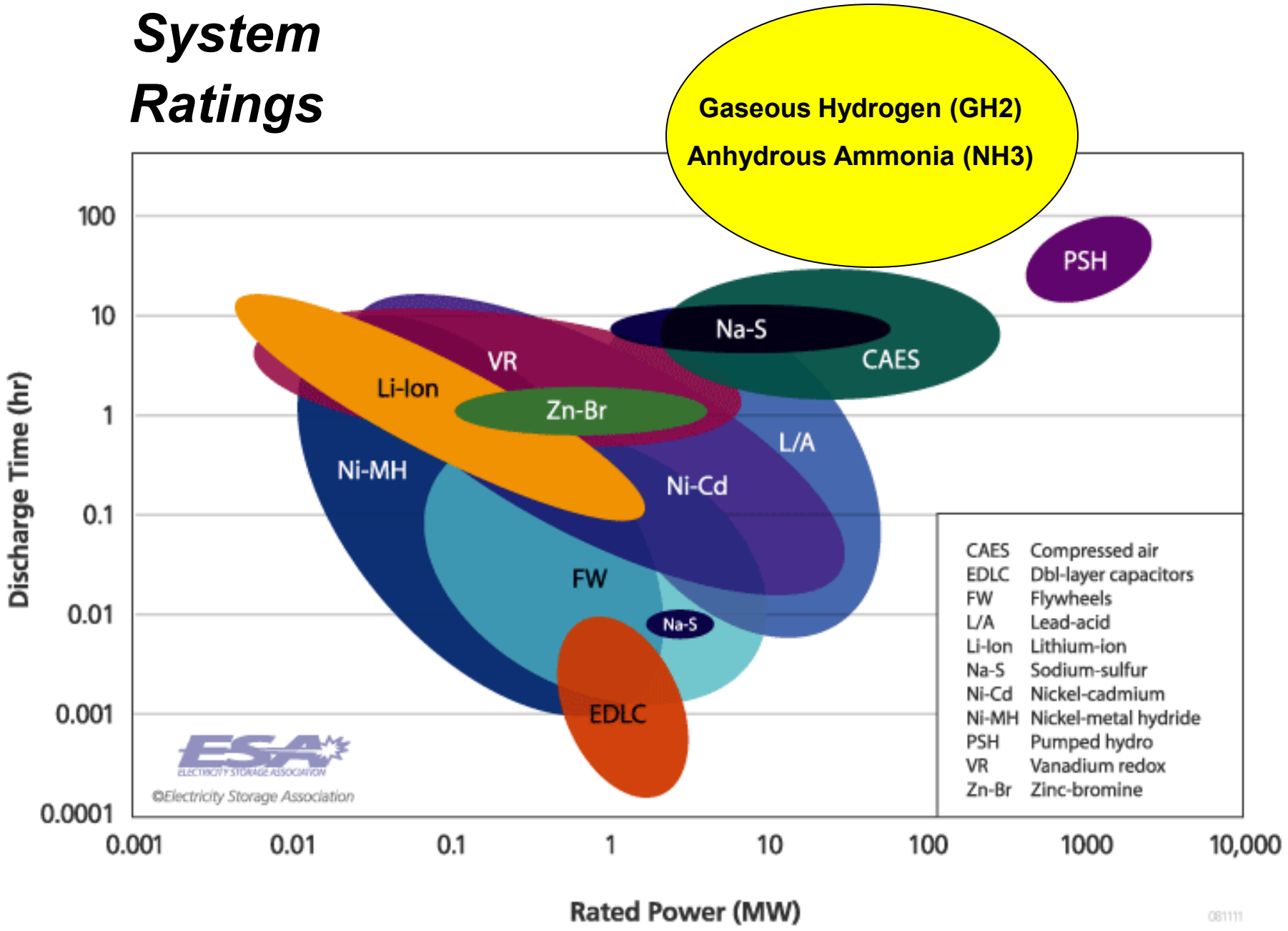
“Atmospheric” Liquid Ammonia Storage Tank (Corn Belt)

-33 C 1 Atm

Each: 30,000 Tons, 190 GWh $ 20 M turnkey

$ 100 / MWh = $ 0.10 / kWh capital cost

System Ratings

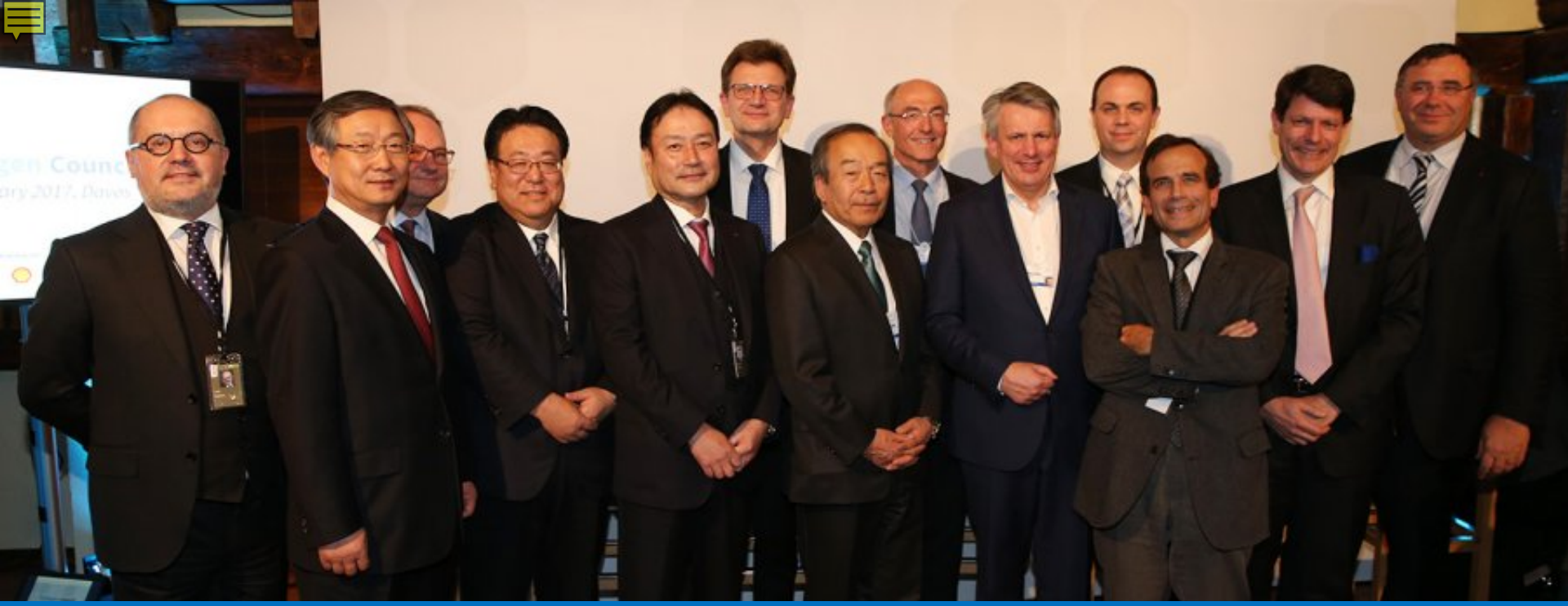


As California goes:

- 2050: RPS + "80 in 50"
- USA ?
- World ?

Far More ambitious: "Hydrogen Council"

- Beyond electricity systems
- Renewables industry, OEM's
- Hydrogen industry, OEM's
- Transport + CHP fuels
- Run the World on Renewables
- ~ 100 % CO2-emissions-free energy



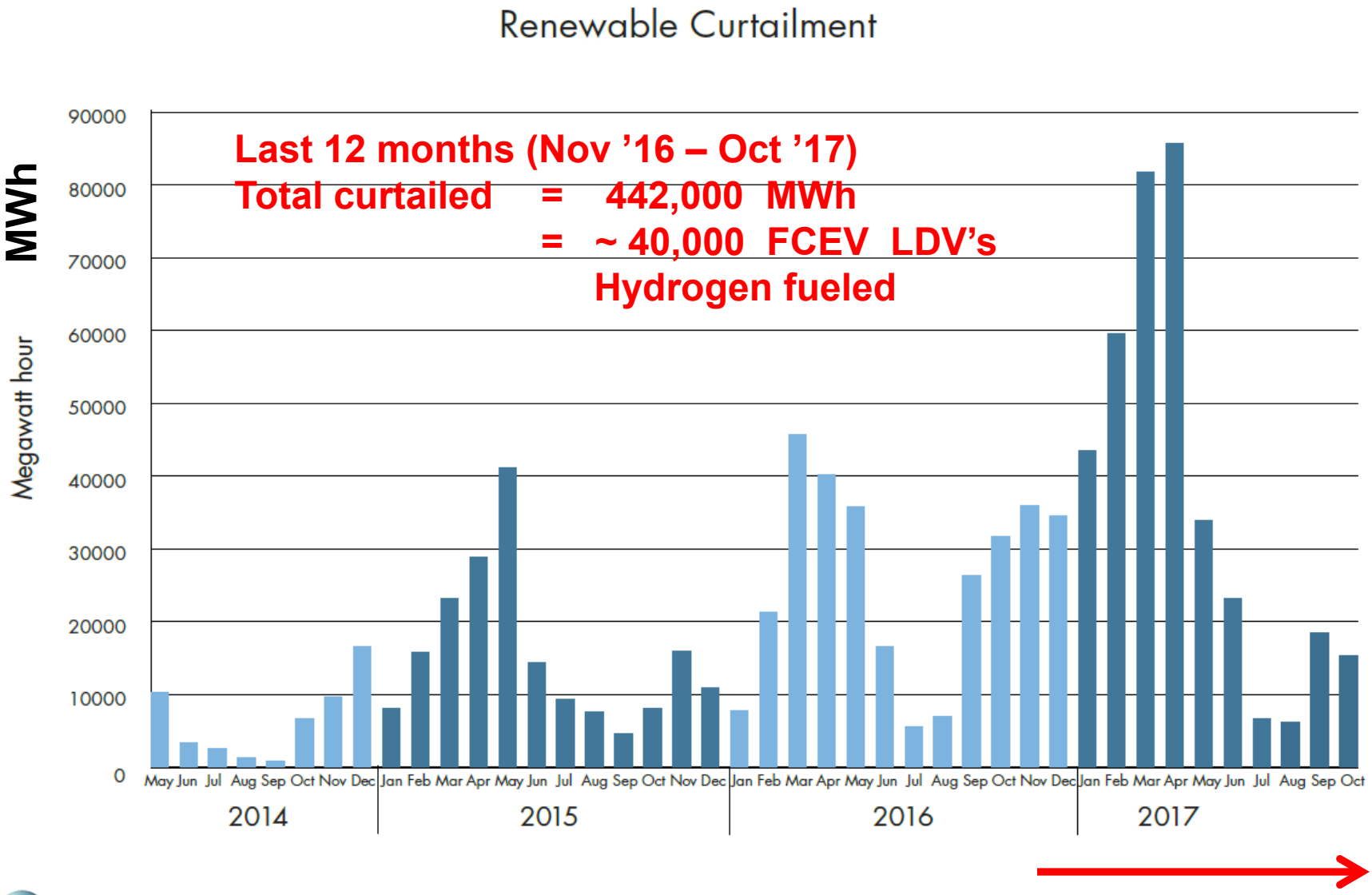
Hydrogen Council
Brussels, 7 Sept 17 24 companies

Hydrogen Council: 60 companies

3M, Airbus, Air Liquide, Air Products, Alstom, Anglo American, Audi AG, BMW GROUP, BP, China Energy, Cummins, Daimler, EDF, ENGIE, Equinor, Faurecia, General Motors, Great Wall Motor, Honda, Hyundai Motor, Iwatani, Johnson Matthey, JXTG Nippon Oil & Energy Corporation, Kawasaki, KOGAS, Linde, Plastic Omnium, Royal Dutch Shell, Sinopec, The Bosch Group, ThyssenKrupp, Total, Toyota Weichai,

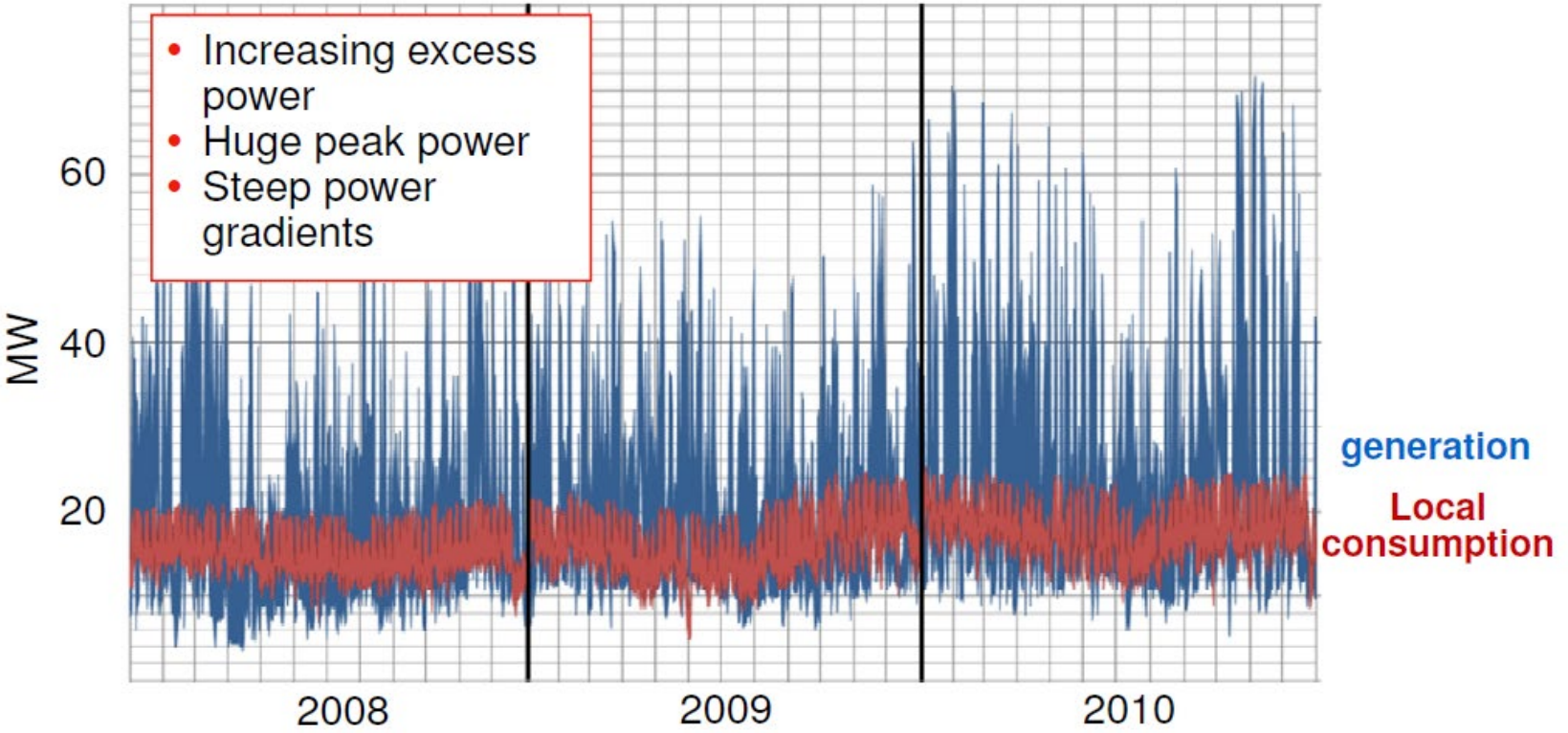
AFC Energy, AVL, Ballard Power Systems, Faber Industries, First Element Fuel (True Zero), W. L. Gore, Hexagon Composites, Hydrogenics, ITOCHU Corporation, The Liebherr Group, Marubeni, McPhy, Mitsubishi Corporation, Mitsubishi Heavy Industries Ltd., Mitsui & Co, Nel Hydrogen, NGK Spark Plugs, Plug Power, Power Assets Holdings Limited, Re-Fire Technology, Royal Vopak, SinoHytec, Southern California Gas, Sumitomo Mitsui Banking Corporation, Sumitomo Corporation, Toyota Tsusho.

California ISO wind + solar production curtailment: no transmission and / or storage capacity



Free Storage + Free Transmission in E.on Natural Gas Pipeline System

Falkenhagen Region in Northern Germany

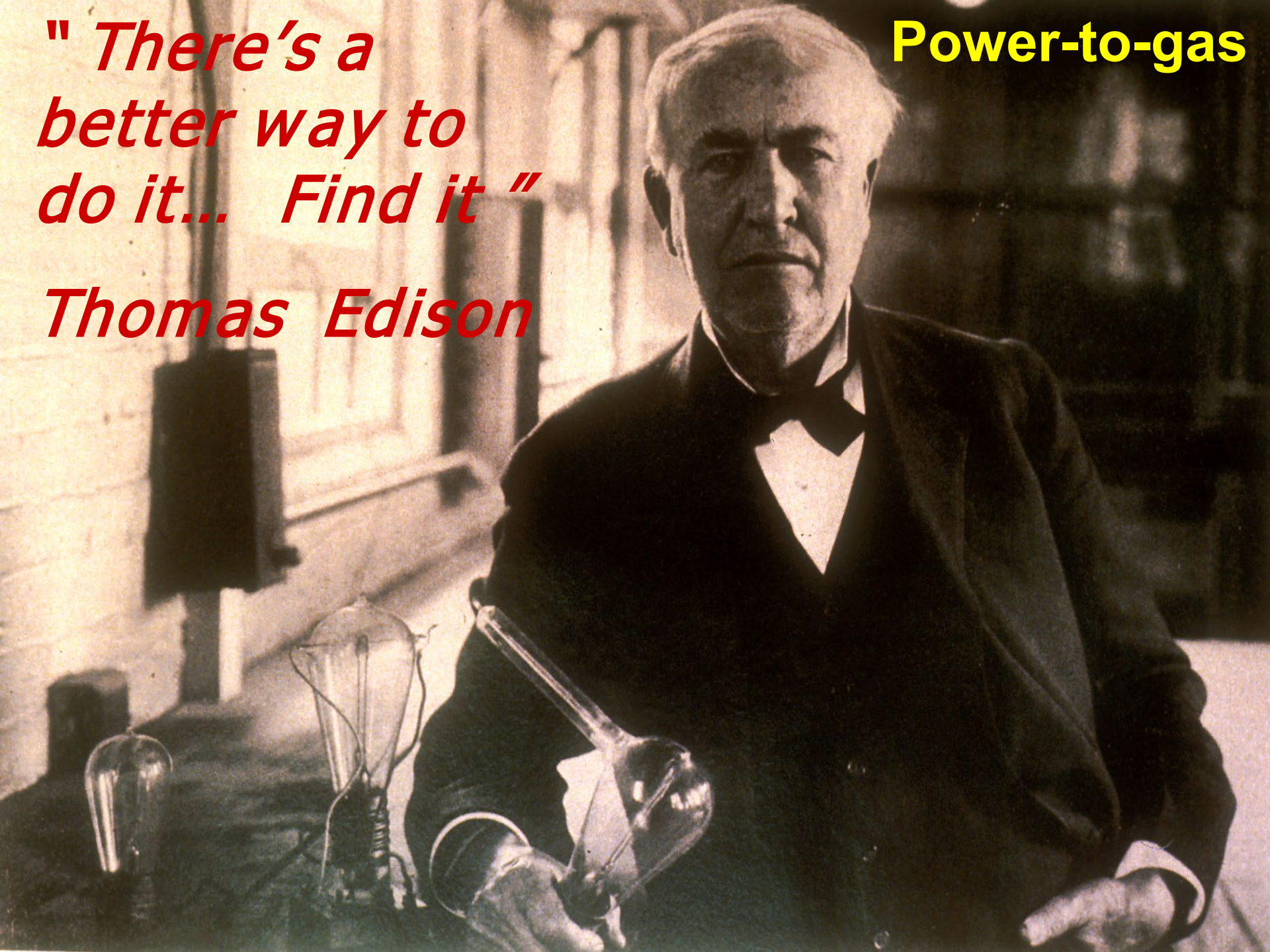


Solution: Storage of excess wind power instead of curtailment.

e·on

31

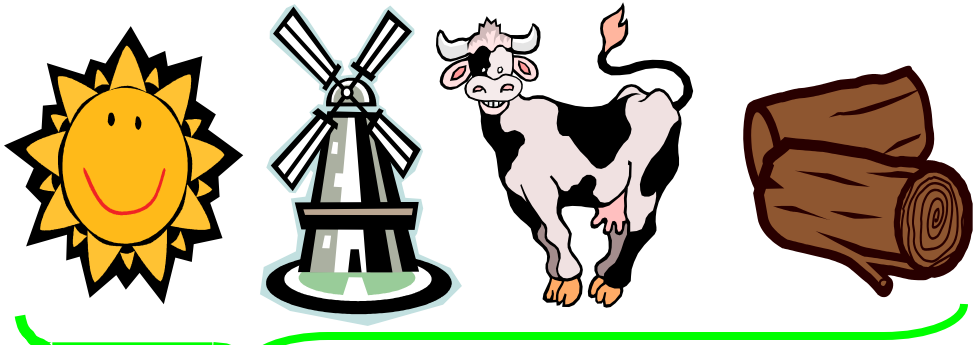
Source: Presentation by Dr. Alexander Vogel, Head of Alternative Energy Systems, E.ON Ruhrgas at Gas to Power Conference, Cologne, Germany – November 2012


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

E.ON first Power-to-Gas plant Injecting hydrogen into natural gas grid

2MW Power-to-Gas Demonstration Plant in Falkenhagen, Germany

2006: The NATURALHY approach: EC, R+D



" Power – to – Gas "

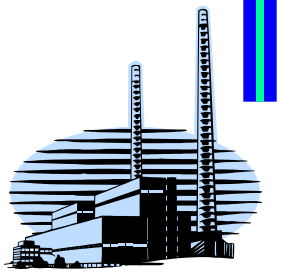
H_2

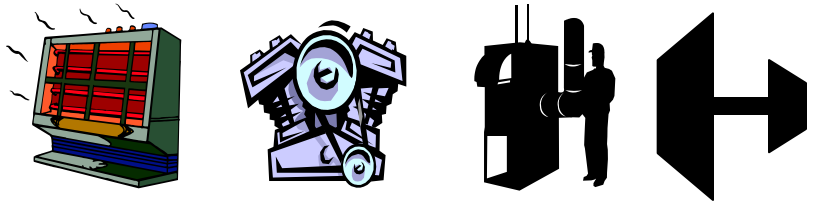
NG

Pure H_2

NATURALHY:

- ***Breaks "chicken-egg" dilemma***
- ***Bridge to sustainable future***

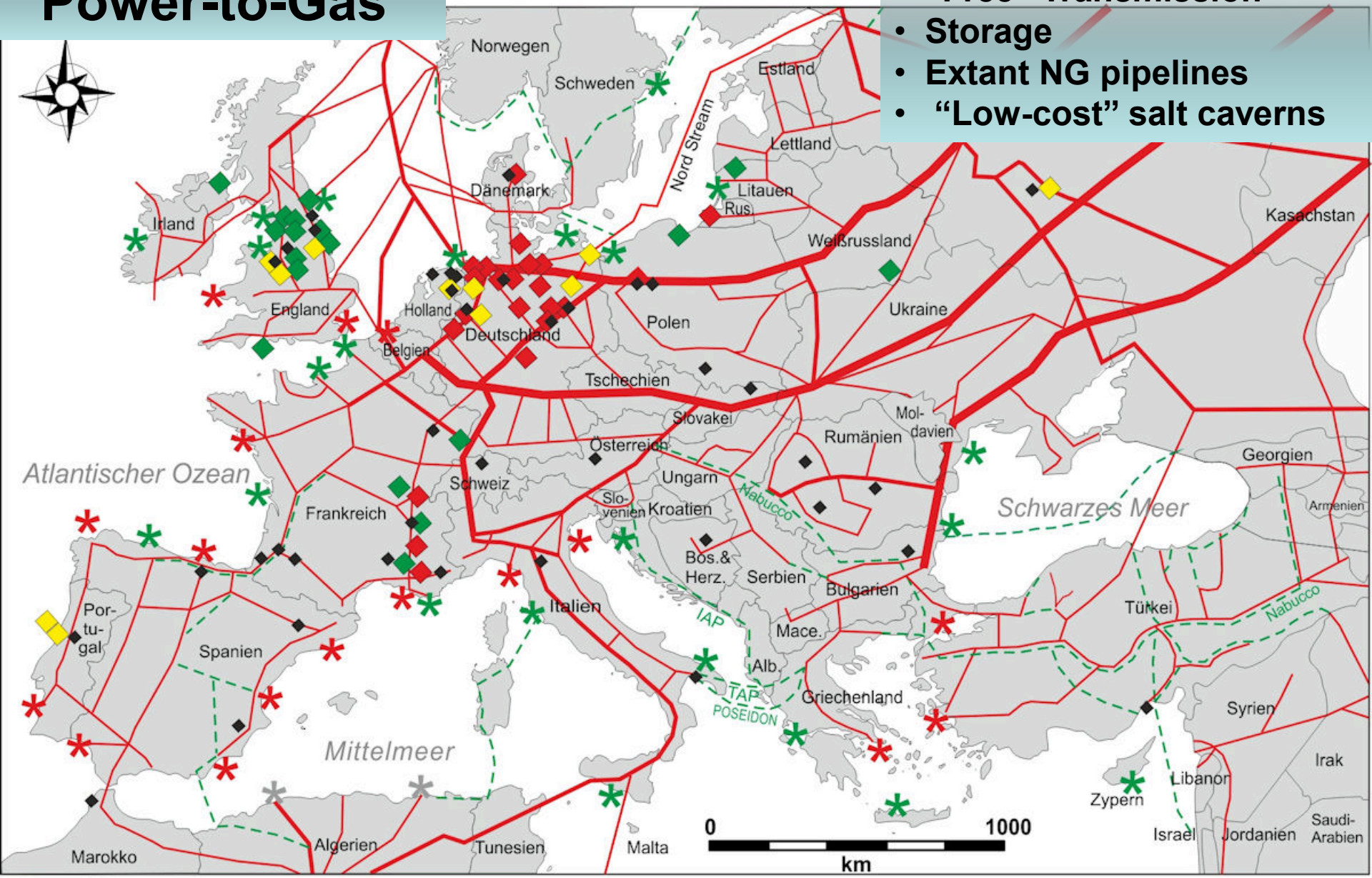




Prepared by
O. Florisson
Gasunie

"Power-to-Gas"

- "Free" Transmission
- Storage
- Extant NG pipelines
- "Low-cost" salt caverns



KBB UT

Gaskavernenspeicher
Gas cavern storage

Gaskavernenspeicher in Planung oder Bau
New gas cavern storage planned/under construction

Erdgasleitungen
Gas pipeline

Erdgasleitungen in Bau bzw. Planung
Gas pipeline planned/under construction

Gaskavernenspeicher in Betrieb bzw. Erweiterung
Existing gas cavern storage under extension

Kavernenspeicher für Rohöl, Flüssiggas, Soleproduktion
Storage of crude oil & LPG, brine production

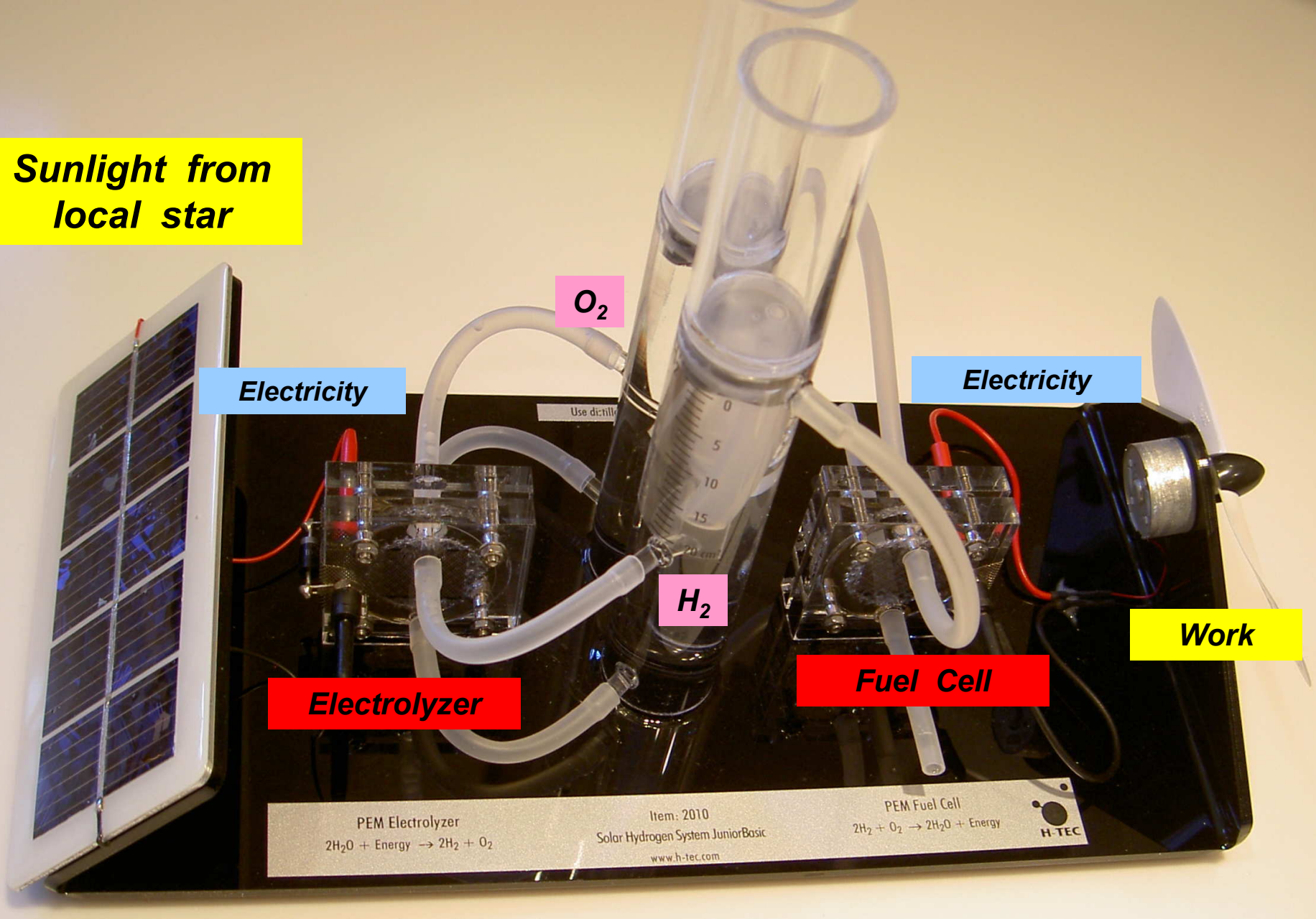
LNG-Importanlage
LNG import terminal

LNG-Importanlage, geplant
LNG import terminal planned

LNG-Exportanlage
LNG export plant

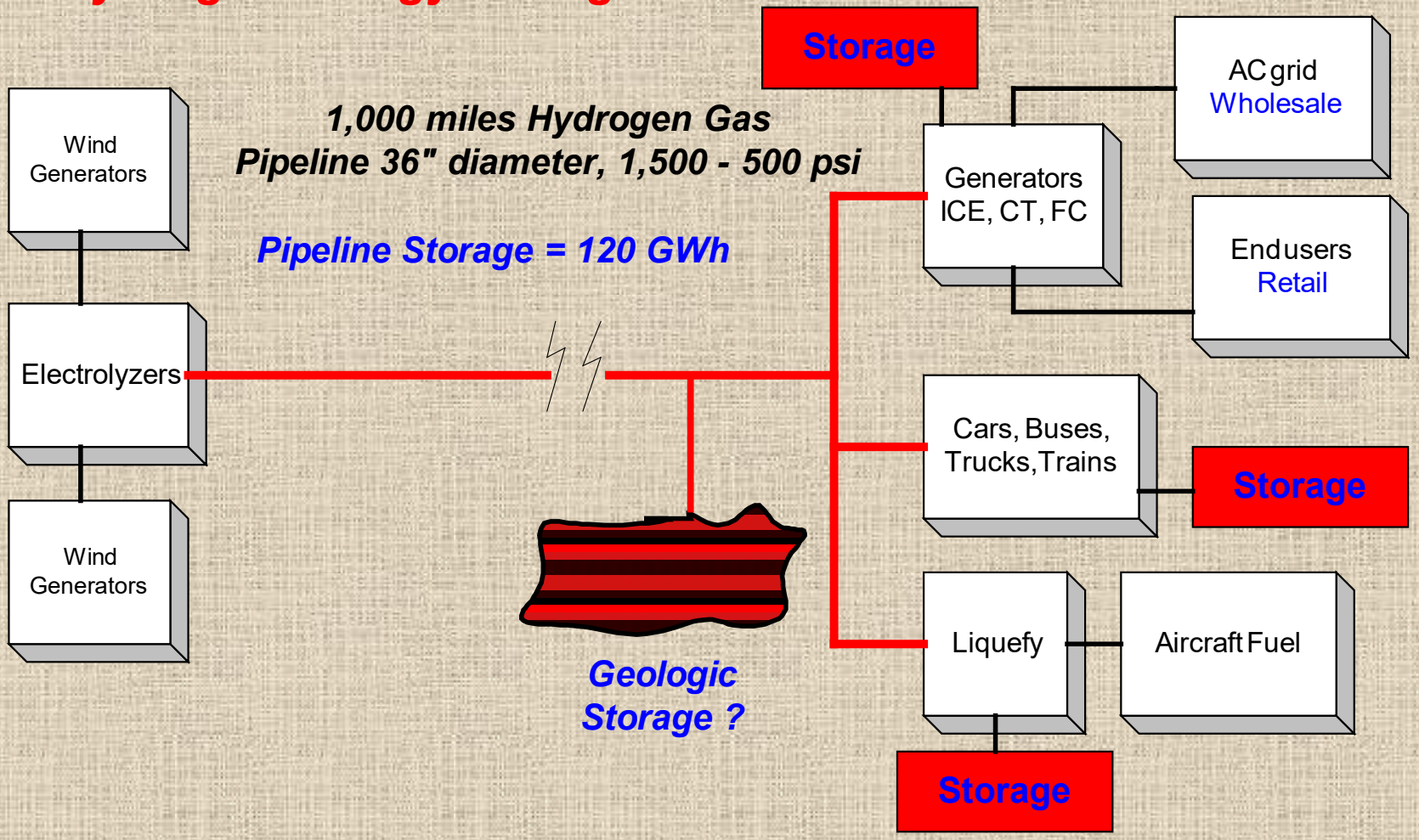
Continental Supergrid – EPRI concept "Energy Pipeline"

~ 2005: Chauncey Starr, Paul Grant, Electric Power Research Institute (EPRI)



Solar Hydrogen Energy System

Hydrogen Energy Storage



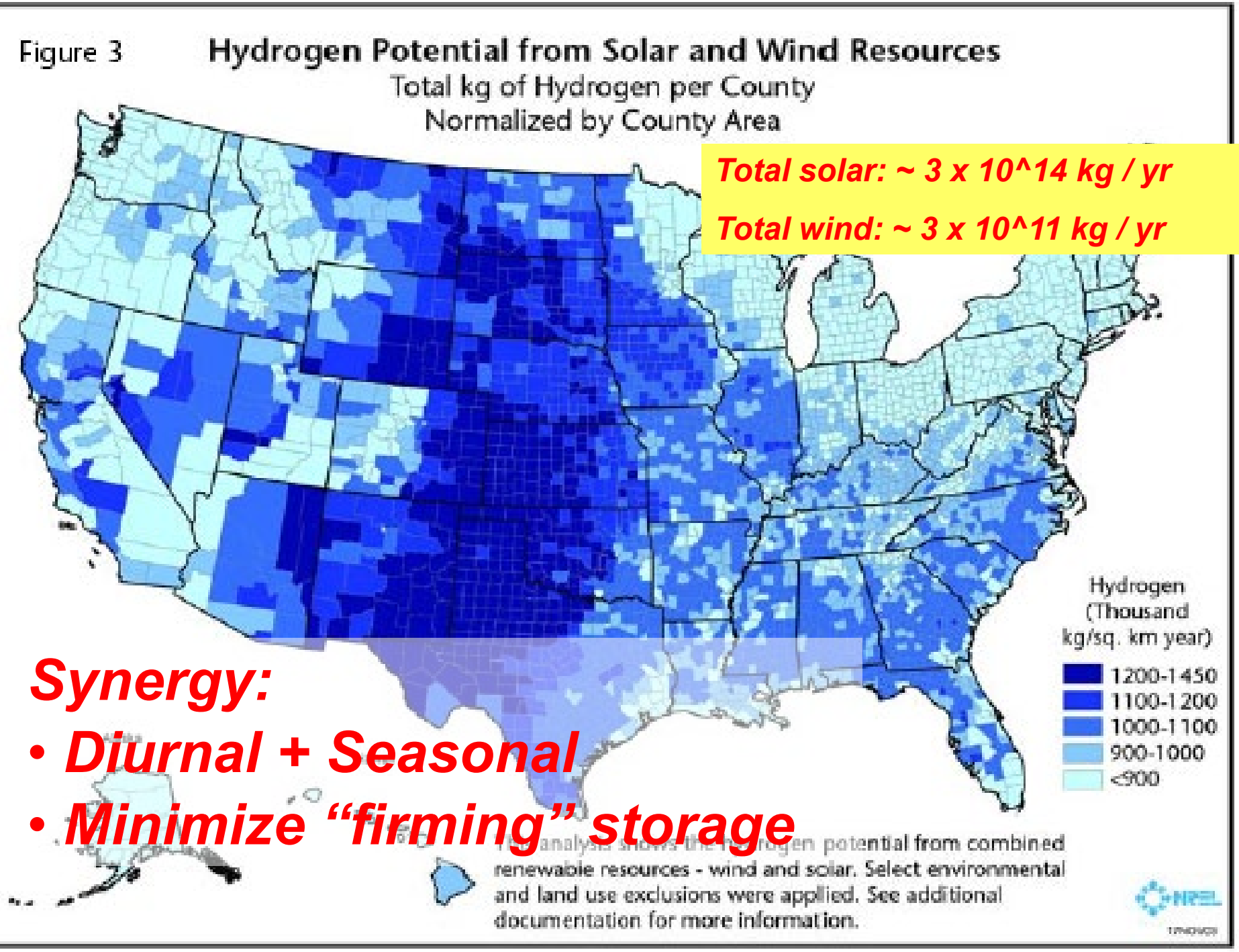
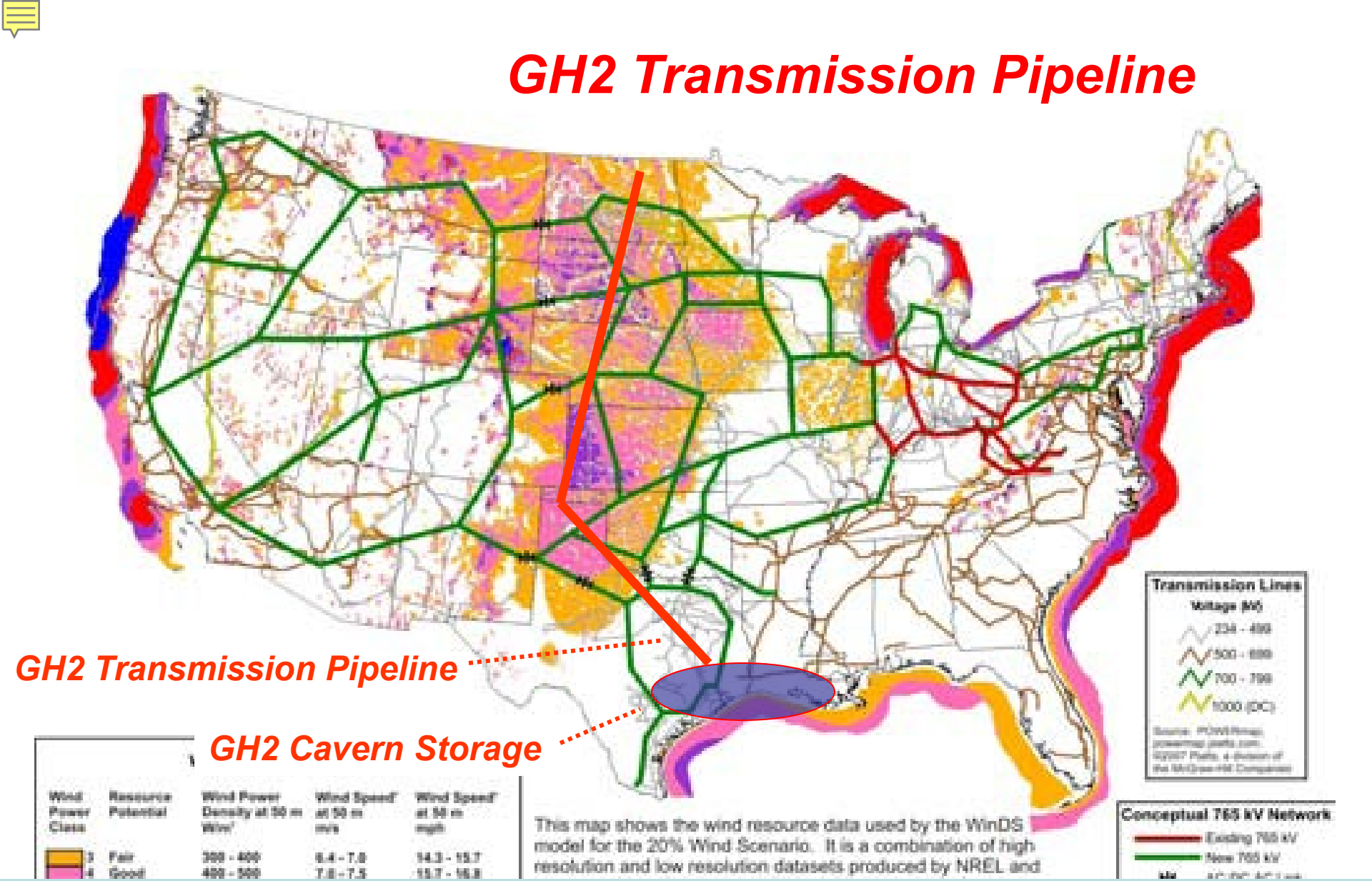


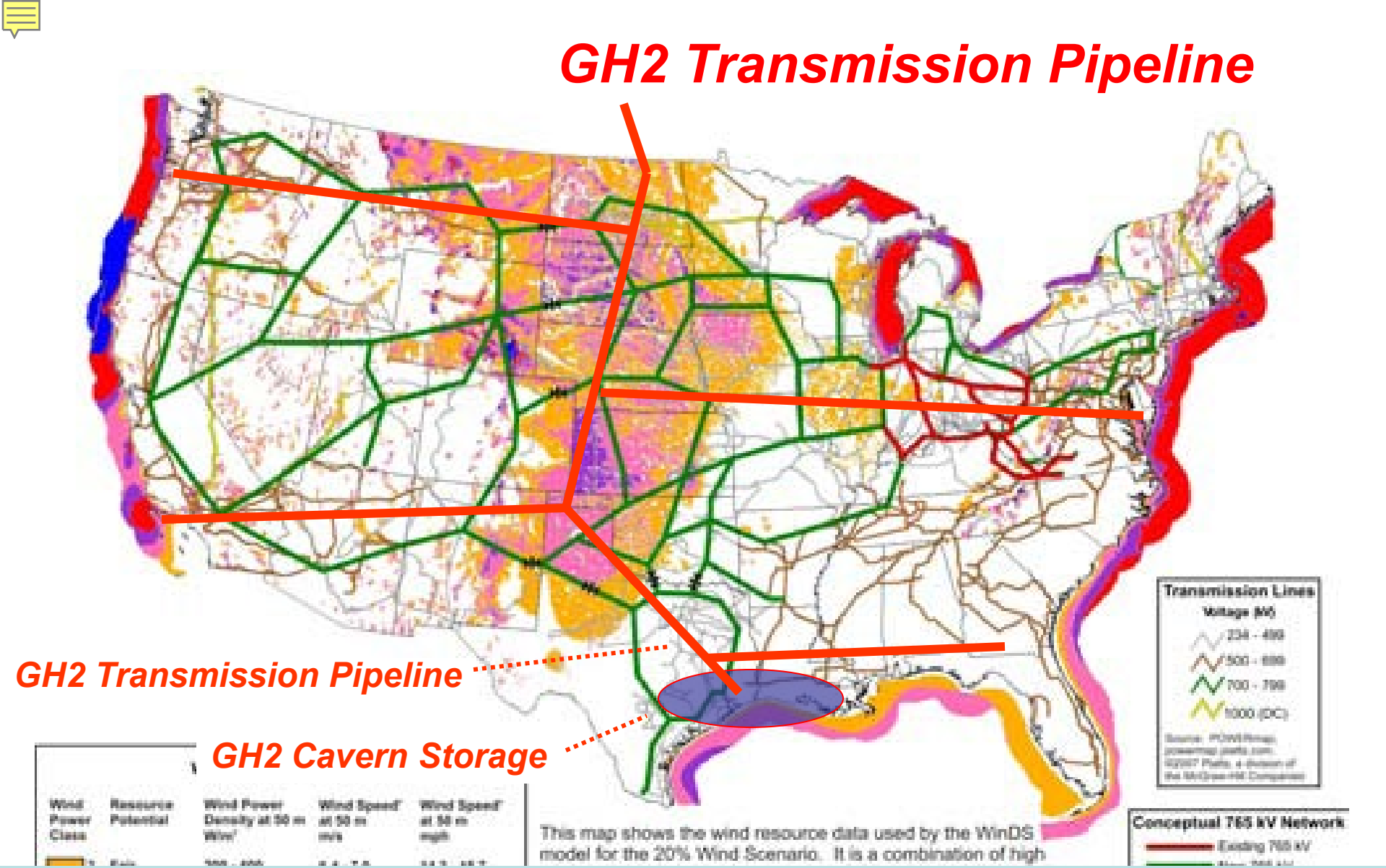
Figure 3
Hydrogen Potential from Solar and Wind Resources
Total kg of Hydrogen per County
Normalized by County Area
Total solar: ~ 3 x 10^14 kg / yr
Total wind: ~ 3 x 10^11 kg / yr
Hydrogen (Thousand kg/sq. km year)
1200-1450
1100-1200
1000-1100
900-1000
<900
Synergy:
• Diurnal + Seasonal
• Minimize "firming" storage
renewable resources - wind and solar. Select environmental and land use exclusions were applied. See additional documentation for more information.

GH2 Transmission Pipeline



Wind Potential ~ 10,000 GW

12 Great Plains states

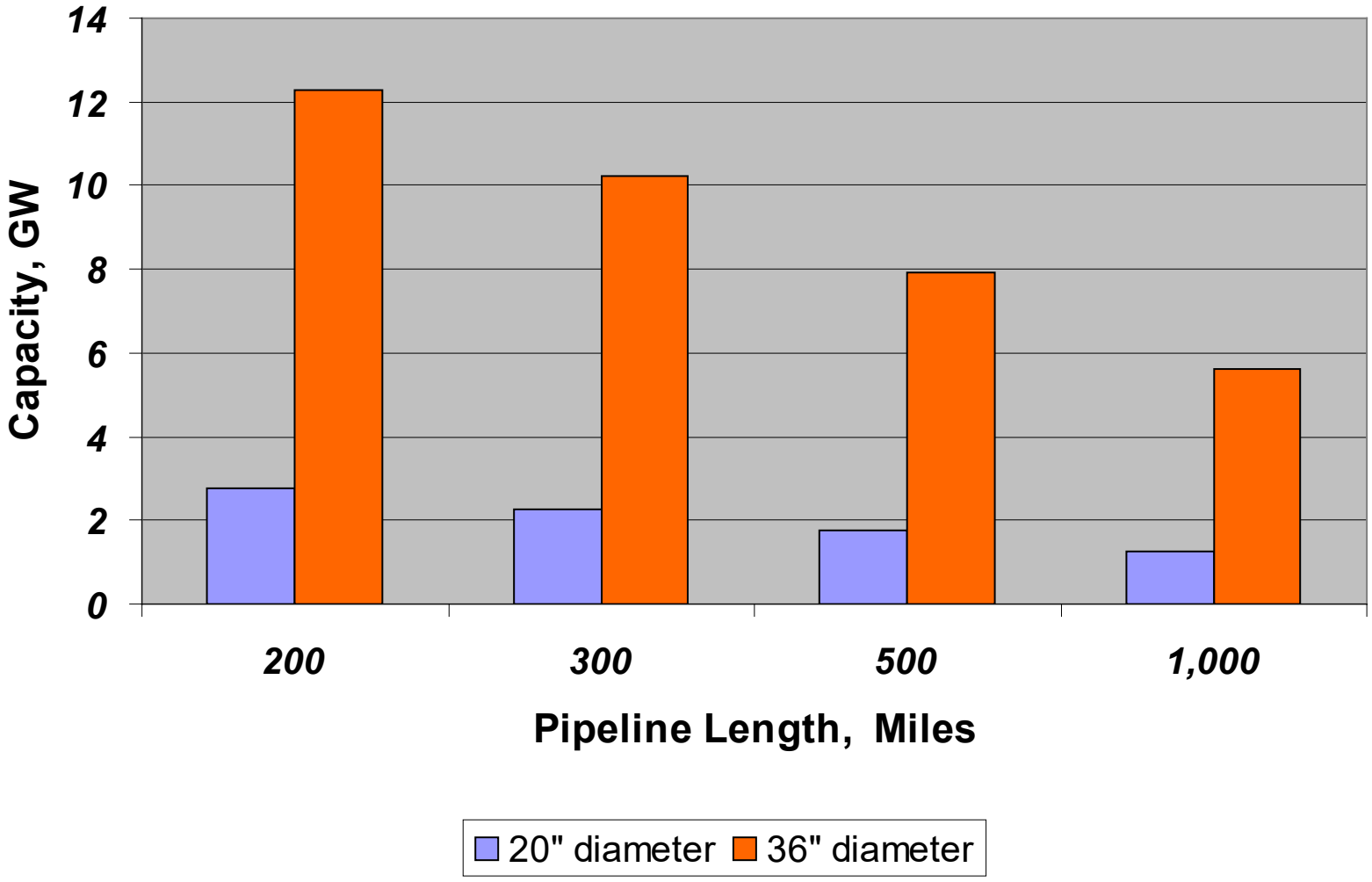


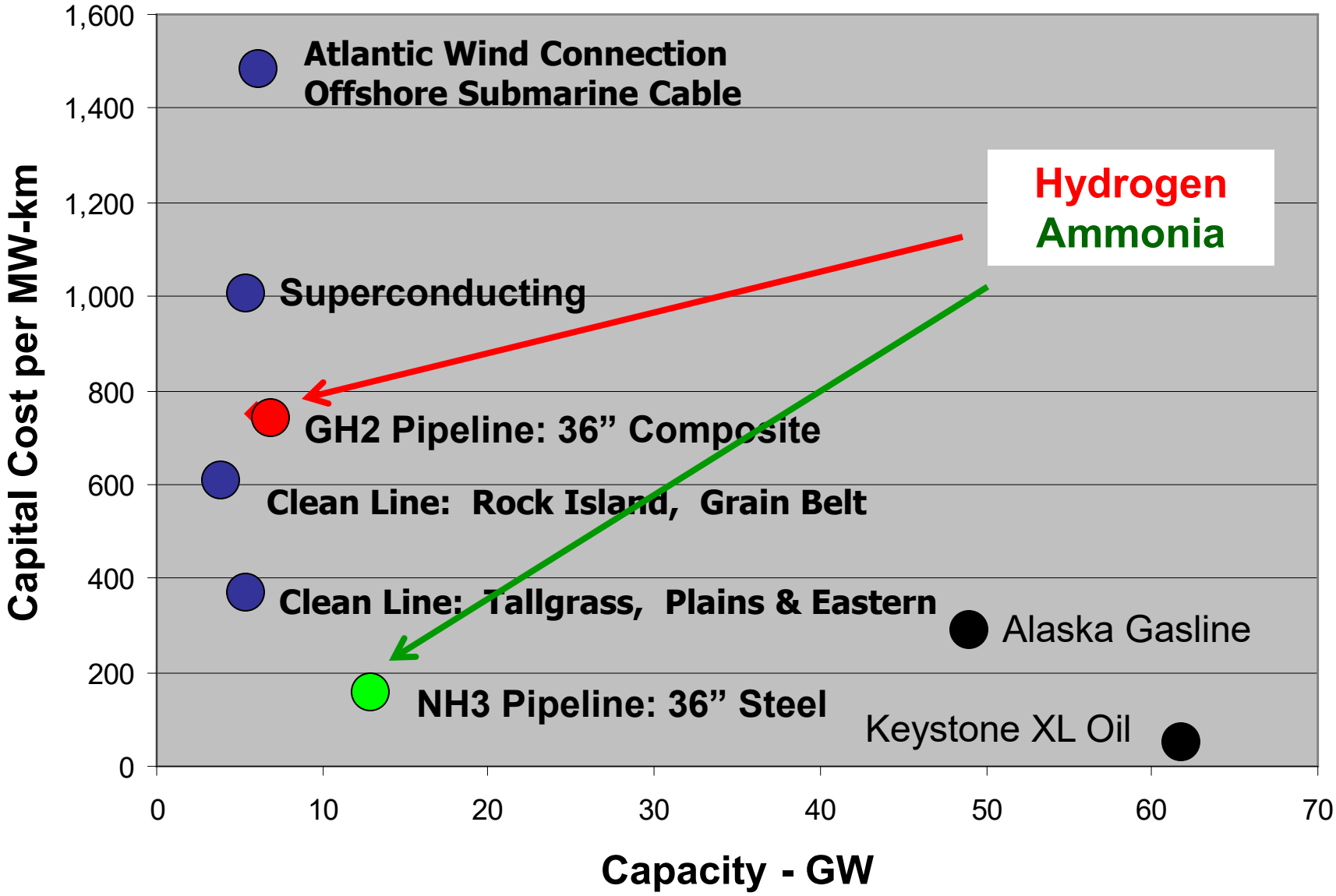
Wind Potential ~ 10,000 GW

12 Great Plains states

Compressorless 20”, 36” GH2 Pipeline Capacity

100 bar = 1,500 psi IN / 30 bar = 500 psi OUT

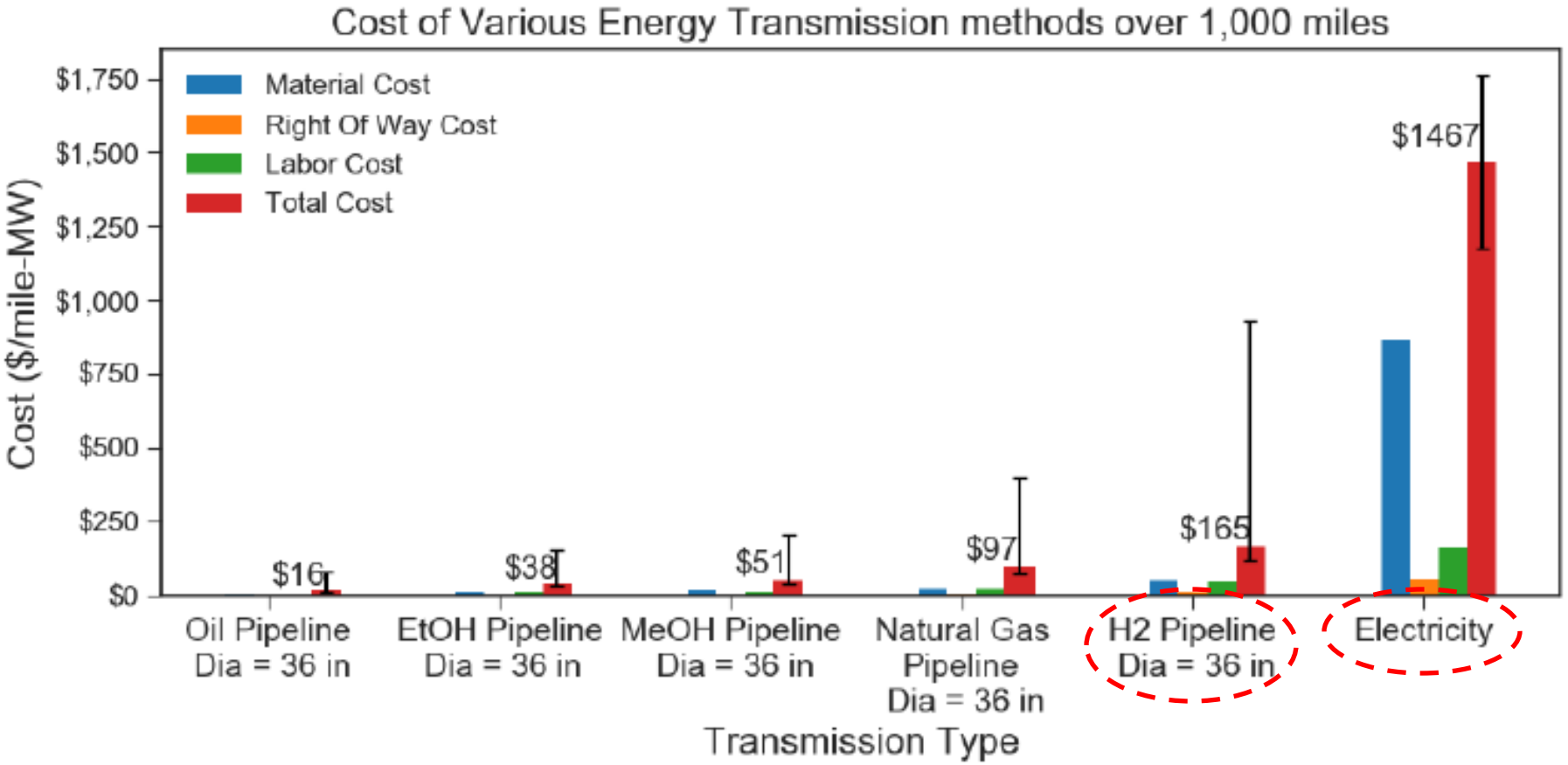




Transmission capital costs per MW-km compared

Pipelines have large capacity and provide large storage

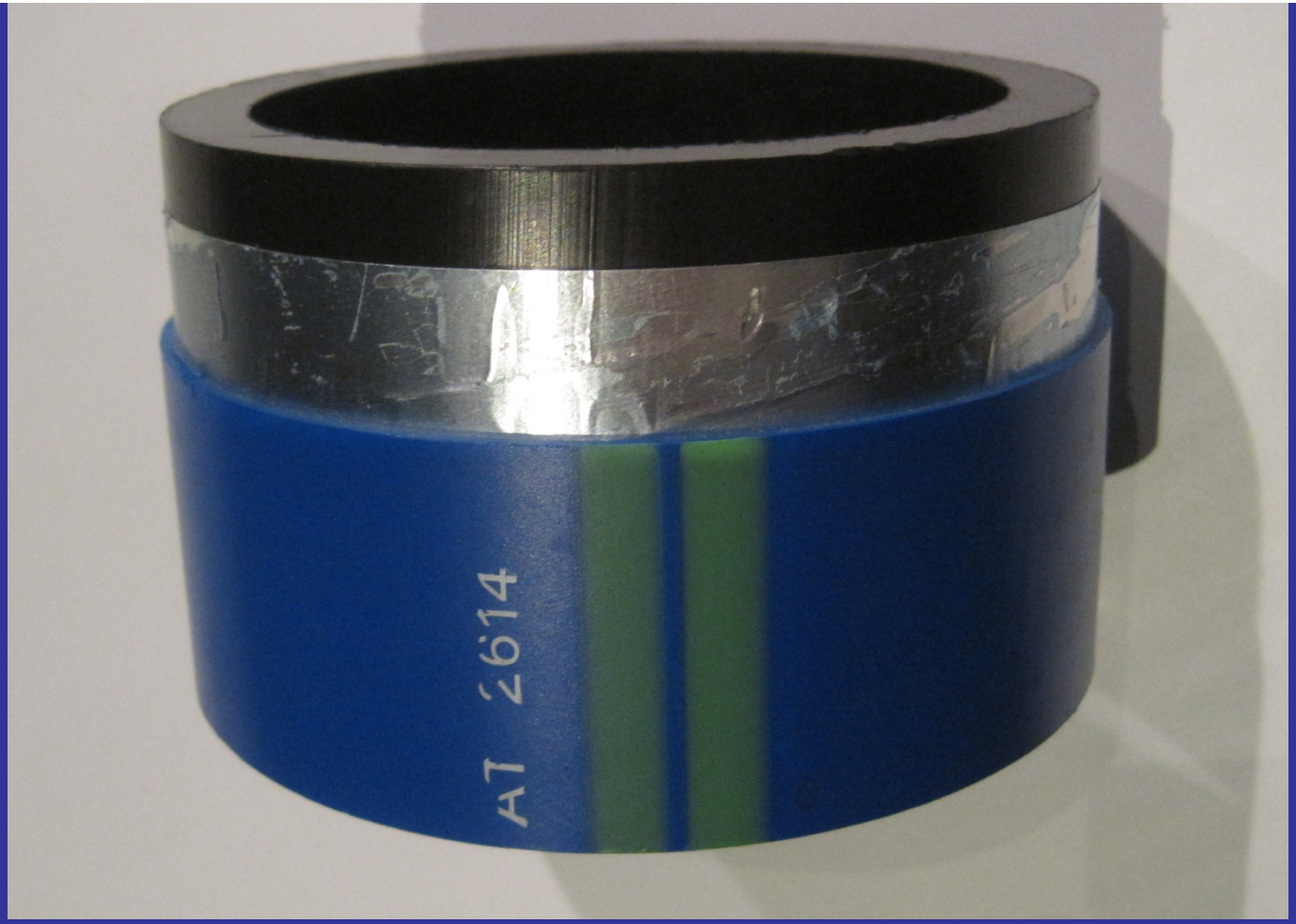
Transmission CAPEX per MW – mile, over 1,000 miles



- **Liquid Pipelines :**
  - ► Least expensive
  - ► High energy density, low pumping energy
  - ► Ammonia (NH_3) not considered
- **Electrical :**
  - > 10 x natural gas
  - > 90 x oil

36” = 8 GW gaseous Hydrogen @ 100 bar

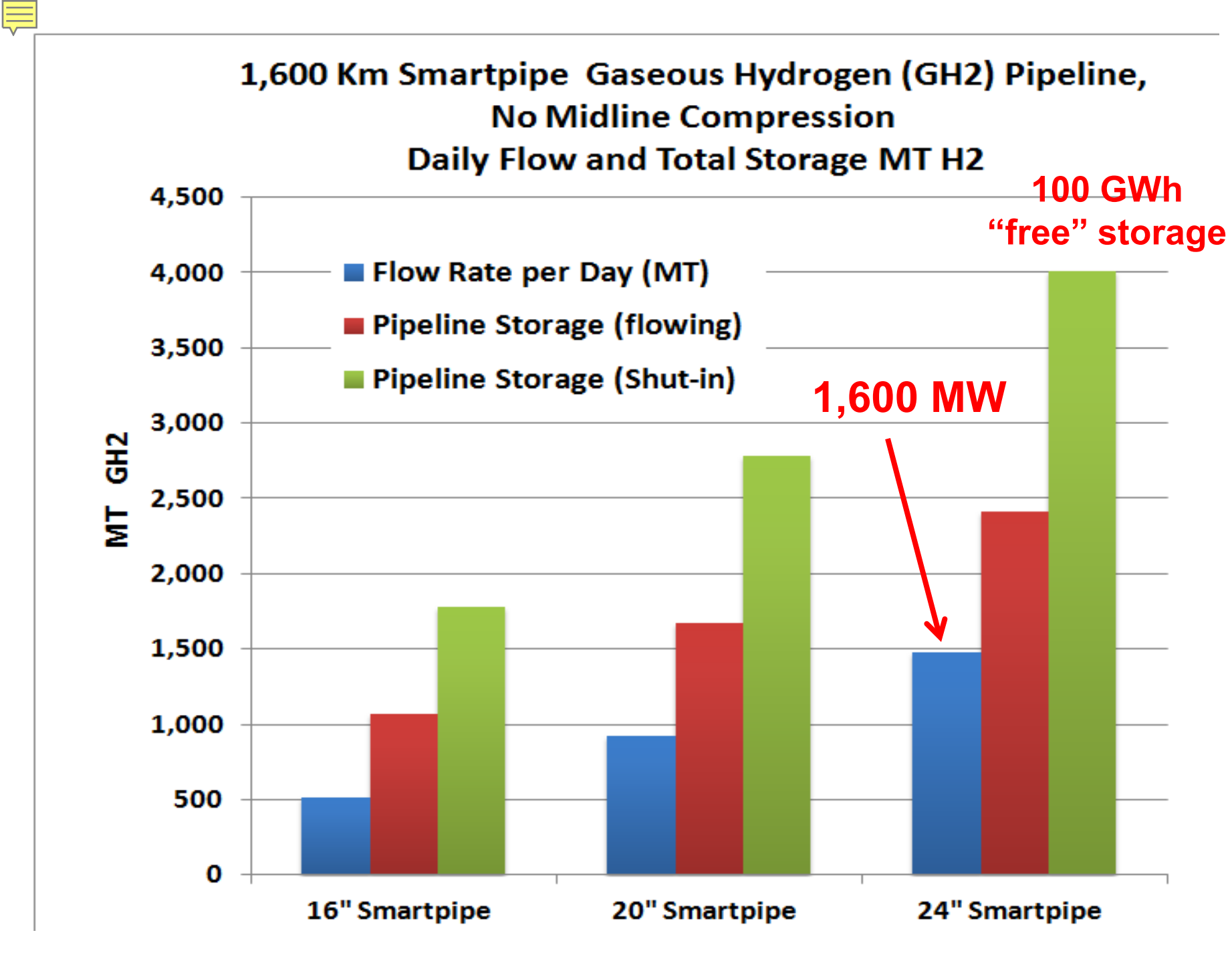
Convert Palm Springs to Long Beach Natural Gas Pipeline ?



Smart Pipe Technologies, Houston

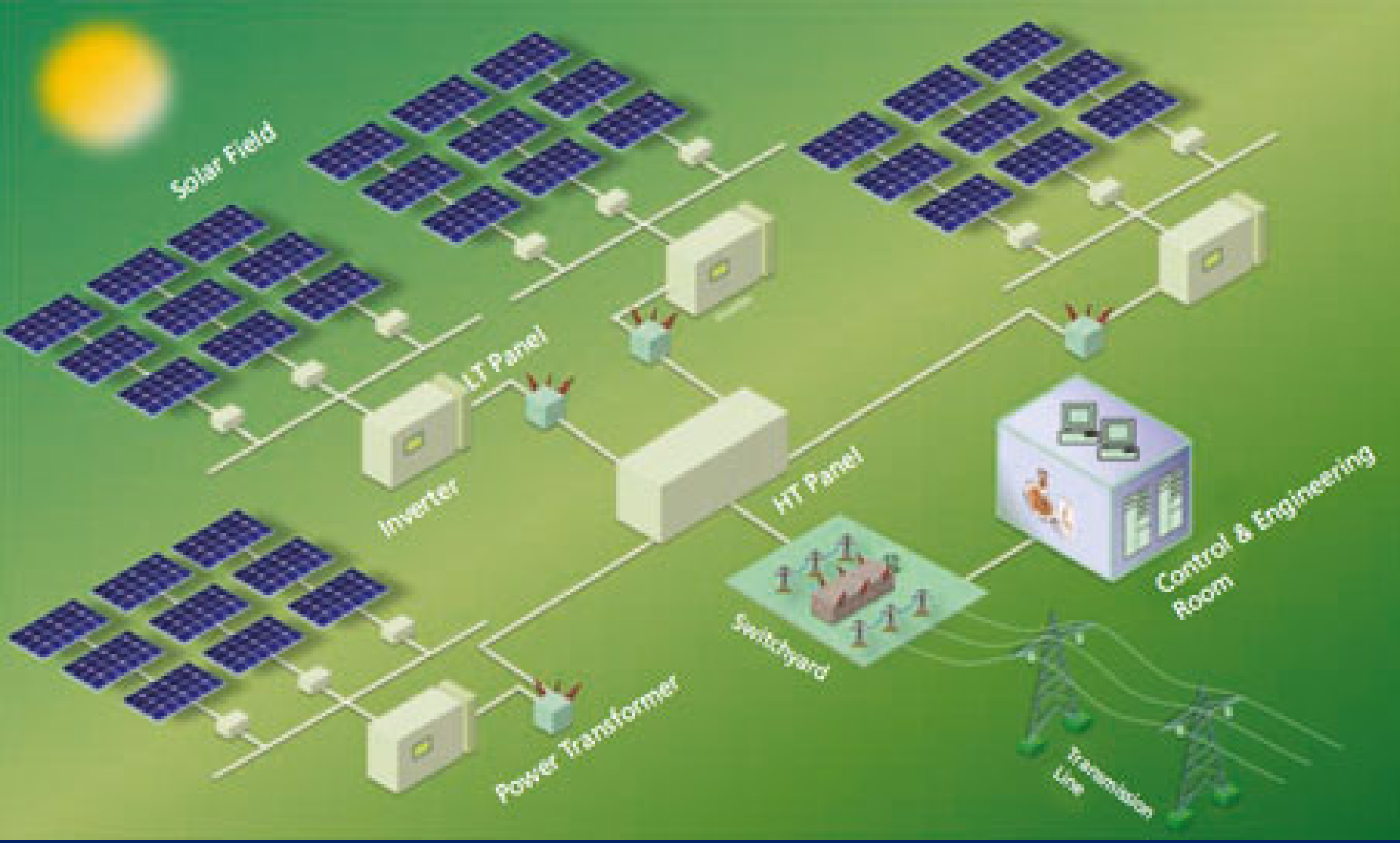
Polymer-metal linepipe avoids hydrogen embrittlement

Smart Pipe Company, Houston
On-site pipeline factory
Continuous process, unlimited length
Hydrogen-compatible: polymer-metal hybrid resists HE, HCC

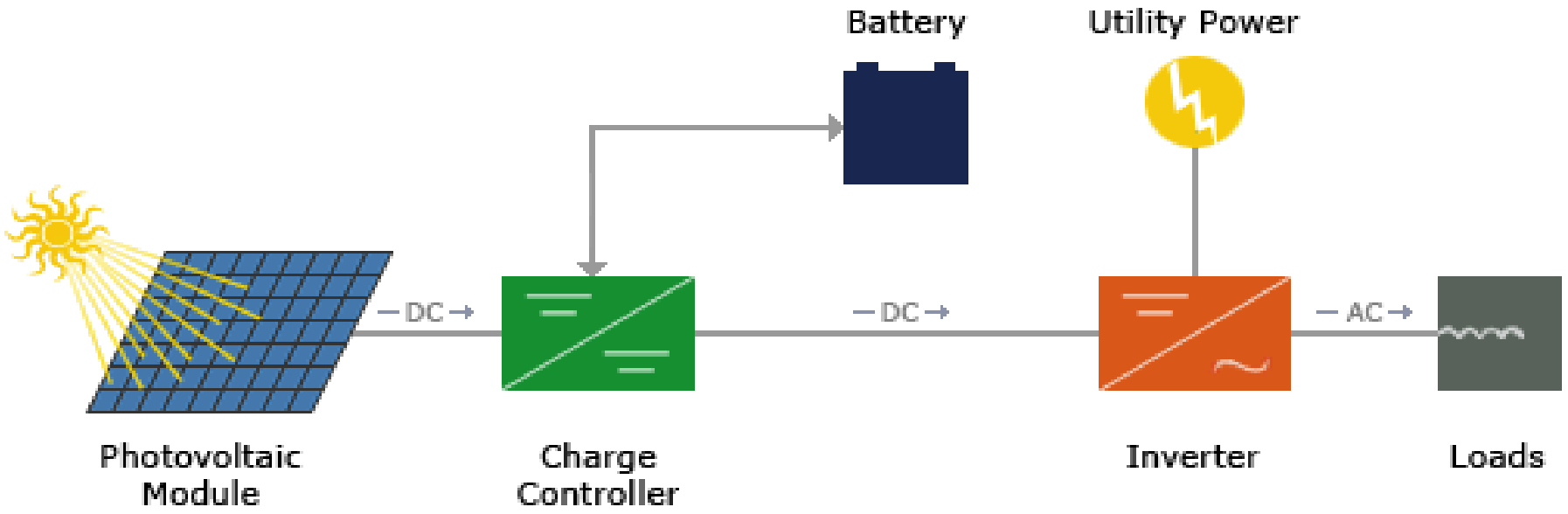

1,600 Km Smartpipe Gaseous Hydrogen (GH2) Pipeline,
No Midline Compression
Daily Flow and Total Storage MT H2
100 GWh
"free" storage
1,600 MW
Flow Rate per Day (MT)
Pipeline Storage (flowing)
Pipeline Storage (Shut-in)
MT GH2
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
16" Smartpipe
20" Smartpipe
24" Smartpipe

- **Entirely with electricity systems, "Grid" ?**
- **Obvious, default**
- **Assume primarily variable generation (VG) ?**
- **Possible, but tech & econ suboptimal ?**
- **Optimum mix: electricity, C-free fuels -- H_2 , NH_3**

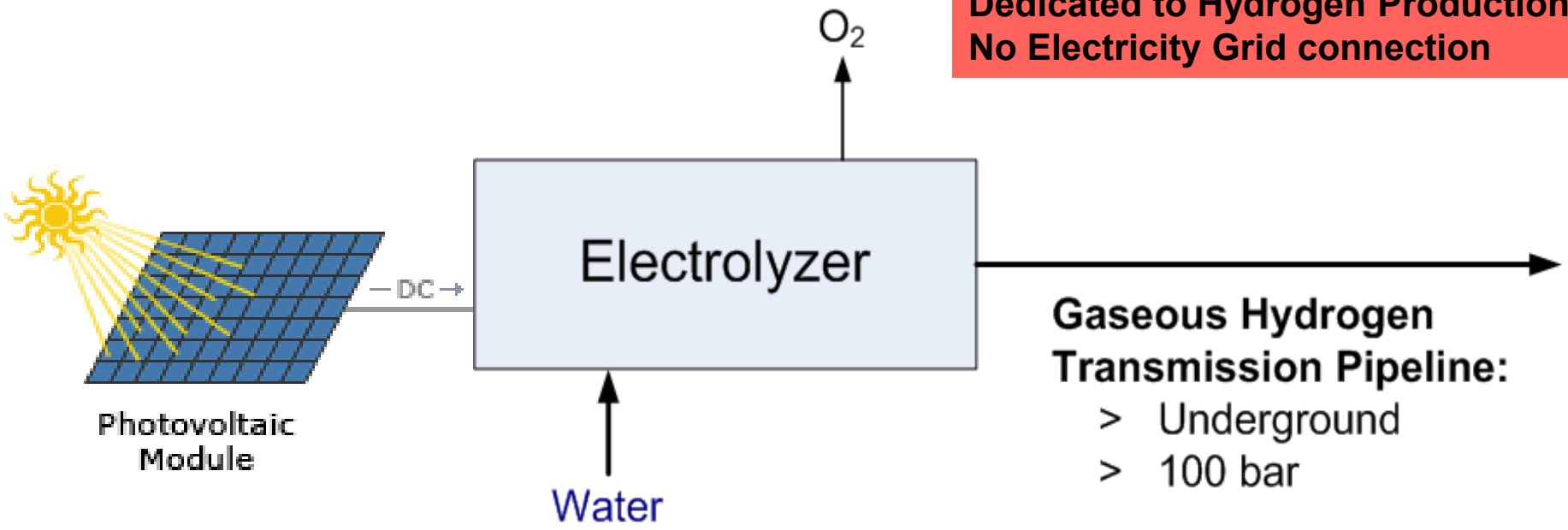
Need diverse collaboration to roadmap: neglected, urgent !



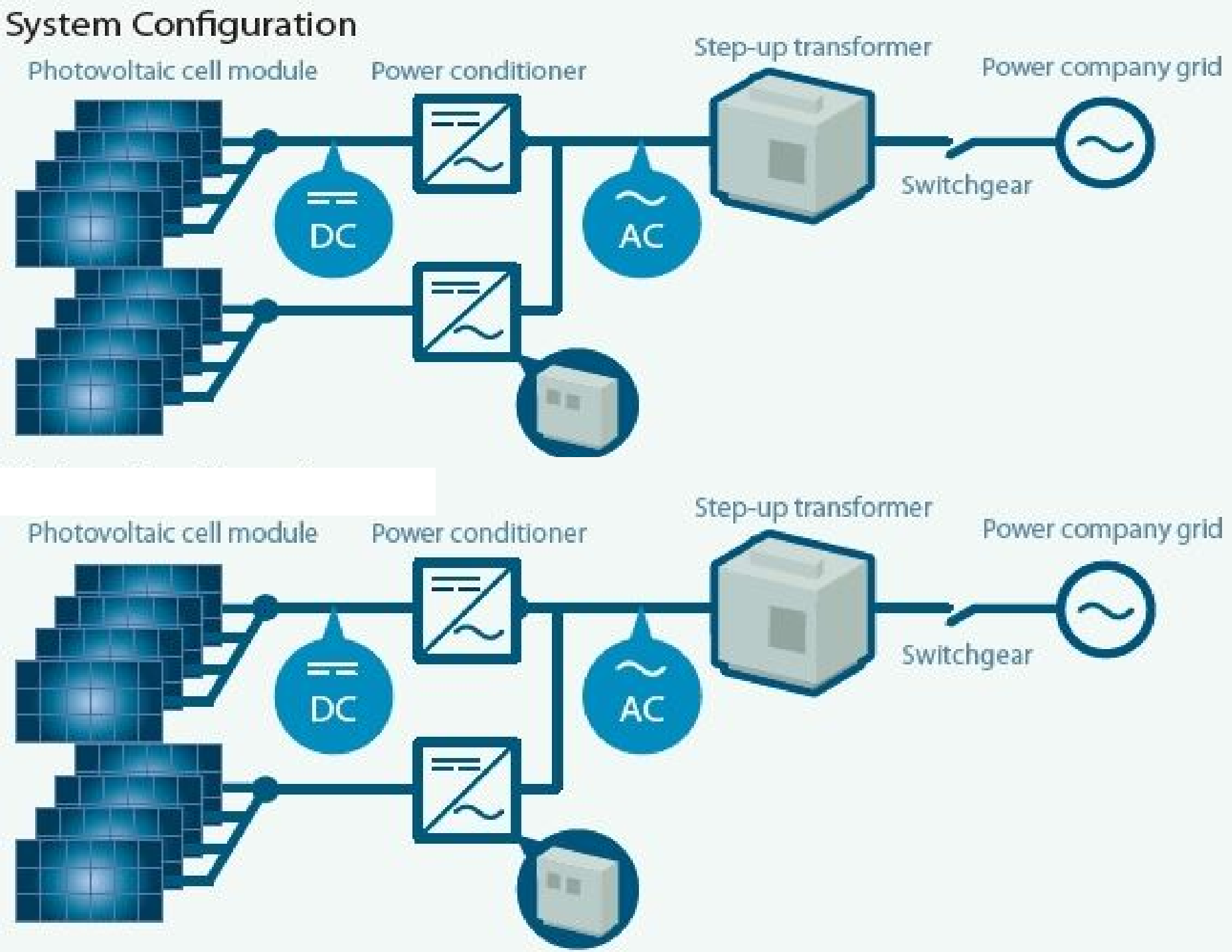
Grid delivery: Complex & Costly Infrastructure



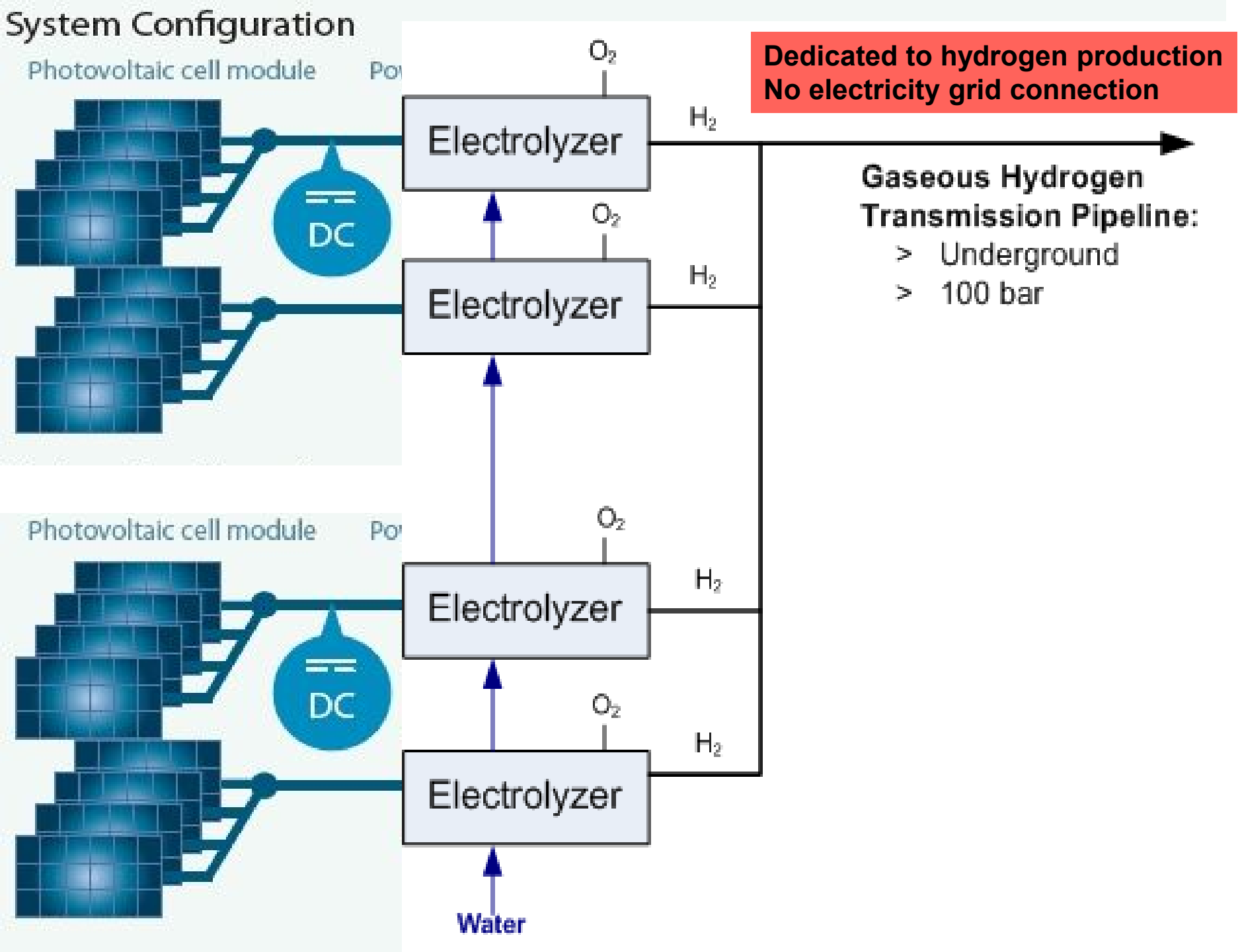
Dedicated to Hydrogen Production
No Electricity Grid connection



System Configuration



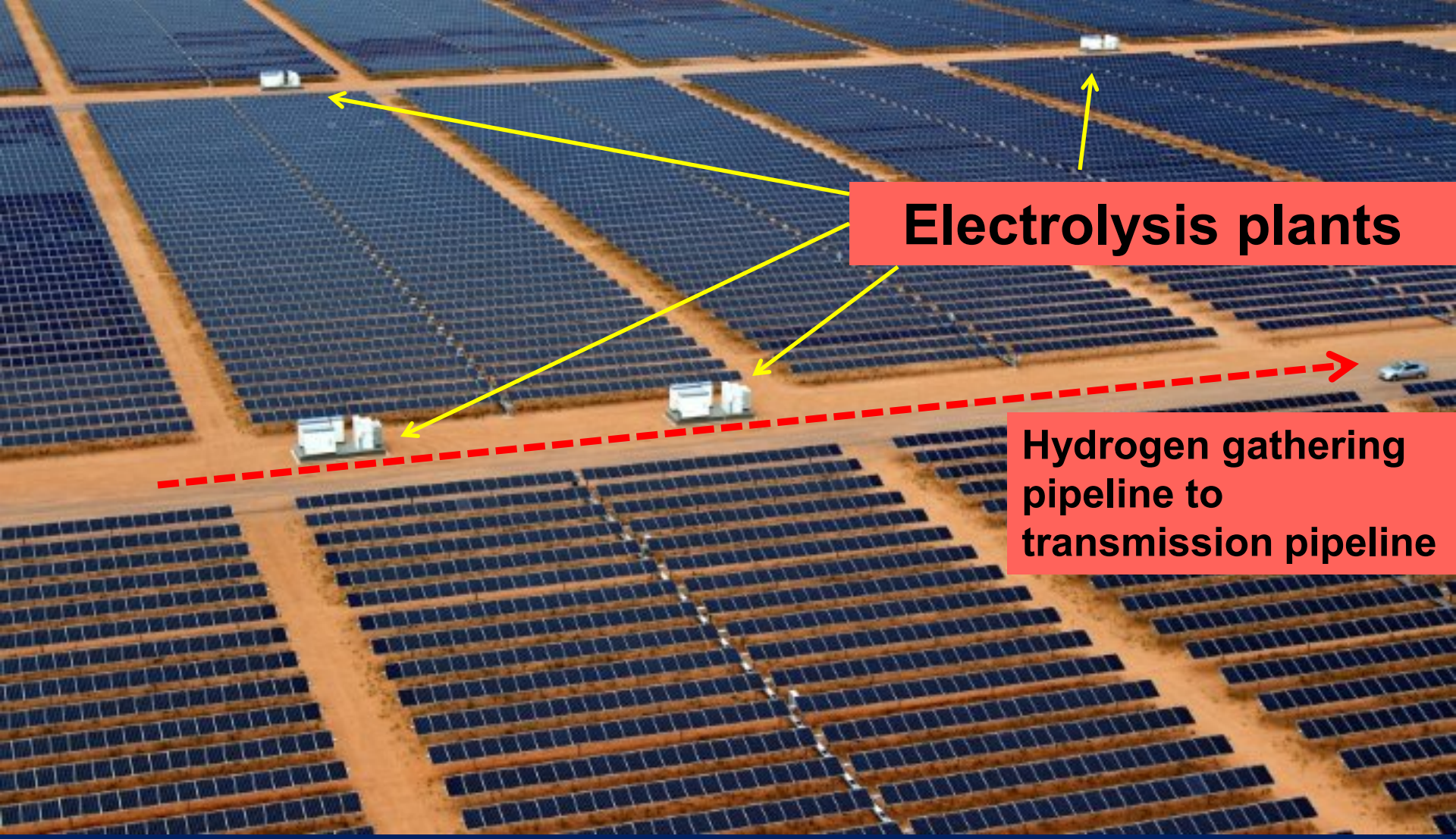
System Configuration



Dedicated to hydrogen production
No electricity grid connection

Gaseous Hydrogen Transmission Pipeline:

- > Underground
- > 100 bar



Dedicated to Hydrogen fuel production
No connection to electricity grid

Grid-quality AC power electronics

No Grid connection: Not needed

1 MW solar inverters

$ 1 Billion Palen Solar Project, east of Palm Springs, CA

500 MW AC, 627 MW DC, > 3 million PV panels

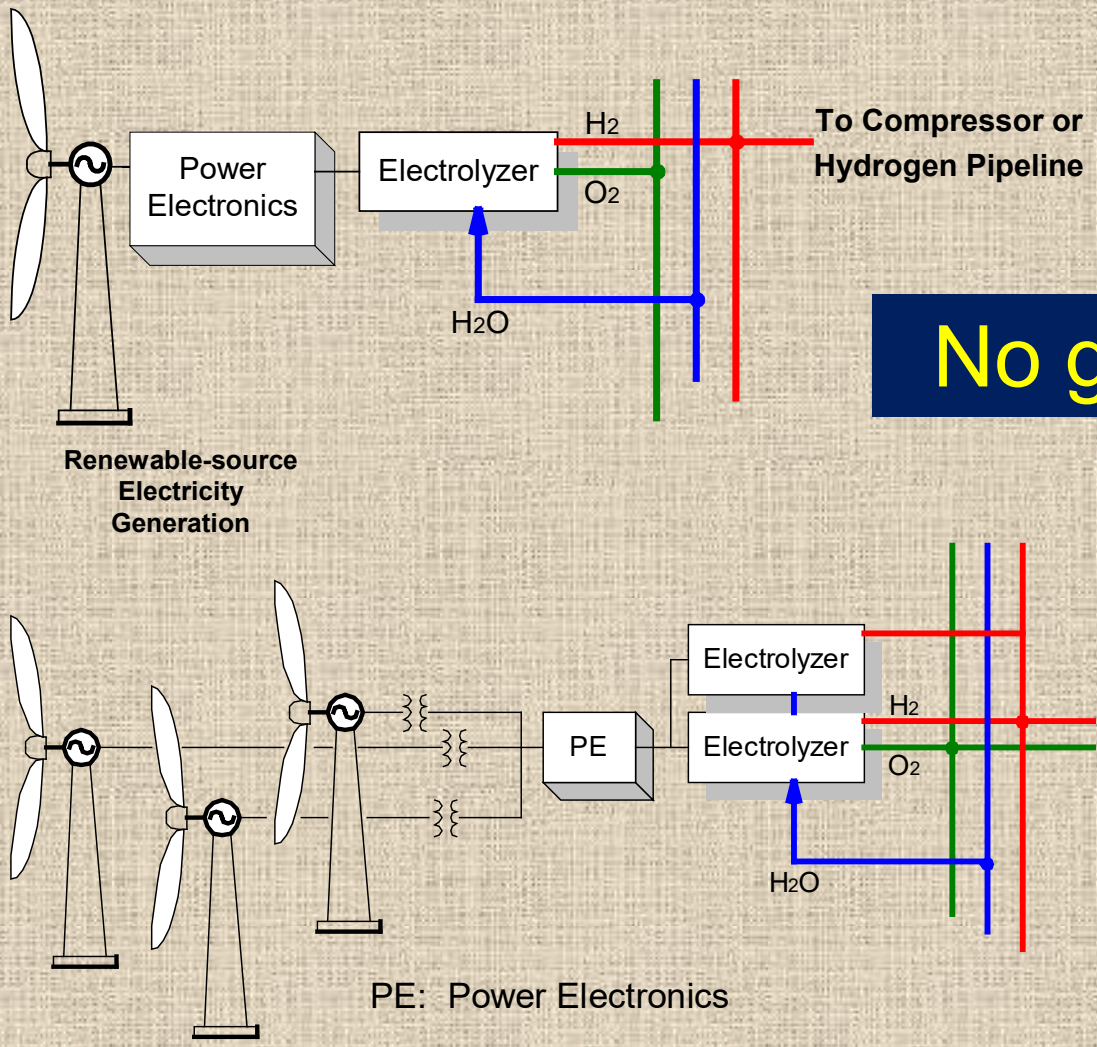
Annual energy production (AEP):

~ 660,000 MWh @ 15% CF, or

~ 13,000 MT hydrogen

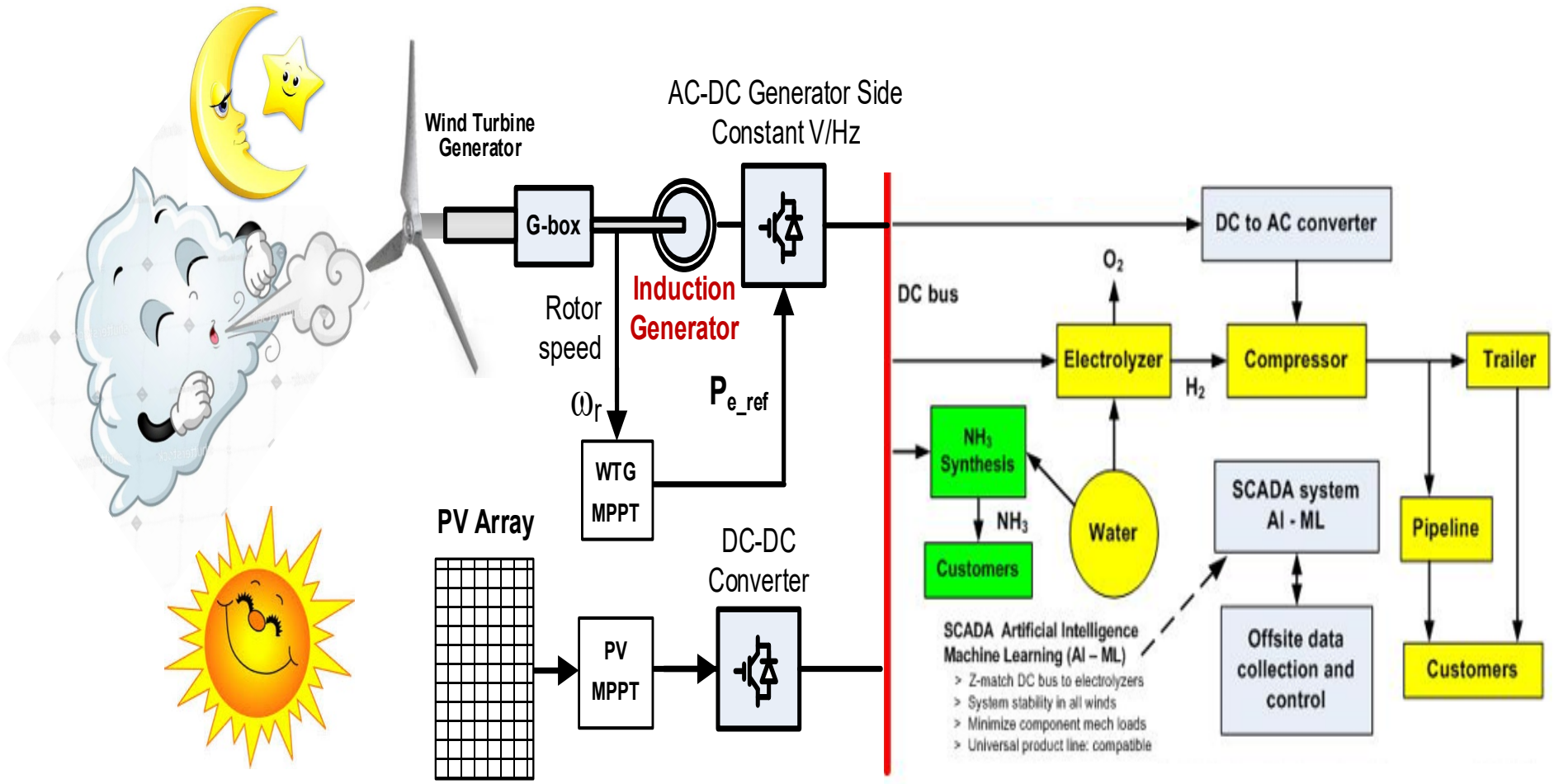
Year 2050 Electricity + Hydrogen Transportation Fuel, California will need :

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



No grid connection

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

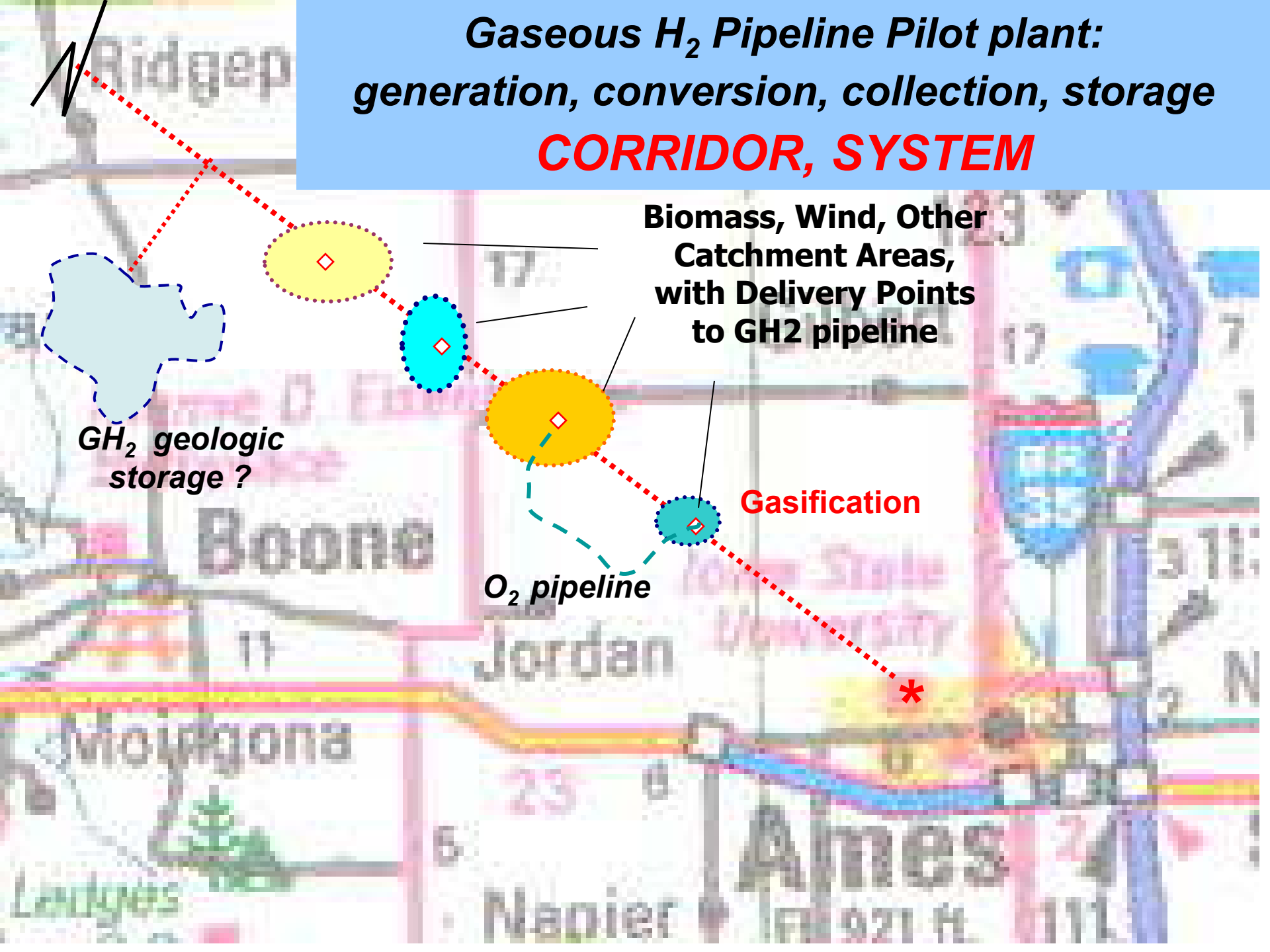


Synergistic wind + PV

- **Co-located, co-generation, single plant**
- **No Grid connection; pipeline export**
- **Diurnal, seasonal**
- **Dedicated hydrogen, ammonia production**

Gaseous H_2 Pipeline Pilot plant: generation, conversion, collection, storage

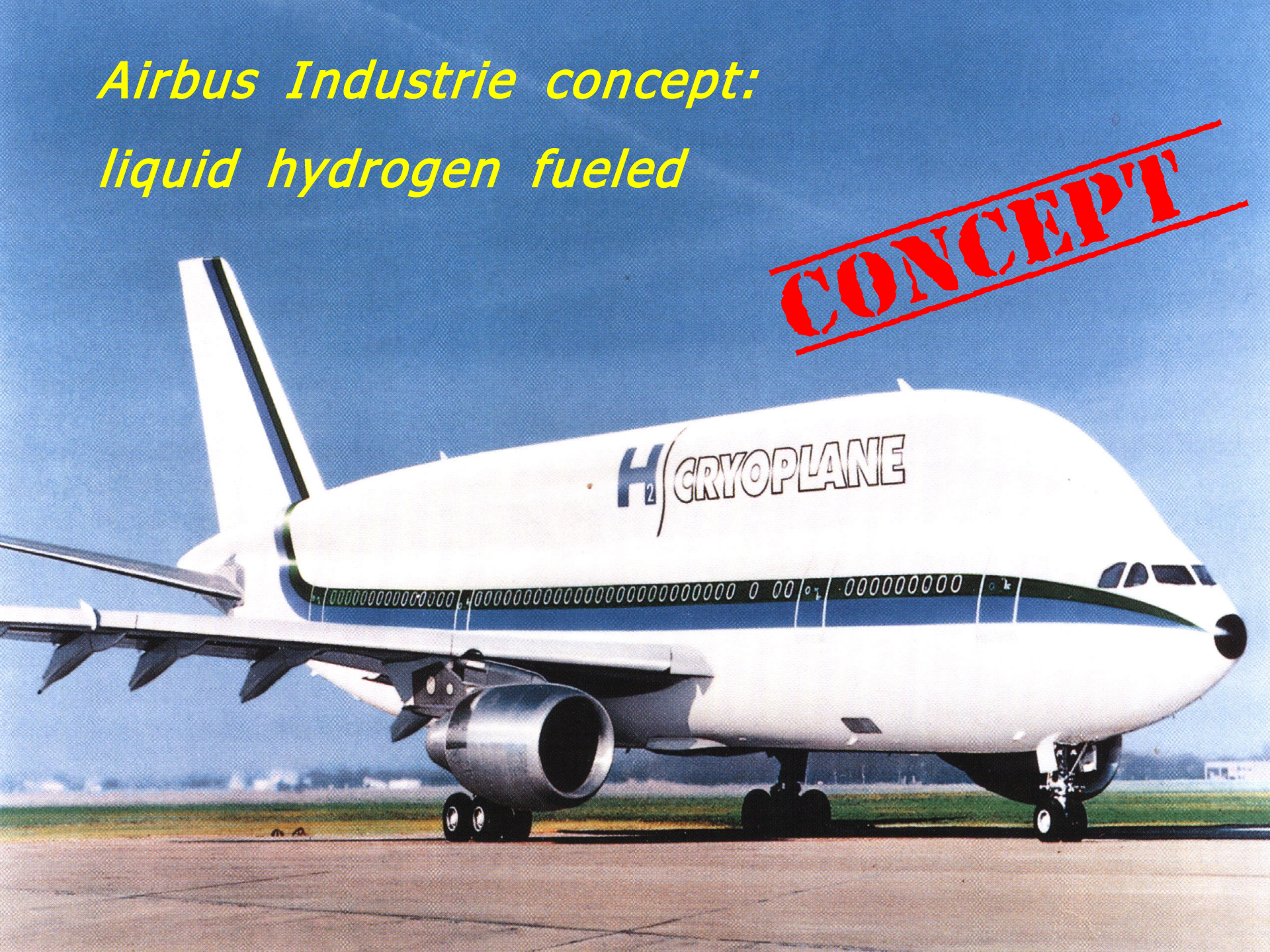
CORRIDOR, SYSTEM

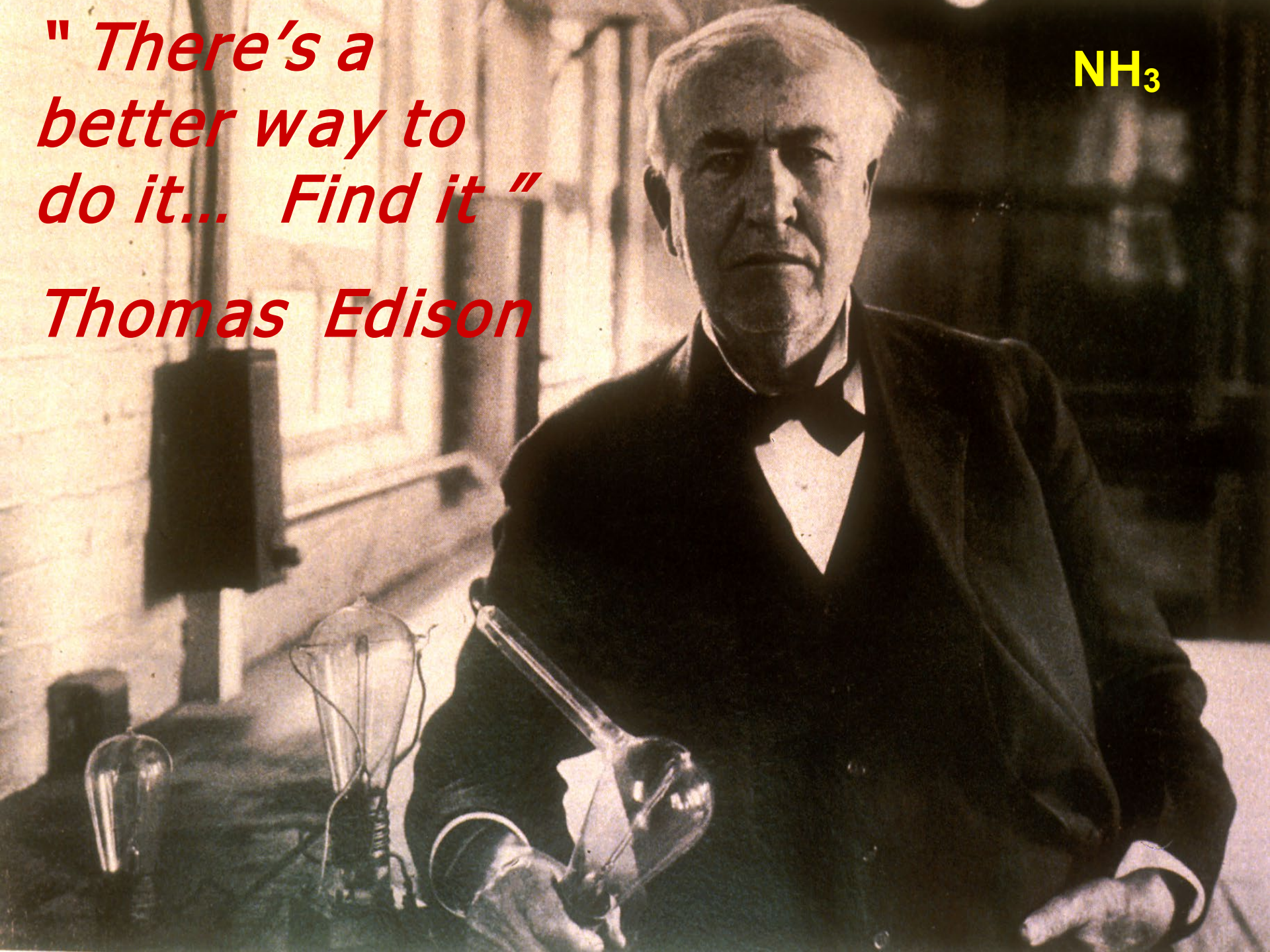


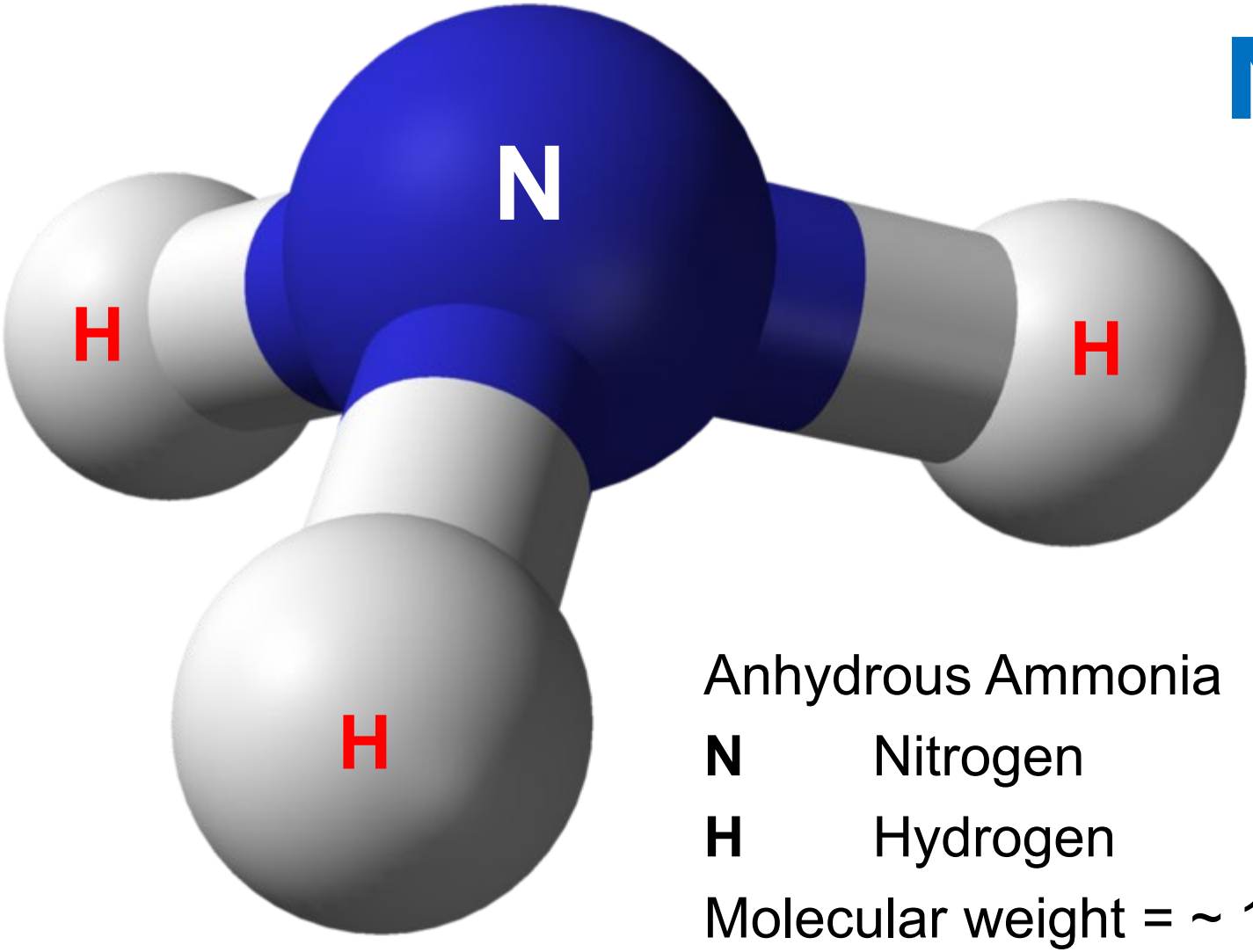
Renewables, Electrochemical energy

Alstom Hydrogen-fueled Fuel Cell Electric drive train


N713TZ
ZUNUM
Zunum Aero 12-seater
Flight tests 2019
Hydrogen-fueled airliner


Airbus Industrie concept:
liquid hydrogen fueled
CONCEPT
H2 CRYOPLANE


" There's a better way to do it... Find it "
Thomas Edison
NH_3



NH_3

Anhydrous Ammonia **NH_3**

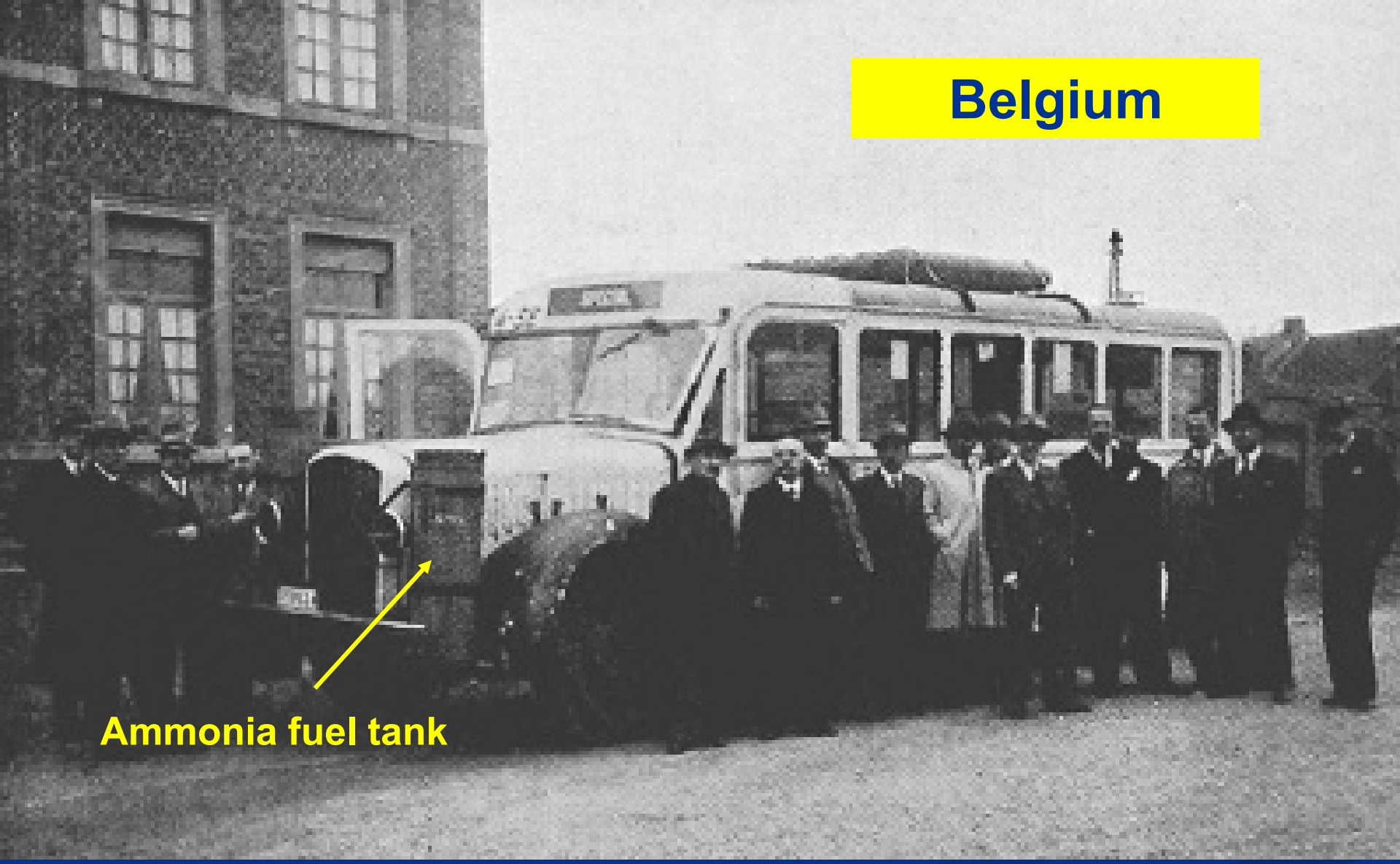
N Nitrogen

H Hydrogen

Molecular weight = ~ 17

18% **H** by weight: “other hydrogen”

$NH_3 + O_2 = N_2 + H_2O$



Ammonia Fueled Bus: Thousands of Problem-free Miles

1943

X-15 rocket plane: NH3 + LOX fuel

Mach 6.7 on 3 Oct 67

199 missions

1959 - 68

Anhydrous ammonia (NH_3)
"The other hydrogen"

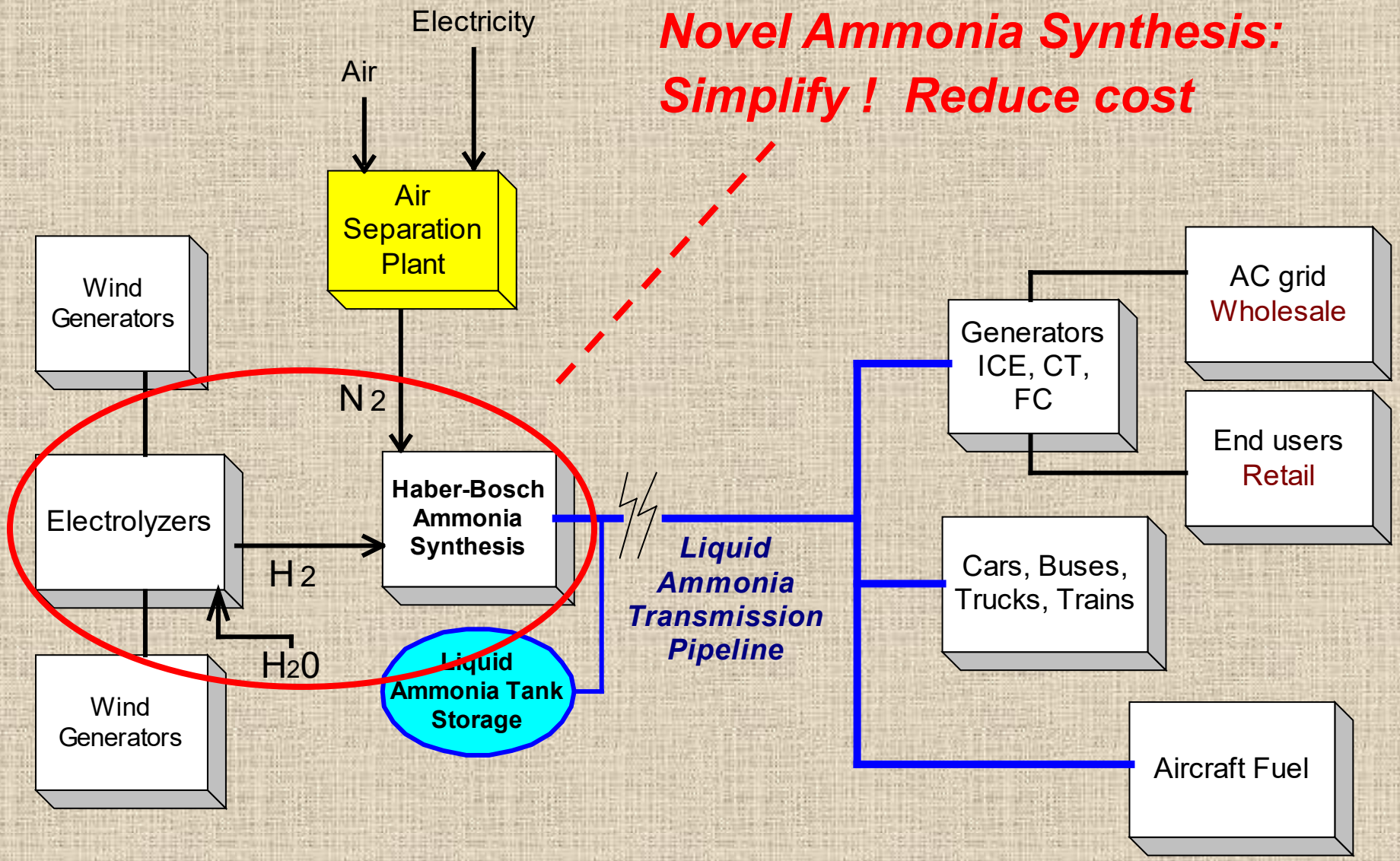
Ammonia Fueled Ships
C-Job Naval Architects **c-job.com**

DNV-GL
Energy Transition
Outlook 2019

USDOE ARPA-E "REFUEL" R&D

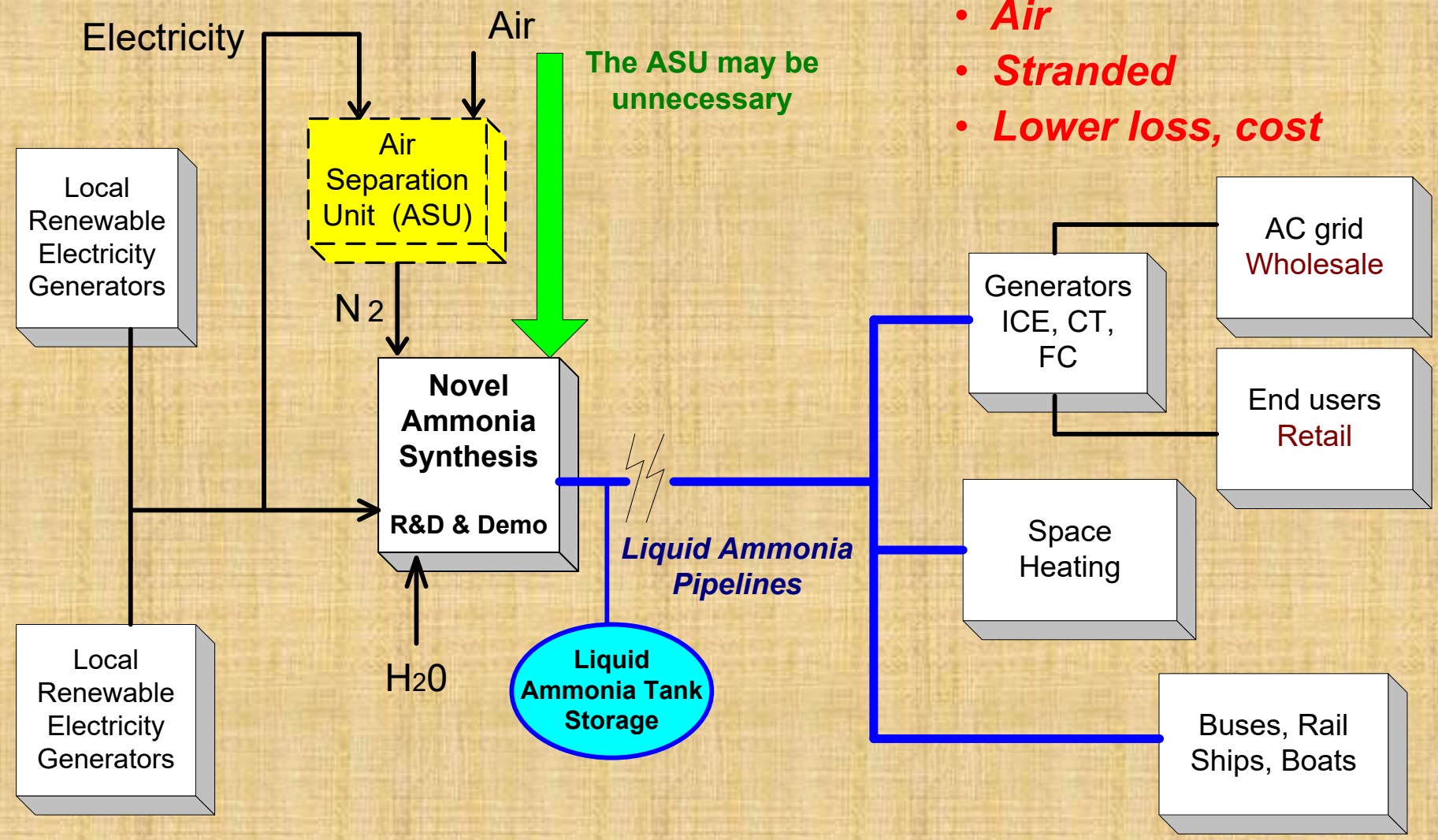
- Eliminate electrolyzer and Haber-Bosch reactor (high T, P)
- NH_3 synthesis directly from electricity, water, air
- Lower capex + O&M costs, higher efficiency
- 13 NH_3 synthesis & cracking projects
- 5 projects, plus Korea (KIER)

RE Ammonia Transmission + Storage Scenario



Novel Ammonia Synthesis

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



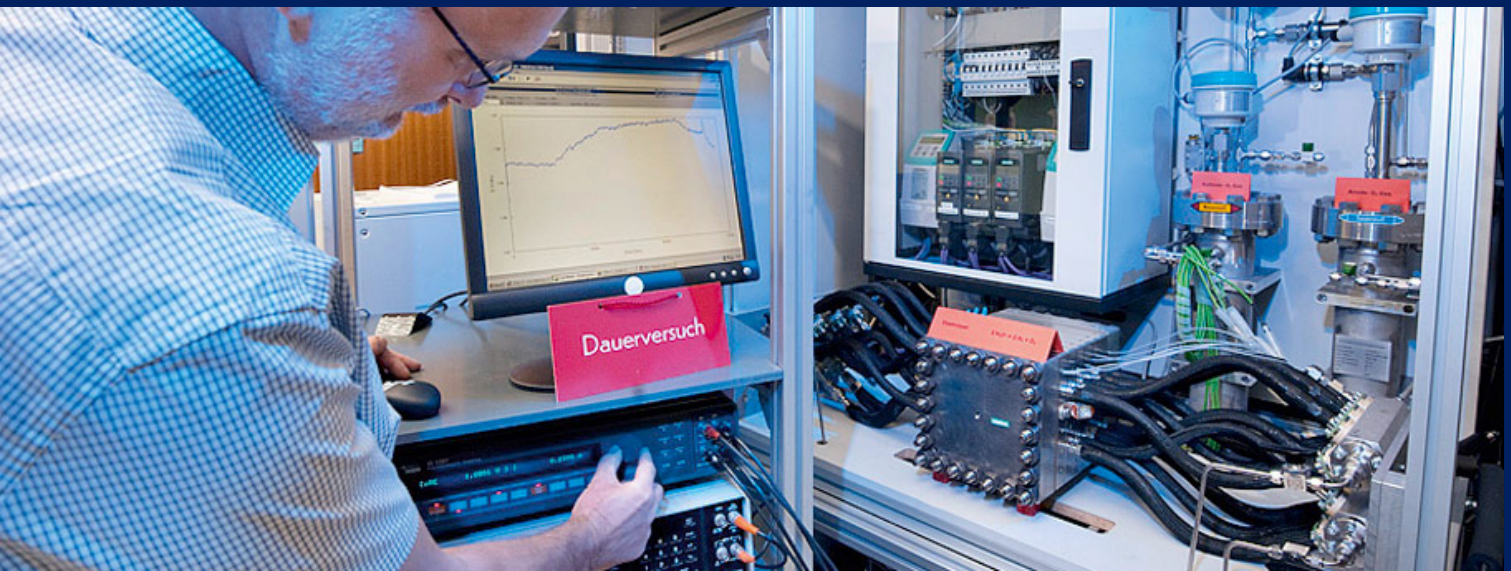
Electrolyzers:

Siemens
Hydrogenics
ProtonOnsite
ITM Power
GE

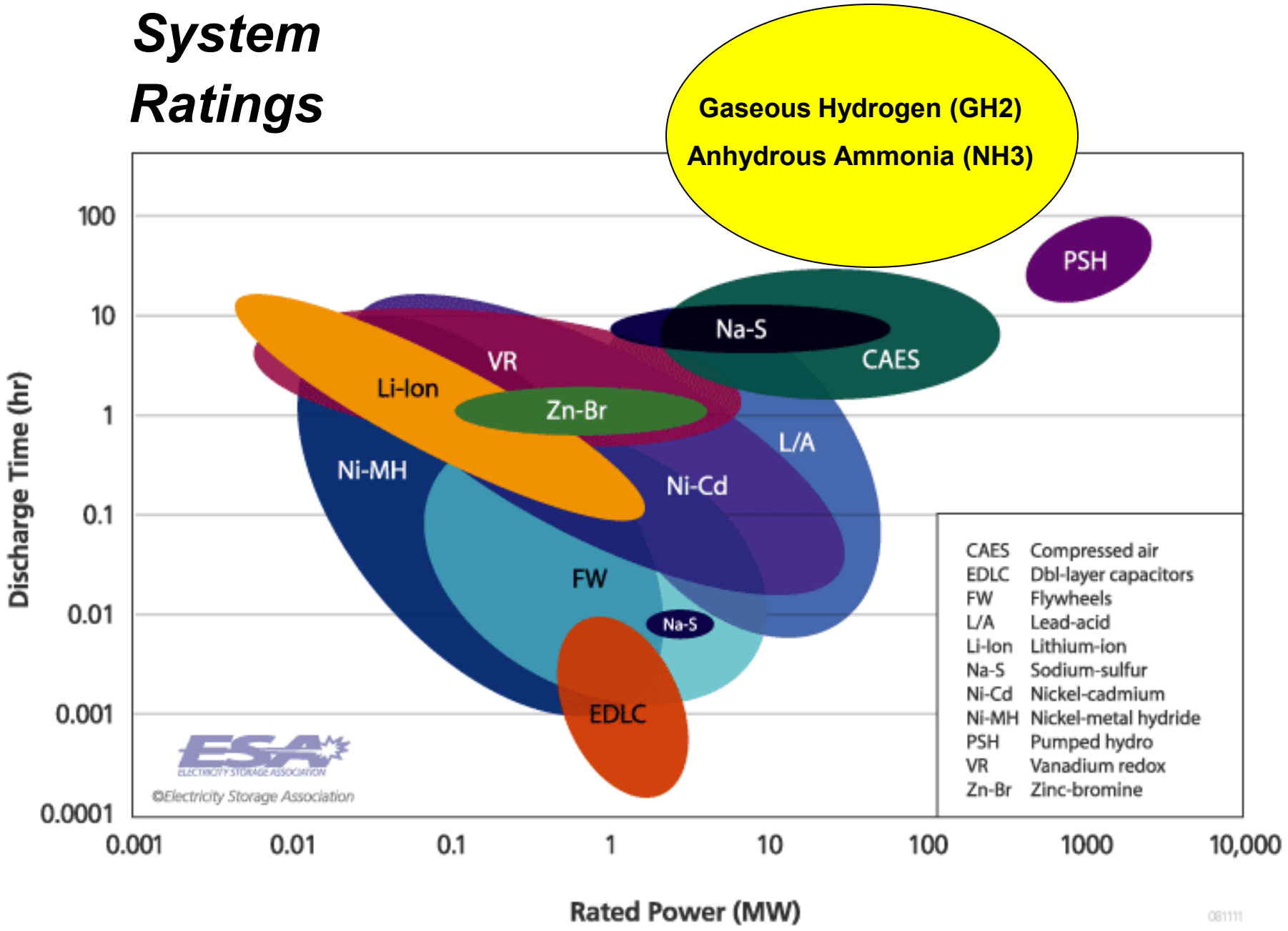
Wind to Hydrogen Power to Gas

“ Energiepark Mainz ”

Siemens, Linde, Stadtwerke Mainz, RheinMain University



System Ratings



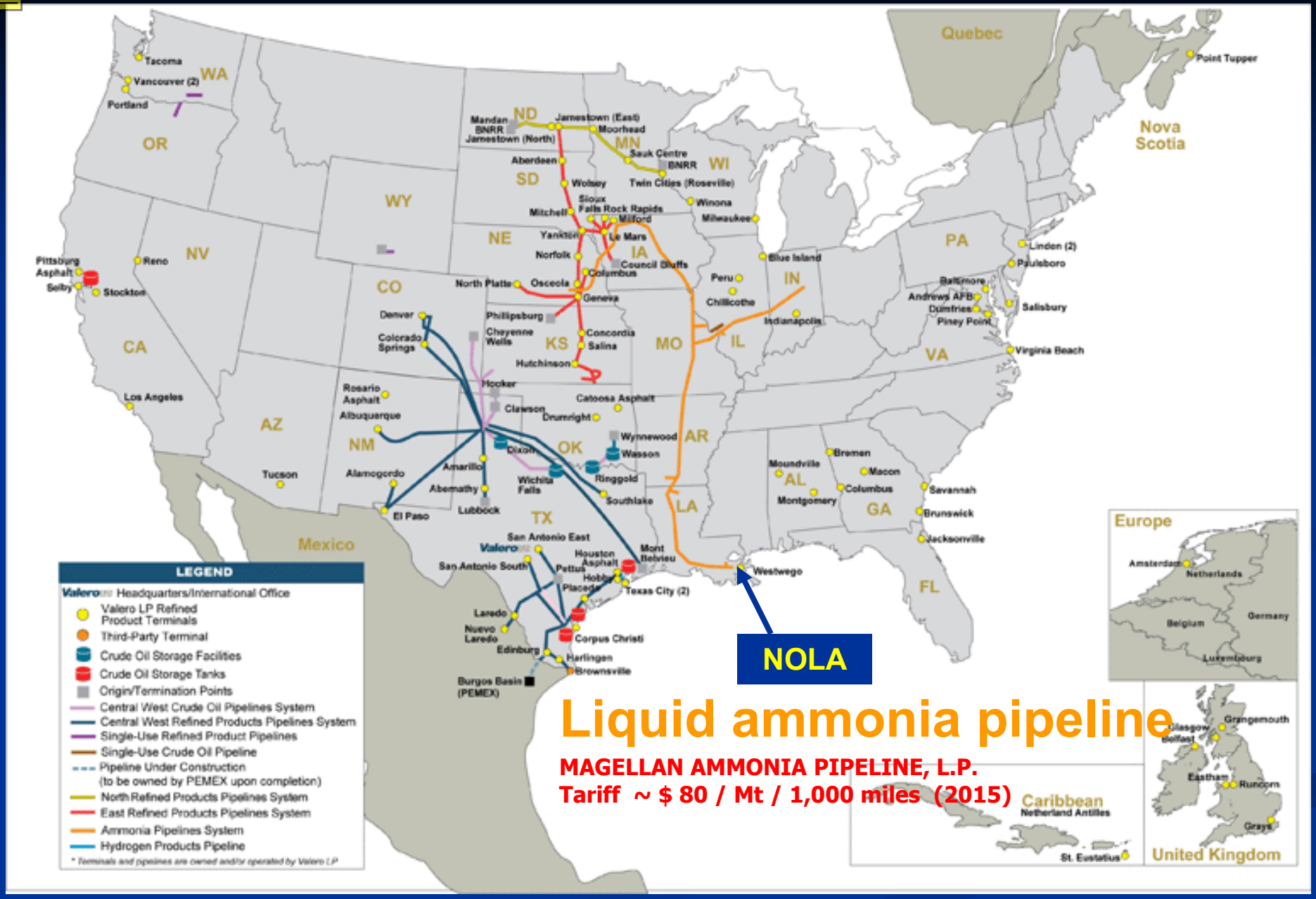
“Atmospheric” Liquid Ammonia Storage Tank (Corn Belt)

-33 C 1 Atm

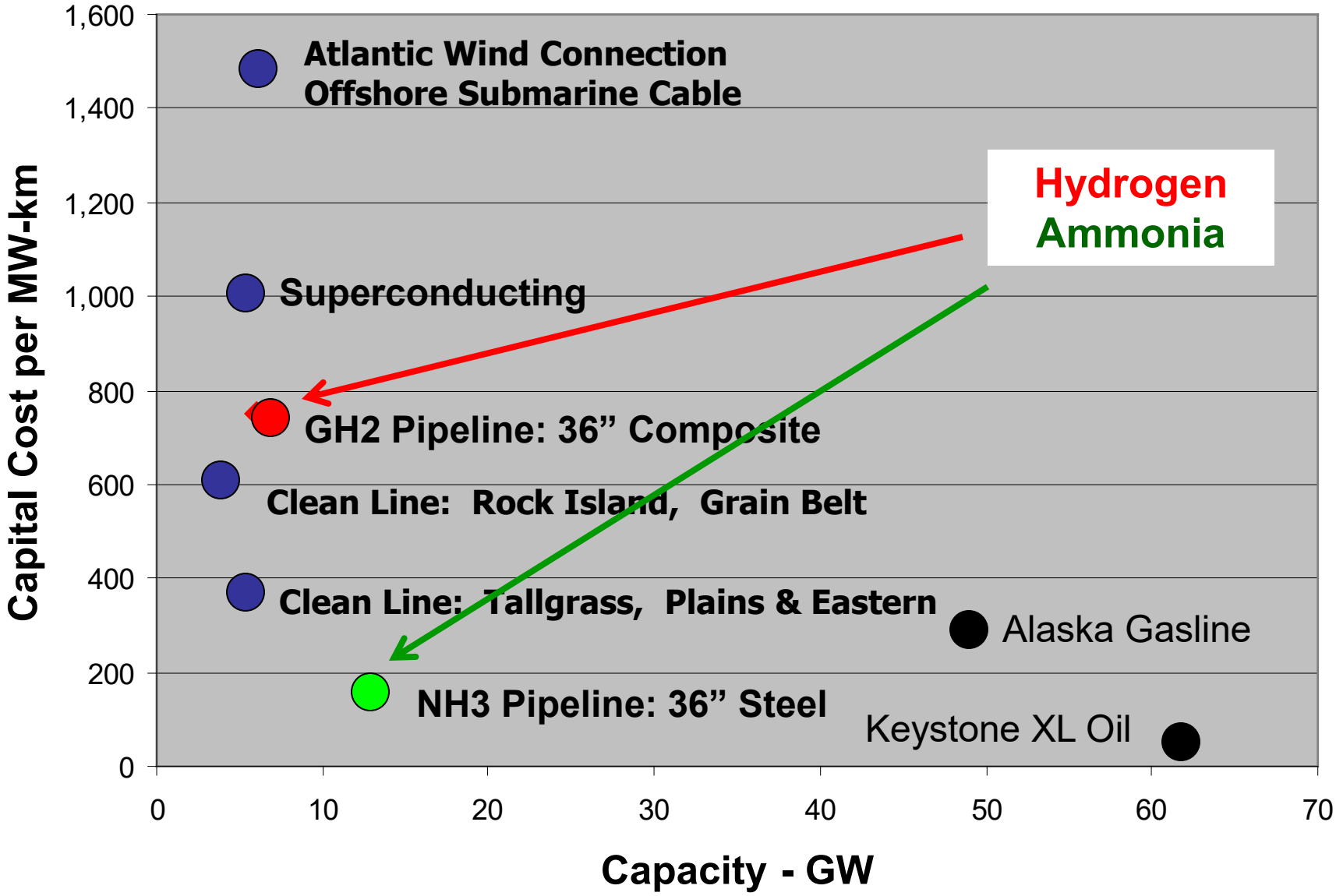
Each: 30,000 Tons, 190 GWh $ 20 M turnkey

$ 100 / MWh = $ 0.10 / kWh capital cost


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



Valero LP Operations

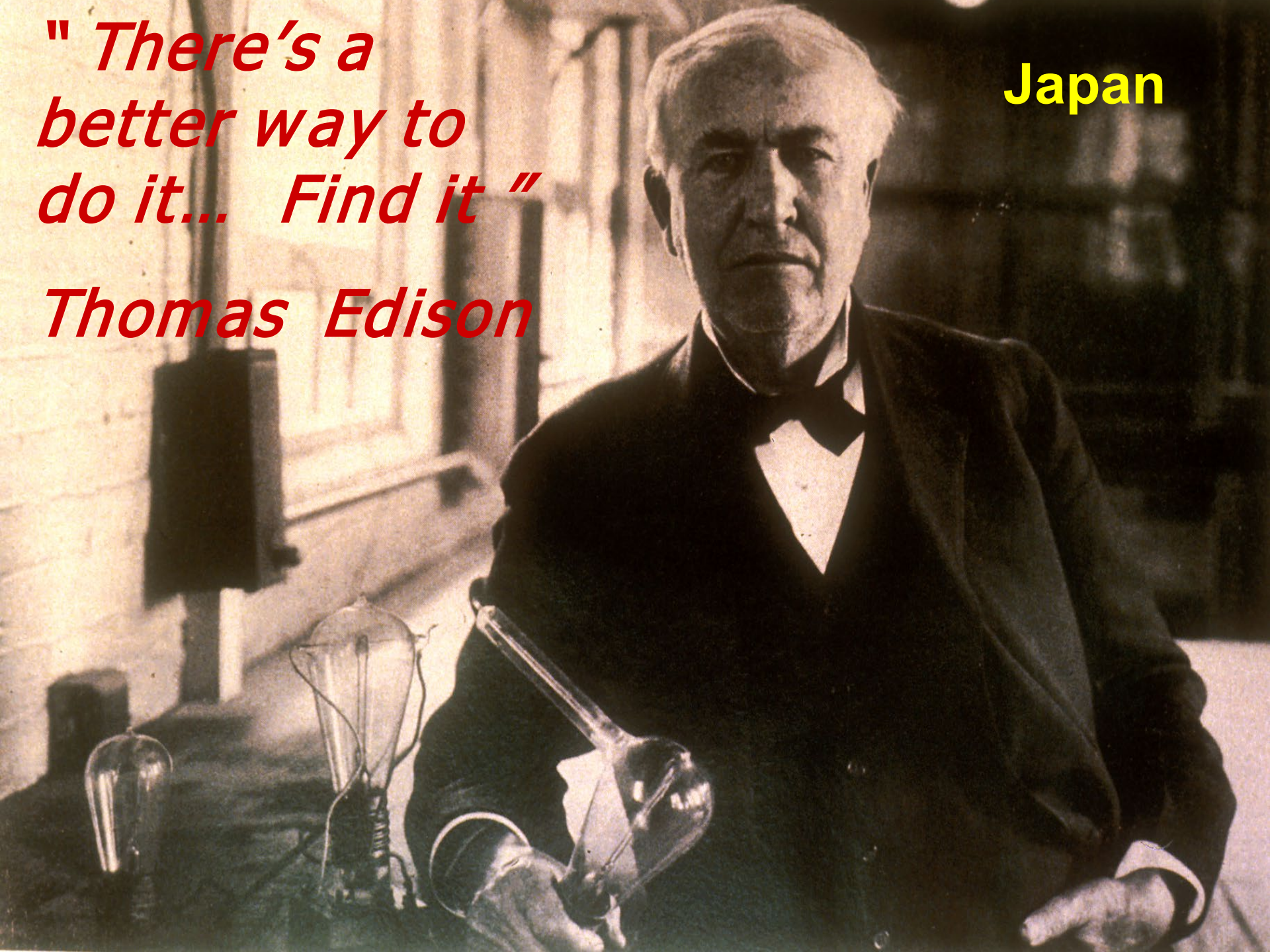


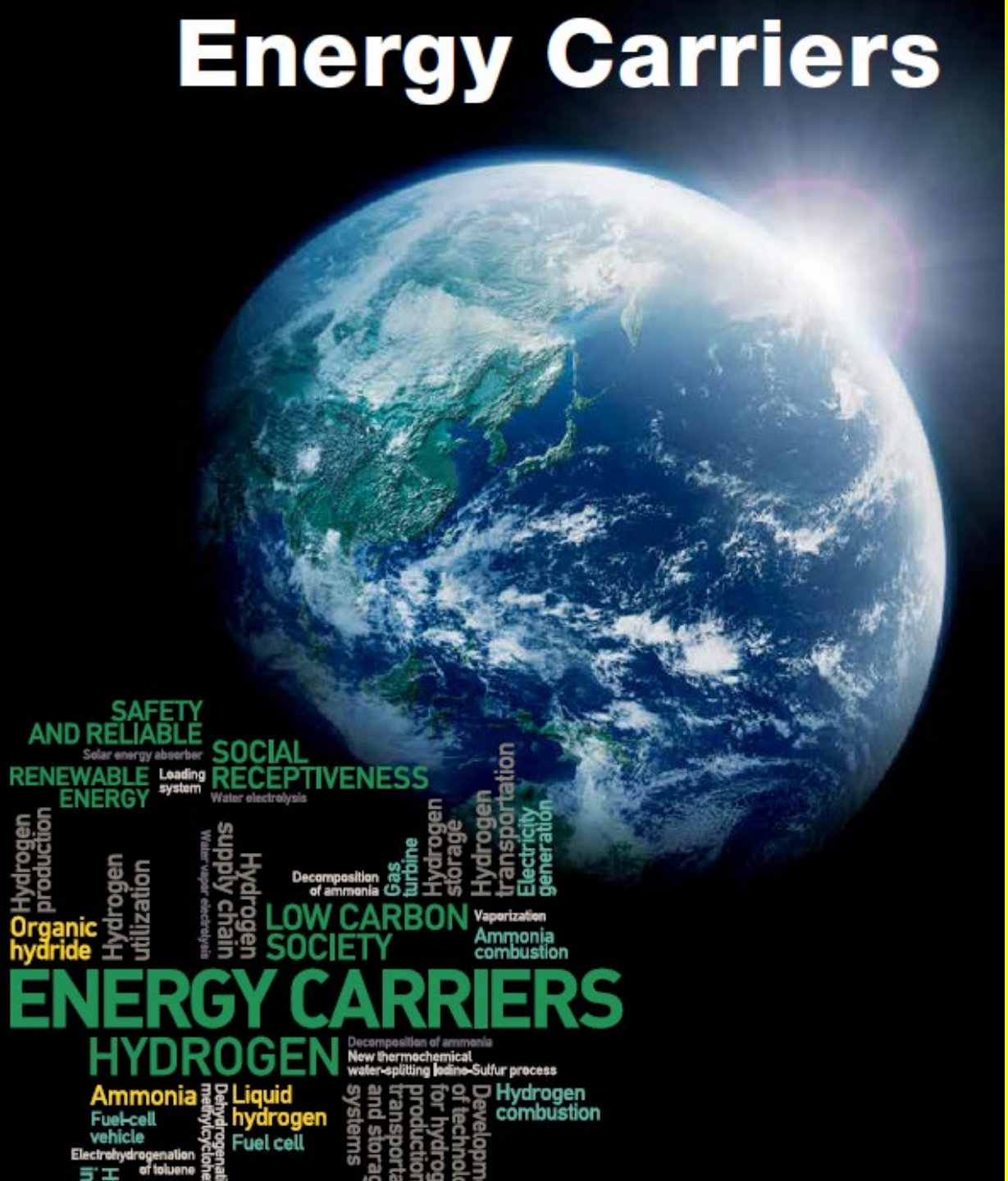
Transmission capital costs per MW-km compared

Pipelines have large capacity and provide large storage

Transmission 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	
• HVDC (800 mi)	500	3,000	0.7	(includes converters)
Hydrogen pipeline:				
36”, 100 bar, 500 miles			0.3	(no compressors)
Ammonia pipeline:				
10”, liquid, 500 miles, with pumping			0.2	


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



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}) from Toluene (C_7H_8)

"Spera": Latin for "hope"

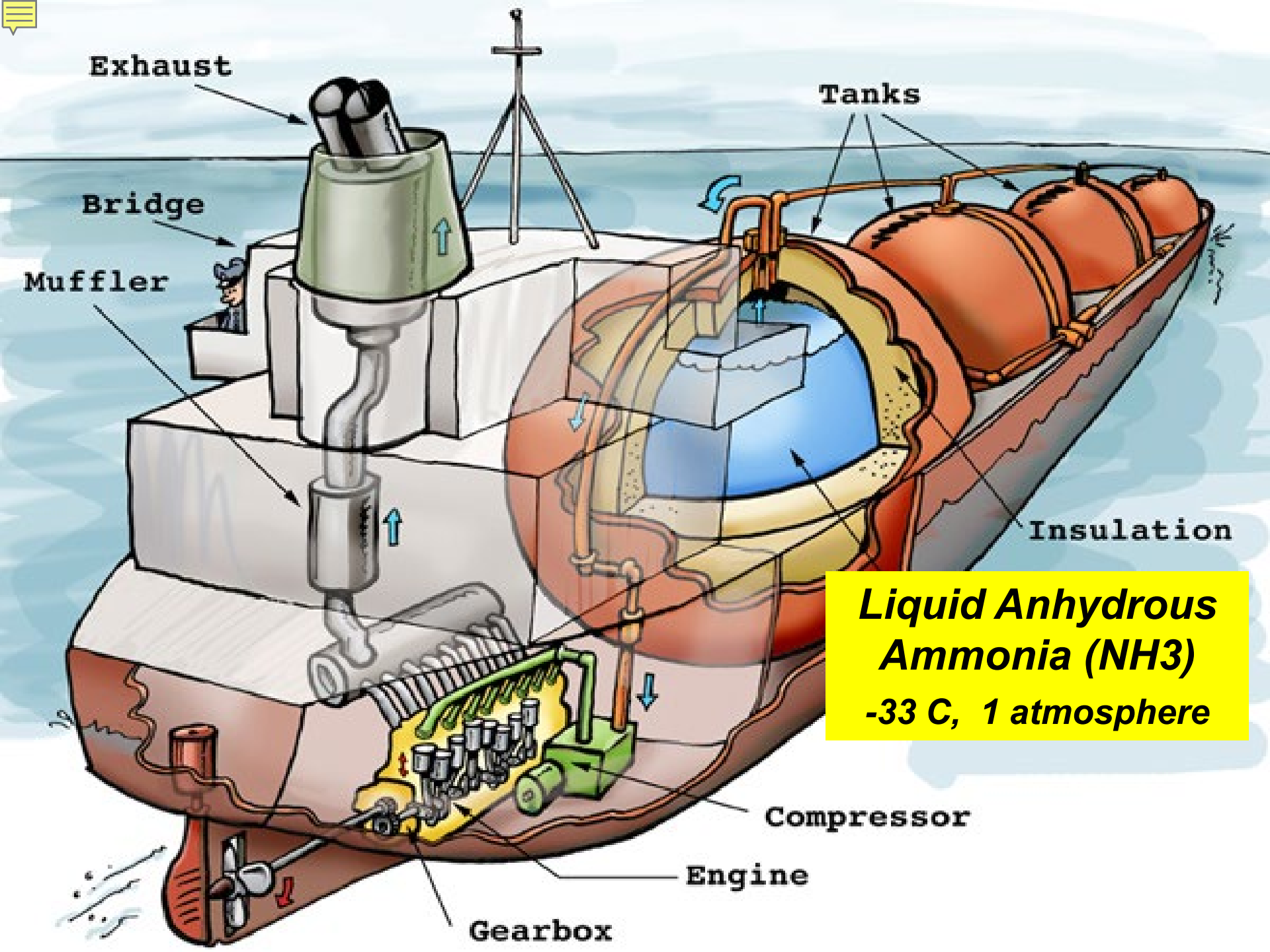
Liquid Hydrogen – LH_2
100 H atoms

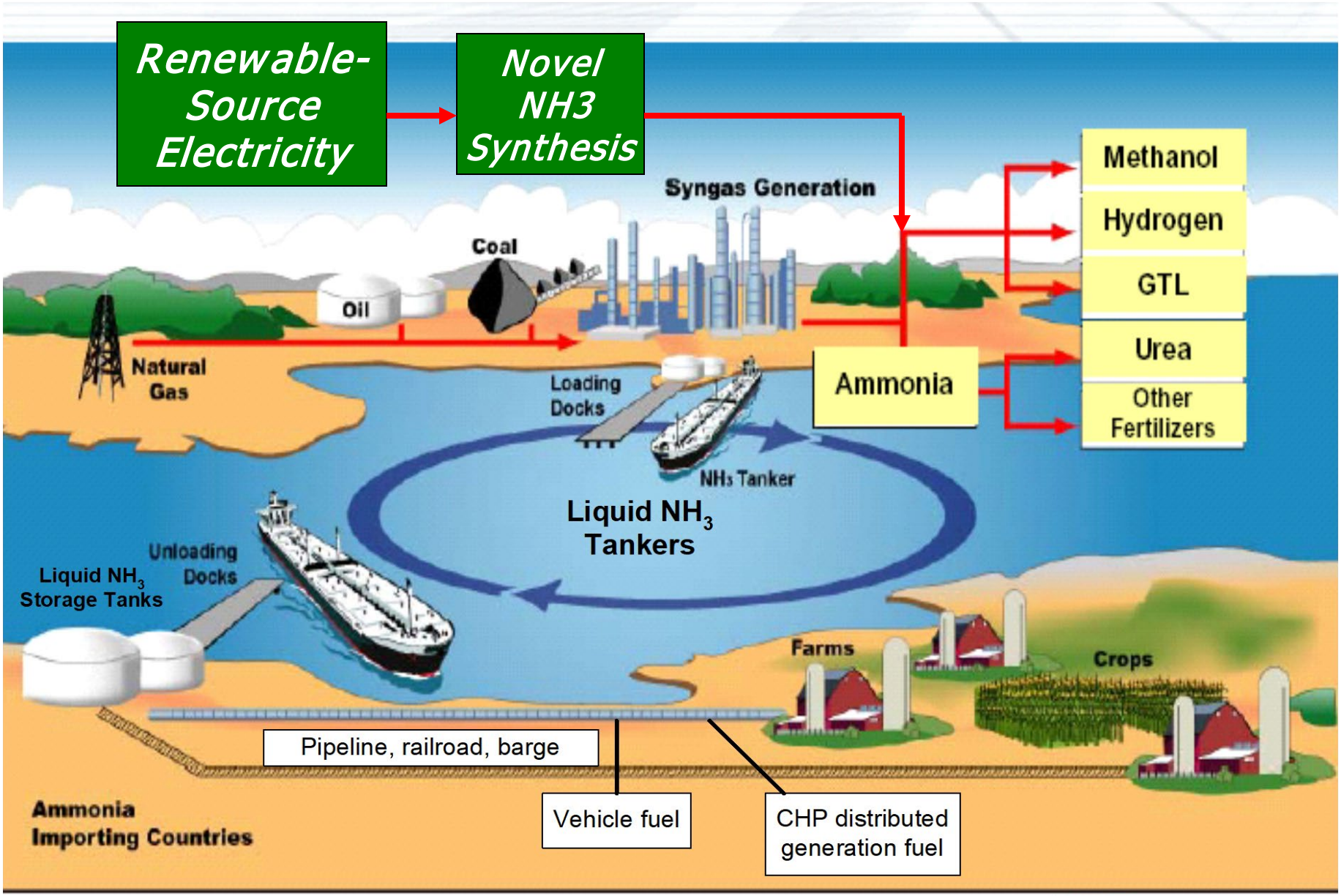
Liquid Anhydrous Ammonia – NH_3
170 H atoms

Spera Hydrogen

Chiyoda Chemical

Methylcyclohexane (MCH) (C_7H_{14}) from Toluene (C_7H_8)

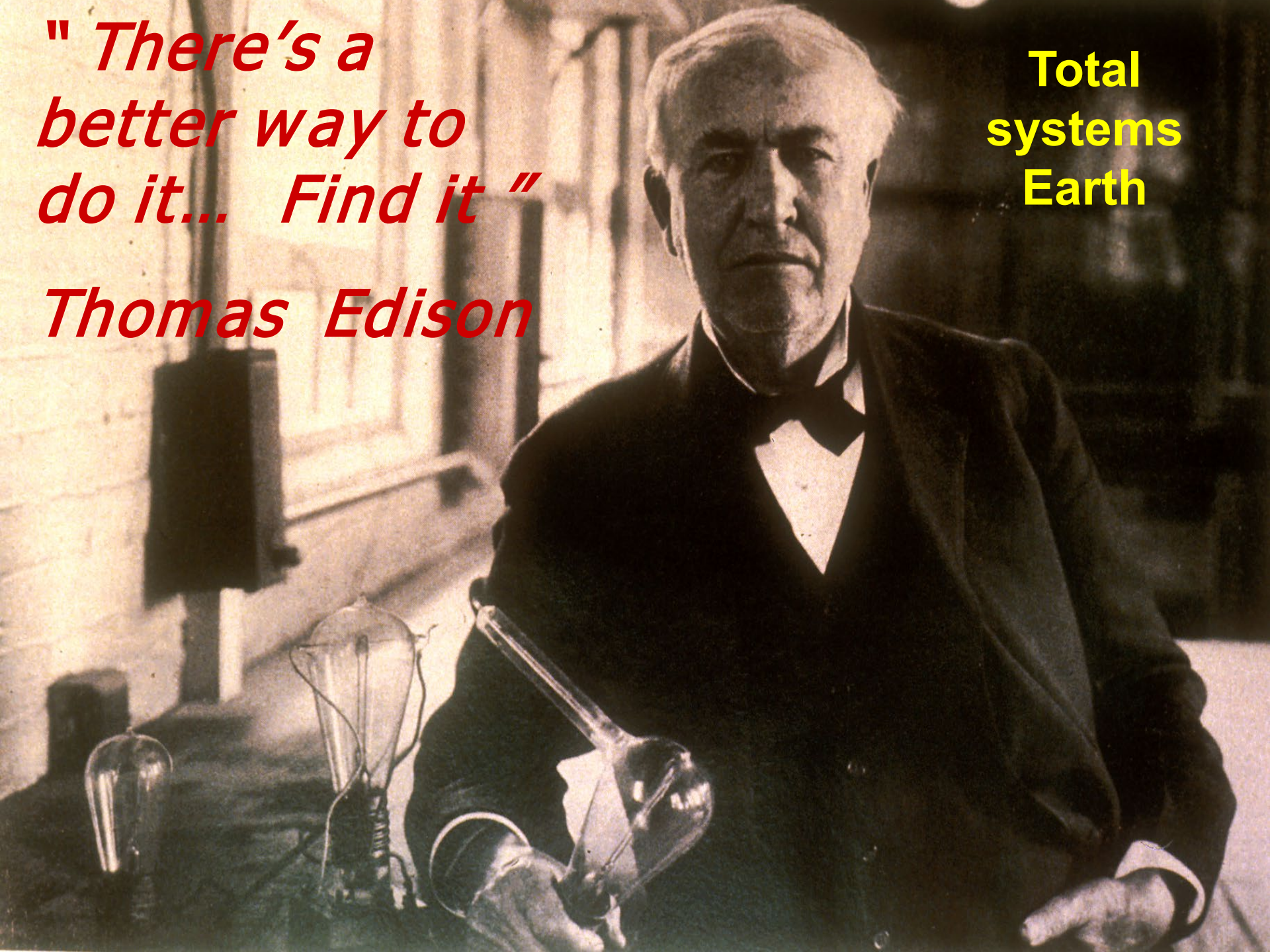

Exhaust
Tanks
Bridge
Muffler
Insulation
Liquid Anhydrous Ammonia (NH3)
-33 C, 1 atmosphere
Compressor
Engine
Gearbox

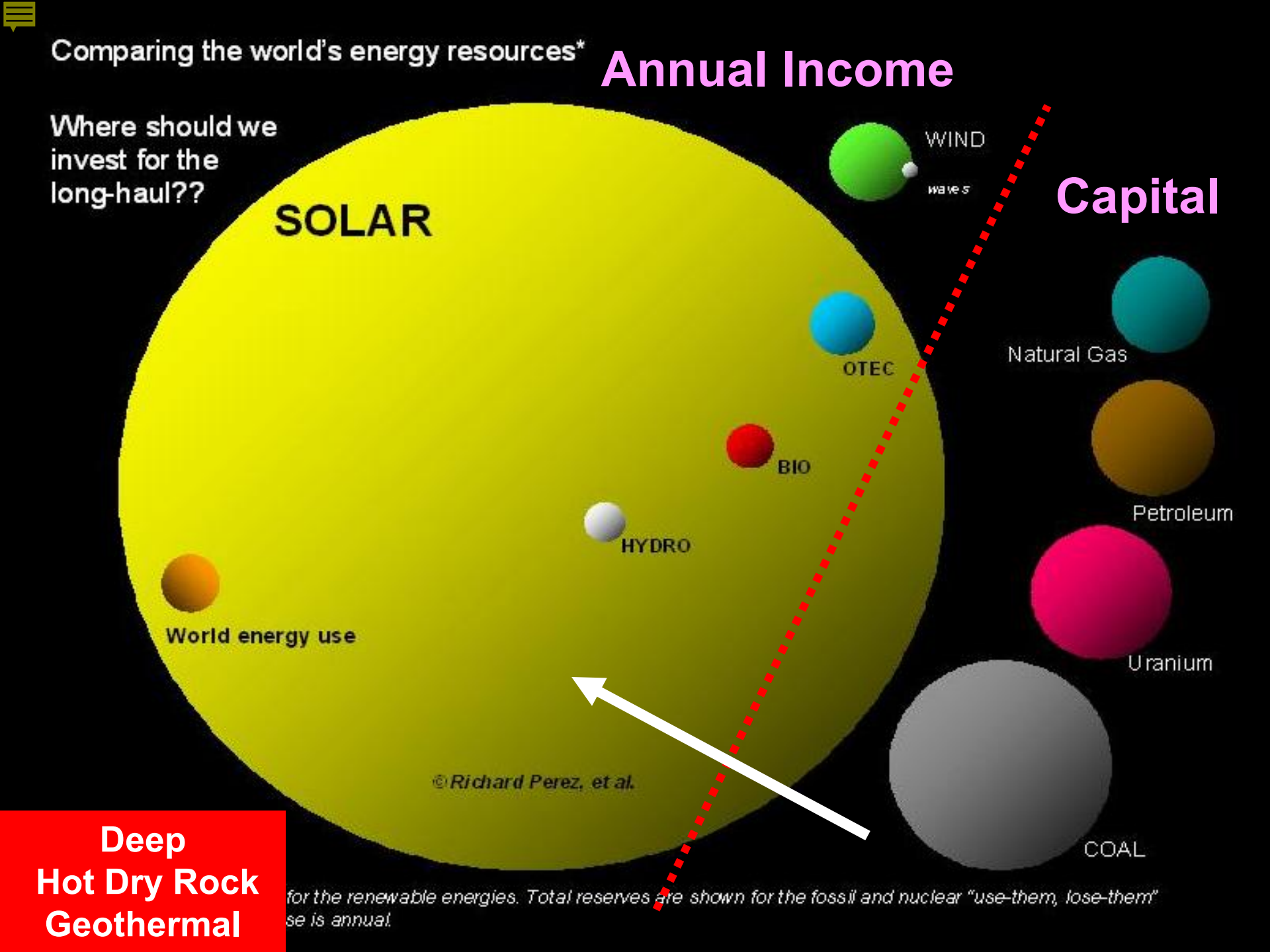


KBR
Energy and Chemicals

Floating Offshore
Deep water, multi - MW

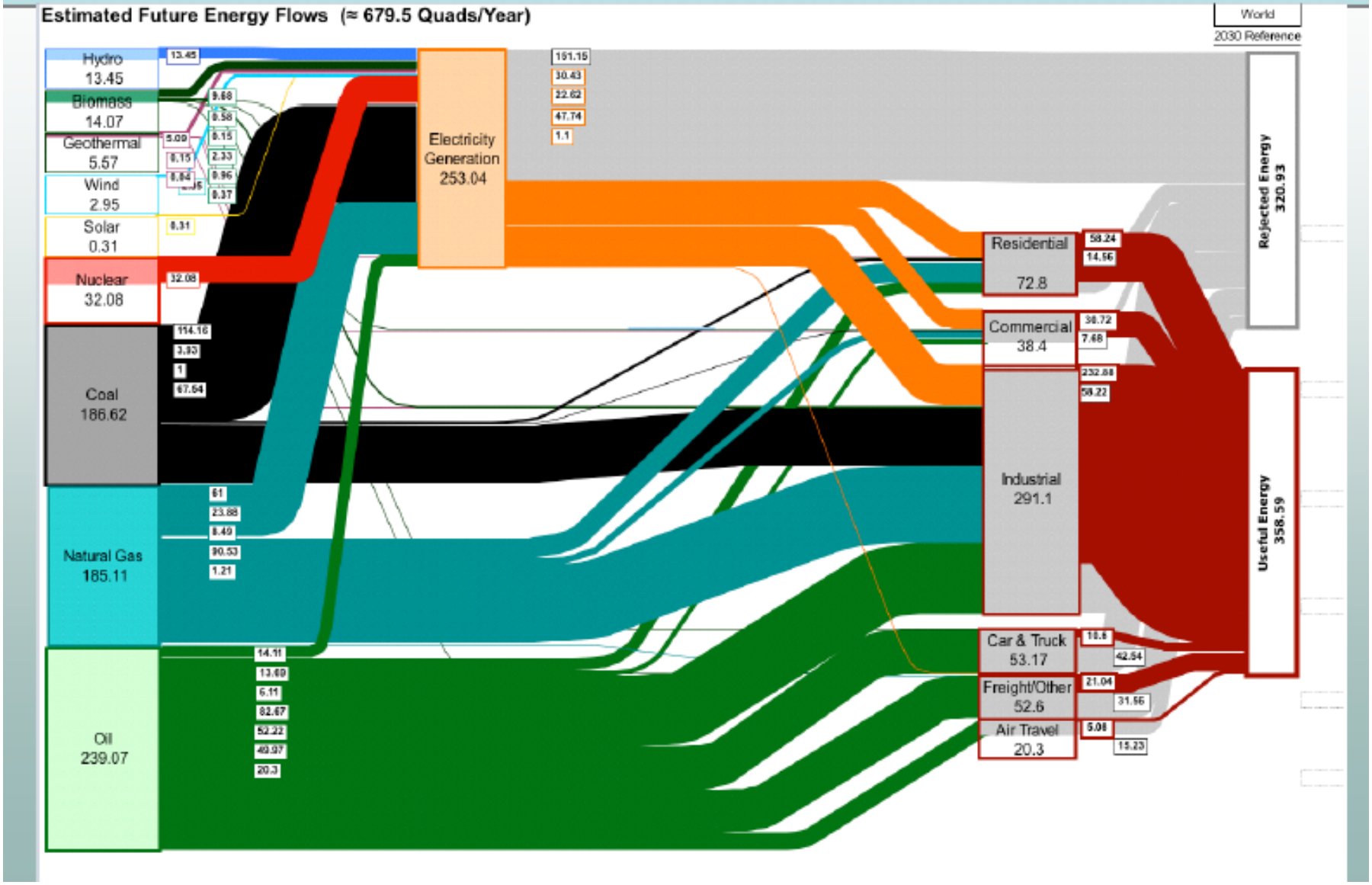
Aleutians wind to Japan via liquid fuel(s) tankers

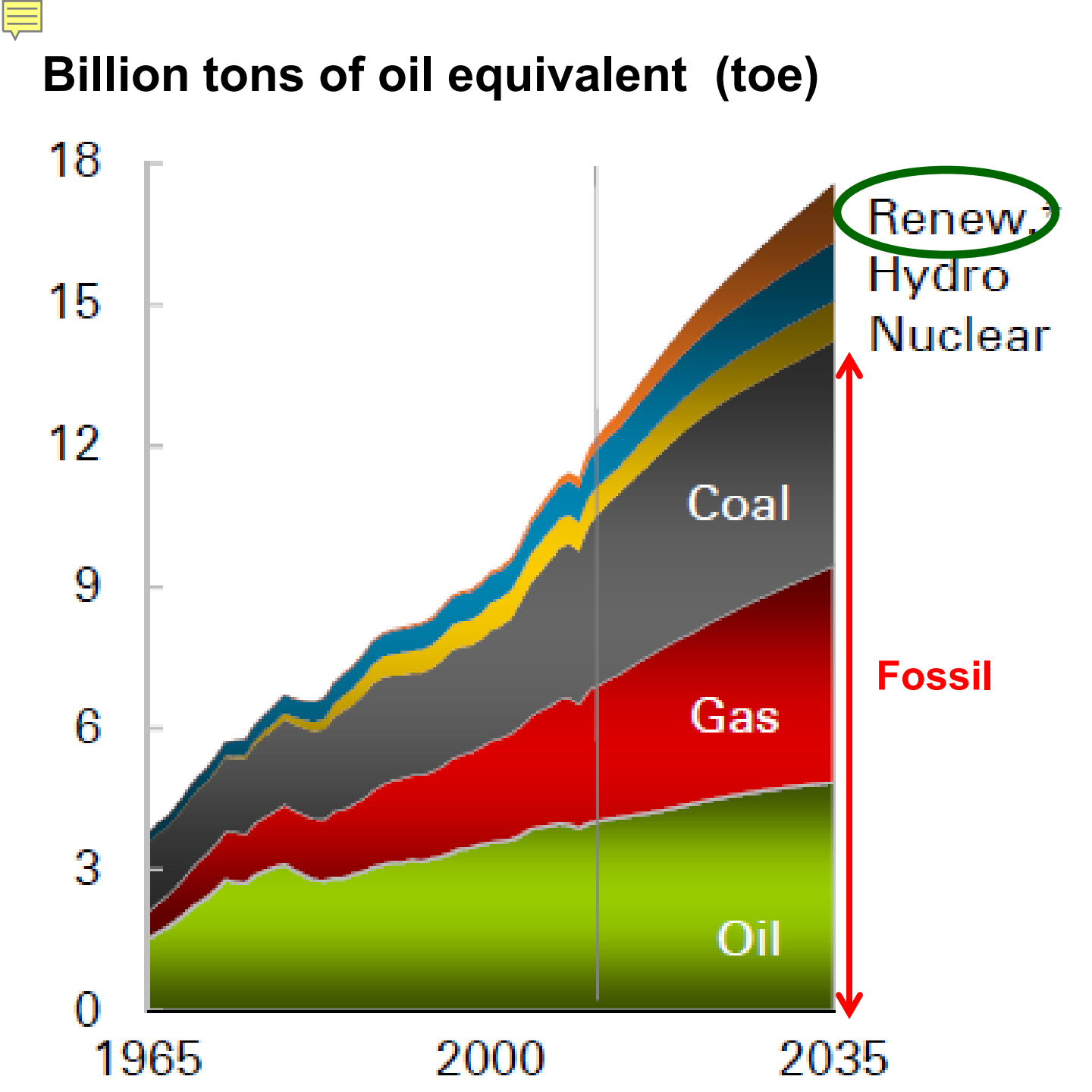

" There's a better way to do it... Find it "
Thomas Edison
Total systems Earth


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.
Deep
Hot Dry Rock
Geothermal
for the renewable energies. Total reserves are shown for the fossil and nuclear "use-them, lose-them"
se is annual.

Projected World Energy ~ 680 Quads/yr

2030 Reference Case (IEO 2006)





World Primary Energy Consumption

BP Energy Outlook To 2035

January '14

“Climate Change”

- Warming
- Severe weather
- Sea level rise
- Ocean acidification
- Species extinction
- Human conflict

“ 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

Transform World's Largest Industry

From ~ 85% fossil → ~ 100% CO2-emiss-free

- **Quickly**
- **Prudently**
- **Profitably**

Via electricity systems, "Grid" ?

- **Entirely ? Try to ? Waste of resources ?**
- **Suboptimal -- tech & econ ?**
- **Obsolete ? Limit to " first & last km, m " of system ?**

Or: C-free fuels systems ?

- **Hydrogen**
- **Anhydrous ammonia (NH_3)**
- **Entirely ?**

Transform World's Largest Industry

Via electricity systems, "Grid" ?

- **Default, obvious**
- **Entirely ? Try to ? Obsolete ?**
- **Suboptimal -- tech & econ ? Waste of resources ?**

Or: C-free fuels systems ? Entirely ?

- **Hydrogen**
- **Anhydrous ammonia (NH_3)**

Hypothesis:

- **Limit elec to "first & last km, m" of energy system**
- **C-free fuels between: pipelines, low-cost bulk storage**

How to know ? Who will model, study, propose ? Urgent !

- **Collaborative; funding**
- **Optimum mix, strategy**
- **Prevent opportunity costs: wasted capital**

Transform World's Largest Industry

Unacceptable: How do much better, faster ?

Very large, urgent :

- **Danger**
- **Responsibility**
- **Opportunity:**
  - **Professional**
  - **Business**
  - **Strategic**
- **Disruption → transformation**
- **Entirely by electricity ? "Think beyond"**

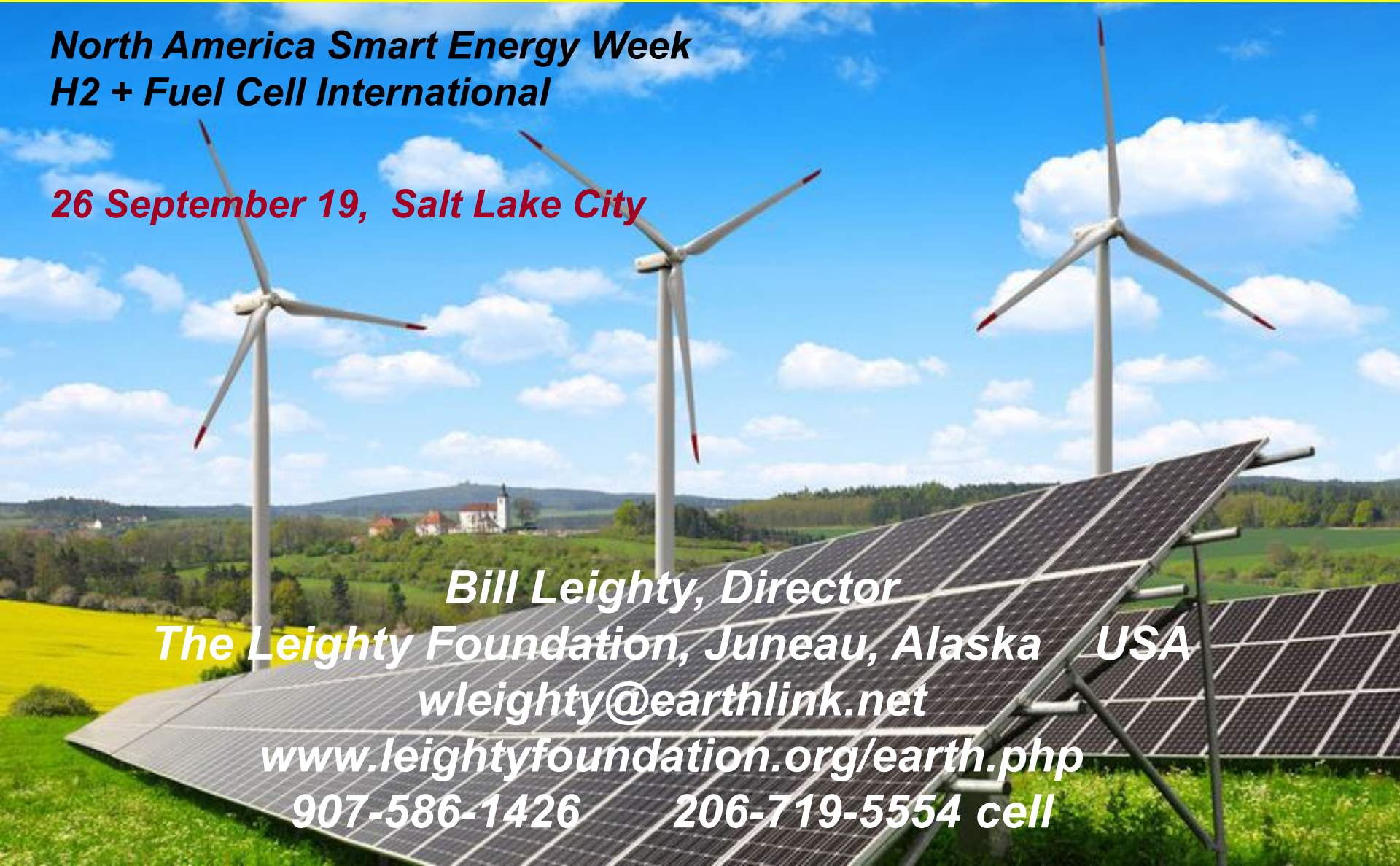
Far more Ambitious:

- Unacceptable scenarios: better, faster
- Renewables industry
- Beyond electricity systems
- Transportation + CHP fuels
- Hydrogen + ammonia fuels
- Run the World on Renewables
- ~ 100 % GHG-emission-free energy
- ~ 100 % GHG-emission-free enterprise

Hypotheses:

- **Electricity confined to " first & last km, or m "**
- **Between is C-free fuels via pipelines, low-cost storage**
- **"Grid" supports the C-free fuel systems, not reverse**
- **Cannot afford suboptimal: time, capital, "climate change"**
- **Scales: DER → global**
- **Need diverse collaboration to roadmap: neglected, urgent !**

Deep Decarbonization of Total Global Energy: Hydrogen and Ammonia C-free Fuels versus Electricity as Integrated CO2-emission-free Energy Systems



North America Smart Energy Week
H2 + Fuel Cell International

26 September 19, Salt Lake City

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The Leighty Foundation, Juneau, Alaska USA
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