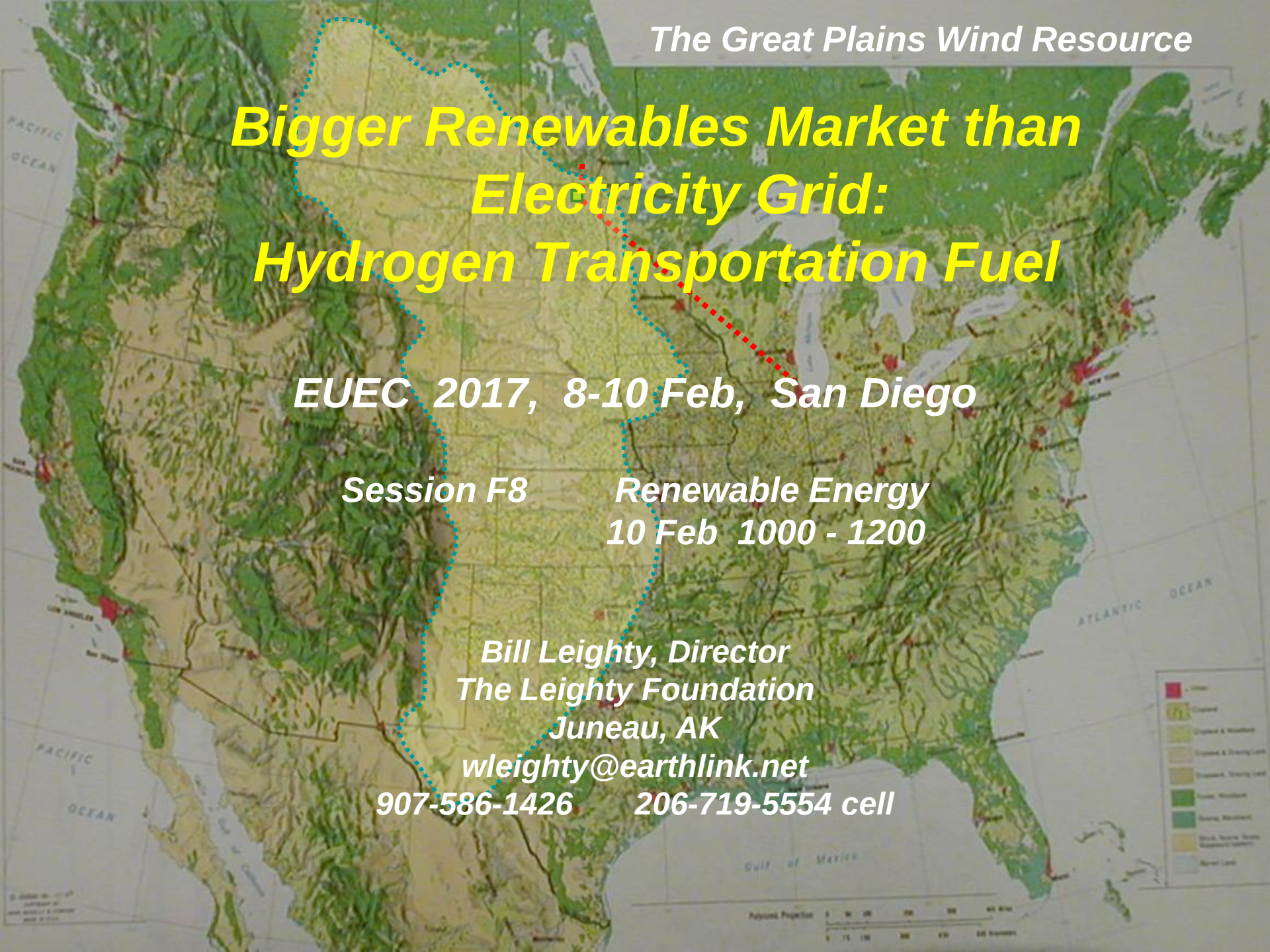


Bigger Renewables Market than Electricity Grid: Hydrogen Transportation Fuel

EUEC 2017, 8-10 Feb, San Diego

Session F8 Renewable Energy
10 Feb 1000 - 1200

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

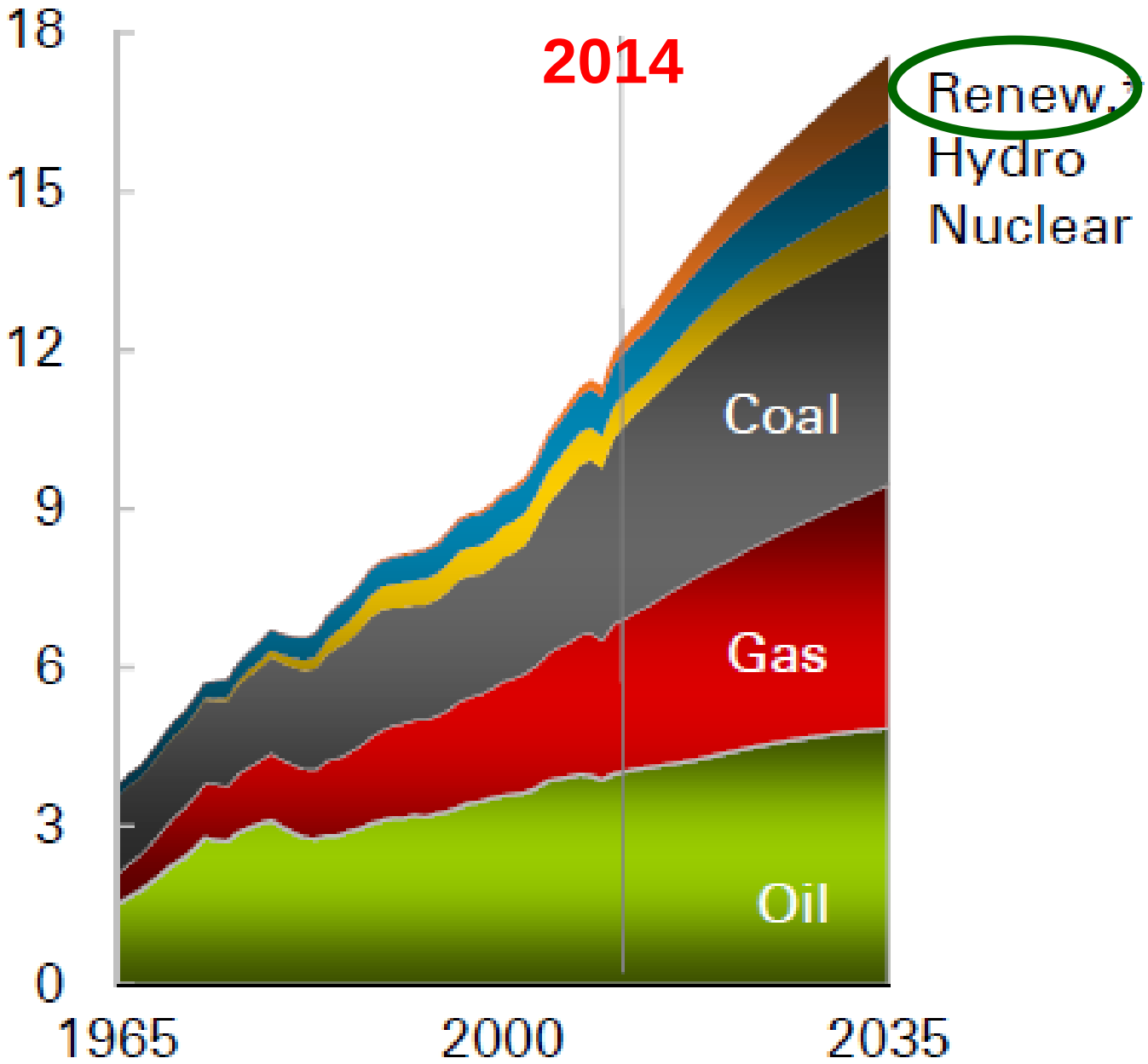
Responsibility + Opportunity

- **Transform world's largest industry**
  ~ 80% fossil → ~ 100% renewable, CO2-emission-free sources
- **Deep decarbonization**
- **All energy, all purposes, sources, global**
- **Quickly, prudently, profitably**

Responsibility + Opportunity

- **All with electricity ?**
  - **Smarter, bigger Grid ?**
  - **Suboptimal ?**
  - **Alternatives ?**
  - **Hydrogen, Ammonia C-free fuels ?**
- **California example**
  - **RPS + “80 in 50” transportation**
  - **Fifth largest economy**
  - **UC Davis ITS - STEPS**

Billion tons of oil equivalent (toe)



World Primary Energy Consumption

BP Energy Outlook 2035

January ‘14

Trouble with Renewables

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

Trouble with Renewables: Big Three

1. Gathering and Transmission
2. Storage: Annual-scale firming
3. Integration
   - Extant energy systems
   - Electricity grid
   - Fuels: CHP, transportation
   - Secure
   - Dispatchable

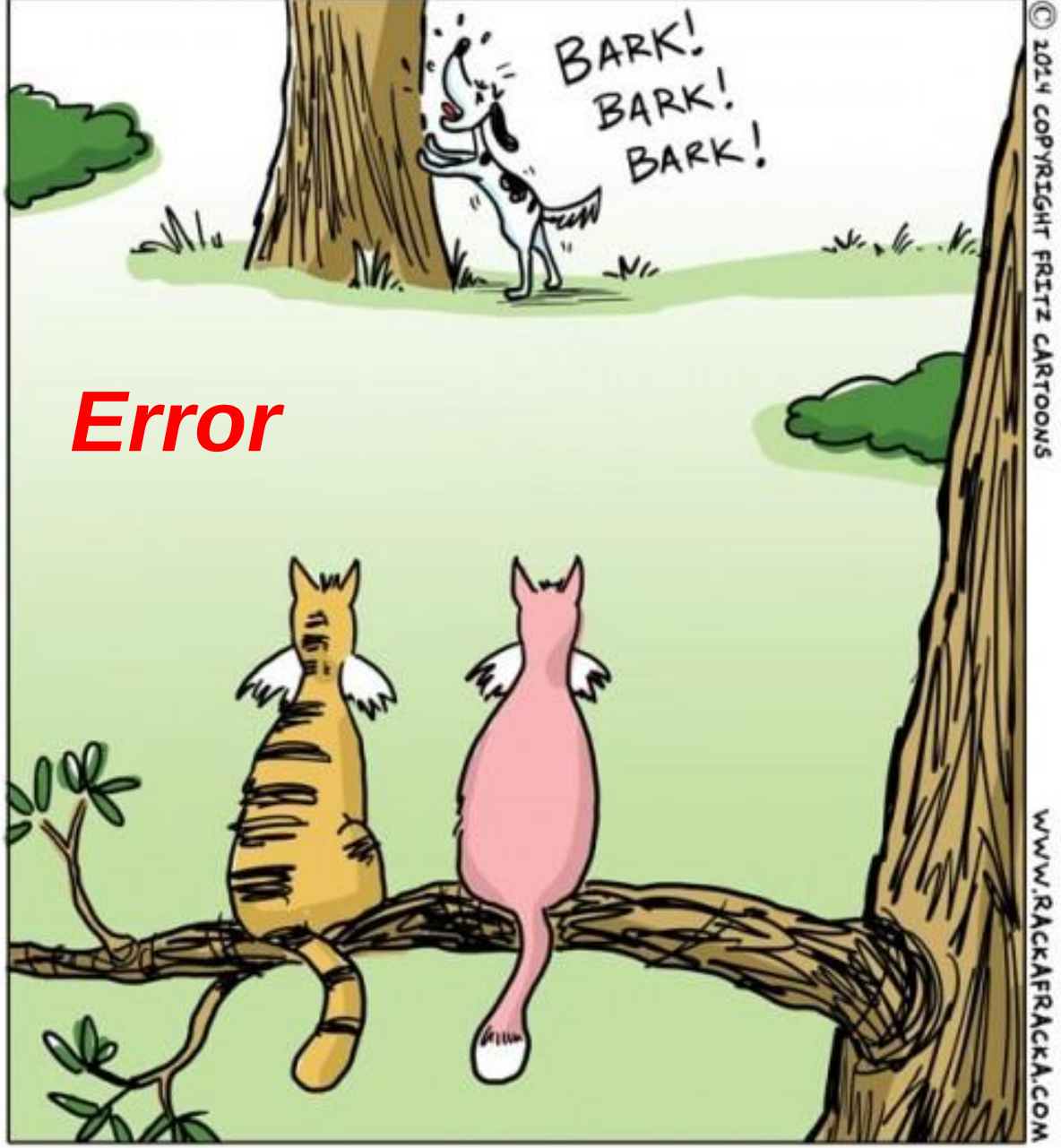
Suboptimal ?
Opportunity cost

US $ 45 trillion

New energy infrastructure invest

By 2030

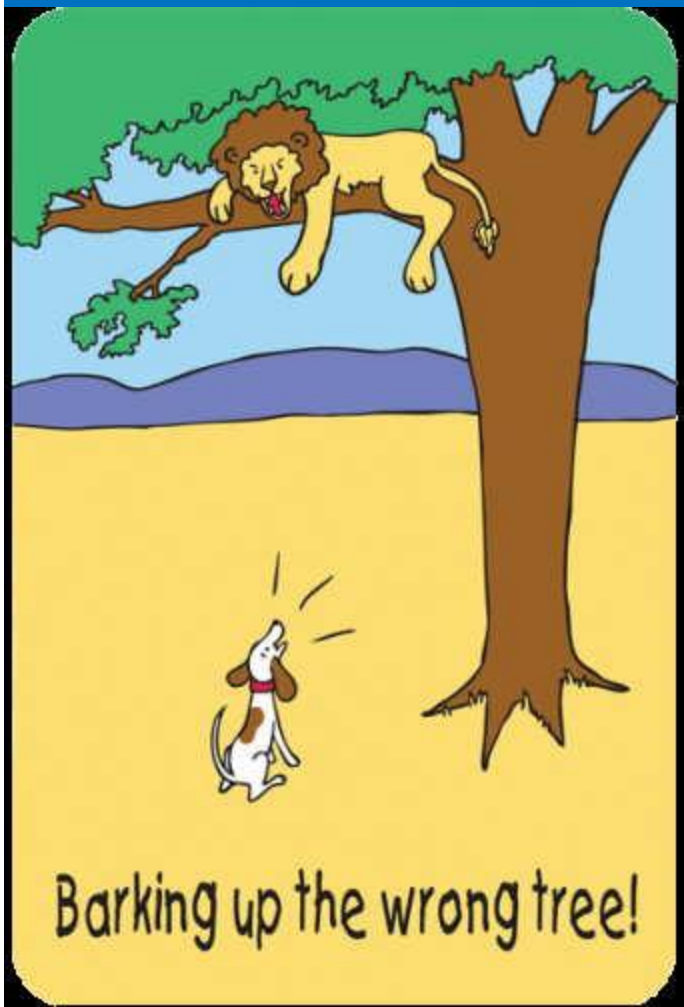
Wires or H2, NH3 pipelines ?



Error

BUSTER WAS CAUGHT BARKING UP THE WRONG TREE AGAIN.

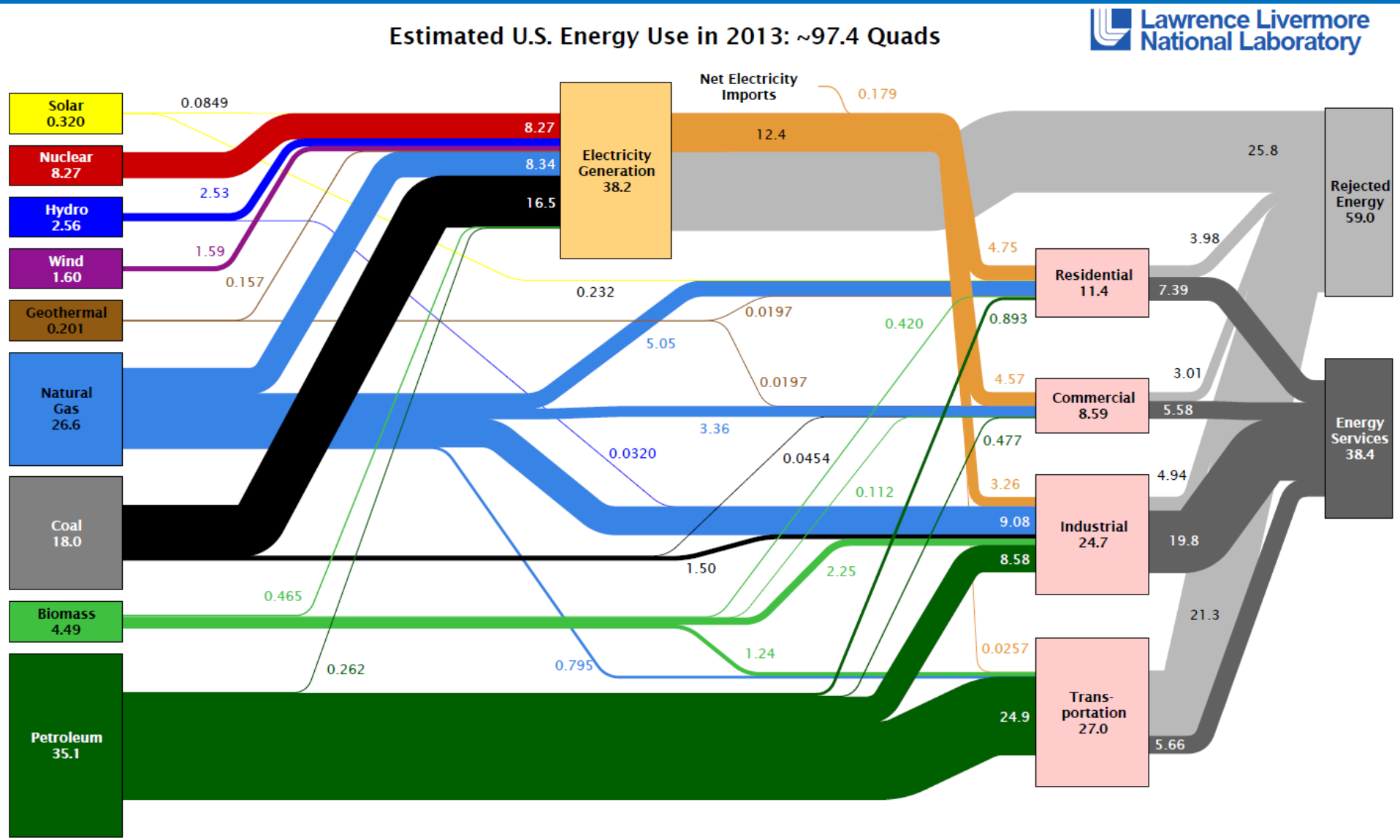
Danger



Utility of the Future

- **Utilities threatened**
  - **Electricity: SCE**
  - **Electricity + gas: PG&E, SDG&E, Xcel**
  - **“Energy” -- Electricity + transport fuel ?**
  - **“Energy” -- Electricity + Hydrogen ?**
- **Hydrogen Renaissance ?**
  - **CEC, 30 Jan “Renewable Hydrogen”**
  - **CEC + CARB: 20 Hydrogen Fuel Station**
  - **Davos, 17 Jan “Hydrogen Alliance”**
  - **USDOE: “H2@SCALE”**
  - **ARPA-E “REFUEL” FOA: Ammonia fuel**
  - **Shell: Hydrogen Business Develop Mgr.**
  - **Siemens: Renewables Hydrogen, Steel, Austria**
  - **Breakthrough Energy, Gates Fdn: Ammonia**

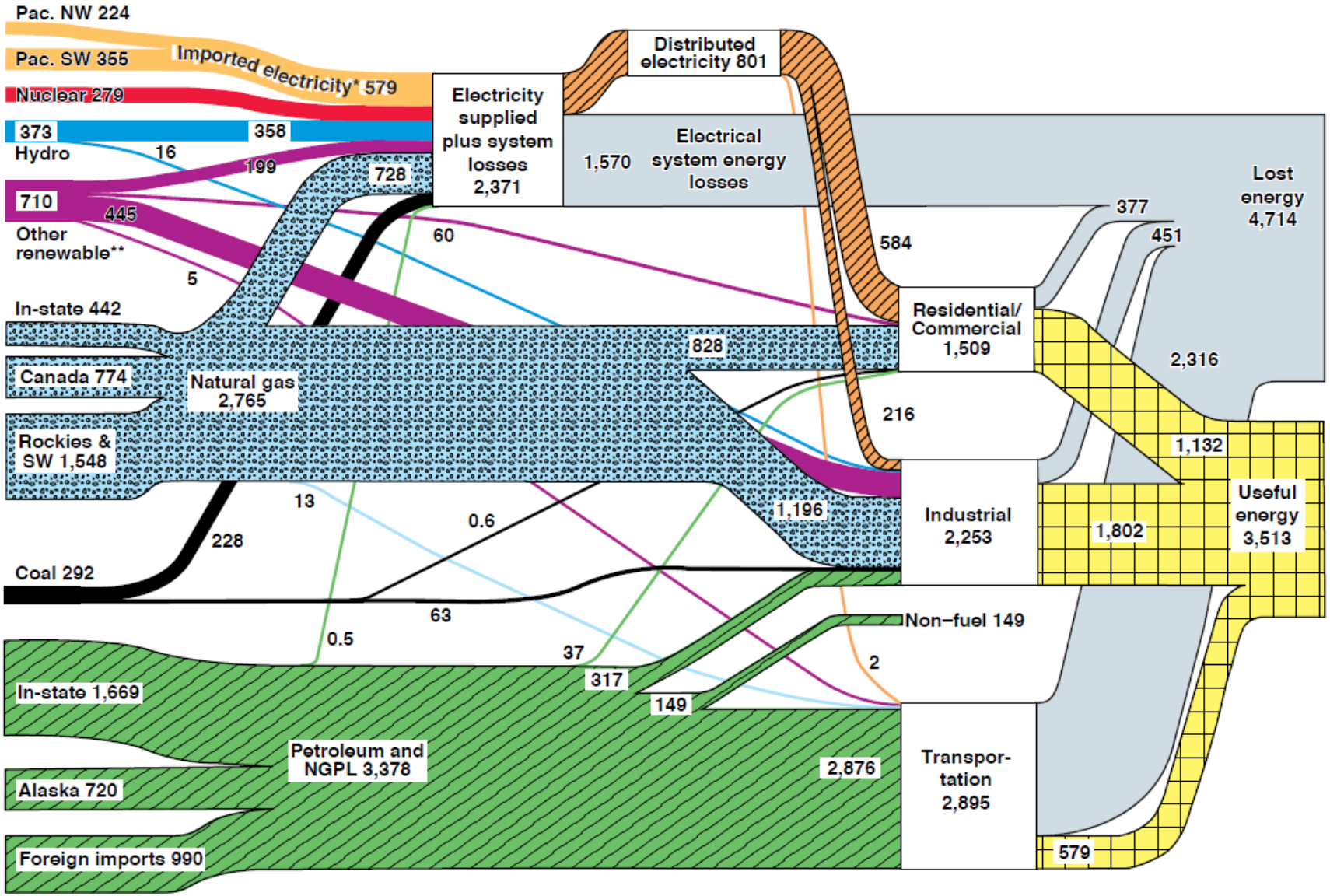
USA Total Energy 2013



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

California Energy Flow Trends– 1999

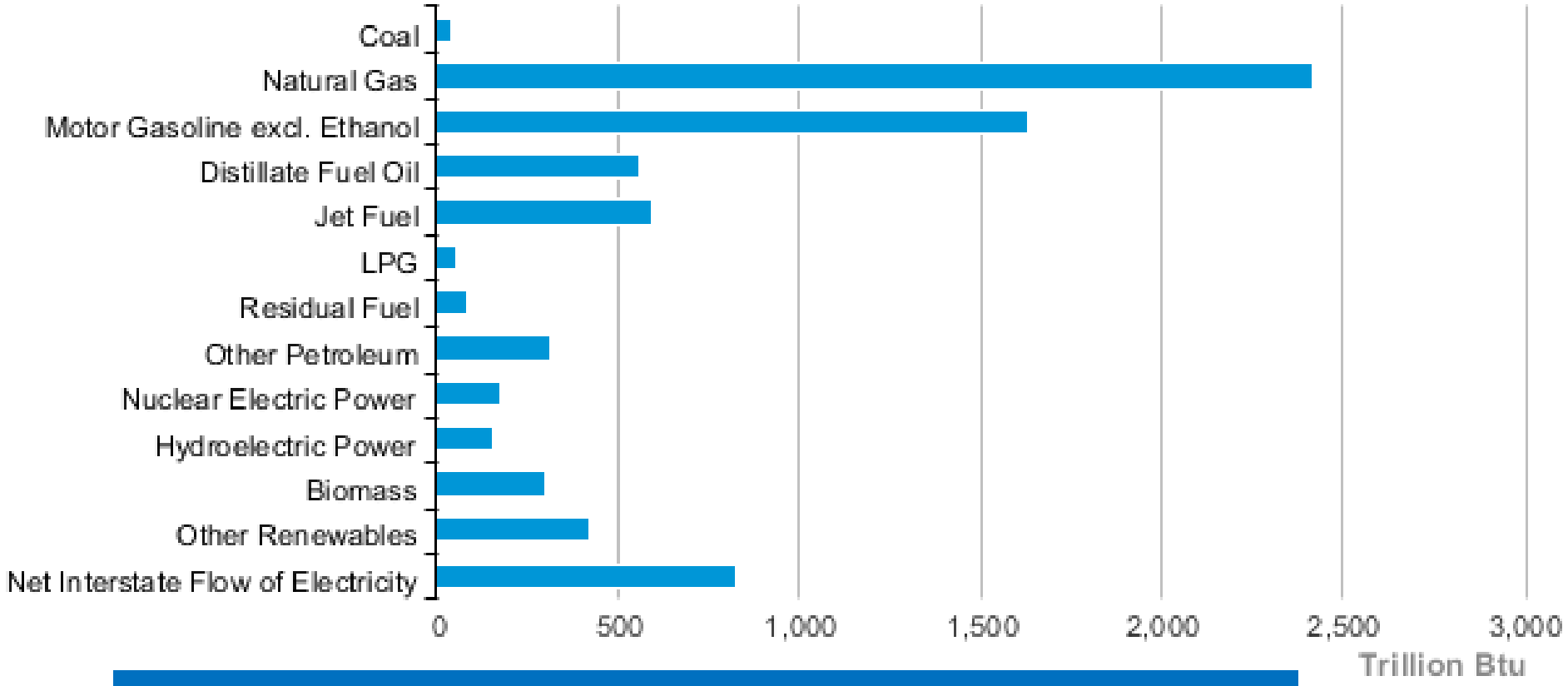
Net Primary Resource Consumption ~8375 Trillion Btu (8.375 Quads)



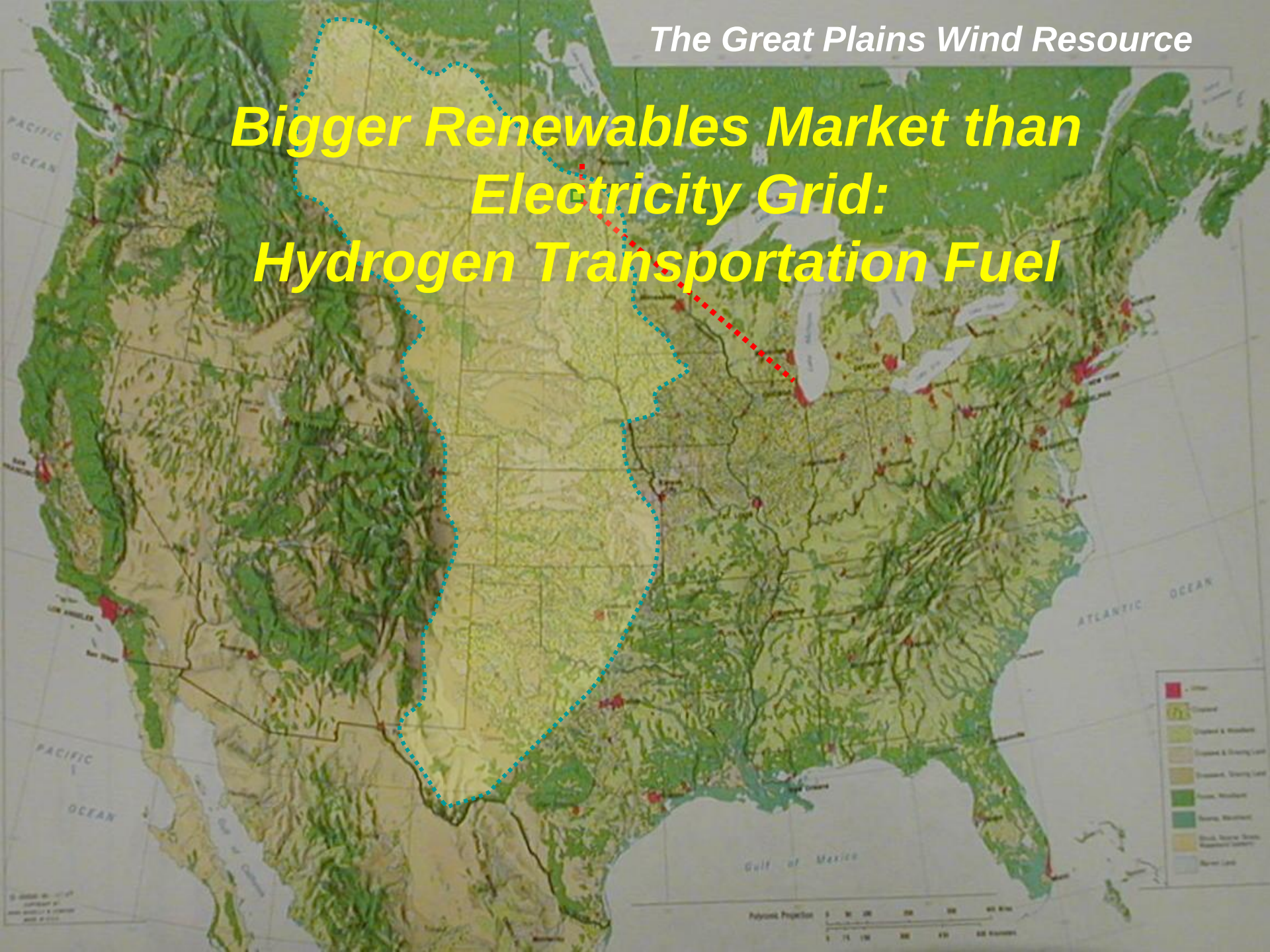
Sources: U.S. Department of Energy's Energy Information Administration and California Energy Commission.
*Electricity flowing into the California control areas: CAISO, LADWP, and IID.
**Other renewable includes geothermal, wood and waste, solar, and wind.

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

California Energy Consumption Estimates, 2014



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


The Great Plains Wind Resource
Bigger Renewables Market than Electricity Grid:
Hydrogen Transportation Fuel
PACIFIC OCEAN
ATLANTIC OCEAN
Gulf of Mexico

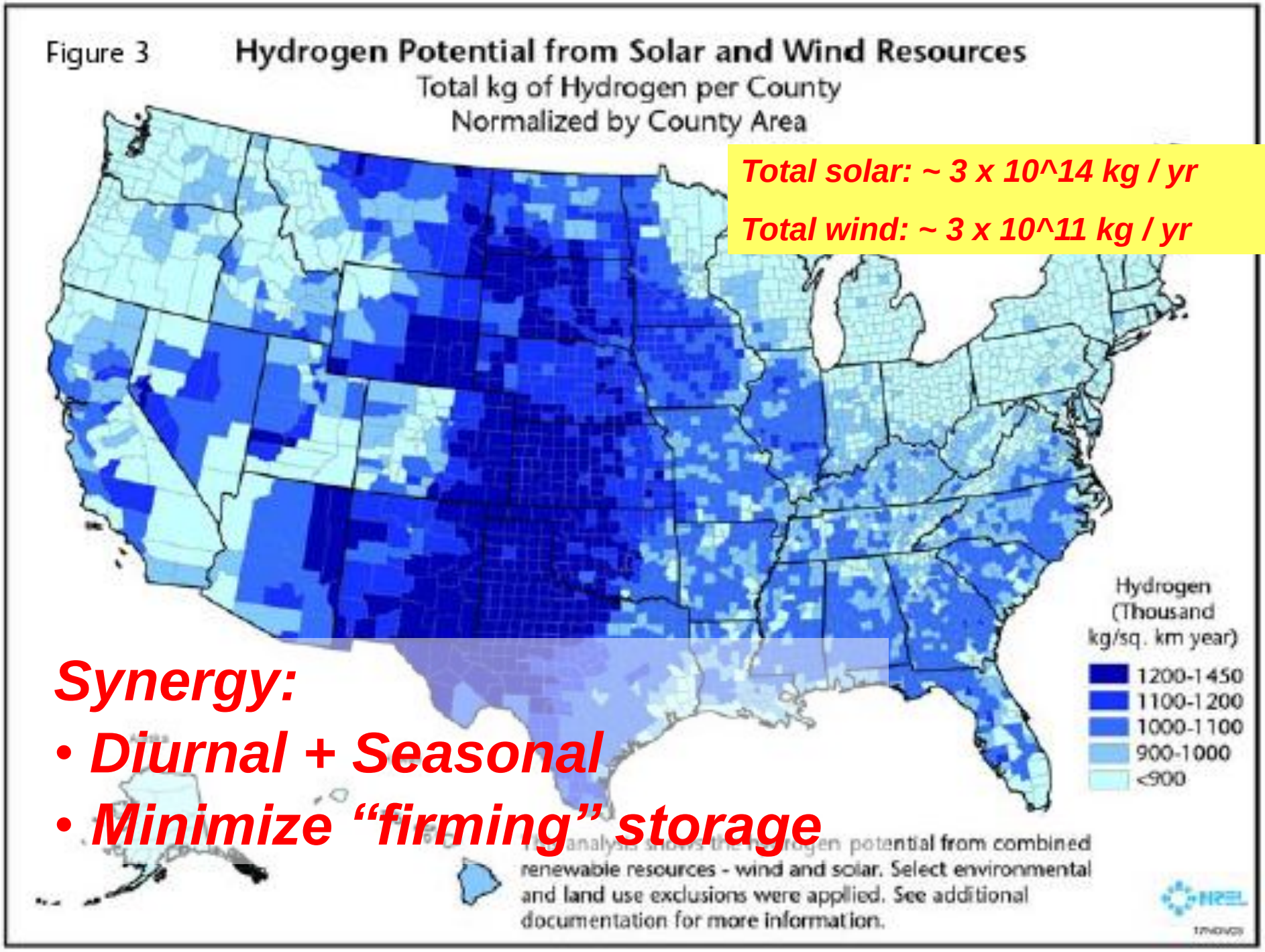
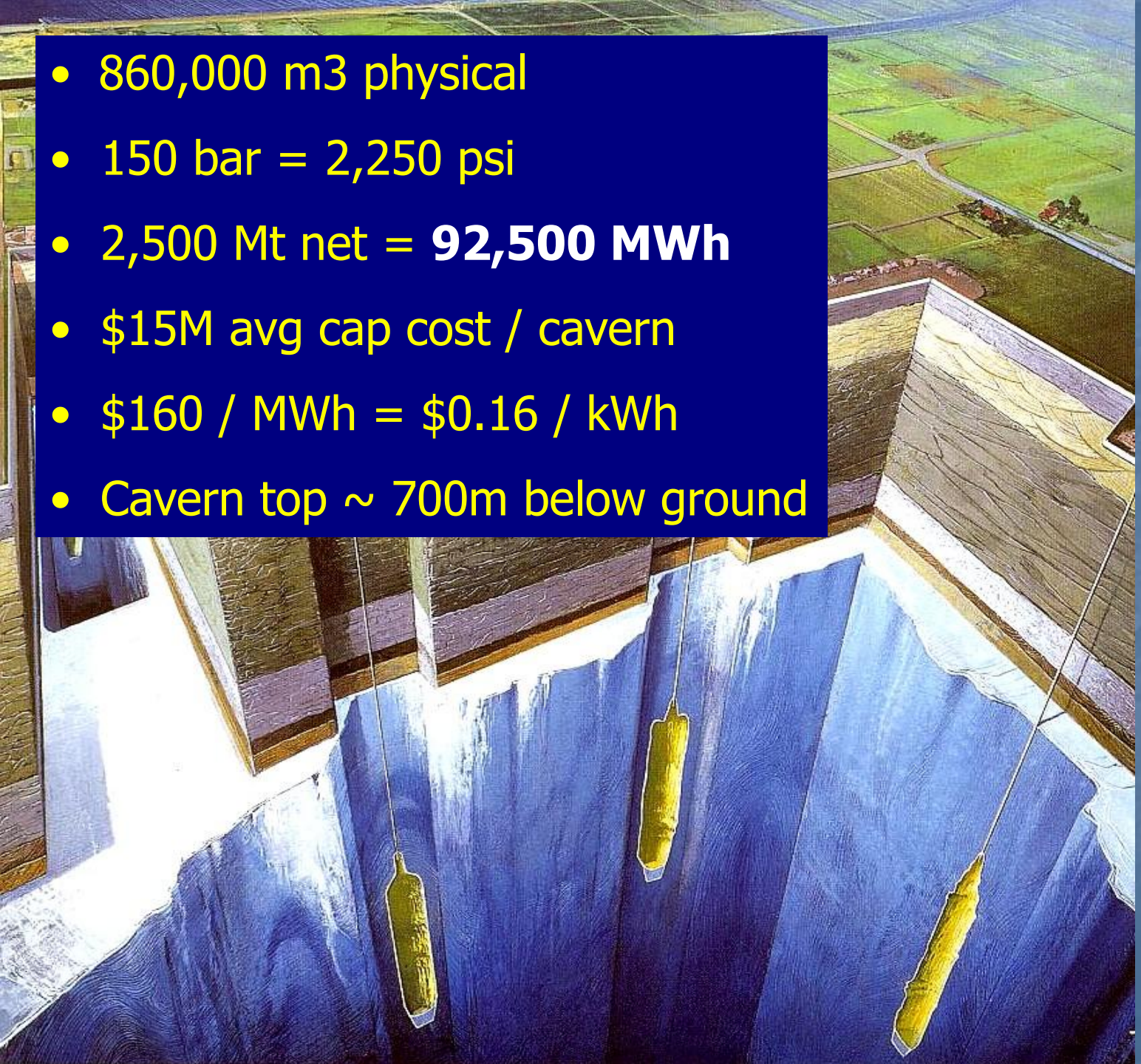


Figure 3
Hydrogen Potential from Solar and Wind Resources
Total kg of Hydrogen per County
Normalized by County Area
Total solar: ~ 3 x 10^14 kg / yr
Total wind: ~ 3 x 10^11 kg / yr
Hydrogen
(Thousand
kg/sq. km year)
1200-1450
1100-1200
1000-1100
900-1000
<900
Synergy:
• Diurnal + Seasonal
• Minimize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



- 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

’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 CAPEX

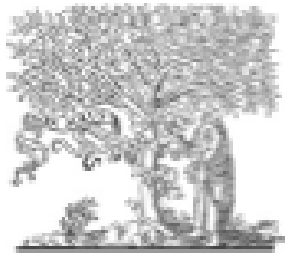
Tesla Gigafactory, Reno, NV
Annual production < 100 GWh
$ 100 / kWh CAPEX ?

UC Davis – ITS – STEPS Joan Ogden, et al

Institute of Transportation Studies – ITS

Sustainable Transportation Energy Pathways – STEPS

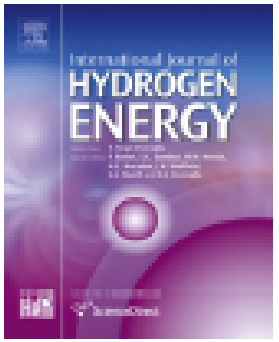
INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 38 (2013) 4250–4265



Available online at www.sciencedirect.com

SciVerse ScienceDirect

journal homepage: www.elsevier.com/locate/he



Renewable and low carbon hydrogen for California – Modeling the long term evolution of fuel infrastructure using a quasi-spatial TIMES model

Christopher Yang, Joan M. Ogden*

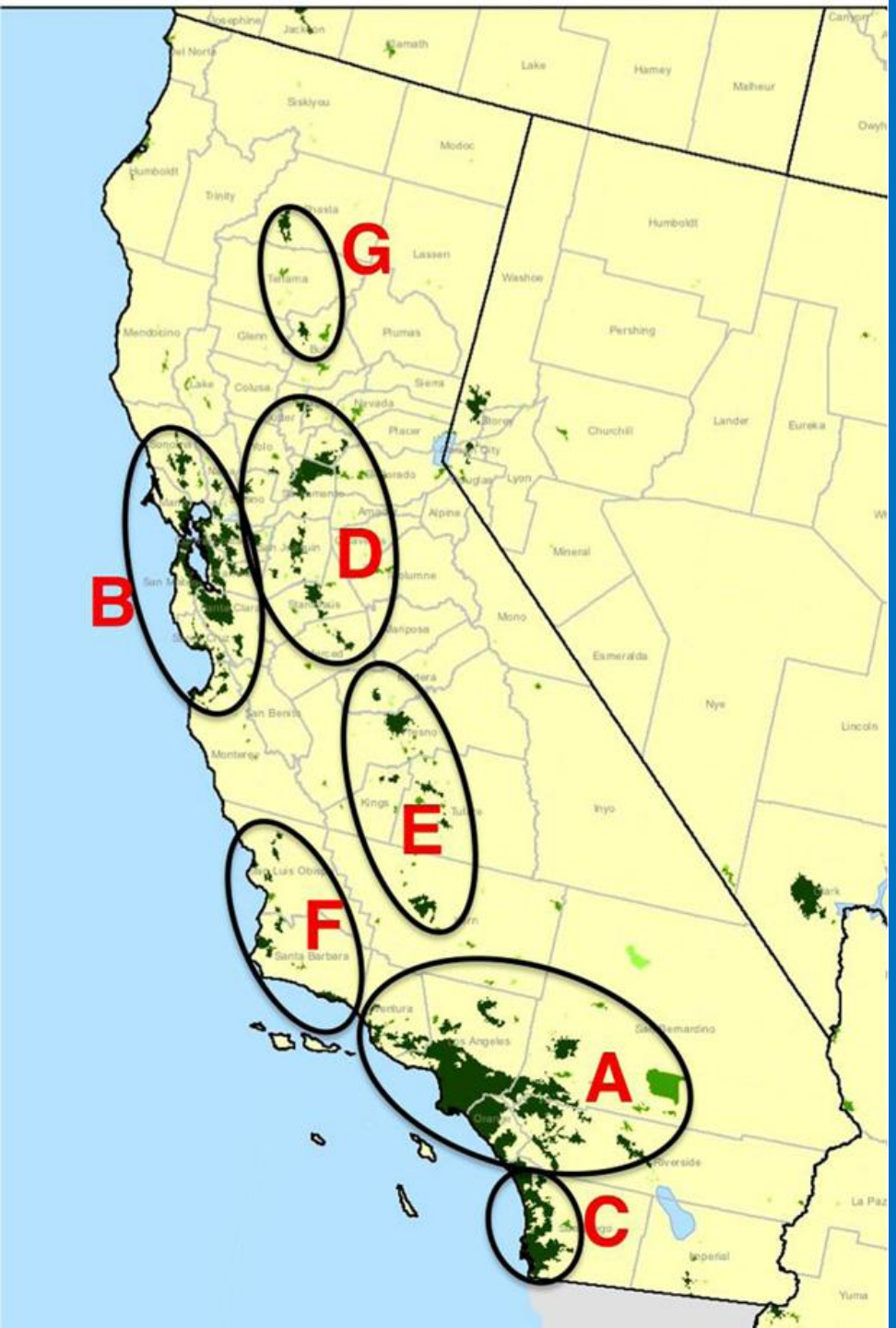
Institute of Transportation Studies, One Shields Avenue, University of California, Davis, Davis, CA 95616, USA

Institute of Transportation Studies (ITS)

Sustainable Transportation Energy Pathways (STEPS)

University of California, Davis (UC Davis)

- Dan Sperling
- Joan Ogden
- Lew Fulton
- Chris Yang
- Mark Delucchi
- Yueyue Fan
- Susan Handy
- Sonia Yeh

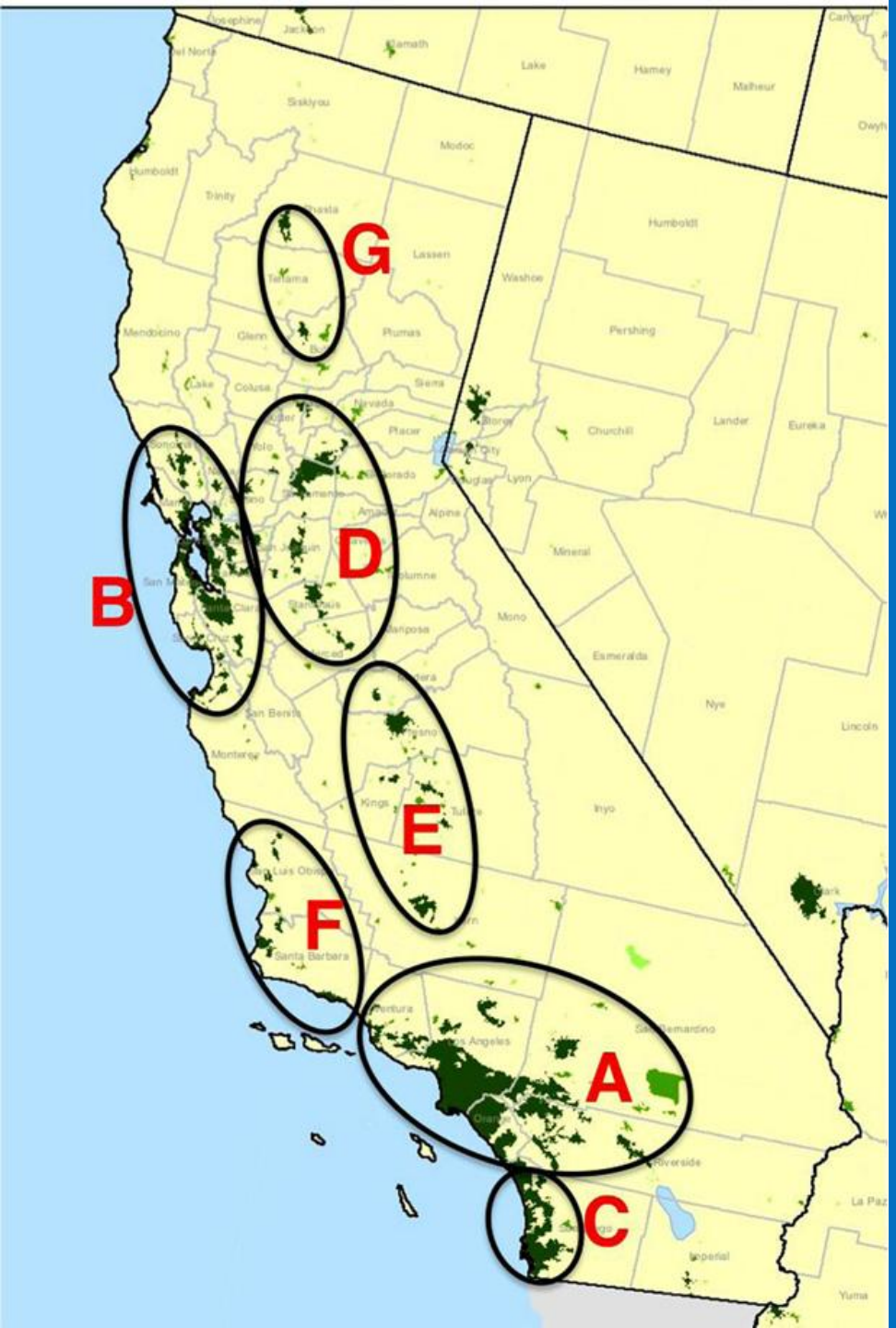


Year 2050 California both:

RPS: 80% renewable

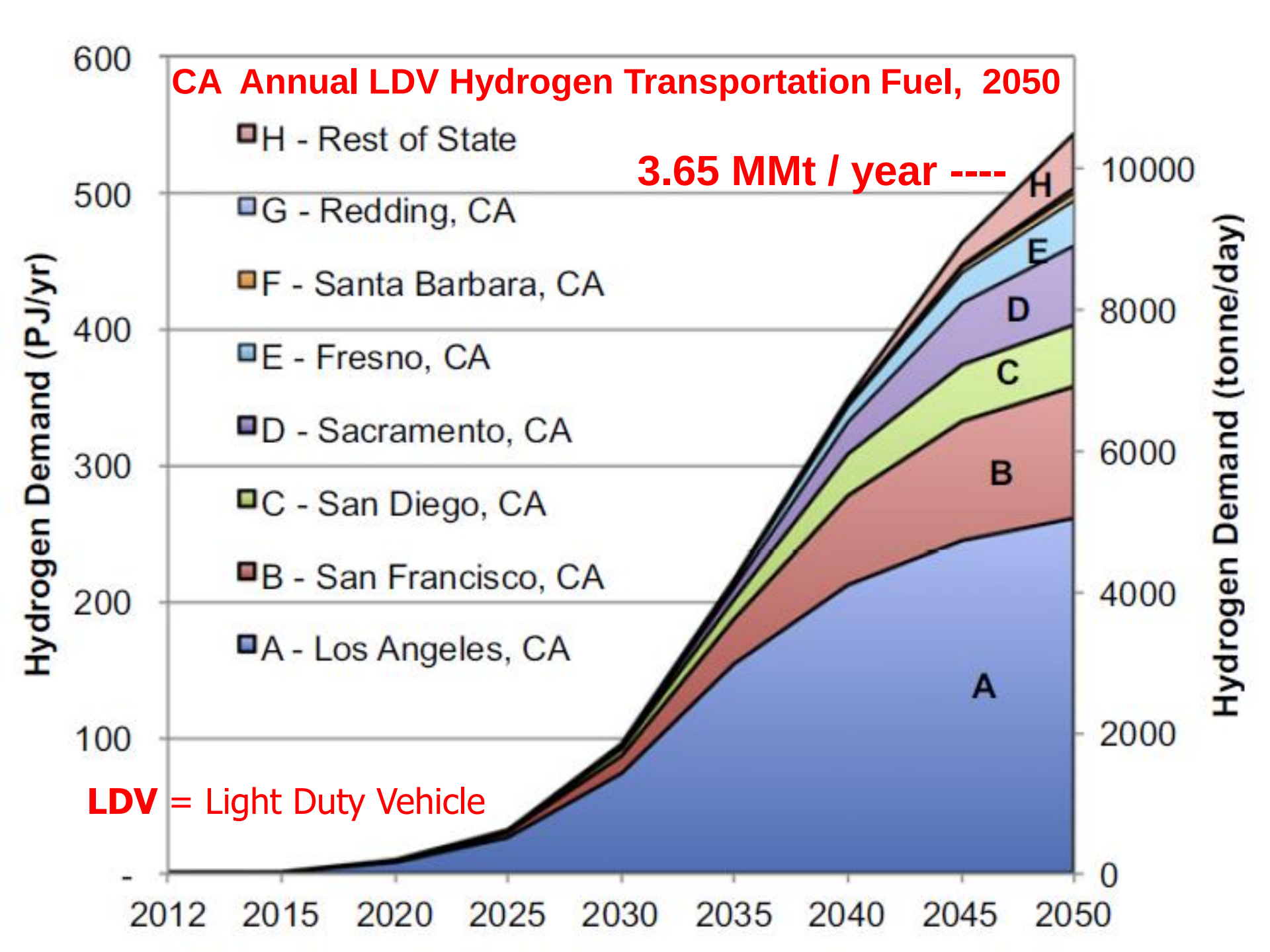
Transport: "80 in 50"

80% reduction in CO2 emissions from transport sector below 1990 by 2050



Transportation sector

- Light duty vehicles (LDV)
- Goods movement (truck)
- Bus
- Aviation
- Rail
- Marine


CA Annual LDV Hydrogen Transportation Fuel, 2050
3.65 MMt / 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
LDV = Light Duty Vehicle

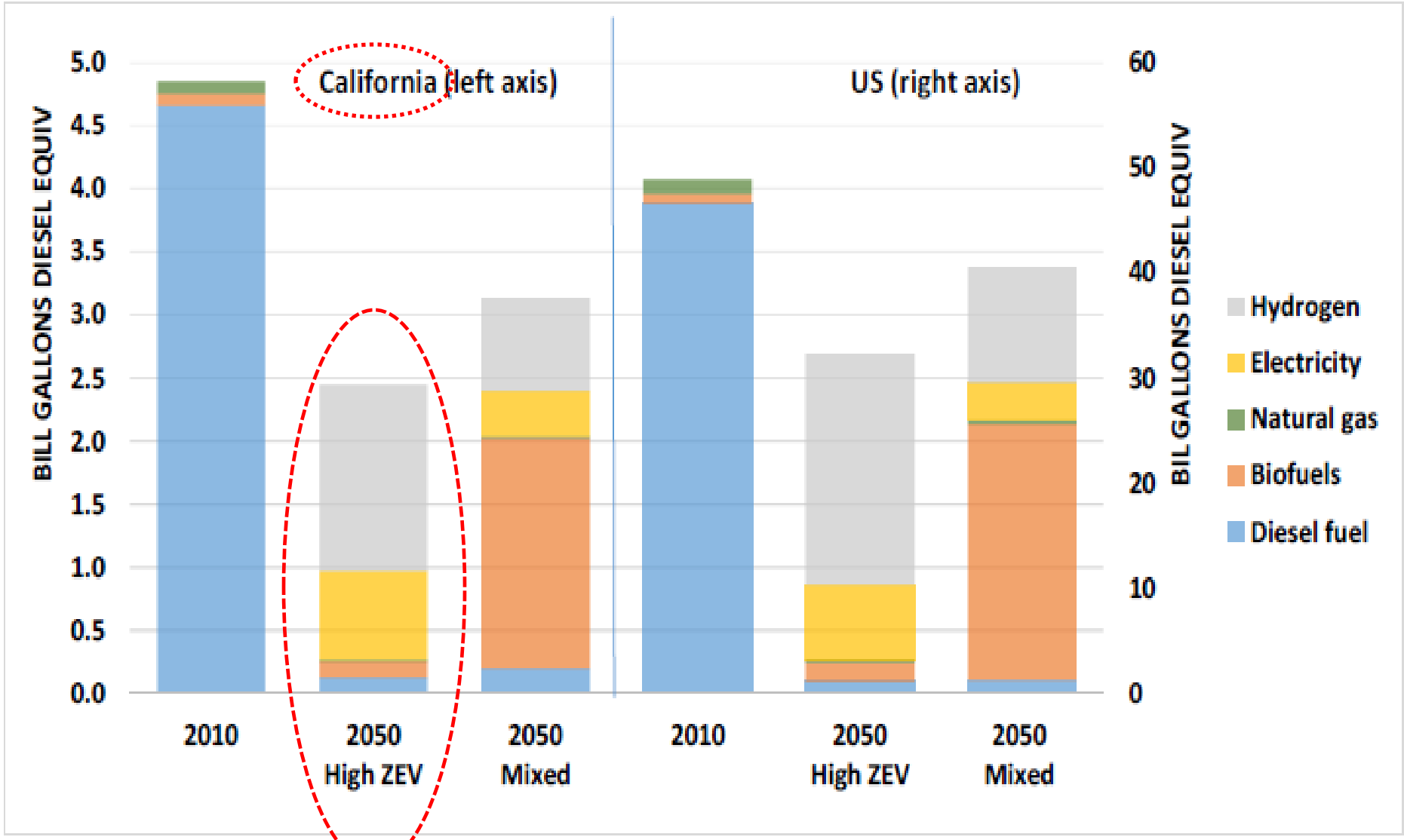
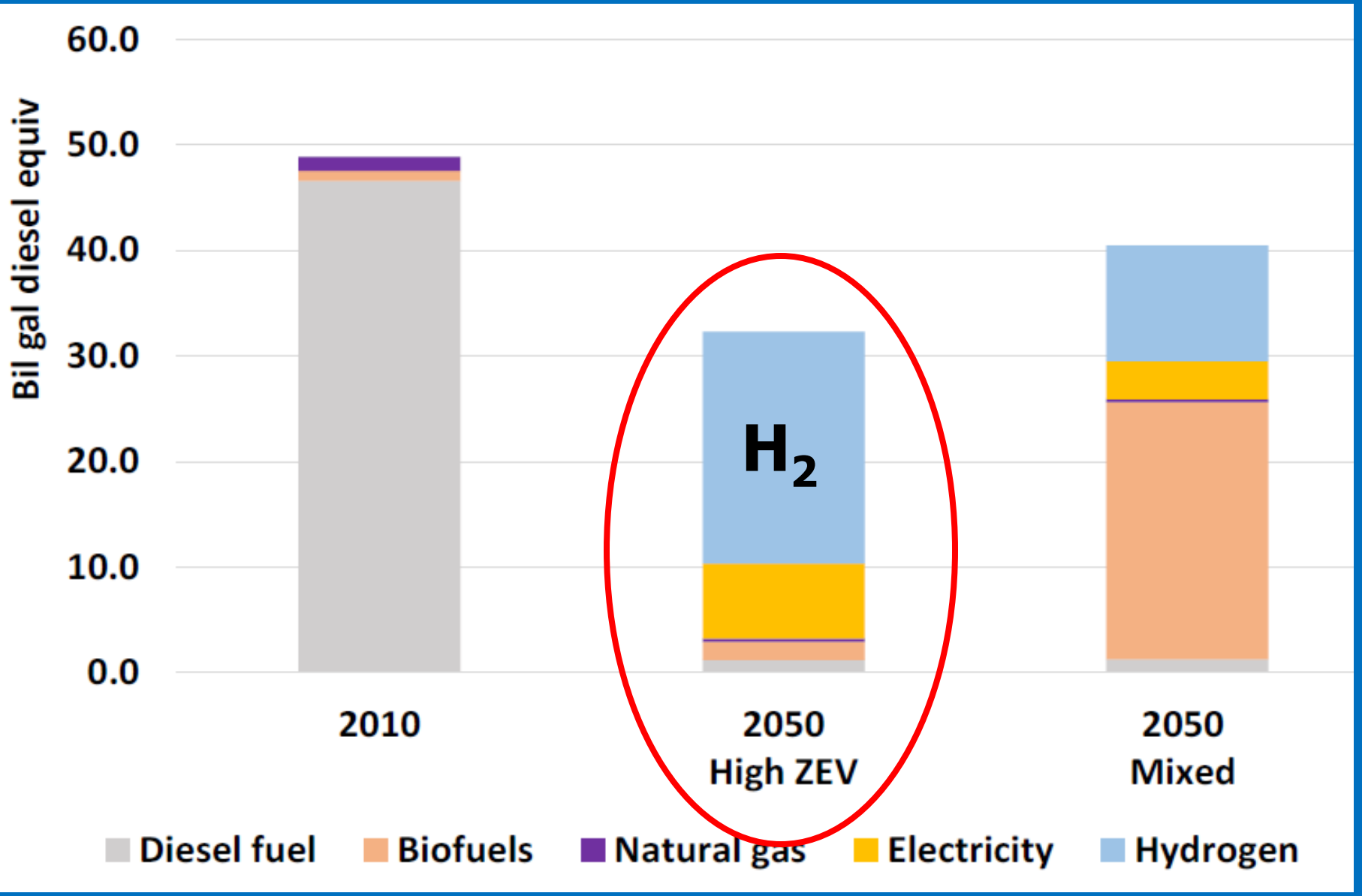


Figure ES-2. Energy use by fuel type, year and scenario, California and U.S. results

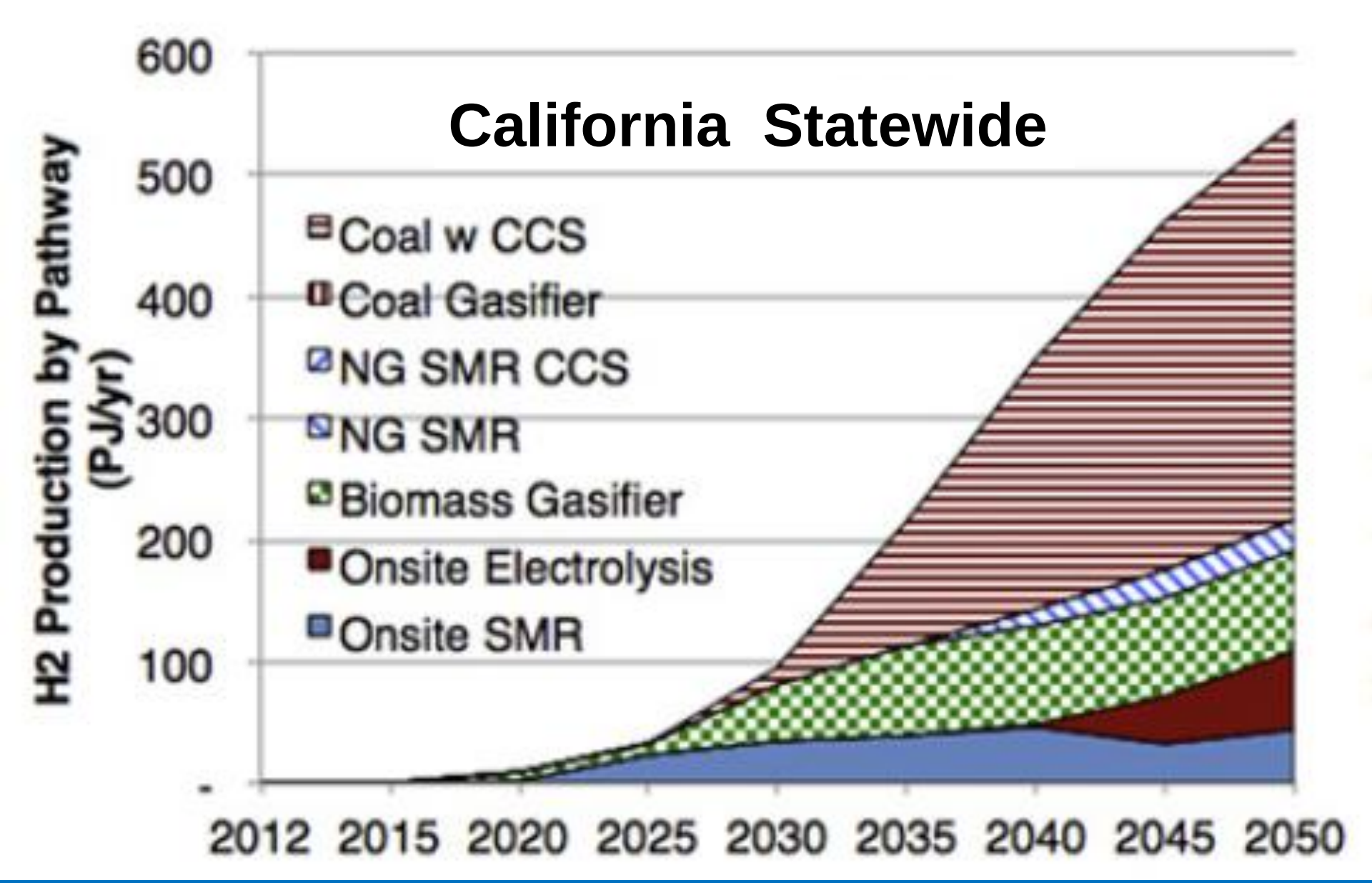
California and USA Trucking -- Year 2050

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



California trucking: "Goods movement"

~ 1.6 million tons / year



California Hydrogen Fuel production

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

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

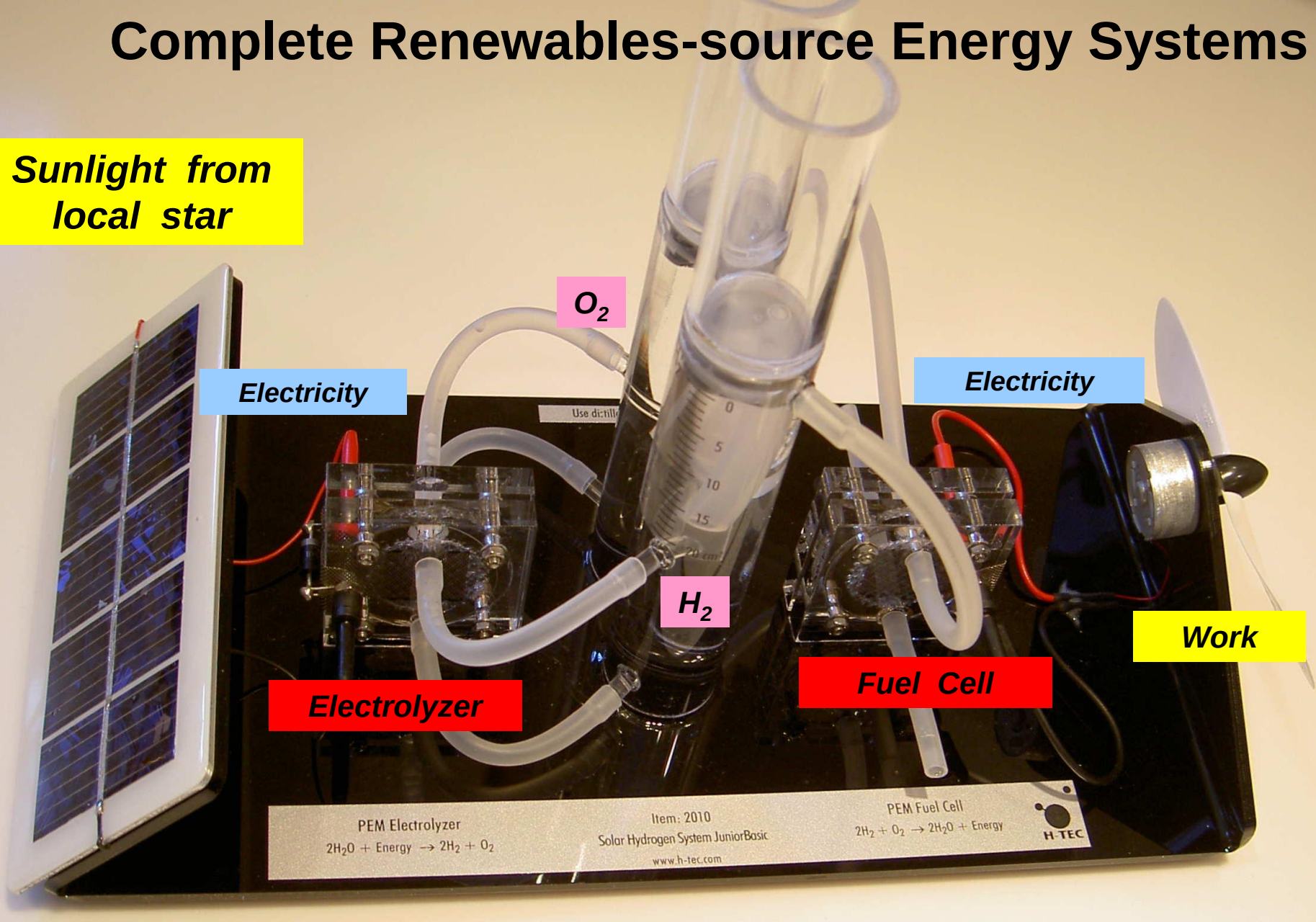
Total = 438 GW nameplate

- **wind + solar + other**
- **CO2-emissions-free energy**

California Energy Economy -- Year 2050

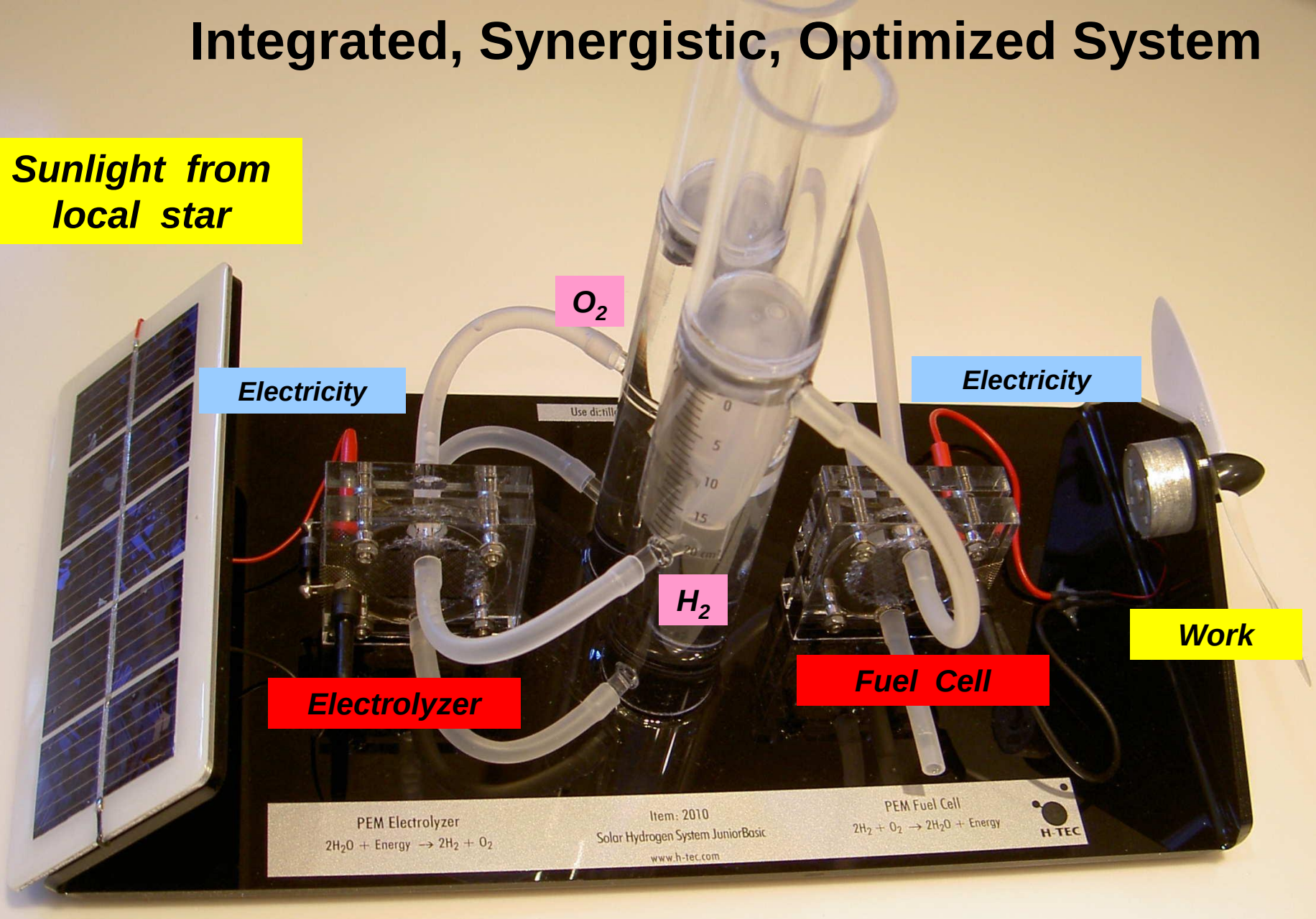
Reference: Year 2015	GW
Total installed nameplate wind generation in California (CA)	6
Total installed nameplate solar generation in California (CA)	12
ELECTRICITY: CA "Power Mix"	**GWh**
2014: Total electricity consumed	296,843
2050: Total electricity demand "Power Mix" is 130 % of 2014	385,896
ELECTRICITY 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

Complete Renewables-source Energy Systems



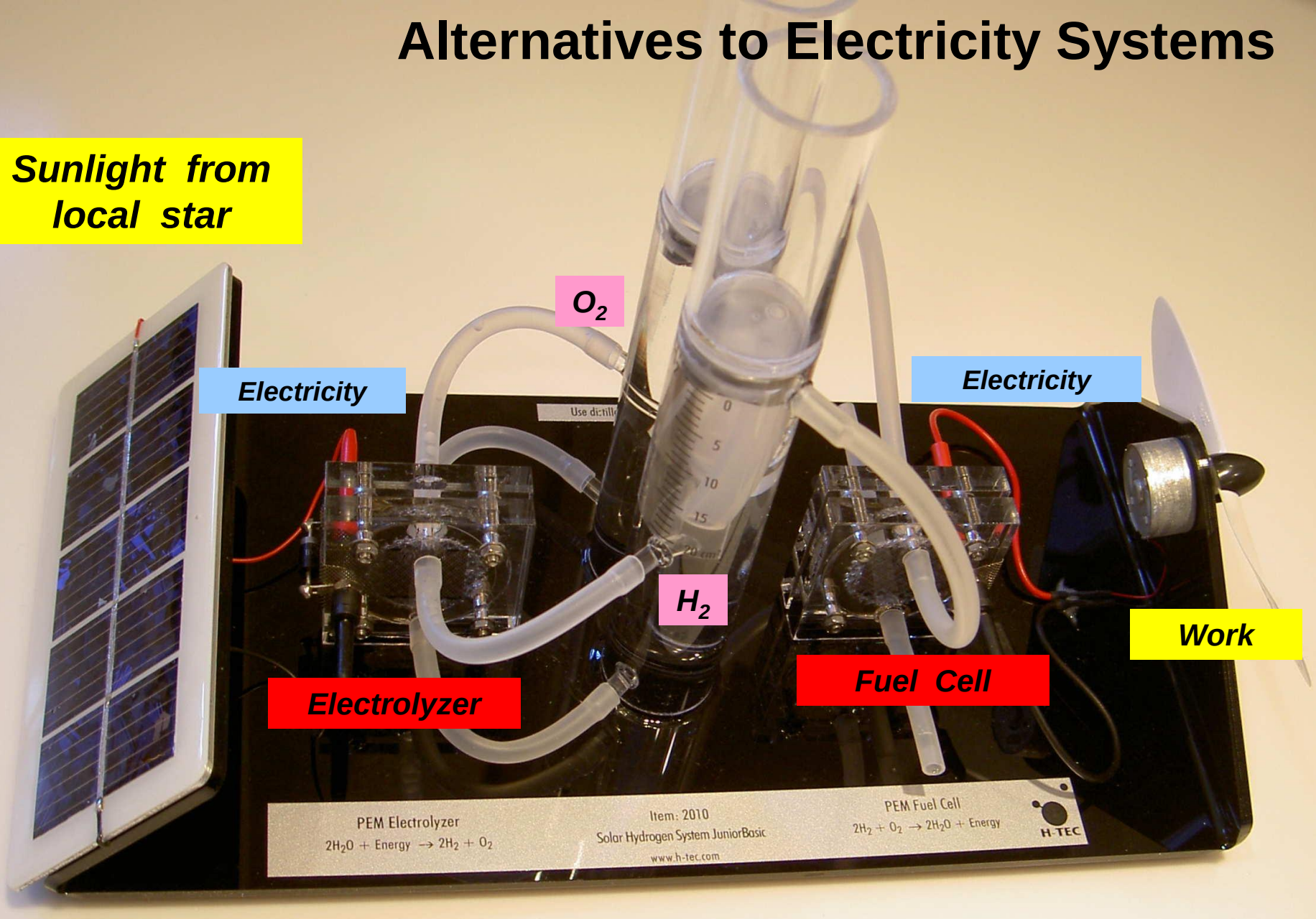
Solar Hydrogen Energy System

Integrated, Synergistic, Optimized System



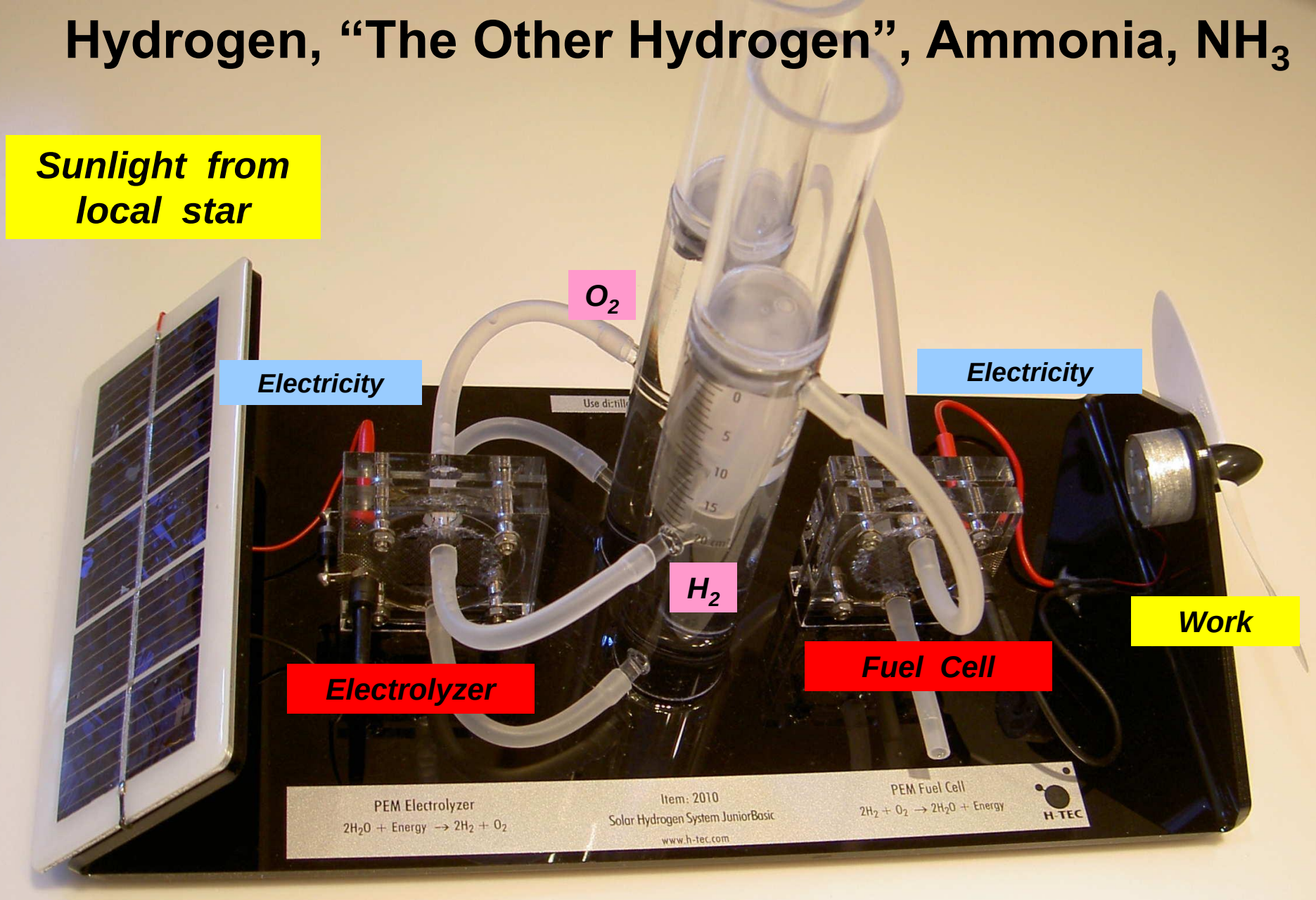
Solar Hydrogen Energy System

Alternatives to Electricity Systems



Solar Hydrogen Energy System

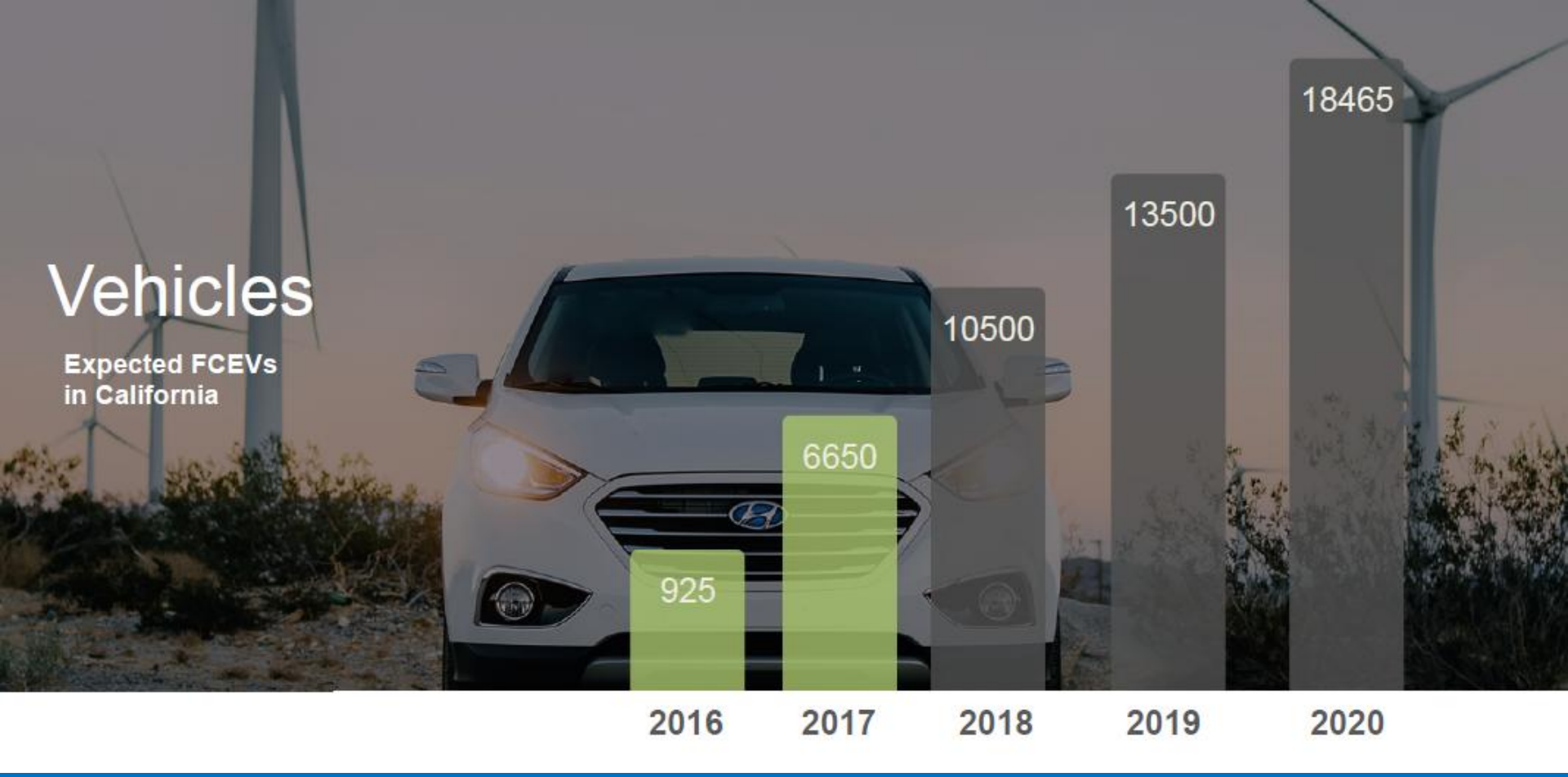
Hydrogen, "The Other Hydrogen", Ammonia, NH_3



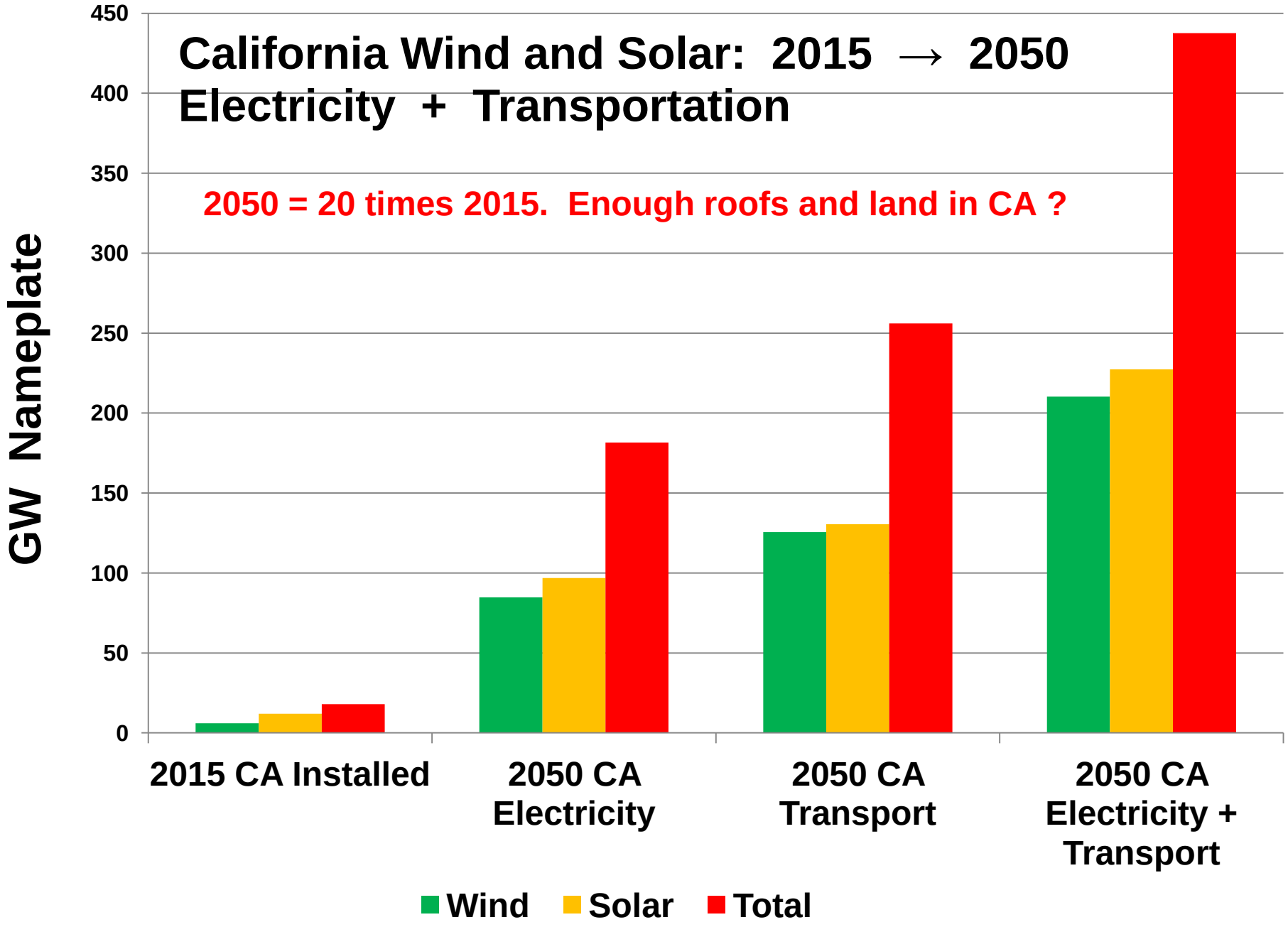
Solar Hydrogen Energy System

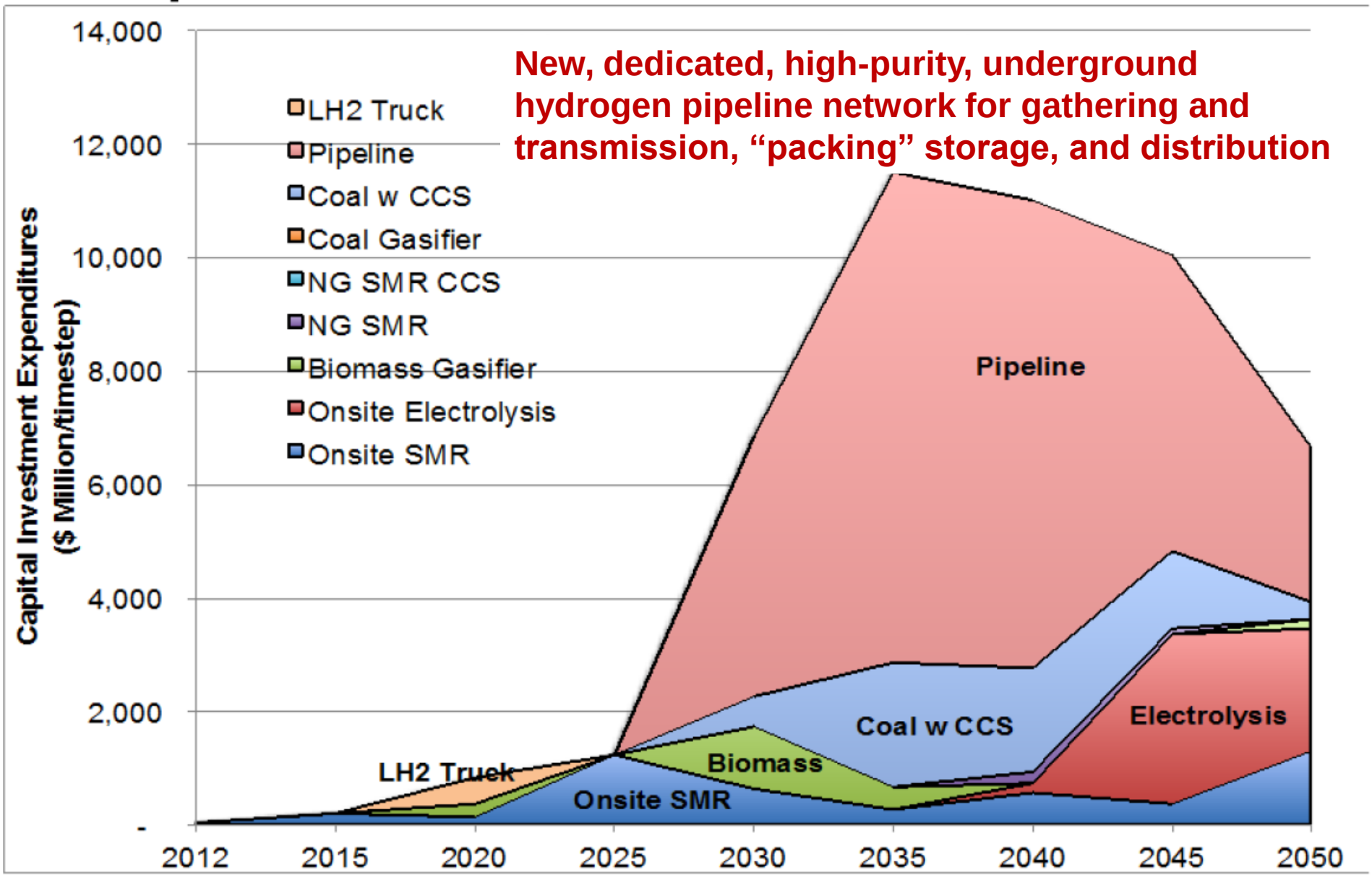
Elon Musk, Tesla Co-Founder, CEO, and Product Architect

"Hydrogen is an incredibly dumb … fuel"
Fuel cell cars "are extremely silly"
"… fuel cell is so bullshit …"



Fuel Cell Hybrid Electric Vehicles Expected in California


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



Capital Investment for Hydrogen Fuel Infrastructure in California
$ 50 Billion cumulative investment : Transition to "green" Hydrogen for "80 in 50"
80 % reduction in CO2 emissions from California transportation sector by year 2050
Source: Institute of Transportation Studies (ITS), STEPS program, UC Davis

As California goes:

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

Far More ambitious:

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

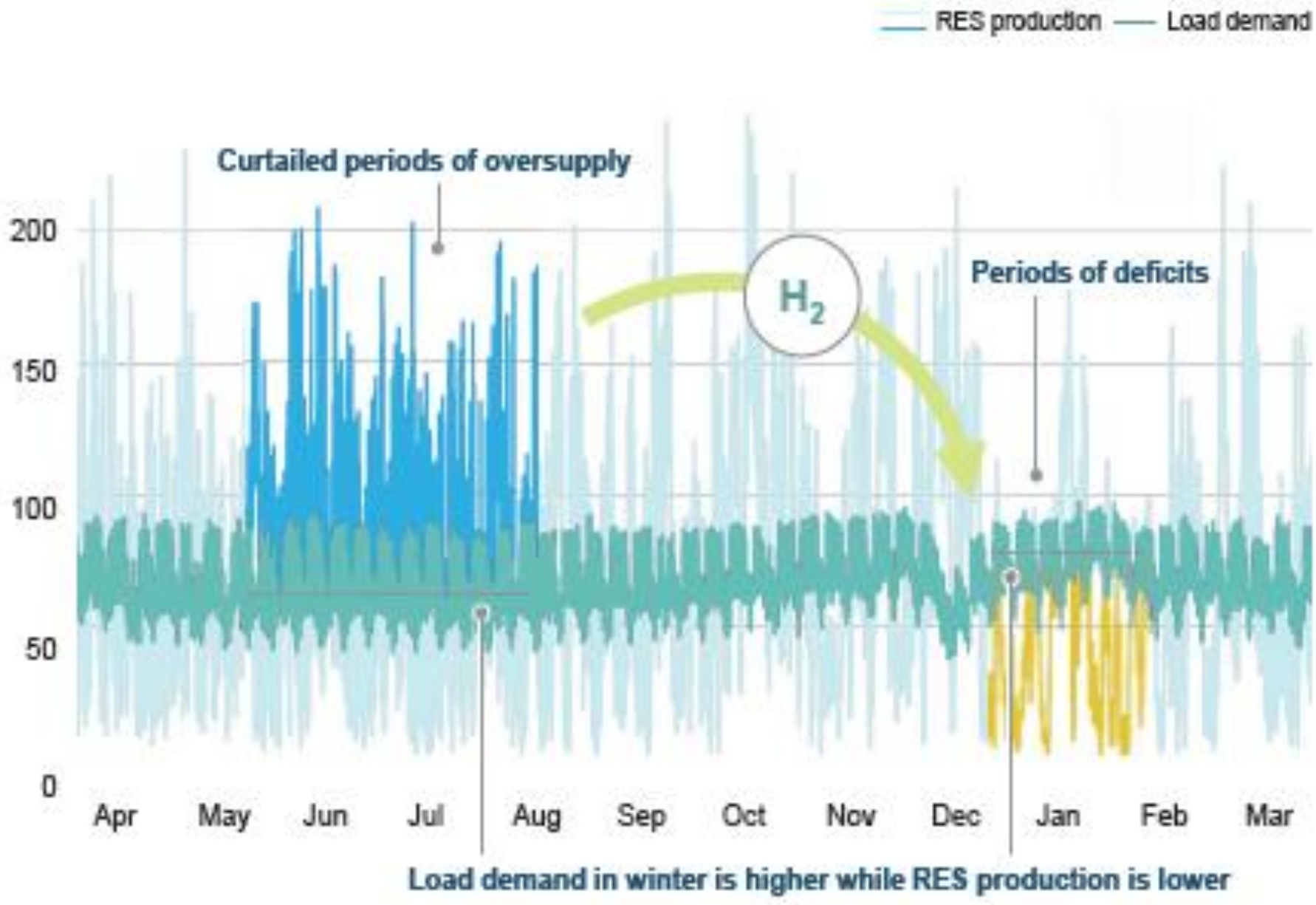
" How Hydrogen Powers the Energy Transition "

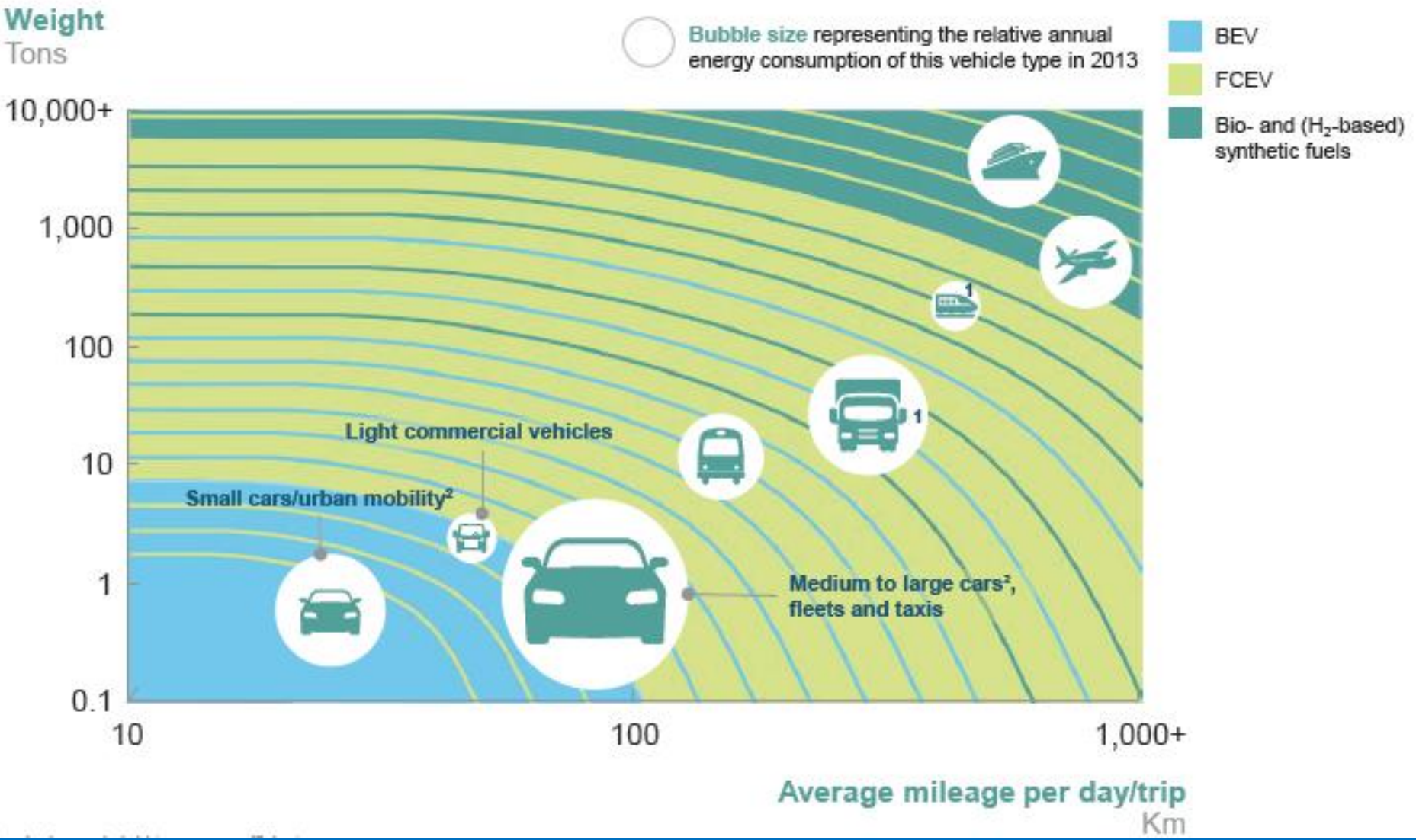
Hydrogen Council

World Economic Forum, Davos, CH 2017

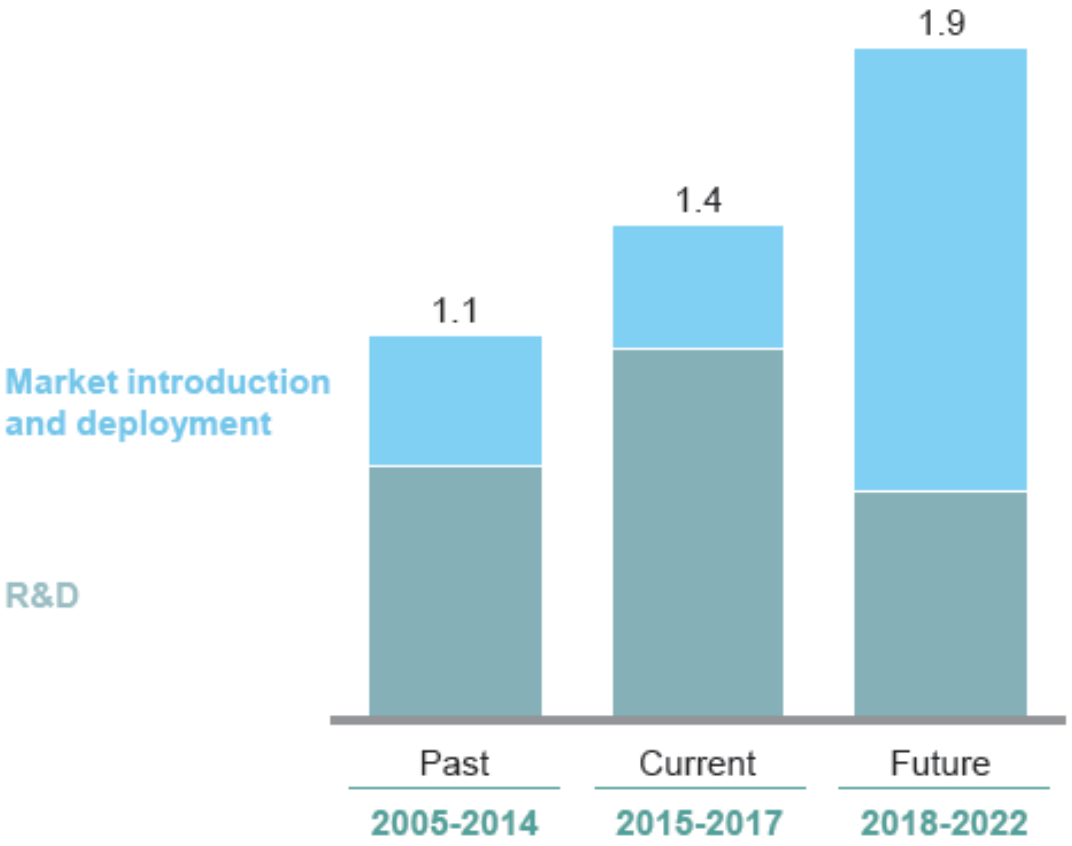
Excess power can be used to produce hydrogen for seasonal energy storage

Simulation for Germany 2050, in GW




Weight
Tons
Bubble size representing the relative annual energy consumption of this vehicle type in 2013
BEV
FCEV
Bio- and (H_2-based) synthetic fuels
10,000+
1,000
100
10
1
0.1
10
100
1,000+
Light commercial vehicles
Small cars/urban mobility²
Medium to large cars², fleets and taxis
1
1
Average mileage per day/trip
Km

Hydrogen Council members plan to orient their increasing annual investments in hydrogen on market development. Investments planned by Hydrogen Council members, in EUR billions per year

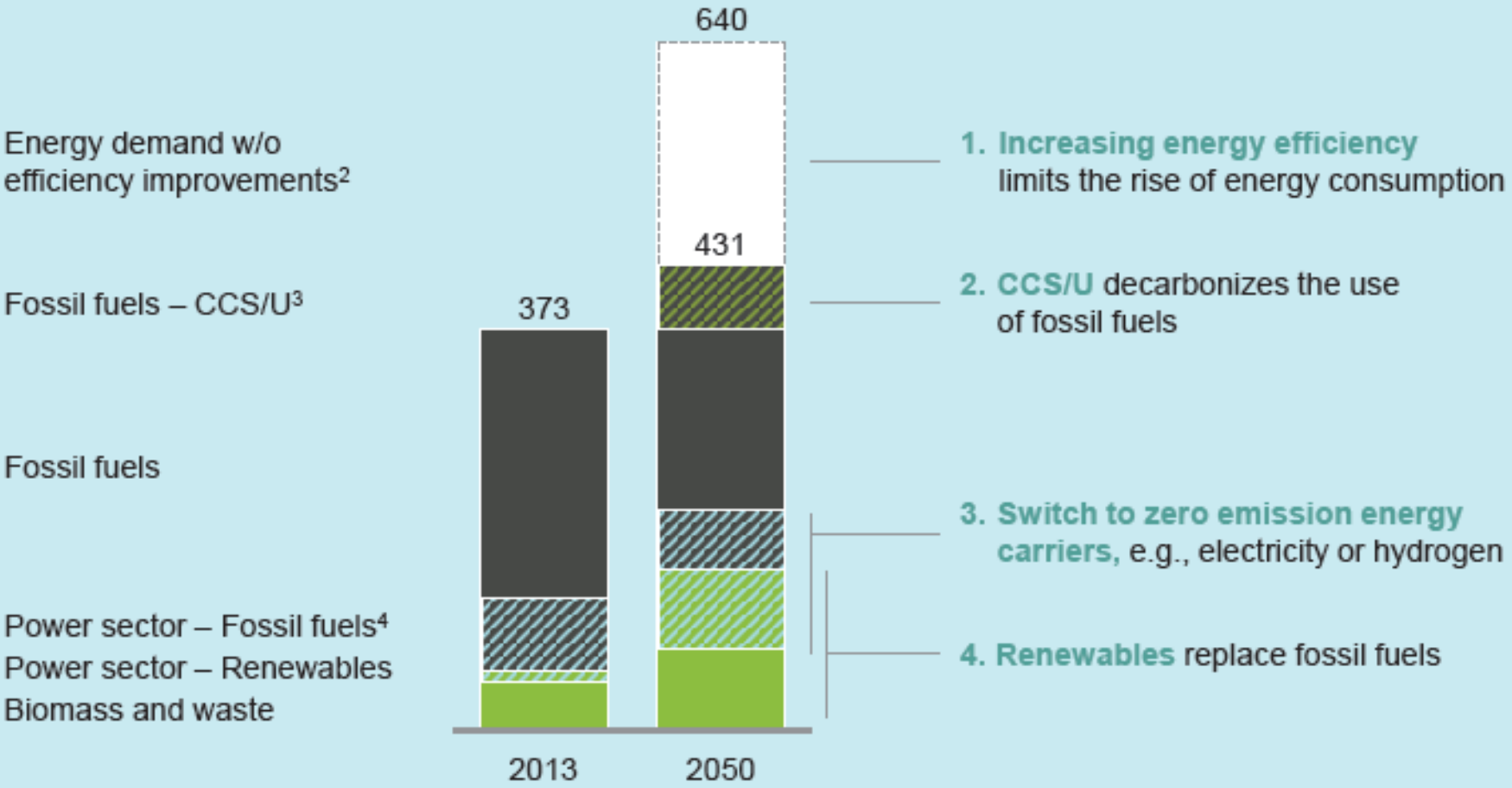


- Hydrogen Council members **plan to invest at least EUR 1.9 billion per year** in hydrogen technology for the coming 5 years
- Investments in market introduction and deployment are growing and are showing the **acceleration of commercialization**

Invest > $ 2 Billion / year: Hydrogen Market Develop Hydrogen Council

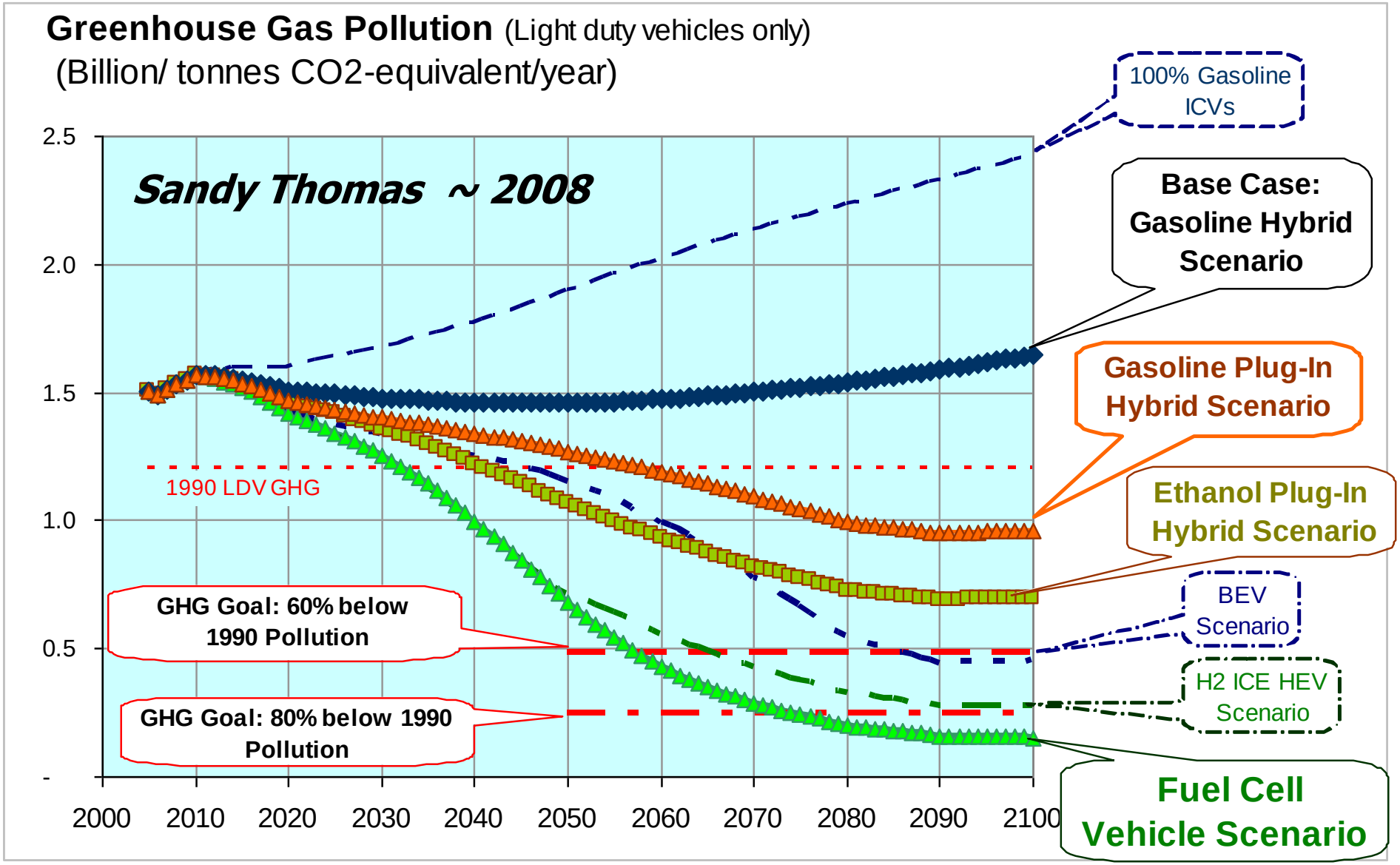
Four major levers to decarbonize the energy system

Final energy consumption[1], 2013 and 2050, in EJ



Decarbonize the entire energy system

80% below 1990 by 2050, CO2 from "cars"



Hydrogen Fuel Cell Bus

Toyota Mirai Fuel Cell car: Hydrogen fuel only

Honda - GM

Honda Fuel Cell car
2016 production ?

Fueling the Honda Clarity Fuel Cell car
3 minutes, 300 mile range

Mercedes-Benz - Ford

“ No one will make money on electric cars in ‘reasonable time’ ”

Dieter Zetsche, Mercedes CEO

Mercedes-Benz B-class Fuel Cell car

Hyundai Tucson Fuel Cell

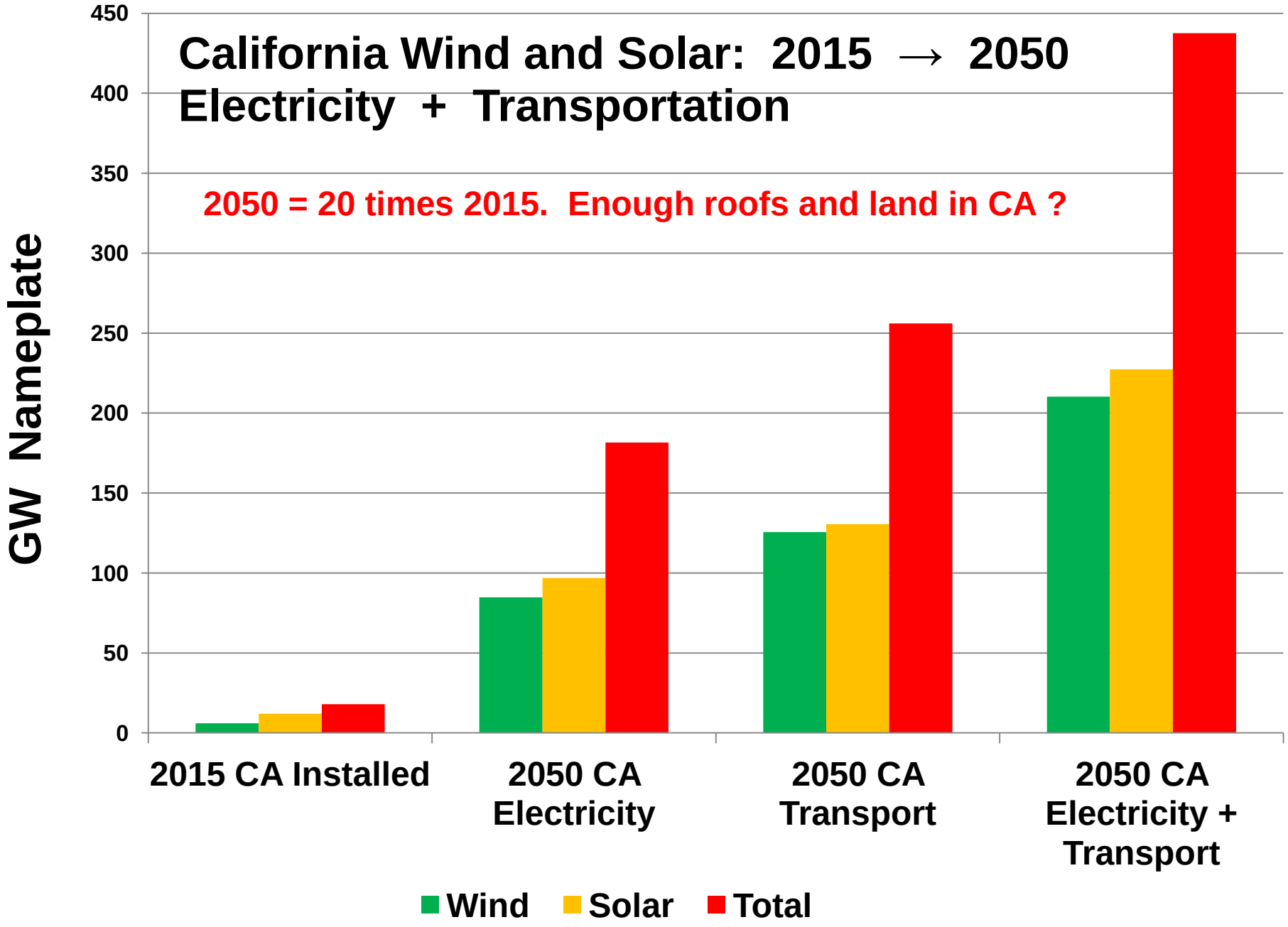
Hydrogen Transportation Fuel Demand
California, year 2050
Million metric tons per year:

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

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 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

Southern CA Hydrogen Stations

Open

Burbank
Fountain Valley - OCSD
Irvine - UC Irvine
Los Angeles - Harbor City
Newport Beach
*Thousand Palms - SunLine Transit
Torrance

In Development

Anaheim
Chino (upgrade)
Diamond Bar (upgrade)
Irvine - UC Irvine (upgrade)
Irvine - Walnut Ave.
Lawndale
Los Angeles - Cal State LA
Los Angeles - West LA 2
Los Angeles - Woodland Hills
Los Angeles - Beverly Blvd.
Mission Viejo
Redondo Beach
San Juan Capistrano
Santa Monica

*Coalinga
Costa Mesa
La Canada Flintridge
Laguna Niguel
Lake Forest
Long Beach
Los Angeles - LAX (upgrade)
Los Angeles - Lincoln Blvd.
Los Angeles - Hollywood Blvd.
Ontario
Orange
Pacific Palisades
*Riverside
*San Diego
*Santa Barbara
South Pasadena

*Not shown on map

California Fuel Cell Partnership
www.cafcp.org/stationmap

January 2015

Northern CA Hydrogen Stations

Open

Emeryville – AC Transit

In Development

Cupertino
Foster City
Mountain View
*West Sacramento

Campbell
Hayward
Mill Valley
Oakland
Palo Alto
Redwood City
*Rohnert Park
San Jose
San Ramon
Saratoga
South San Francisco
*Truckee
Woodside

*Not shown on map

California Fuel Cell Partnership
DRIVING FOR THE FUTURE

Managed by BKi

Germany Hydrogen Fuel Stations 2023

H_2 Mobility

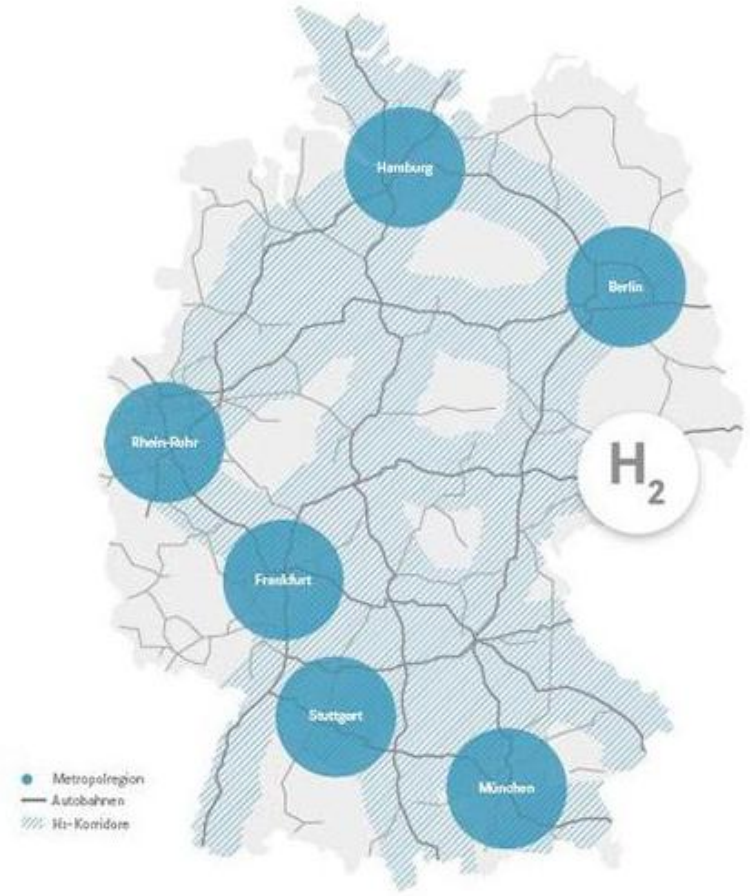
DAIMLER TOTAL AIR LIQUIDE OMV Linde

Partners:

Air Liquide	**Shell**
Daimler	**Total**
Linde	**OMV**

Targets:

- **100 by 2017**
- **400 by 2023**
- **€ 350 million invest**
- **90 km max spacing on freeways**



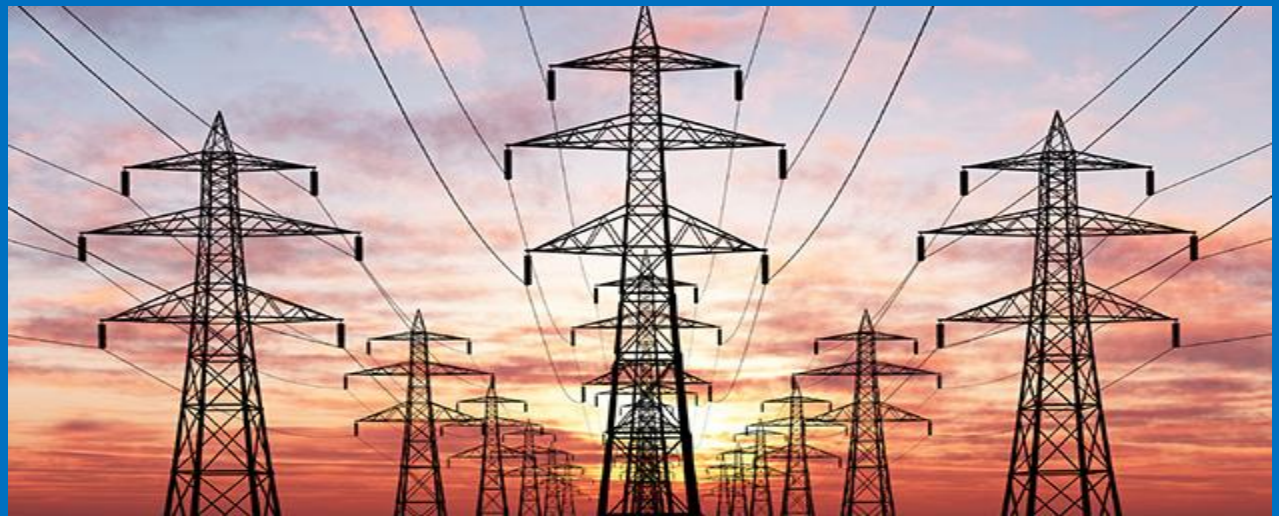
H_2 Mobility

Japan: Hydrogen Society has begun!
100 Fueling Stations 2015

Iwatani

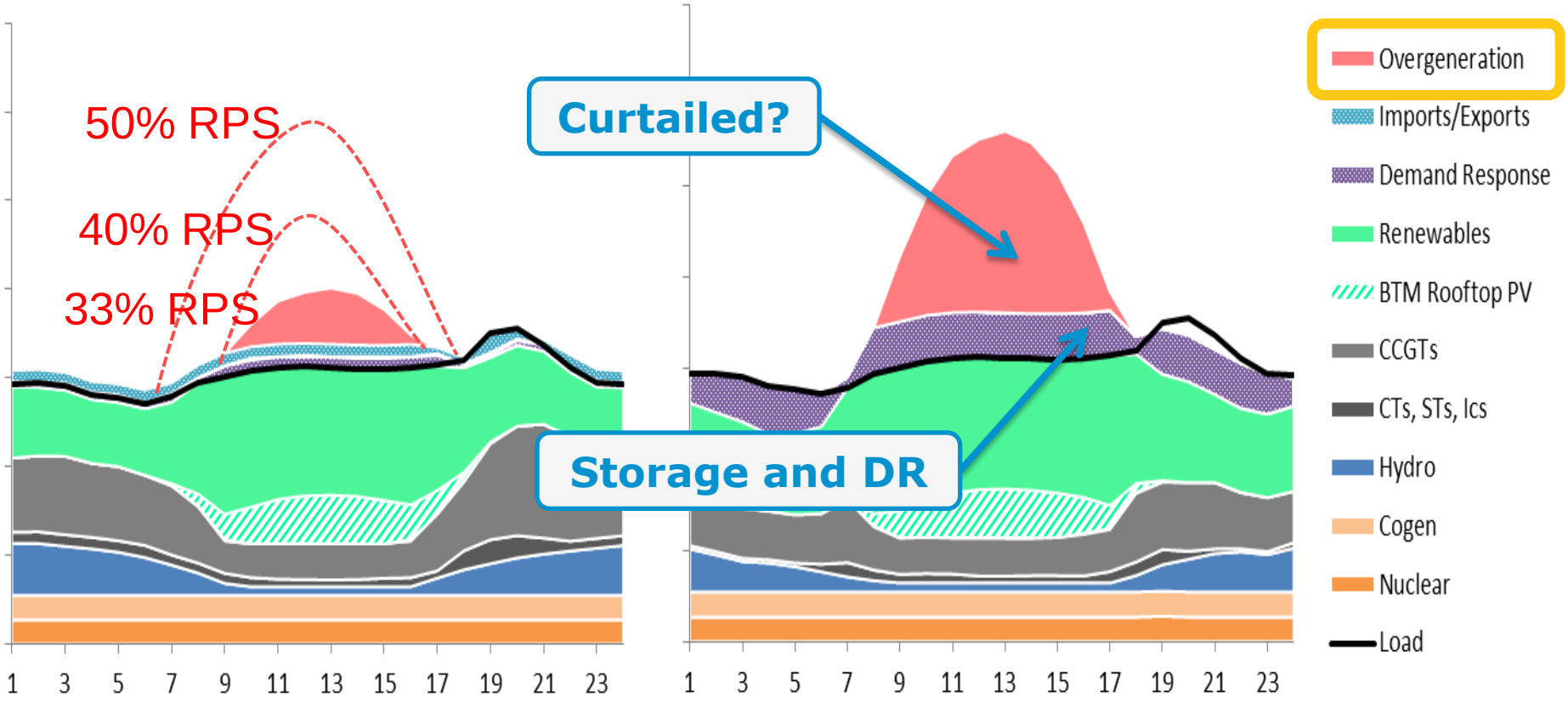
If your only tool is a hammer …

If your only product is electricity …



The world looks like wires

California's surplus renewable generation



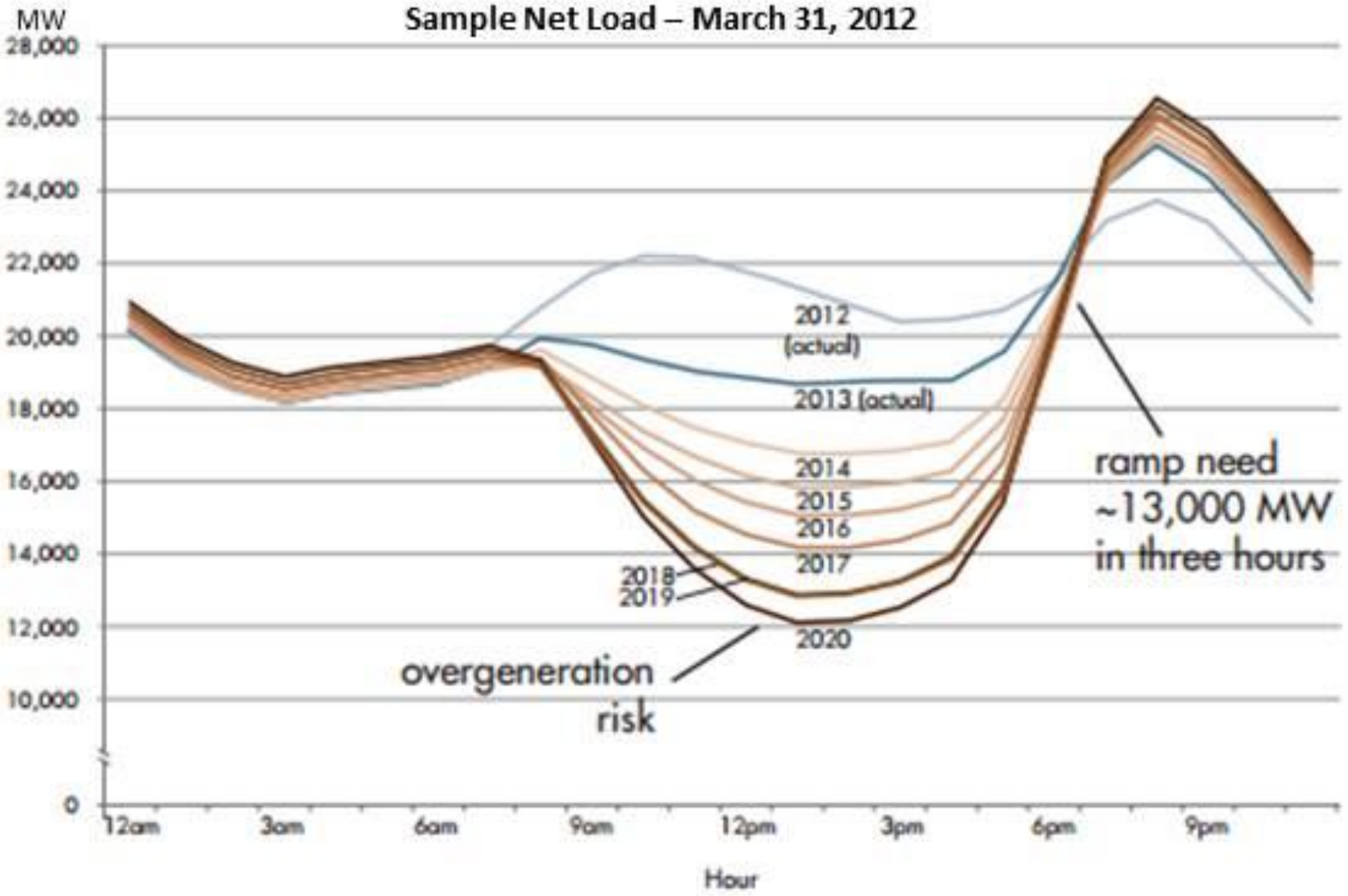
Do Not Cite
For Illustrative Purposes Only

Energy+Environmental Economics

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

CA "Duck Curve": solar overgeneration, steep ramp

Electric utilities NET load



CA Independent System Operator - CAISO

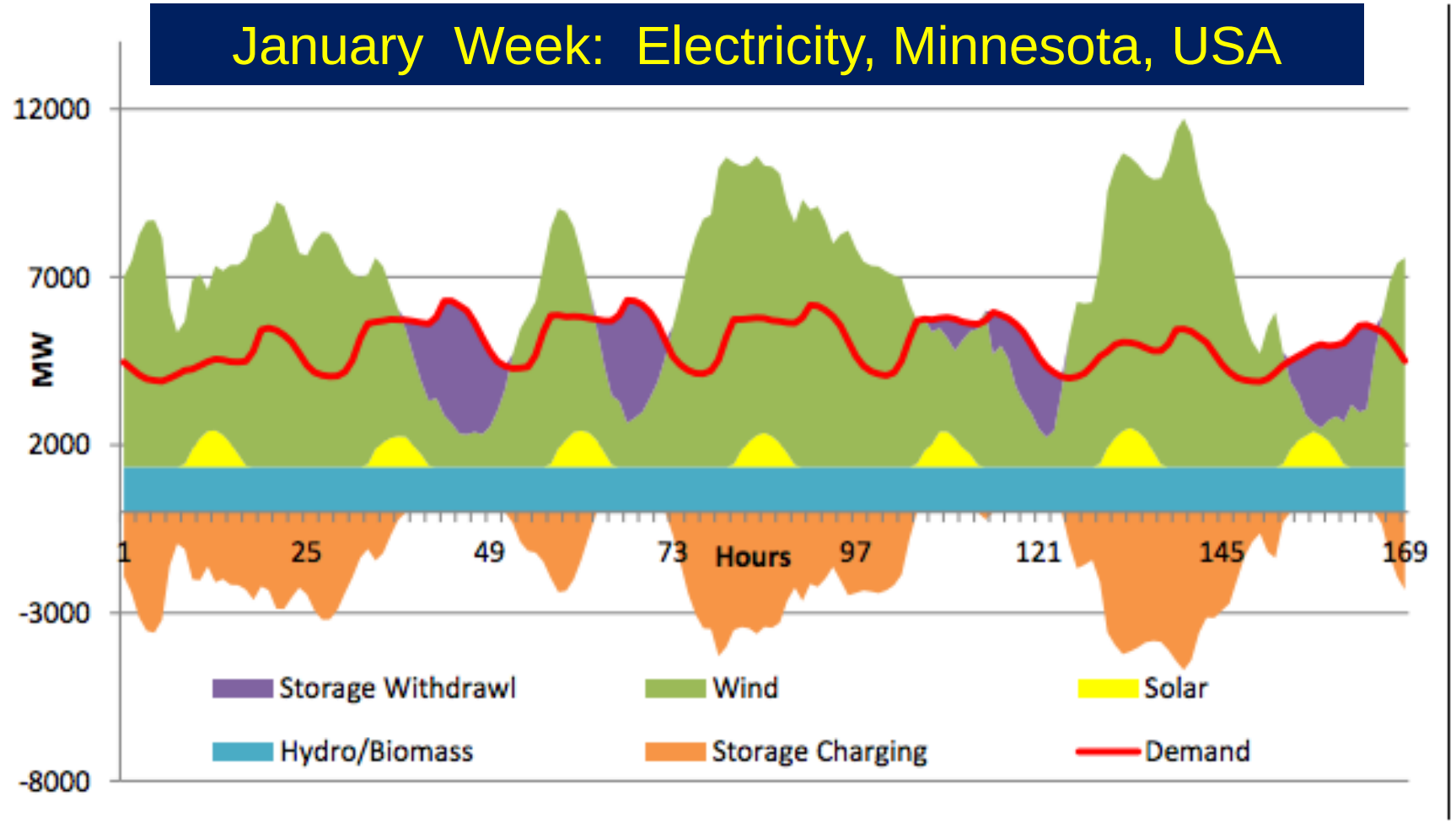


Figure III-6: Hourly supply and demand with storage, January 1-7, 2007. *Source: IEER.*

Hypothetical:
100 % Renewable Electricity System in Minnesota
Avoid curtailment: large storage

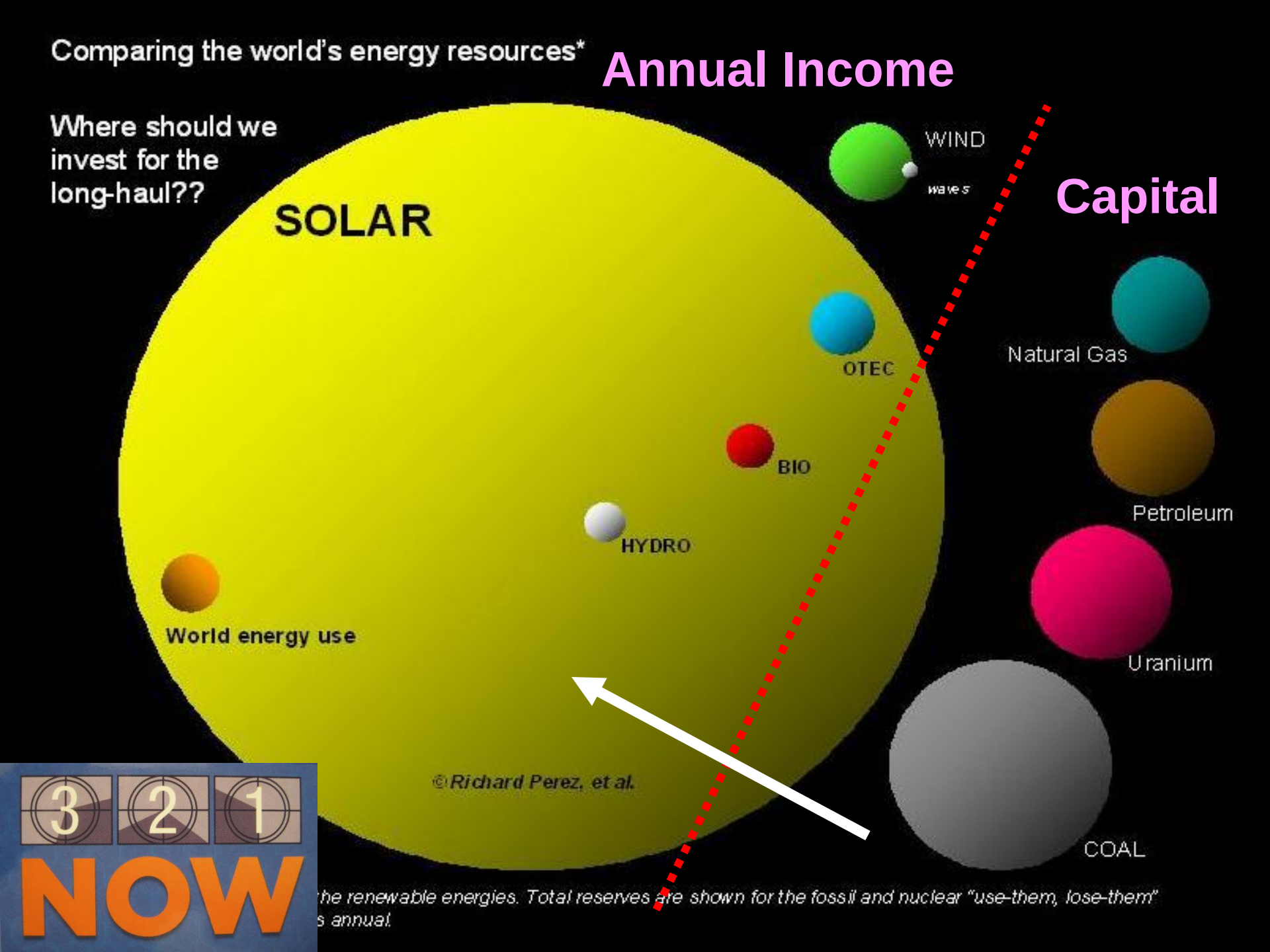
Far more ambitious:

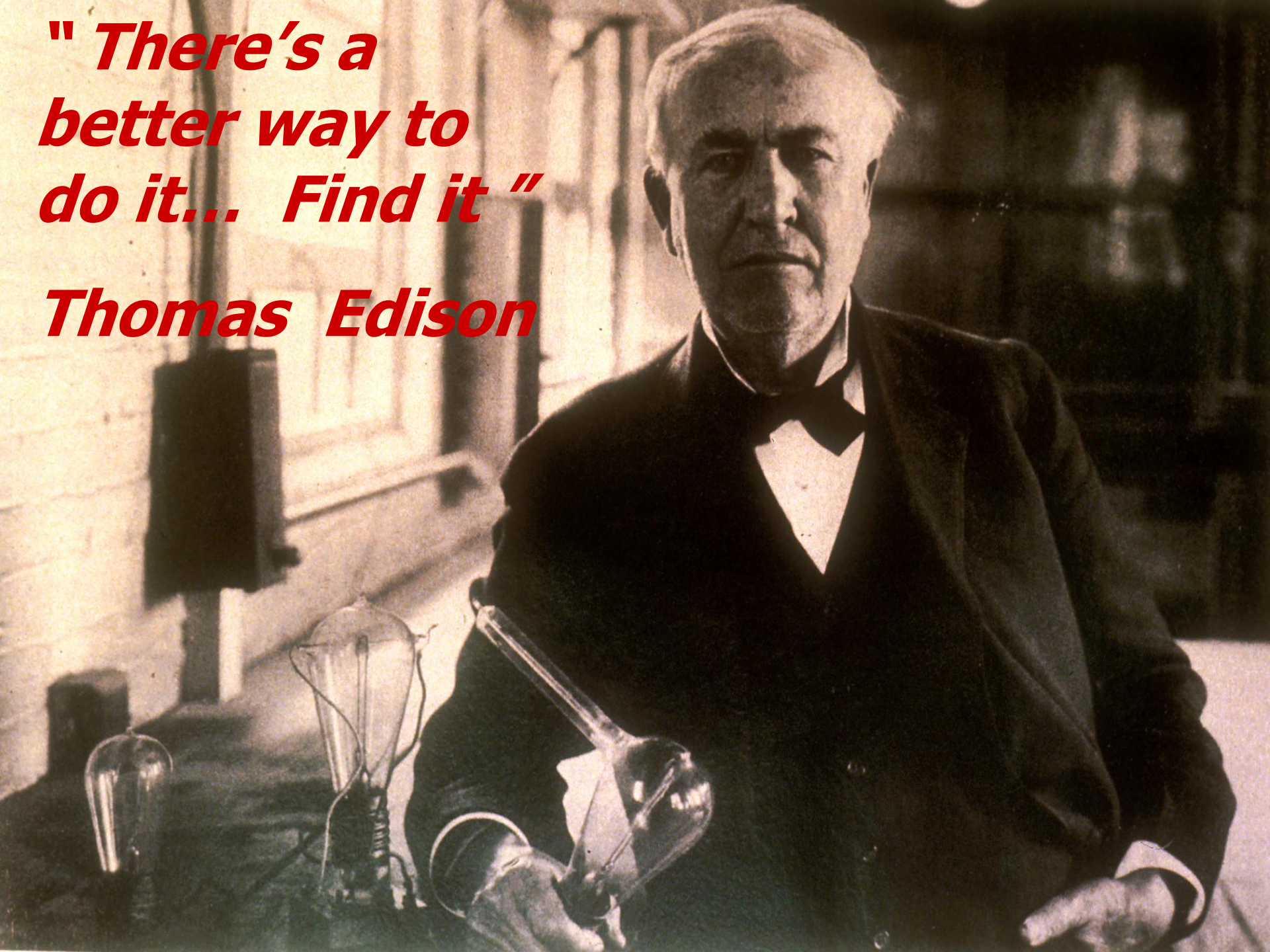
- Hydrogen industry
- Renewables industry
- Beyond electricity systems
- Transportation + CHP fuels
- Run the World on Renewables
- ~ 100 % CO2-emissions-free energy

Transform World's Largest Industry

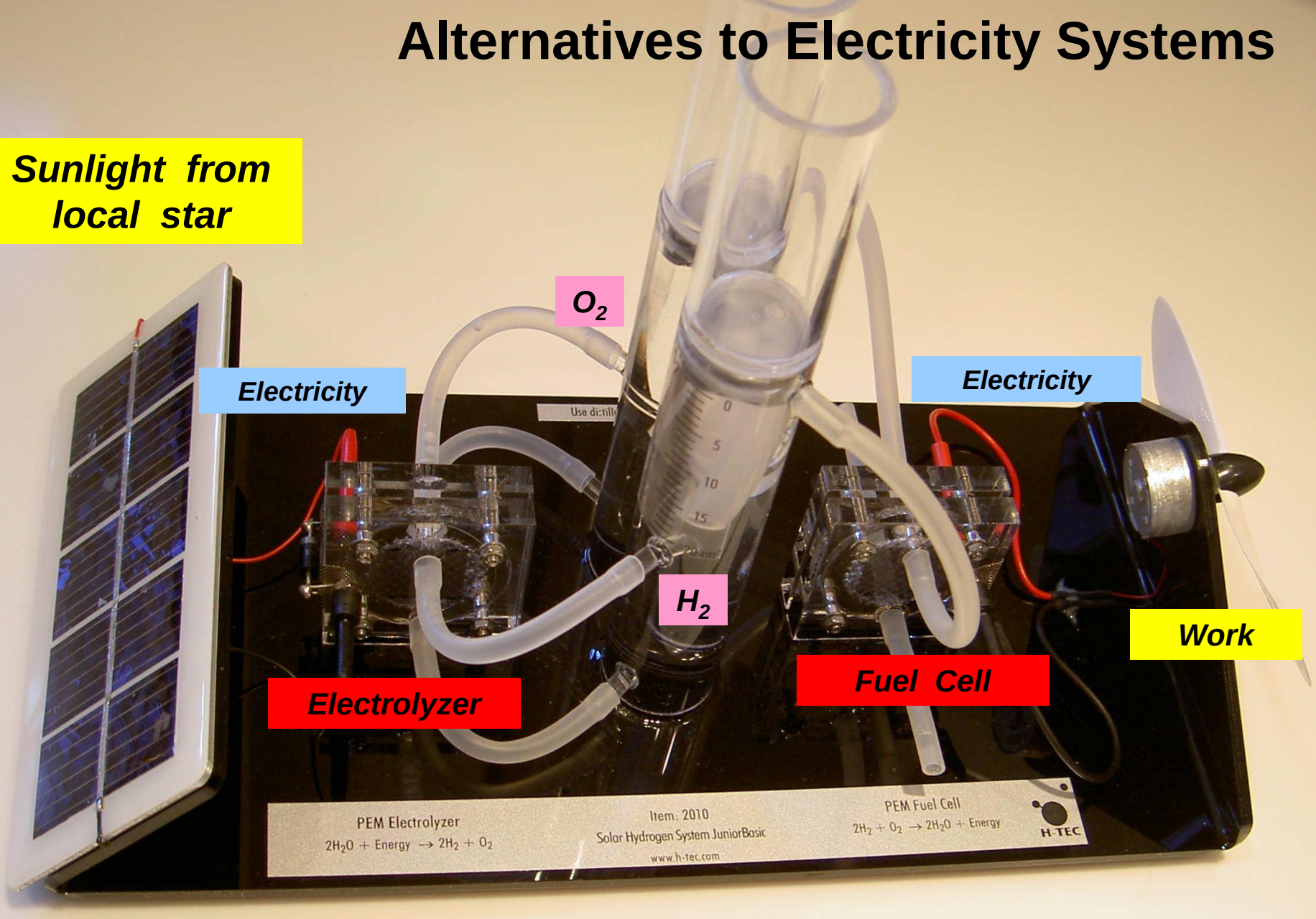
Run the World on Renewables --

Including some nuclear ?

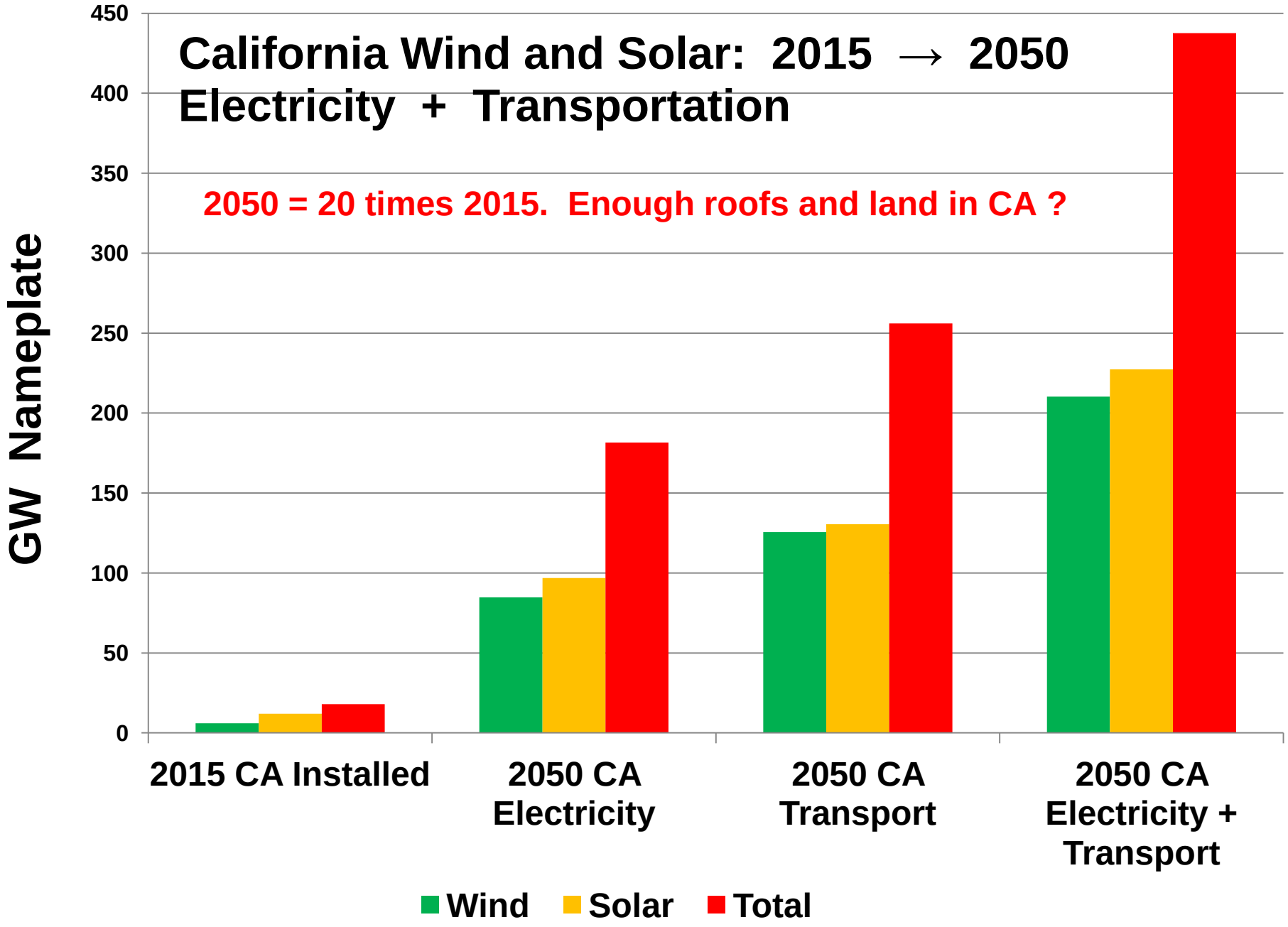

Comparing the world's energy resources*
Annual Income
Capital
Where should we invest for the long-haul??
SOLAR
WIND
waves
OTEC
BIO
HYDRO
World energy use
Natural Gas
Petroleum
Uranium
COAL
© Richard Perez, et al.
he renewable energies. Total reserves are shown for the fossil and nuclear "use-them, lose-them"
s annual
3 2 1
NOW


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

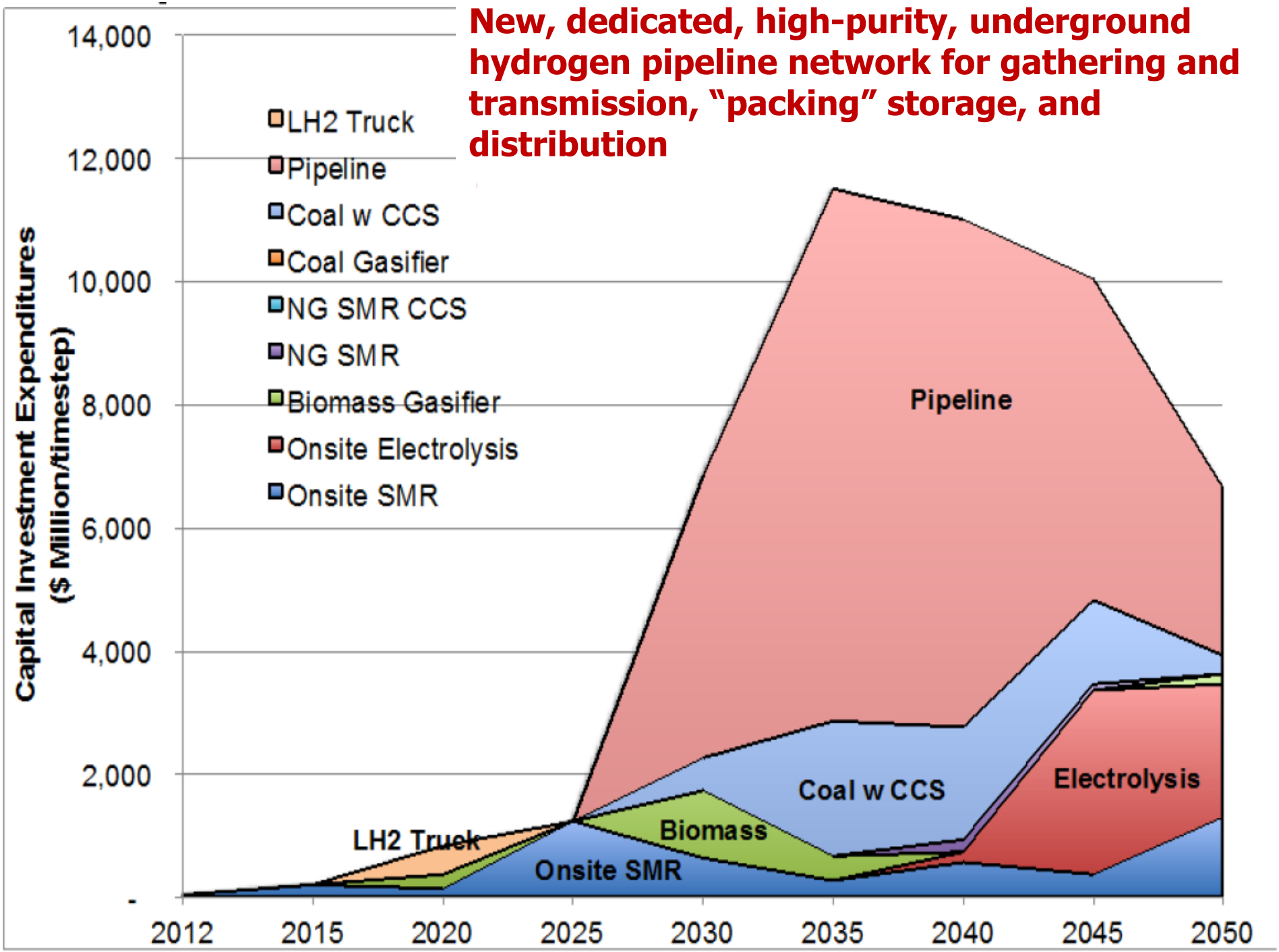
Alternatives to Electricity Systems



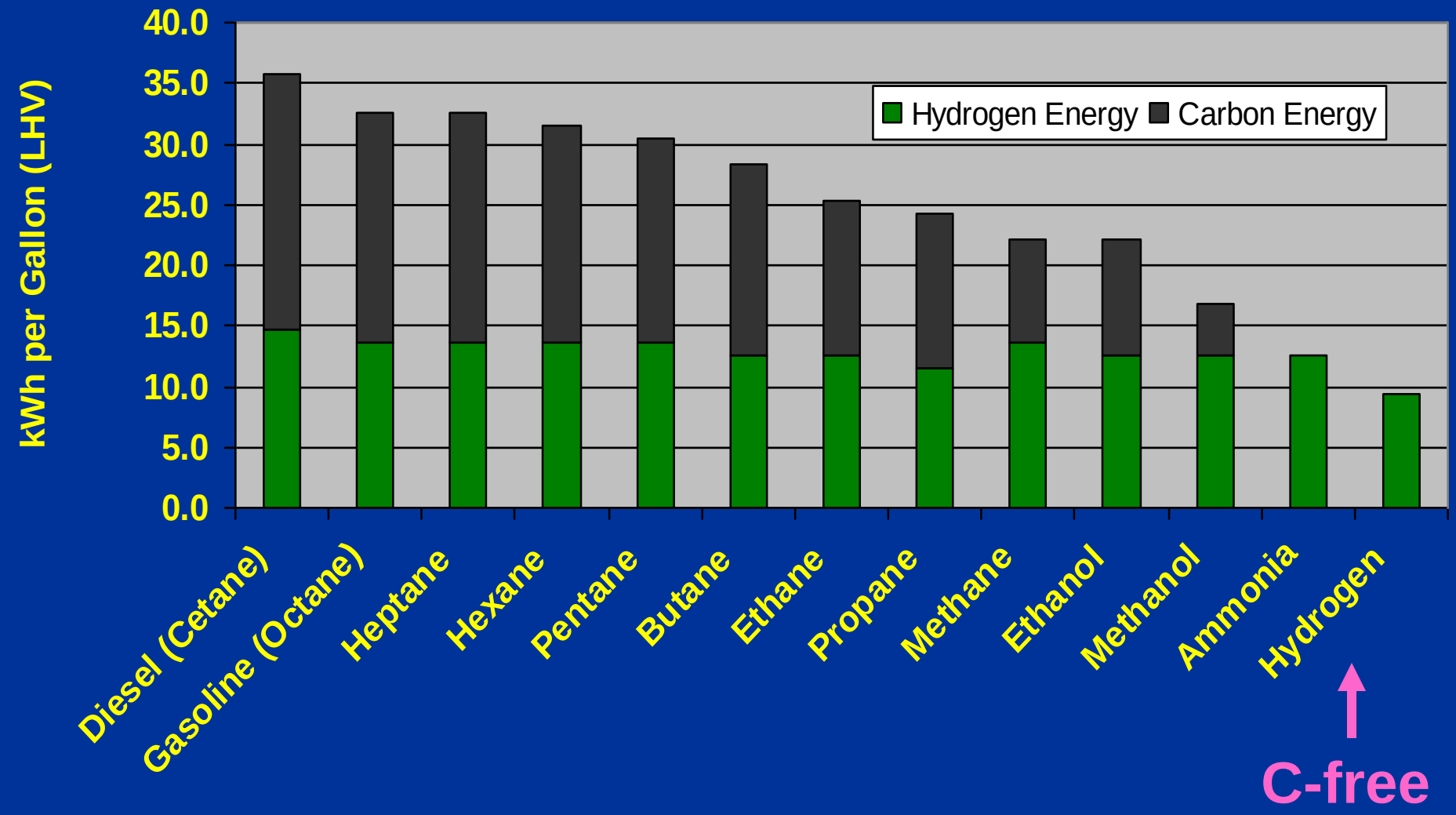
Solar Hydrogen Energy System


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

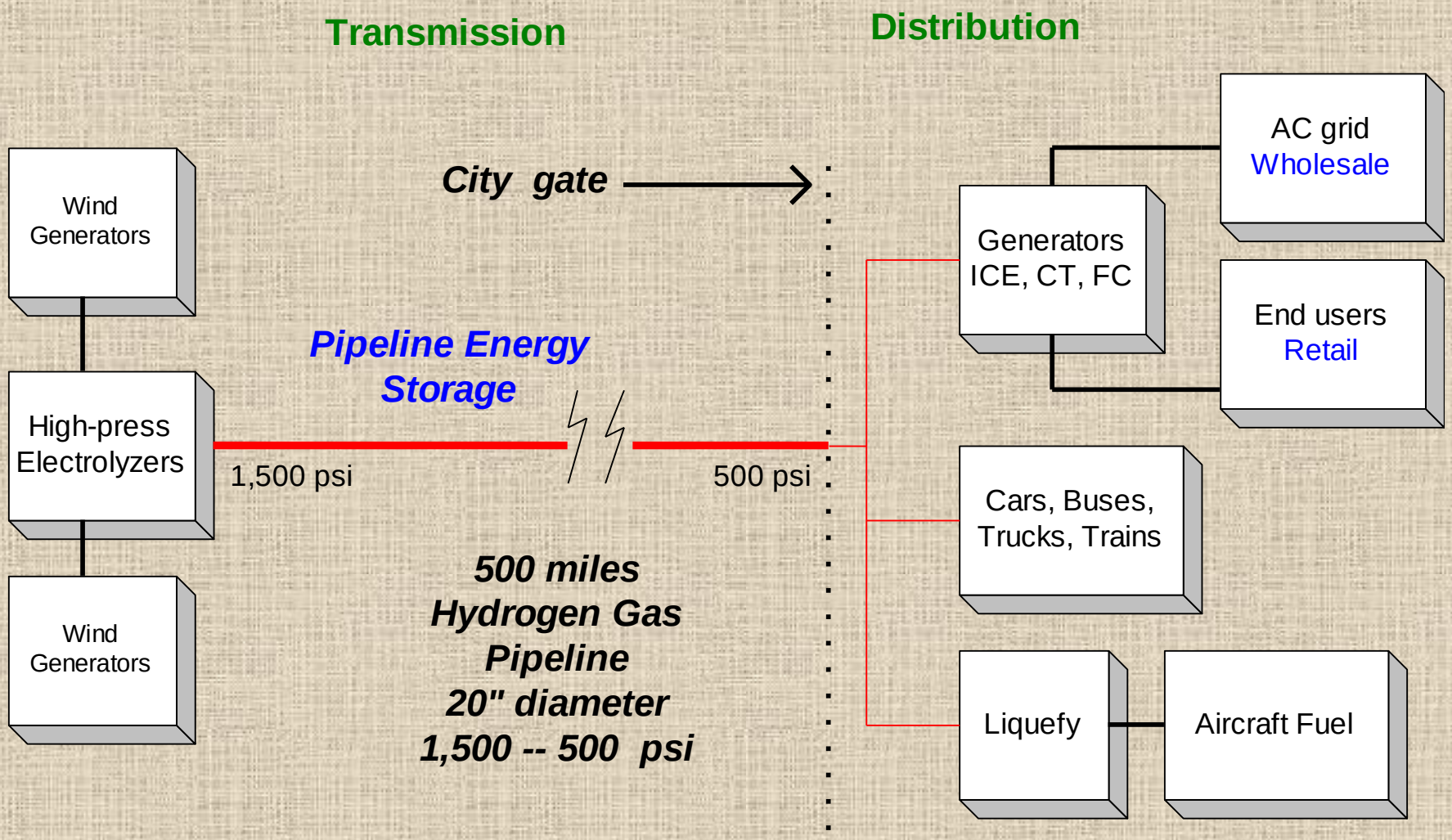
New, dedicated, high-purity, underground hydrogen pipeline network for gathering and transmission, "packing" storage, and distribution



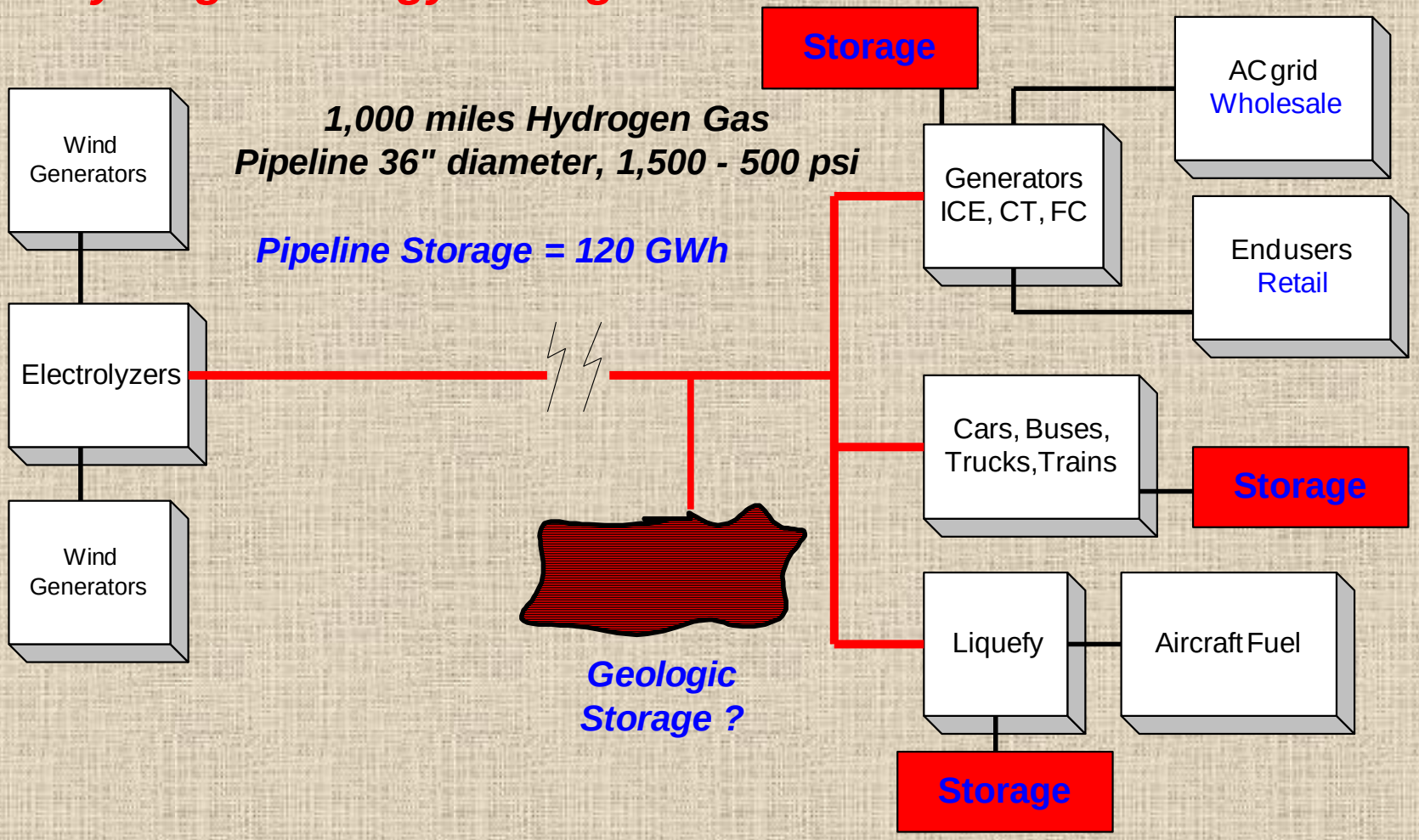
Volumetric Energy Density of Fuels (Fuels in their Liquid State)



Compressorless system: No geologic storage



Hydrogen Energy Storage



The New Benchmark in Electrolysis

MW PEM Stack

Electrical Power Input	1.5 MW (overdrive)
Hydrogen Output	285 Nm3/h
Max. Operating Pressure	40 bar (g)
Certifications	PED (97/23/EC)

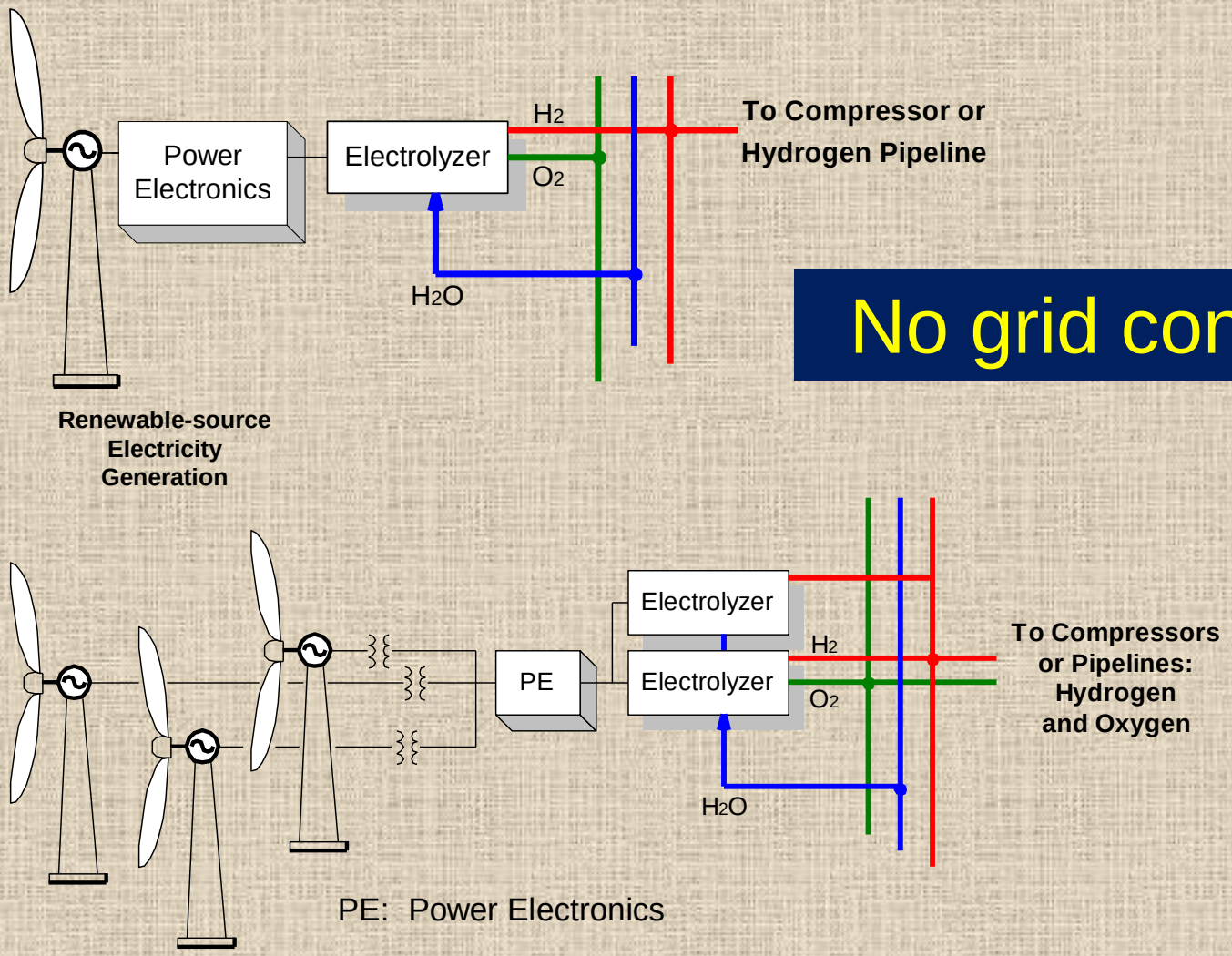
Electrolyzers:

Siemens
Hydrogenics
ProtonOnsite
ITM Power
GE

Wind to Hydrogen Power to Gas

“ Energiepark Mainz ”

Siemens, Linde, Stadtwerke Mainz, RheinMain University



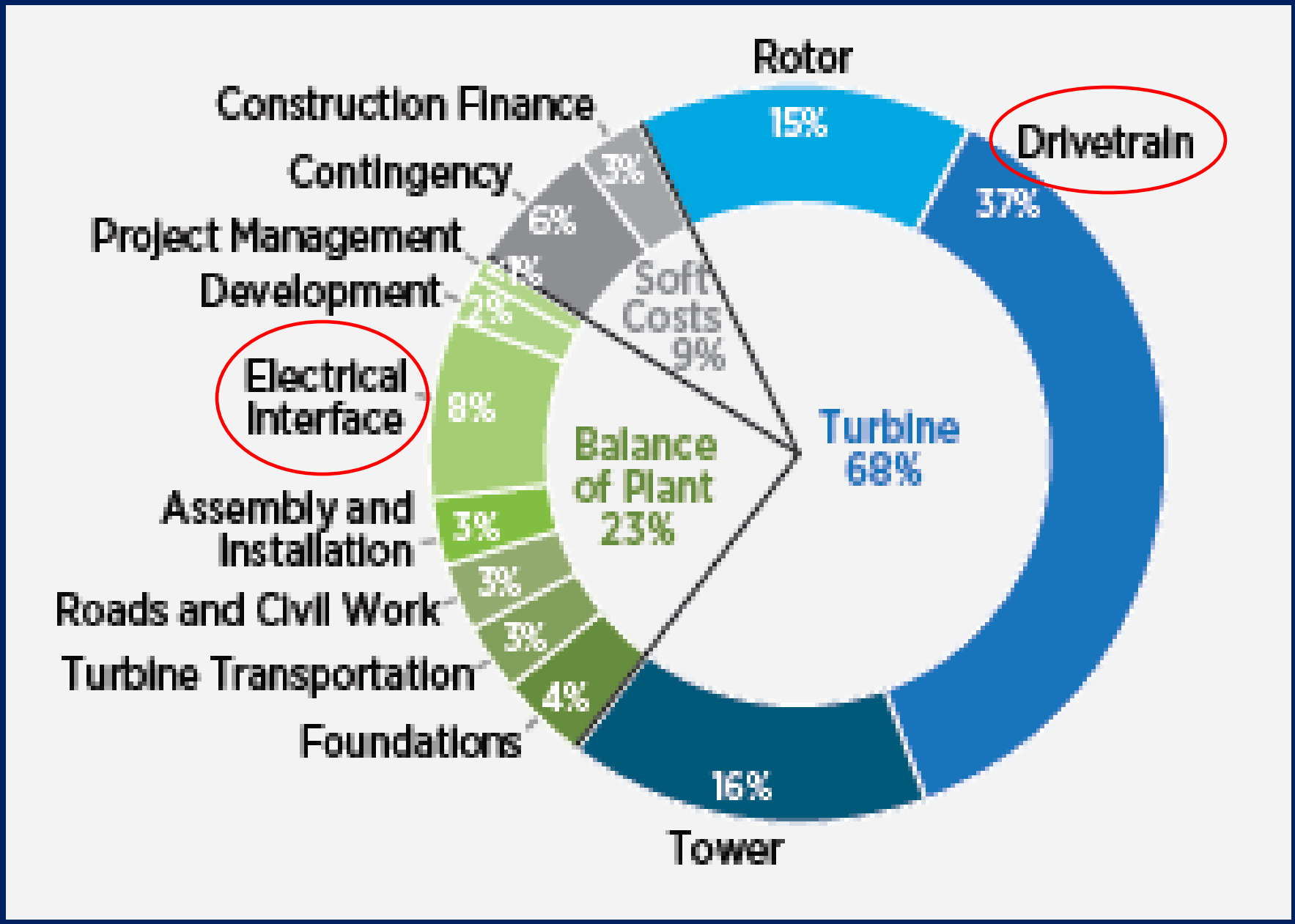
No grid connection

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

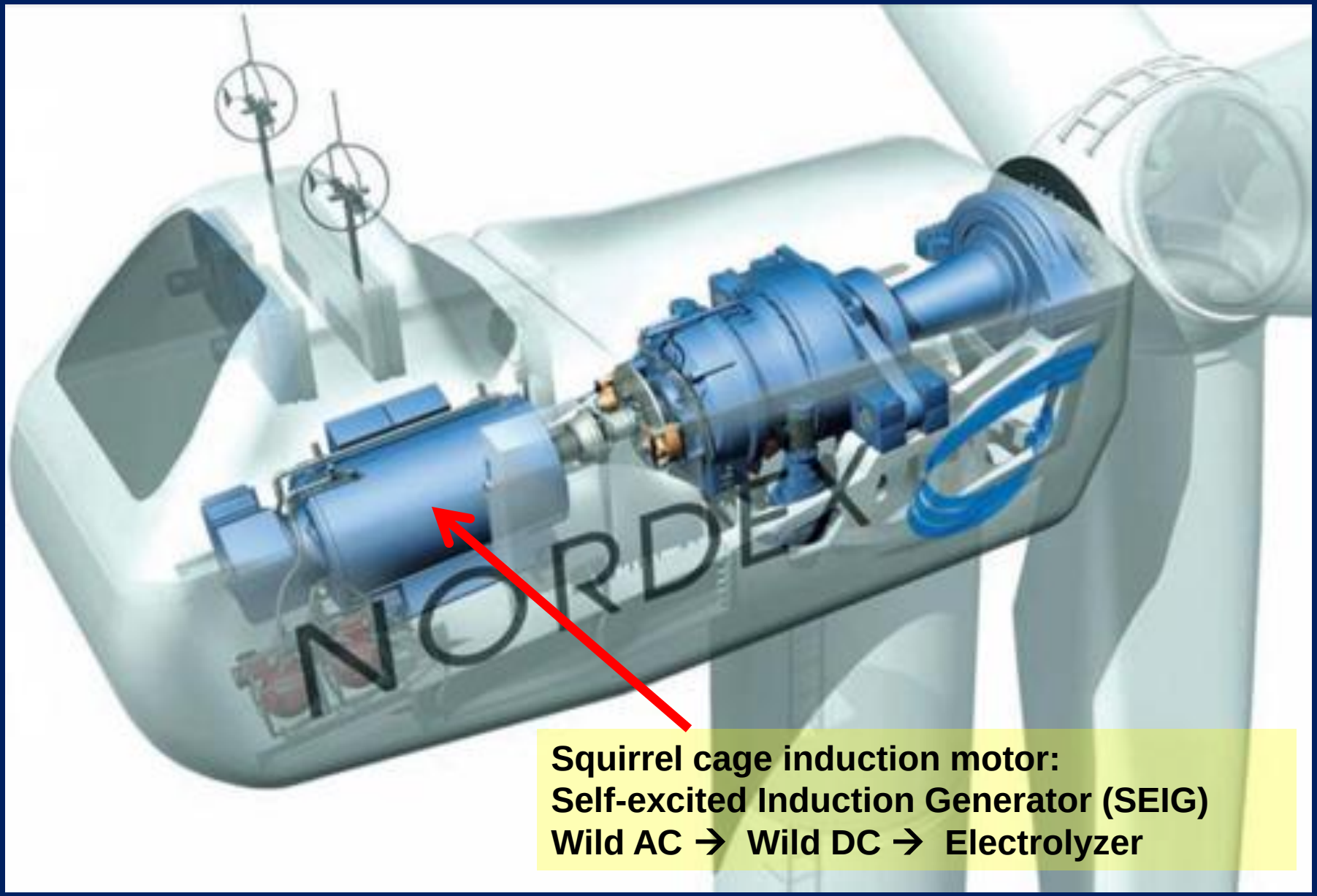
Lower COE – Cost of Energy
Wind System Capex + O&M
PV System Capex + O&M

Electricity component savings pay for Hydrogen and Ammonia systems:

- ***Conversion***
- ***Transmission***
- ***Storage***



Installed CAPEX: land-based, utility-scale



Dedicated Hydrogen Production: No Grid Connection

Hundreds of km underground high voltage cable

No Grid connection:
Simple Power Electronics

ABB ACS800 low voltage wind turbine converter

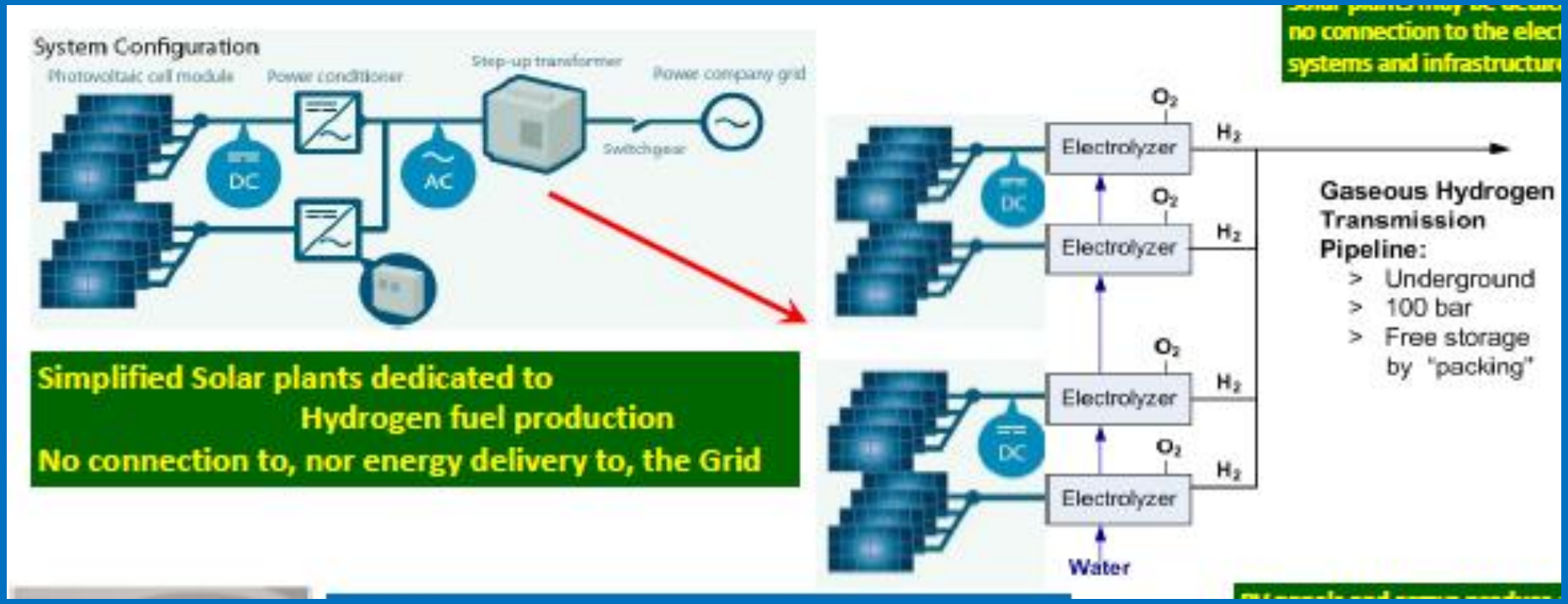
Offshore Wind

Offshore Wind

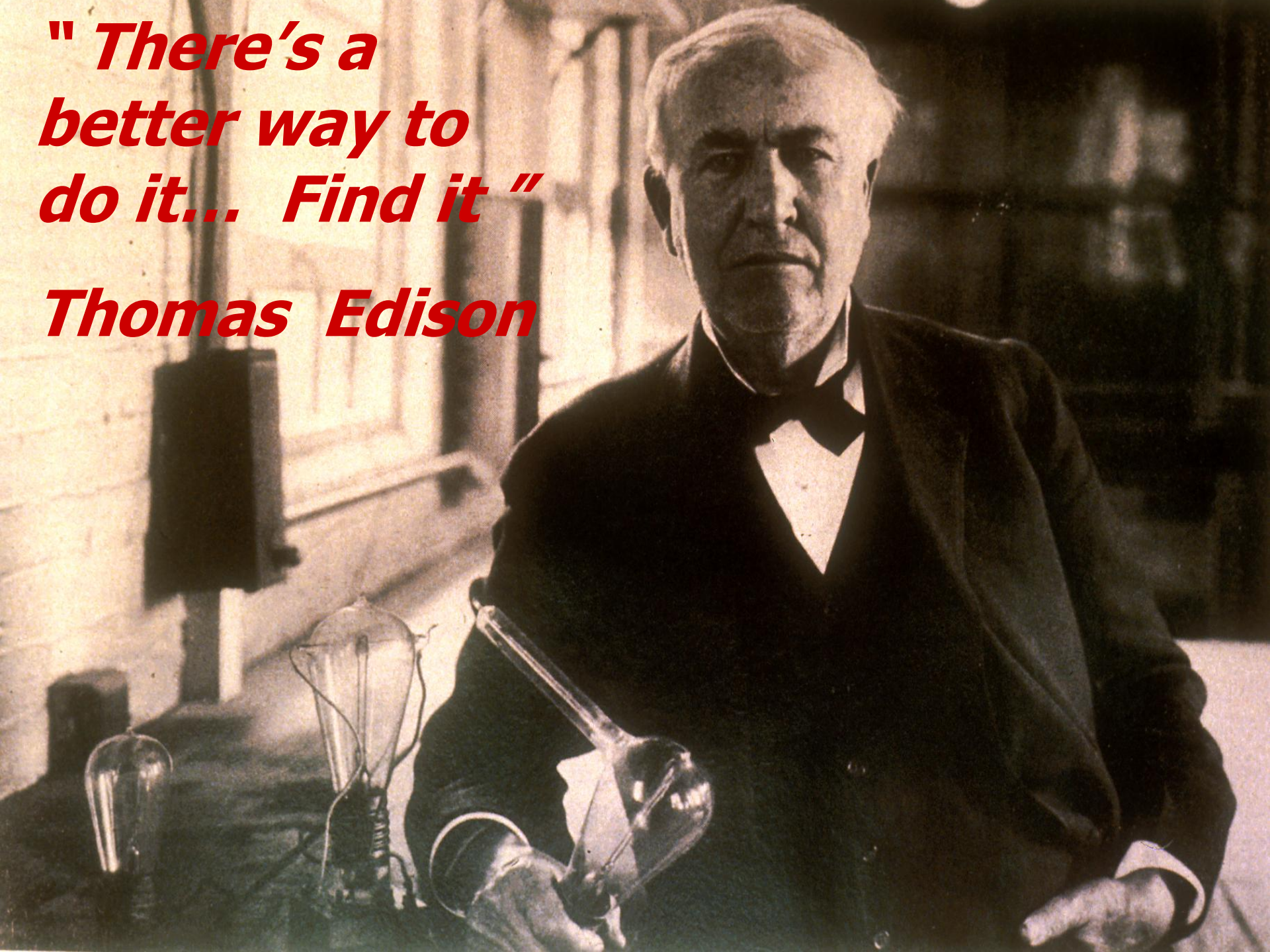
Offshore Wind

PV – to – Hydrogen Delivery to Gaseous Hydrogen (GH2) pipeline

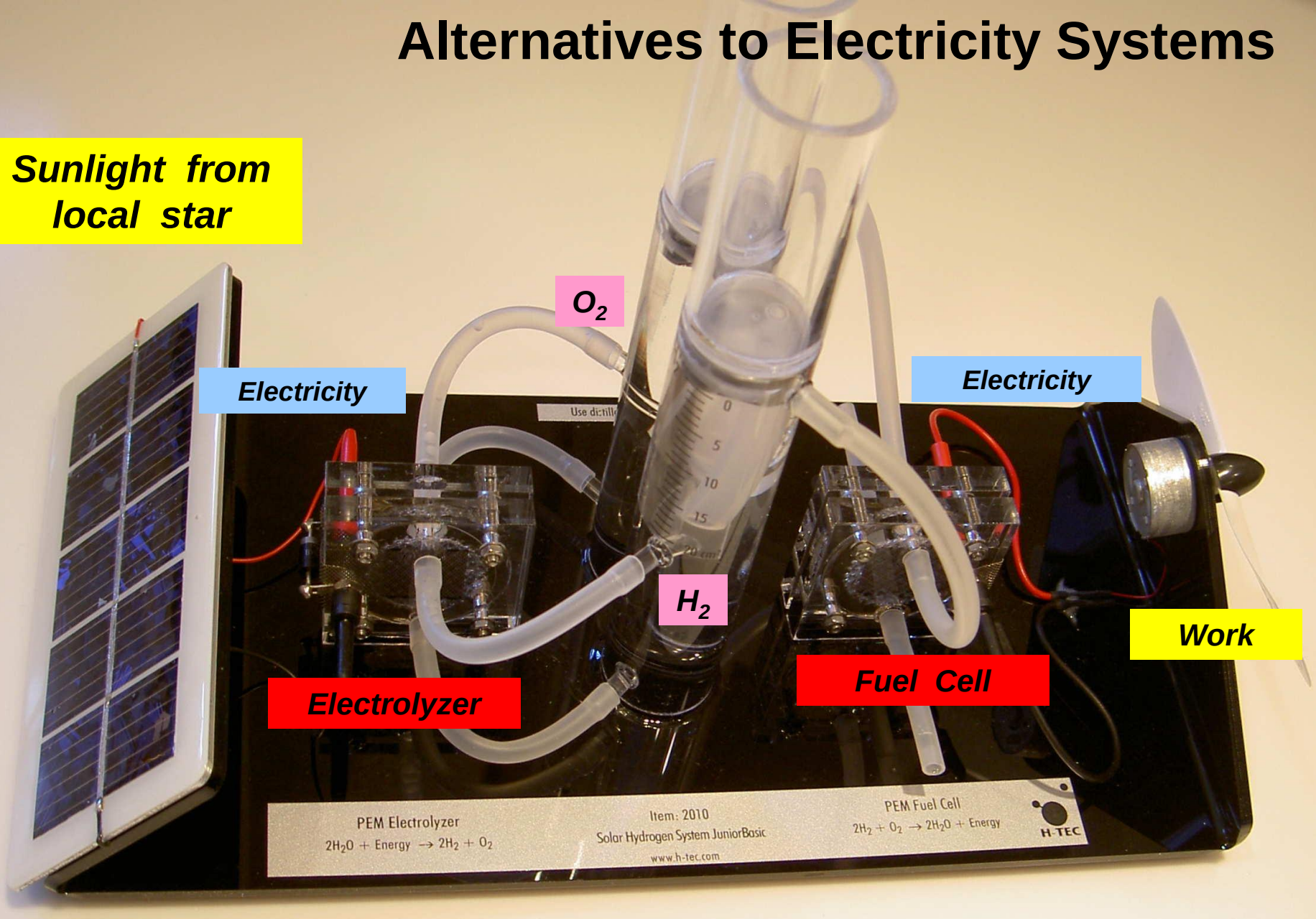
- New, dedicated
- High-purity: Fuel cell grade, 99.999 %
- Underground
- Gathering, transmission, storage, distribution
- “Free” storage by “packing” *a la* natural gas



Gas-fired Peaker


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

Alternatives to Electricity Systems



Solar Hydrogen Energy System


The Great Plains Wind Resource
PACIFIC
OCEAN
ATLANTIC
OCEAN
PACIFIC
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

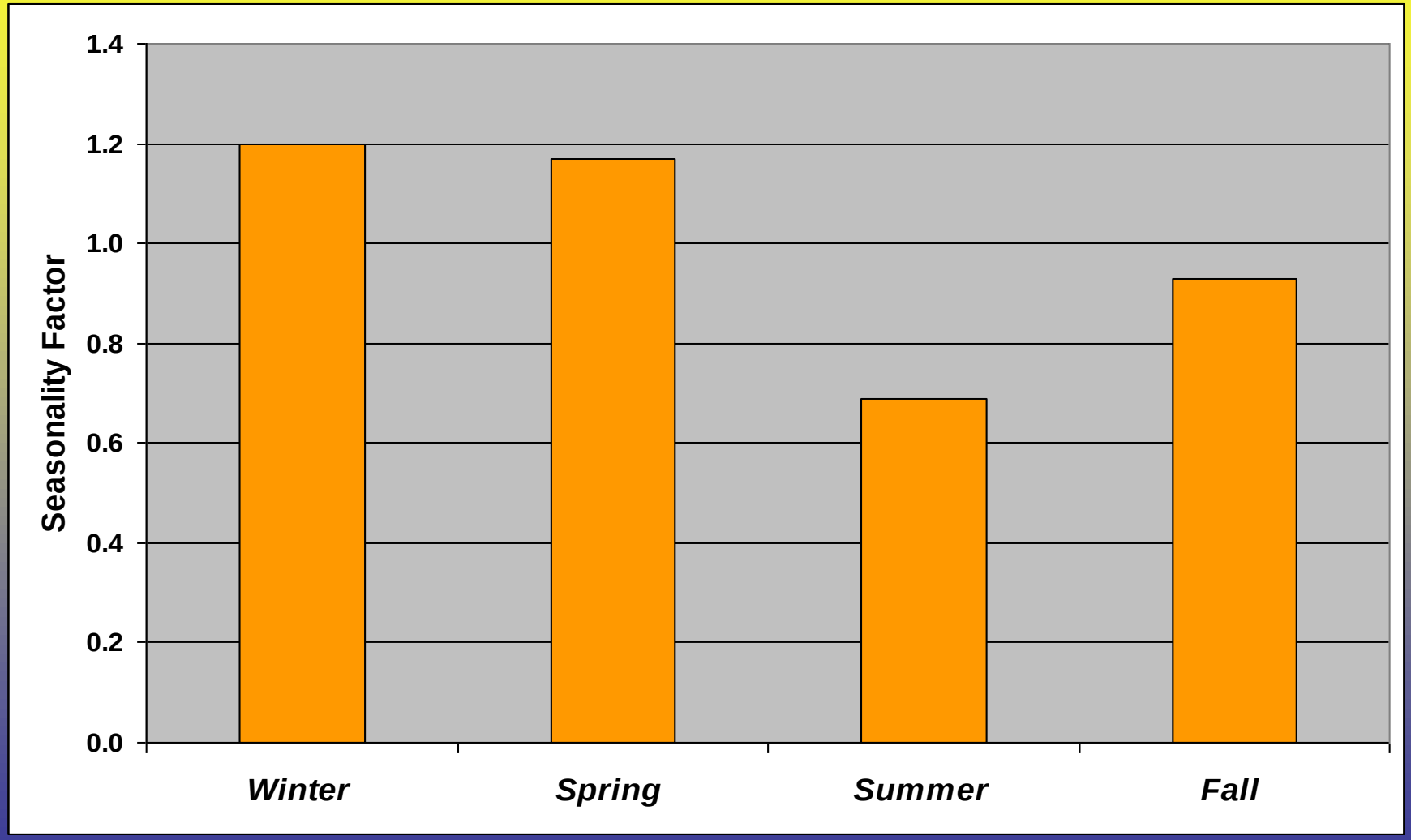
Capacity at 500 miles length **Capacity Factor (CF) = 30%**

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

Wind Seasonality, Northern Great Plains

Normalized to 1.0 per season



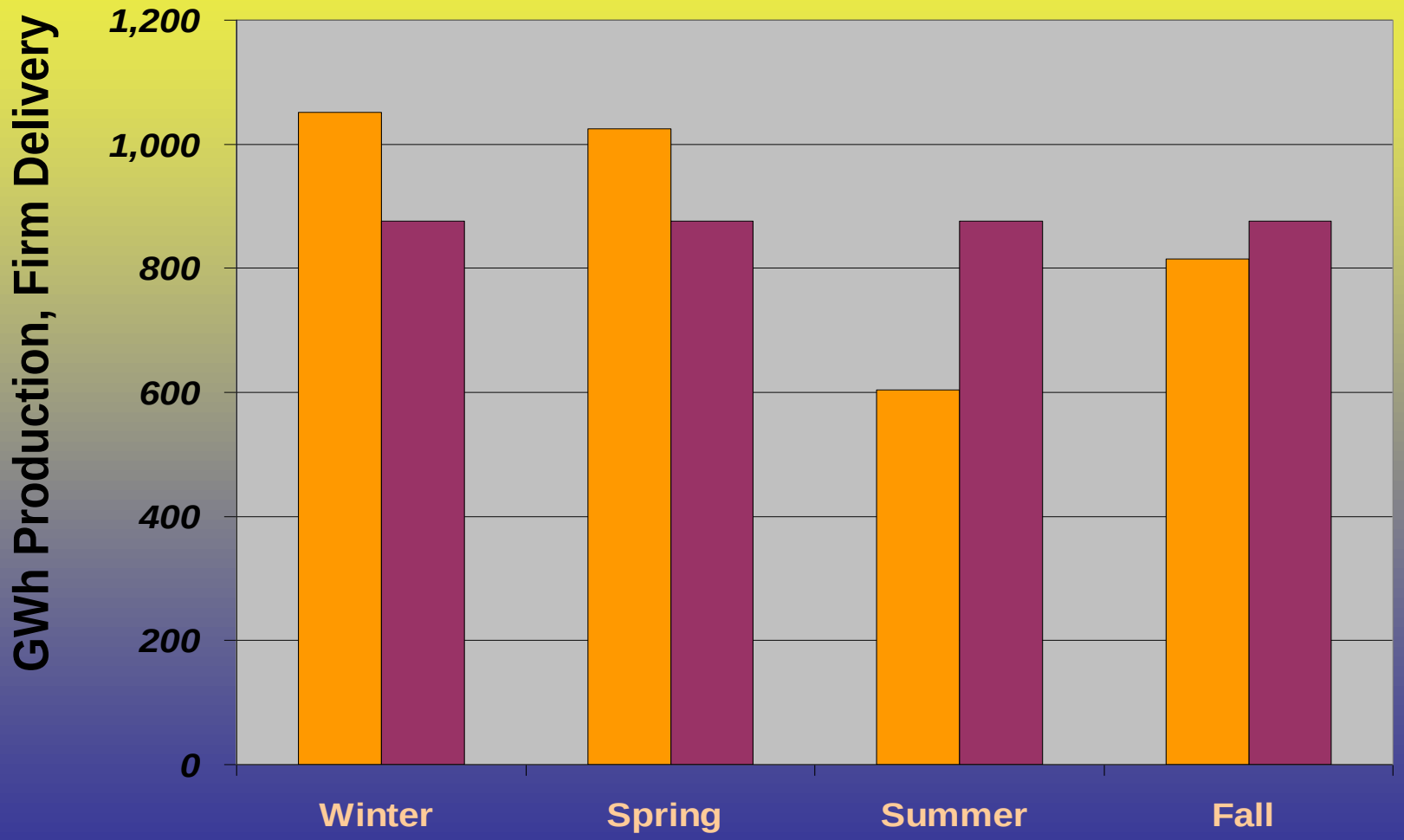
Wind Seasonality, Northern Great Plains

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

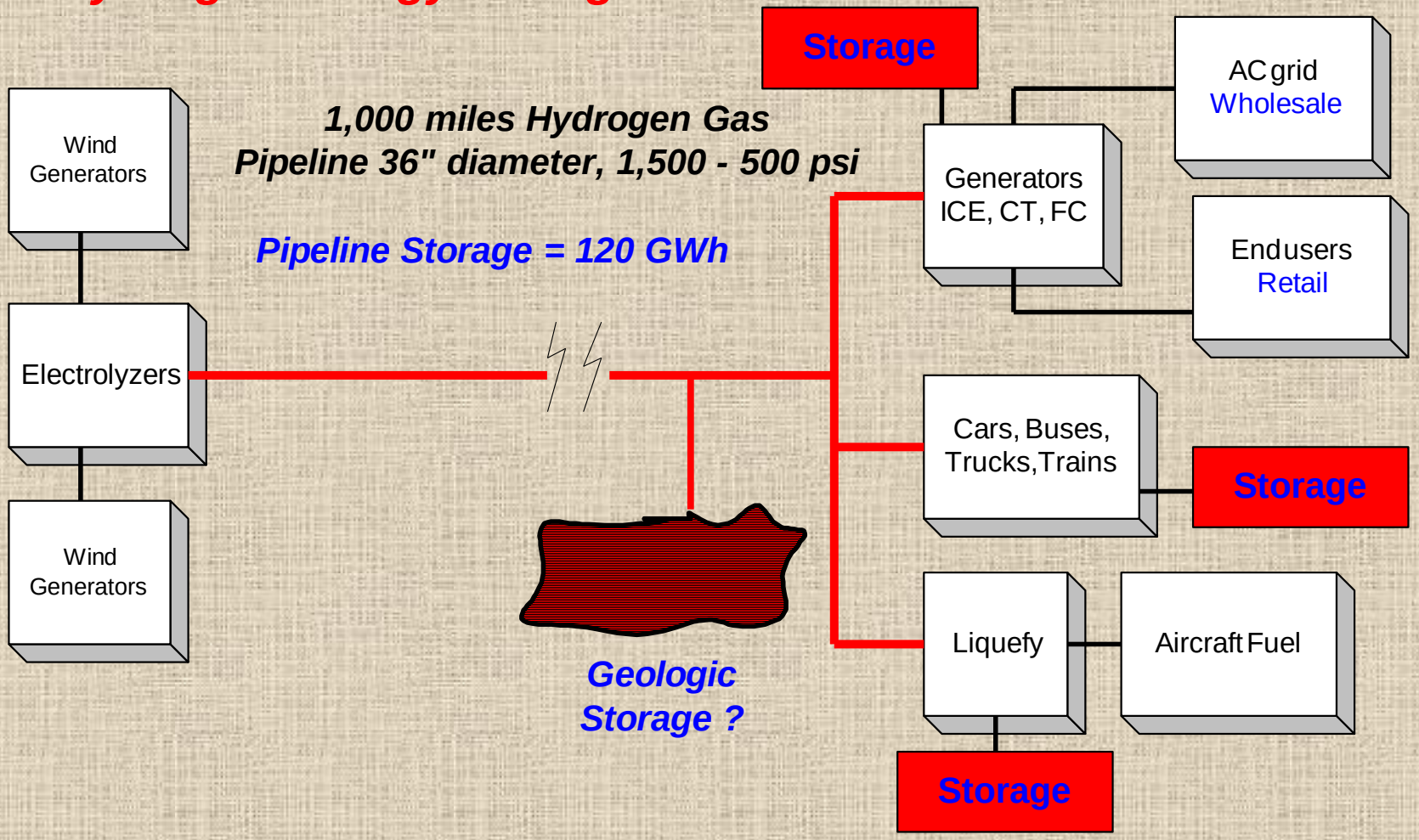


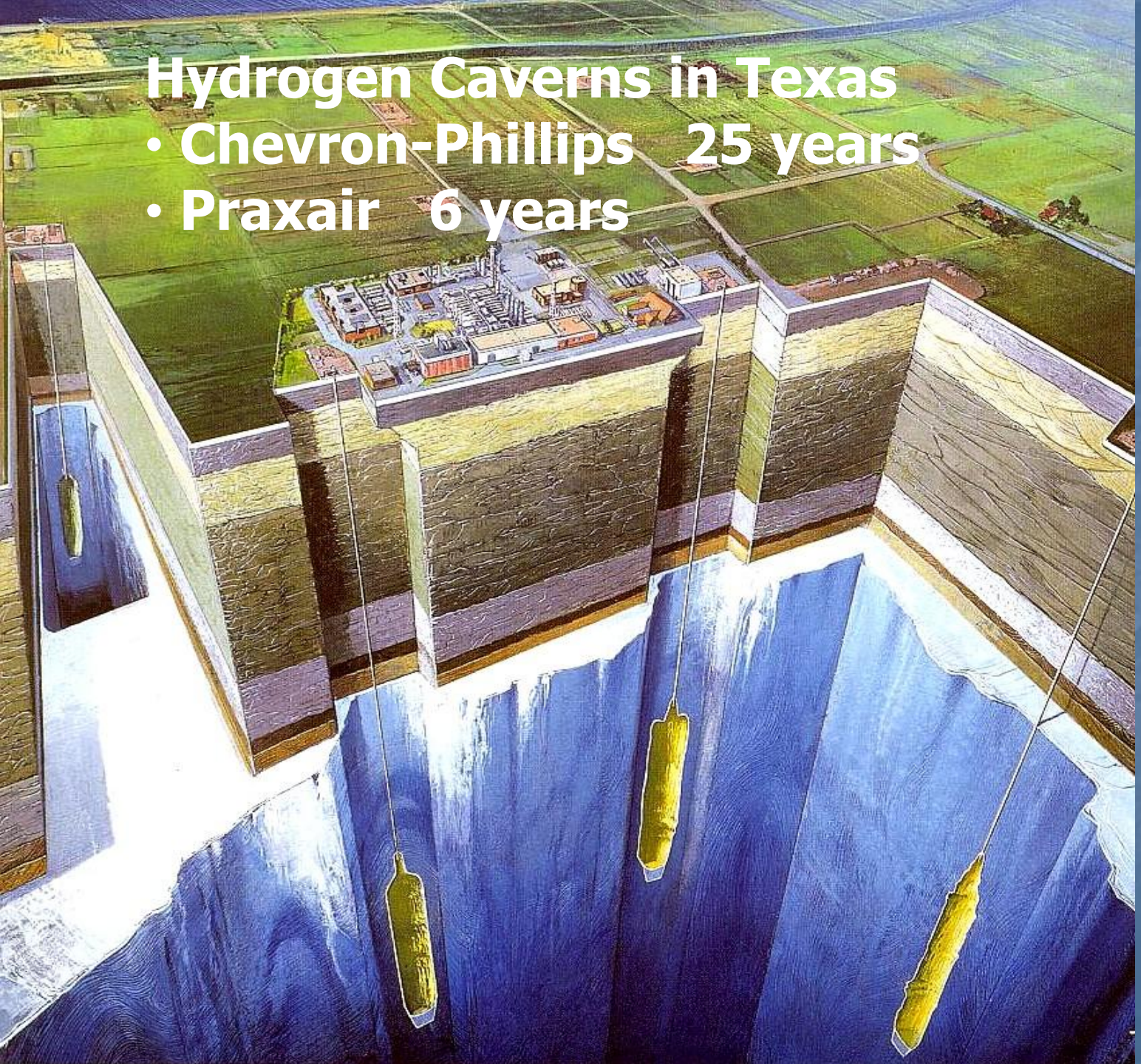
320 GWh

Annual firming, 1,000 MW wind

- **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**

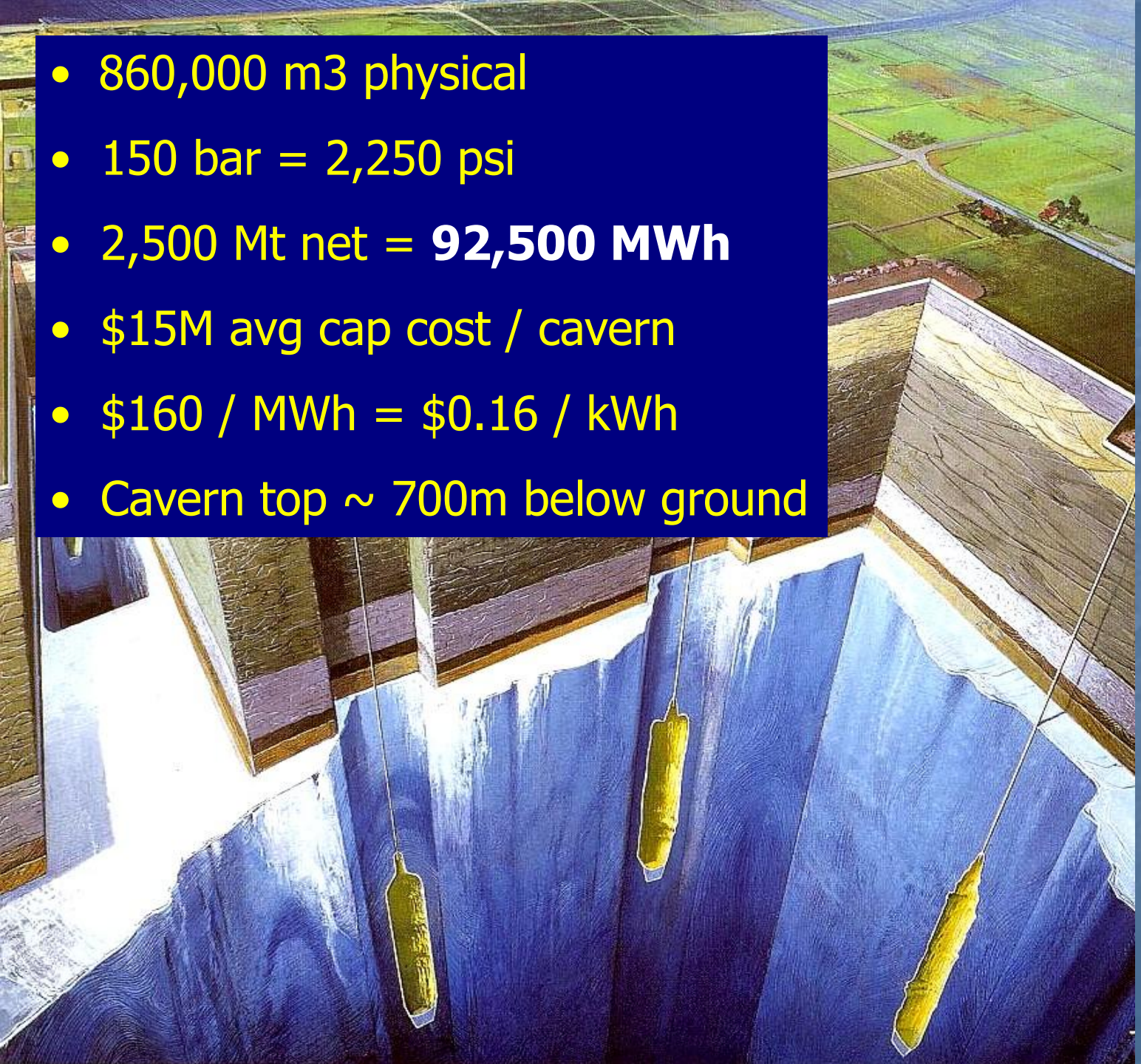
Hydrogen Energy Storage





Domal Salt Storage Caverns

PB ESS



- 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

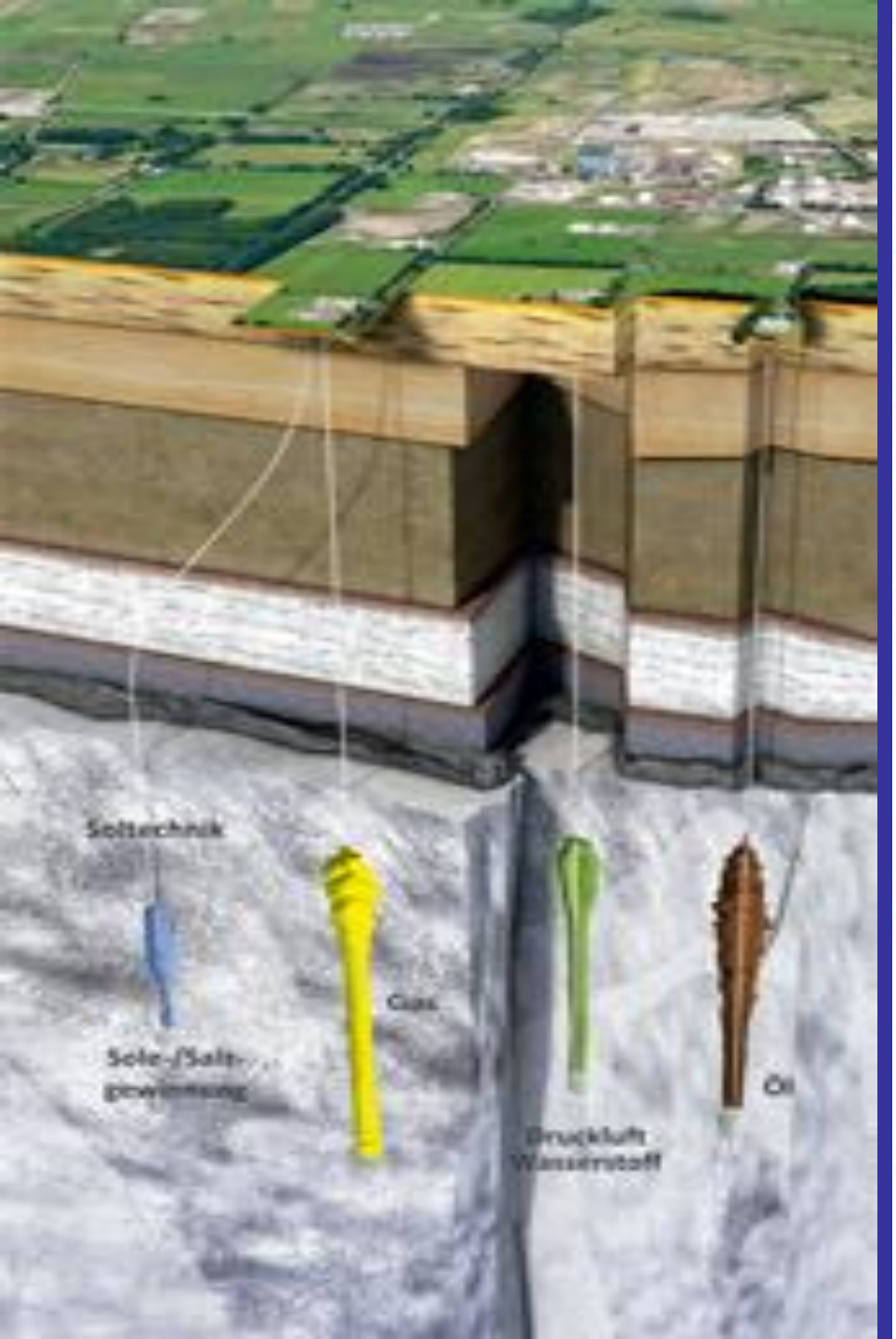
"Clemens Terminal" Conoco Phillips 20 years

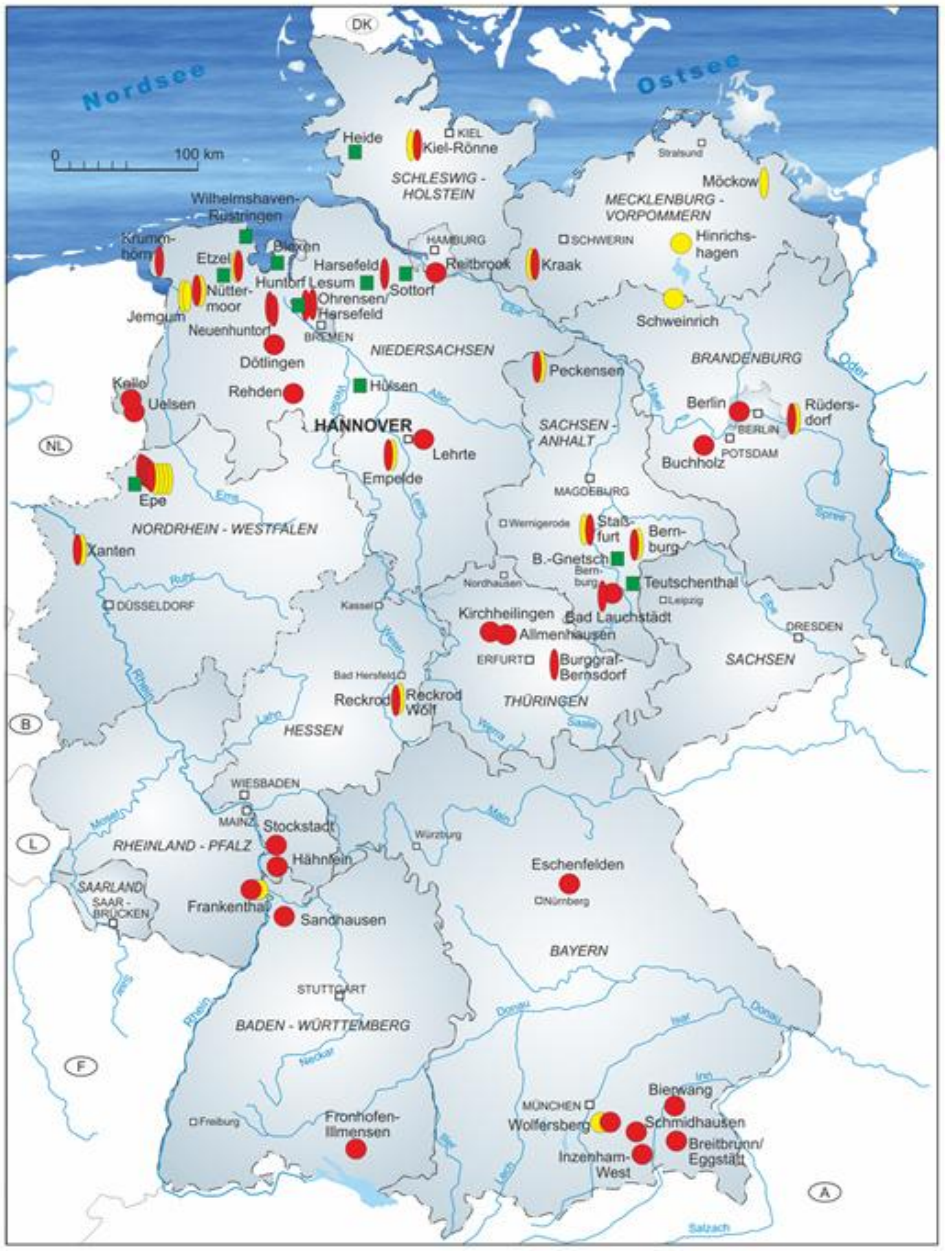
Praxair `07

PB ESS

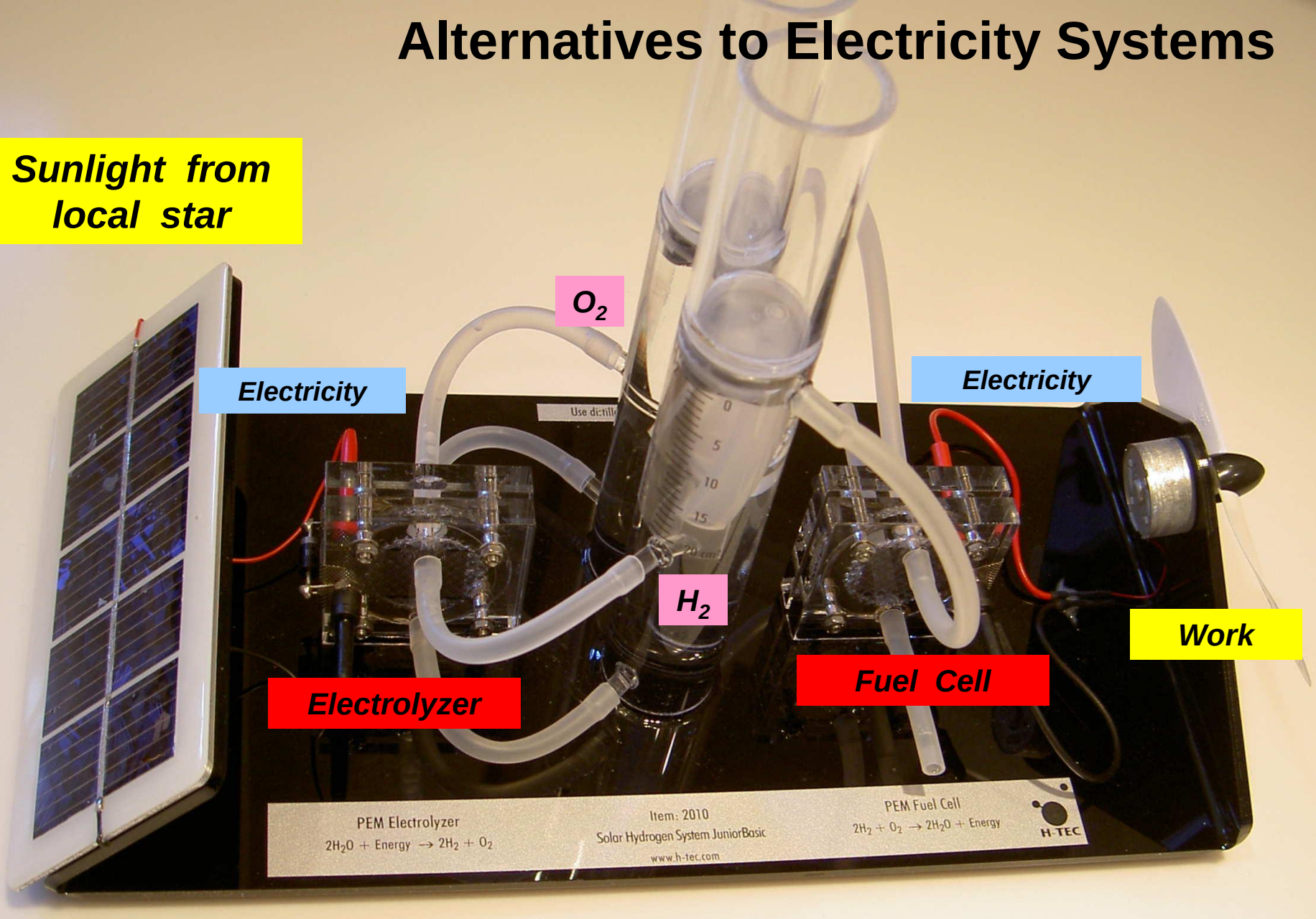
Renewable-source GH2 geologic storage potential

Candidate formations for manmade, solution-mined, salt caverns


Solterchnik
Gas
Sole-/Salz-
gewinnung
Druckluft
Wasserstoff
Öl


DK
Nordsee
Ostsee
0
100 km
Heide
KIEL
Kiel-Rönne
SCHLESWIG - HOLSTEIN
Stralsund
Möckow
MECKLENBURG - VORPOMMERN
Wilhelmshaven-
Rüstringen
Krumm-
hörn
Etzel
Bexten
HAMBURG
Harsefeld
Reitbrook
Kraak
SCHWERIN
Hinrichs-
hagen
Nütter-
moor
Huntorf
Lesum
Sottorf
Jemgum
Ohrensen/
Harsefeld
Neuenhuntorf
BREMEN
Schweinrich
Elbe
Dötlingen
NIEDERSACHSEN
BRANDENBURG
Oder
Peckensen
Kalle
Uelsen
Rehden
Hülsen
Aller
Berlin
BERLIN
Rüders-
dorf
HANNOVER
Lehrte
SACHSEN - ANHALT
NL
Buchholz
POTSDAM
Empelde
MAGDEBURG
Ems
Epe
Weser
Wernigerode
Staß-
furt
Bern-
burg
NORDRHEIN - WESTFALEN
Spree
Xanten
B.-Gnetsch
Bern-
burg
Teutschenthal
Nordhausen
Ruhr
Kassel
Leipzig
DÜSSELDORF
Kirchheilingen
Bad Lauchstädt
Elbe
Allmenhausen
DRESDEN
Werra
ERFURT
Burggraf-
Bernsdorf
SACHSEN
Bad Hersfeld
Rhein
Reckrod
Reckrod
Wölf
THÜRINGEN
B
HESSEN
Saale
Lahn
WIESBADEN
Mosel
MAINZ
Stockstadt
Main
Würzburg
L
RHEINLAND - PFALZ
Hähnlein
Eschenfelden
SAARLAND
SAAR -
BRÜCKEN
Frankenthal
Sandhausen
Nürnberg
BAYERN
Neckar
STUTTGART
Rhein
Donau
BADEN - WÜRTTEMBERG
Iller
F
Inn
Bierwang
MÜNCHEN
Freiburg
Fronhofen-
Illmensen
Wolfersberg
Schmidhausen
Breitbrunn/
Eggstätt
Inzenham-
West
Lech
A
Salzach
Erdgas
Porenspeicher
in Betrieb
in Planung oder Bau
Kavernenspeicher
in Betrieb
in Planung oder Bau
Rohöl, Mineralprodukte, Flüssiggas
Kavernenspeicher
in Betrieb
(Quelle: LBEG, 2010)

Alternatives to Electricity Systems



Solar Hydrogen Energy System

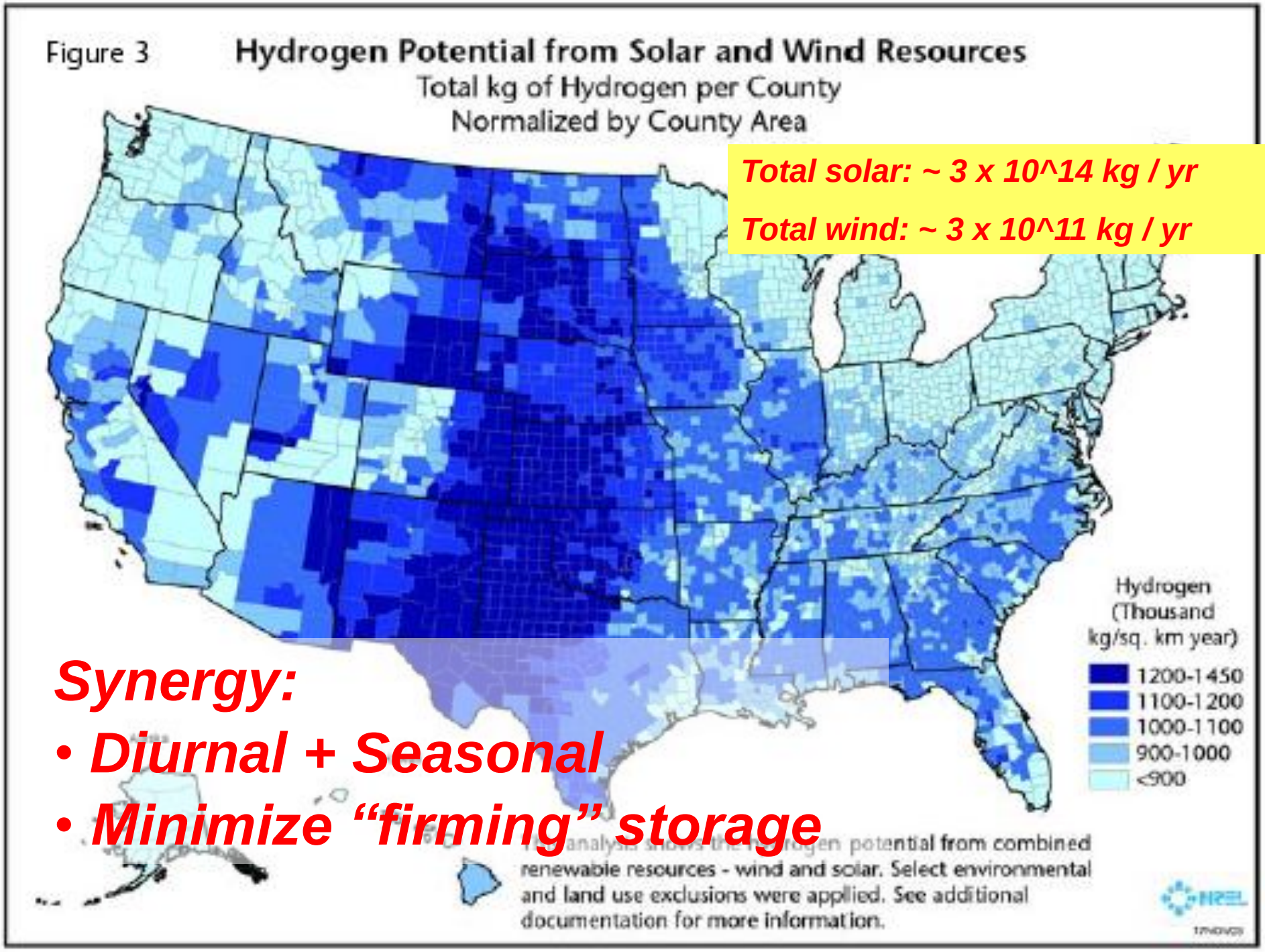
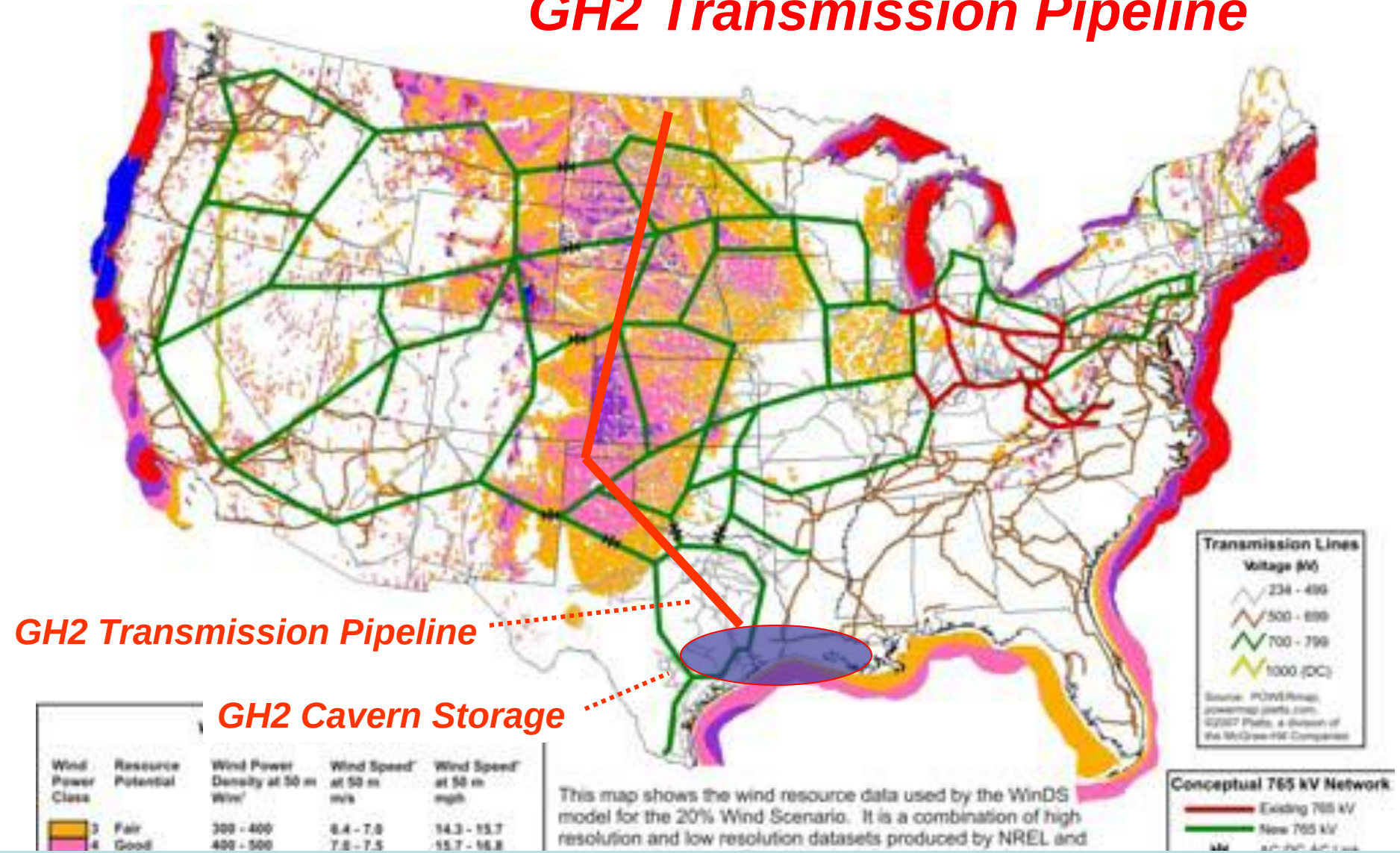
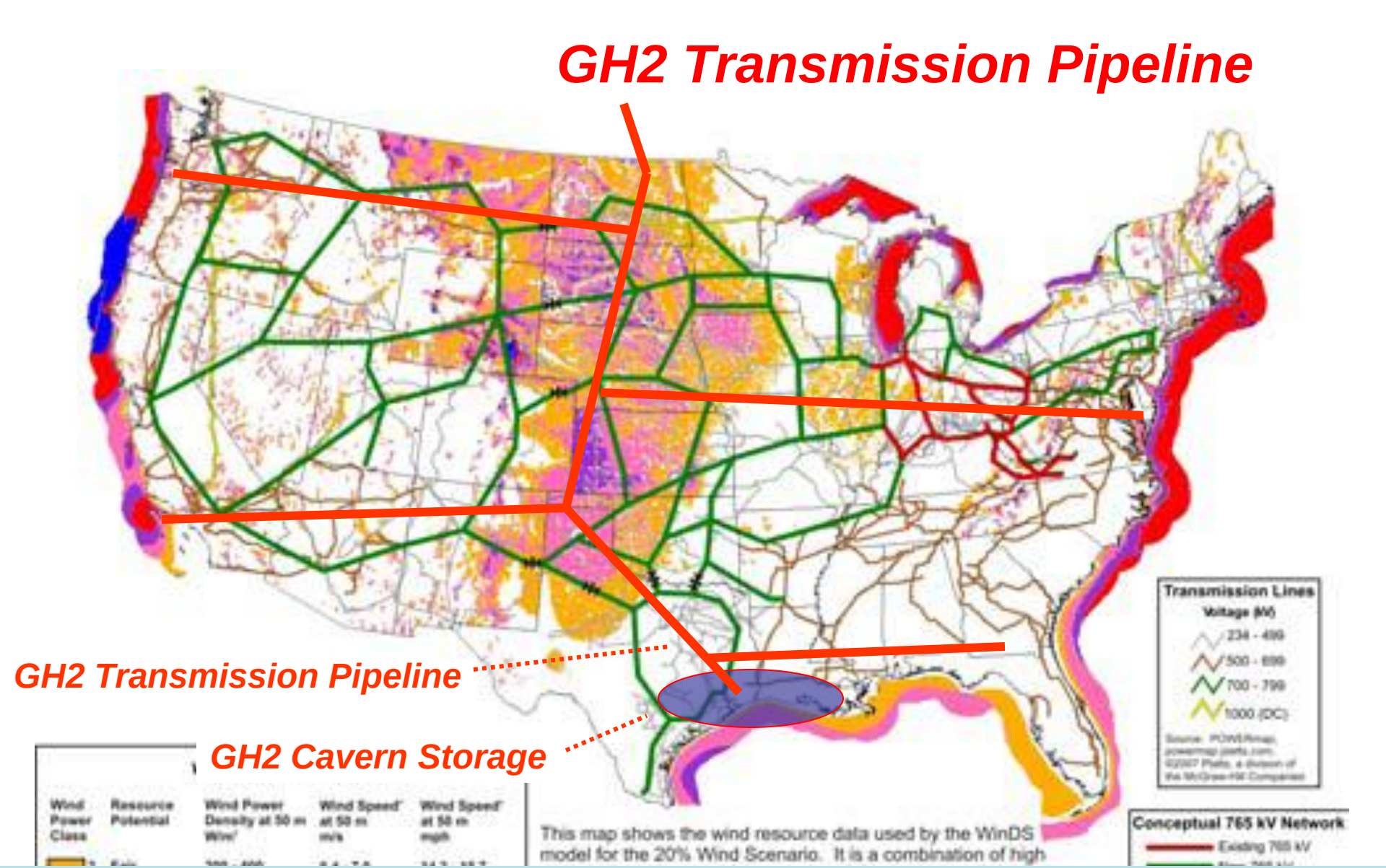


Figure 3
Hydrogen Potential from Solar and Wind Resources
Total kg of Hydrogen per County
Normalized by County Area
Total solar: ~ 3 x 10^14 kg / yr
Total wind: ~ 3 x 10^11 kg / yr
Hydrogen
(Thousand
kg/sq. km year)
1200-1450
1100-1200
1000-1100
900-1000
<900
Synergy:
• Diurnal + Seasonal
• Minimize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



Wind Potential ~ 10,000 GW

12 Great Plains states

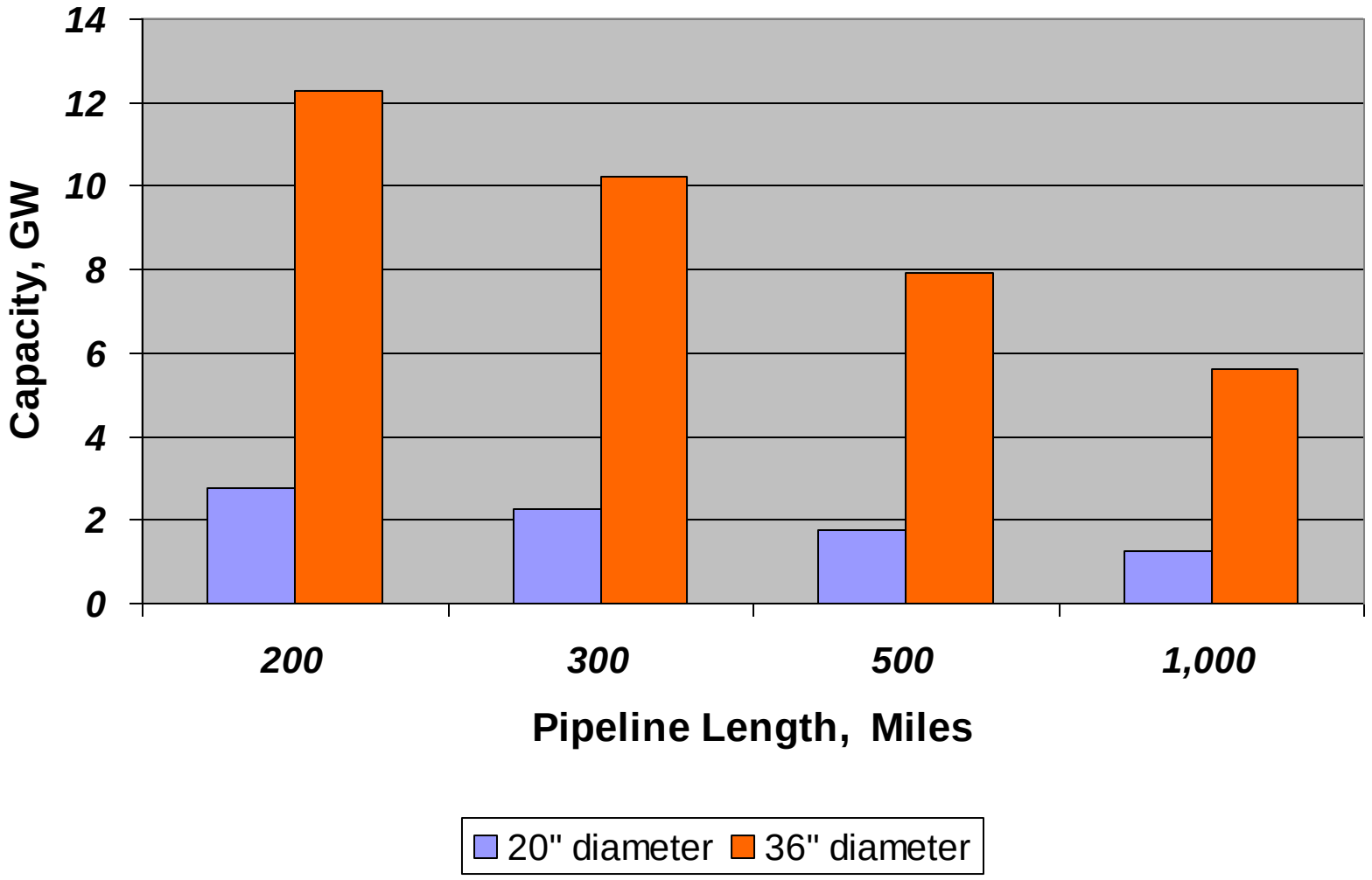


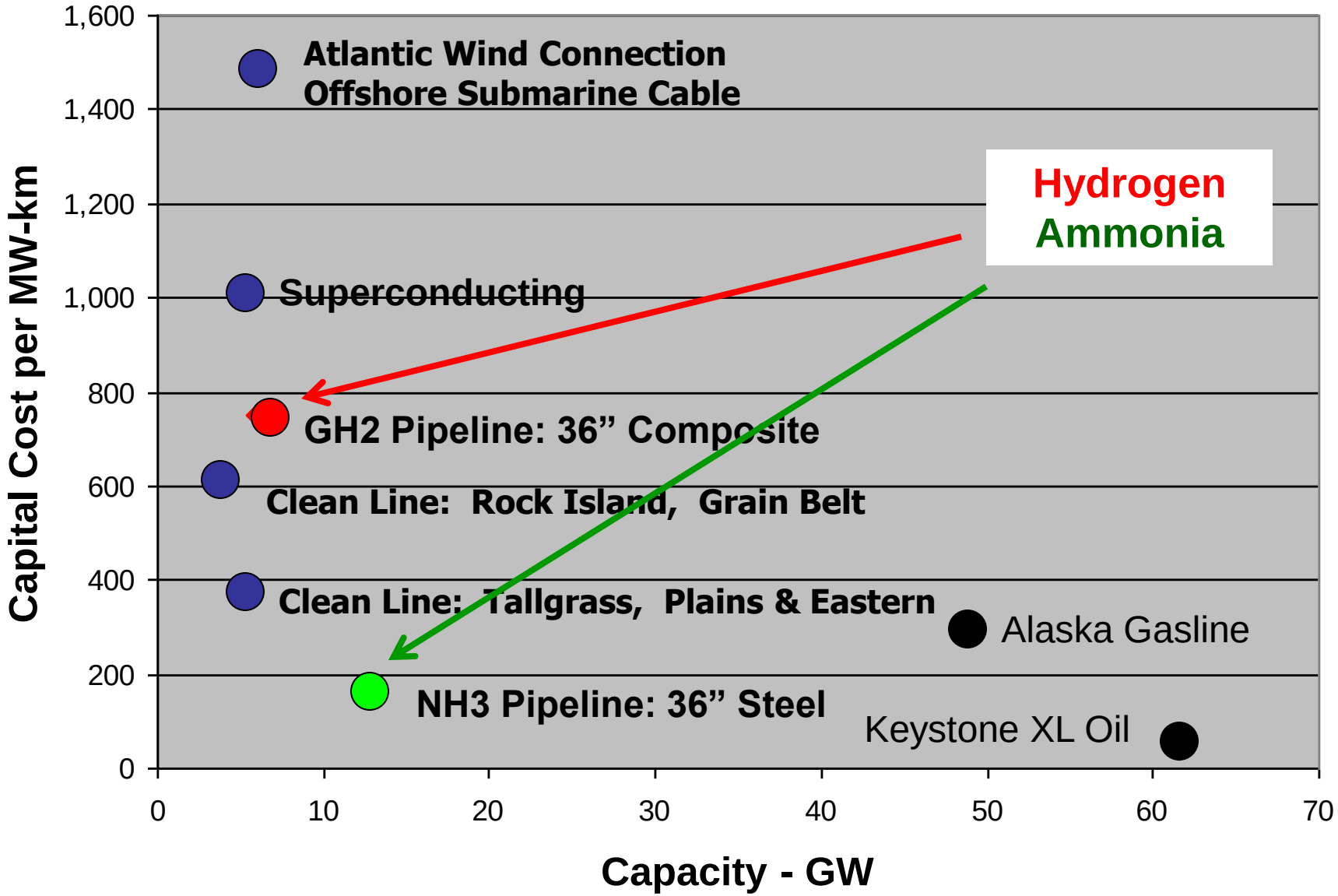
Wind Potential ~ 10,000 GW

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

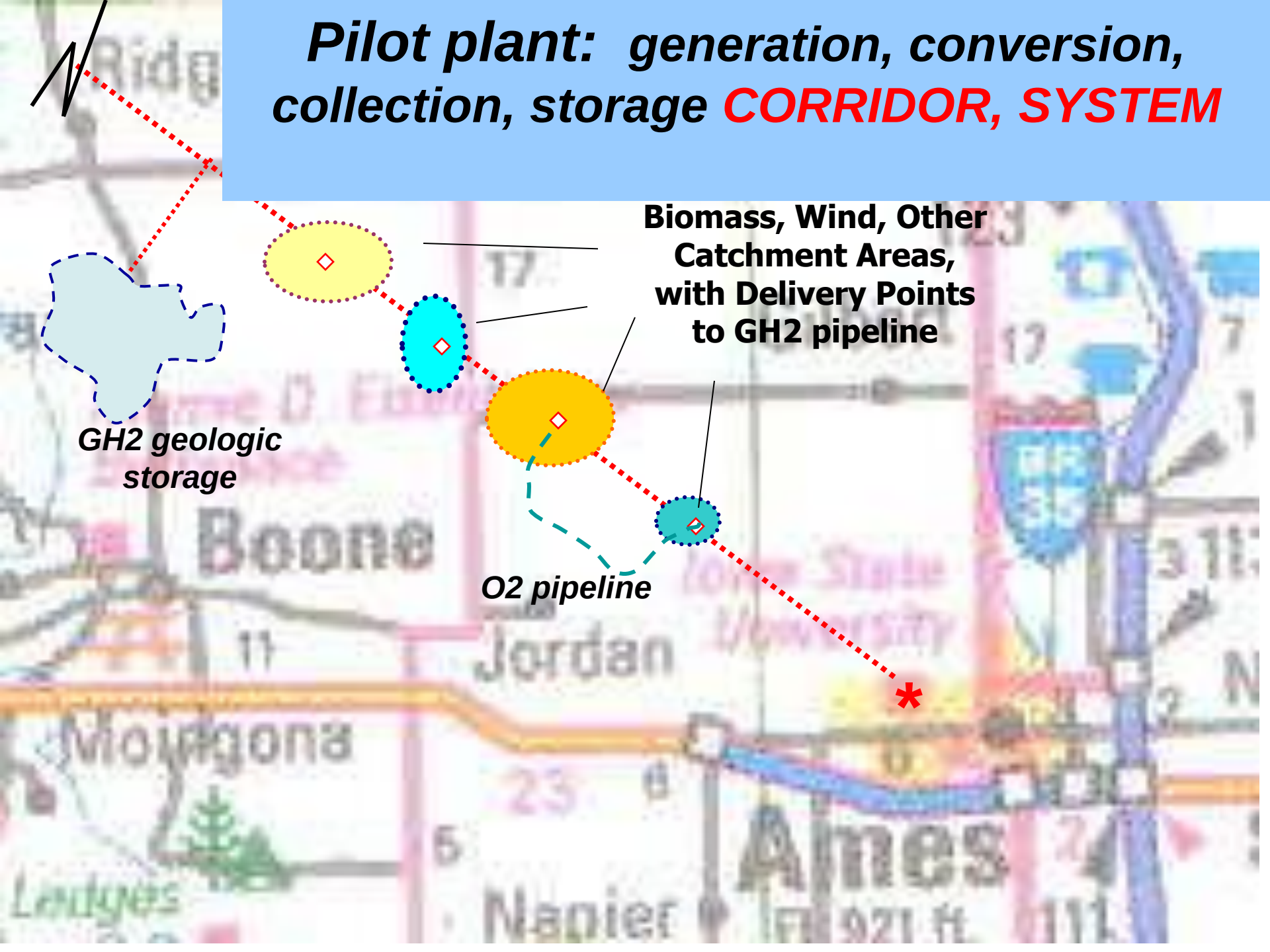
Pipelines have large capacity and provide large storage

Future "Energy" Utility: the International Renewable Hydrogen Transmission Demonstration Facility (IRHTDF)

IPHE: International Partnership for the Hydrogen Economy

- 19 countries
- Since 2003

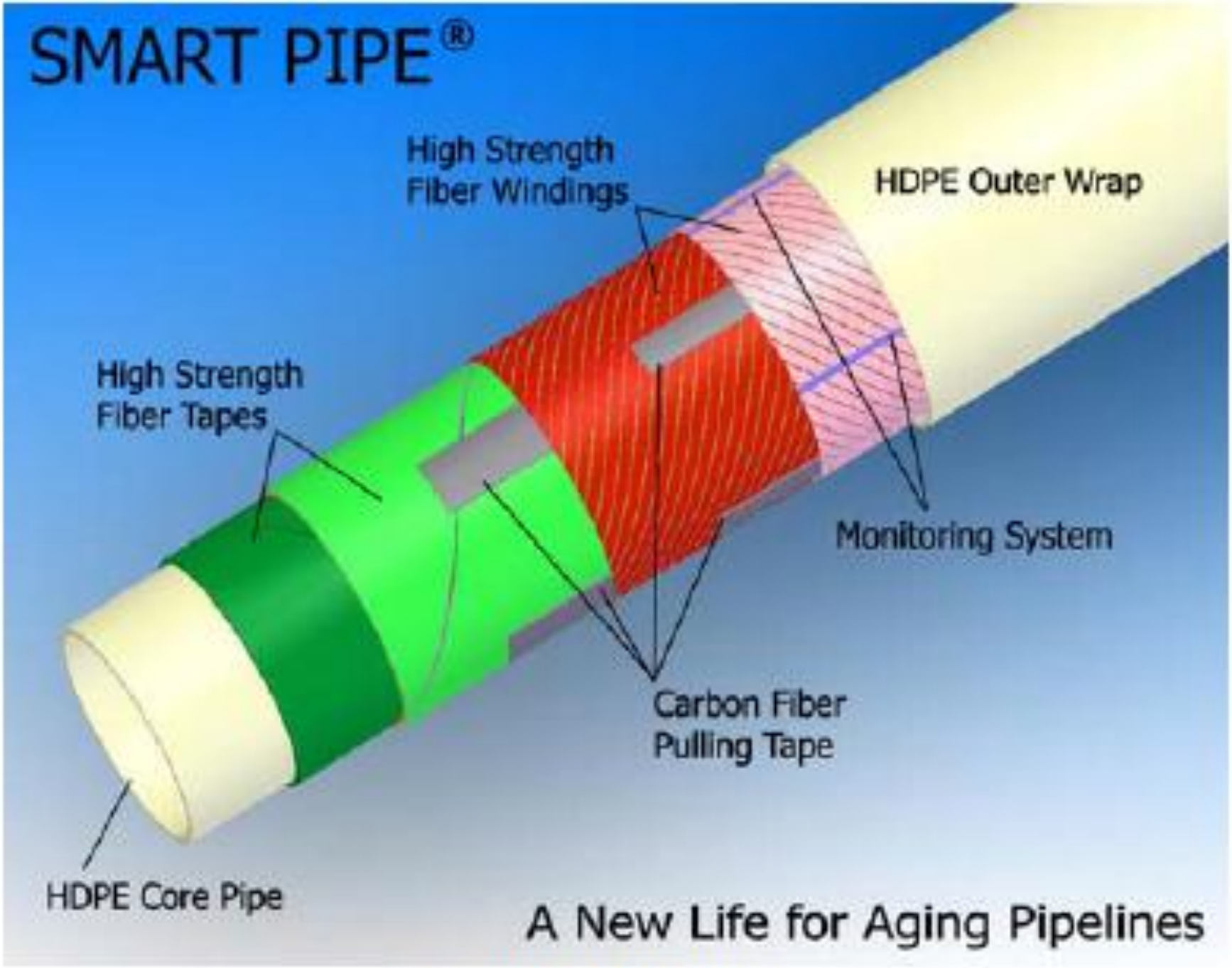
Pilot plant: generation, conversion, collection, storage CORRIDOR, SYSTEM



Questar " Southern Trails Pipeline "

Out-of-service "Western section" for sale

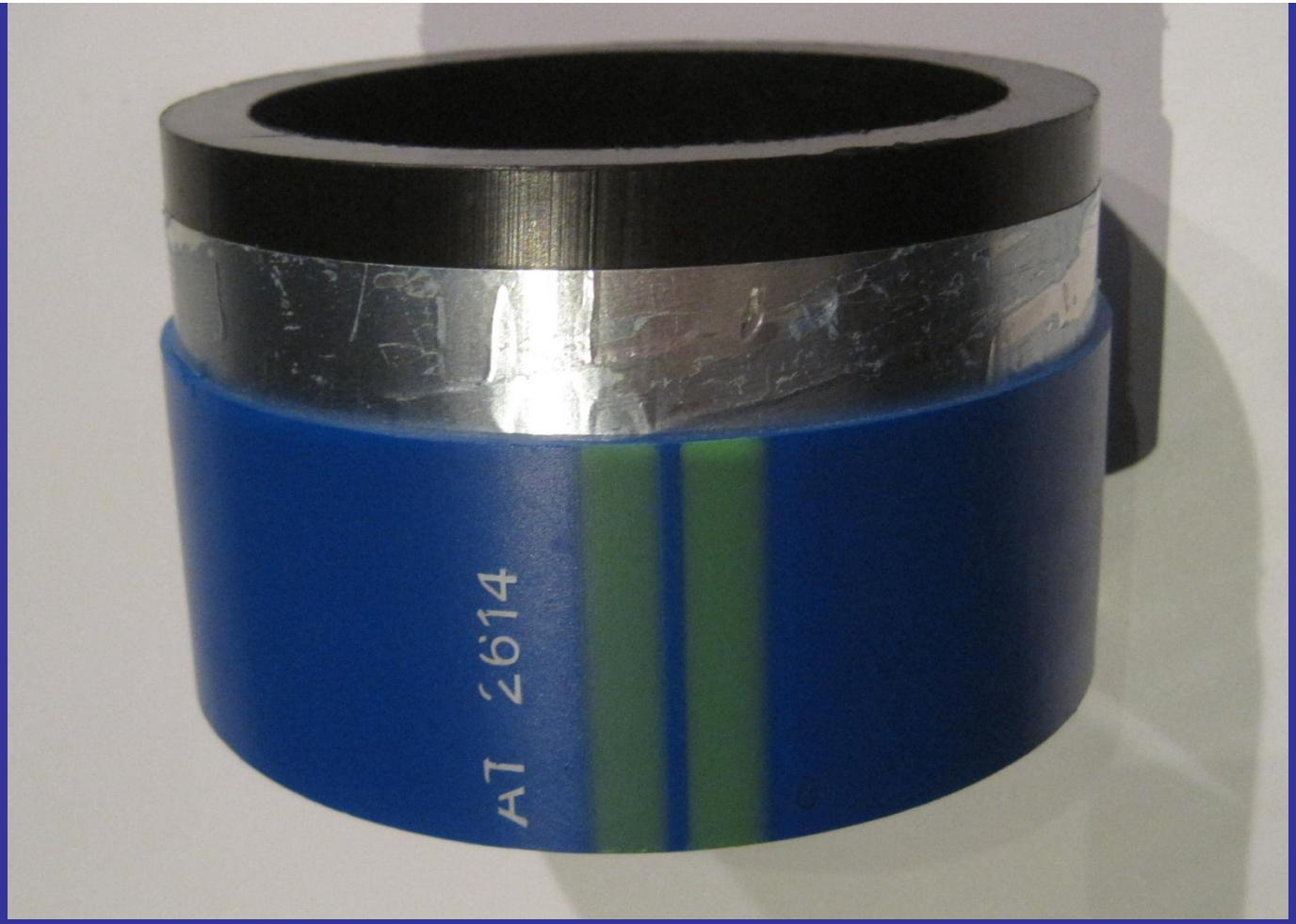
96 miles, 16", Whitewater to Long Beach, CA, former crude oil



PATENT PENDING

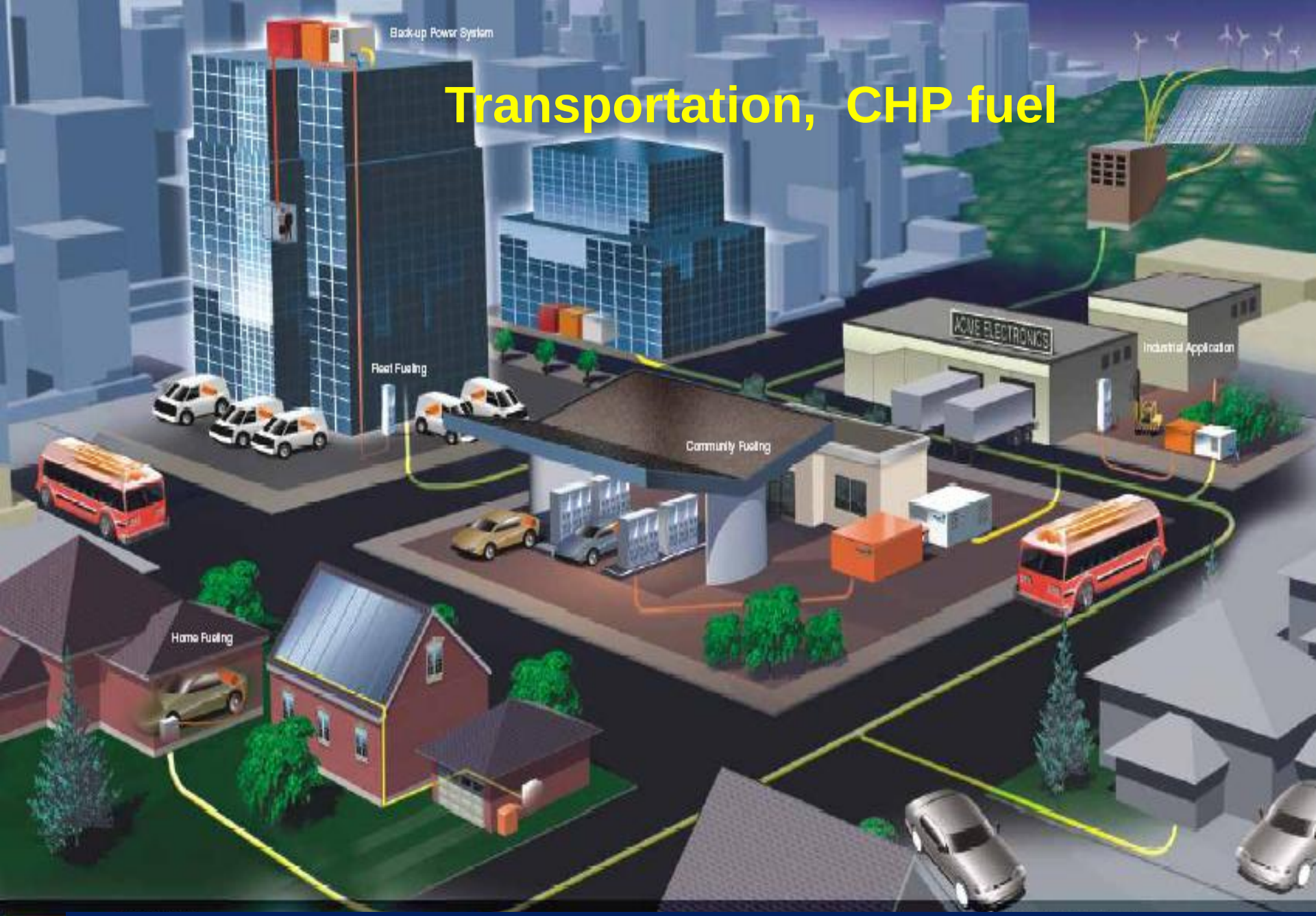
36” = 8 GW gaseous Hydrogen @ 100 bar

Convert Palm Springs to Long Beach Natural Gas Pipeline ?



Smart Pipe Technologies, Houston

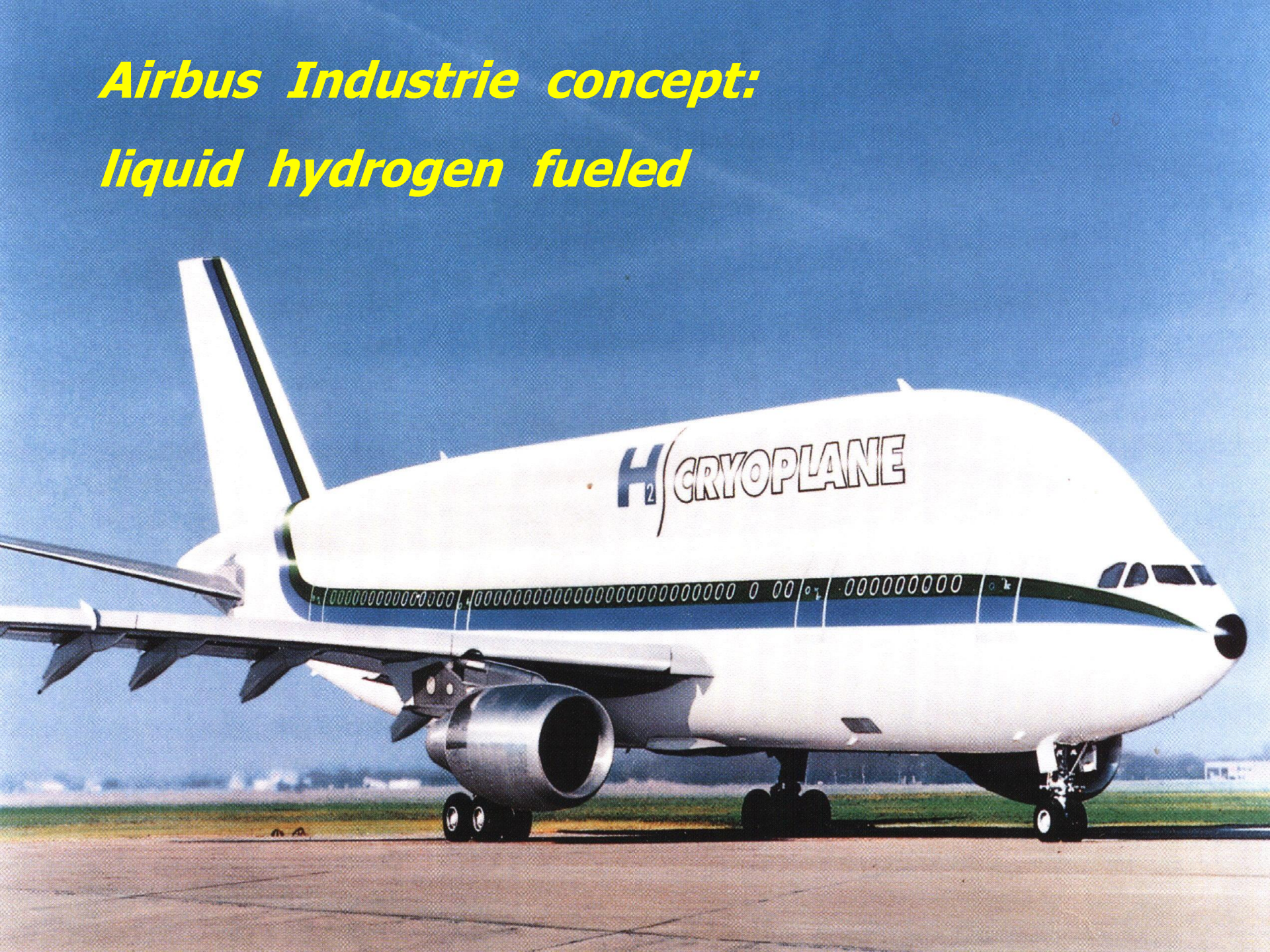
Polymer-metal linepipe avoids hydrogen embrittlement



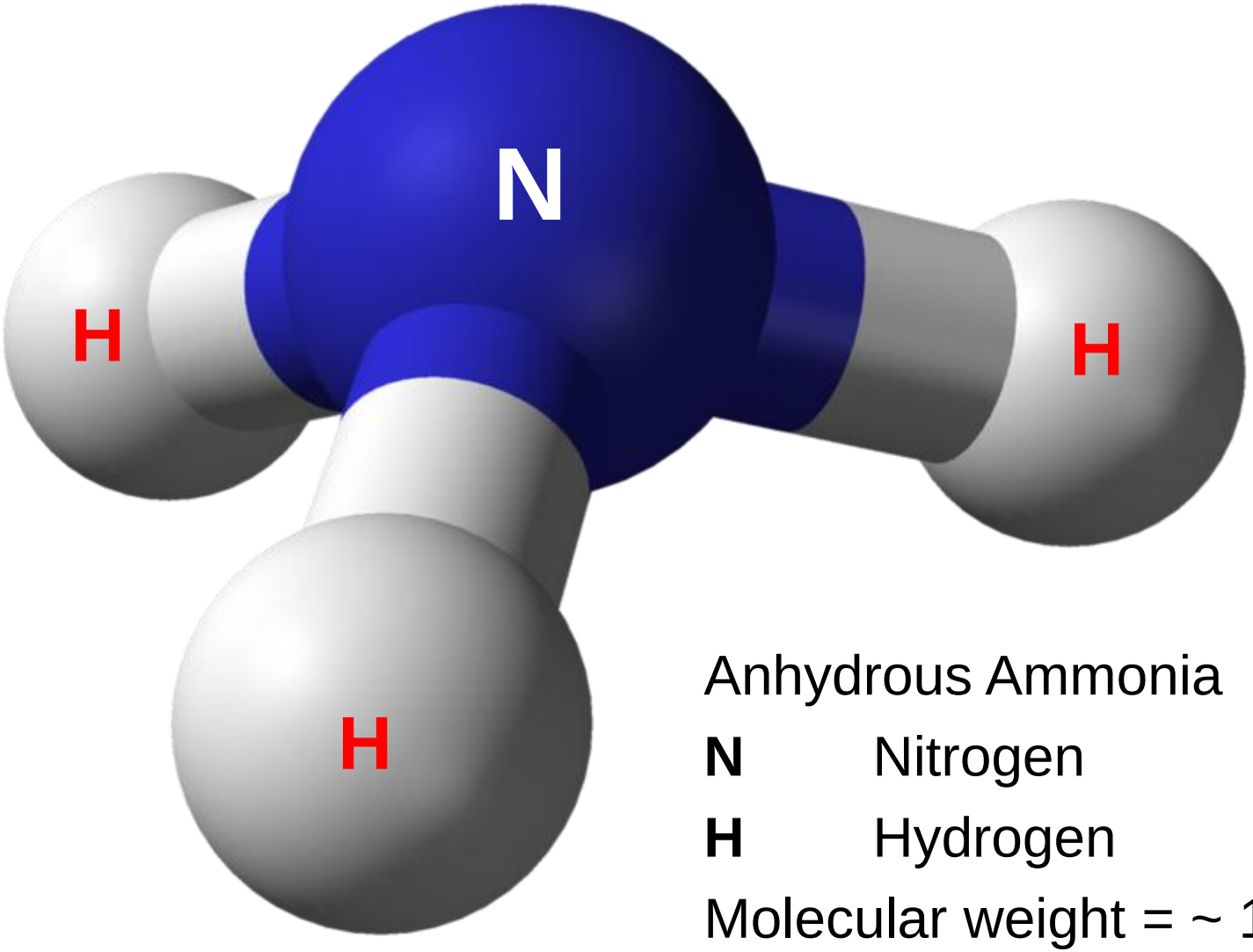
Transportation, CHP fuel

Renewables, Electrochemical energy

Airbus Industrie concept: liquid hydrogen fueled



Energy Systems Integration Facility -- ESIF
NREL, Golden, CO



Anhydrous Ammonia **NH_3**

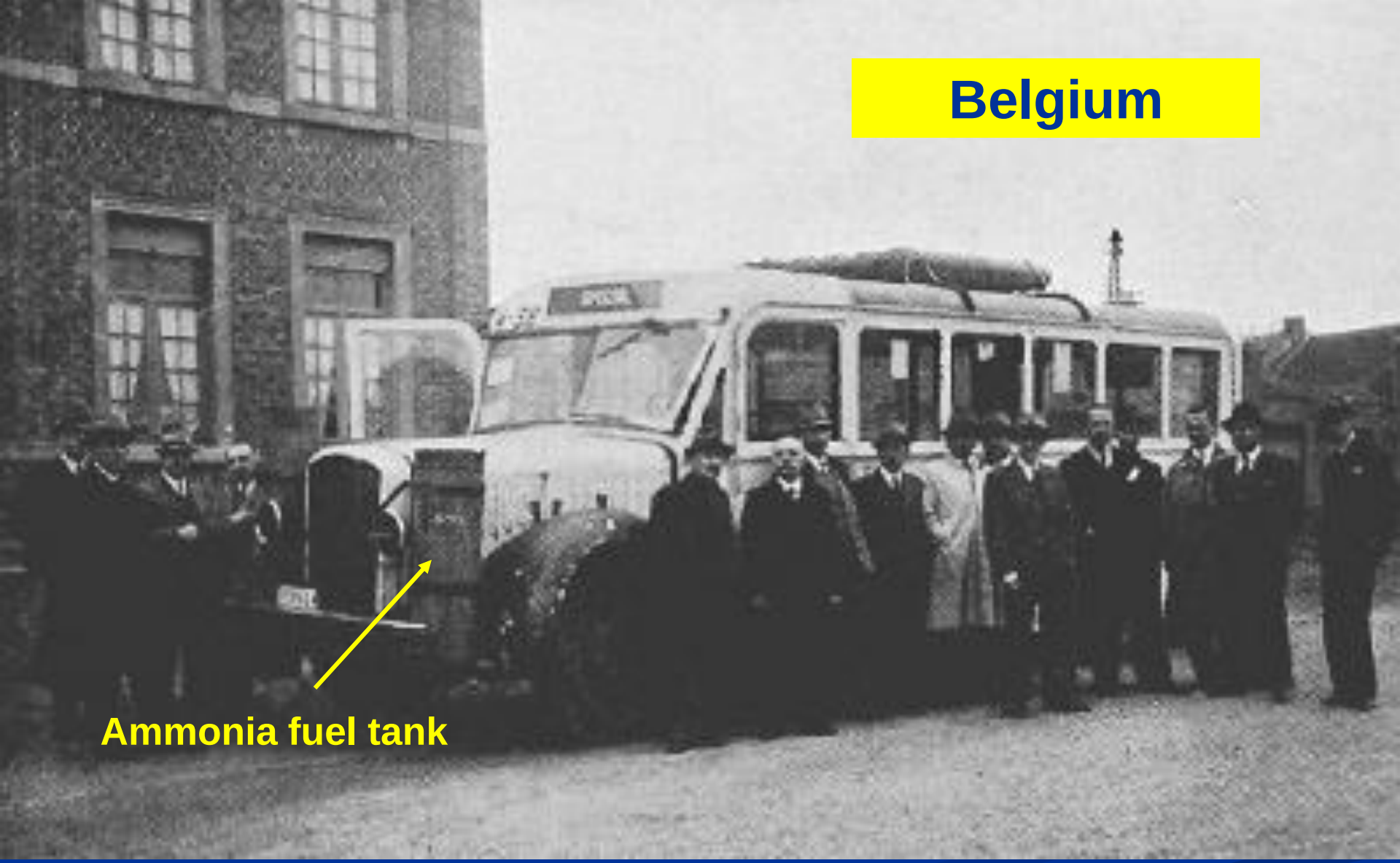
N Nitrogen

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

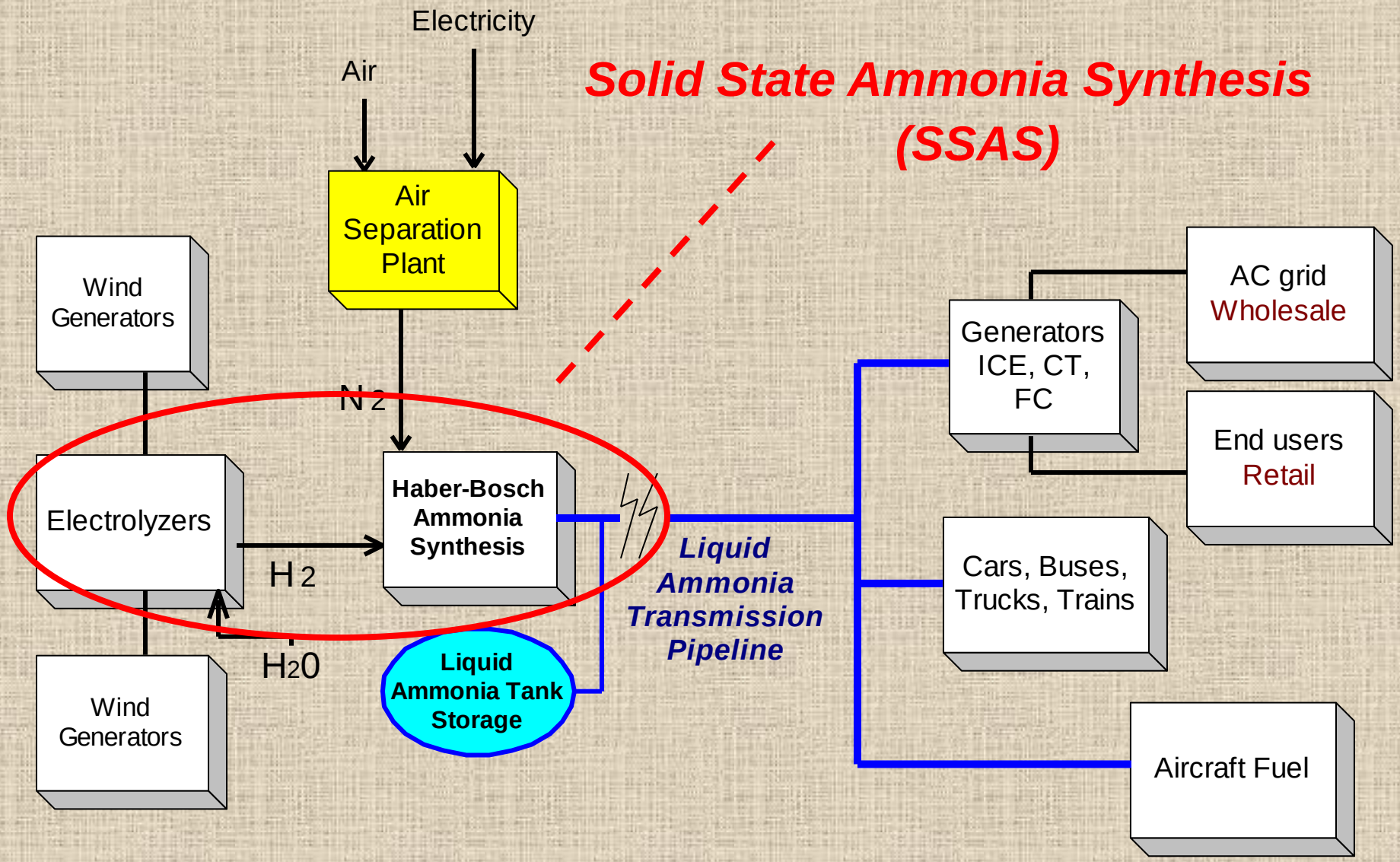
Mach 6.7 on 3 Oct 67

199 missions

1959 - 68

NH_3 Ag Fertilizer Tanks, Wind Generators, NW Iowa

RE Ammonia Transmission + Storage Scenario



’09 ARPA-E “Grids” Goal: $100 / kWh

Total storage = 380 GWh

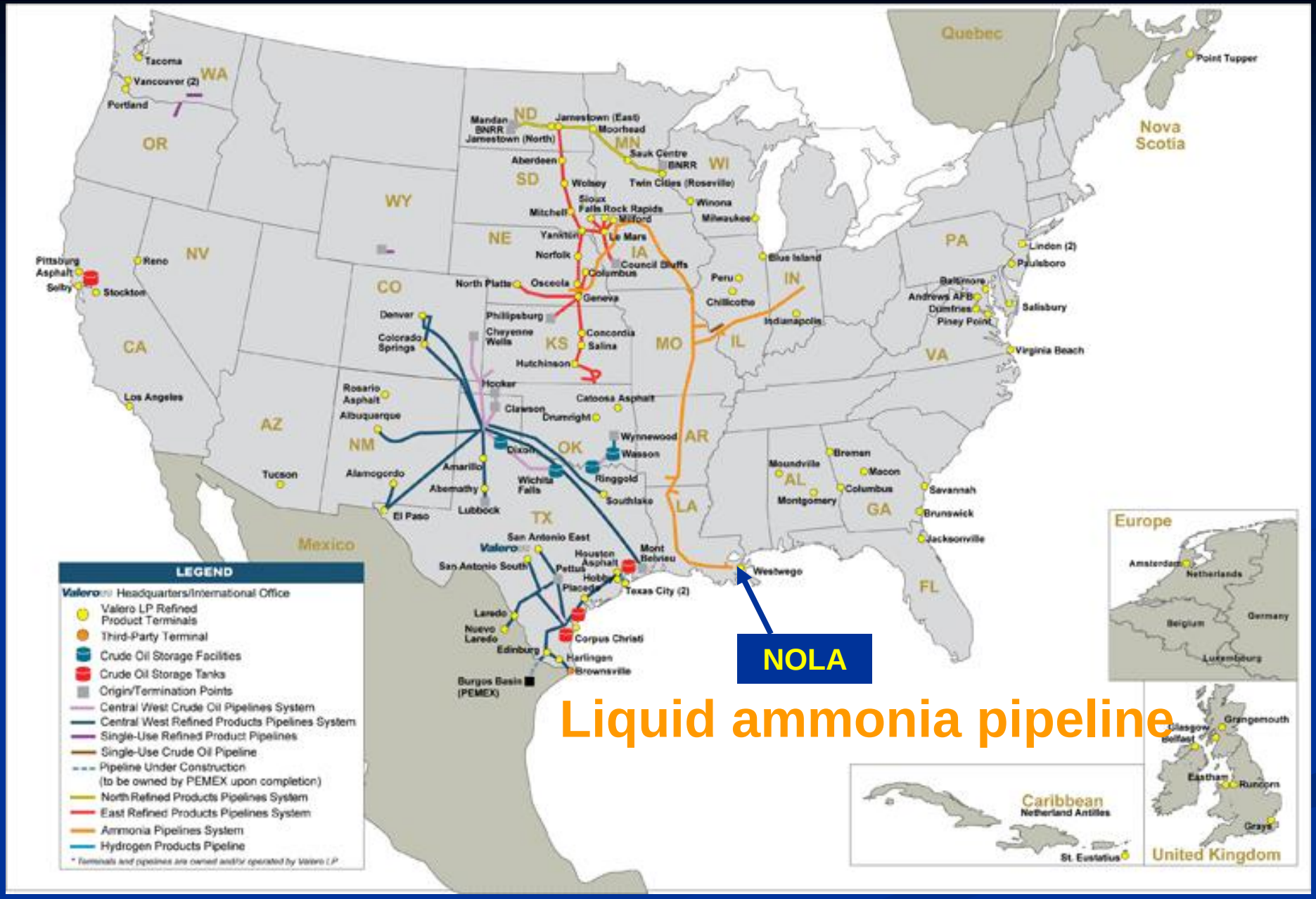
“Atmospheric” Liquid Ammonia Storage Tank (Corn Belt)

-33 C 1 Atm

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

$ 80 / MWh = $ 0.08 / kWh CAPEX

Tesla Gigafactory, Reno, NV
Annual production < 100 GWh
$ 100 / kWh CAPEX ?



Valero LP Operations

Capital Cost per GW-mile

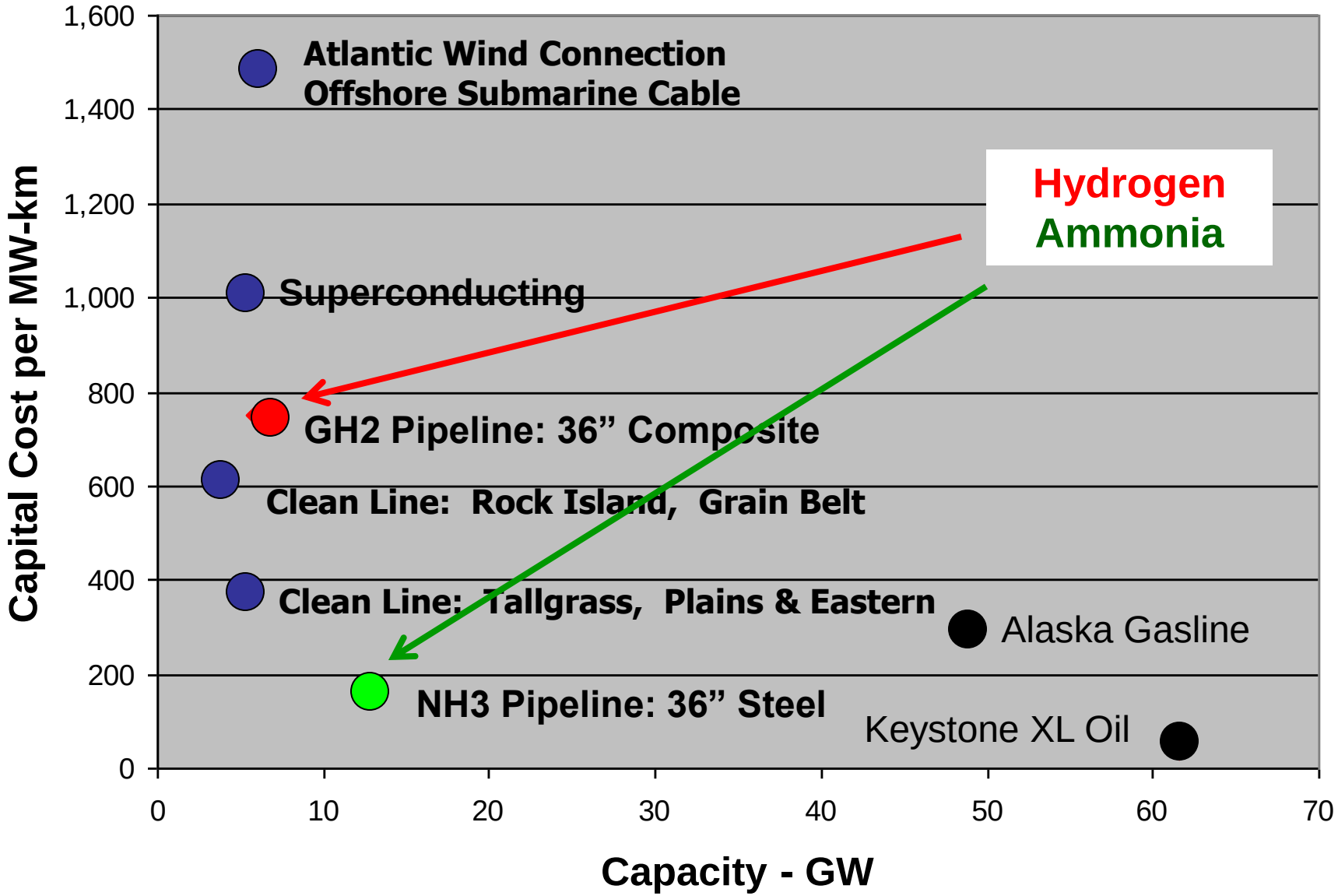
Electricity :	KV	Capacity MW	$M / GW - mile
• SEIA:	765	5,000	1.3
	345	1,000	2.6
• AEP-AWEA	765	5,000	3.2
Consensus ?			2.5

Hydrogen pipeline:

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

Ammonia pipeline:

10” , liquid, 500 miles, with pumping 0.2



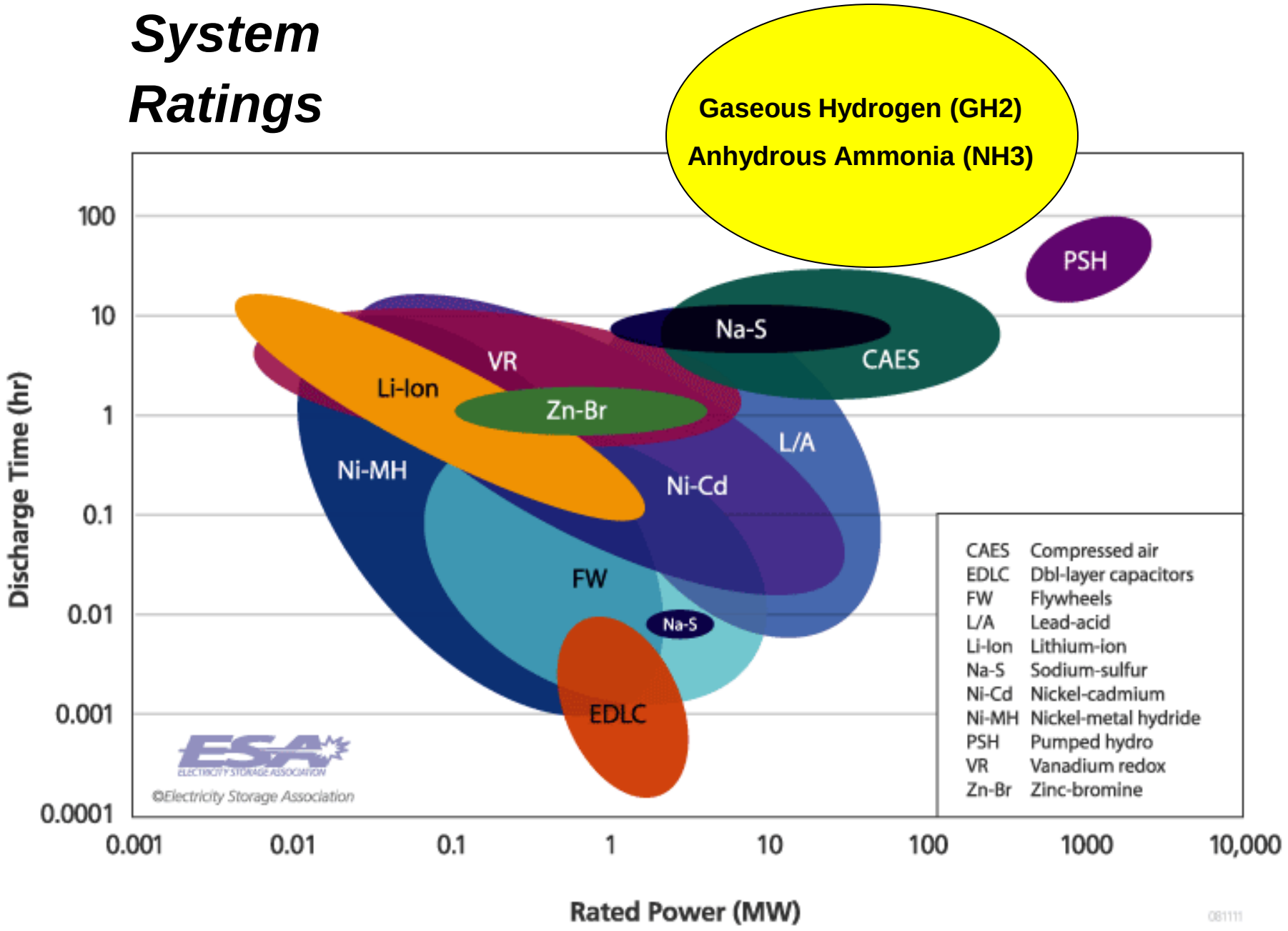
Transmission capital costs per MW-km compared

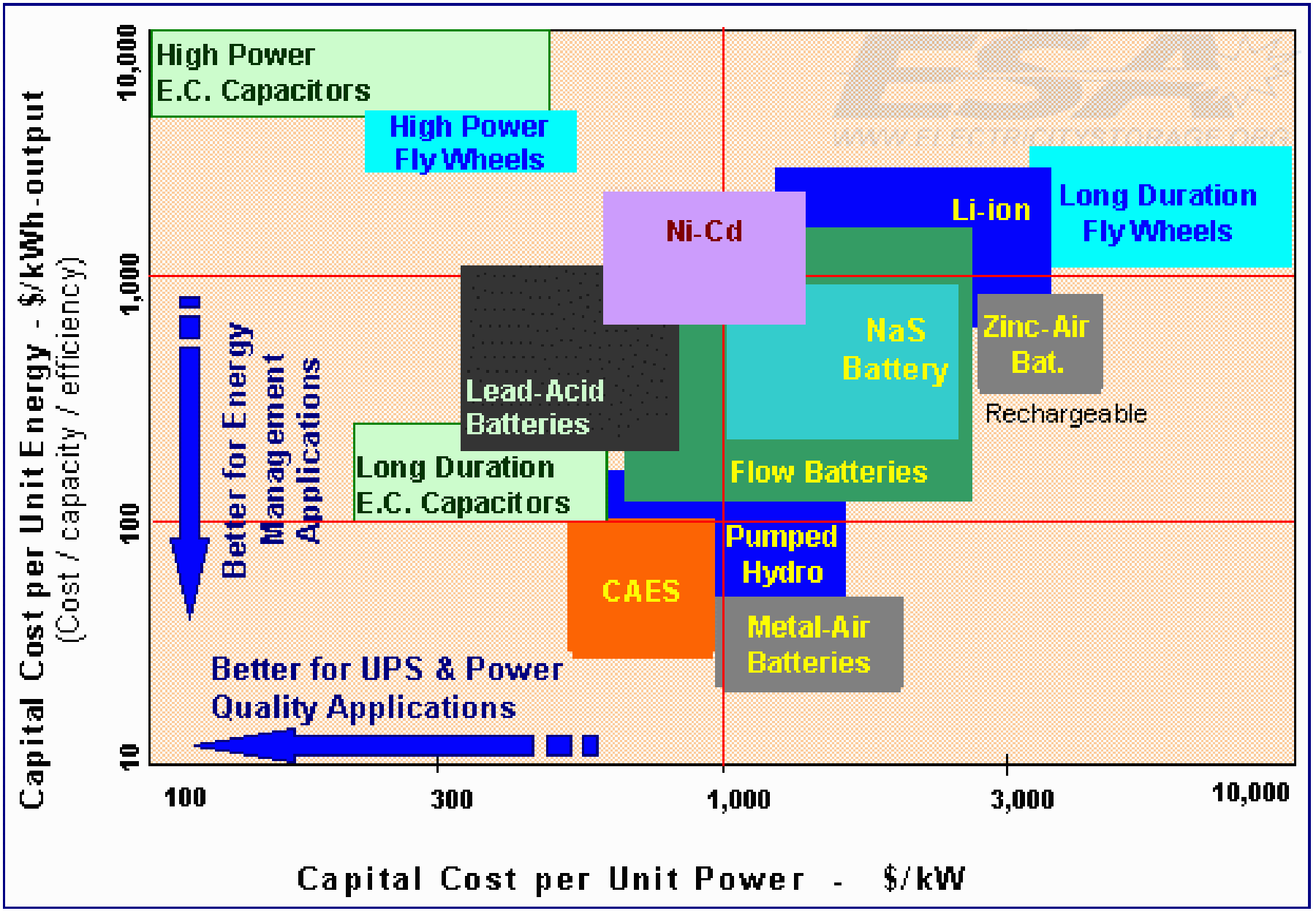
Pipelines have large capacity and provide large storage

320 GWh
Annual firming 1,000 MW Great Plains wind

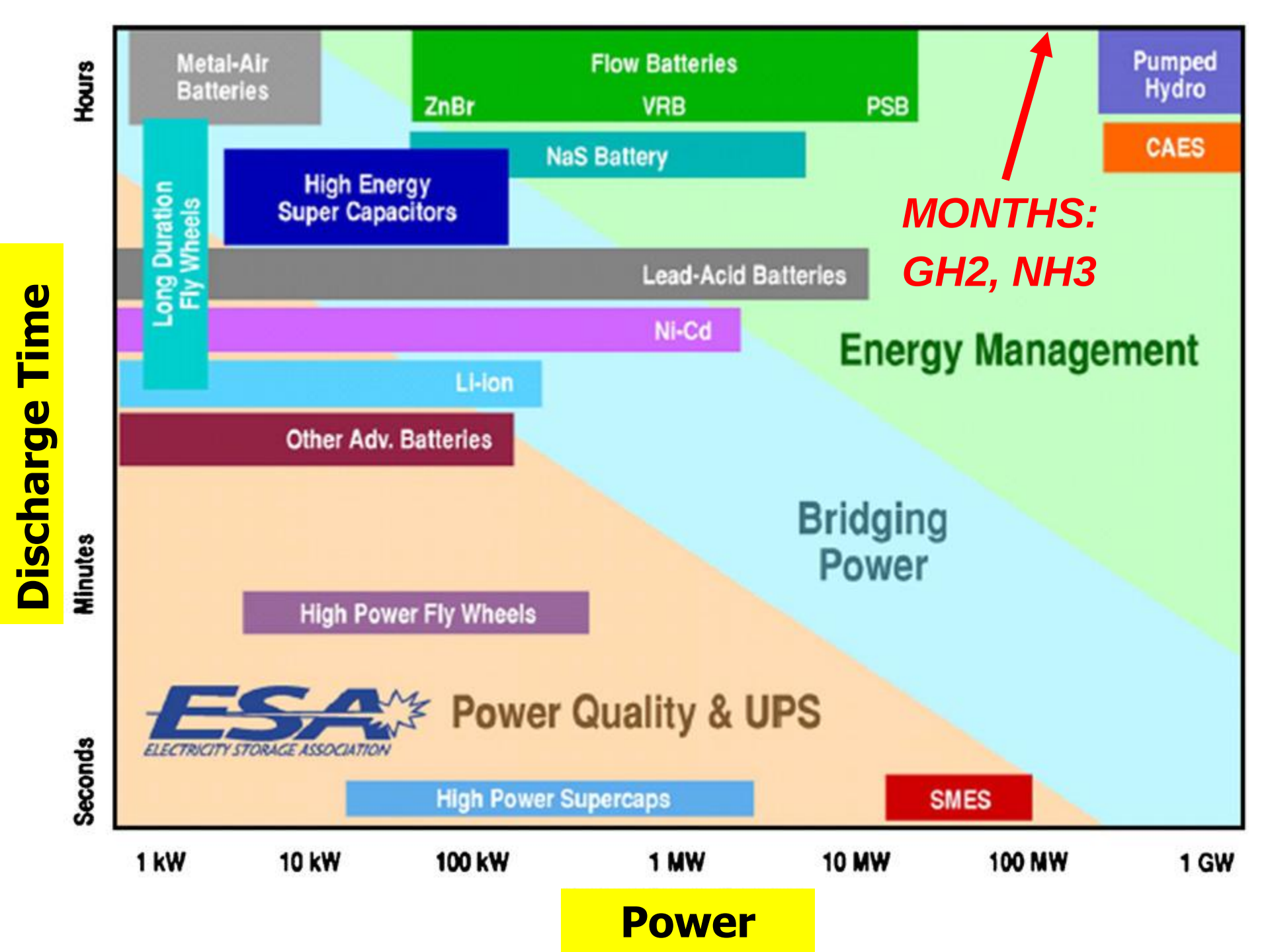
- **CAES (compressed air energy storage)**
  - **O&M: $46 / MWh typical**
  - **Iowa: Power = 268 MW**
    Energy capacity = 5,360 MWh
    Capital: 268 MW @$800 / kW = $214 M
    Storage @ $40 / kWh = $ 13 Billion
    Storage @ $1 / kWh = $ 325 Million
- **Battery**
  - **O&M: 90% efficiency round-trip**
  - **Capital: $ 500 / kWh = $ 160 Billion**
  - **Capital: $ 100 / kWh = $ 32 Billion**
- **GH2 (3 hydrogen caverns) Capital $70 Million**
- **NH3 (2 ammonia tanks) Capital $30 Million**

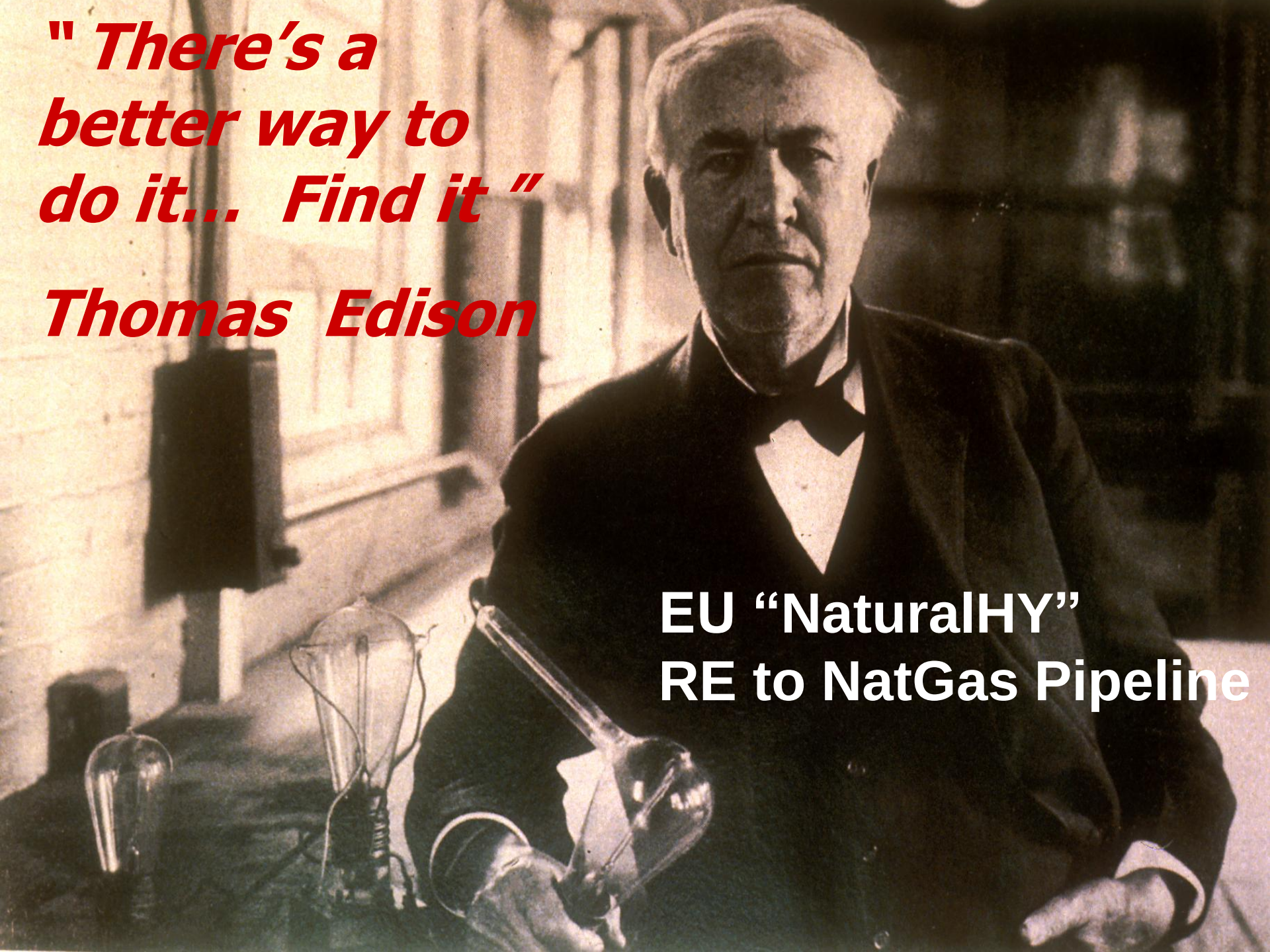
System Ratings



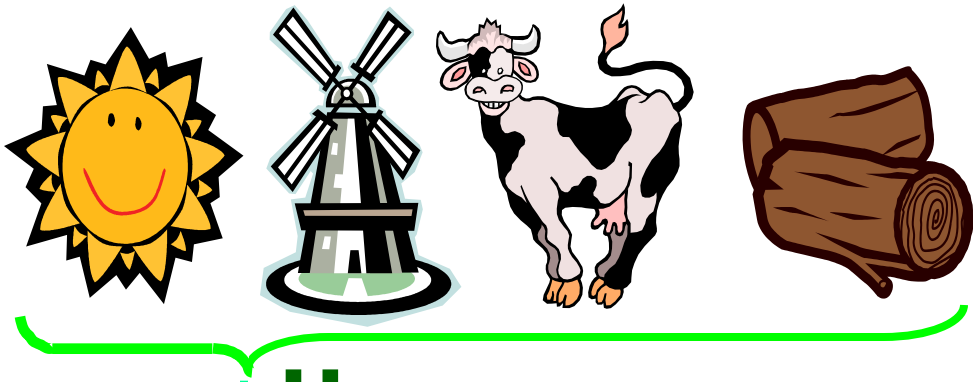

Capital Cost per Unit Energy - $/kWh-output
(Cost / capacity / efficiency)
10,000
1,000
100
10
High Power
E.C. Capacitors
High Power
Fly Wheels
Ni-Cd
Li-ion
Long Duration
Fly Wheels
NaS
Battery
Zinc-Air
Bat.
Rechargeable
Lead-Acid
Batteries
Long Duration
E.C. Capacitors
Flow Batteries
Pumped
Hydro
CAES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

GH2 and NH3


Discharge Time
Hours
Minutes
Seconds
Metal-Air Batteries
Flow Batteries
ZnBr
VRB
PSB
Pumped Hydro
CAES
NaS Battery
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


" There's a better way to do it... Find it "
Thomas Edison
EU "NaturalHY"
RE to NatGas Pipeline

2006: The NATURALHY approach: EC, R+D



" Power – to – Gas "

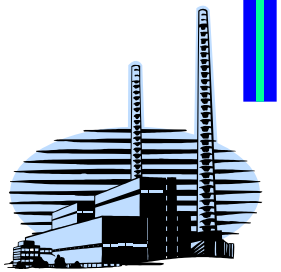
H_2

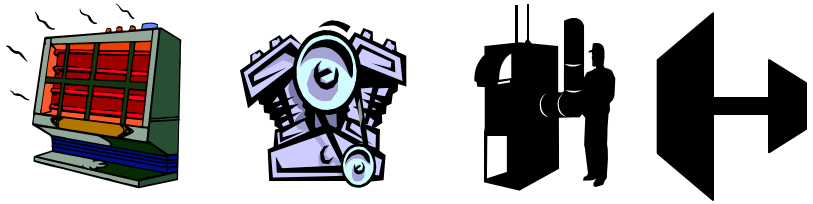
NG

Pure H_2

NATURALHY:

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

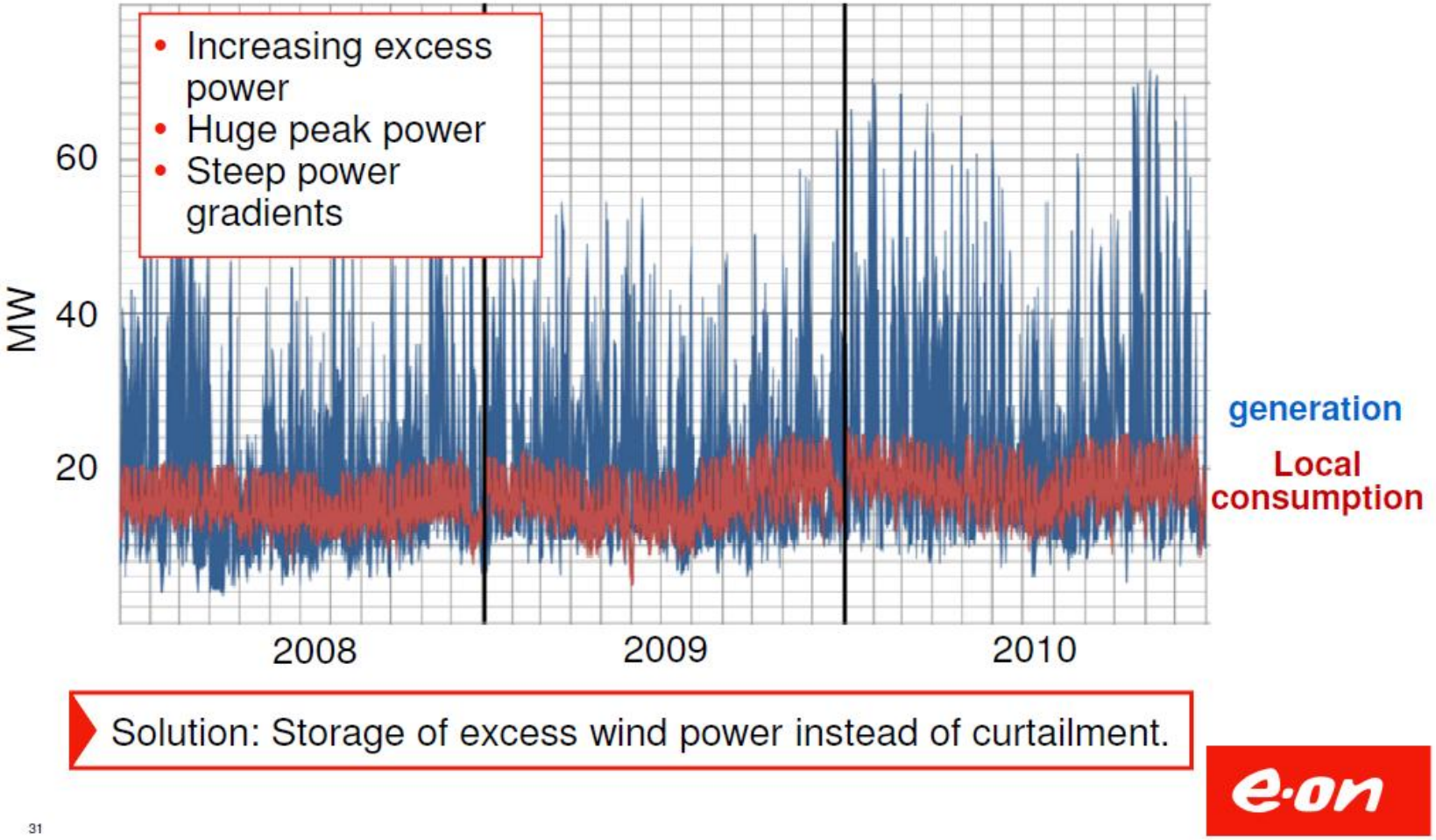




Prepared by
O. Florisson
Gasunie

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

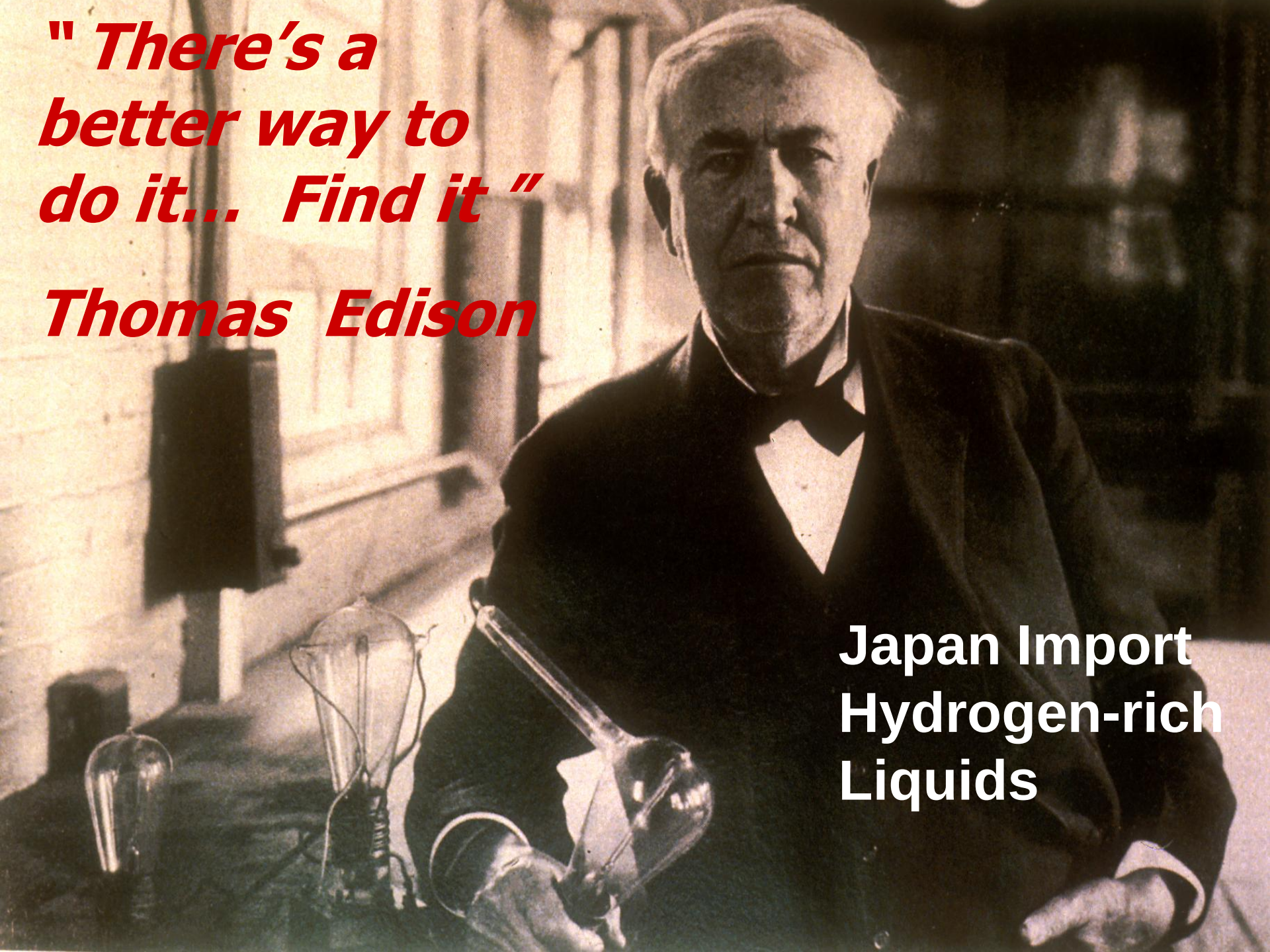
Falkenhagen Region in Northern Germany



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

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

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


" There's a better way to do it... Find it "
Thomas Edison
Japan Import Hydrogen-rich Liquids

Aleutians wind to Japan via liquid fuel(s) tankers

Alternatives to Electricity:
Japan to import Hydrogen-rich liquid fuels

1. Liquid Hydrogen (LH2)

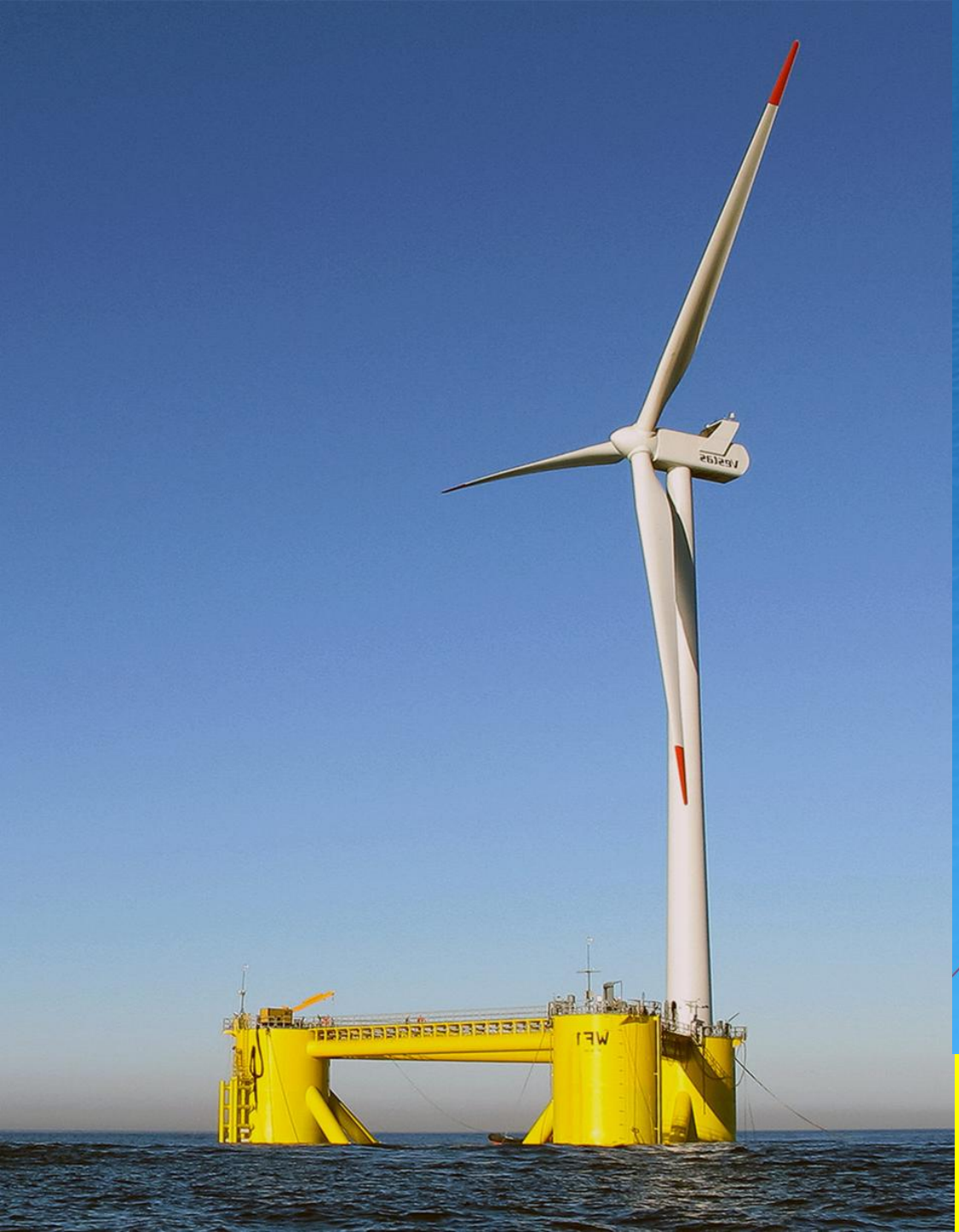
   Kawasaki

2. Liquid anhydrous ammonia (NH3)

   Sumitomo

3. Cycle: Toluene (C7H8) ← →
   Methylcyclohexane (C7H14) (MCH)

   Chiyoda



Floating Offshore
Deep water, multi - MW

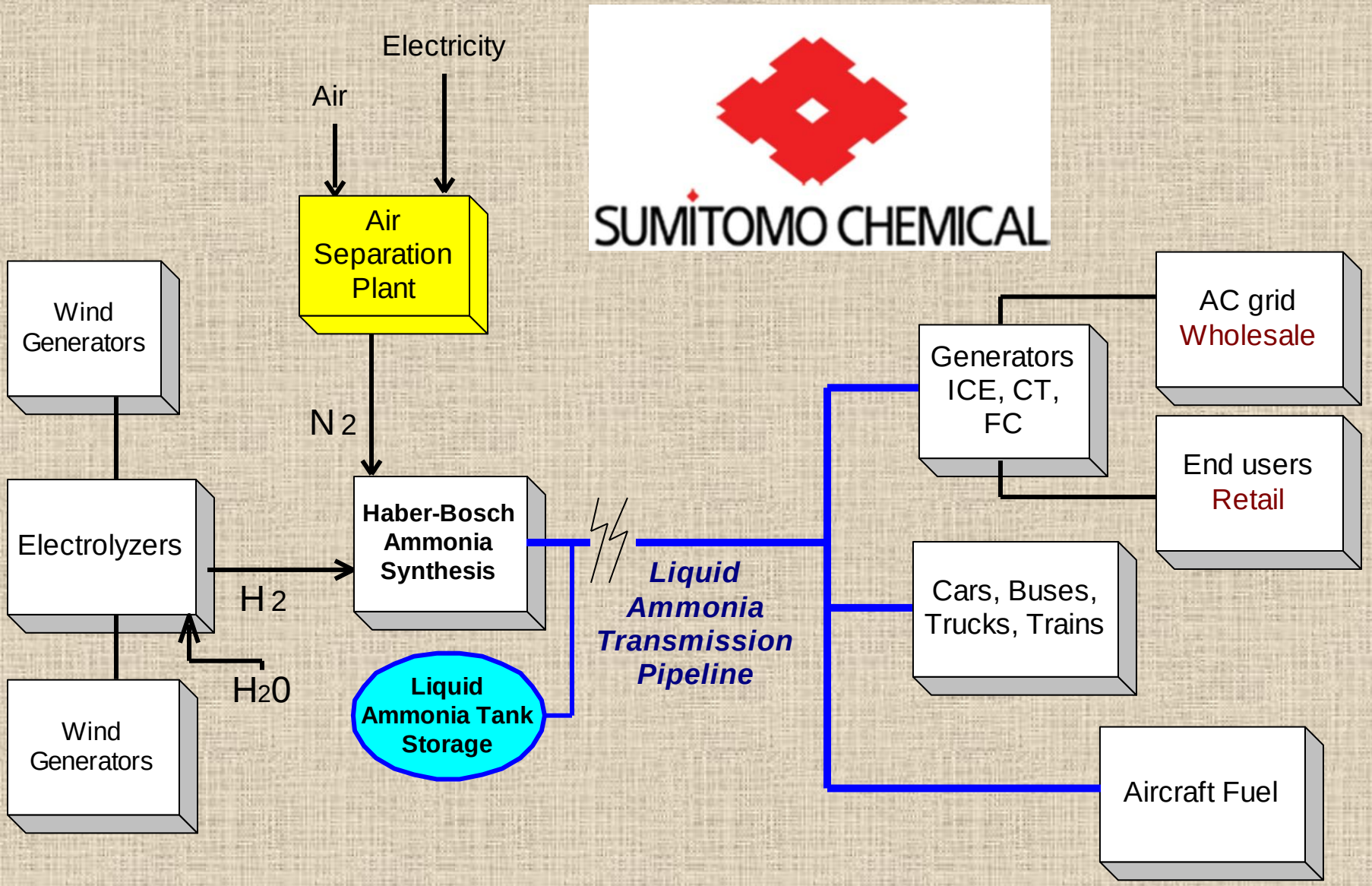
Japan: Import Carbon-emissions-free liquid Hydrogen fuel

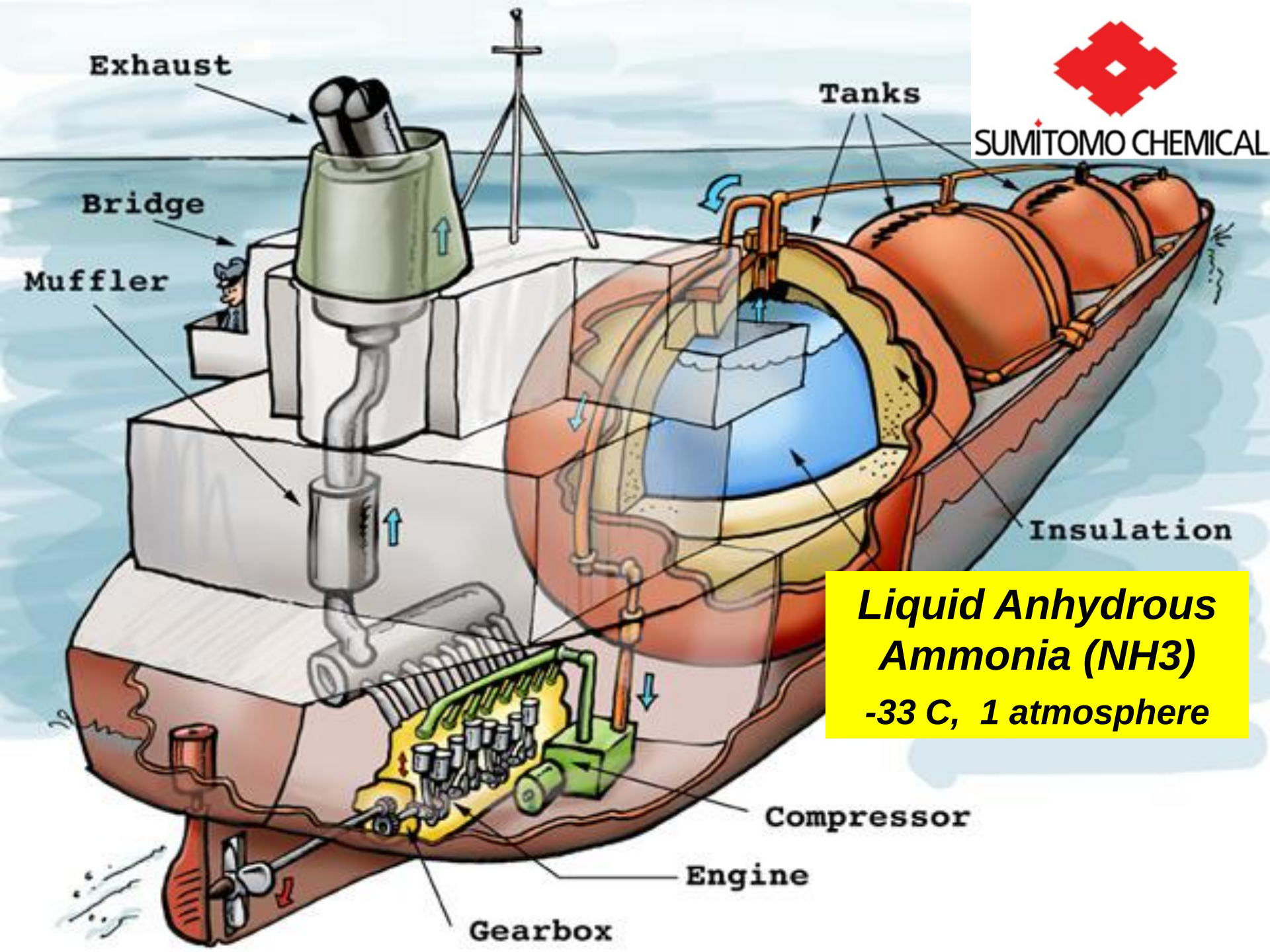
Kawasaki LH2 ocean tanker, truck

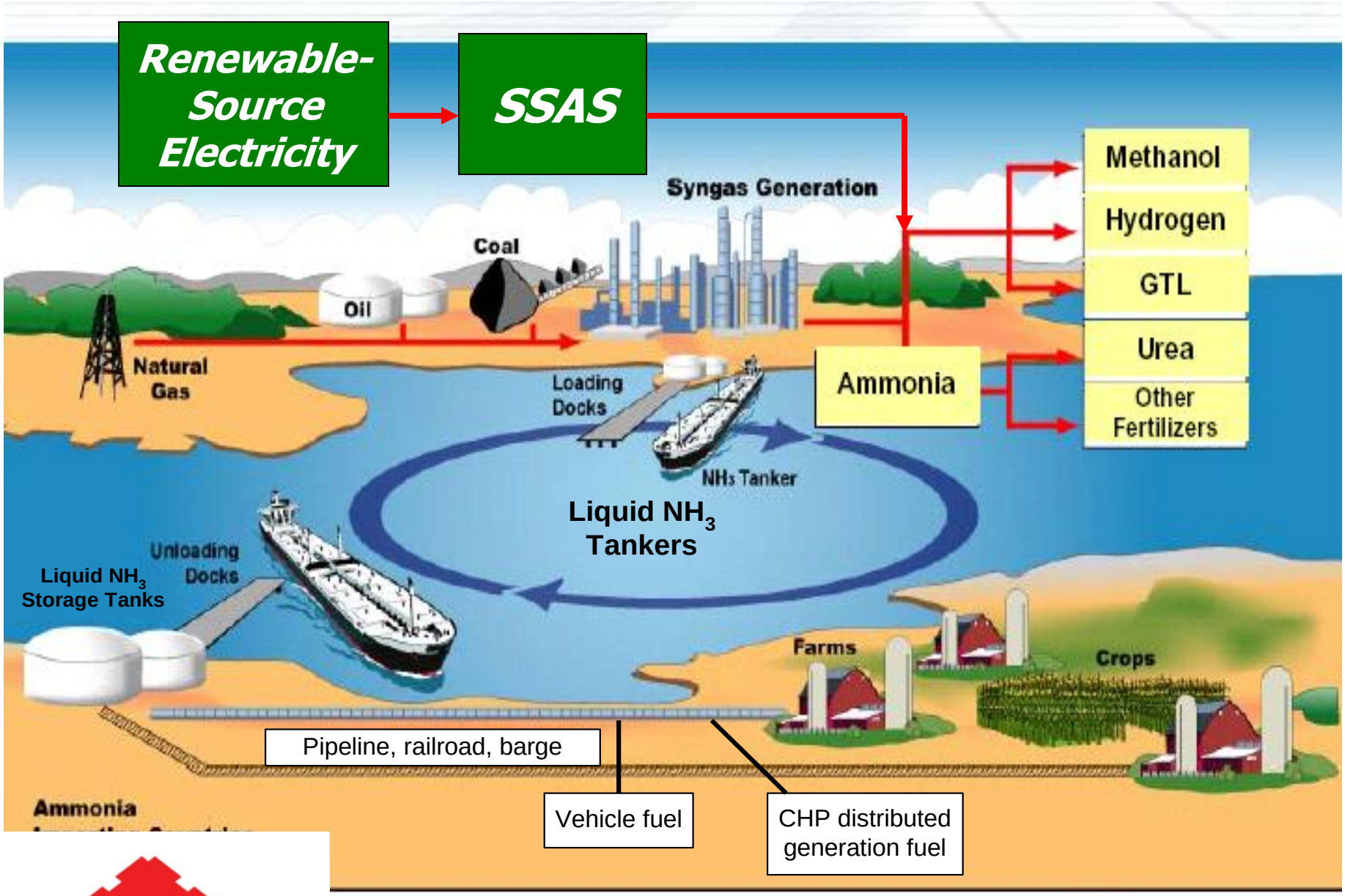
World Smart Energy Week

Tokyo, 26 Feb 14

RE Ammonia Transmission + Storage Scenario




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



SUMITOMO CHEMICAL

KBR
Energy and Chemicals

Japan
Chiyoda Chemical

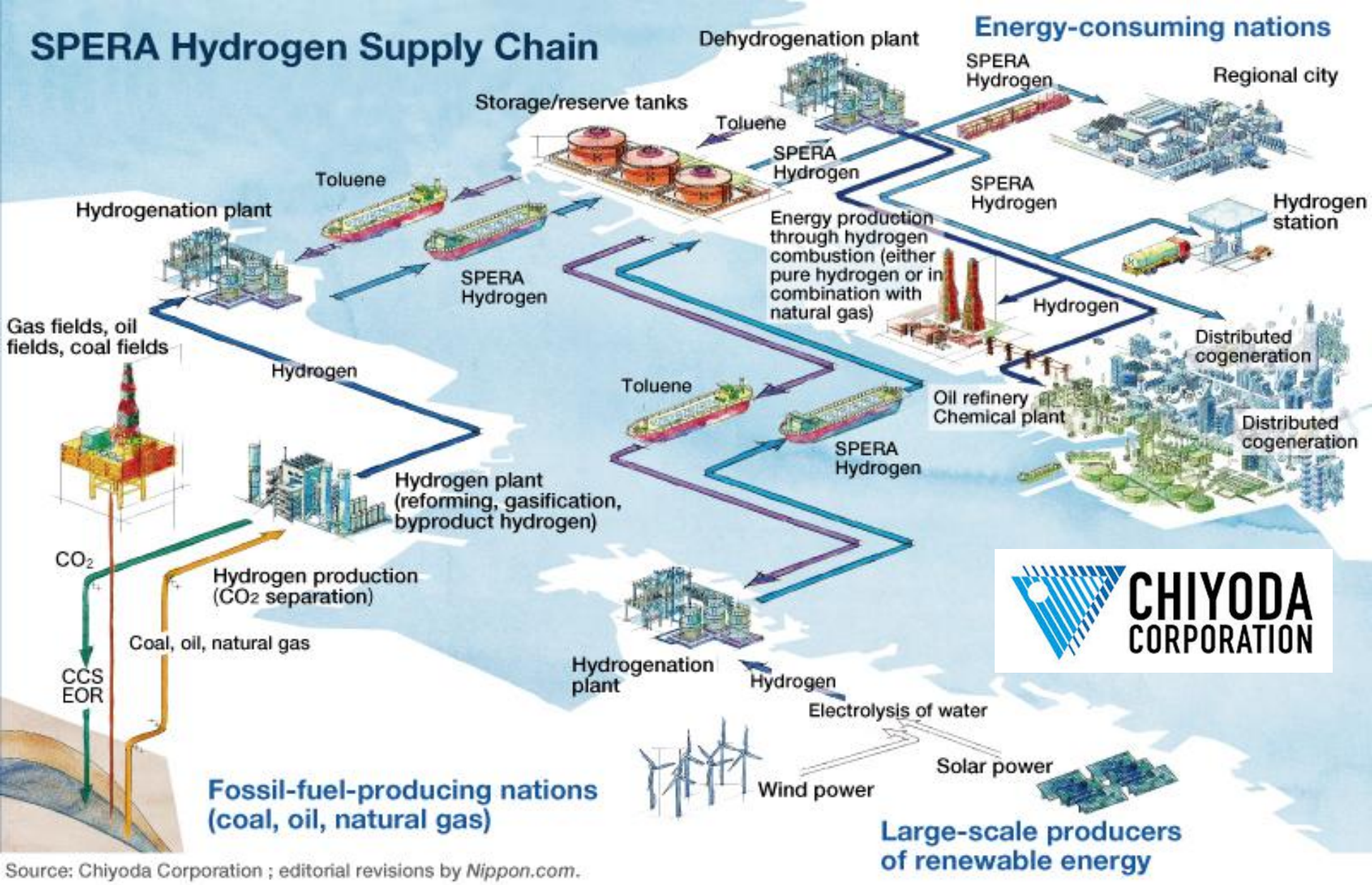
CHIYODA CORPORATION

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

"Spera": Latin for "hope"

Spera Hydrogen

Chiyoda Chemical



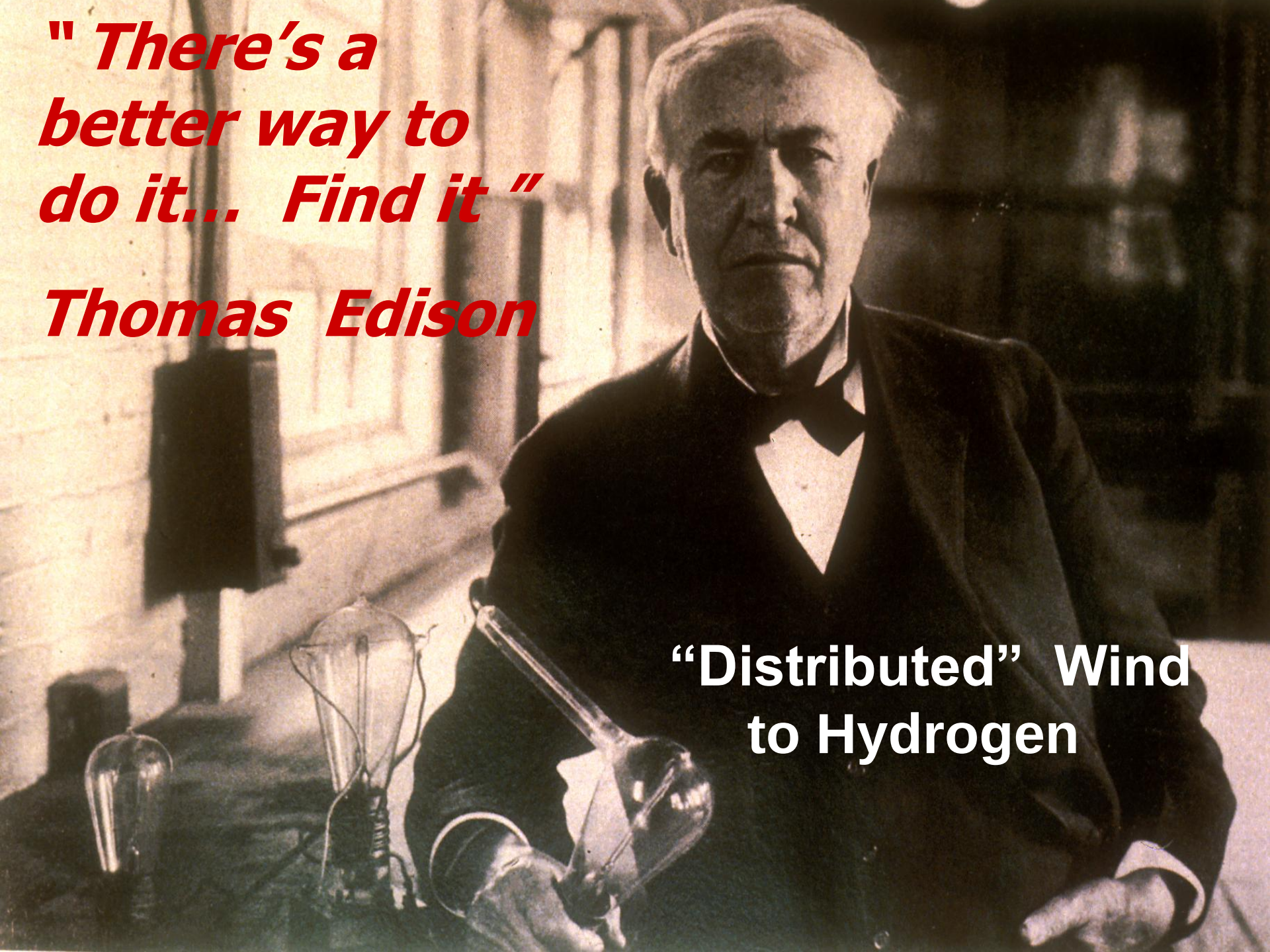
Source: Chiyoda Corporation ; editorial revisions by *Nippon.com*.

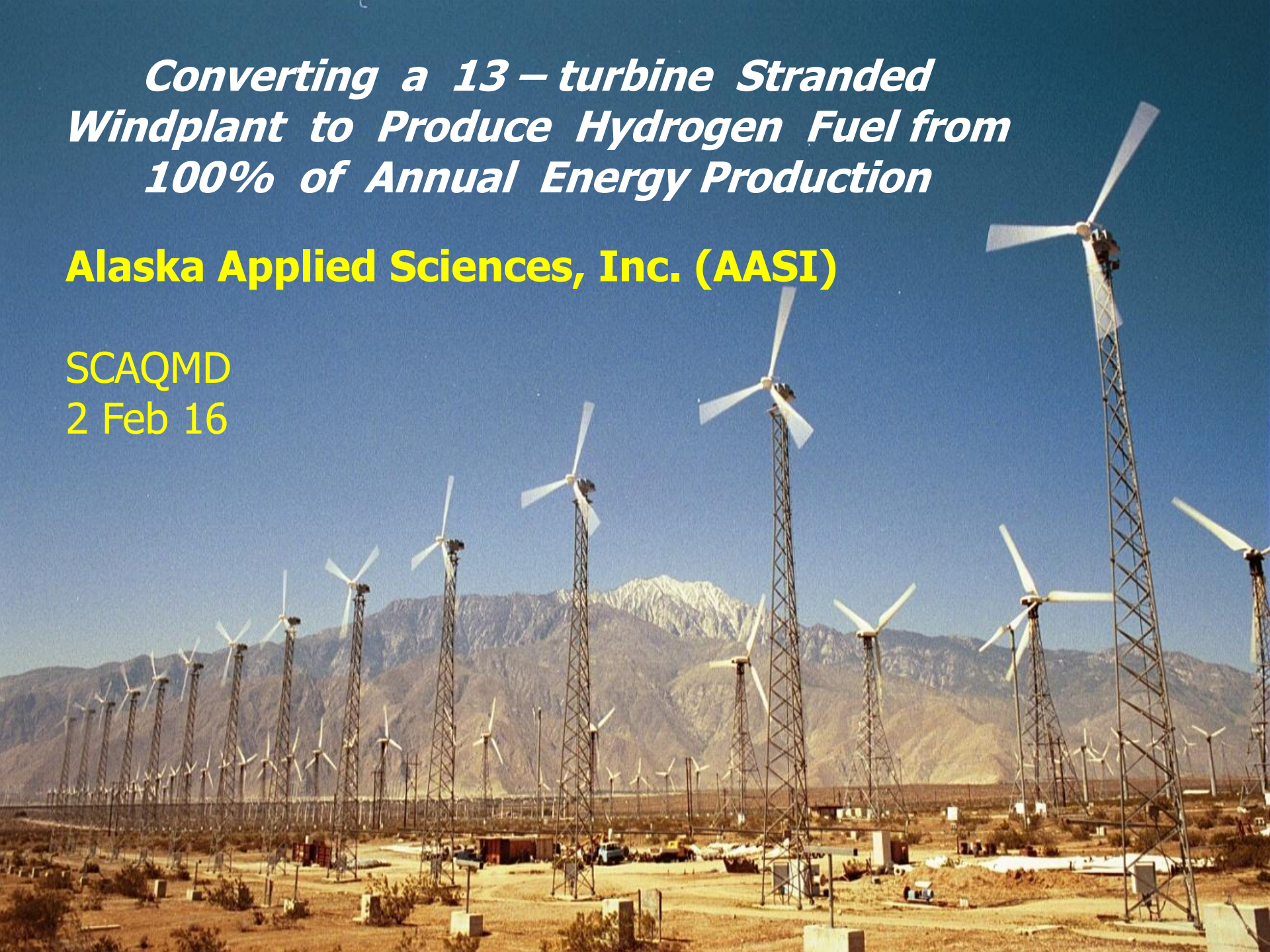
Chiyoda Chemical and Heavy Industry
Organic hydride import cycle:
Toluene (C_7H_8) ←→ Methylcyclohexane (C_7H_{14})

Global Total Energy System

Energy Systems Integration Facility -- ESIF

NREL, Golden, CO

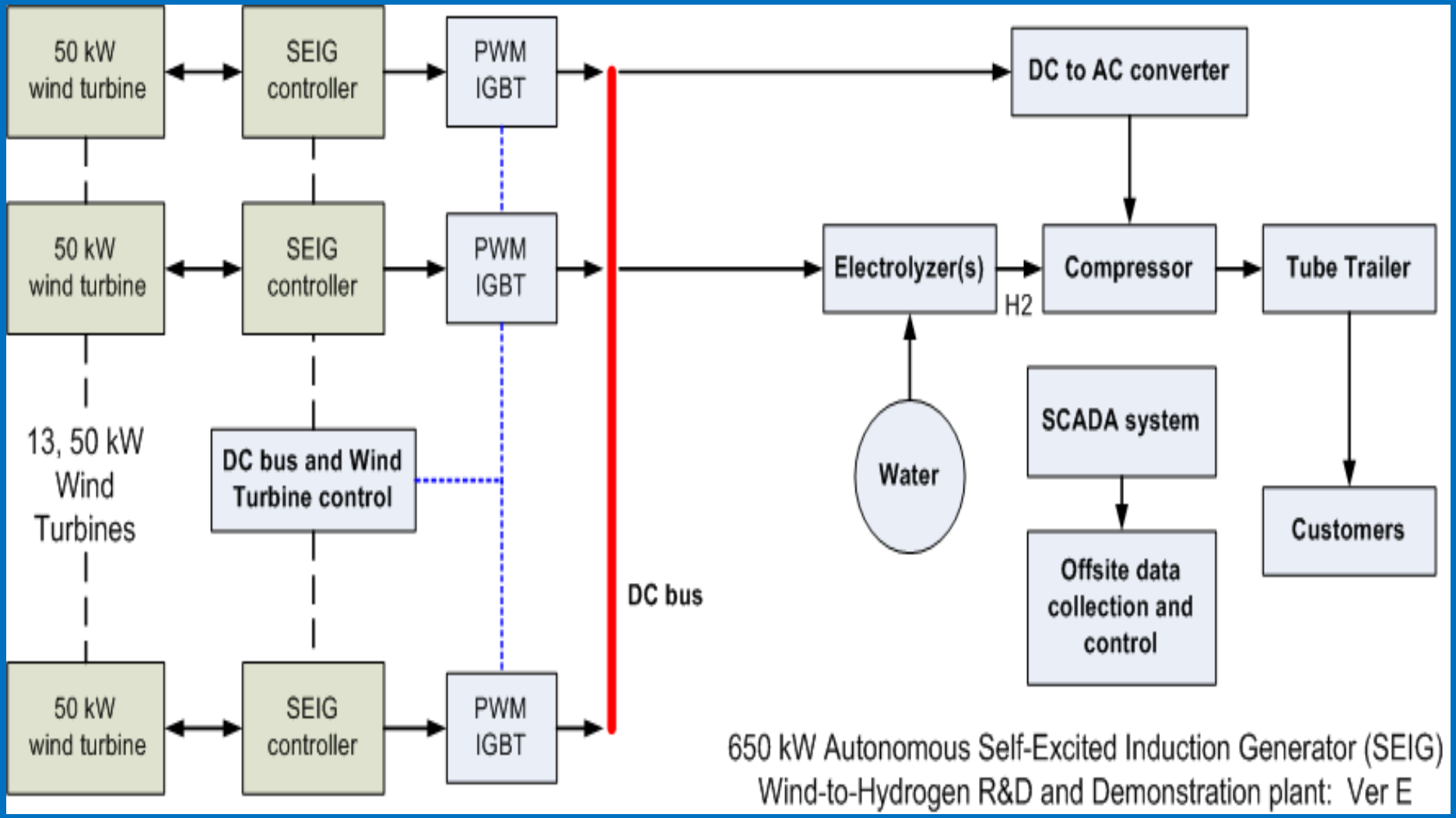

" There's a better way to do it... Find it "
Thomas Edison
"Distributed" Wind to Hydrogen



Converting a 13 – turbine Stranded Windplant to Produce Hydrogen Fuel from 100% of Annual Energy Production

Alaska Applied Sciences, Inc. (AASI)

SCAQMD
2 Feb 16



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

Palm Springs windplant, Alaska Applied Sciences, Inc.

1. **R&D & Demo project: 13 turbines, 50 kW**
2. **Novel generating system: induction motors**
3. **Close-coupled to electrolysis stacks**
4. **All harvested energy delivered as H2 fuel**
5. **No connection to SCE grid**

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

but only after they have tried everything else ”

Winston Churchill

Conclusions
Future "Energy" Utility
Electricity + Fuel

- **Far more ambitious: H_2, NH_3, renewables**
- **"Energy" = Electricity + Hydrogen, Ammonia**
- **H_2 fuel bigger market than electricity grid**
- **H_2 pipeline pilot plant demo: begin now**
- **Wind-to-H_2, Solar-to-H_2 fuel demos now:**
  - **Plants**
  - **Pipeline pilot plants**
- **New business models**

Utility of the Future

- **Utilities threatened**
  - **Electricity: SCE**
  - **Electricity + gas: PG&E, SDG&E, Xcel**
  - **“Energy” -- Electricity + transport fuel ?**
  - **“Energy” -- Electricity + Hydrogen ?**
- **Hydrogen Renaissance ?**
  - **CEC, 30 Jan “Renewable Hydrogen”**
  - **CEC + CARB: 20 Hydrogen Fuel Station**
  - **Davos, 17 Jan “Hydrogen Alliance”**
  - **USDOE: “H2@SCALE”**
  - **ARPA-E “REFUEL” FOA: Ammonia fuel**
  - **Shell: Hydrogen Business Develop Mgr.**
  - **Siemens: Renewables Hydrogen, Steel, Austria**
  - **Breakthrough Energy, Gates Fdn: Ammonia**

Responsibility + Opportunity

- **Transform world's largest industry**
  ~ 80% fossil → ~ 100% renewable, CO2-emission-free sources
- **Deep decarbonization**
- **All energy, all purposes, sources, global**
- **Quickly, prudently, profitably**
- **Far more ambitious**
- **Complete renewable systems**
- **Beyond electricity**
- **Profitable: Industry leads, capital flows**

Responsibility + Opportunity

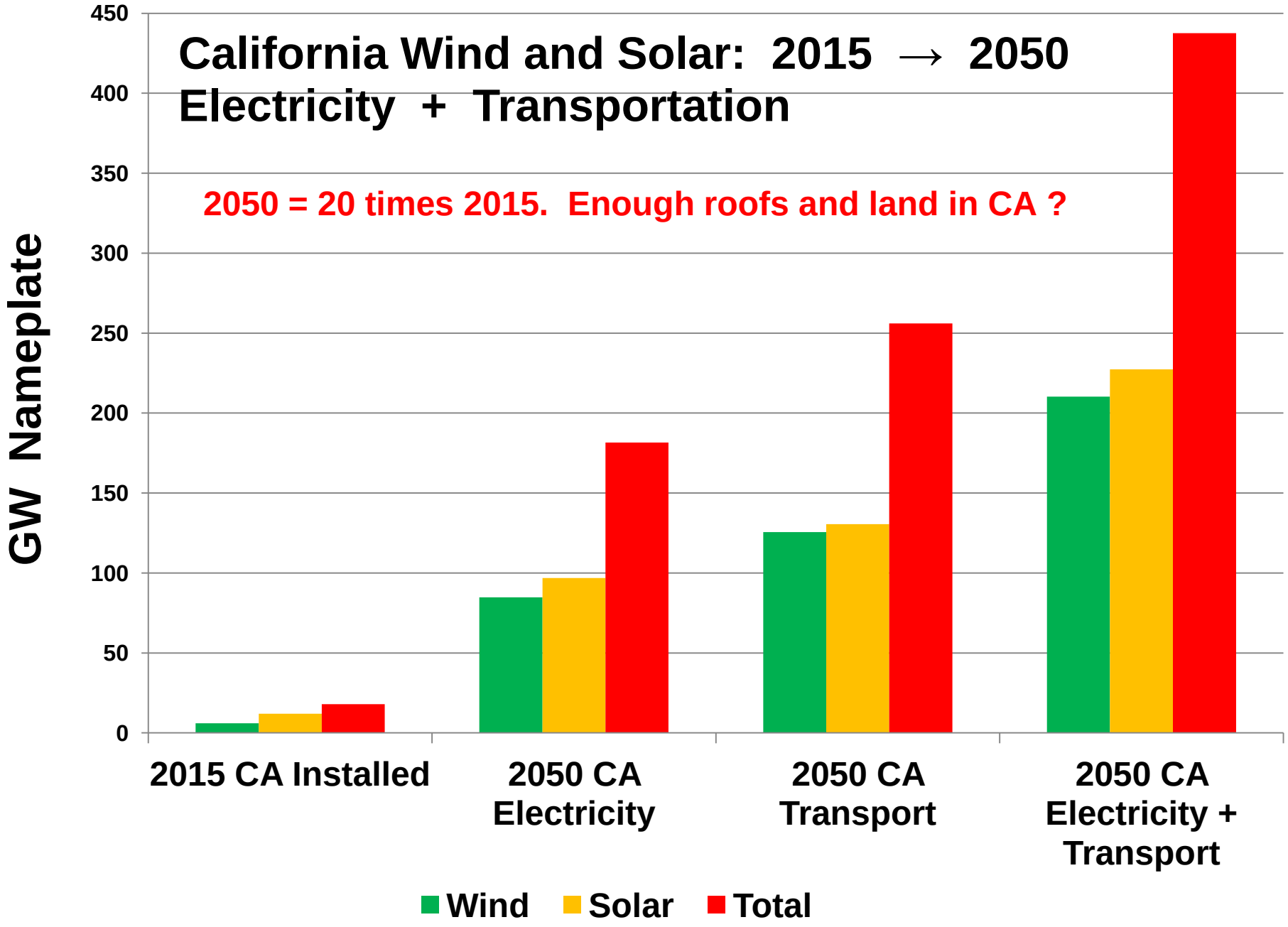
- **All with electricity ?**
  - **Smarter, bigger Grid ?**
  - **Suboptimal ?**
  - **Alternatives ?**
  - **Hydrogen, Ammonia C-free fuels ?**
- **California example**
  - **RPS + “80 in 50” transportation**
  - **Fifth largest economy**
  - **UC Davis ITS - STEPS**

Far more ambitious:

- Beyond electricity systems
- Renewables industry
- Hydrogen industry
- Transportation + CHP fuels
- Run the World on Renewables
- ~ 100 % CO2-emission-free energy

Alternatives to Electricity Systems

- Complete Renewables-source Energy systems
- Integrated, Synergistic, Optimized
  - Gathering + transmission
  - Annual-scale firming storage
  - Integration, delivery, end-use
- Hydrogen: Energy carrier, storage medium
- "The other Hydrogen" -- Ammonia


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

Bigger Market than Electricity Grid ?
CO2-emission-free Hydrogen and Ammonia Fuels

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