Bigger Market for Renewables than the Electricity Grid: Carbon-Free Hydrogen Fuel for Transportation and CHP

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9B - Novel Non-Electric Energy Storage Technologies
Energy Storage II
Wednesday, December 6, 2017
0930 - 1130
REV 10 Jan 2022
Session Chair: Jeff Myles, Surrette Battery Co.
902-597-4012 Email: jeff@surrette.com

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PowerGen International

5 – 7 December 2017, Las Vegas

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Transform World's Largest Industry

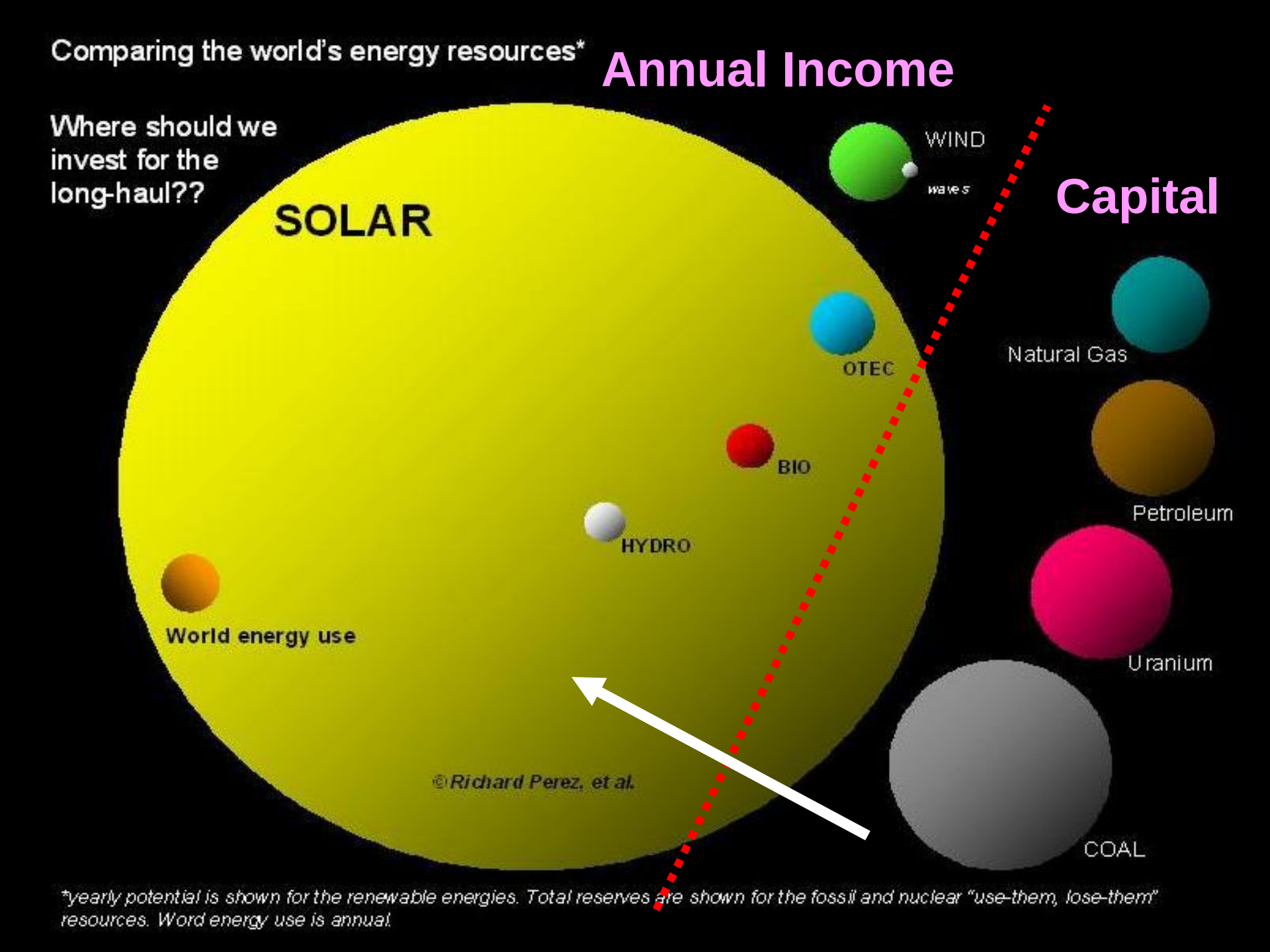
Run the World on Renewables --

Including some nuclear ?

Transform World's Largest Industry

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

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

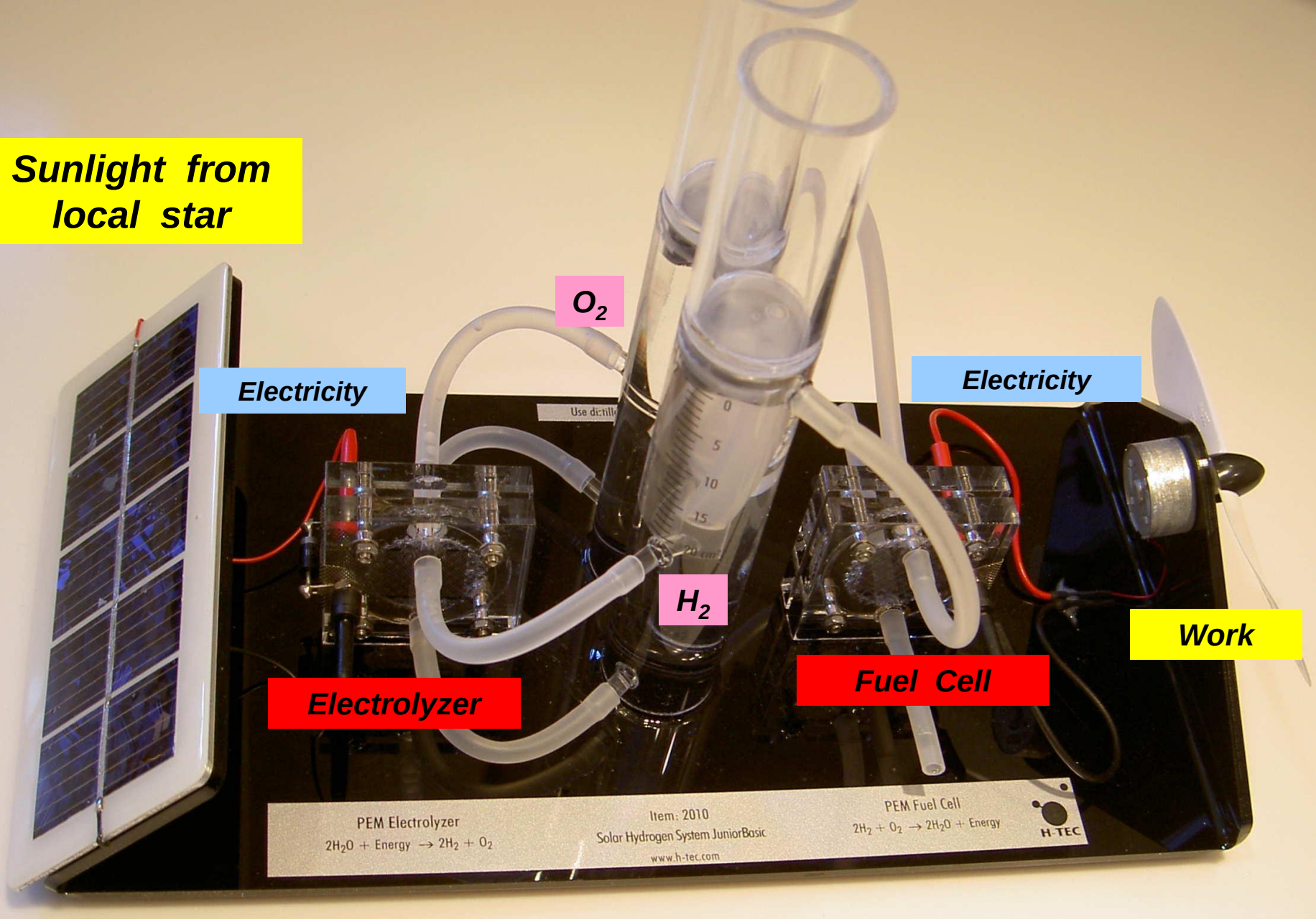

Comparing the world's energy resources*
Annual Income
Where should we invest for the long-haul??
SOLAR
WIND
waves
Capital
OTEC
Natural Gas
BIO
Petroleum
HYDRO
World energy use
Uranium
© Richard Perez, et al.
COAL
*yearly potential is shown for the renewable energies. Total reserves are shown for the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

Far more Ambitious:

- Renewables industry
- Hydrogen industry
- Beyond electricity systems
- Transportation + CHP fuels
- Run the World on Renewables
- ~ 100 % CO_2-emission-free energy

Transform World's Largest Industry

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

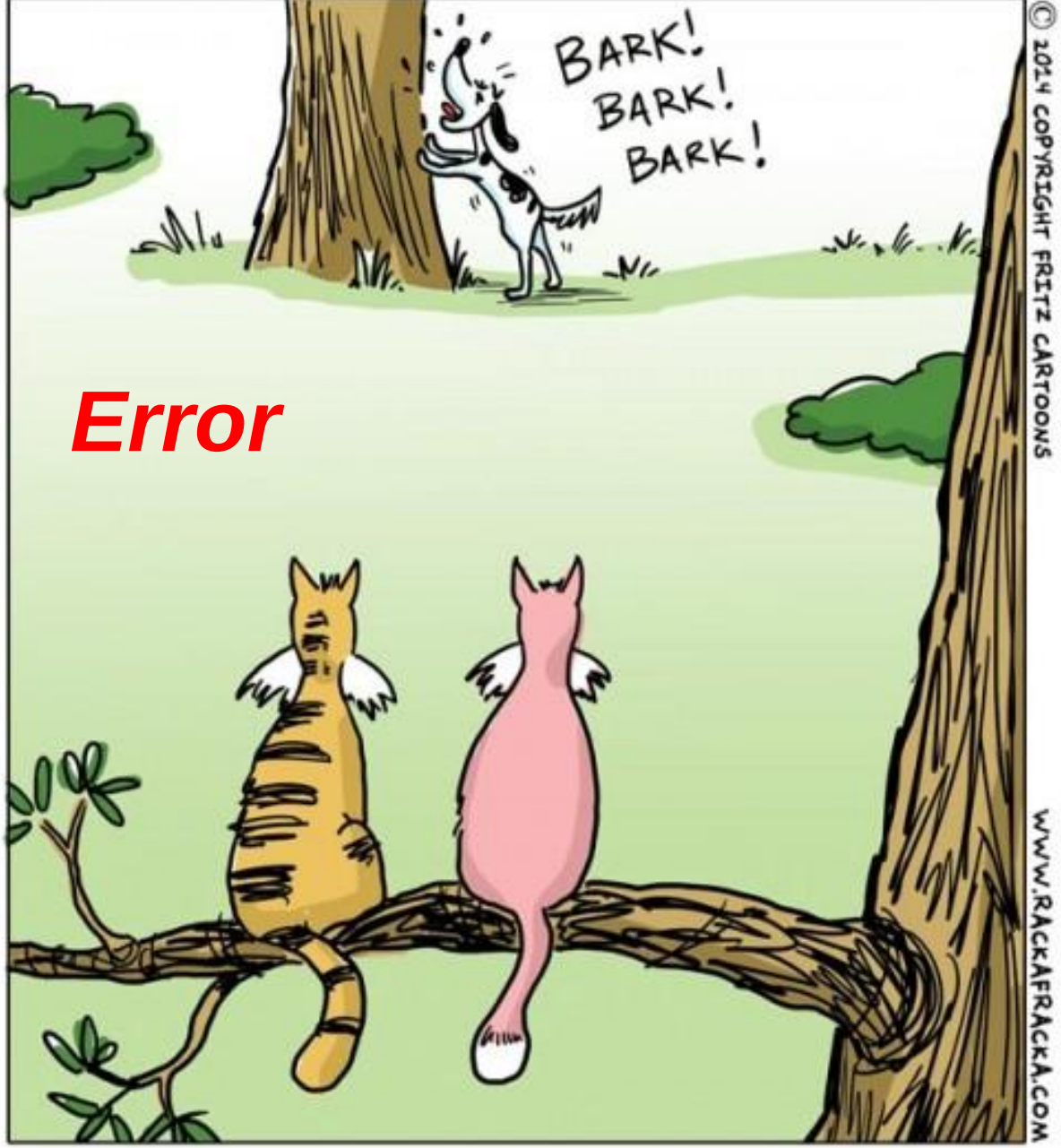


Solar Hydrogen Energy System

Tech, econ suboptimal ?
Opportunity cost

Global $ 45 trillion new infrastructure by 2030

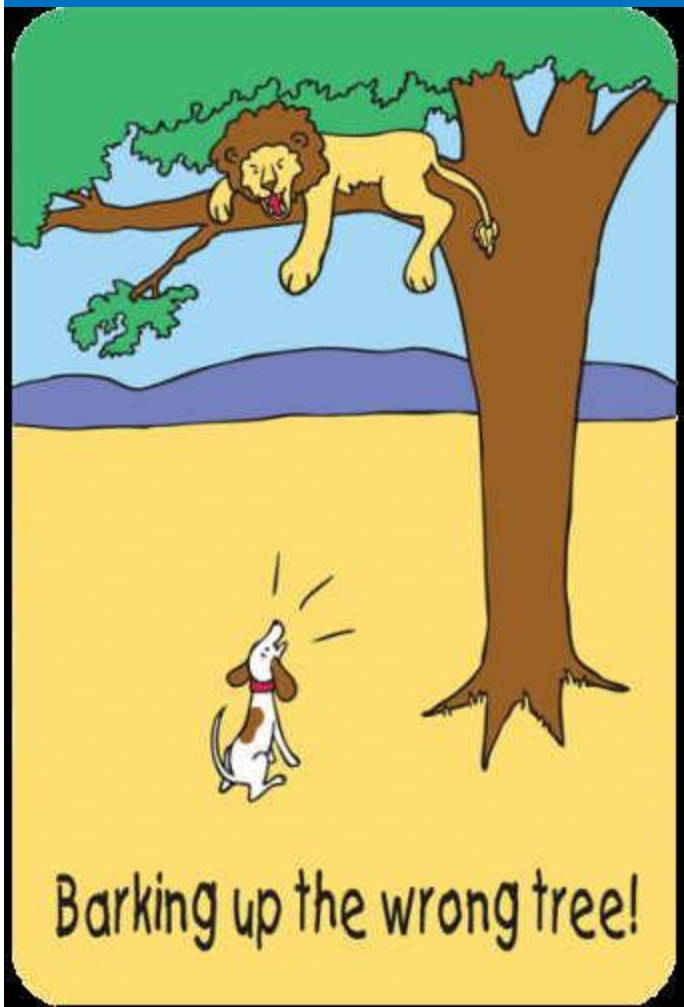
Electricity share ? NH_3 ? H_2 ?



Error

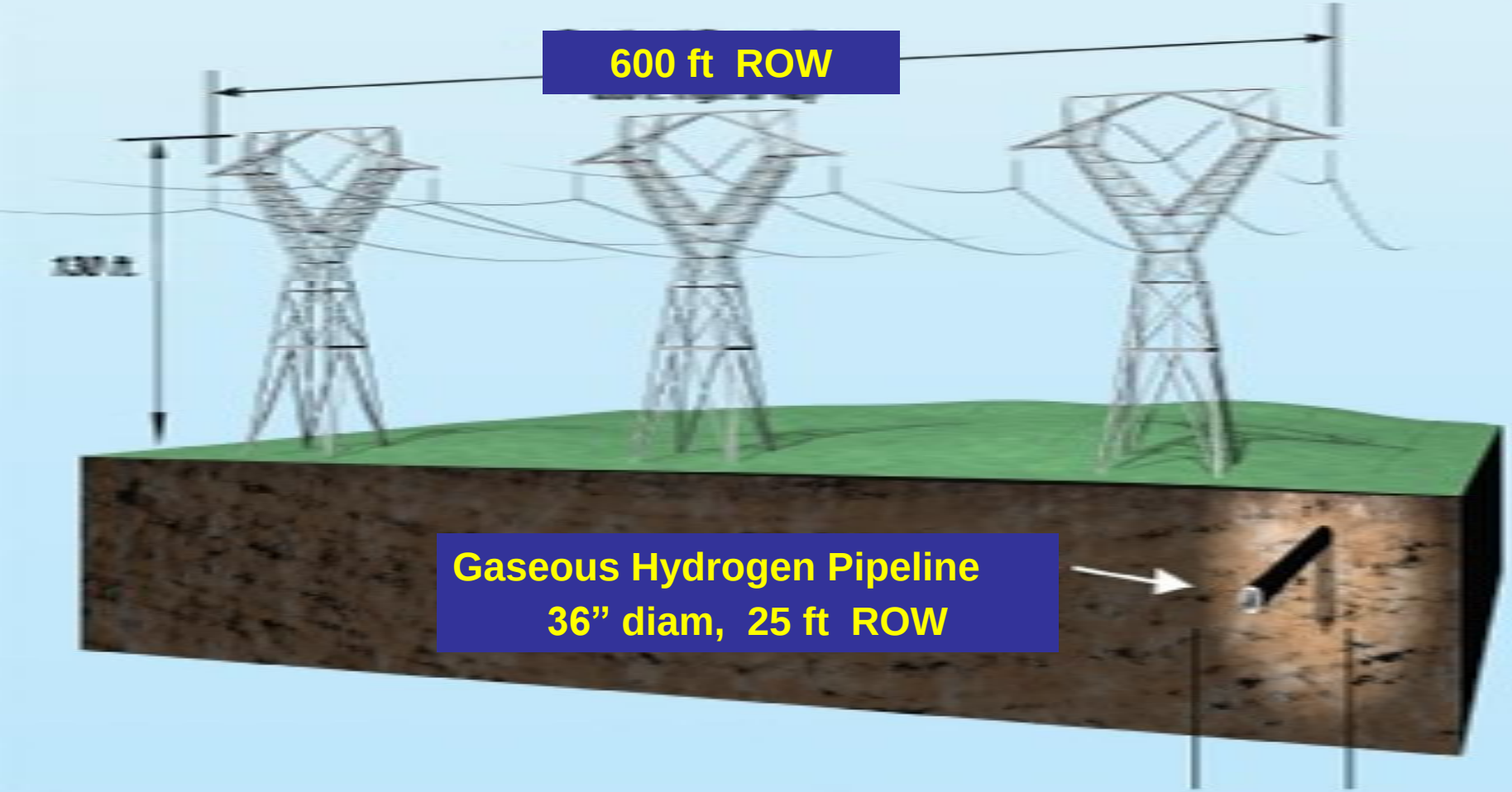
BUSTER WAS CAUGHT BARKING UP THE WRONG TREE AGAIN.

Danger



Transform World's Largest Industry

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

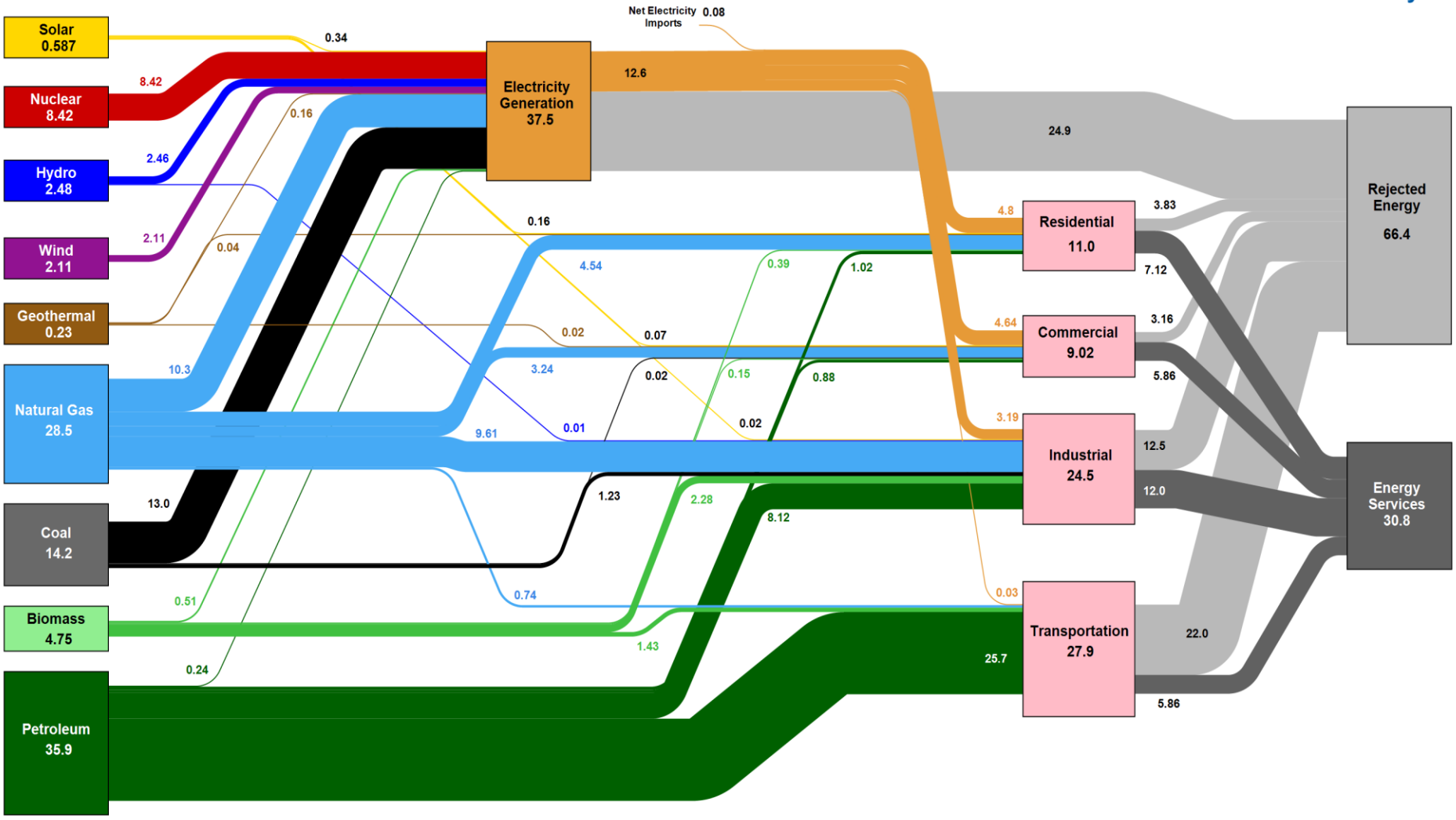


Out of Sight, Out of Harm’s Way

8,000 MW alternatives: HVAC vs Hydrogen Pipeline


Zion, IL
Near Zion nuclear plant, Oct 02

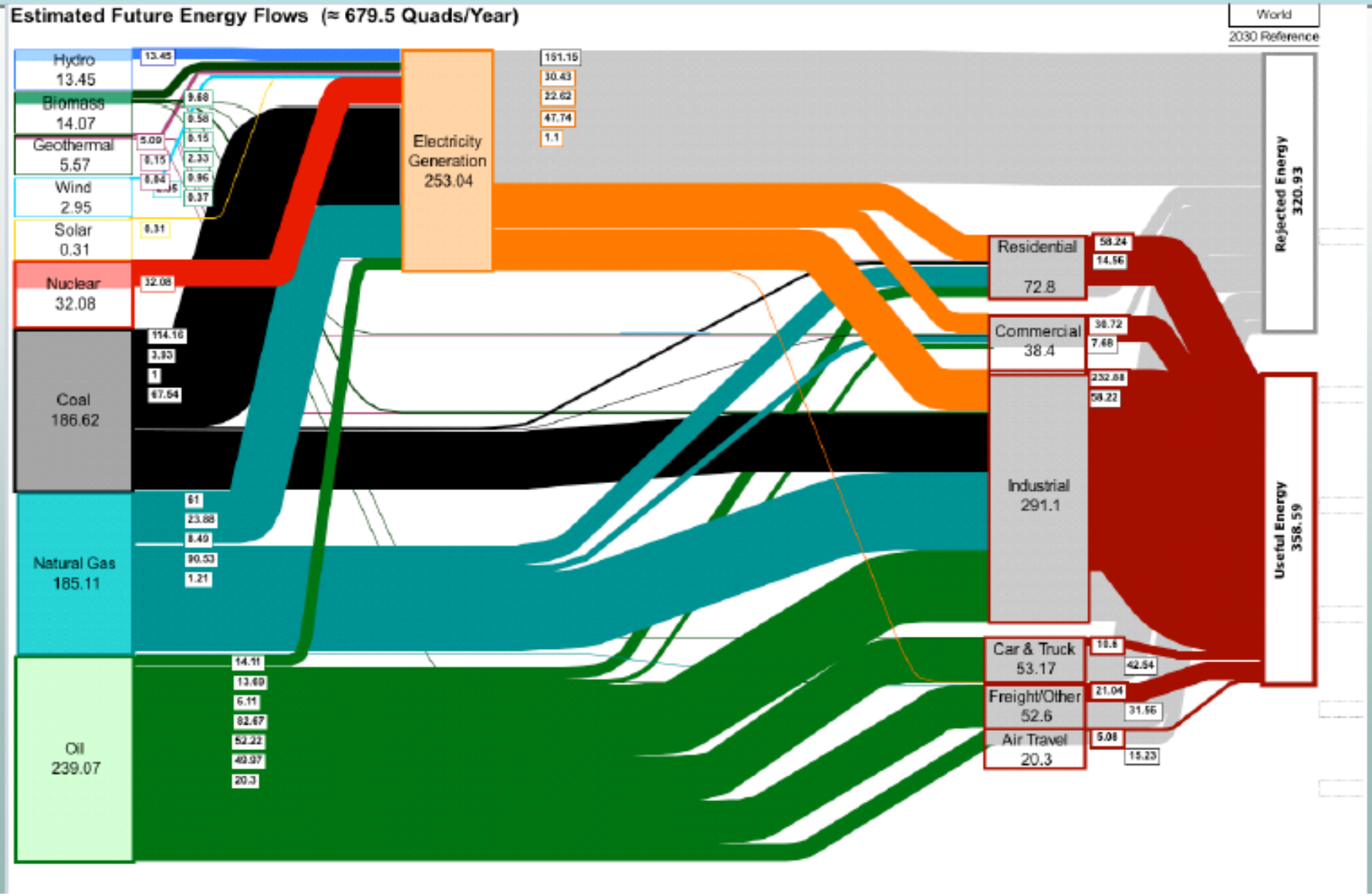
Estimated U.S. Energy Consumption in 2016: 97.3 Quads



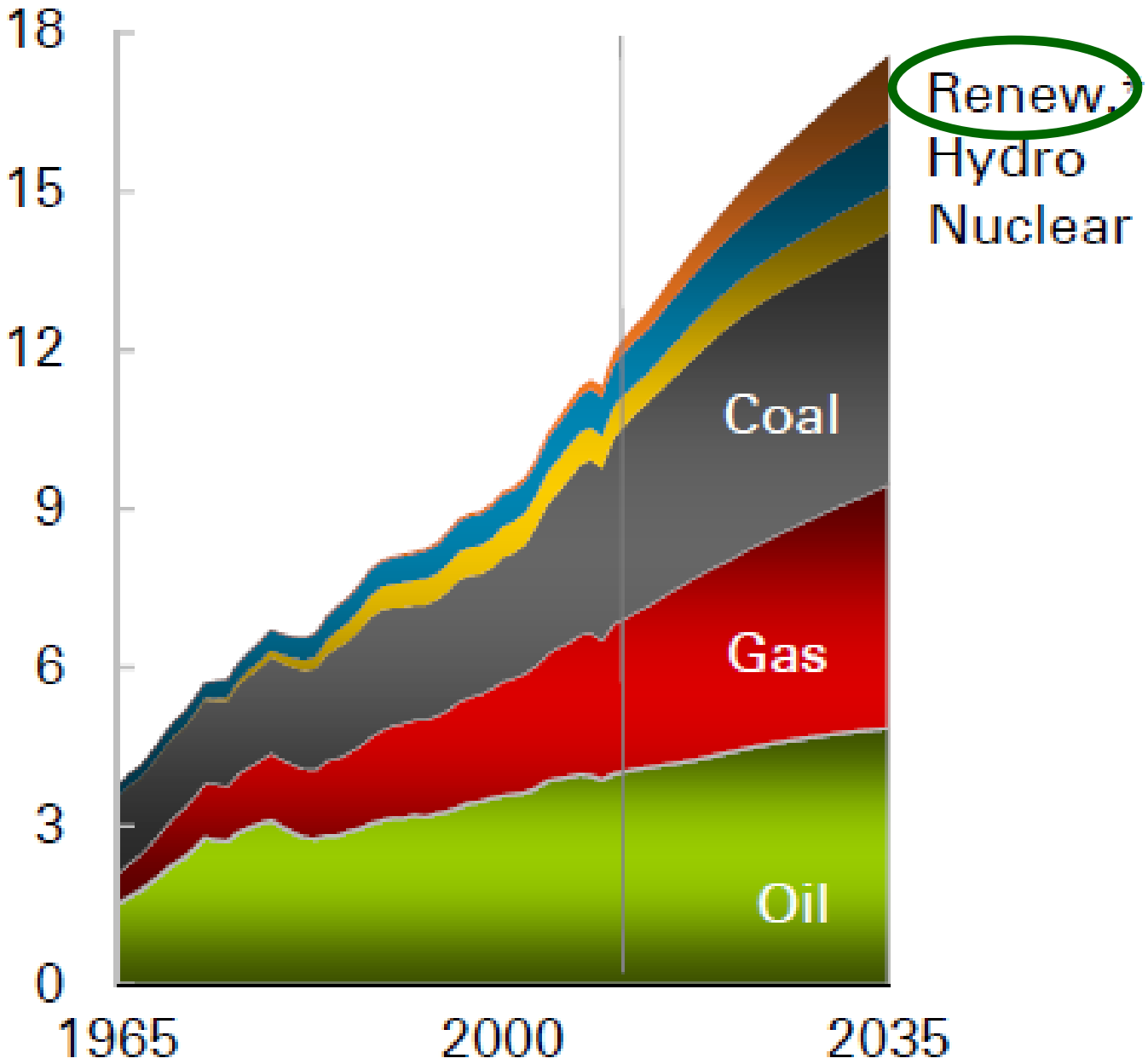
Source: LLNL March, 2017. Data is based on DOE/EIA MER (2016). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. This chart was revised in 2017 to reflect changes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



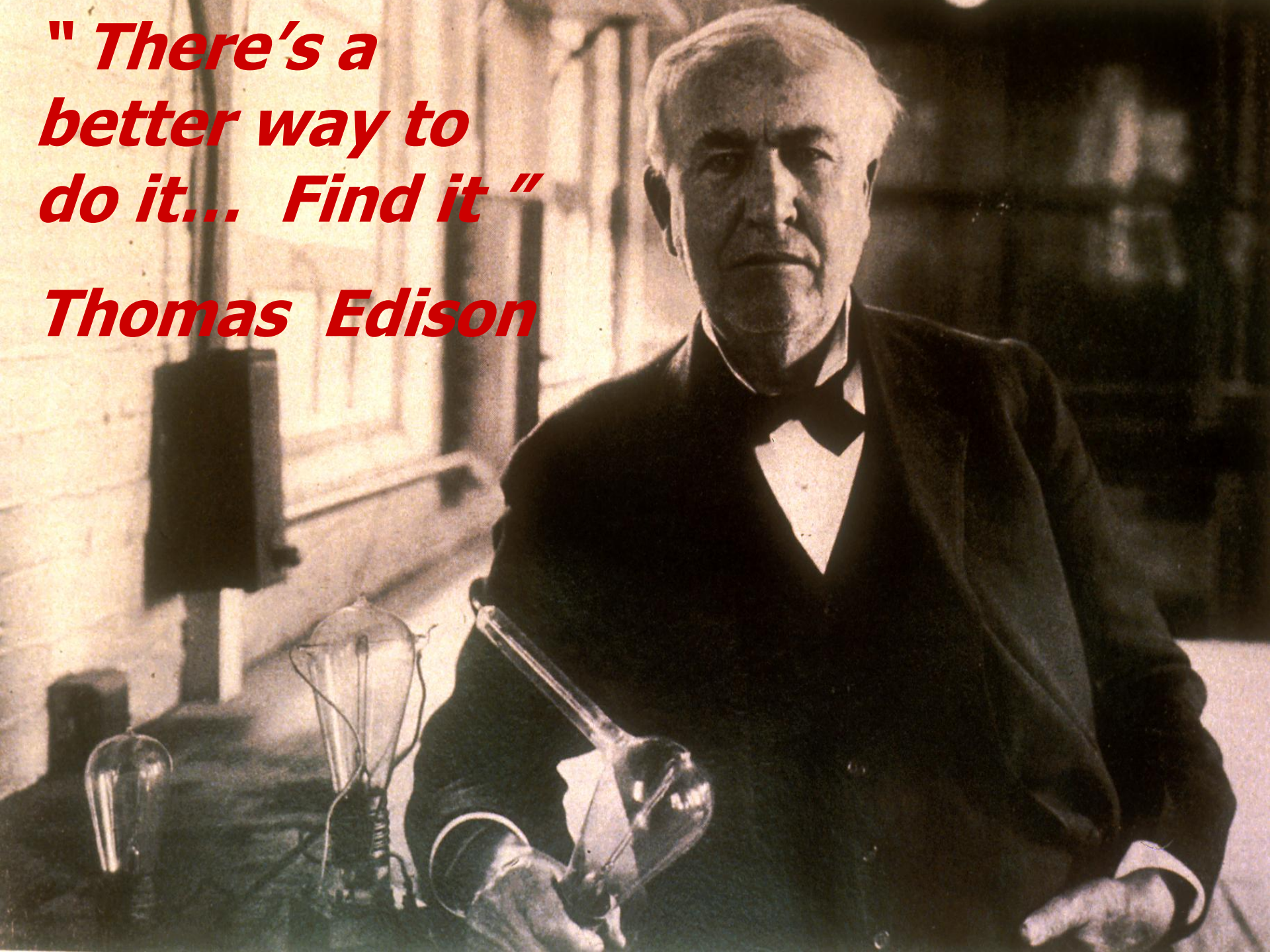
Billion tons of oil equivalent (toe)



World Primary Energy Consumption

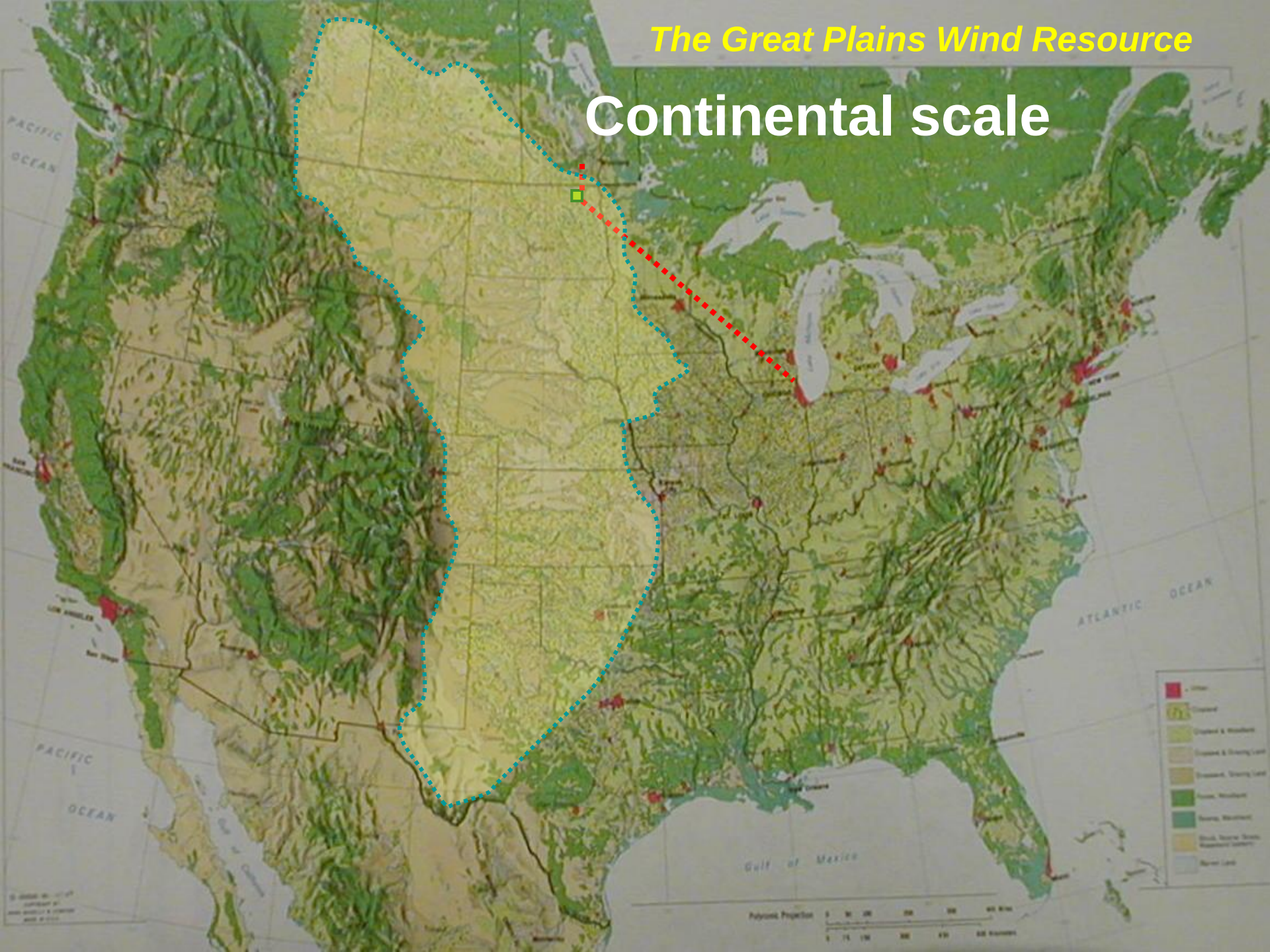
BP Energy Outlook 2035

January ‘14


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

The Great Plains Wind Resource

Continental scale



Exporting From 12 Windiest Great Plains States

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

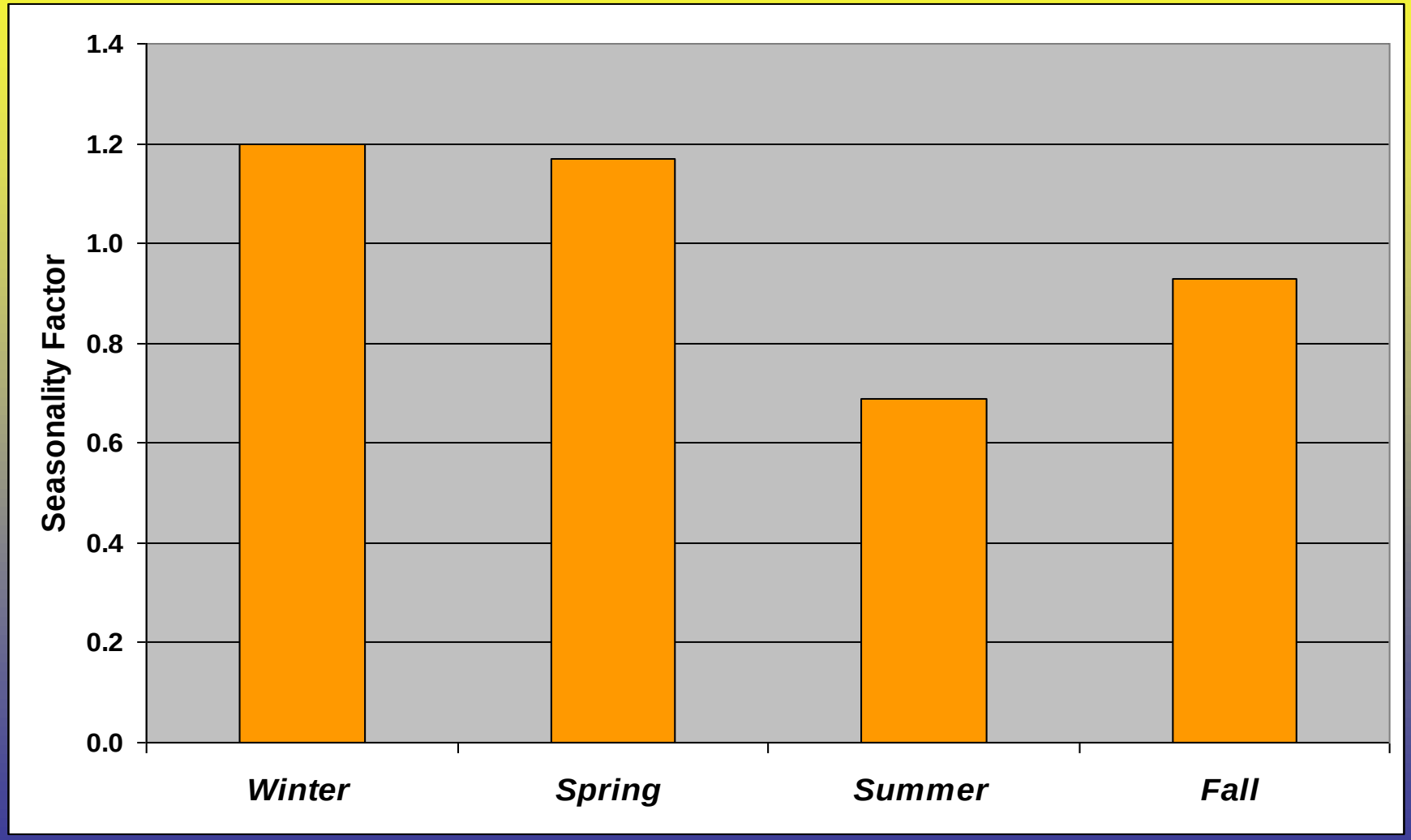
Capacity at 500 miles length **Capacity Factor (CF) = 30%**

State	Annual Energy Production (TWh)	Nameplate Installed Capacity (MW)	Nameplate Installed Capacity (GW)	6 GW 36" GH2 Hydrogen Pipelines	$ Billion Total Capital Cost	3 GW 500 KV HVDC Electric Lines	$ Billion Total Capital Cost
Texas	6,528	1,901,530	1,902	317		634	
Kansas	3,647	952,371	952	159		317	
Nebraska	3,540	917,999	918	153		306	
South Dakota	3,412	882,412	882	147		294	
Montana	3,229	944,004	944	157		315	
North Dakota	2,984	770,196	770	128		257	
Iowa	2,026	570,714	571	95		190	
Wyoming	1,944	552,073	552	92		184	
Oklahoma	1,789	516,822	517	86		172	
Minnesota	1,679	489,271	489	82		163	
New Mexico	1,645	492,083	492	82		164	
Colorado	1,288	387,220	387	65		129	
TOTALS	33,711	9,376,694	9,377	1,563	$1,500	3,126	$2,000

Wind energy source: Archer, Jacobson 2003

Wind Seasonality, Northern Great Plains

Normalized to 1.0 per season



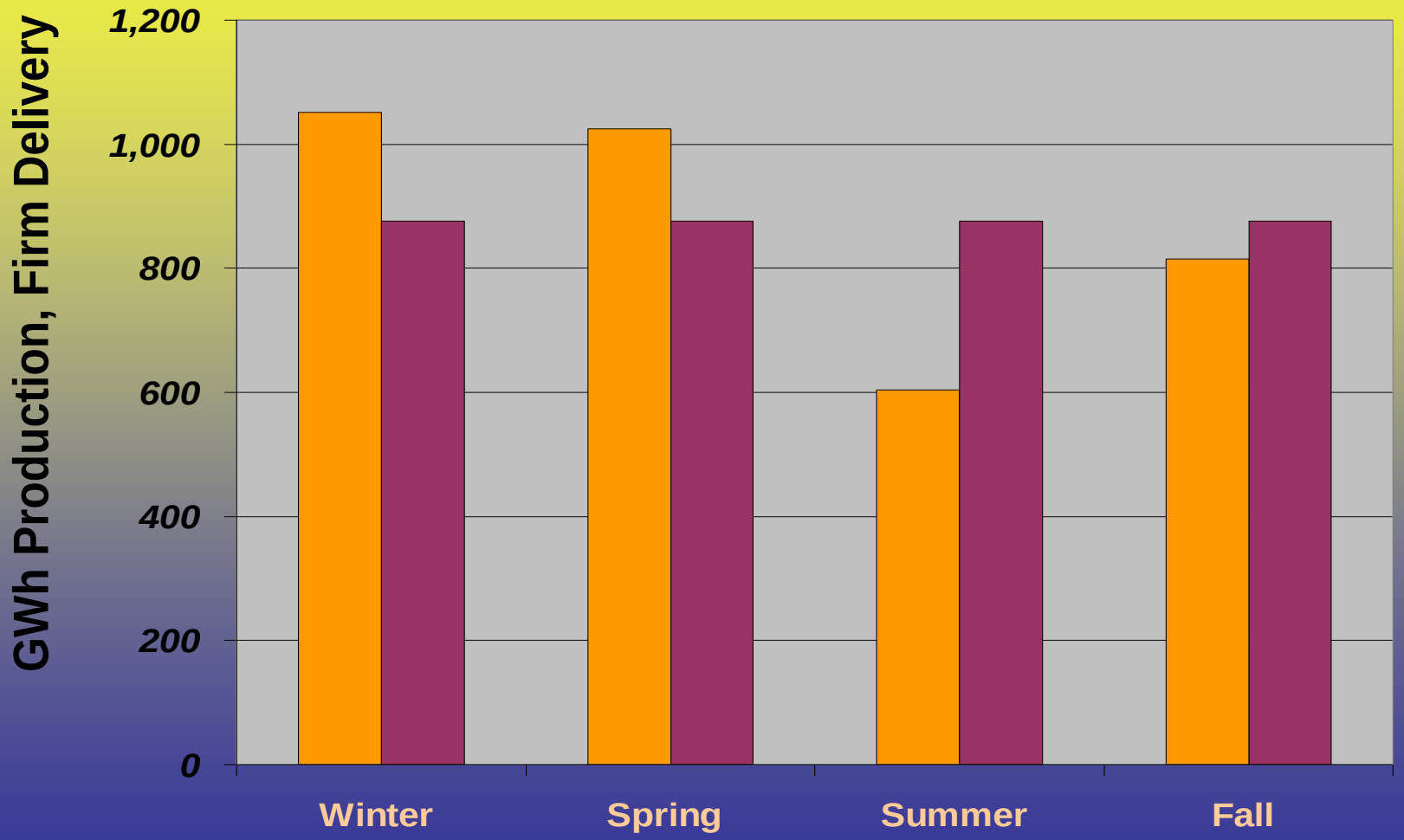
Wind Seasonality, Northern Great Plains

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

"Firm" goal = 875 GWh / season

Storage: 320 GWh per 1,000 MW wind

Source: NREL, D. Elliott



320 GWh

Annual firming, 1,000 MW wind nameplate

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

TESLA 20 MW / 80 MWh battery
SCE Mira Loma Battery Storage Facility, Ontario, CA
Cost: undisclosed

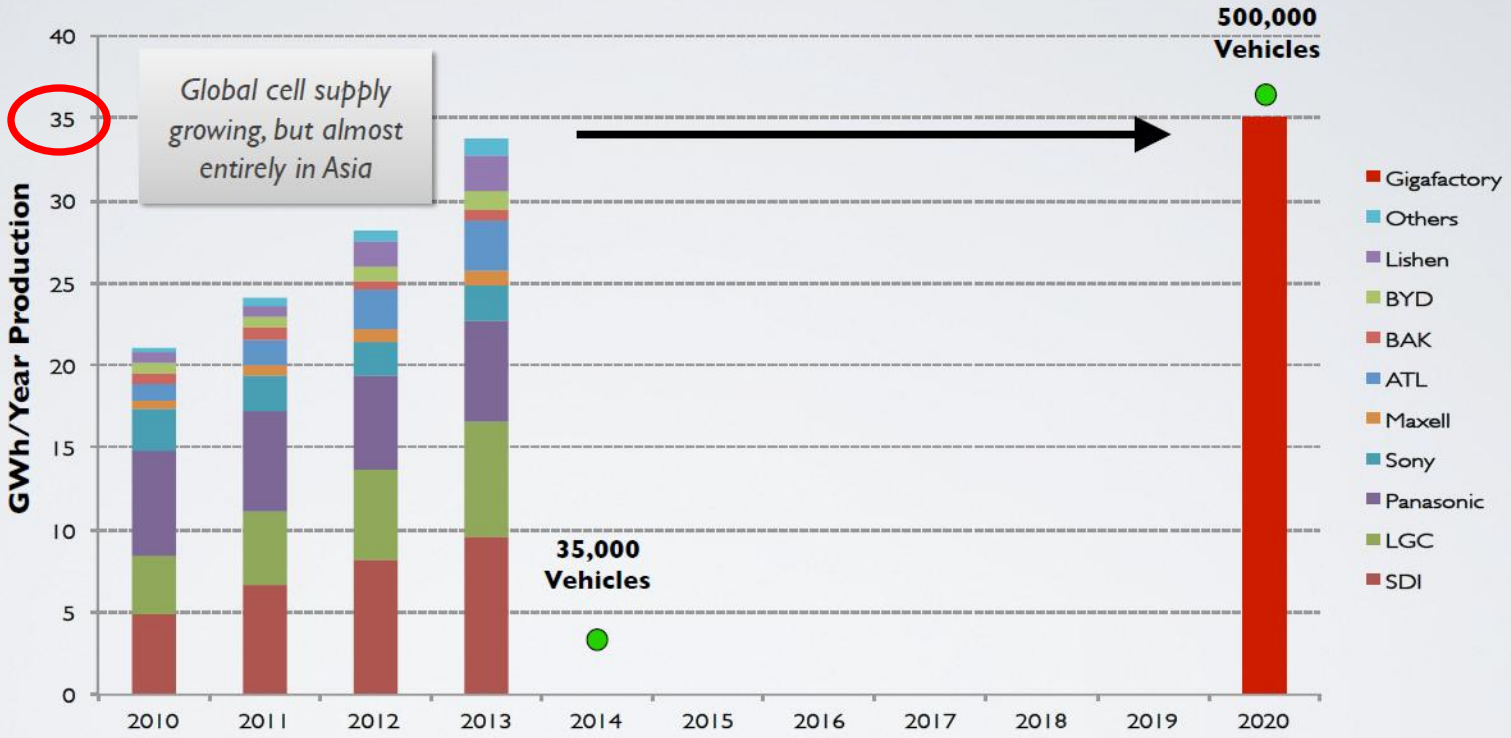
TESLA 100 MW / 129 MWh battery
South Australia
"Cost me over $ 50 million" (if failed) -- Elon Musk
129 MWh @ $ 50 million = $ 390 / kWh capex

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**

Planned 2020 Gigafactory Production Exceeds 2013 Global Production

35 GWh / year total



Battery pack cost/kWh reduced >30% by Gen III volume ramp in 2017

Source: IIT Takeshita 2013

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**

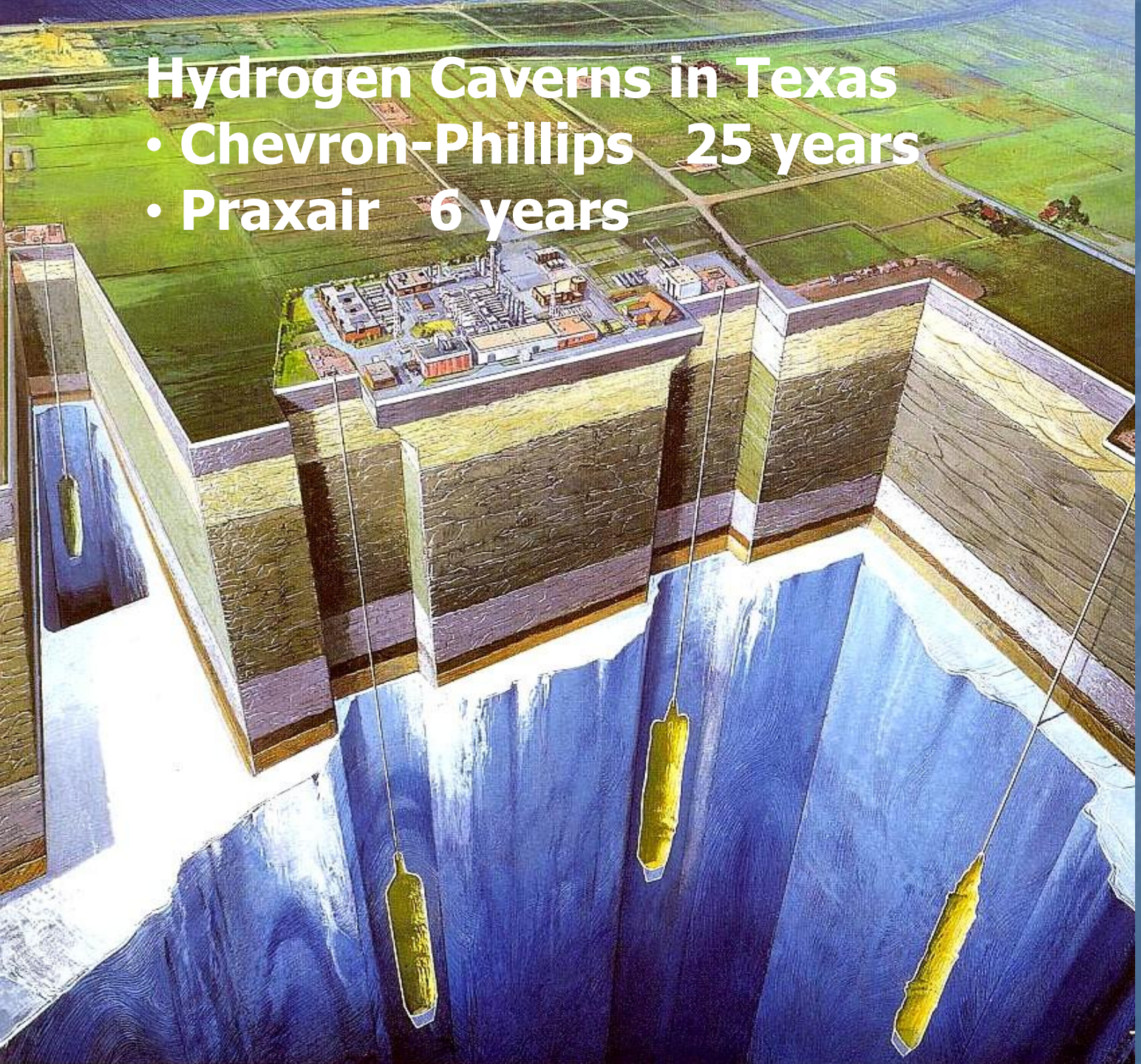
Global total 2017 = 103 GWh / year (Bloomberg)
Global total 2021 = 278 GWh / year

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

Near Berlin: Tesla's first full battery cell factory will produce up to 250 GWh / year

18 June 2021

https://electrek.co/2020/11/24/tesla-first-battery-cell-factory-produce-up-to-250-gwh/



Domal Salt Storage Caverns

Each:

90 GWh

$ 15 million capex

$ 0.20 / kWh

’09 ARPA-E “Grids” Goal: $100 / kWh

Total storage = 380 GWh

“Atmospheric” Liquid Ammonia Storage Tank (Corn Belt)

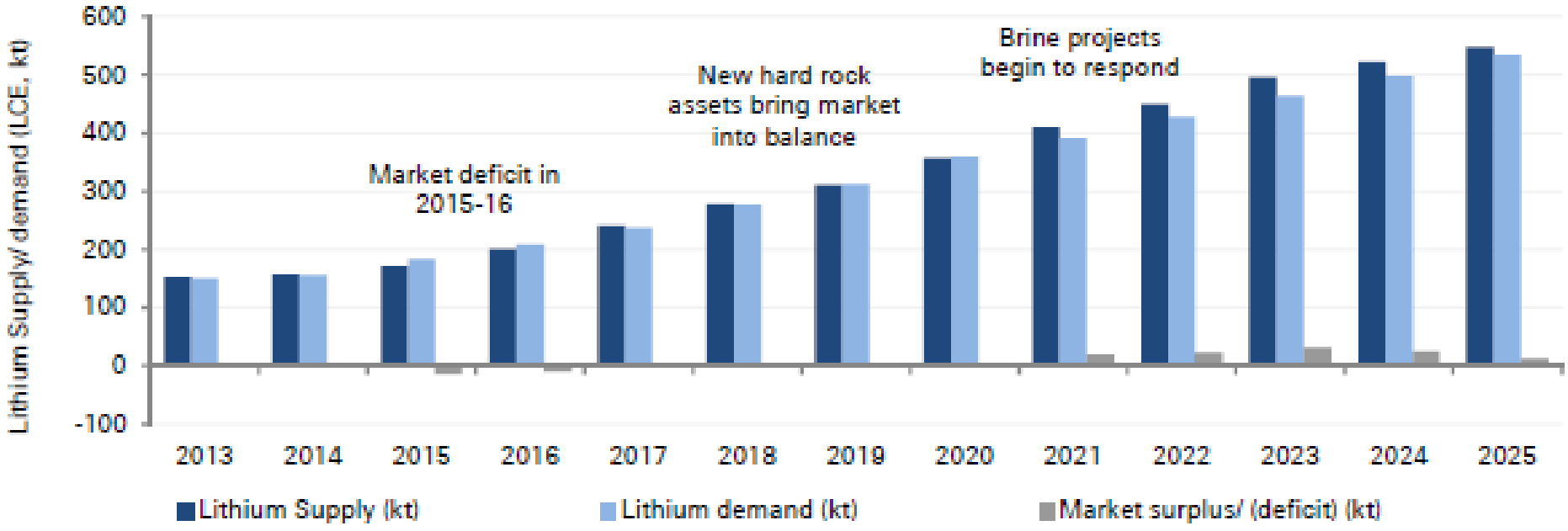
-33 C 1 Atm

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

$ 80 / MWh = $ 0.08 / kWh capital cost

Global Lithium Carbonate Equivalent (LCE)
kt = 1,000 tons
Supply – Demand balance to 2025

Figure 1: Global Lithium Supply and demand balance



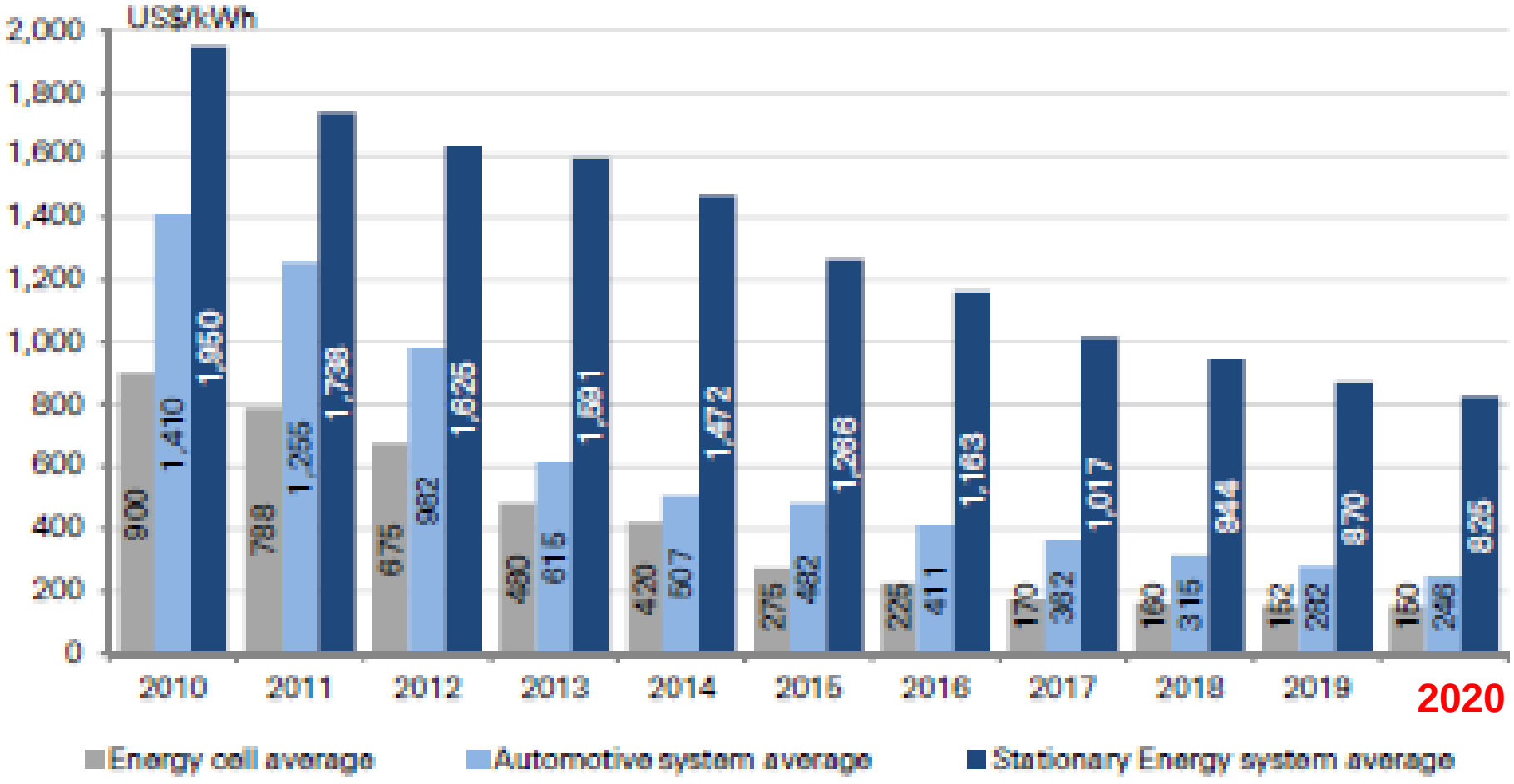
Source: Deutsche Bank, United States Geological Society, company data

Average Li-Ion battery cost / kWh through 2020: profitable ?

Cells $ 150

Automotive system $ 246

Stationary system $ 826



California “State of the State” 2017 Electricity sector only; nameplate

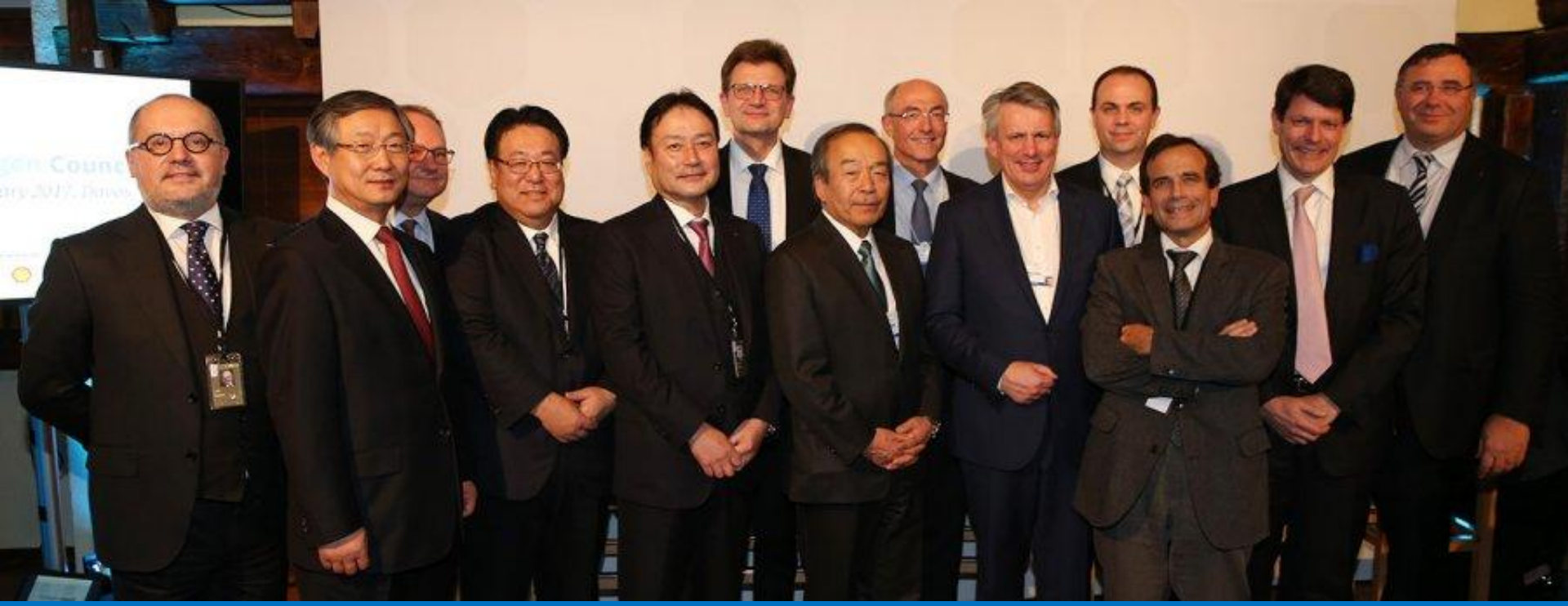
- 20,000 MW of utility scale renewables
  - Solar peak 8,545 MW (Sept ‘16) – doubled in 2 years
- + 5,000 MW to meet 33% RPS
- + 12,000 - 16,000 MW to meet 50% by 2030
- 4,500 MW of consumer rooftop solar
  - 11,000 new / month = 50 - 70 MW / month = ~ 750 MW / year
- Add transportation energy for “ 80 in 50 “ ?

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



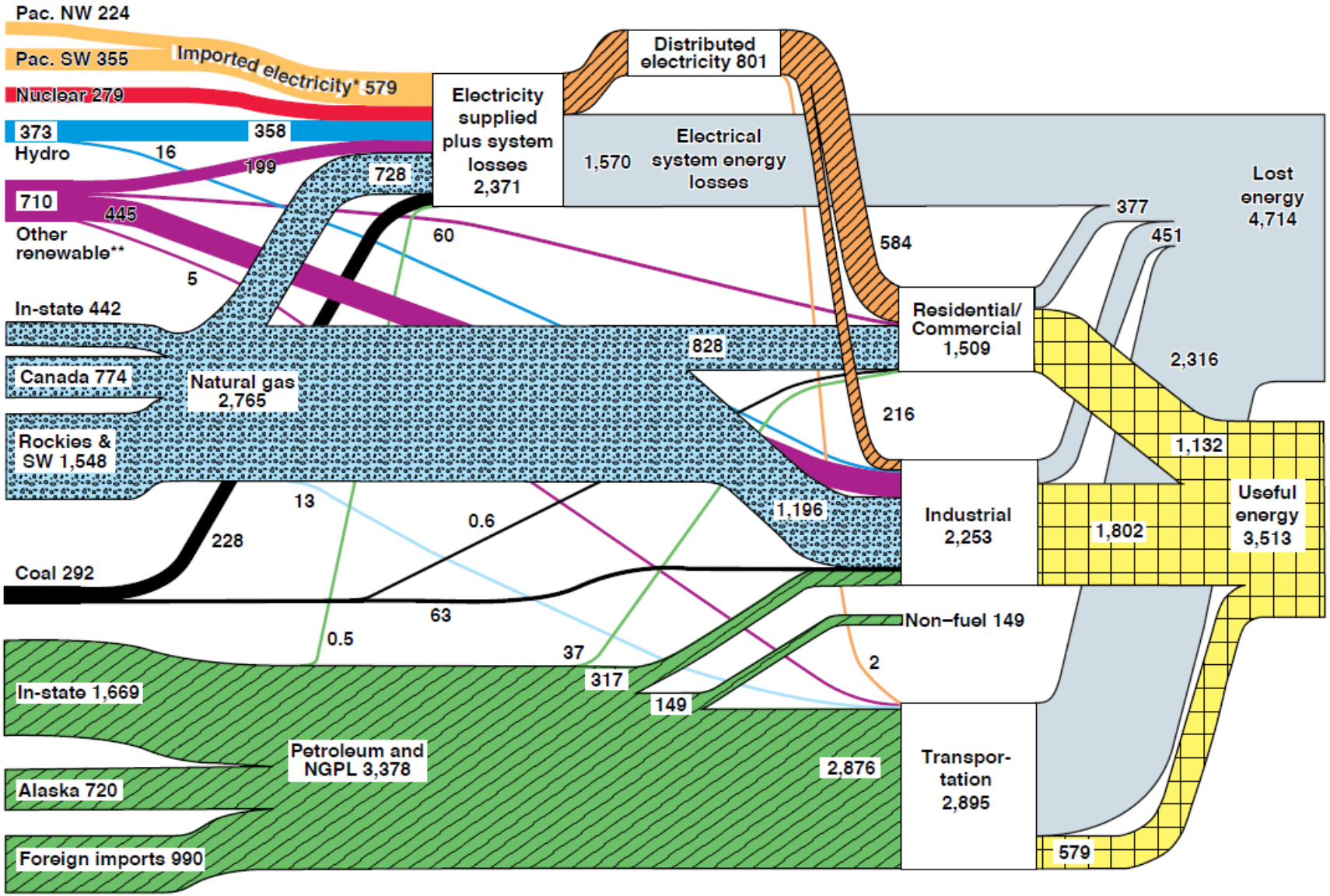
Hydrogen Council
Brussels, 7 Sept 17 24 companies

Hydrogen Council: 24 companies

Air Liquide
Alstom
Anglo American
Audi
BMW GROUP
Daimler
ENGIE
Faber Industries
Faurecia
First Element Fuel
Gore
Honda
Hyundai Motor
Iwatani
Kawasaki
Mitsui & Co
Plastic Osmium
Plug Power
Royal Dutch Shell
Statoil
The Linde Group
Total
Toyota,Toyota Tsusho

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

2016: CAISO enables market participation

Bulk Energy Storage

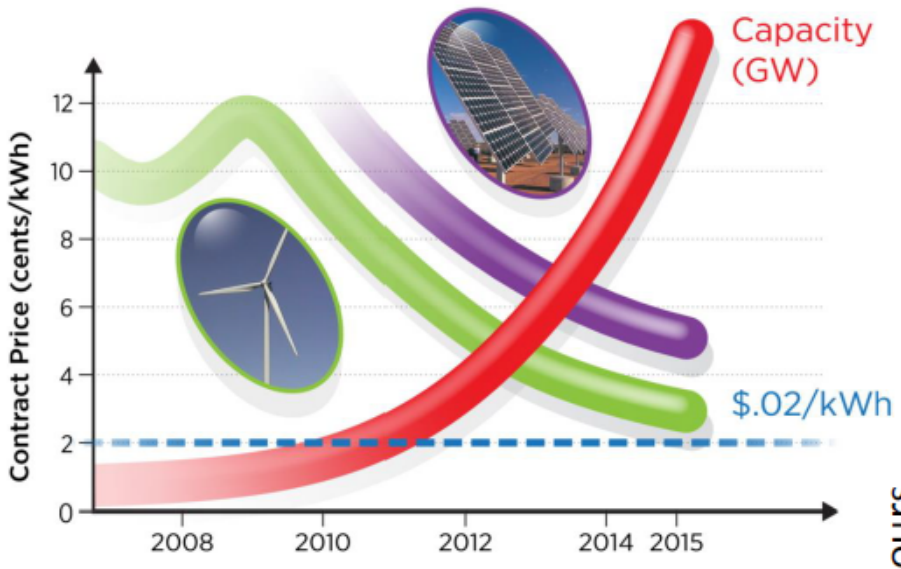
- Transmission-connected
- Distribution-connected

Distributed Energy Resource Provider (DERP)

- Pathway to bundle & participate
- Behind the Meter
- Generation & storage

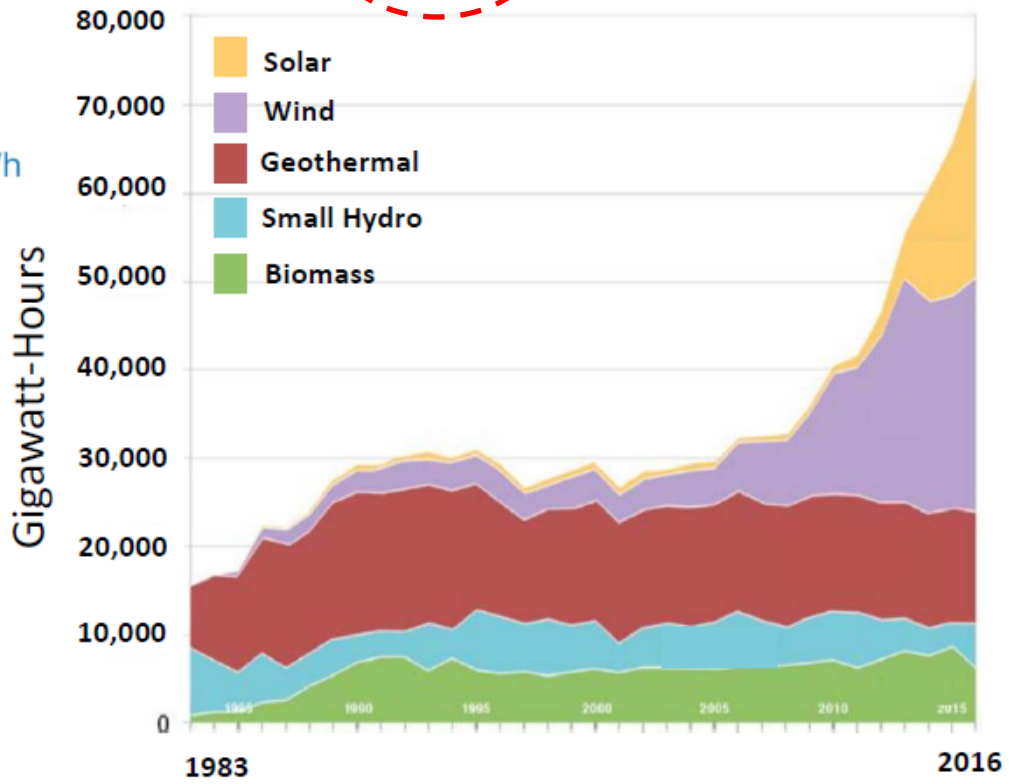
Changing Economics: Intermittent Electricity

Falling Renewable Prices



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

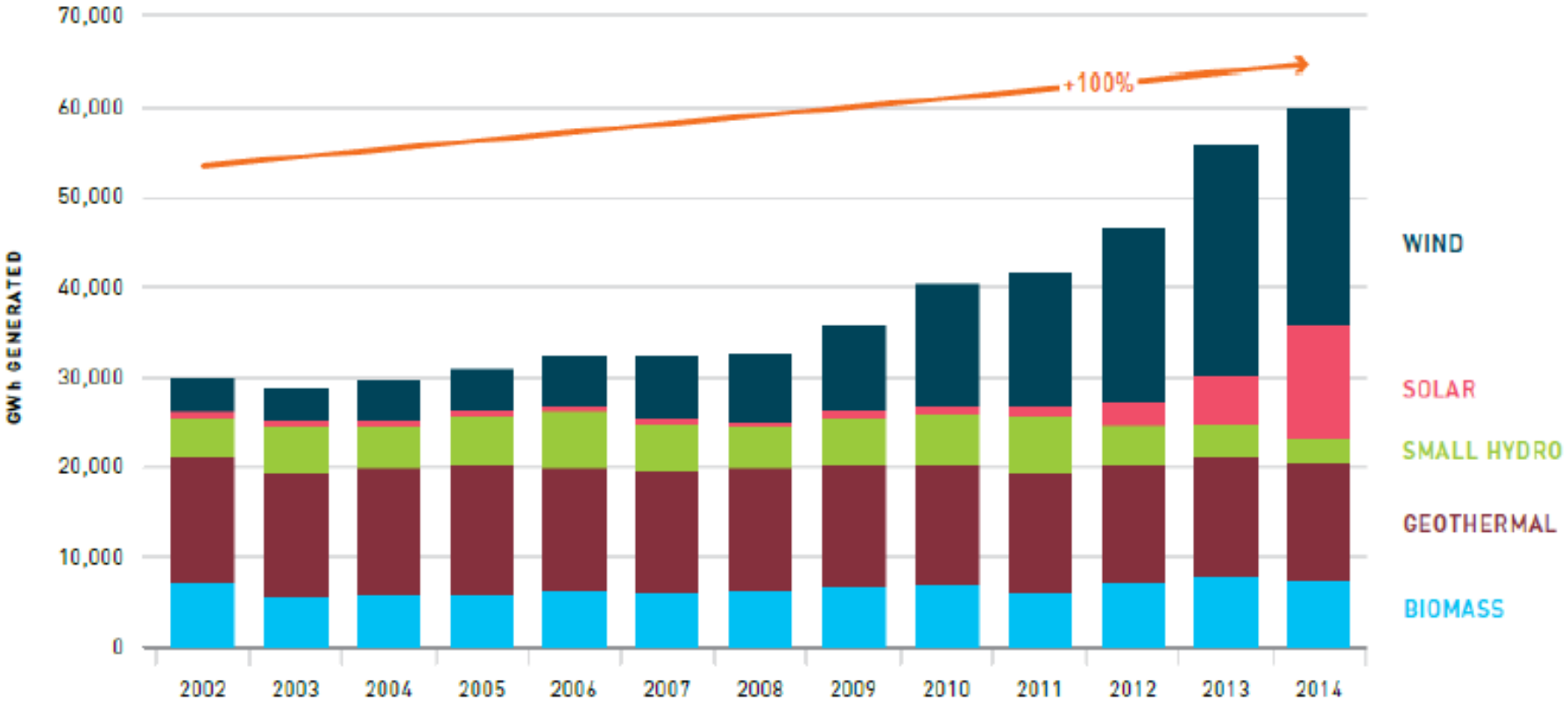
Growth in California Renewable Generation



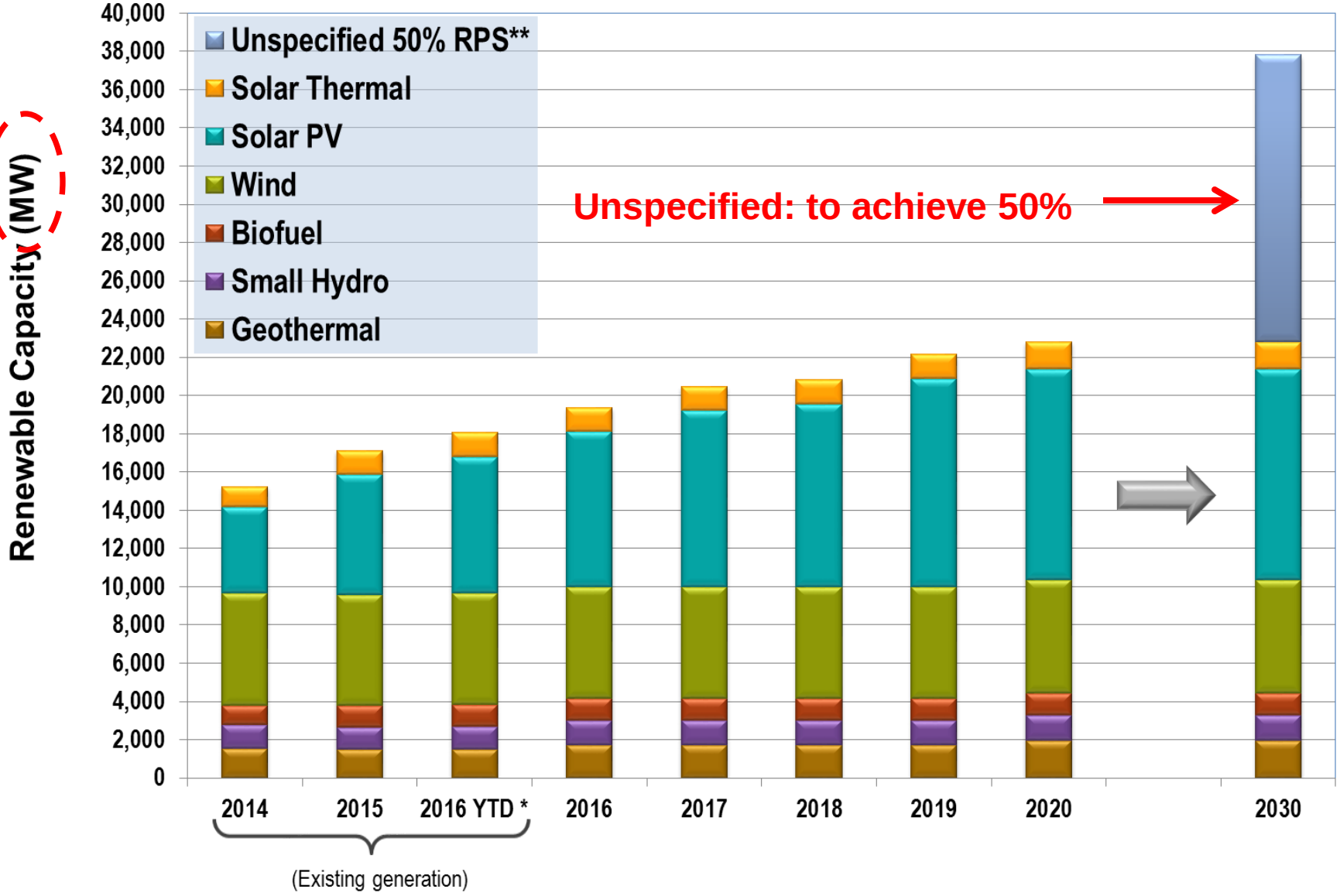
Source: California Energy Commission
http://www.energy.ca.gov/renewables/tracking_progress/documents/ renewable.pdf

Steady Growth for California Renewables

Energy:
GWh by source



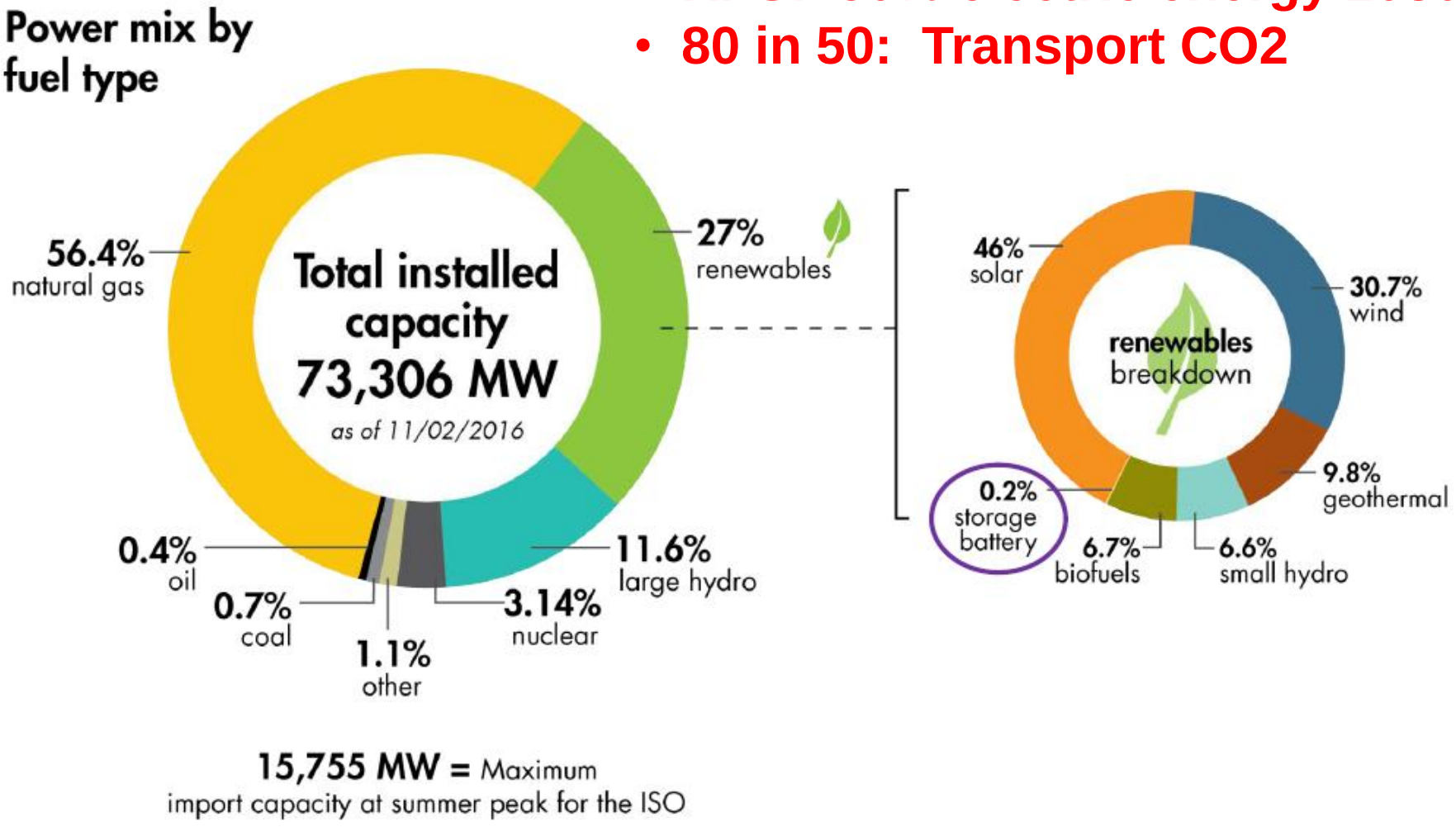
California Renewables to 2030: 50% RPS



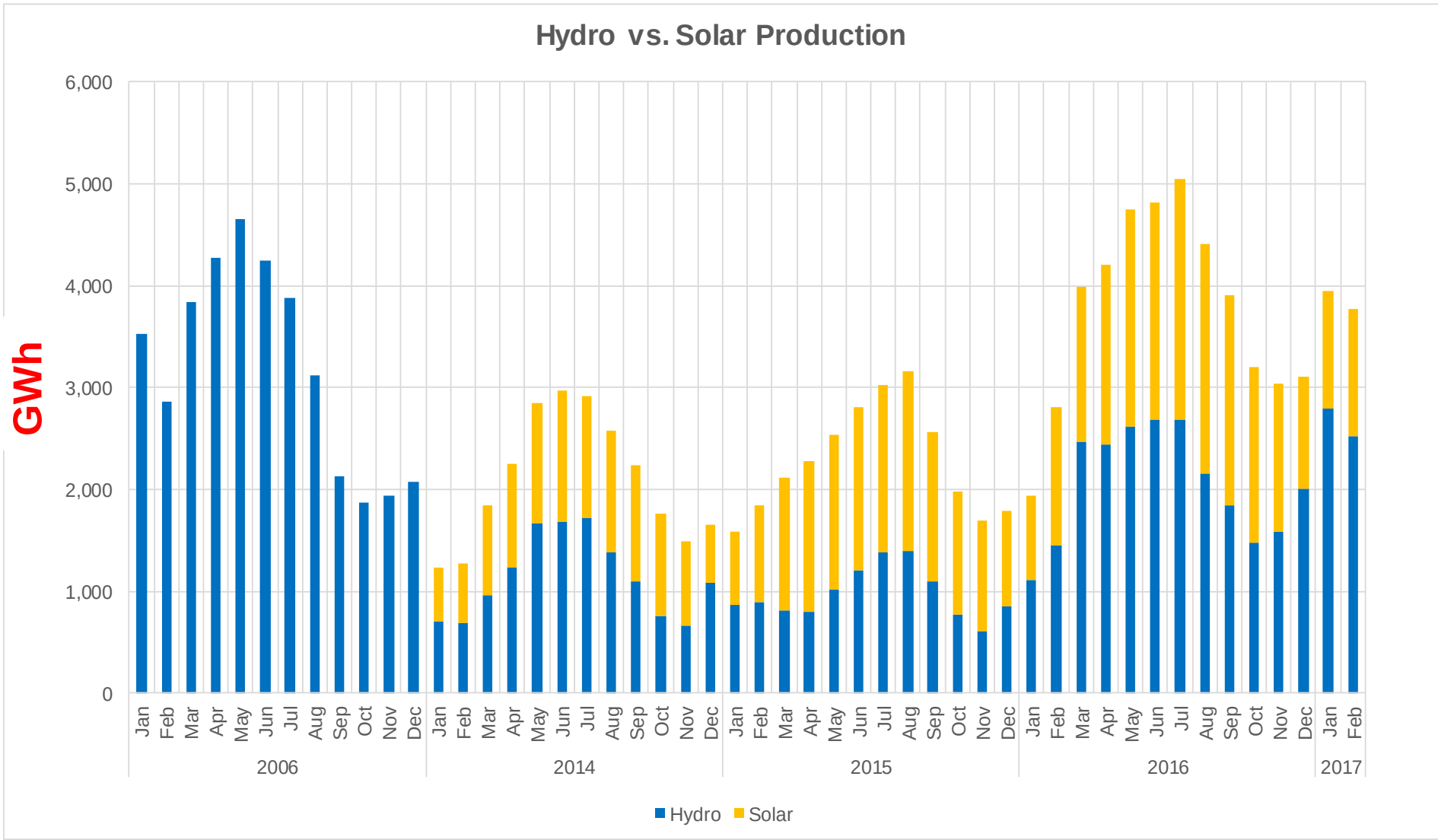
ISO Resource Mix **Electricity only**

- Good progress toward State's goals

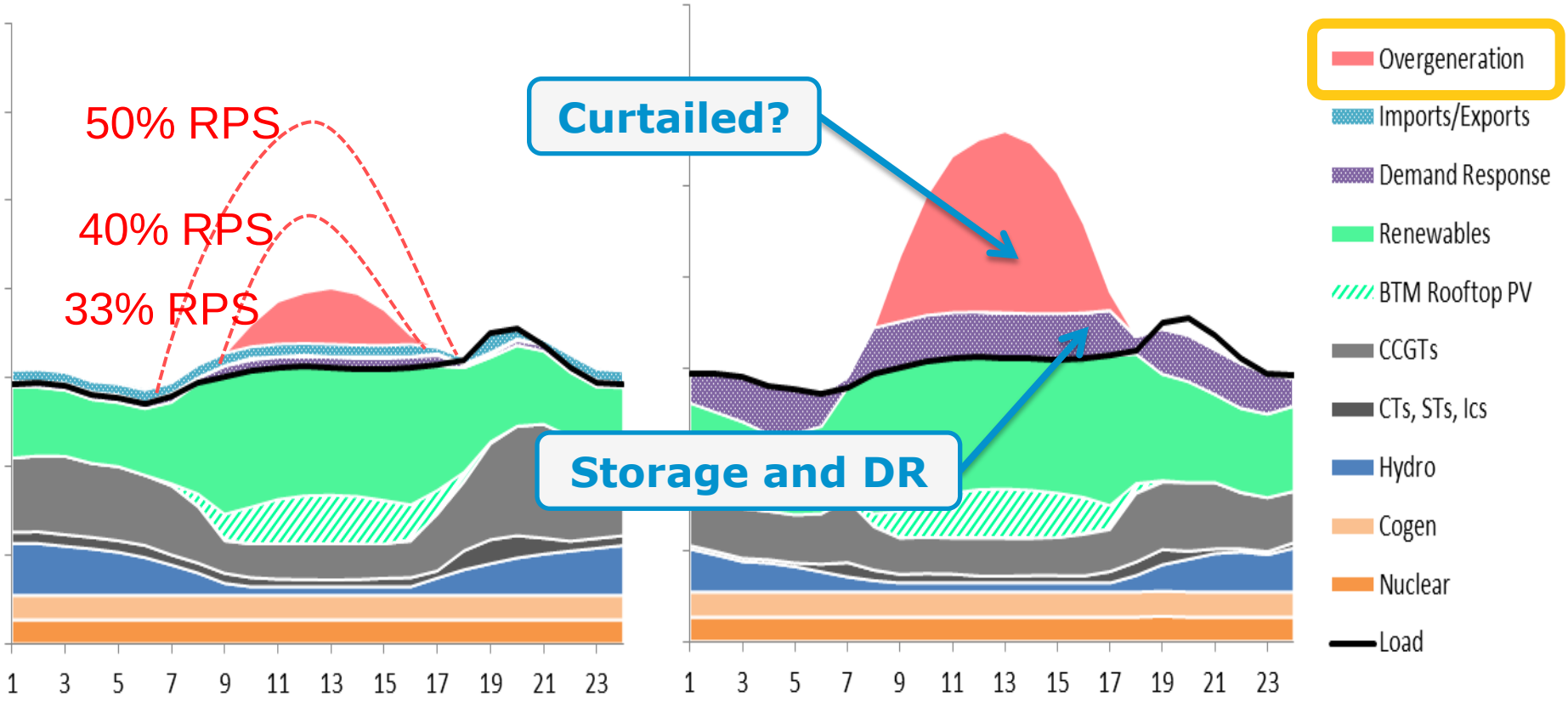
- **RPS: 50% electric energy 2030**
- **80 in 50: Transport CO2**



Solar ascent in CA drought years



California's surplus renewable generation

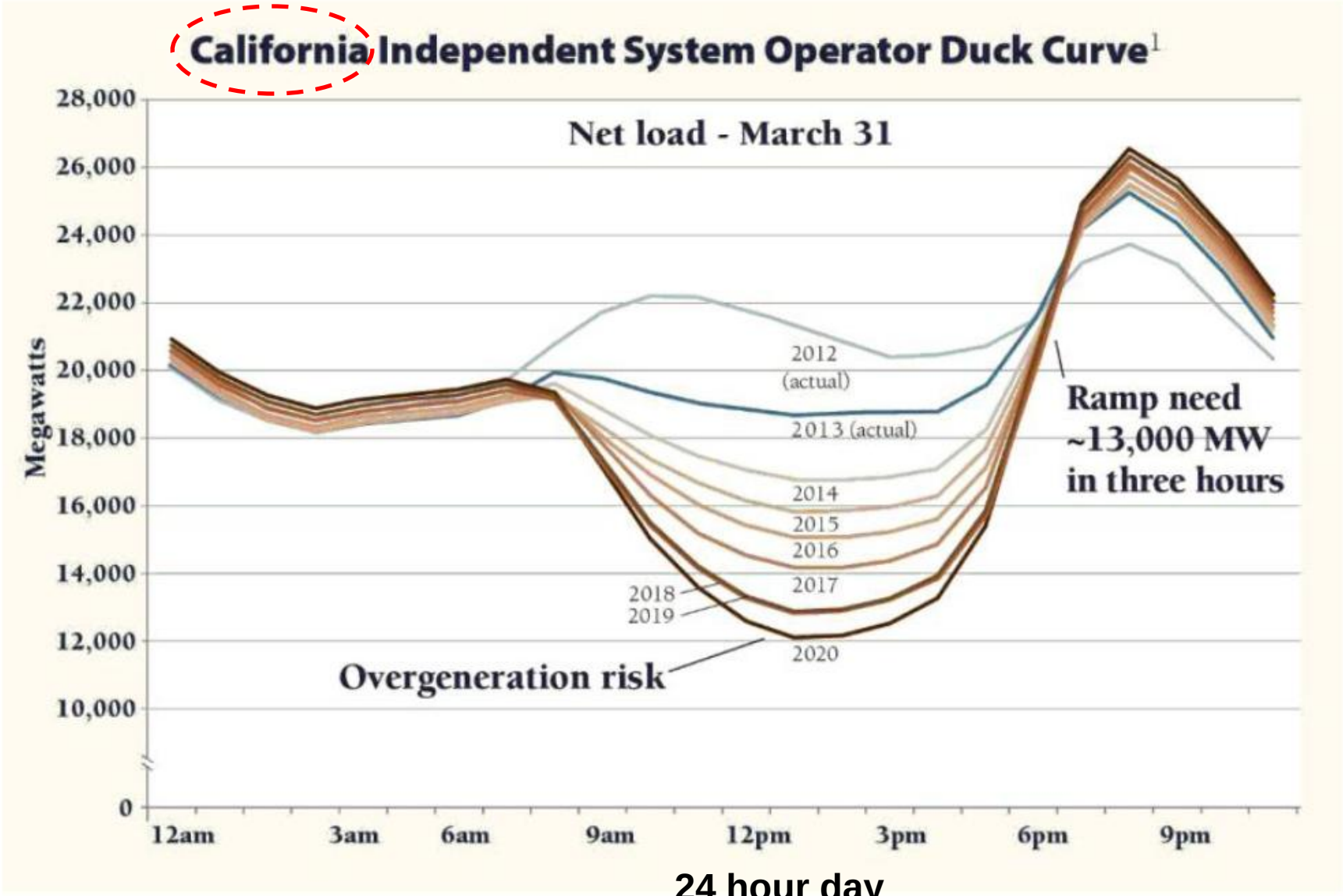


Do Not Cite
For Illustrative Purposes Only

Energy+Environmental Economics

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

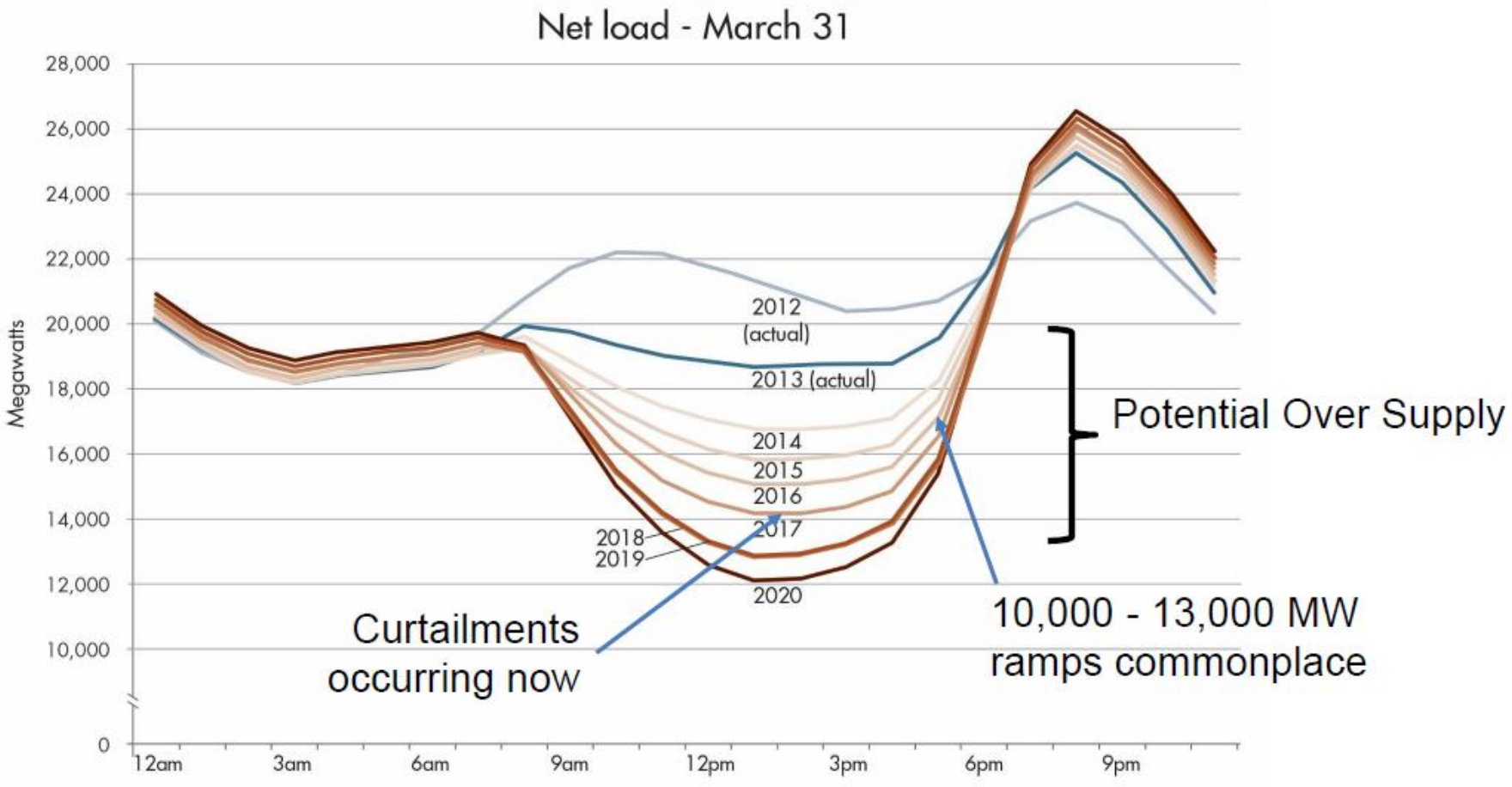
Changing Energy System: Grid Flexibility



24 hour day

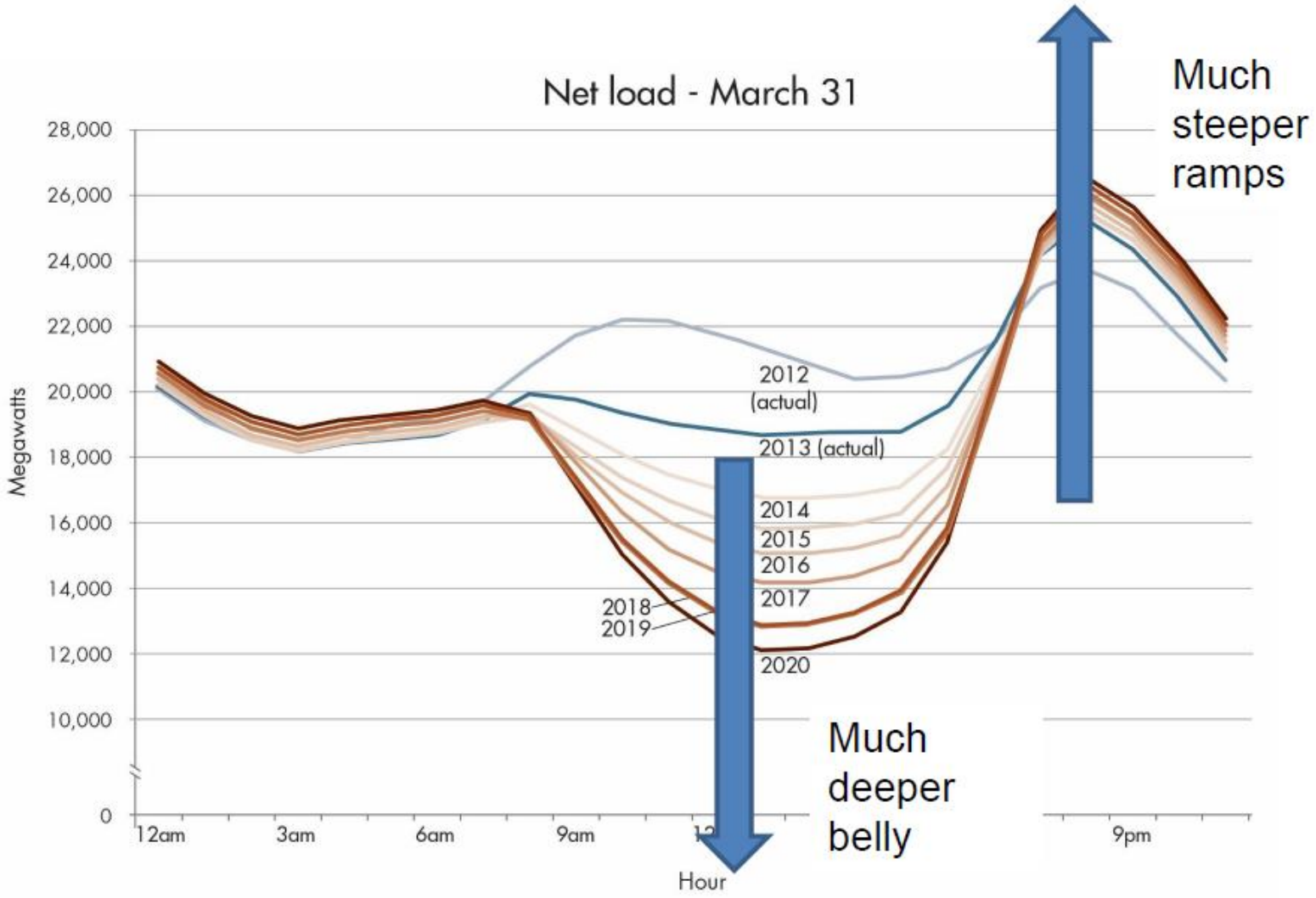
Clean, plentiful renewables…what's the problem?

- *Oversupply and Steep Ramps*



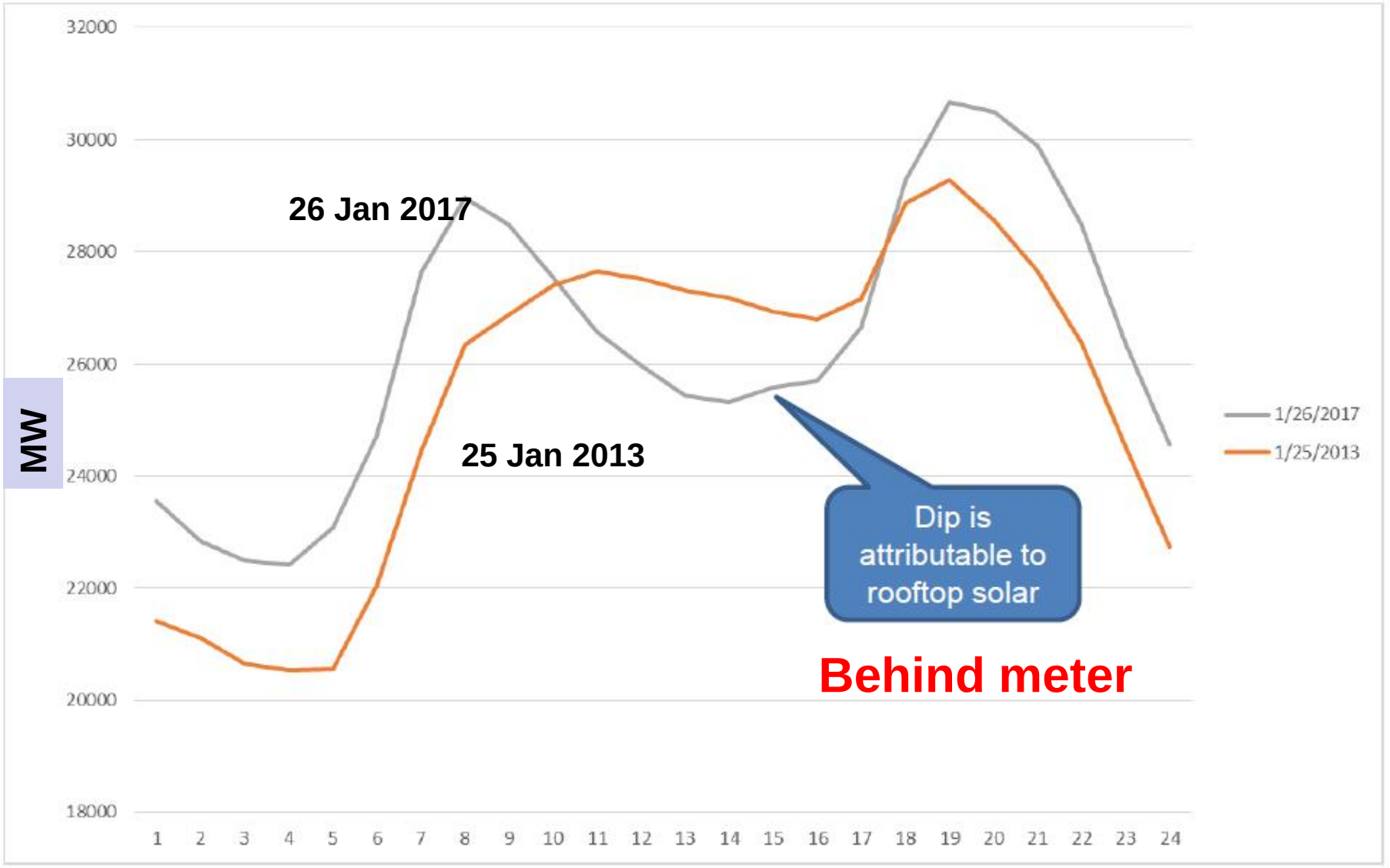
24 hour day

ISO working on a 50% duck curve

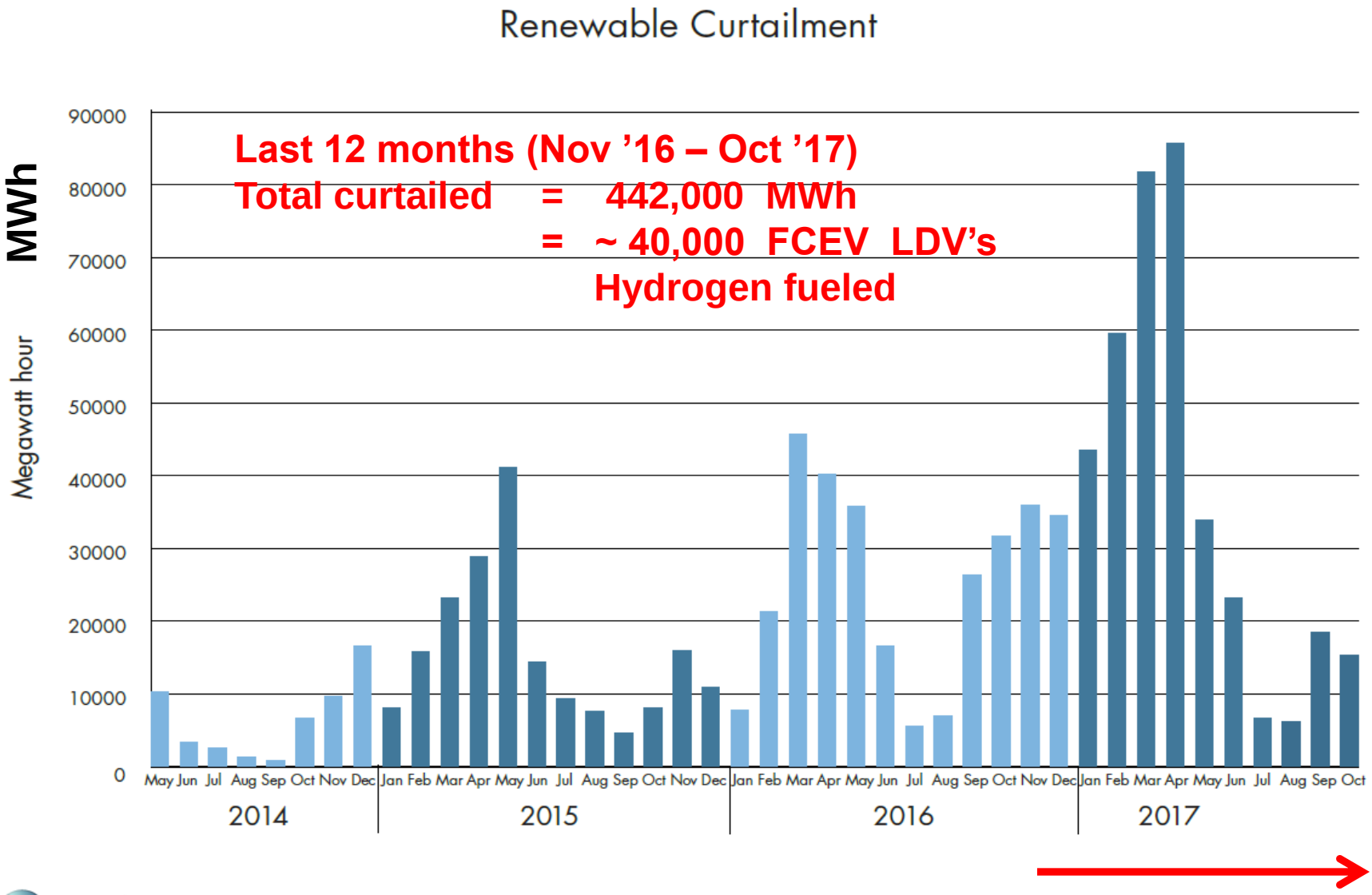


24 hour day

NOT the Duck: ISO gross load curve is changing



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



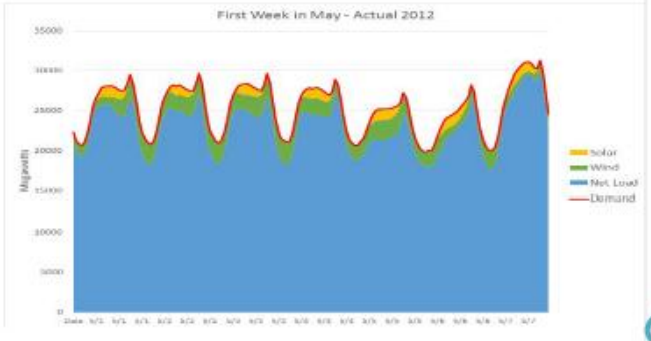
CA: Fuel 40,000 FCV's today –

- With curtailed wind + solar
- Water electrolysis @ 55 kWh / kg H2
- 15,000 miles / year, LDV's
- Wasted clean energy
- Stranded: No elecricity transmission, pipelines
- No electricity storage
- Future curtailment bigger
- Stifle new wind + solar: Limits cash flow

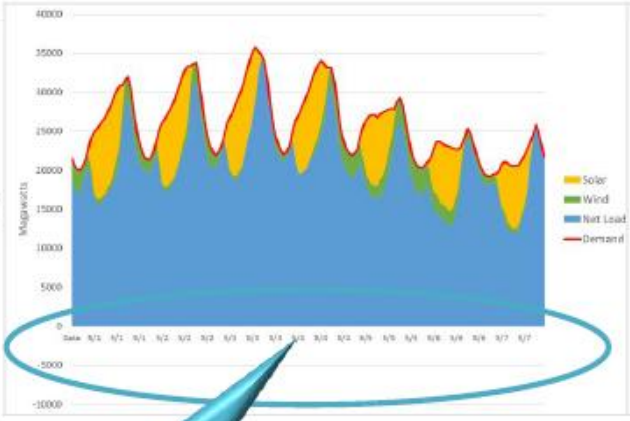
Evolving structure of power supply - California **Electricity sector**

Huge ramp rates up and down

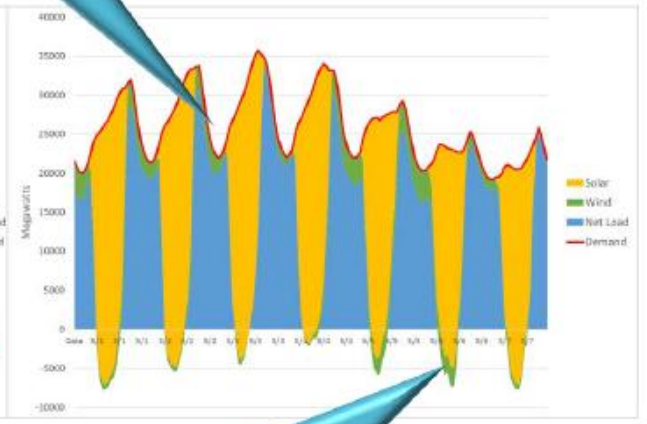
First week of May 2012 (actual)



First week of May 2017 (actual)



First week of May 2030 (modelled)



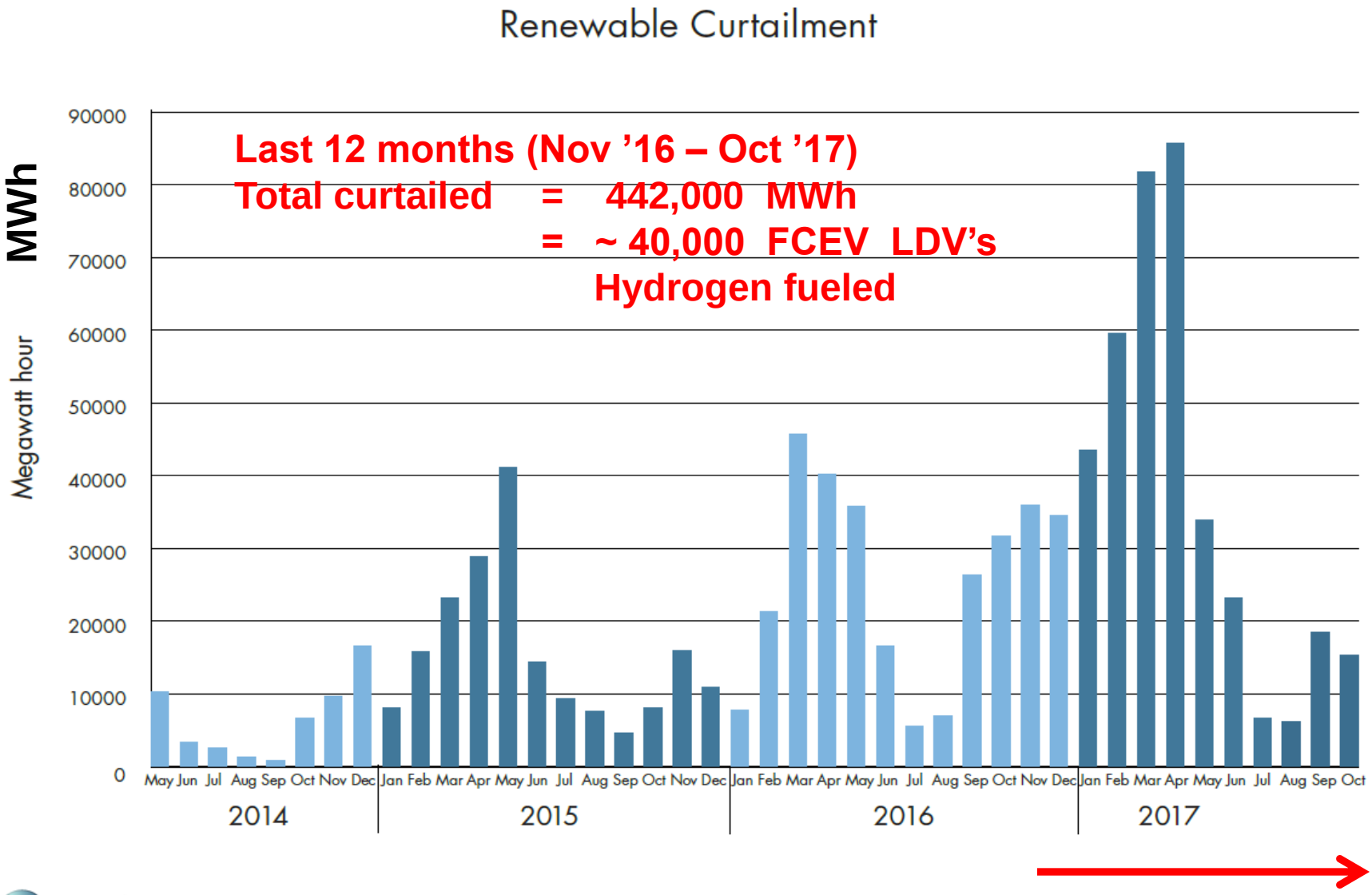
No more "baseload"

Lots of DR, storage and export - or curtailment

Or Hydrogen, Ammonia Production: Transport + CHP fuel

Source: CAISO; CEC proposed IRP; LM Power; Bloomberg New Energy Finance

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



CA: Fuel ??? FCV's in 2030 –

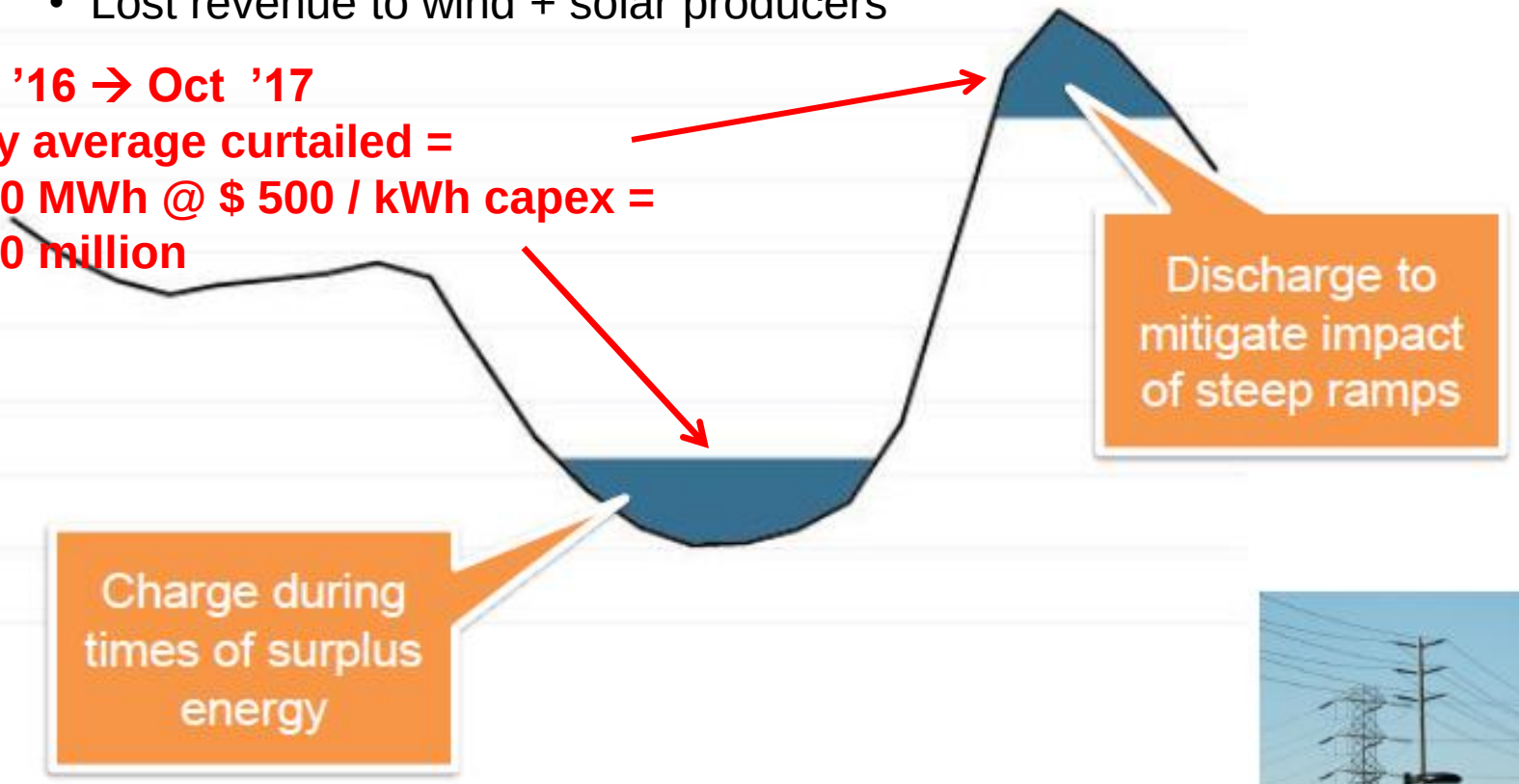
- **New Hydrogen pipeline system ?**
- **Rising Hydrogen transport fuel demand**
- With curtailed wind + solar
- **Plus wind + solar dedicated to Hydrogen**
- Water electrolysis @ 55 kWh / kg H2
- 15,000 miles / year, LDV's
- Wasted clean energy
- No transmission
- No storage
- Future curtailment bigger
- Stifle new wind + solar
- Limits cash flow

Relief !

Diurnal electricity storage to mitigate operational problems:

- Grid stability
- Steep PM ramp
- Rapid variation in wind + solar output
- Lost revenue to wind + solar producers

Oct ’16 → Oct ’17
Daily average curtailed =
1,200 MWh @ $ 500 / kWh capex =
$ 600 million

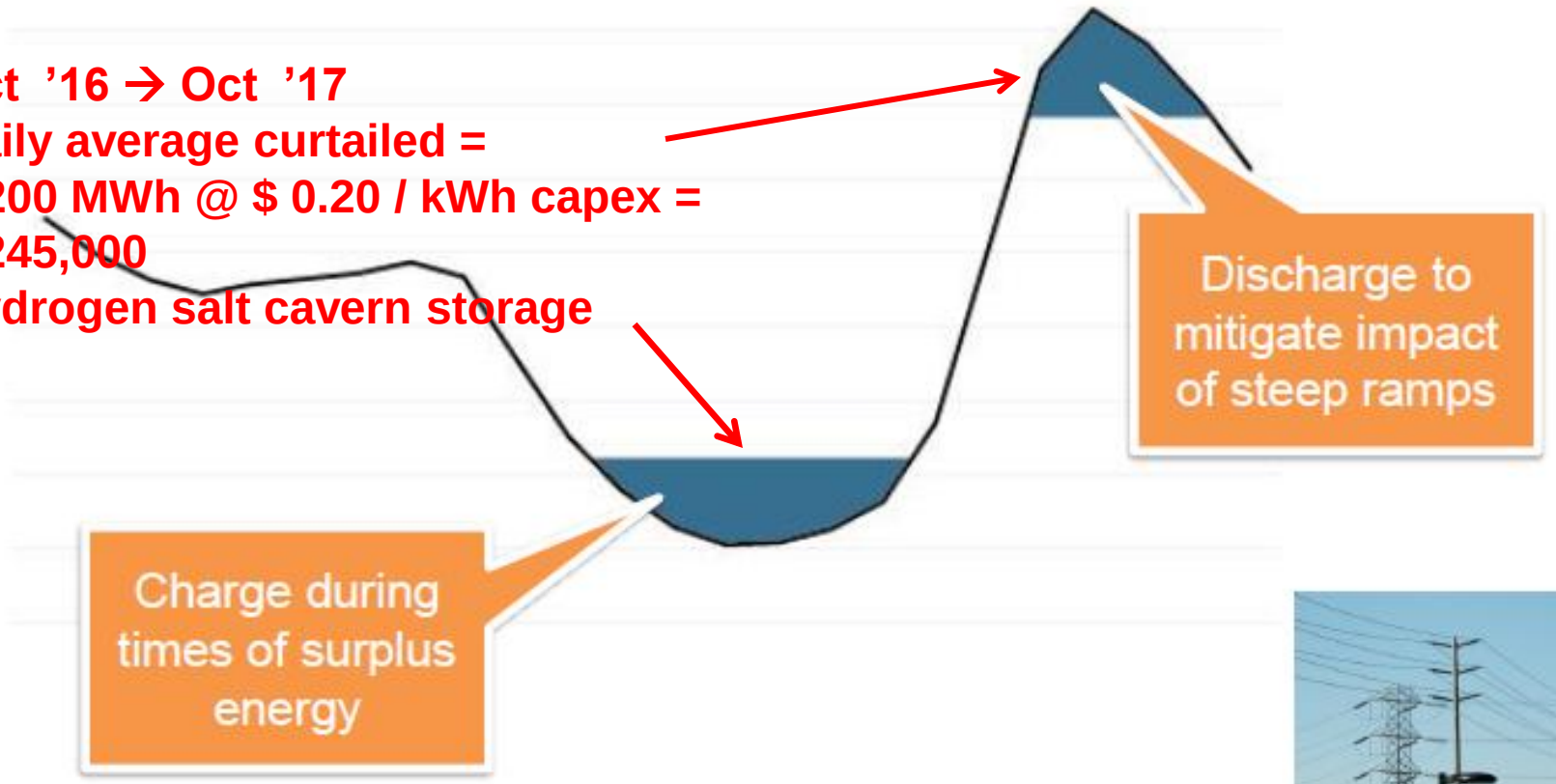


TESLA 20 MW / 80 MWh battery
SCE Mira Loma Battery Storage Facility
Ontario, CA
@ $ 500 / kWh capex = $ 40 million

Hydrogen storage to mitigate operational problems:

- Low-cost, annual-scale storage
- Requires CA-scale, continental-scale hydrogen pipeline network
- Transport and CHP fuels

Oct ’16 → Oct ’17
Daily average curtailed =
1,200 MWh @ $ 0.20 / kWh capex =
$ 245,000
Hydrogen salt cavern storage



TESLA 20 MW / 80 MWh battery
SCE Mira Loma Battery Storage Facility
Ontario, CA
@ $ 500 / kWh capex = $ 40 million

California Hydrogen Transport Policies:

- **> Set stage**
- **> Launch**
- **> Scale-up**

Renewable and low-to zero–C energy requirements

- RPS: Renewable Portfolio Standard -- electricity
- SB100 failed: 100% elec in 2045
- LCFS: Low Carbon Fuel Standard
- SB1505: 1/3 of Hydrogen “renewable”

Vehicle emissions requirements

- ZEV Regulation: Zero Emission Vehicle
- AB8: 100 Hydrogen fuel stations, ARFVT
- Sustainable Freight Action Plan
- Ports Clean Air Action Plan

Hydrogen Fuel Cell Bus

Toyota Mirai Fuel Cell car: Hydrogen fuel only

Mercedes-Benz - Ford

Mercedes-Benz B-class Fuel Cell car

Honda - GM

Honda “Clarity” fuel cell car
2016 production

Hyundai Tucson Fuel Cell

3 - minute Hydrogen fueling

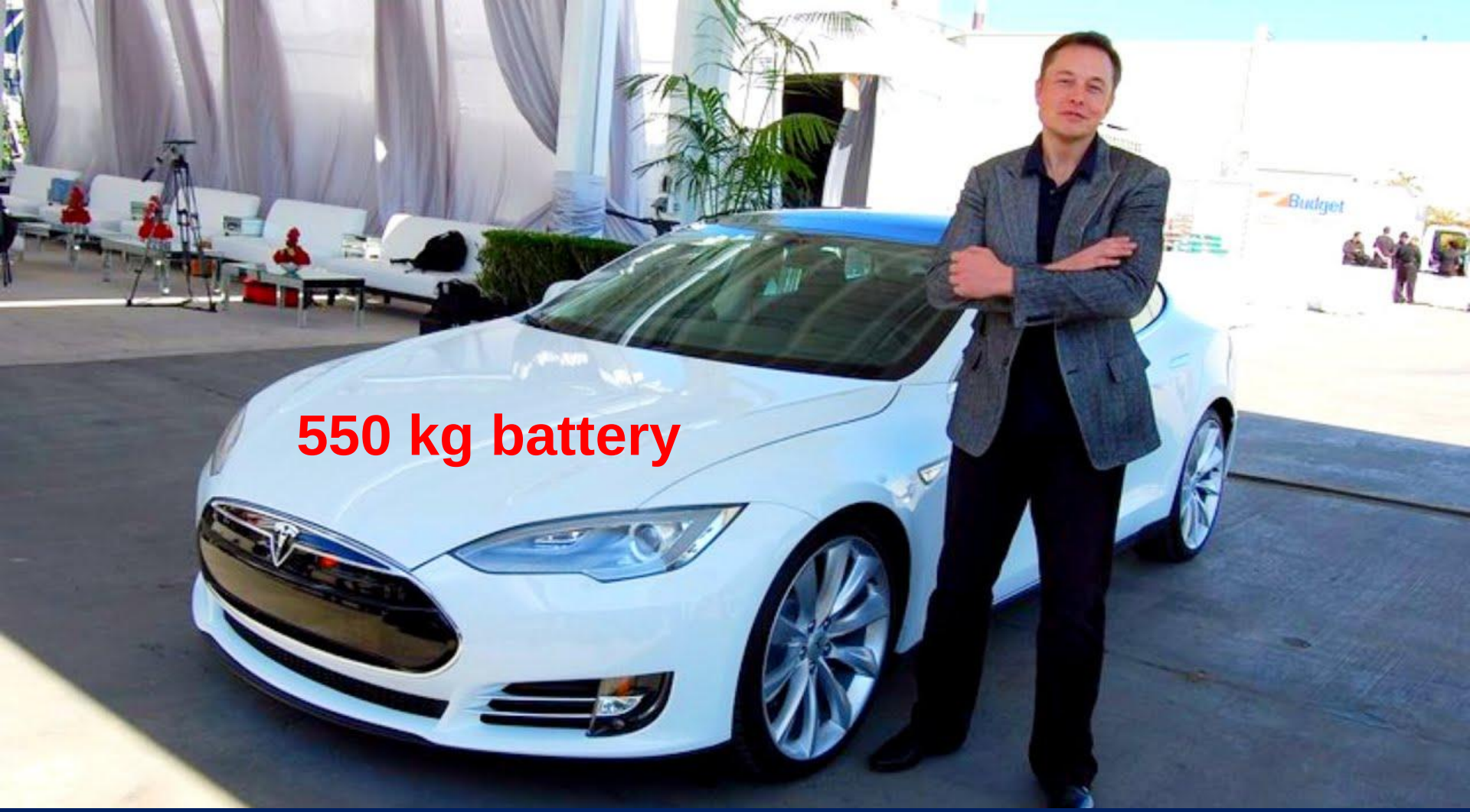
Hydrogen fueling the Honda “Clarity” Fuel Cell car
3 minutes

Toyota Fuel Cell Electric Truck

Hydrogen-fueled Class 8 “electric” tractor

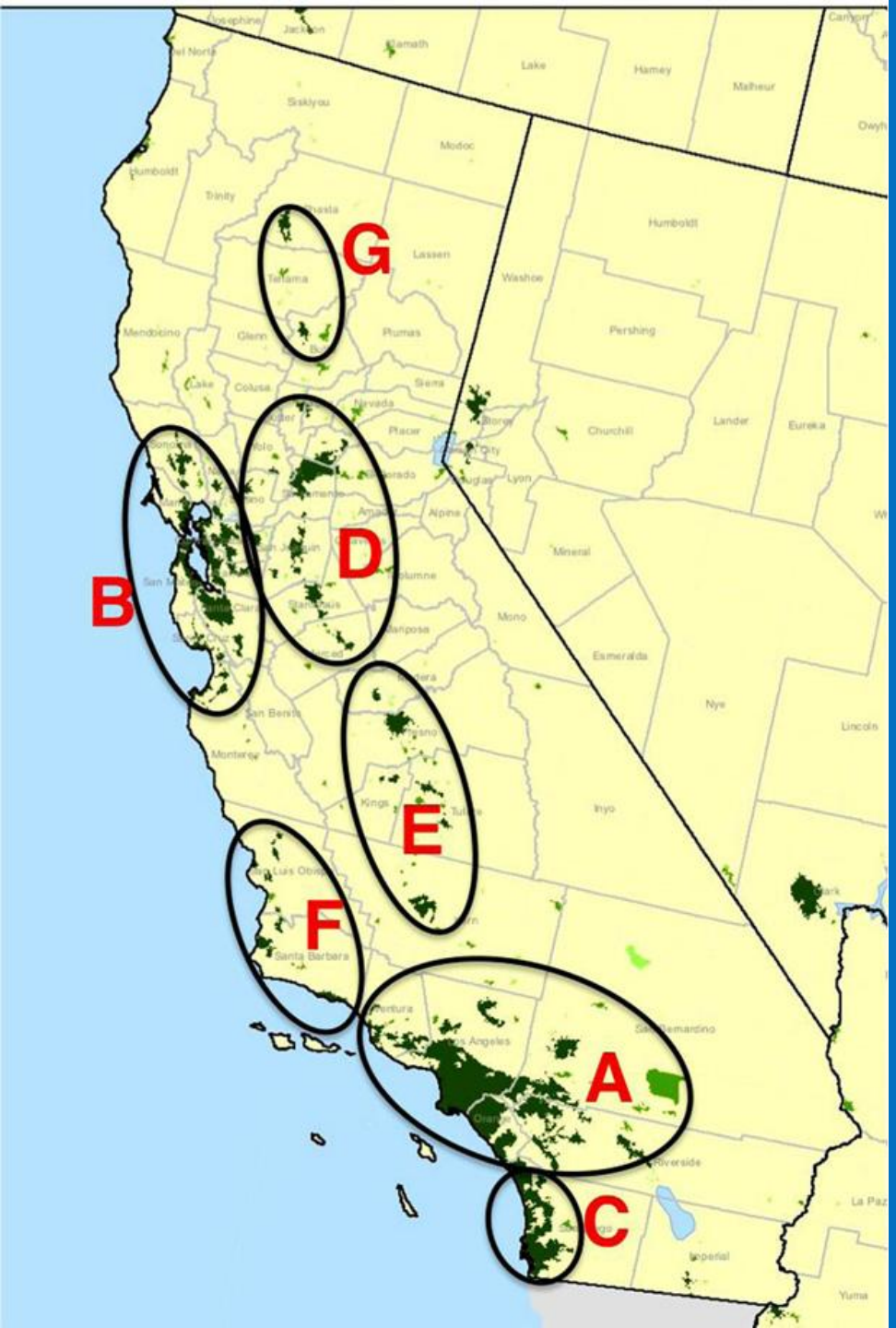
Two Toyota “Mirai” fuel cells: total drive power

“Nikola One” Fuel Cell Truck – Class 8 tractor



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 …"

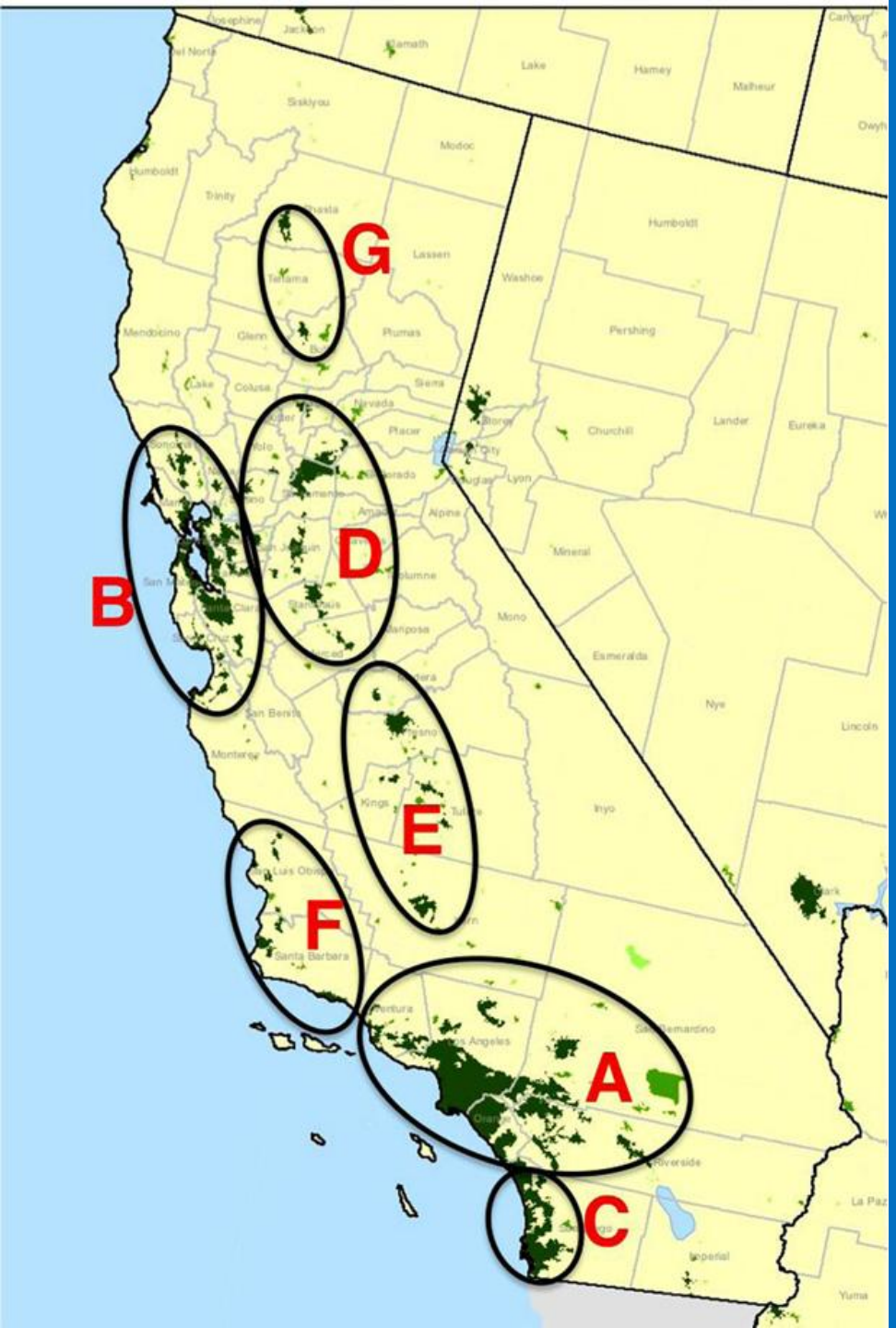


IF: Year 2050 California both:

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

Southern CA Hydrogen Stations

Open

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

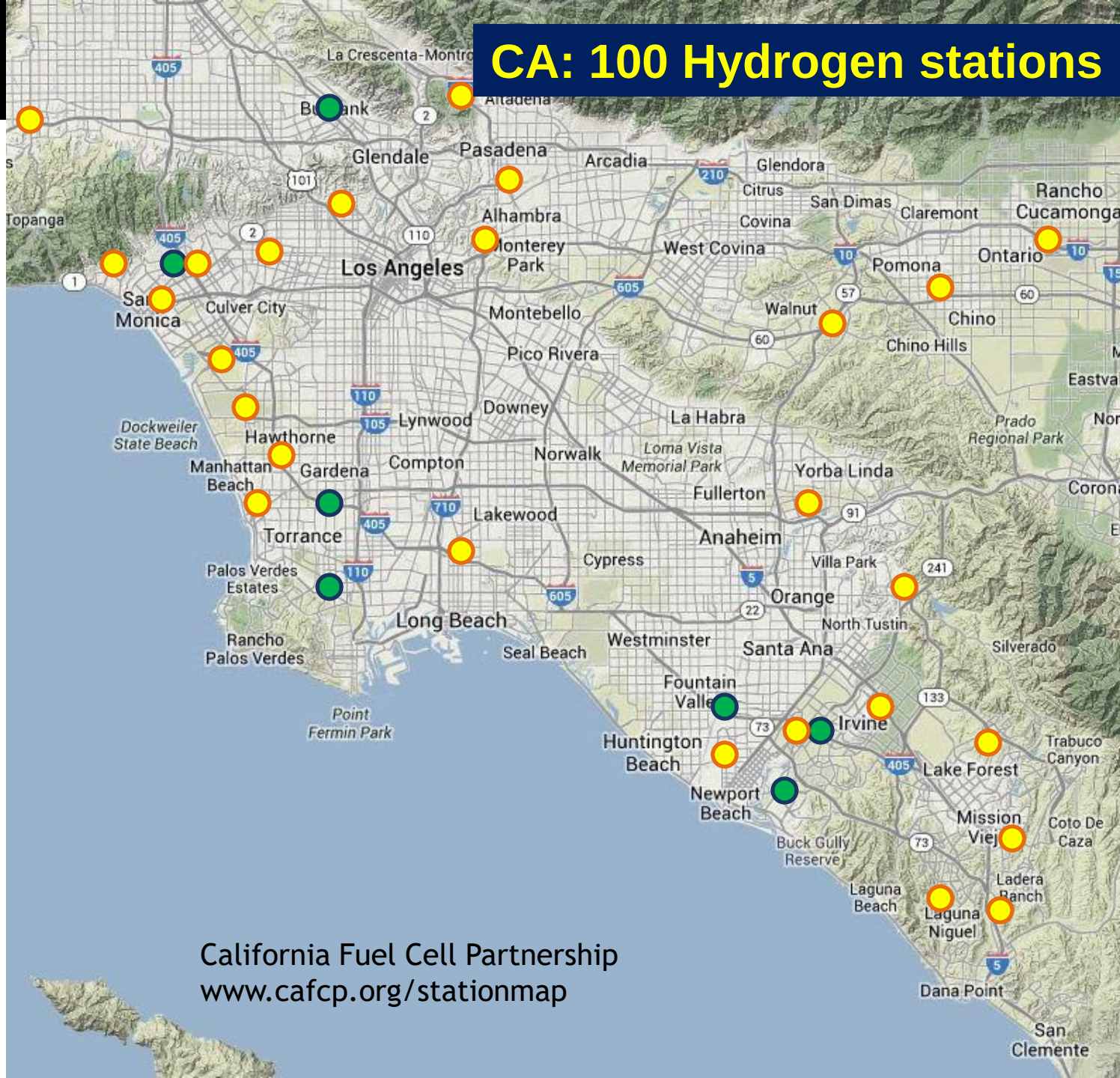
In Development

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

CA: 100 Hydrogen stations



California Fuel Cell Partnership
www.cafcp.org/stationmap

January 2015

Northern CA Hydrogen Stations

Open

Emeryville – AC Transit

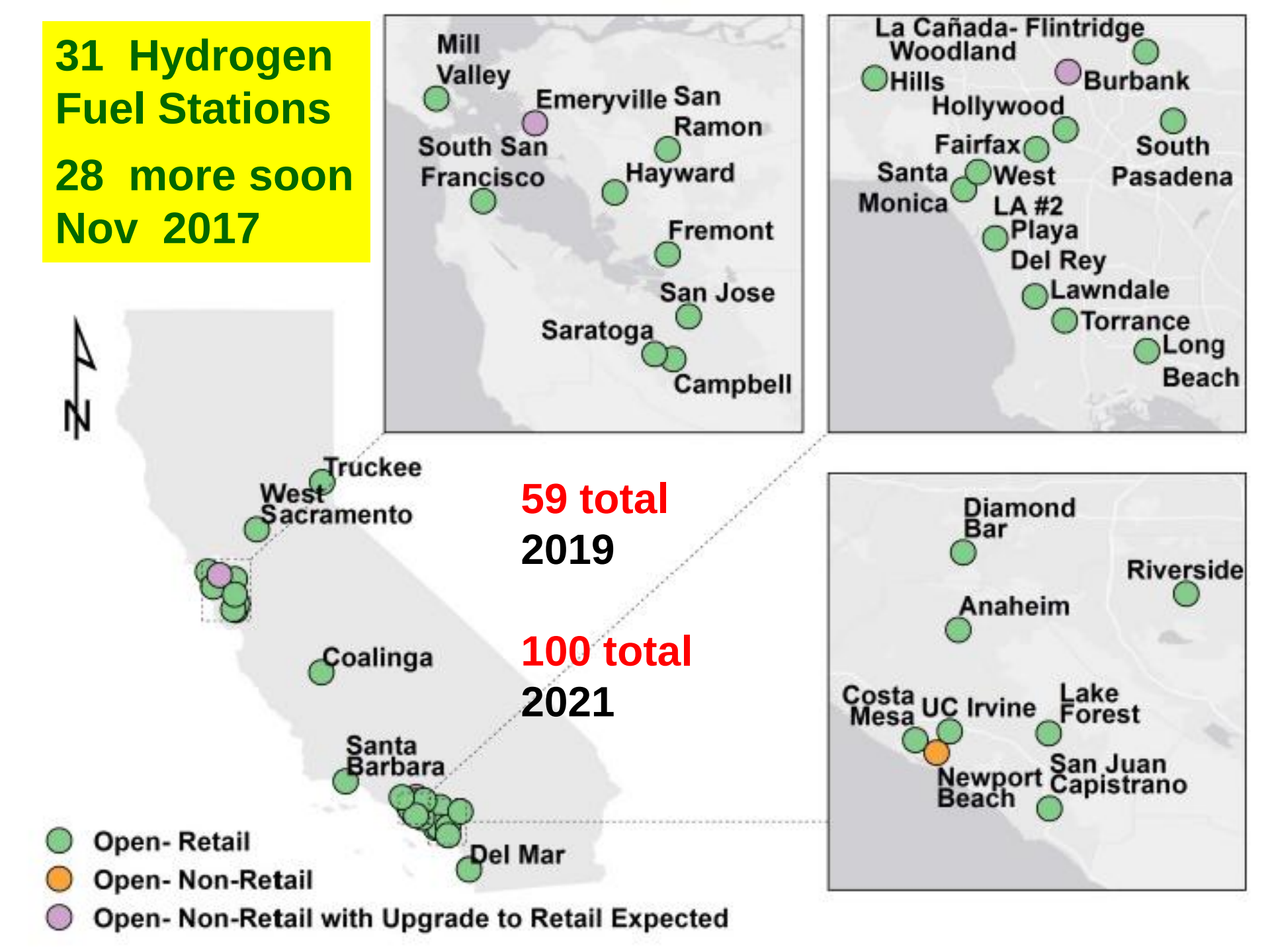
In Development

Cupertino
Foster City
Mountain View
*West Sacramento

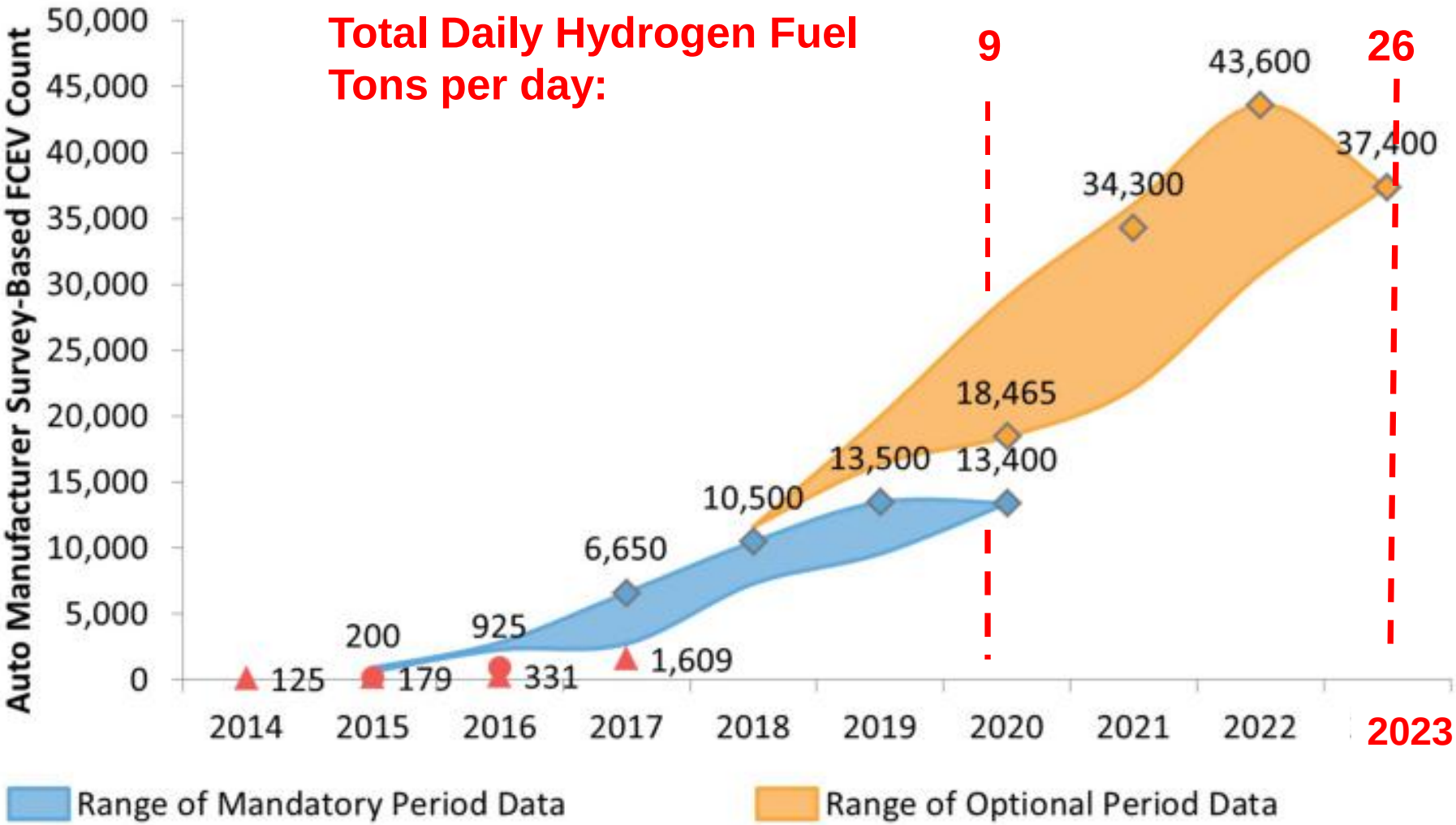
Campbell
Hayward
Mill Valley
Oakland
Palo Alto
Redwood City
*Rohnert Park
San Jose
San Ramon
Saratoga
South San Francisco
*Truckee
Woodside

*Not shown on map

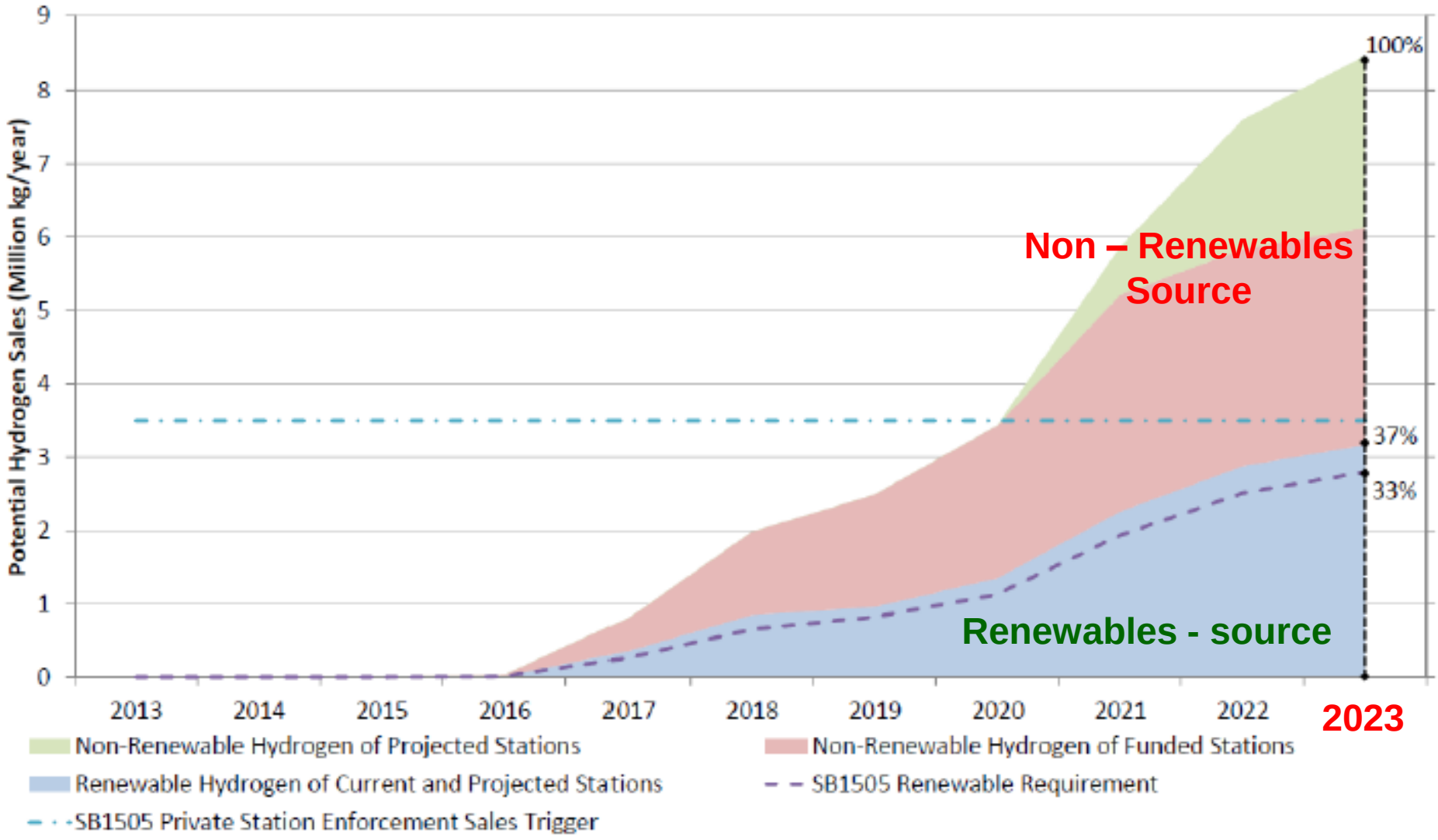
California Fuel Cell Partnership
DRIVING FOR THE FUTURE
Managed by BKi


31 Hydrogen Fuel Stations
28 more soon Nov 2017
Mill Valley
Emeryville
San Ramon
South San Francisco
Hayward
Fremont
San Jose
Saratoga
Campbell
La Cañada- Flintridge
Woodland Hills
Burbank
Hollywood
Fairfax
South Pasadena
Santa Monica
West LA #2
Playa Del Rey
Lawndale
Torrance
Long Beach
N
Truckee
West Sacramento
59 total
2019
100 total
2021
Diamond Bar
Riverside
Anaheim
Coalinga
Costa Mesa
UC Irvine
Lake Forest
Santa Barbara
Newport Beach
San Juan Capistrano
Del Mar
Open- Retail
Open- Non-Retail
Open- Non-Retail with Upgrade to Retail Expected

California FCEV's: carmaker estimates, to 2023



Potential Hydrogen Fuel Sales, California
Thousands Tons / year To 2023

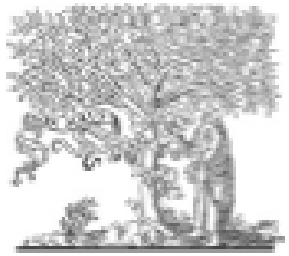


UC Davis – ITS – STEPS Joan Ogden, et al

Institute of Transportation Studies – ITS

Sustainable Transportation Energy Pathways – STEPS

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



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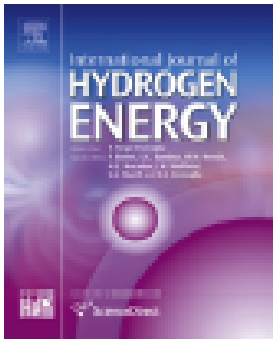


Renewable and low carbon hydrogen for California – Modeling the long term evolution of fuel infrastructure using a quasi-spatial TIMES model

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

California, Year 2050, if ALL are true :

- Electricity RPS
- “ 80 in 50 “ Transport
- Same modal mix
- FCEV’s displace BEV’s, except LDV’s
- CA builds Hydrogen pipeline net
- Many Hydrogen fueling stations

RPS	Renewable Portfolio Standard, electricity sector
FCEV	Fuel Cell Electric Vehicle, Hydrogen fueled
LDV	Light Duty Vehicle

California, Year 2050, both:

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

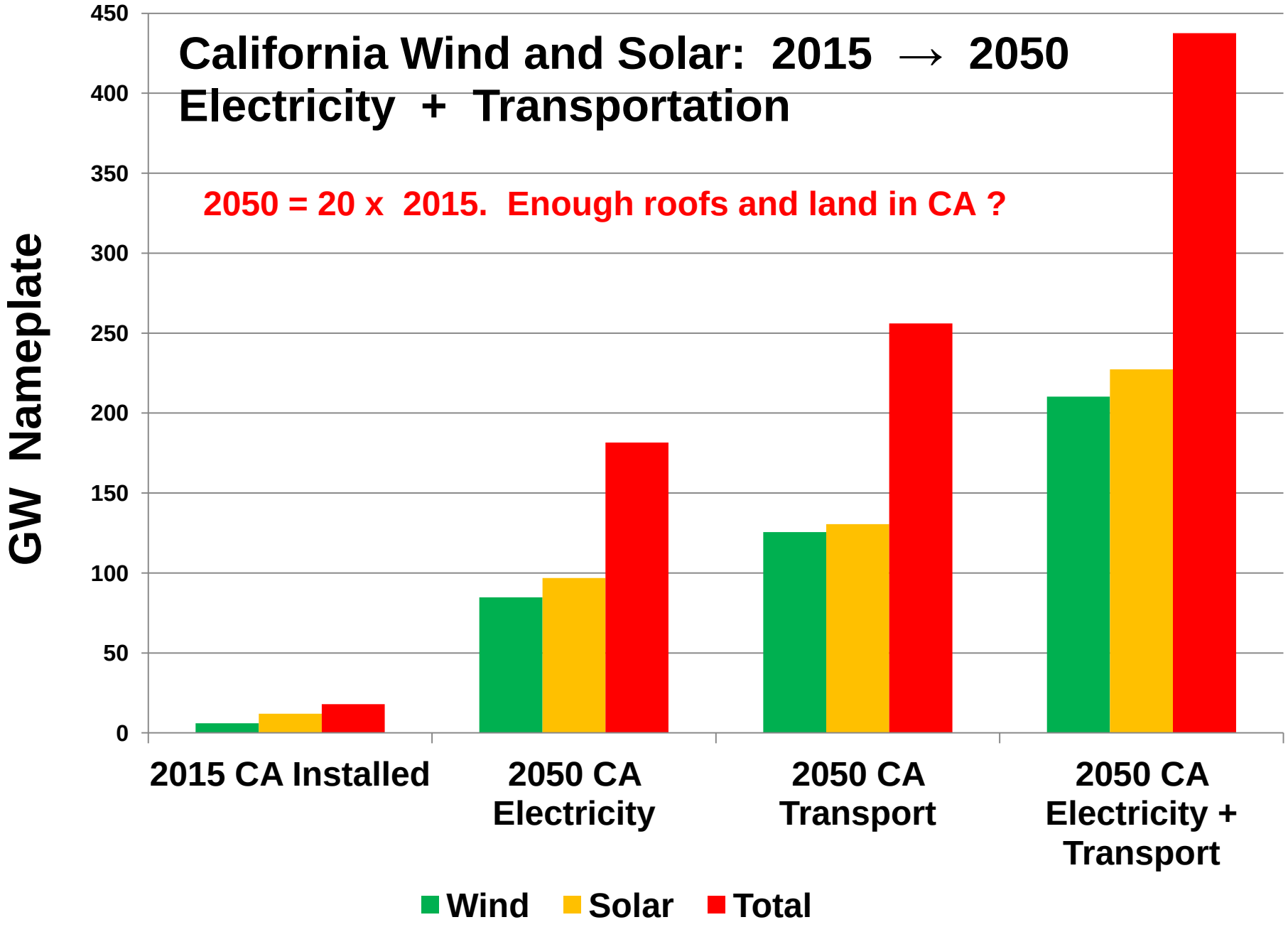
- 210 GW wind = 35 times Year 2015 installed wind - electricity capacity in CA

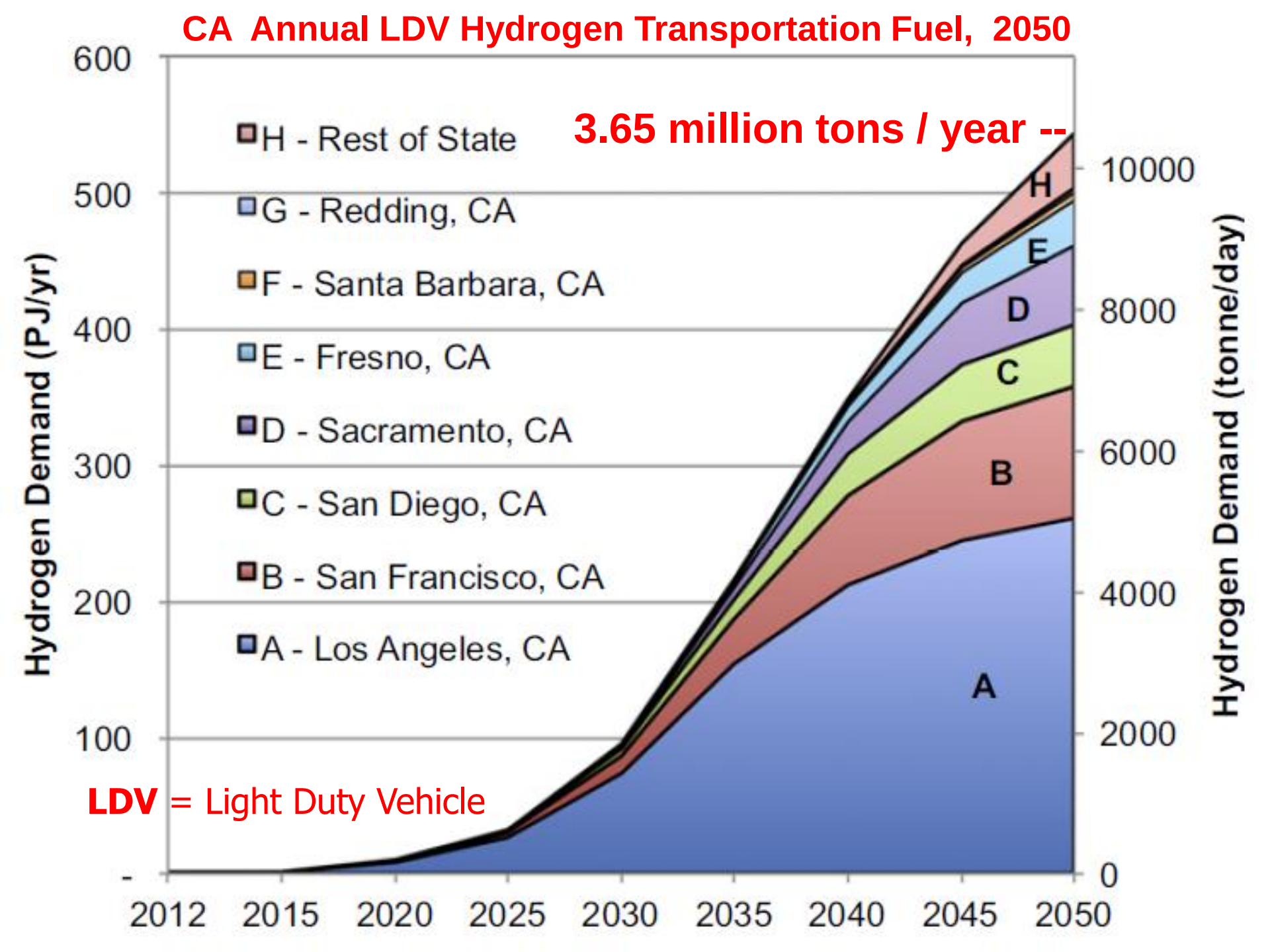
PLUS

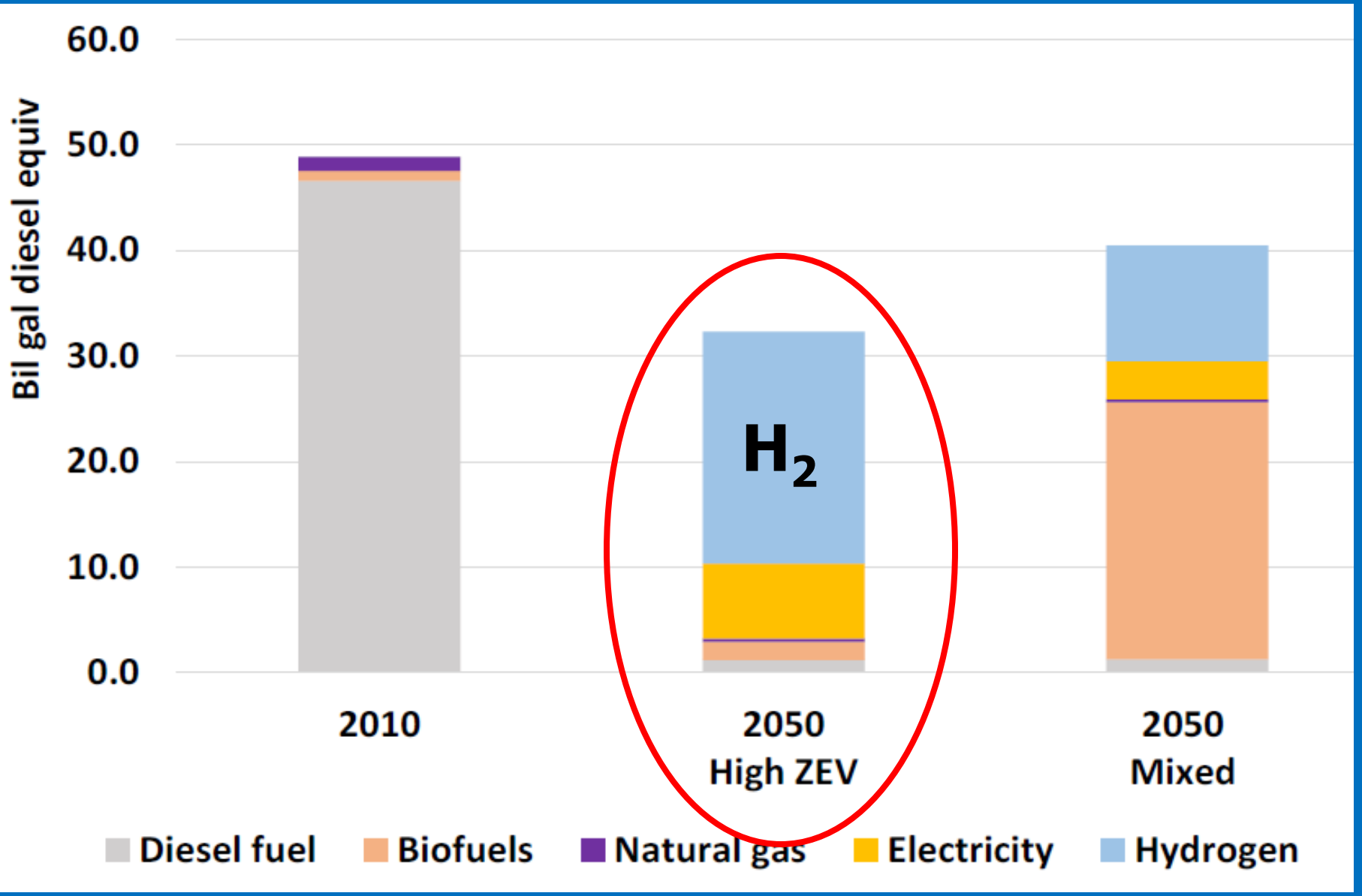
- 230 GW solar = 19 times Year 2015 installed solar - electricity capacity in CA

Total = 440 GW nameplate

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


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


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



California trucking: "Goods movement"

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

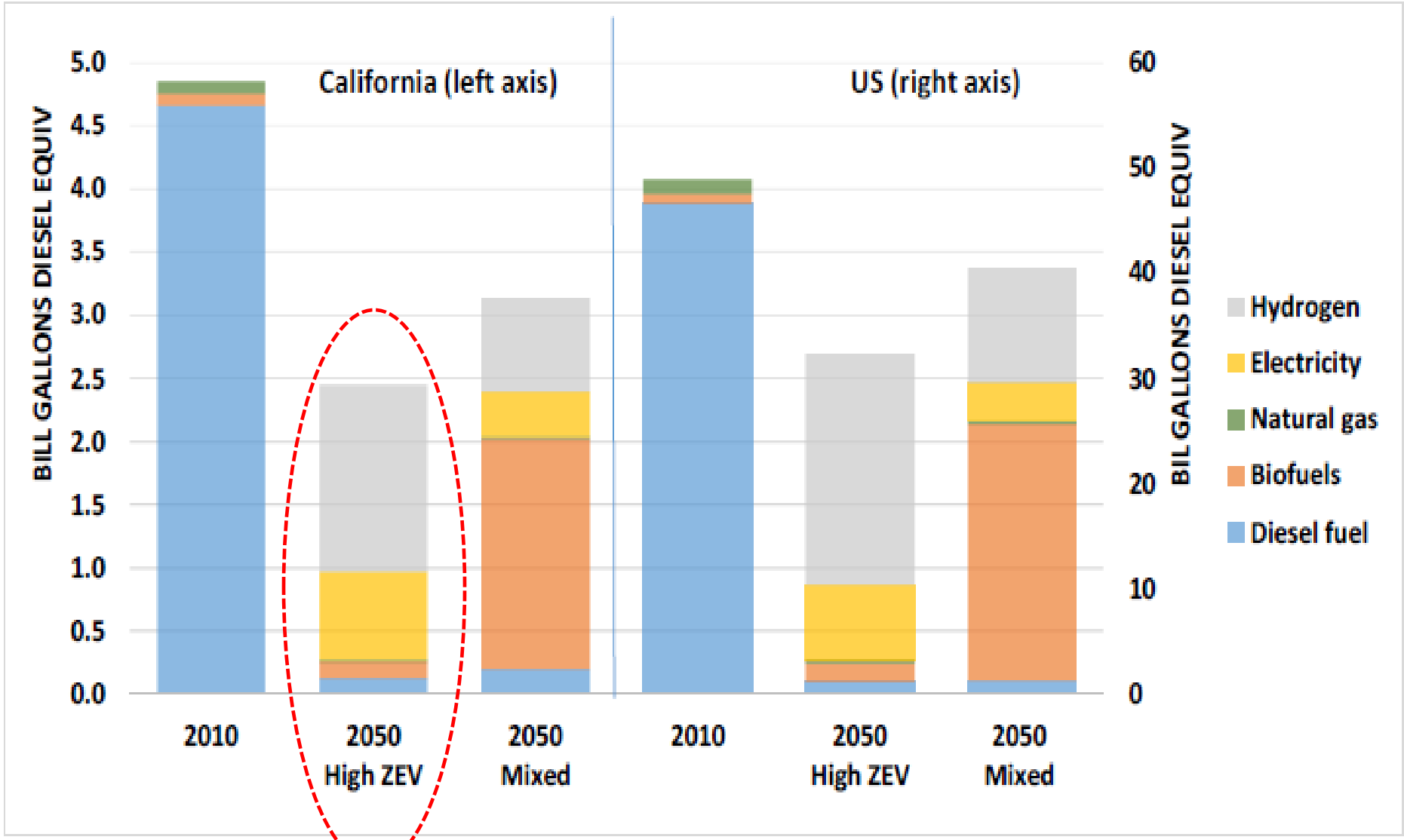


Figure ES-2. Energy use by fuel type, year and scenario, California and U.S. results

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:

IF:

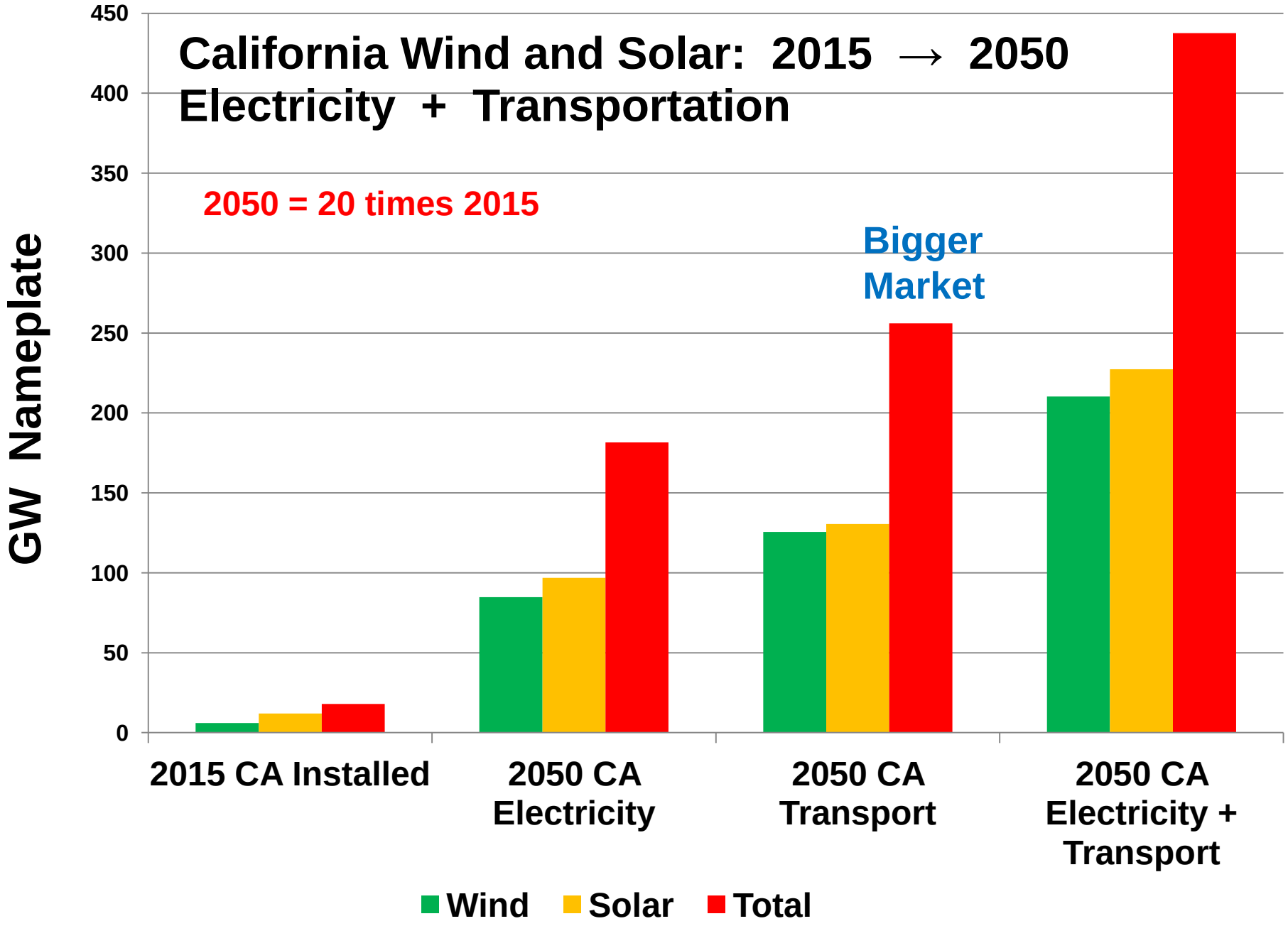
- CA meets RPS and "80 in 50" goals
- Hydrogen-fueled FCHEV's displace BEV's
- CA builds new, underground, H2 pipeline system
- Transport modal mix same as 2016
- Many Hydrogen fueling stations (500 ?)

Then: **7.4 million tons per year**

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
Bigger Market
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

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**
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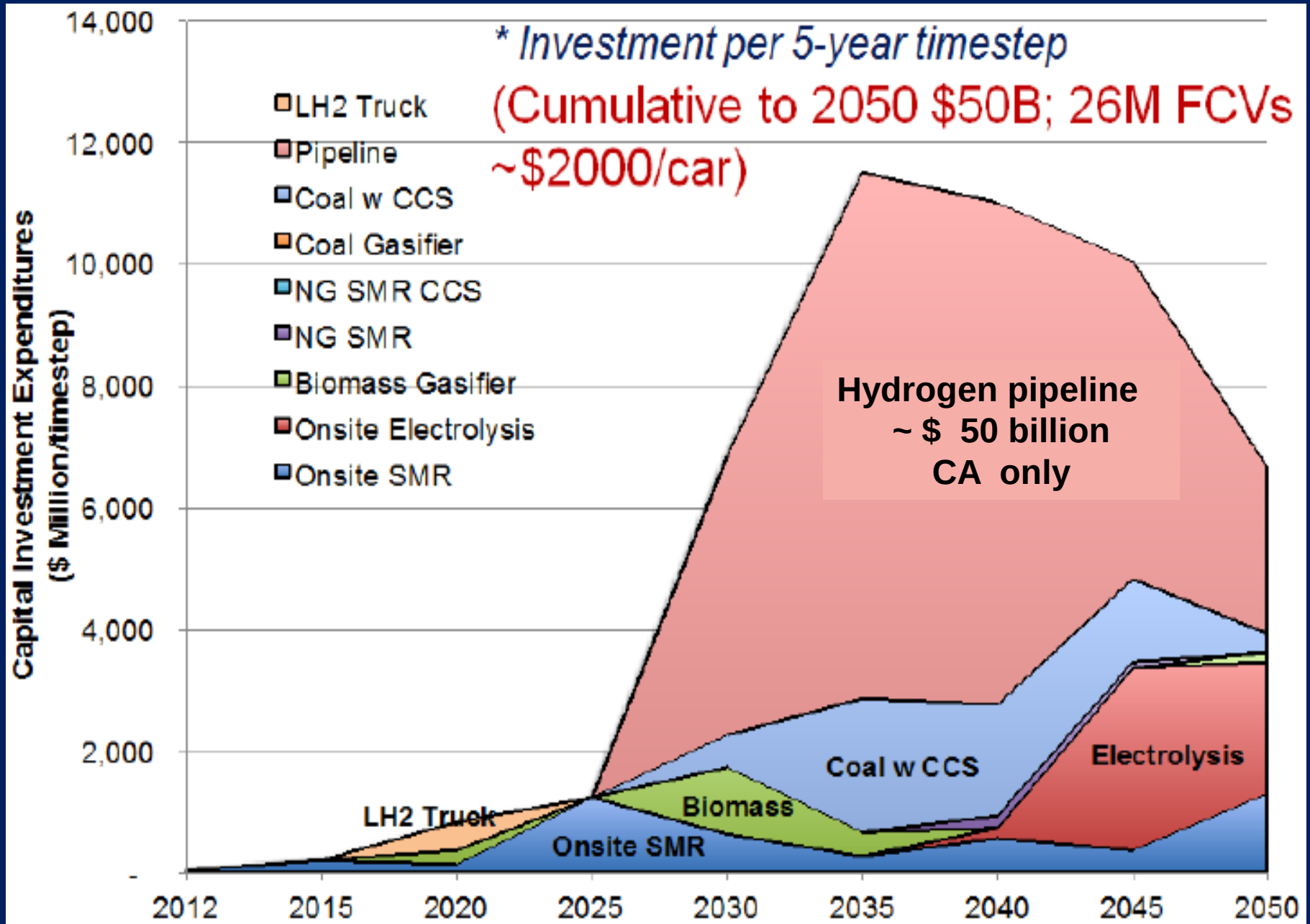
TOTAL CA RENEWABLE ELECTRICITY + TRANSPORT ENERGY in Year 2050	**GW**
Equivalent nameplate wind + solar + other @ CF (varies)	438

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

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

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

"Hydrogen Transition" UC Davis, ITS "NEXTSteps"



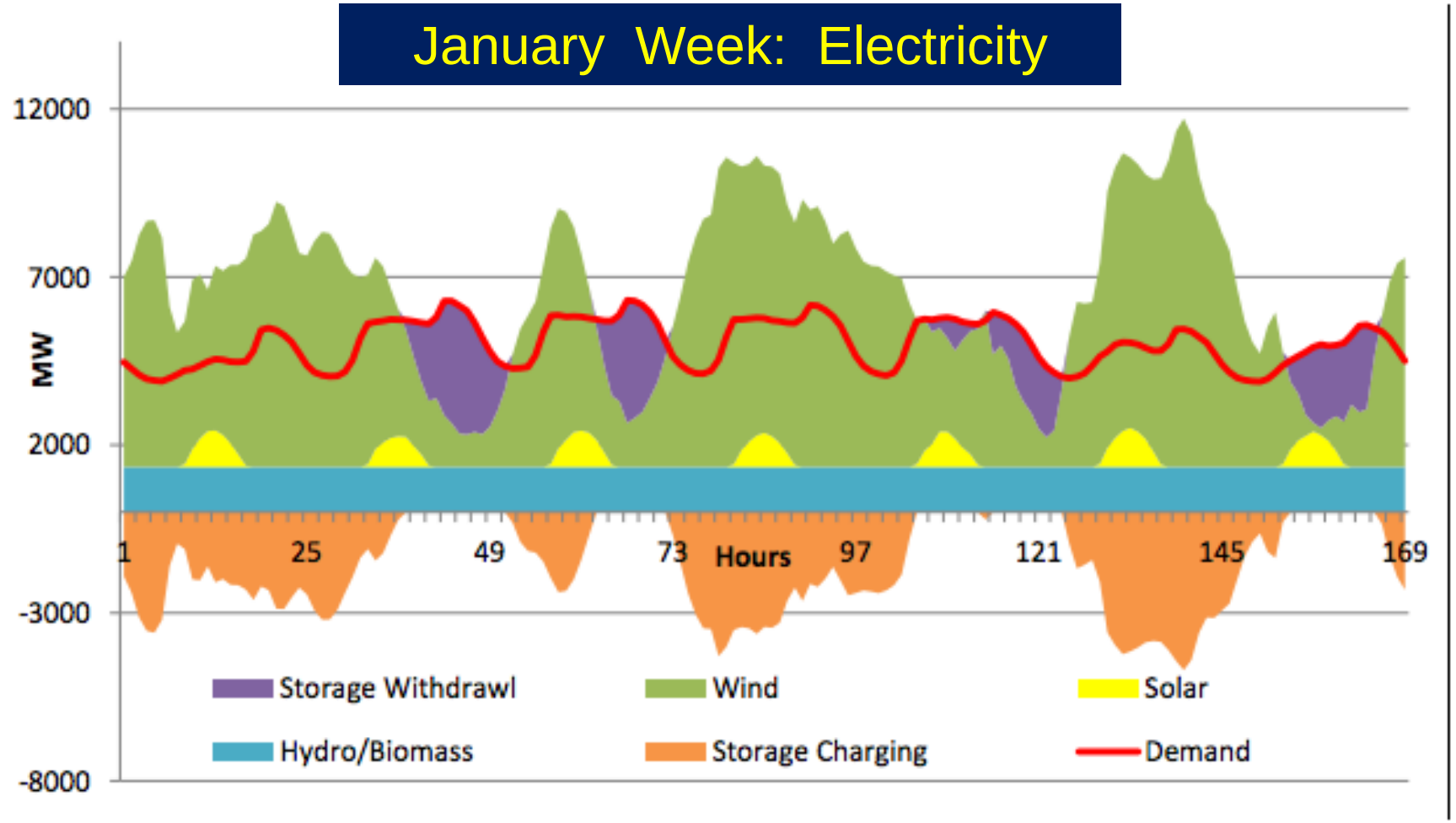
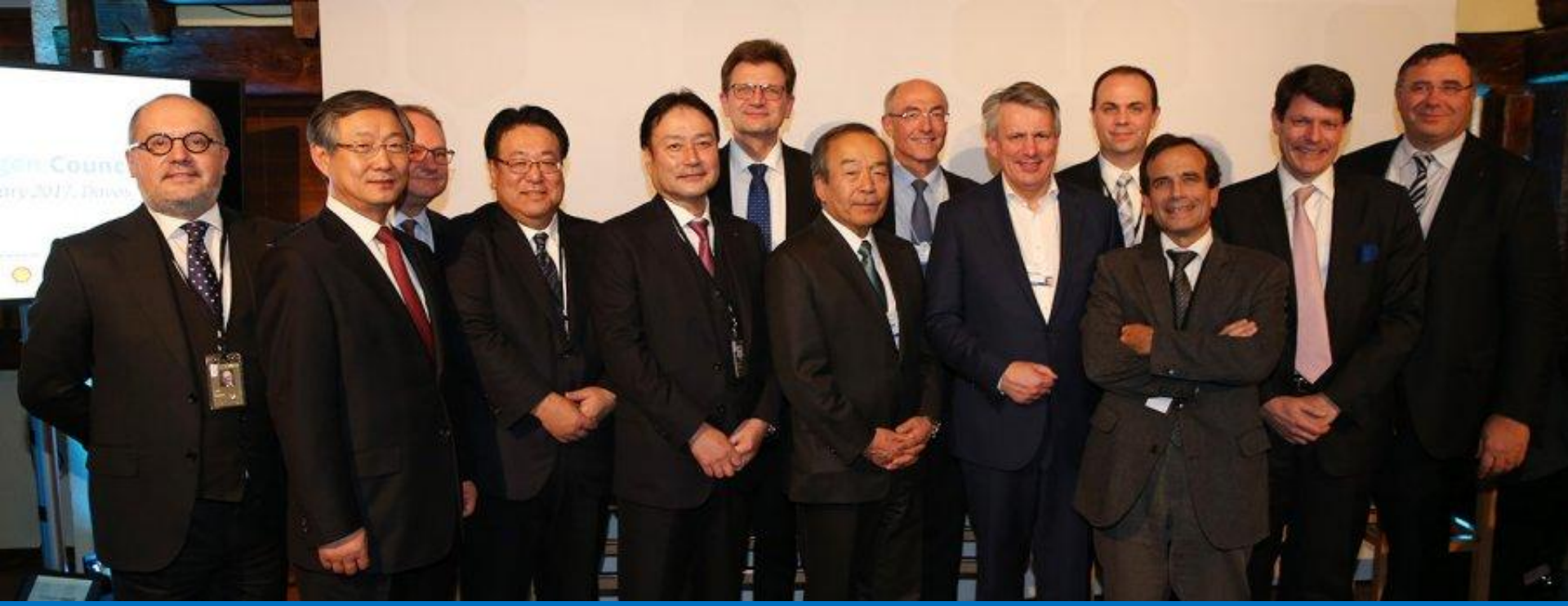


Figure III-6: Hourly supply and demand with storage, January 1-7, 2007. *Source: IEER.*

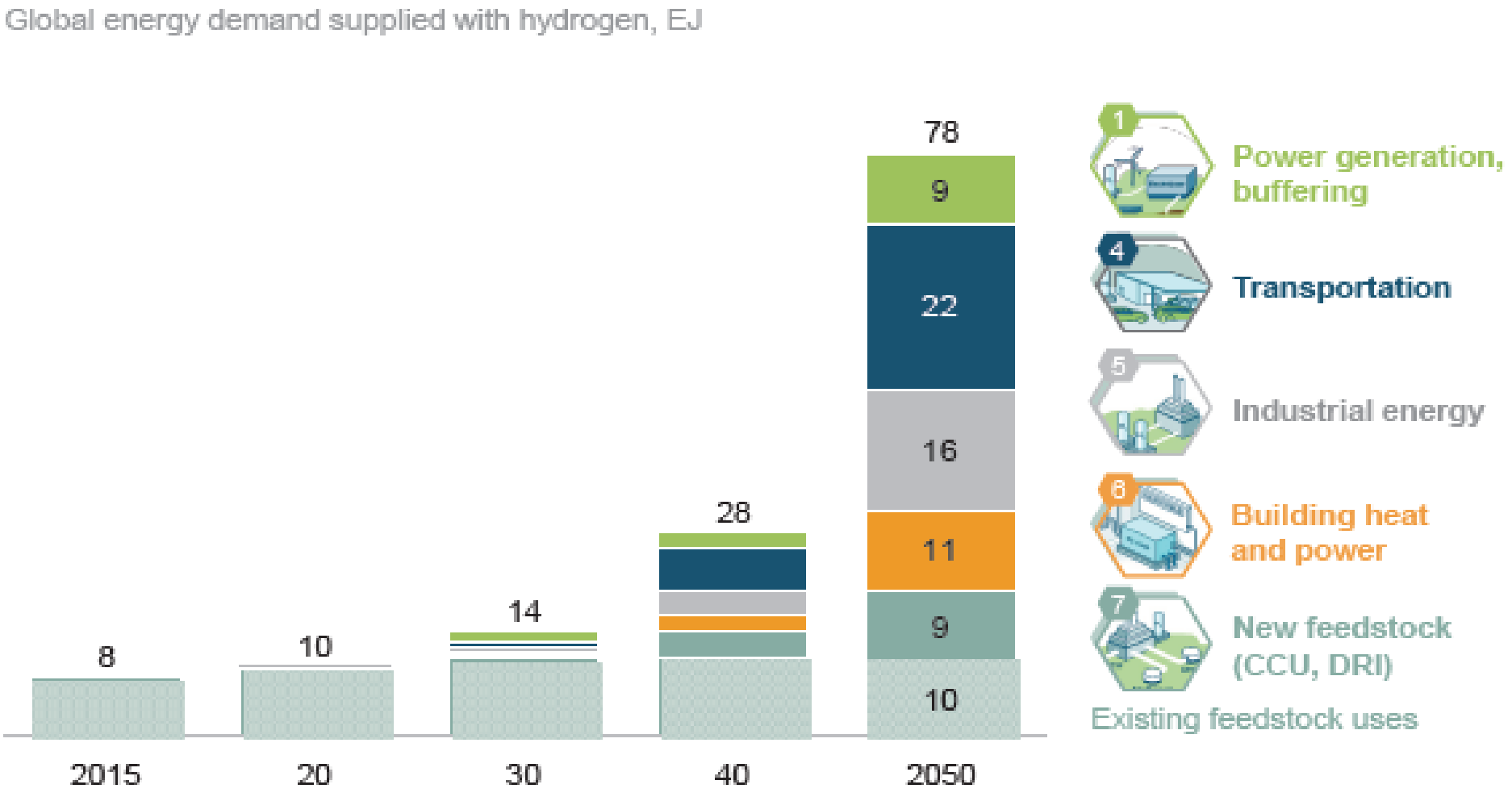
Minnesota: Hypothetical
100 % Renewable Electricity System in



Hydrogen Council
Brussels, 7 Sept 17 24 companies

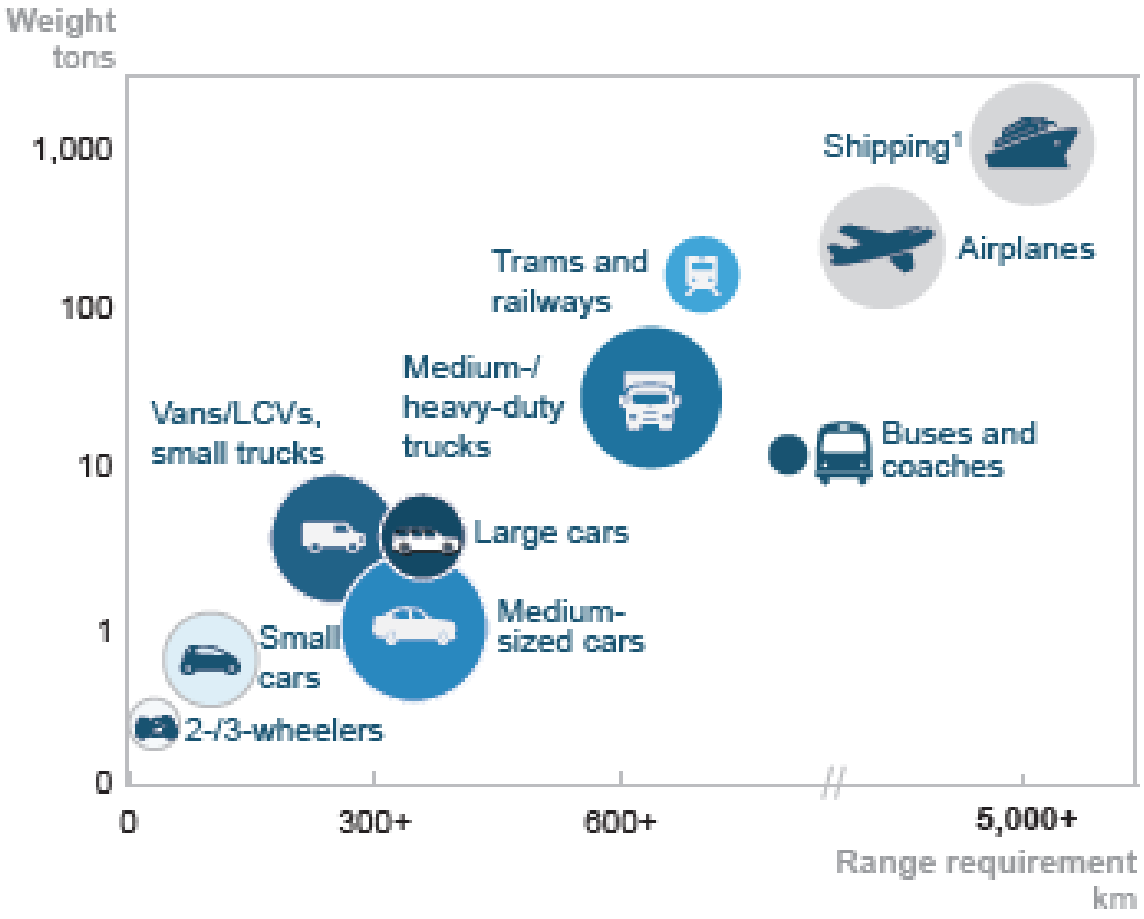
“ The Roadmap: Hydrogen, scaling up “

Global Hydrogen demand 10 x increase by 2050: EJ



Source: Hydrogen Council, Roadmap, Nov 2017

FCEVs help decarbonize transport: longer ranges and more weight



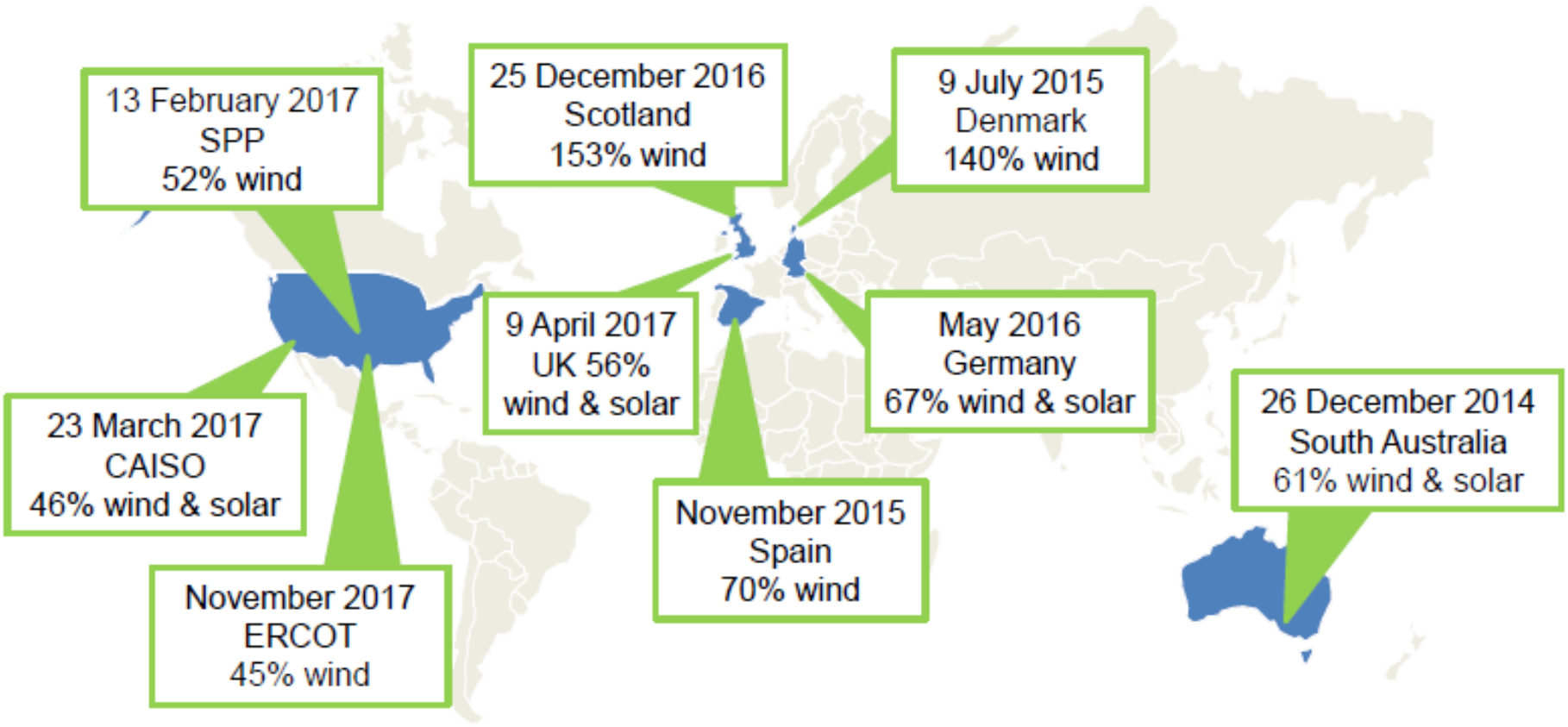
Bubble size roughly representing the annual energy consumption of vehicle type in 2050 (1 EJ)

Bubble color representing the market share of hydrogen vehicles in 2050

FCEV sales share 2050	FCEV fuel share 2050
<10%	Up to 5%
10-20%	
20-30%	
30-40%	
40-50%	
>50%	

Source: Hydrogen Council, Roadmap, Nov 2017

High Levels of Renewable Penetration



At what external costs ?

- **> Capex + Opex**
- **> Grid stability**
- **> Backup generation**

Source: Bloomberg New Energy Finance, various

Germany Hydrogen Fuel Stations 2023

H_2 Mobility

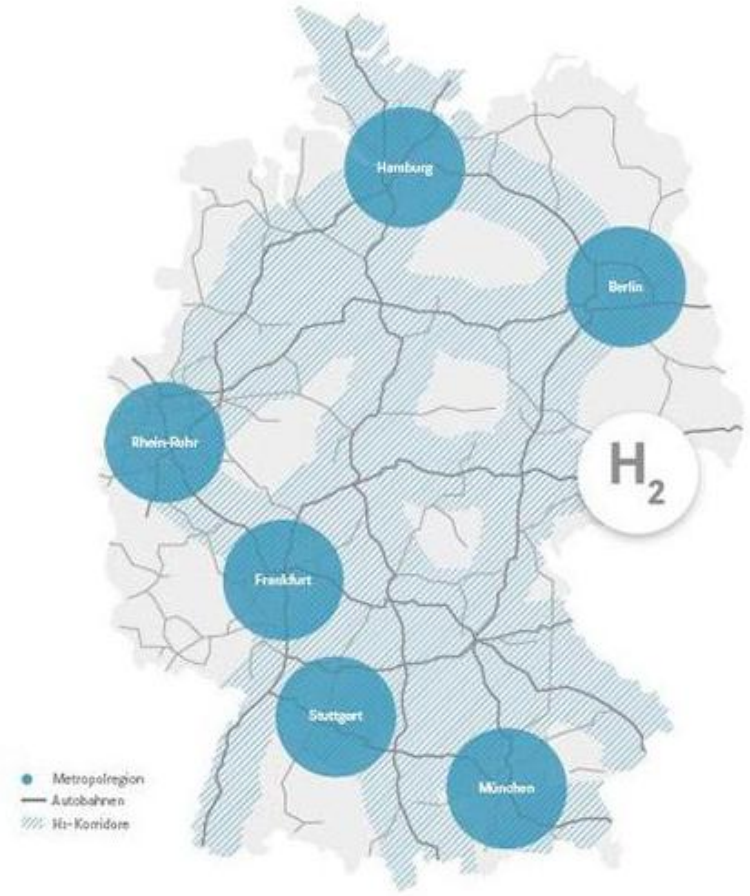
DAIMLER TOTAL AIR LIQUIDE OMV Linde

Partners:

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

Targets:

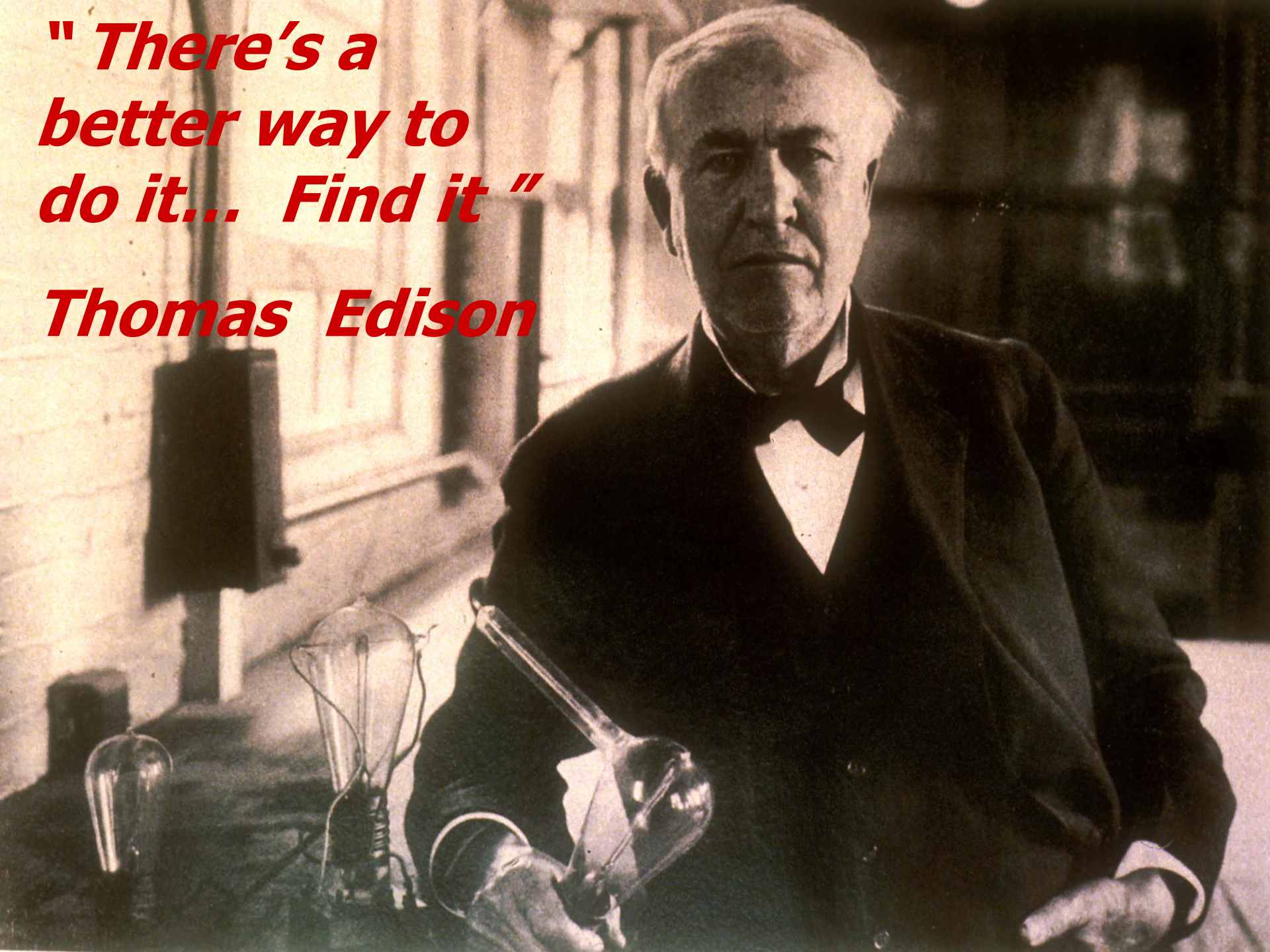
- **100 by 2017**
- **400 by 2023**
- **€ 350 million invest**
- **90 km max spacing on freeways**



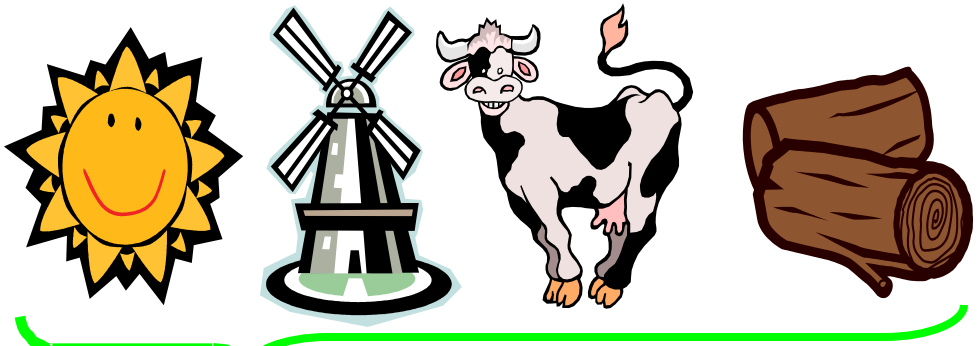
H_2 Mobility

Japan: Hydrogen Society has begun !
147 road fueling stations, June 2021

iwatani


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

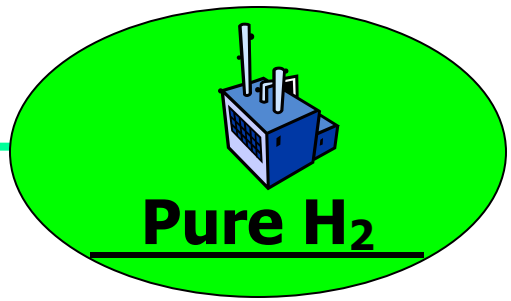
2006: The NATURALHY approach: EC, R+D



" Power – to – Gas "

H_2

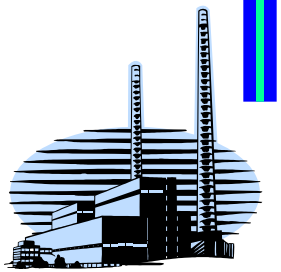
NG

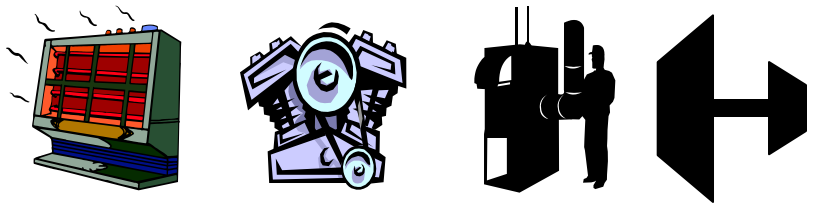


Pure H_2

NATURALHY:

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

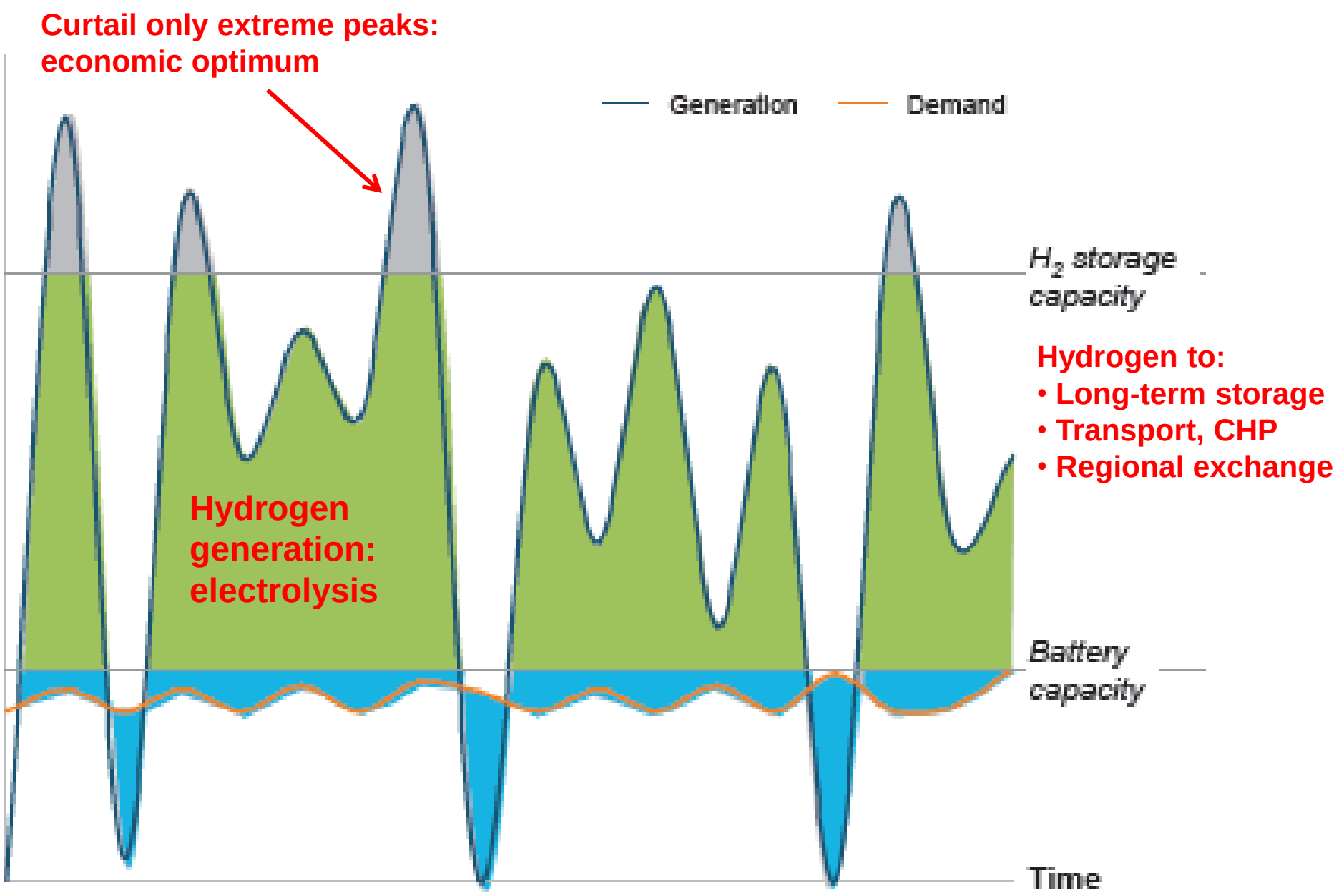




Prepared by
O. Florisson
Gasunie

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

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



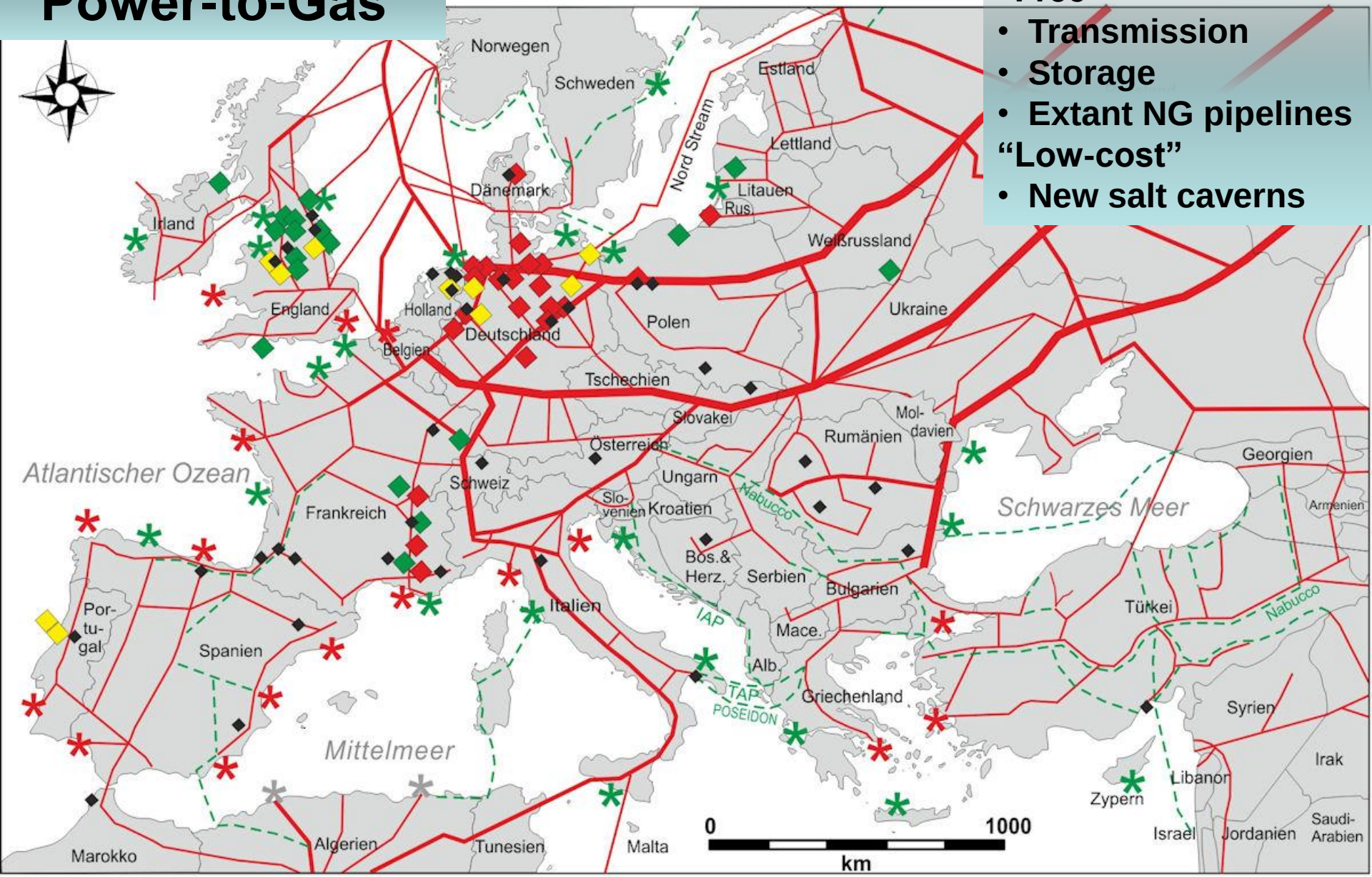
1 Demand-side load balancing, etc.

SOURCE: McKinsey

“Power-to-Gas”

“Free”
- **Transmission**
- **Storage**
- **Extant NG pipelines**

“Low-cost”
- **New 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

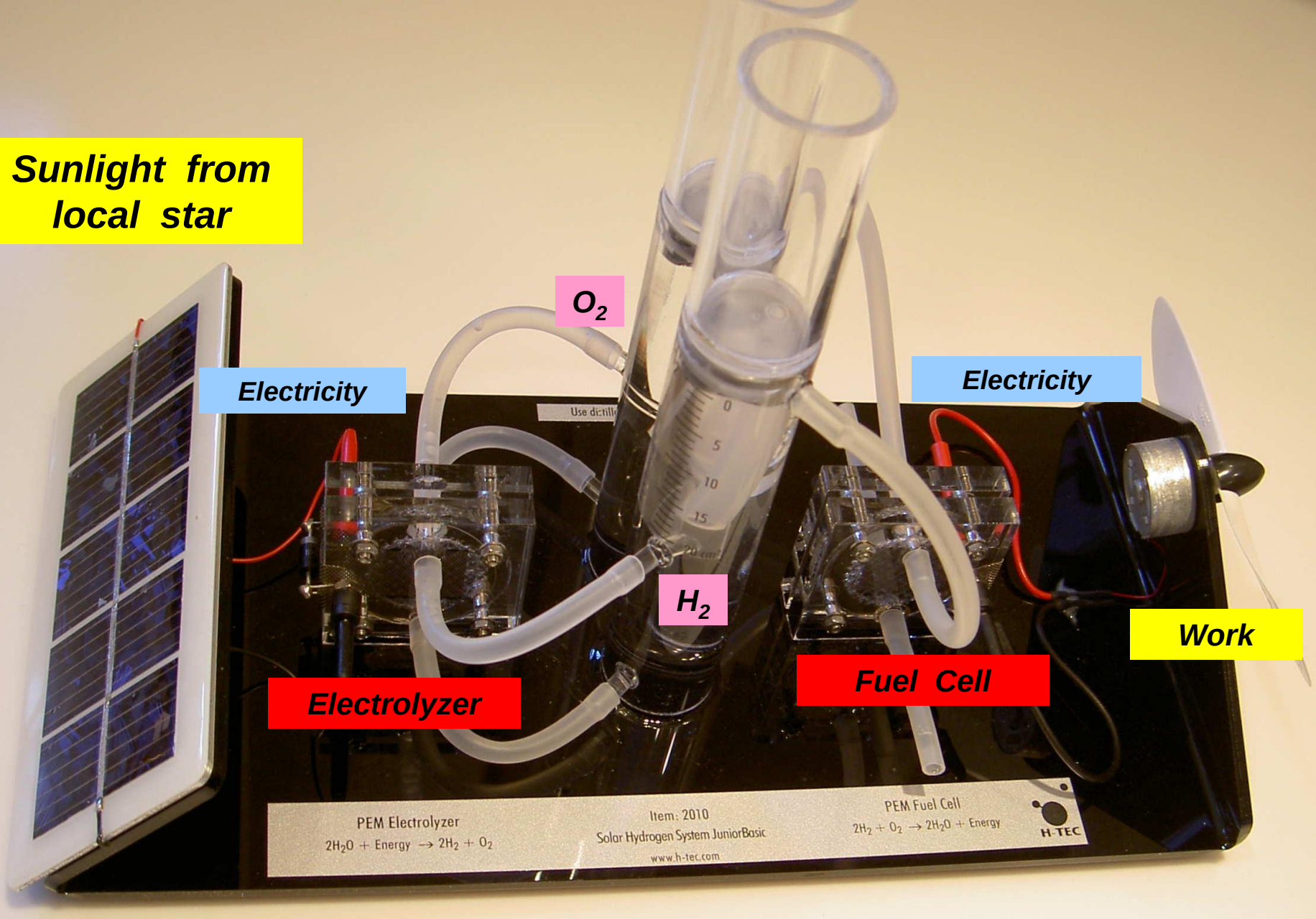
Gaskavernenspeicher in Betrieb bzw. Erweiterung
Existing gas cavern storage under extension

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

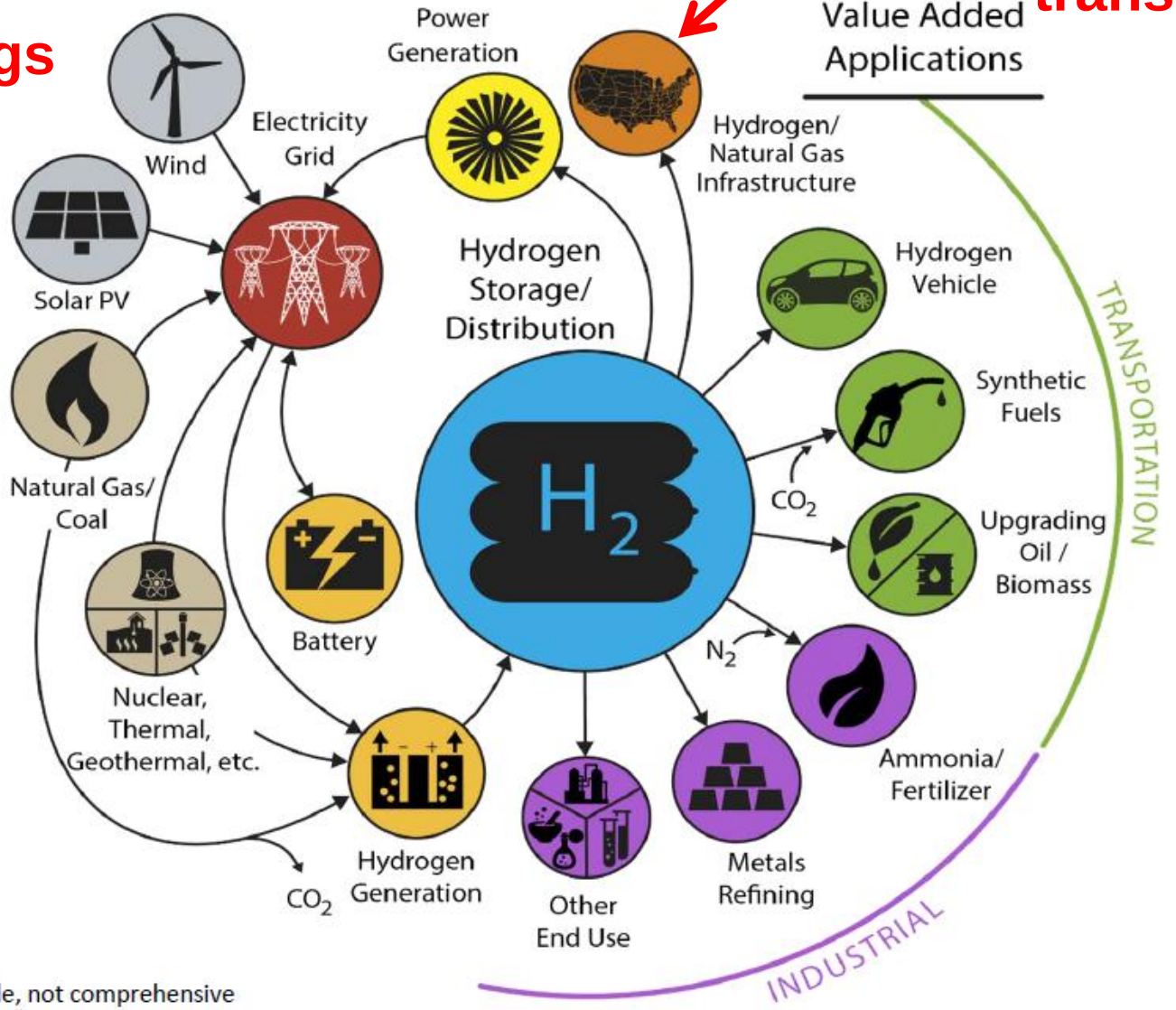


Solar Hydrogen Energy System

H_2 at Scale Energy System

"Power-to-gas"
"free" bulk storage, transmission

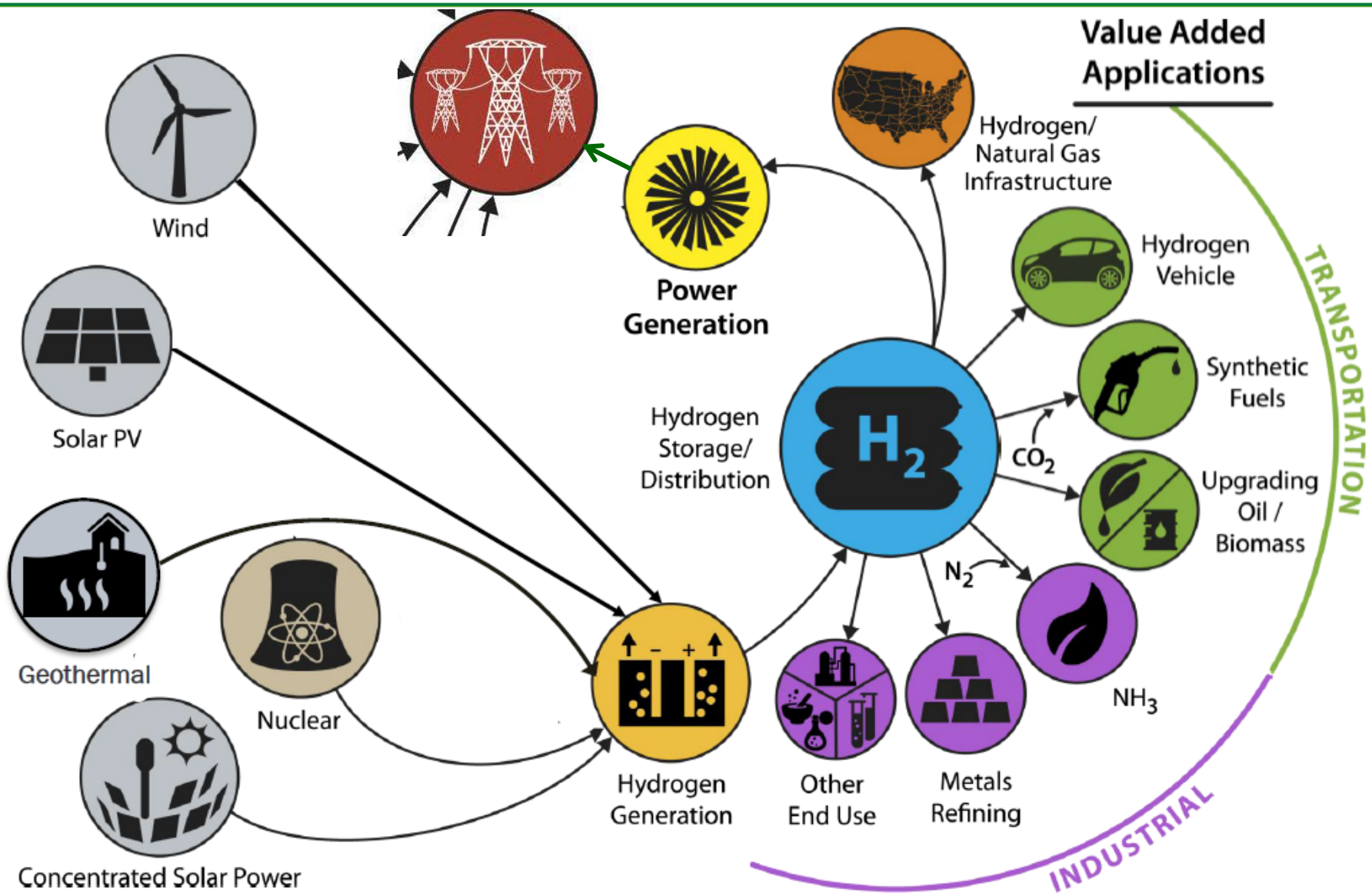
Tail wags dog ?



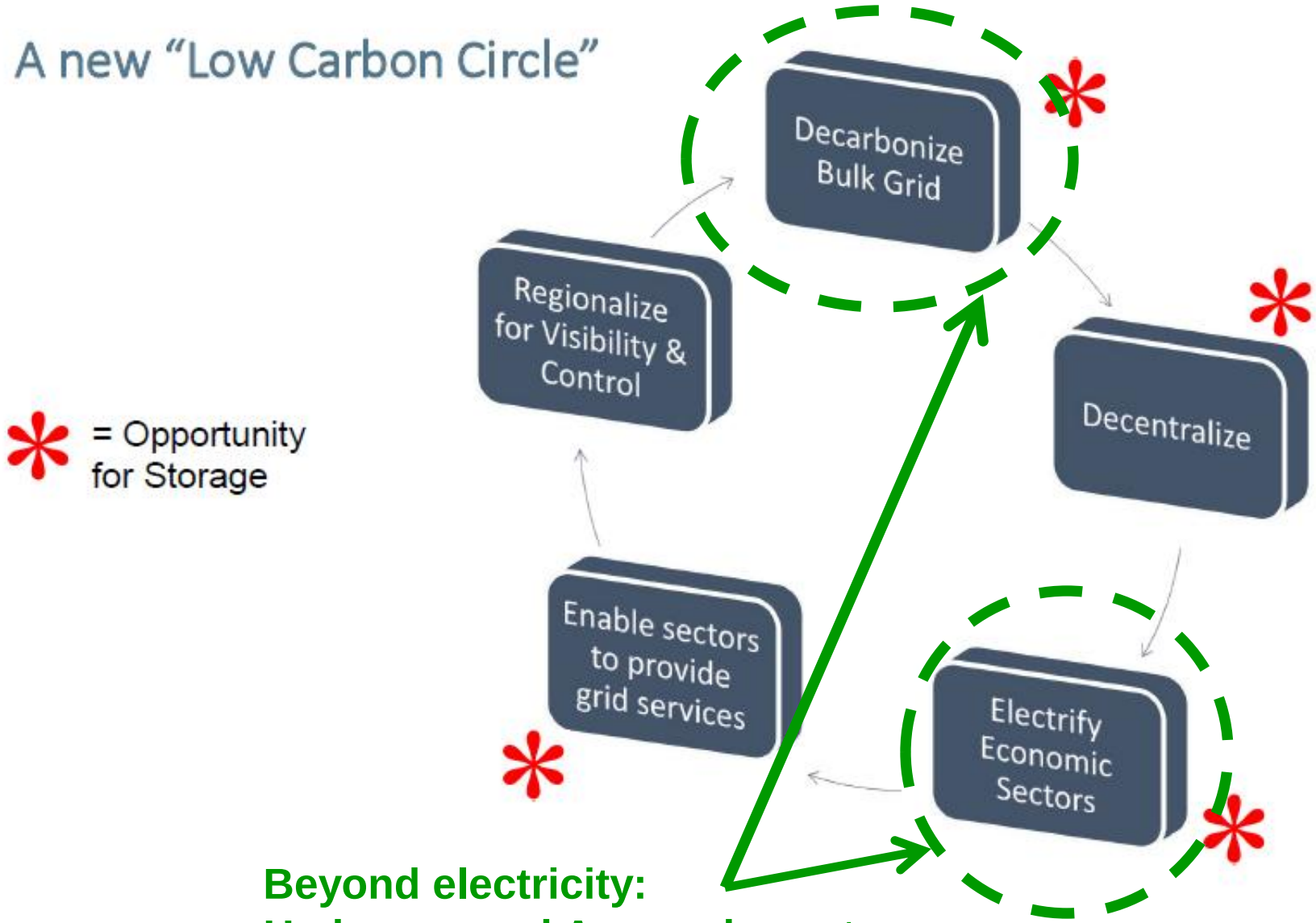
*Illustrative example, not comprehensive
Source: NREL

H_2 at Scale Energy System

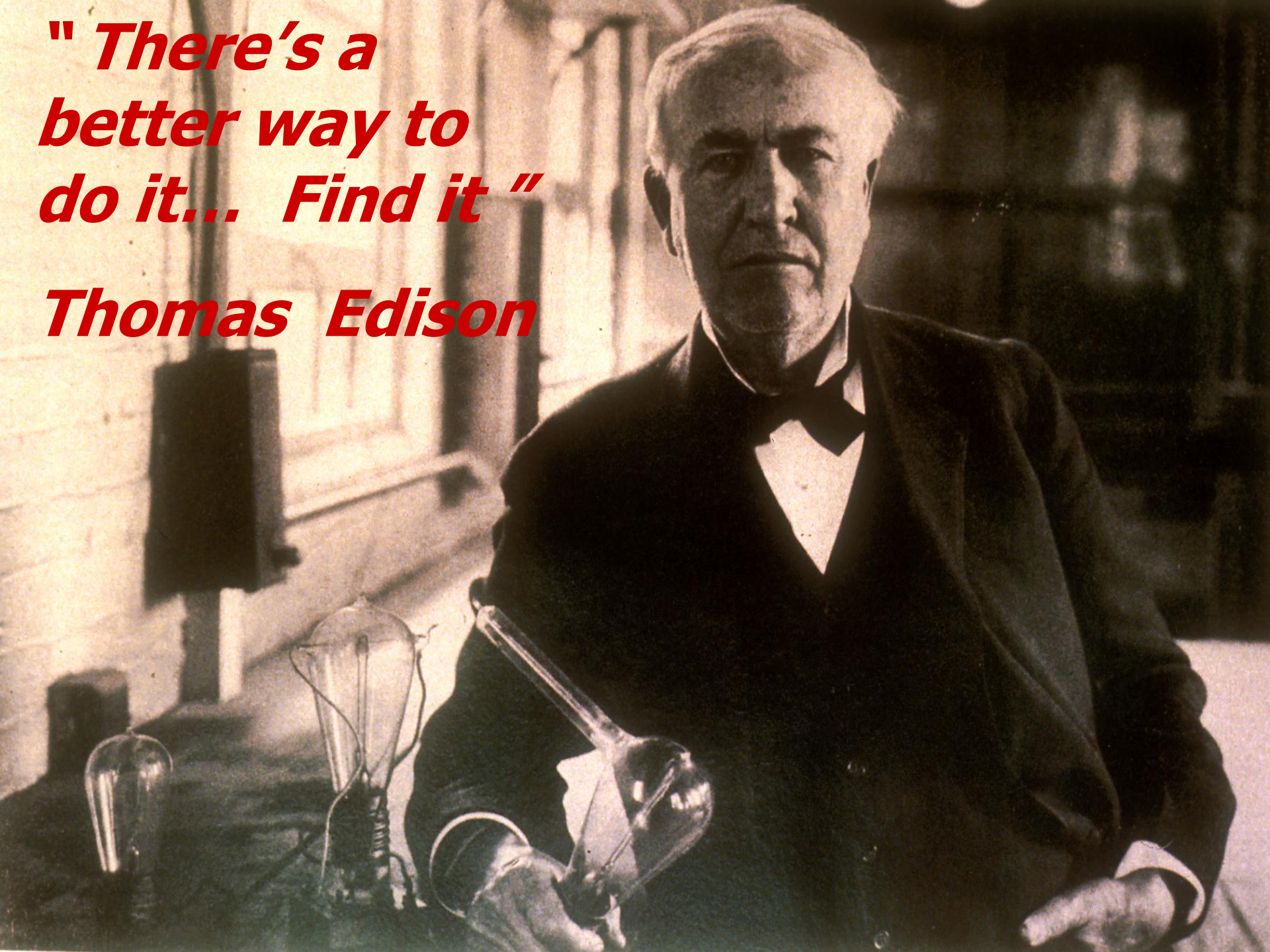
Tail wags dog ?



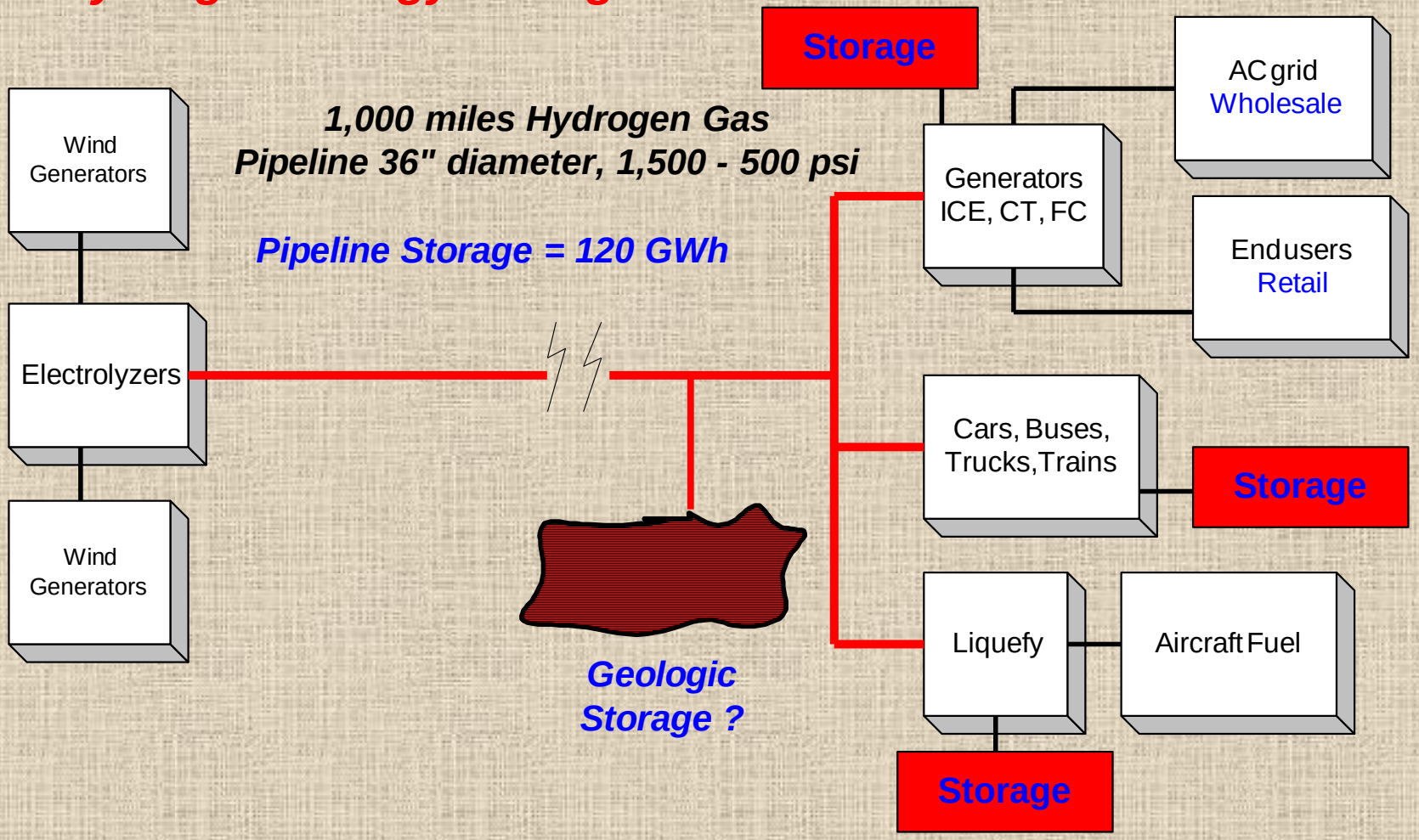
A new "Low Carbon Circle"

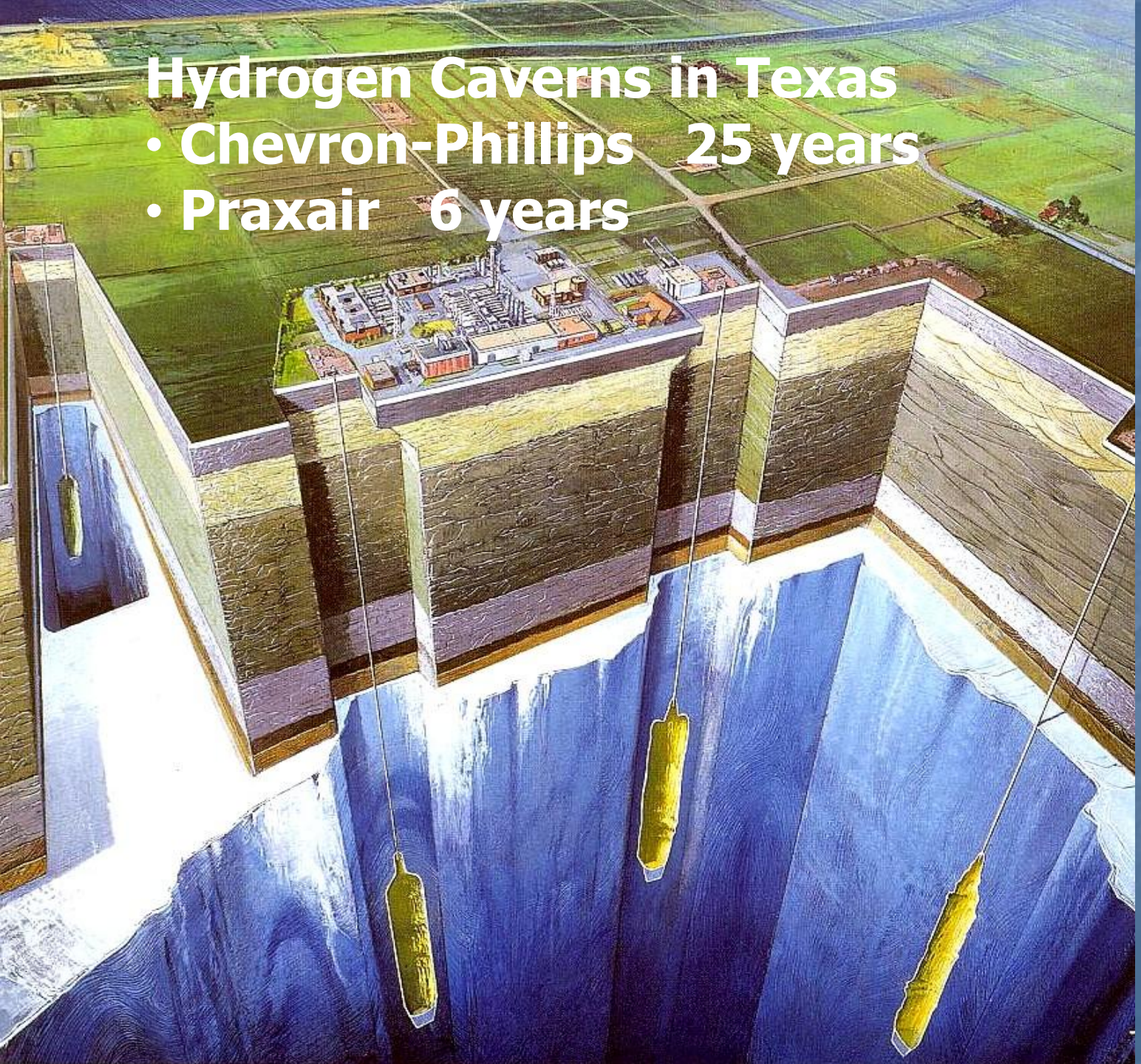


Beyond electricity:
Hydrogen and Ammonia systems


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

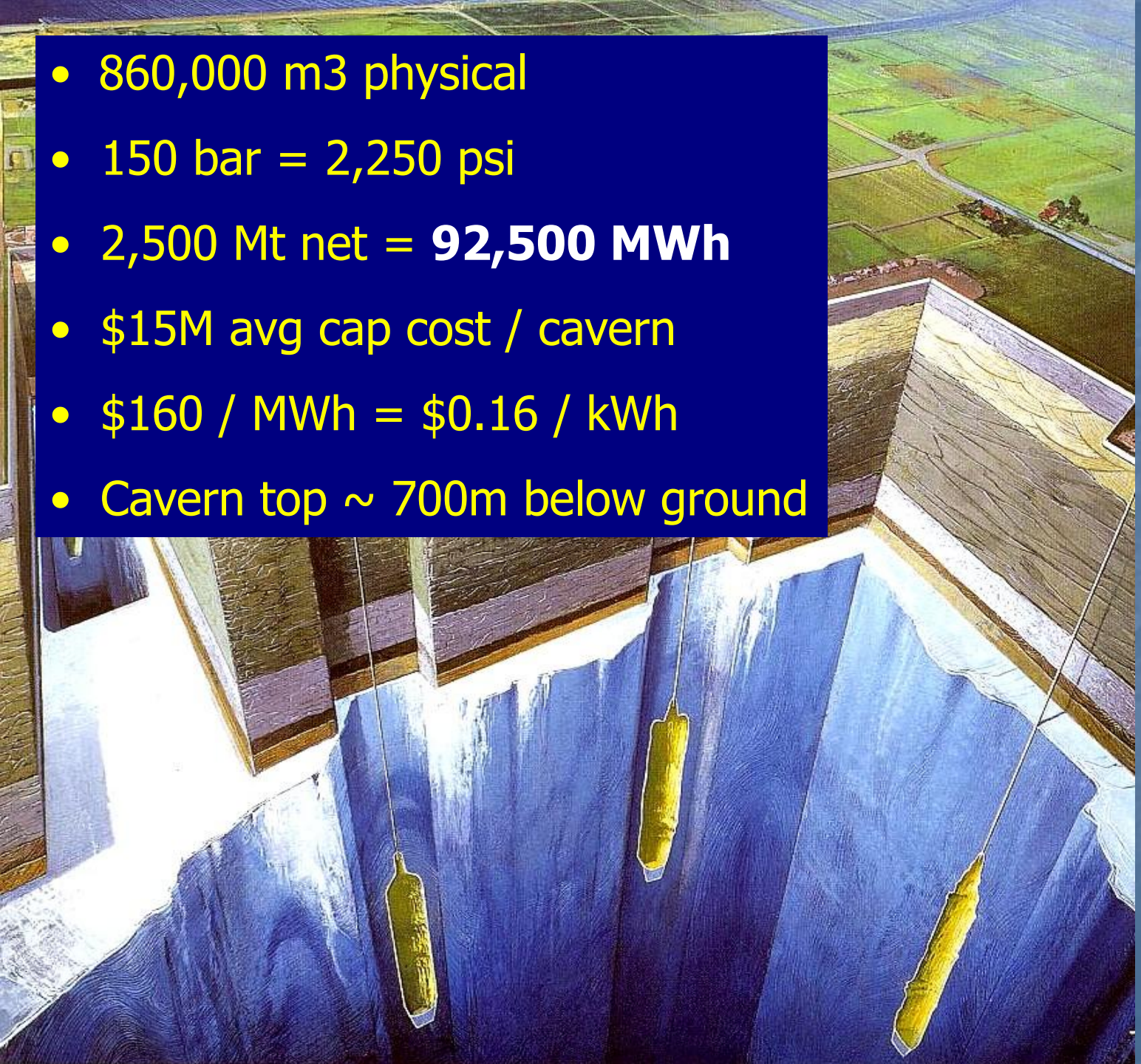
Hydrogen Energy Storage





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

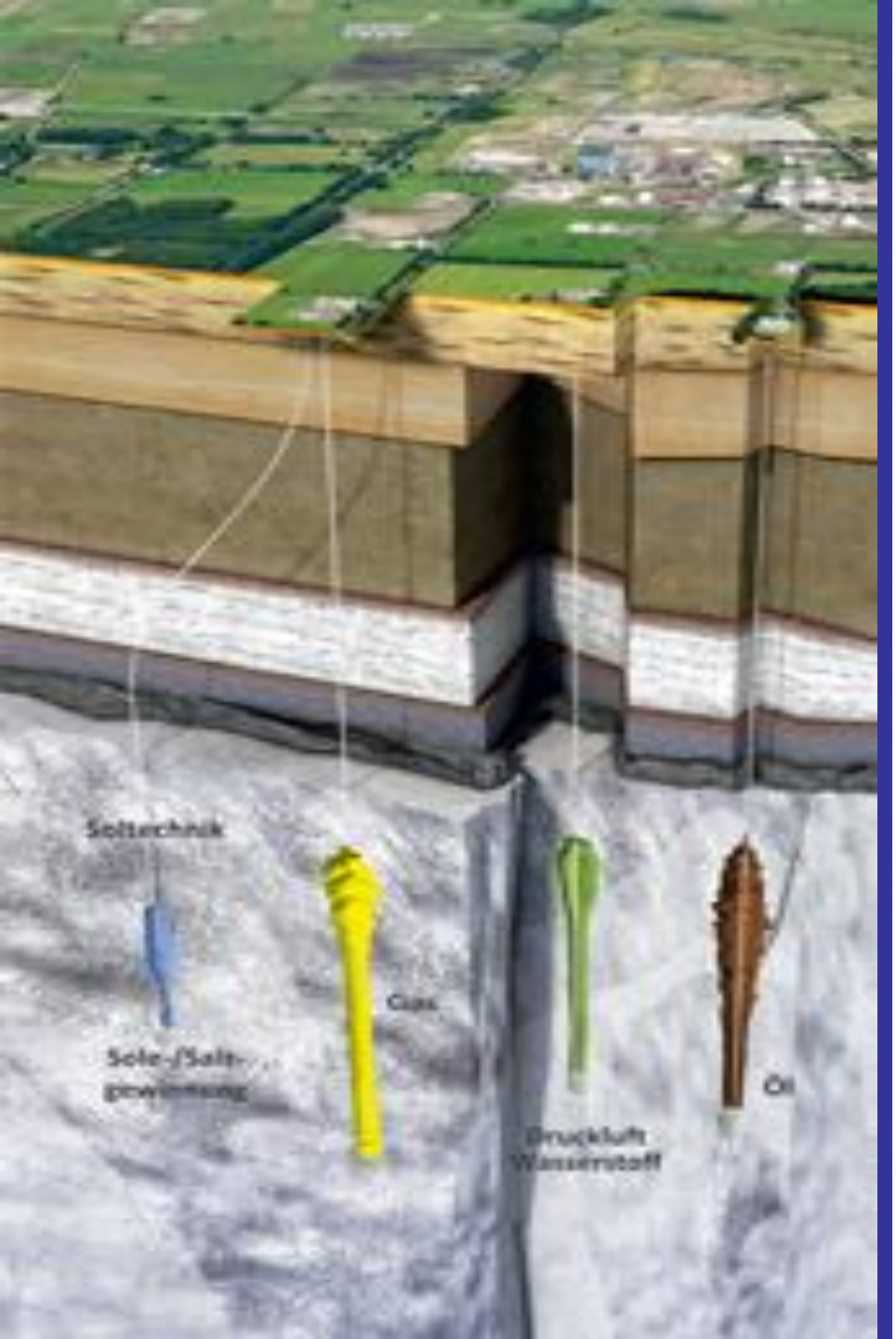
"Clemens Terminal" Conoco Phillips 20 years

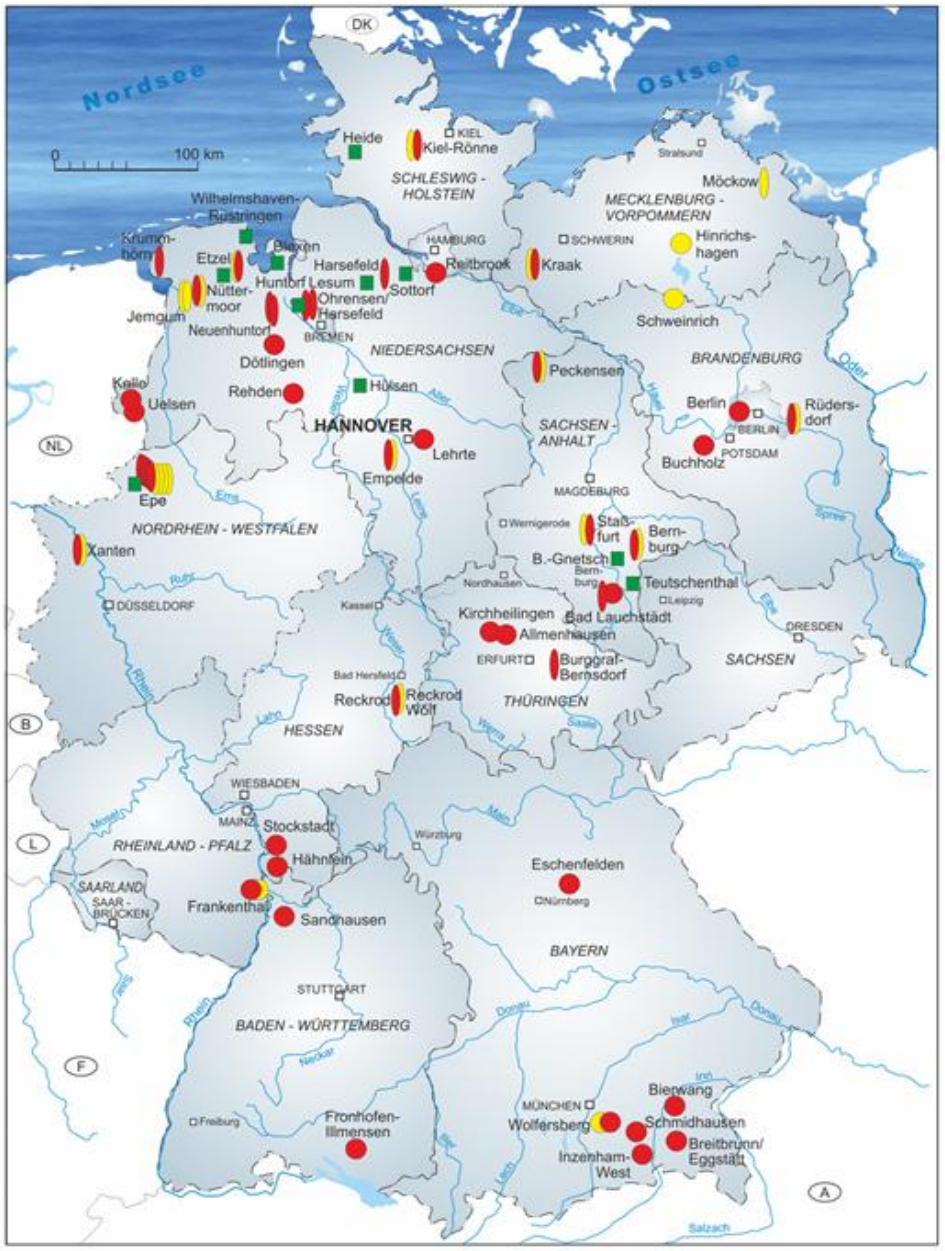
Praxair `07

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)

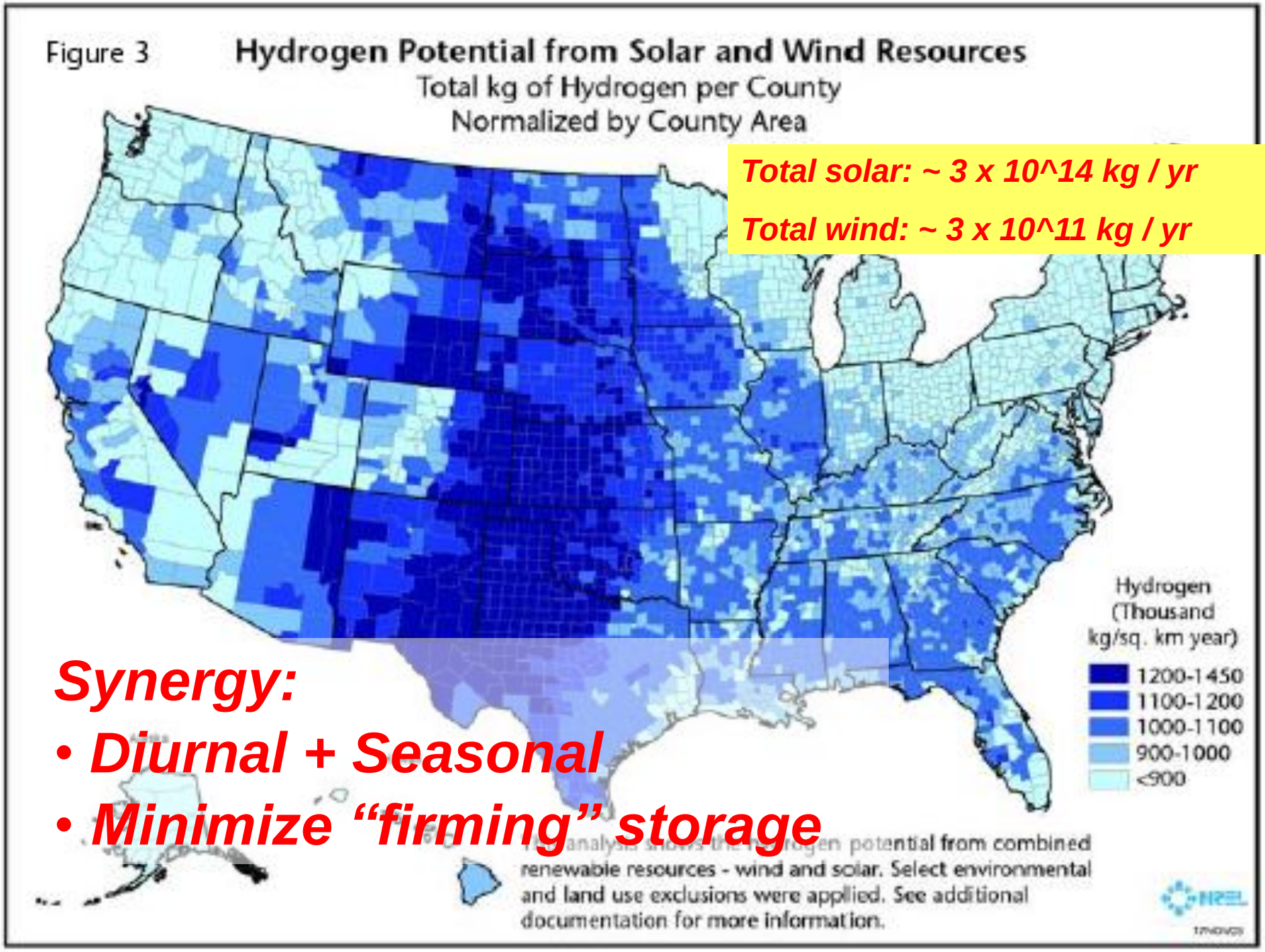
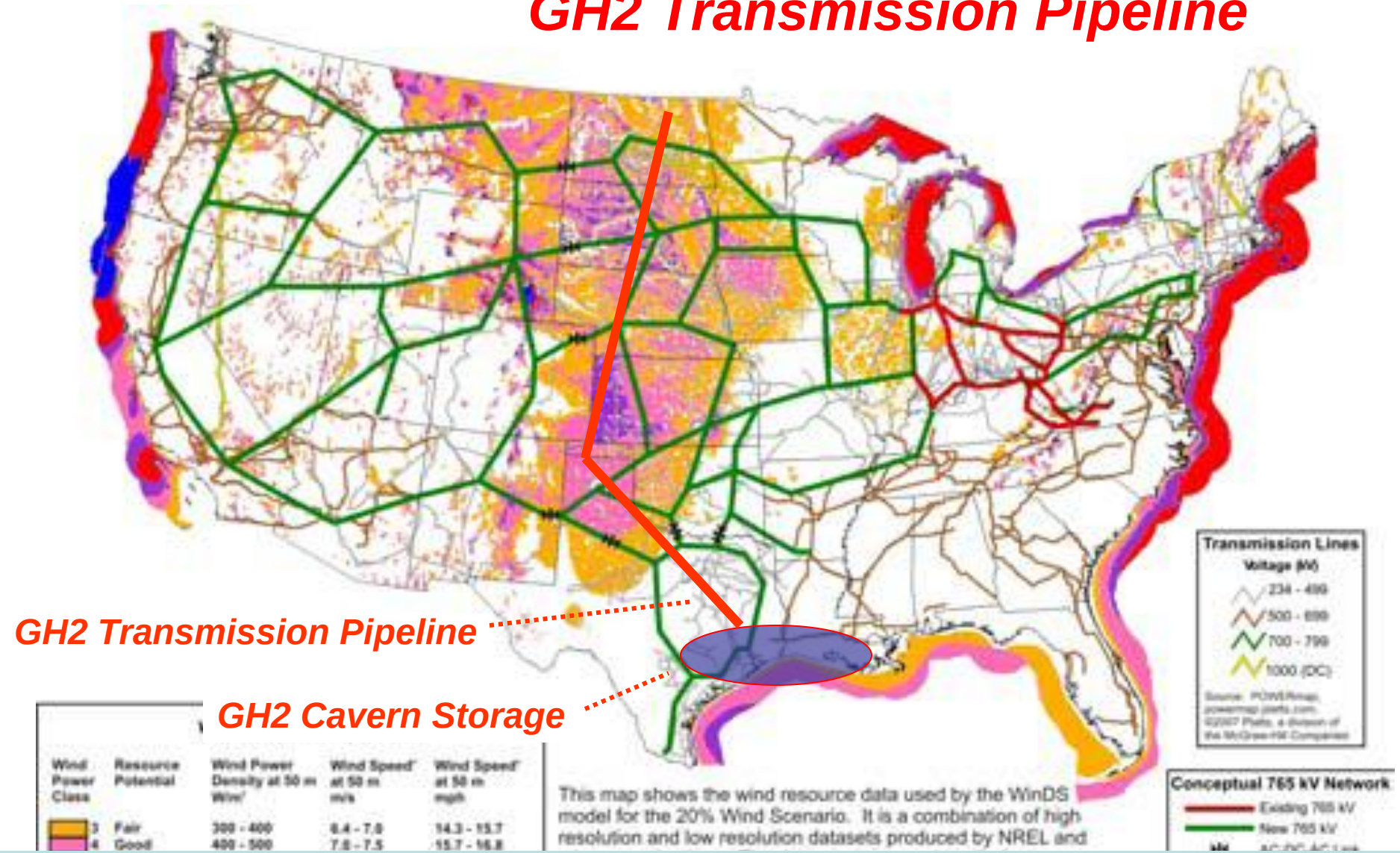
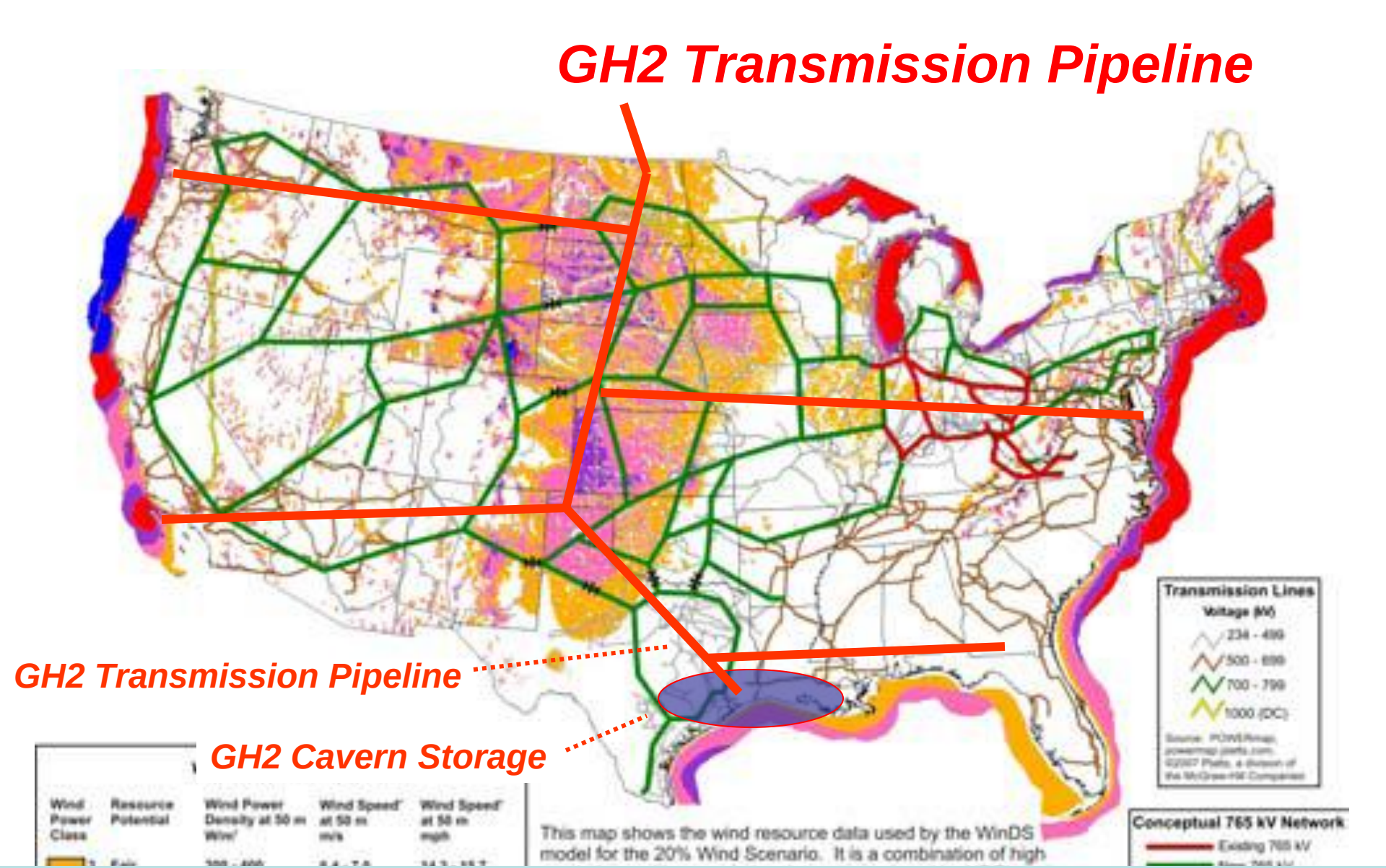


Figure 3
Hydrogen Potential from Solar and Wind Resources
Total kg of Hydrogen per County
Normalized by County Area
Total solar: ~ 3 x 10^14 kg / yr
Total wind: ~ 3 x 10^11 kg / yr
Hydrogen
(Thousand
kg/sq. km year)
1200-1450
1100-1200
1000-1100
900-1000
<900
Synergy:
• Diurnal + Seasonal
• Minimize "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

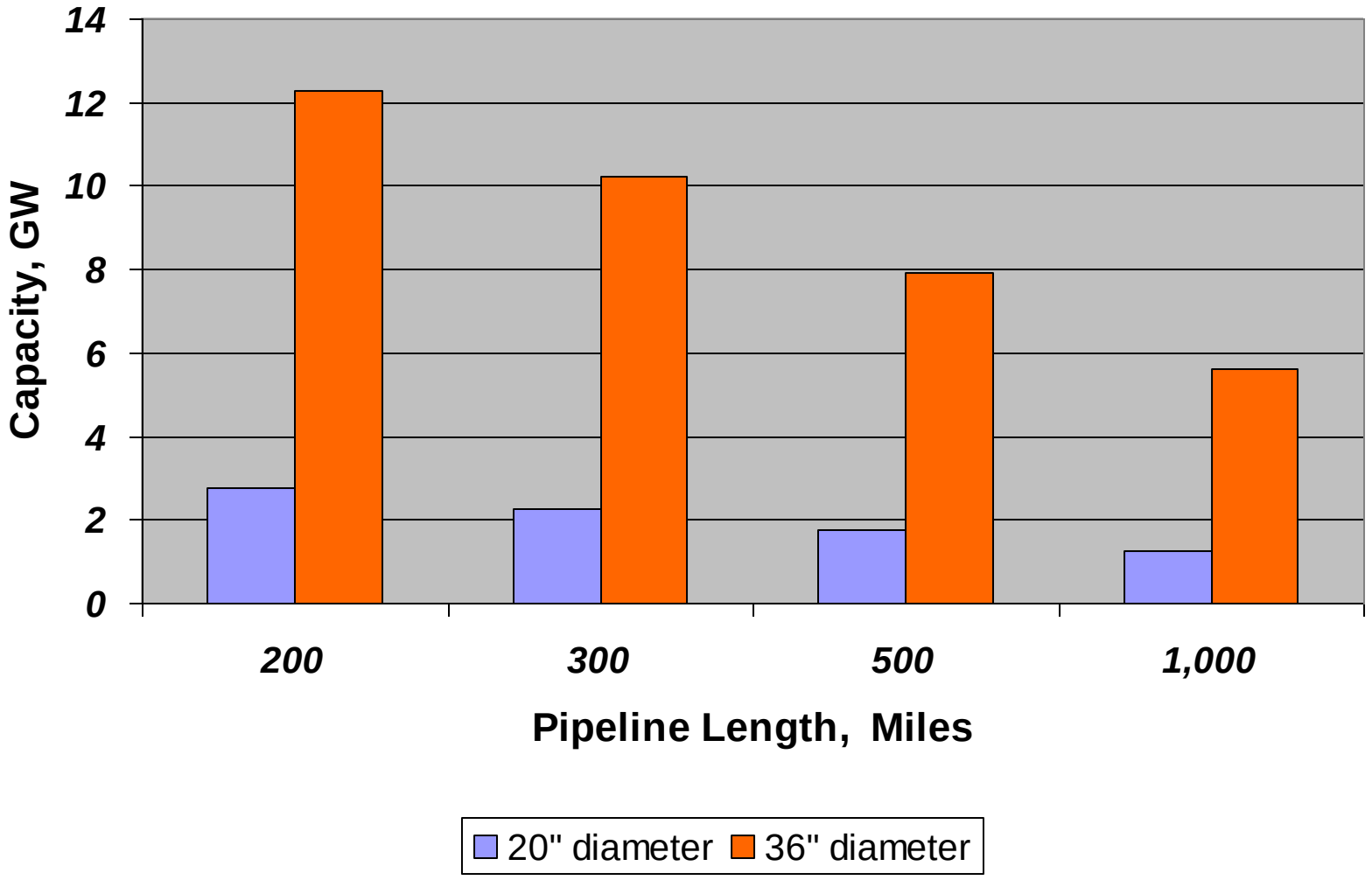


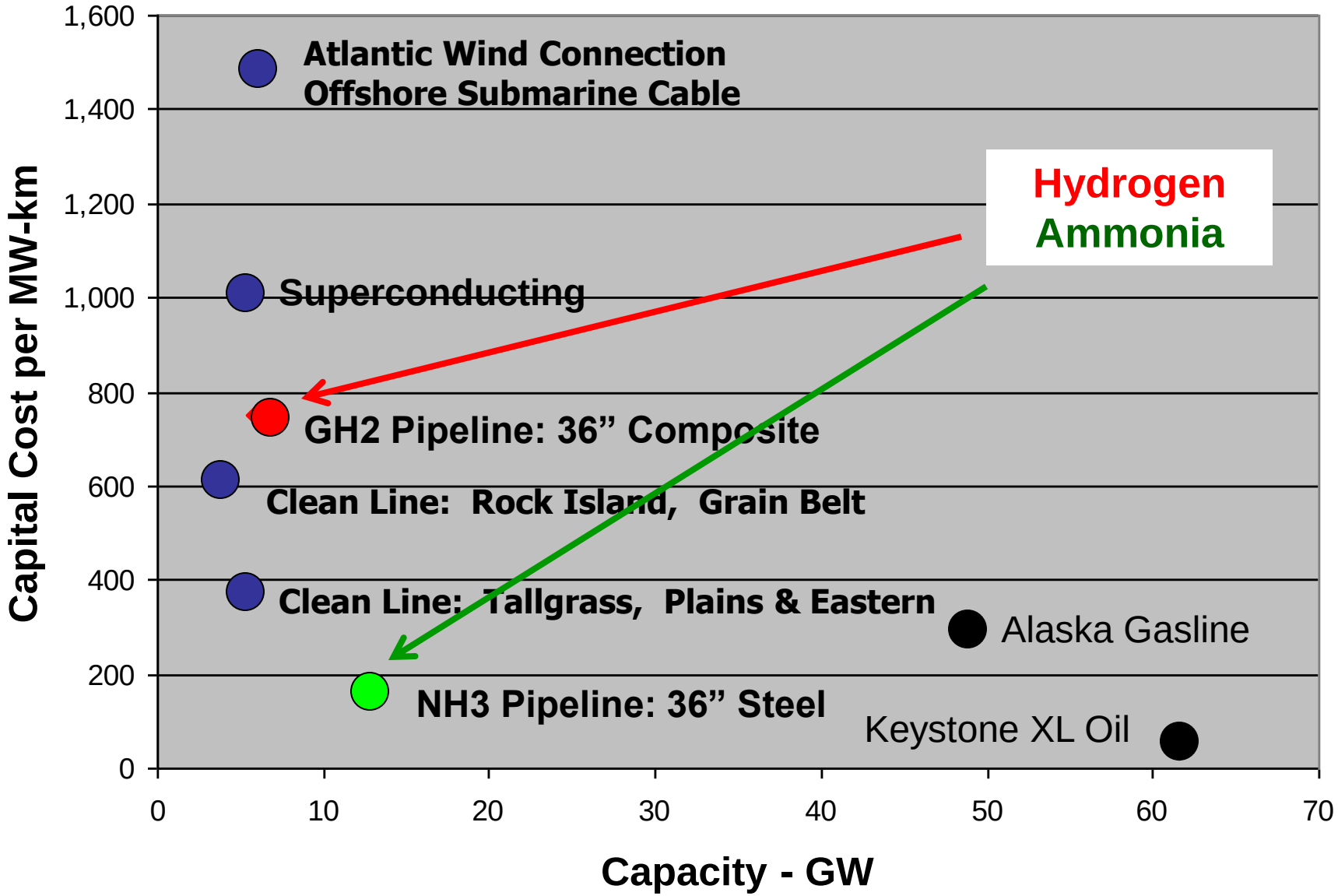
Wind Potential ~ 10,000 GW

12 Great Plains states

Compressorless 20”, 36” GH2 Pipeline Capacity

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



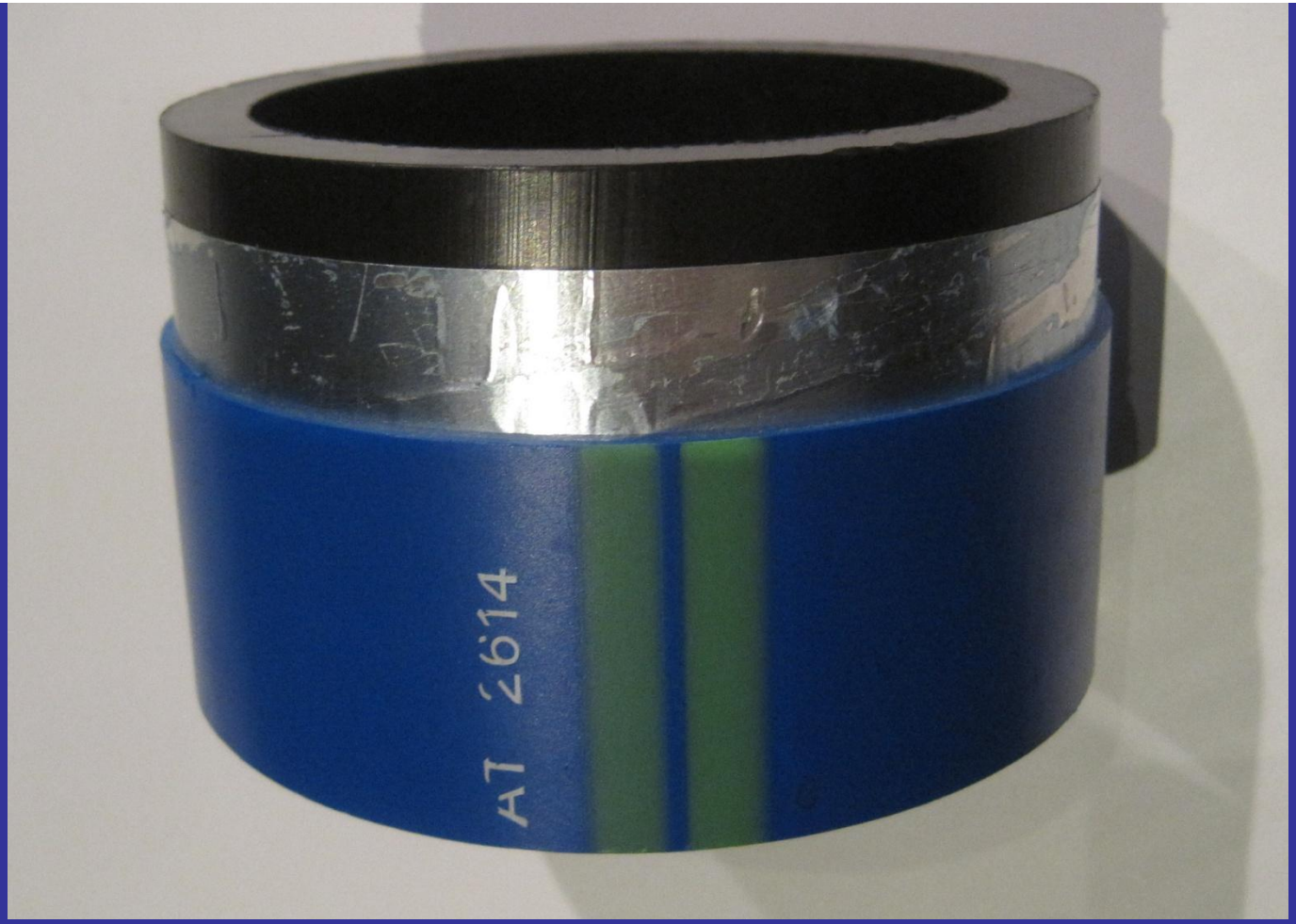


Transmission capital costs per MW-km compared

Pipelines have large capacity and provide large storage

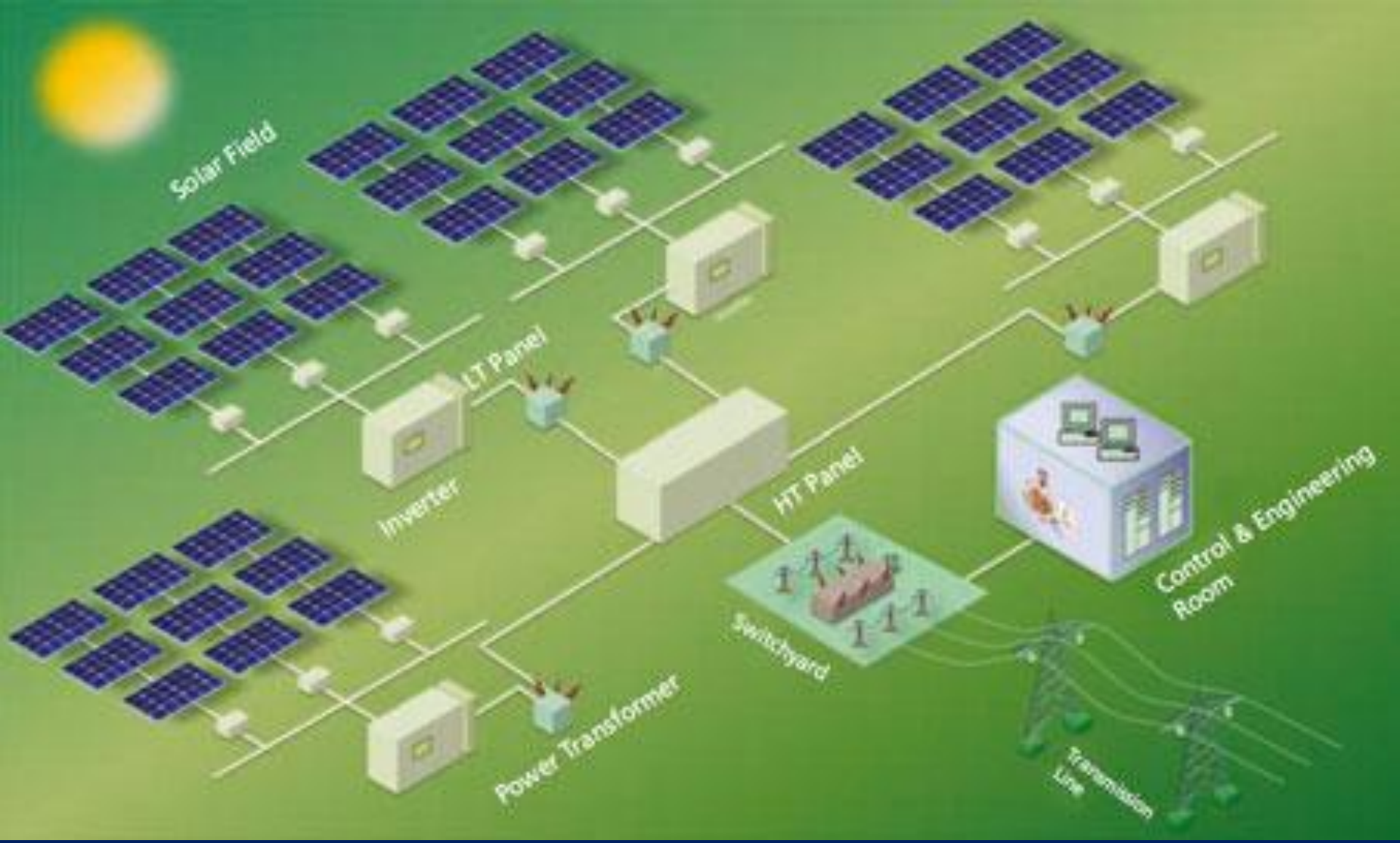
36” = 8 GW gaseous Hydrogen @ 100 bar

Convert Palm Springs to Long Beach Natural Gas Pipeline ?



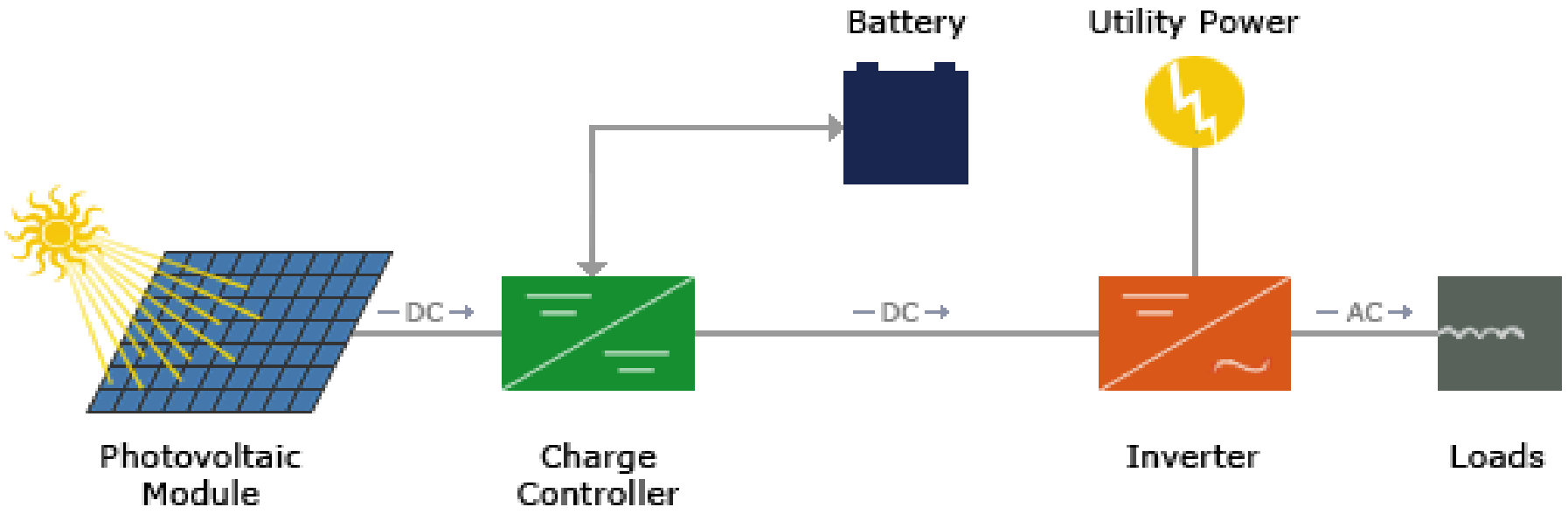
Smart Pipe Technologies, Houston

Polymer-metal linepipe avoids hydrogen embrittlement

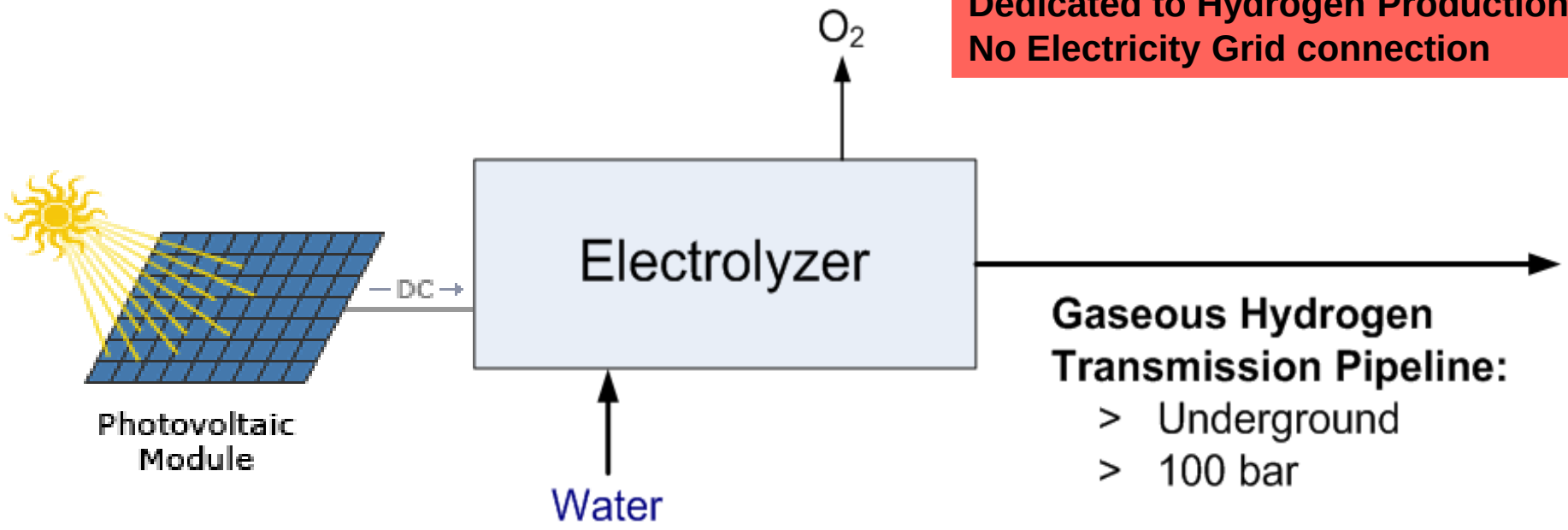


Grid delivery: Complex & Costly Infrastructure

1 MW solar inverters



Dedicated to Hydrogen Production
No Electricity Grid connection

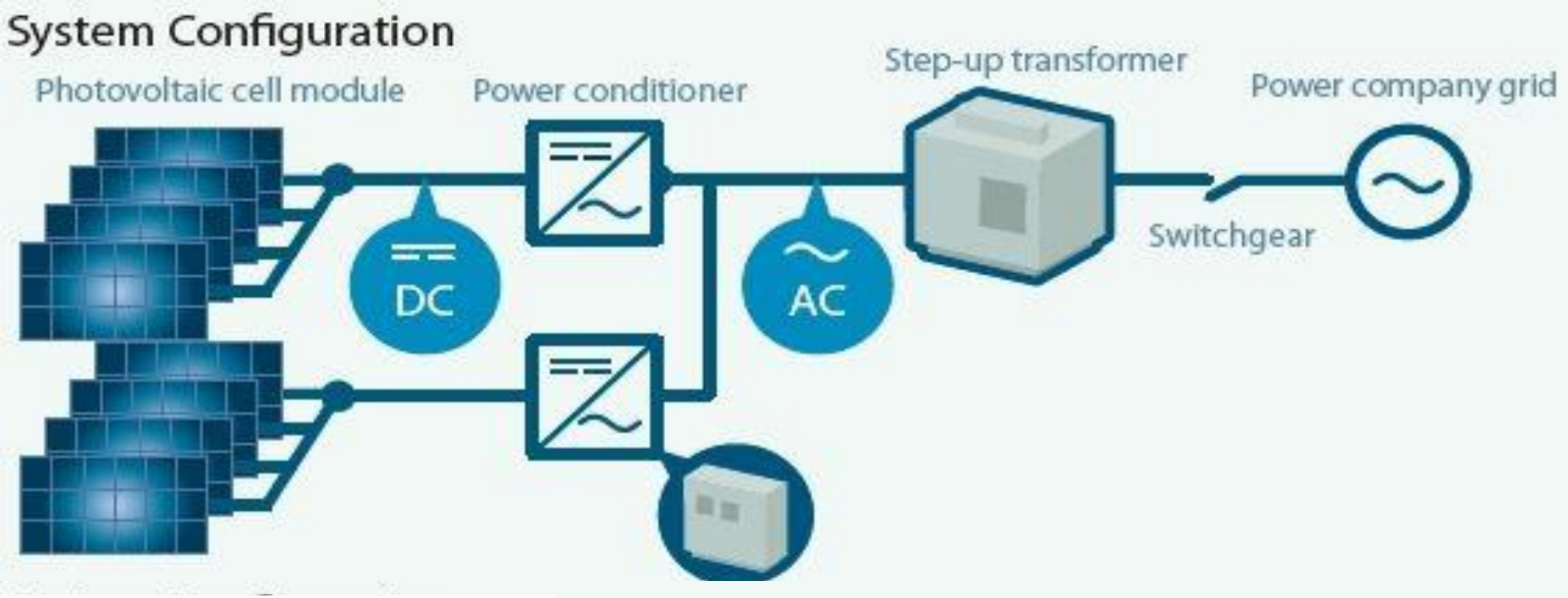


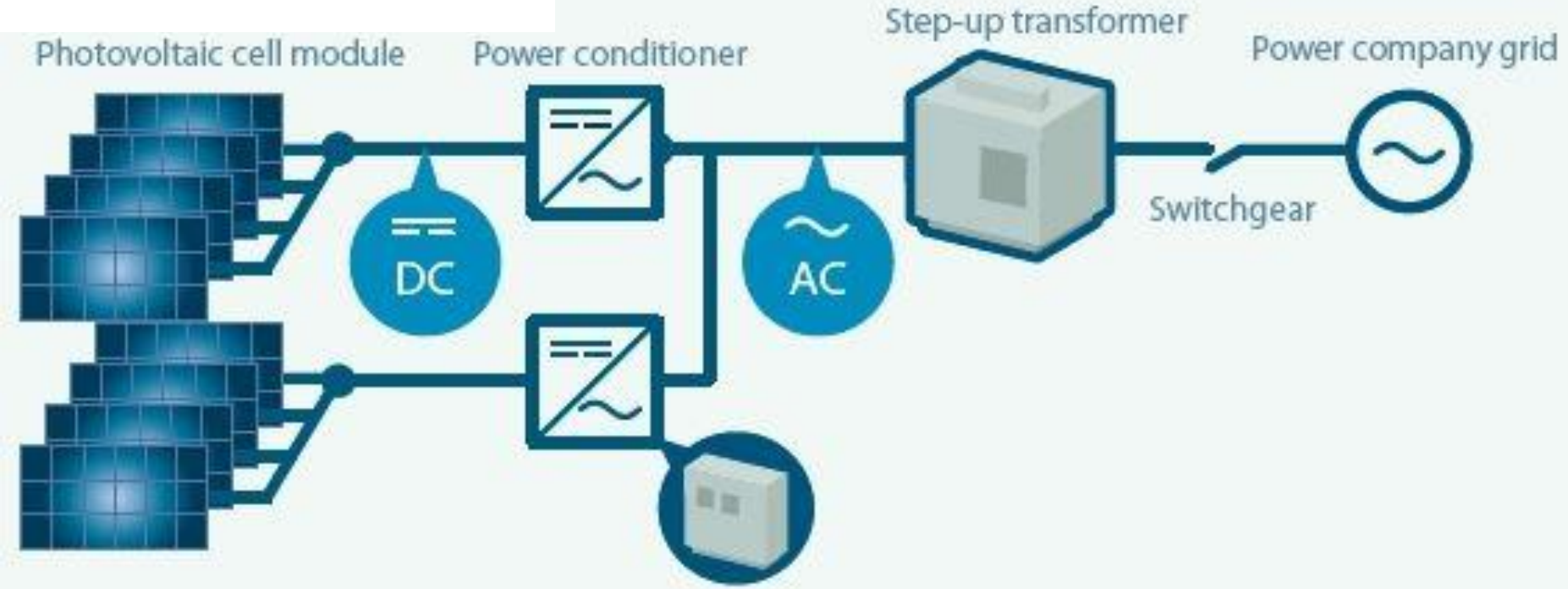
The New Benchmark in Electrolysis

1 MW PEM Stack

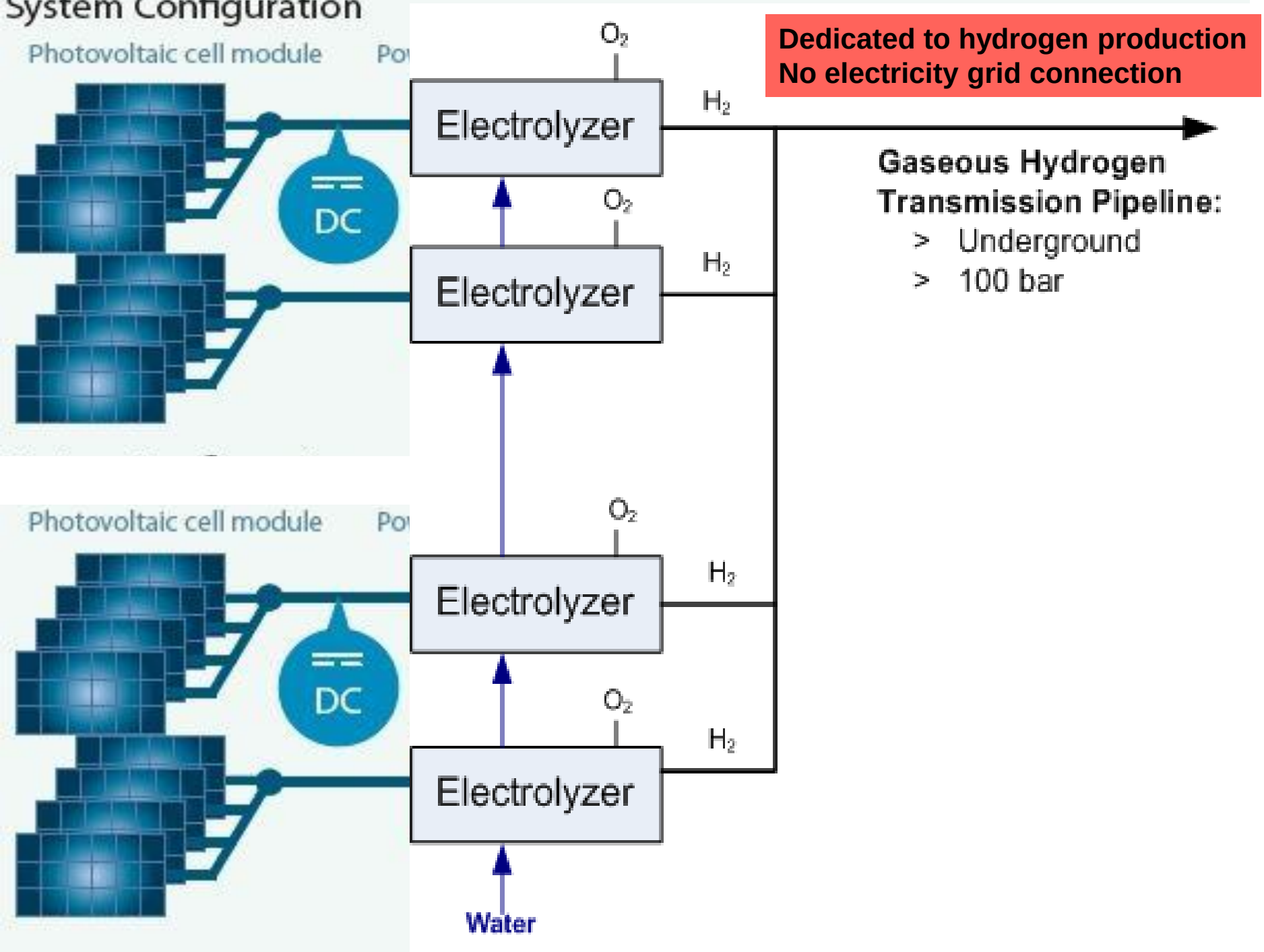
Electrical Power Input	1.5 MW (overdrive)
Hydrogen Output	285 Nm3/h
Max. Operating Pressure	40 bar (g)
Certifications	PED (97/23/EC)

System Configuration





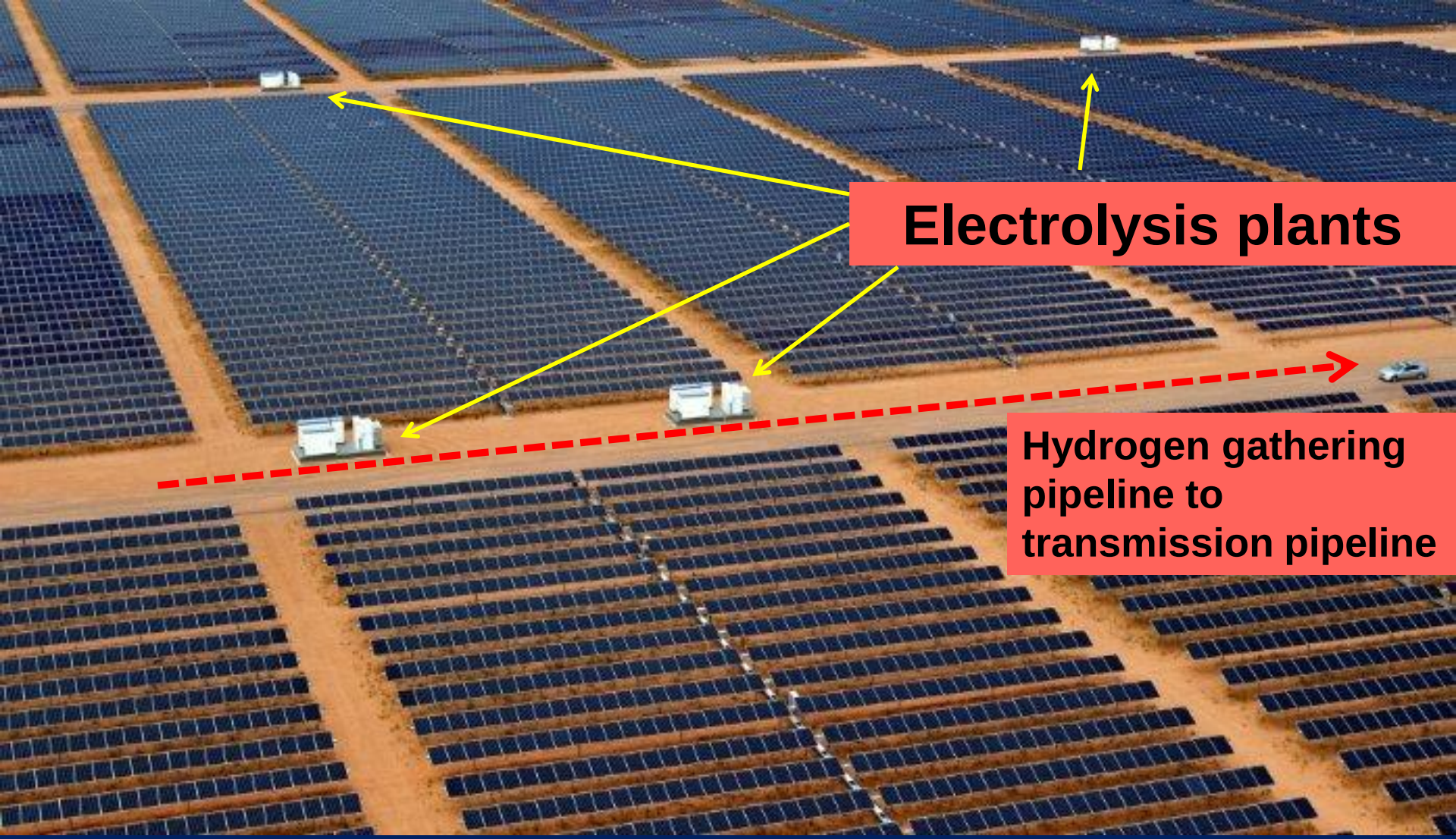
System Configuration



Dedicated to hydrogen production
No electricity grid connection

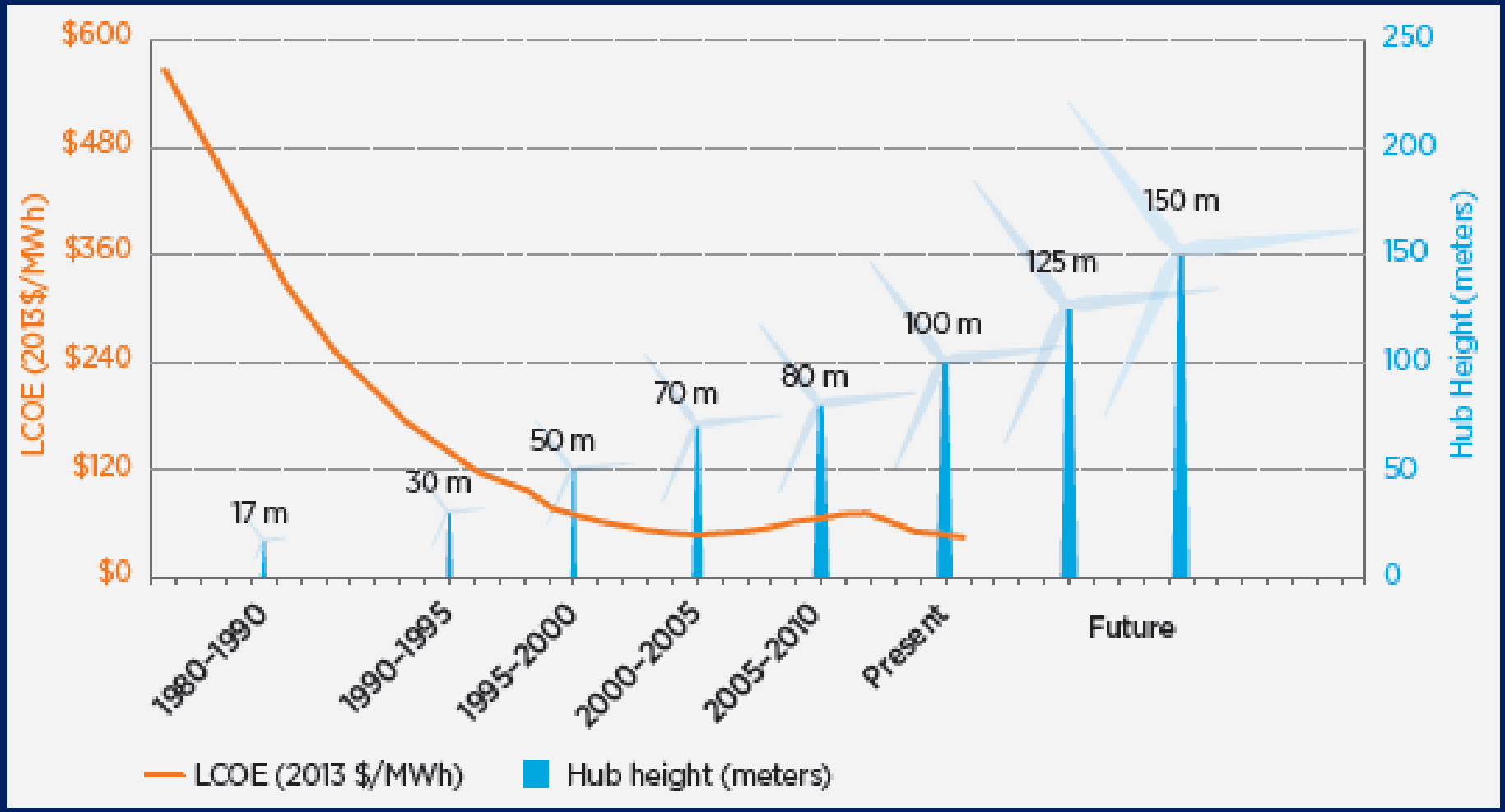
Gaseous Hydrogen Transmission Pipeline:

- Underground
- 100 bar



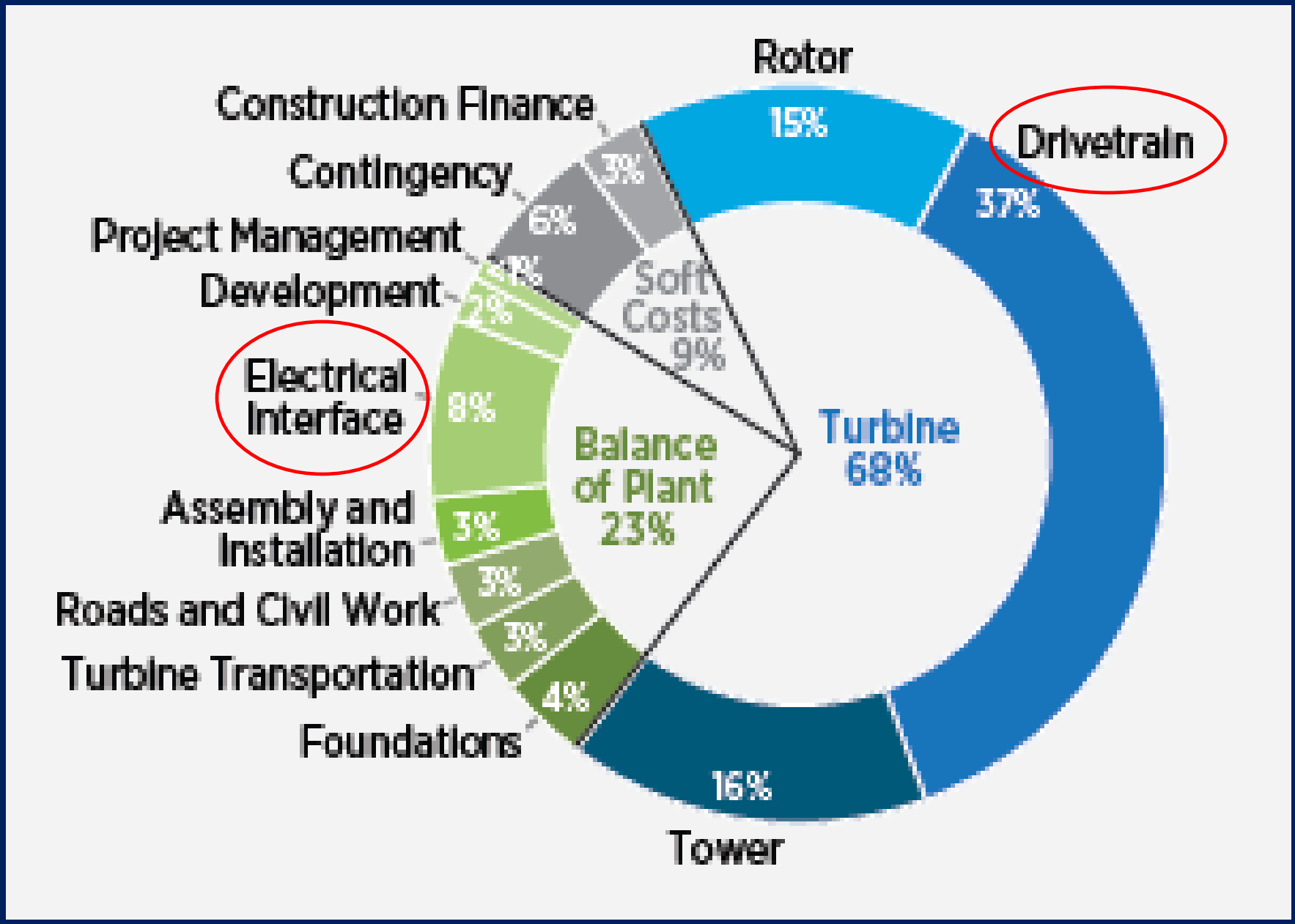
Dedicated to Hydrogen fuel production
No connection to electricity grid

Sonnedix 15.5 MW Salinas, Puerto Rico

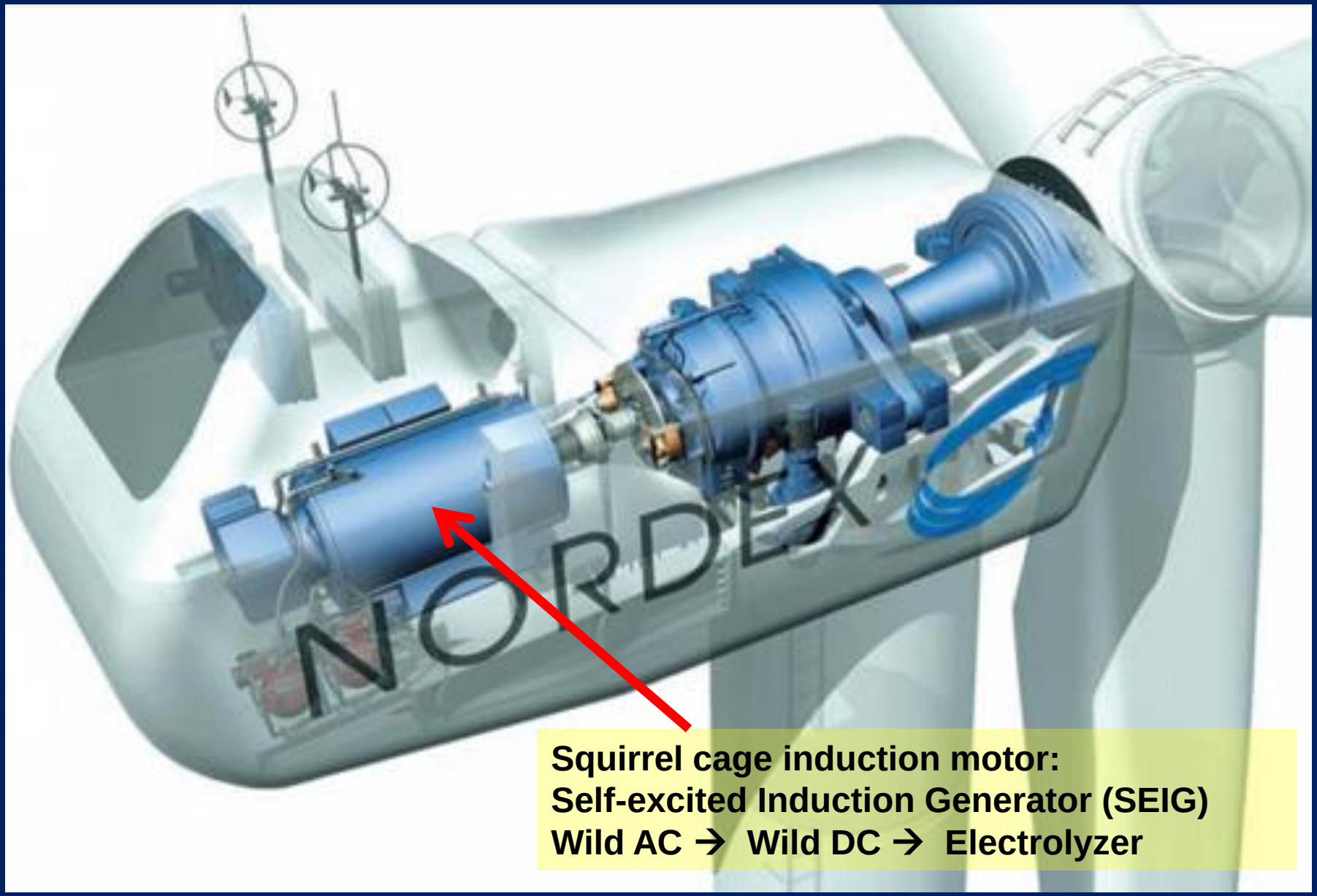


Wind LCOE reduction

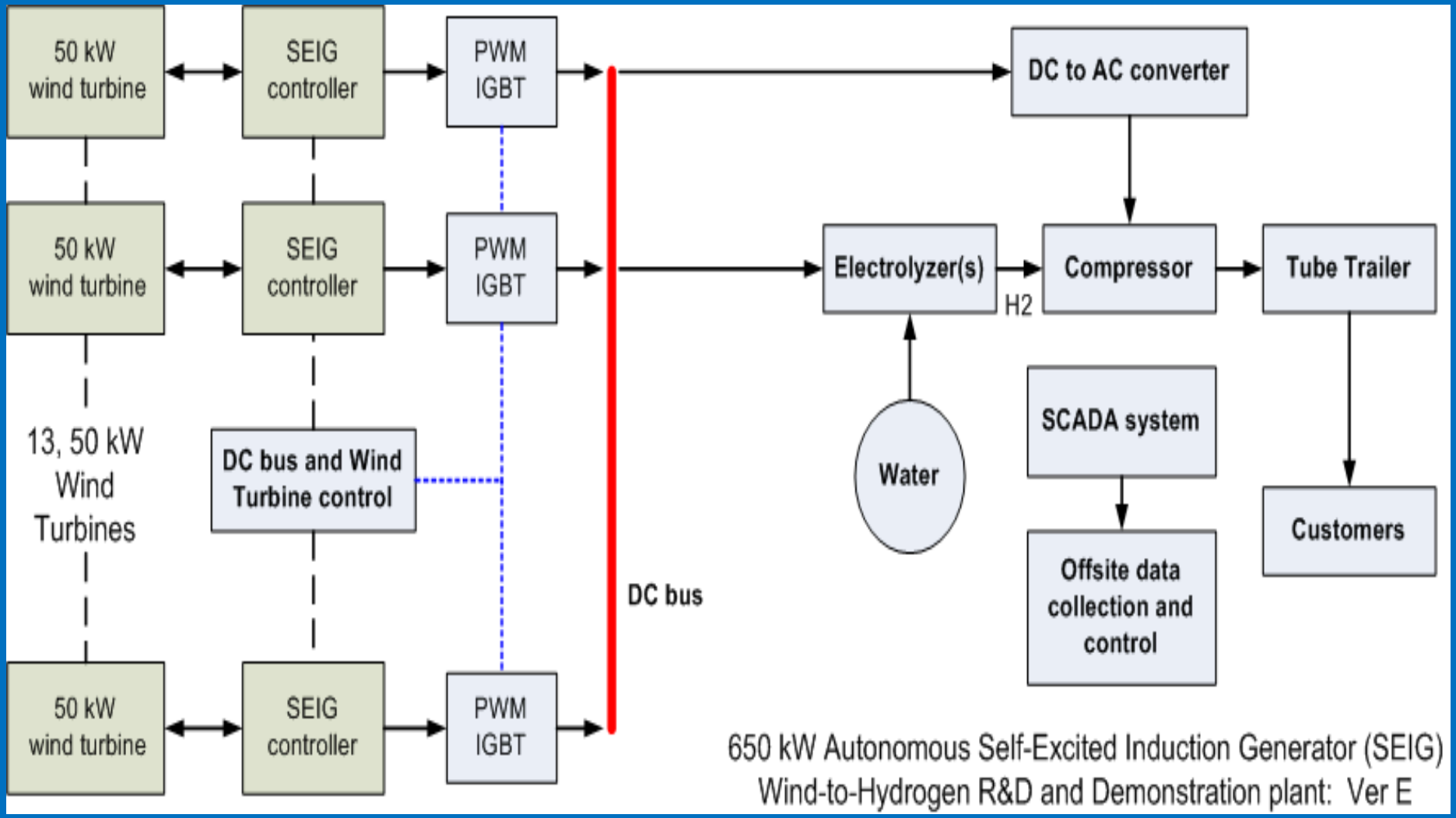
" Wind Vision " Executive Summary



Installed CAPEX: land-based, utility-scale

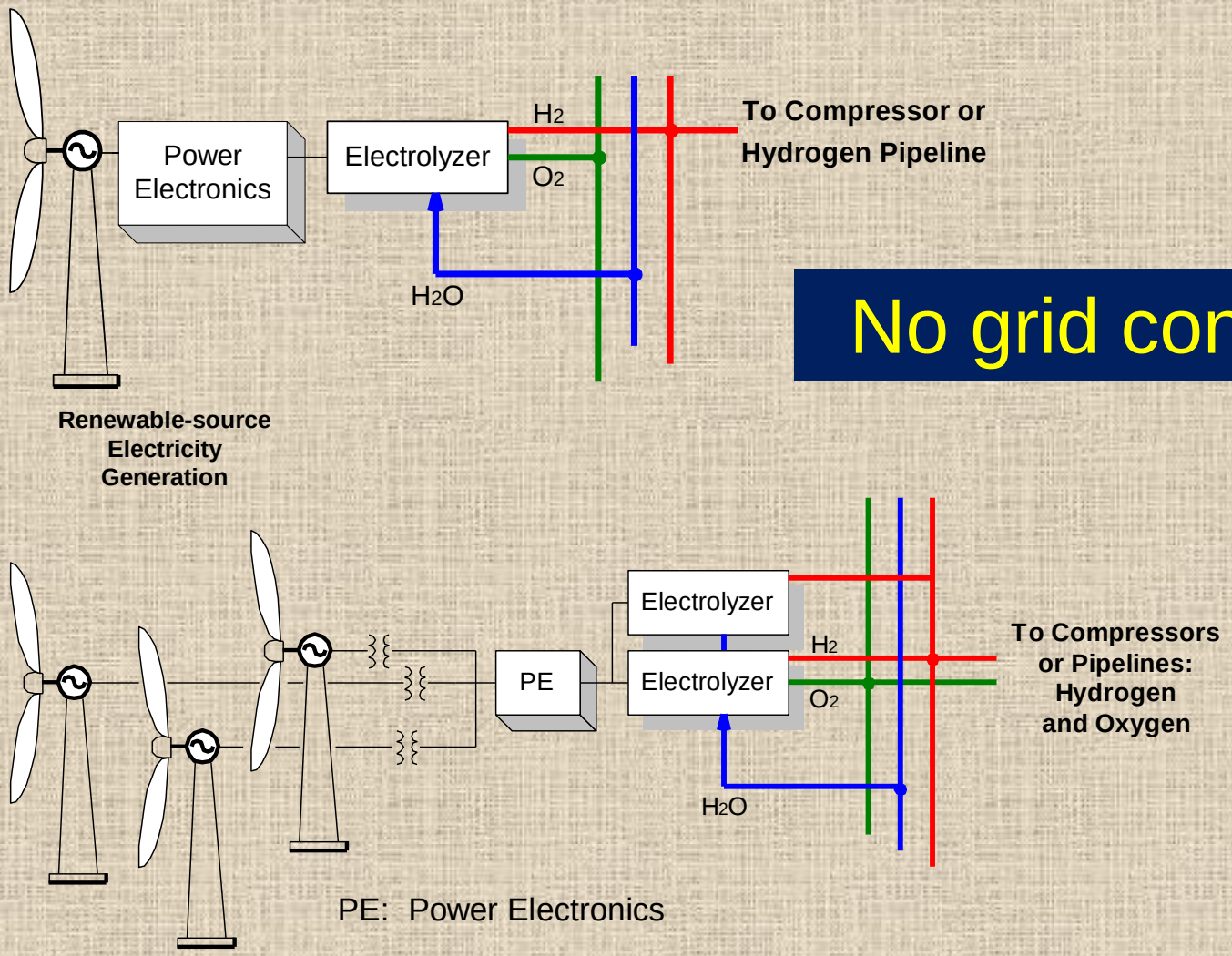


Dedicated Hydrogen Production: No Grid Connection



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

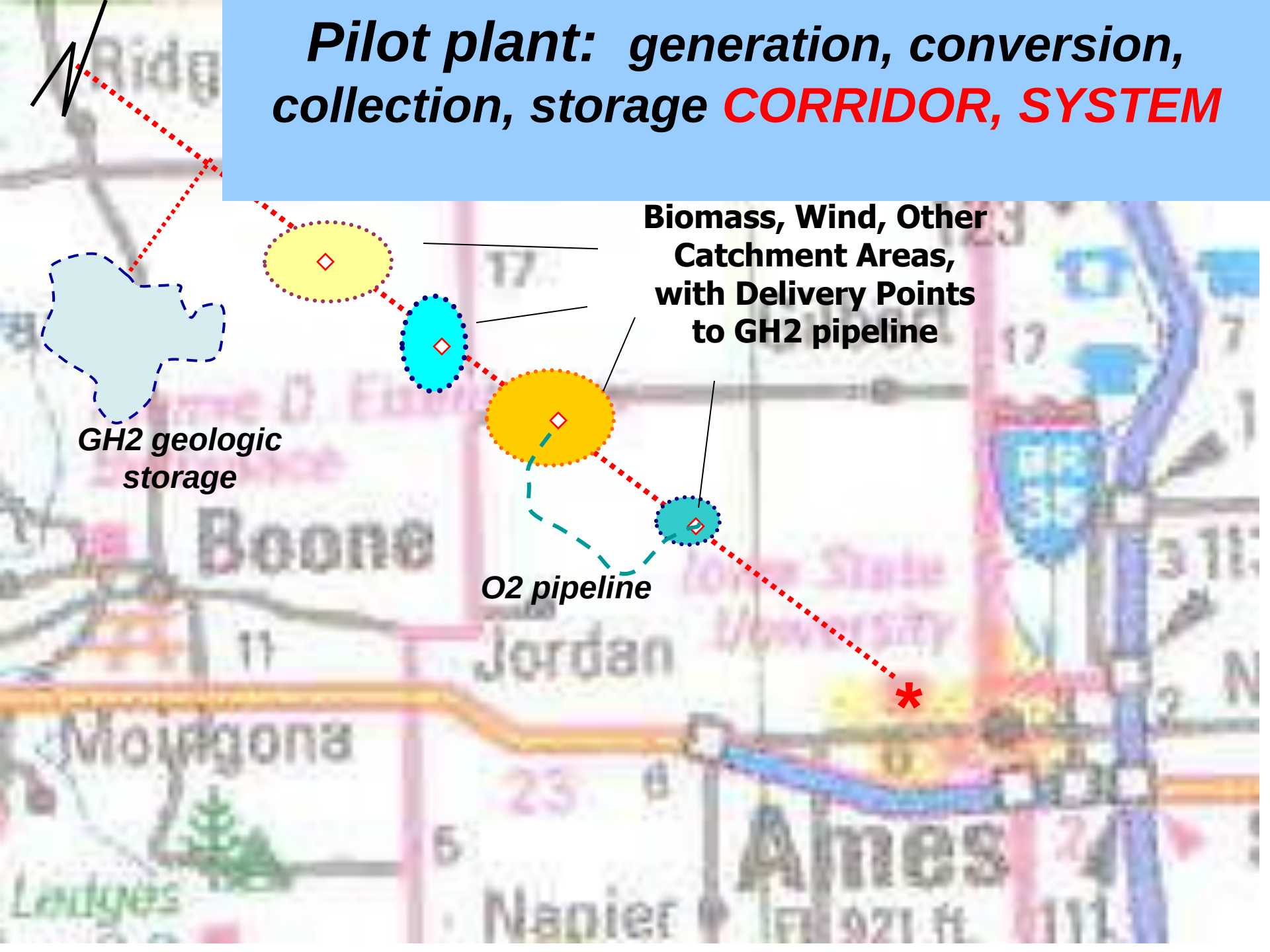
ABB ACS800 low voltage wind turbine converter



No grid connection

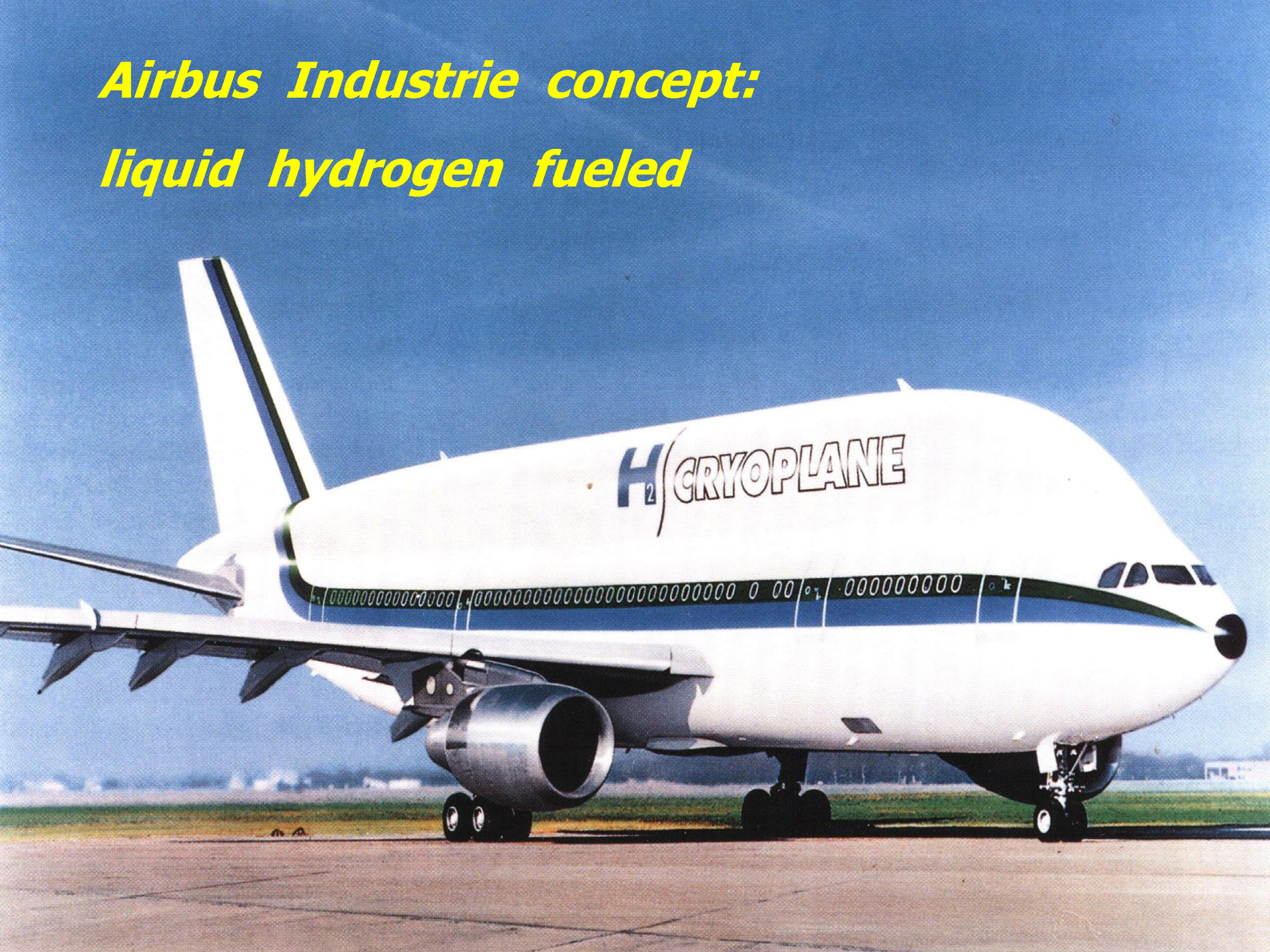
Topology Options: H_2 and O_2 Production and Gathering from Renewable Energy Generation

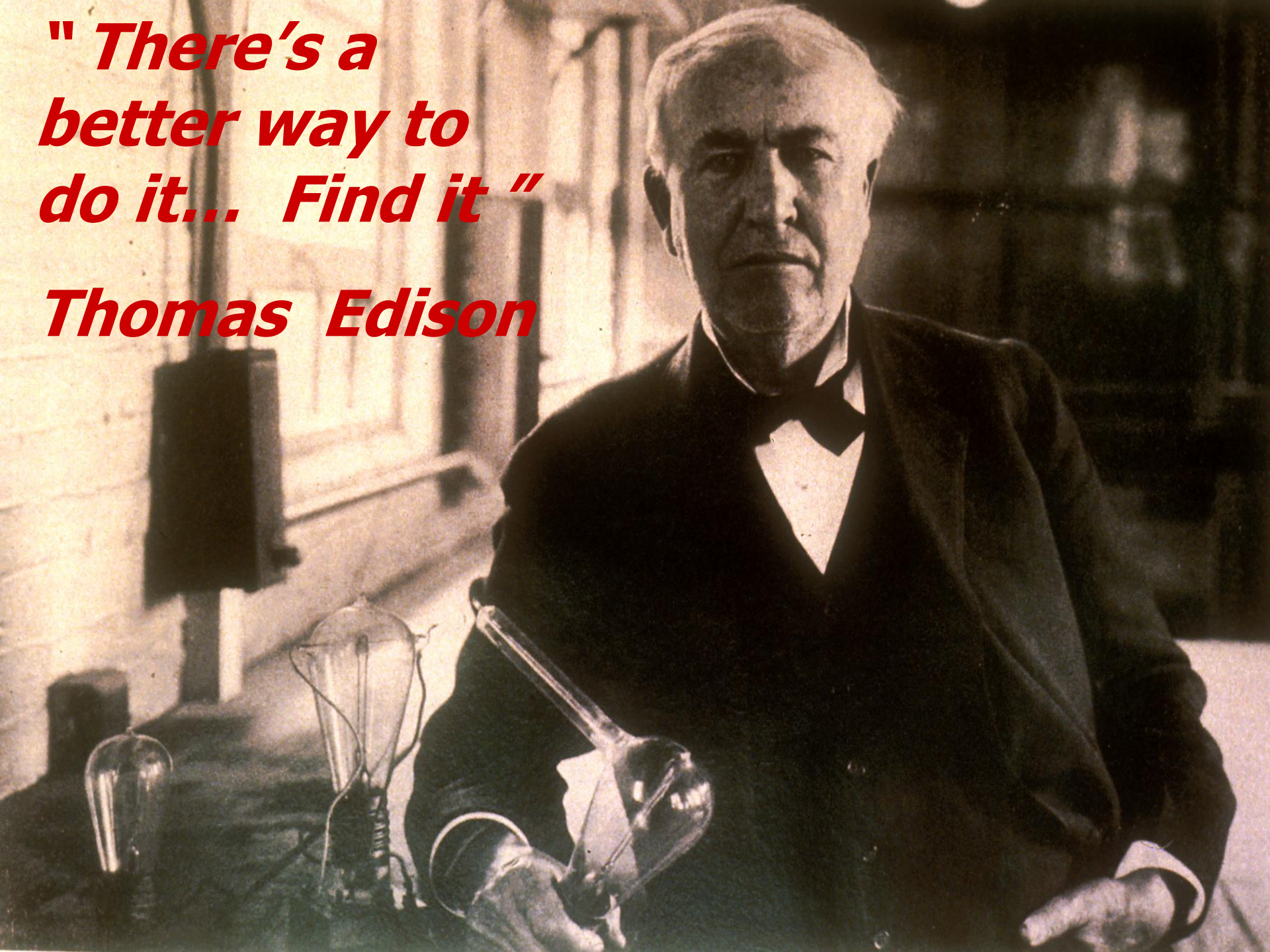
Pilot plant: generation, conversion, collection, storage CORRIDOR, SYSTEM

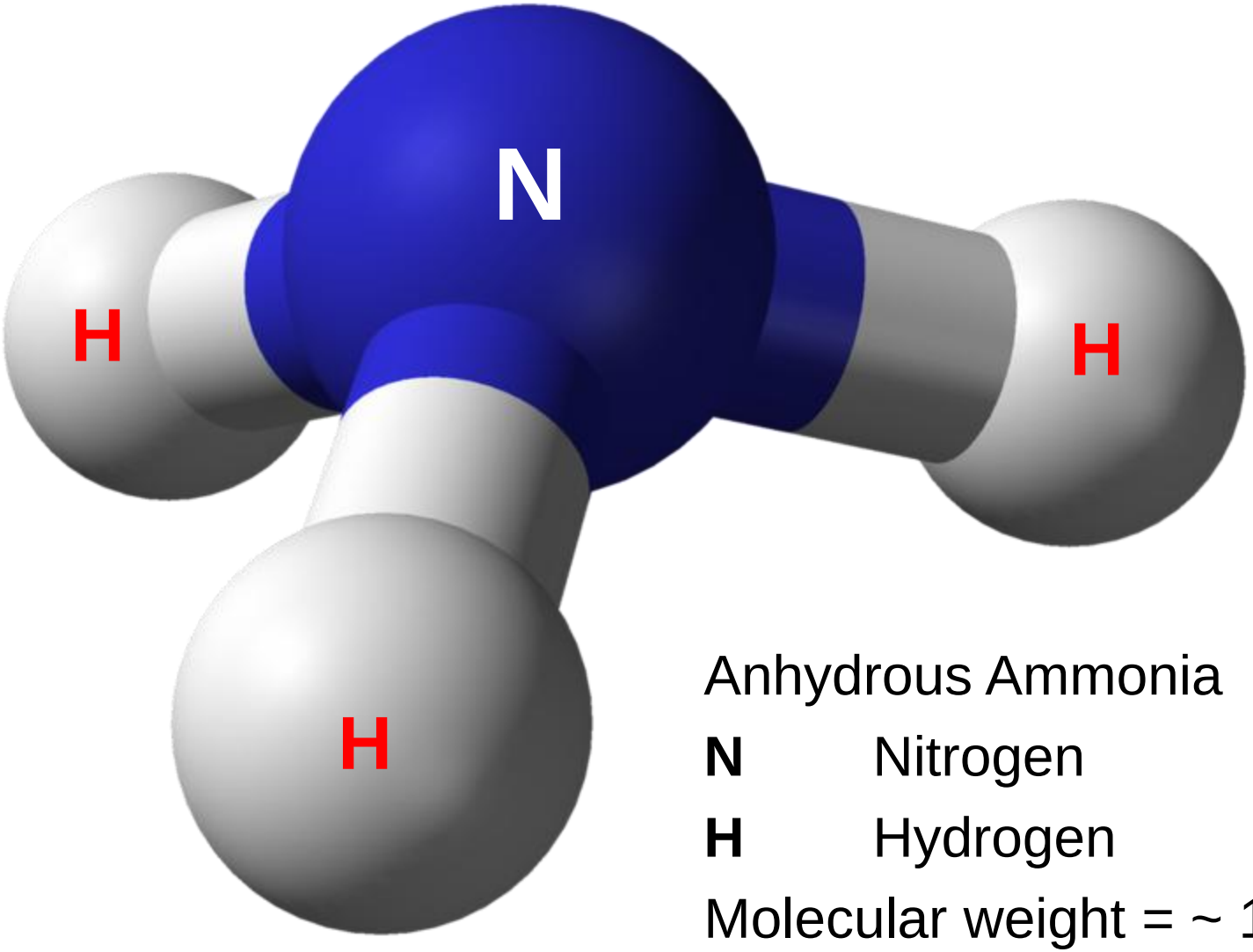


Renewables, Electrochemical energy

Airbus Industrie concept: liquid hydrogen fueled




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



Anhydrous Ammonia **NH_3**

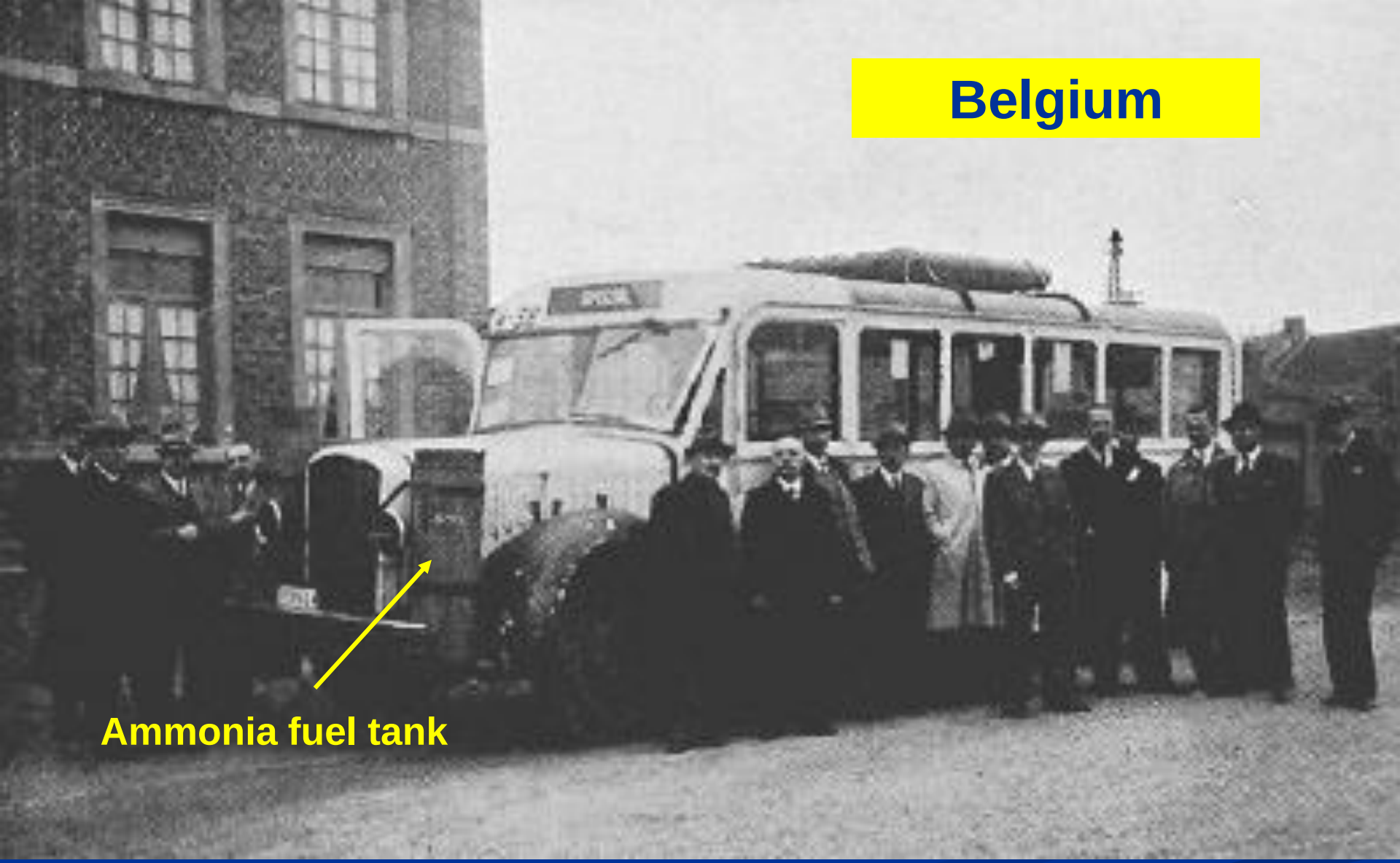
N Nitrogen

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

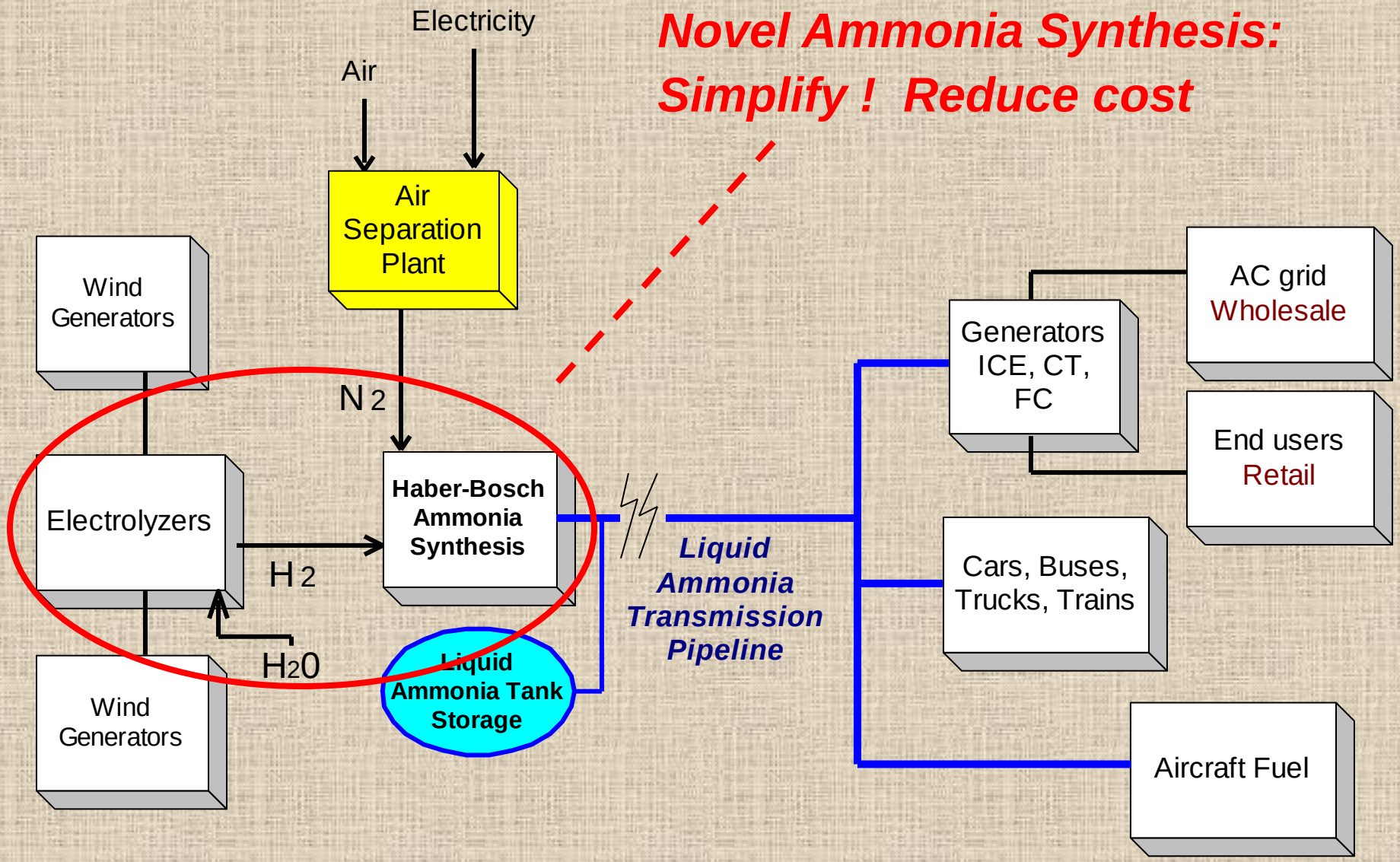
199 missions

1959 - 68

Liquid Hydrogen – LH2
100 H atoms

Liquid Anhydrous Ammonia – NH3
170 H atoms

RE Ammonia Transmission + Storage Scenario



USDOE ARPA-E "REFUEL" R&D

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

’09 ARPA-E “Grids” Goal: $100 / kWh

Total storage = 380 GWh

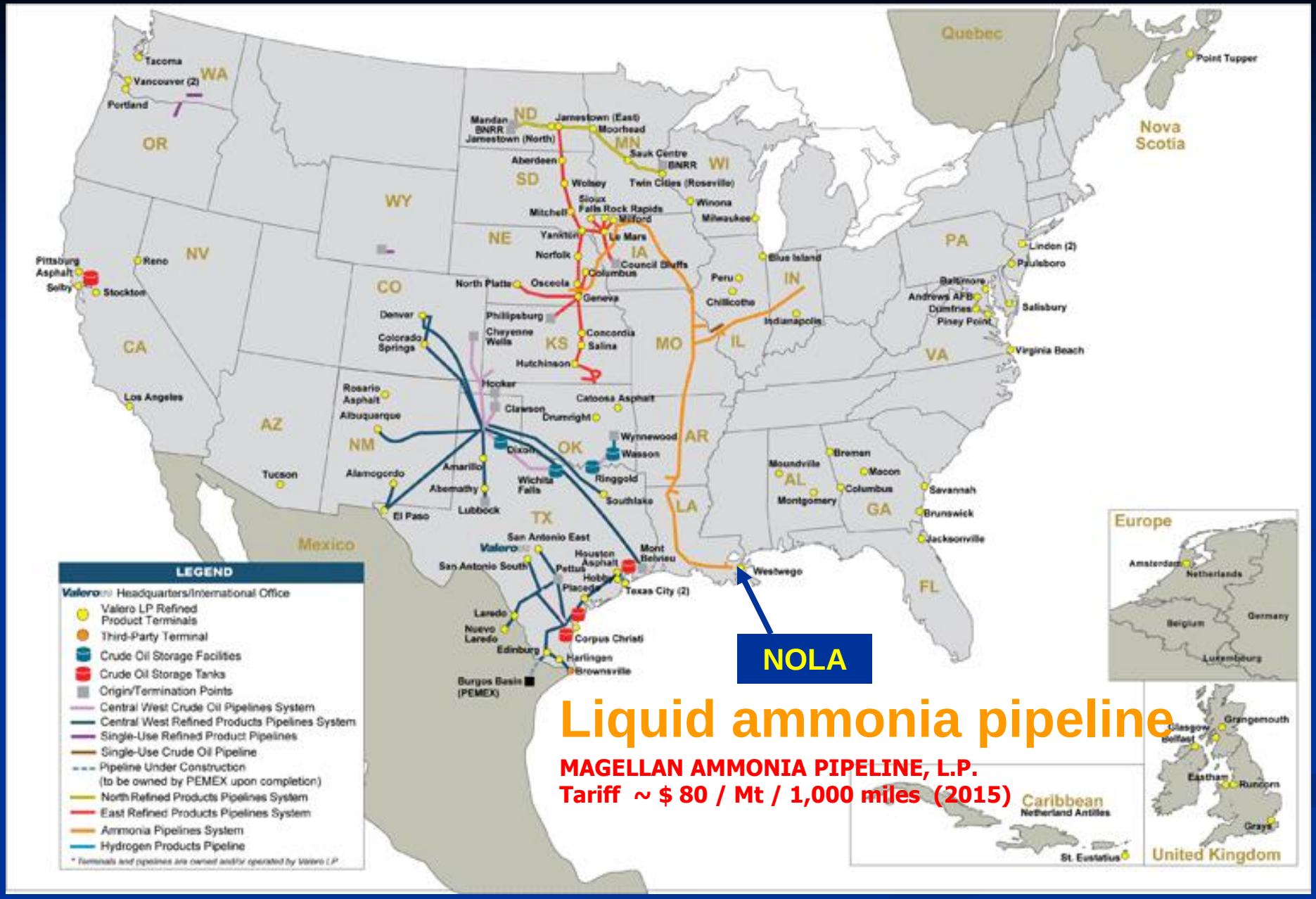
“Atmospheric” Liquid Ammonia Storage Tank (Corn Belt)

-33 C 1 Atm

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

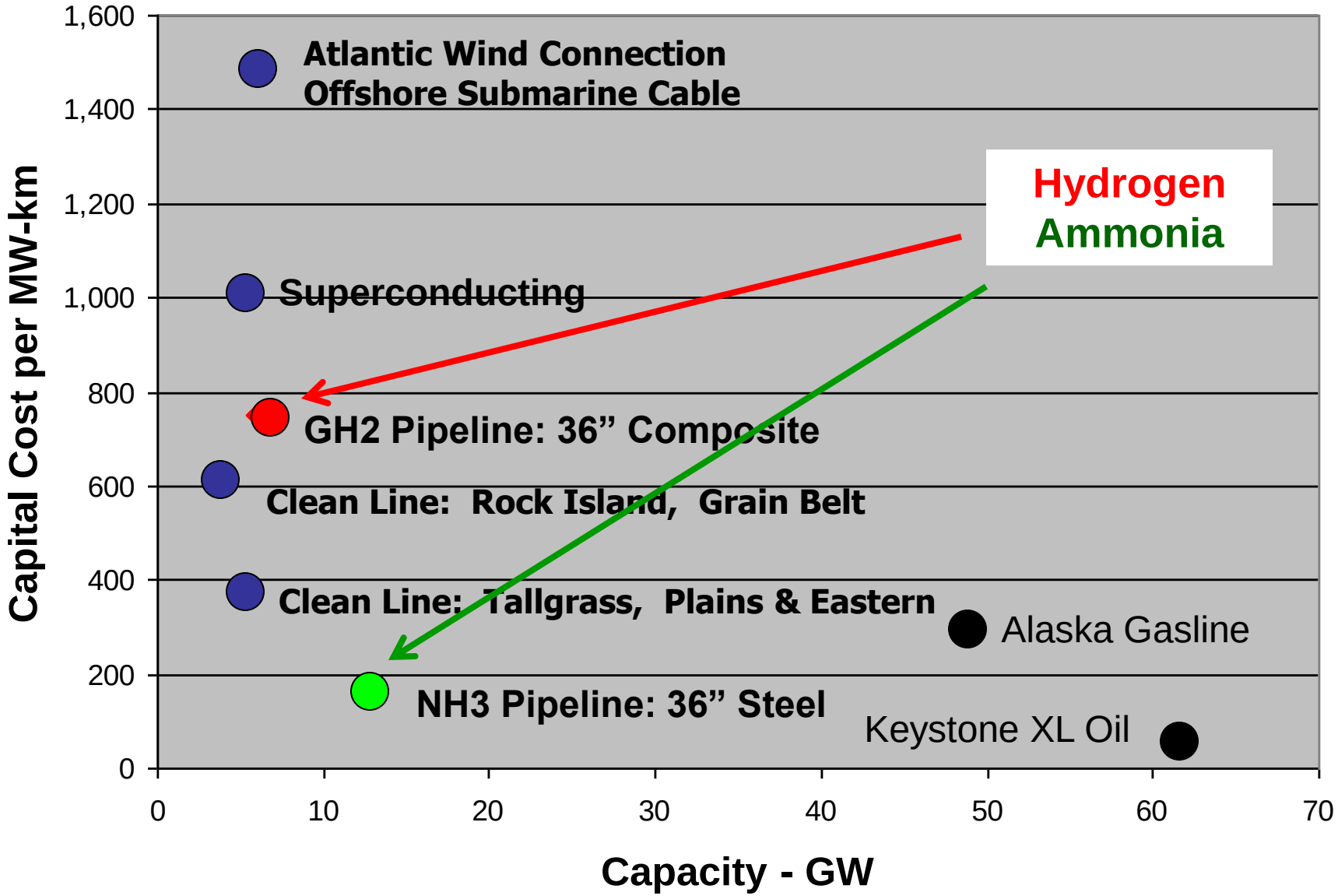
$ 80 / MWh = $ 0.08 / kWh capital cost


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



Liquid ammonia pipeline

MAGELLAN AMMONIA PIPELINE, L.P.
Tariff ~ $ 80 / Mt / 1,000 miles (2015)



Transmission capital costs per MW-km compared

Pipelines have large capacity and provide large storage

Capital Cost per GW-mile

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

Hydrogen pipeline:

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

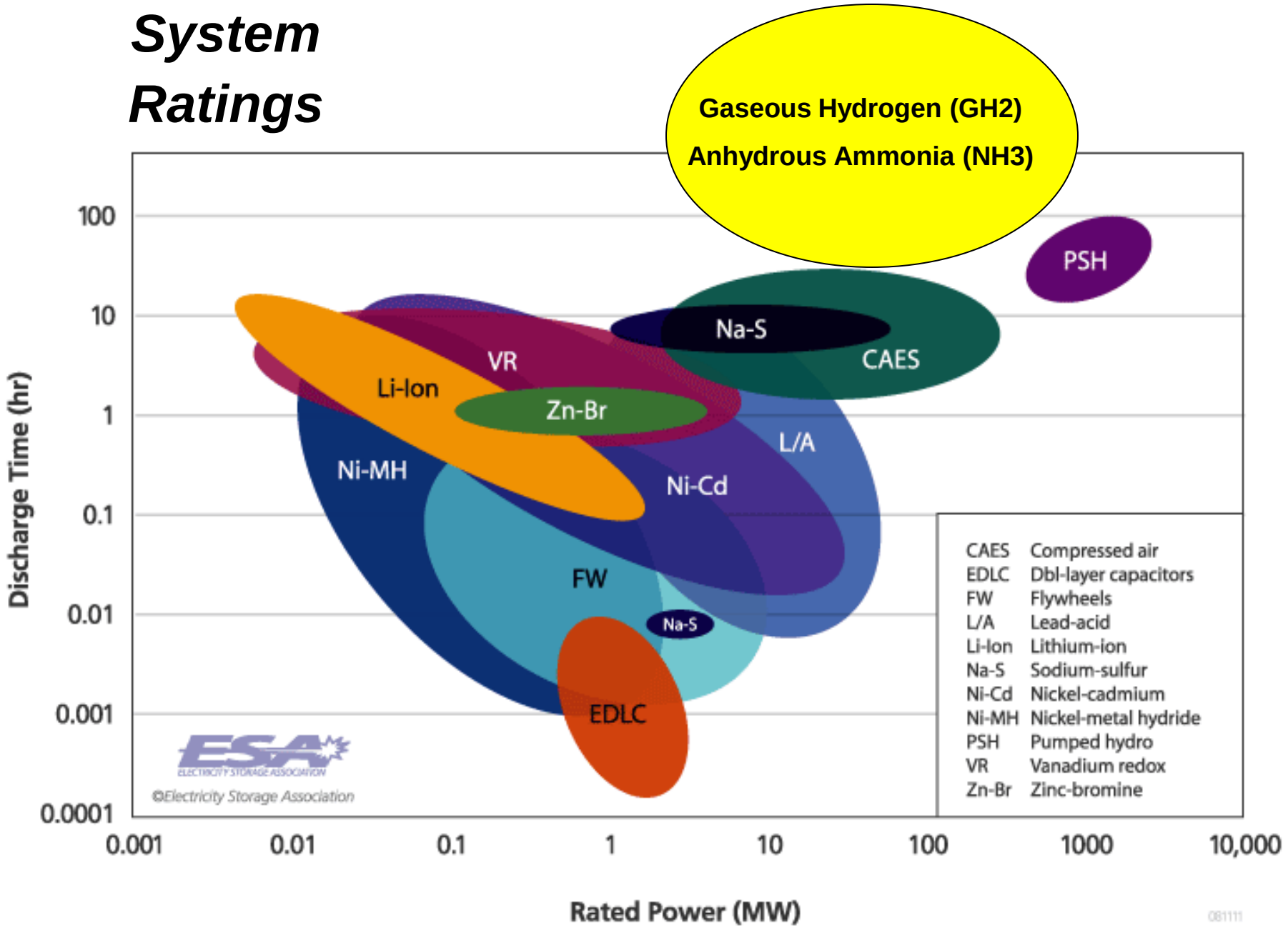
Ammonia pipeline:

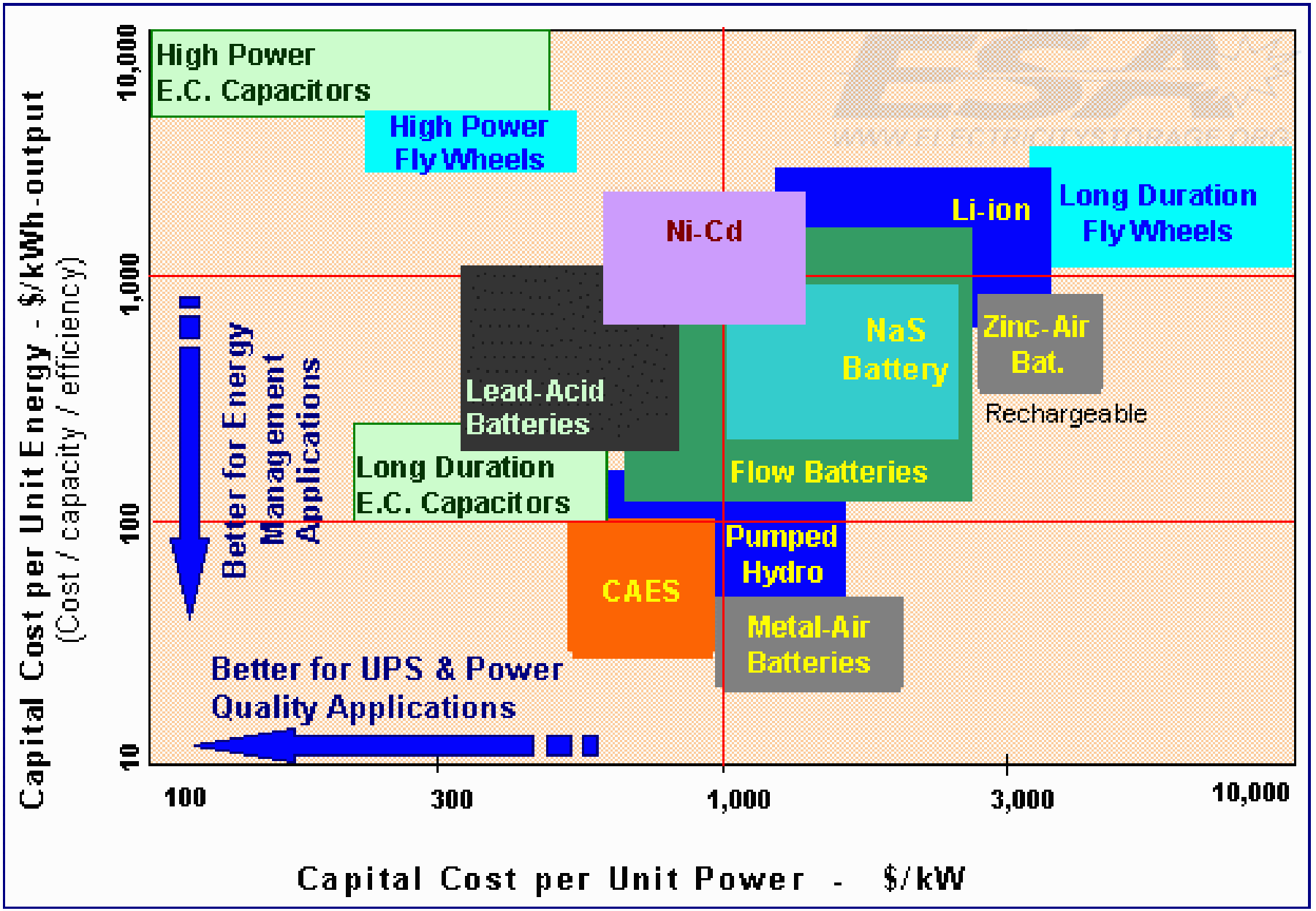
10”, liquid, 500 miles, with pumping 0.2

320 GWh
Annual firming, 1,000 MW wind

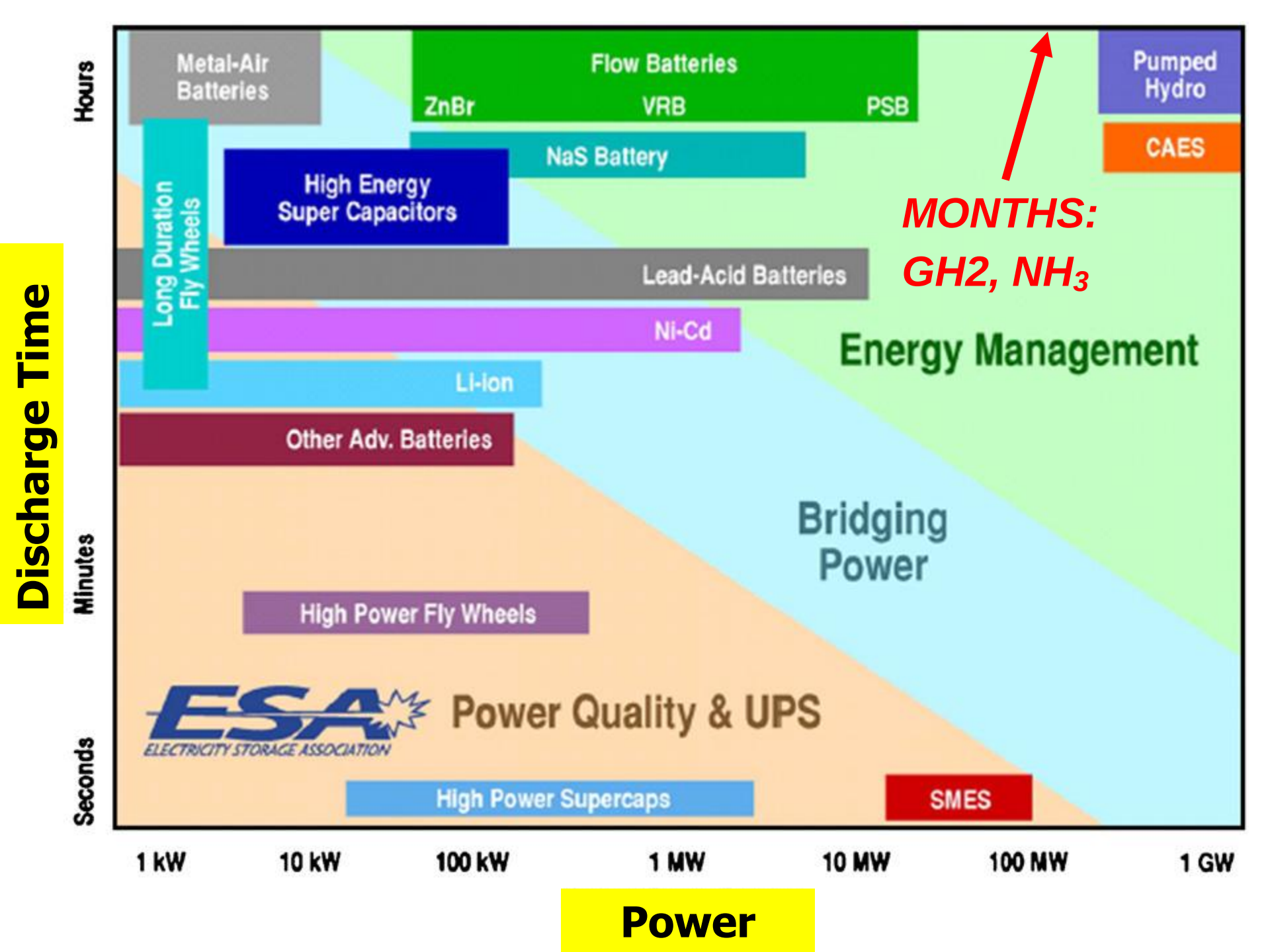
- **CAES (compressed air energy storage)**
  - **O&M: $46 / MWh typical**
  - **Iowa: Power = 268 MW**
    Energy capacity = 5,360 MWh
    Capital: 268 MW @$800 / kW = $214 M
    Storage @ $40 / kWh = $ 13 Billion
    Storage @ $1 / kWh = $ 325 Million
- **Battery**
  - **O&M: 90% efficiency round-trip**
  - **Capital: $500 / kWh = $ 160 Billion**
  - **Capital: $300 / kWh = $ 96 Billion**
- **GH2 (3 hydrogen caverns) Capital $70 Million**
- **NH3 (2 ammonia tanks) Capital $30 Million**

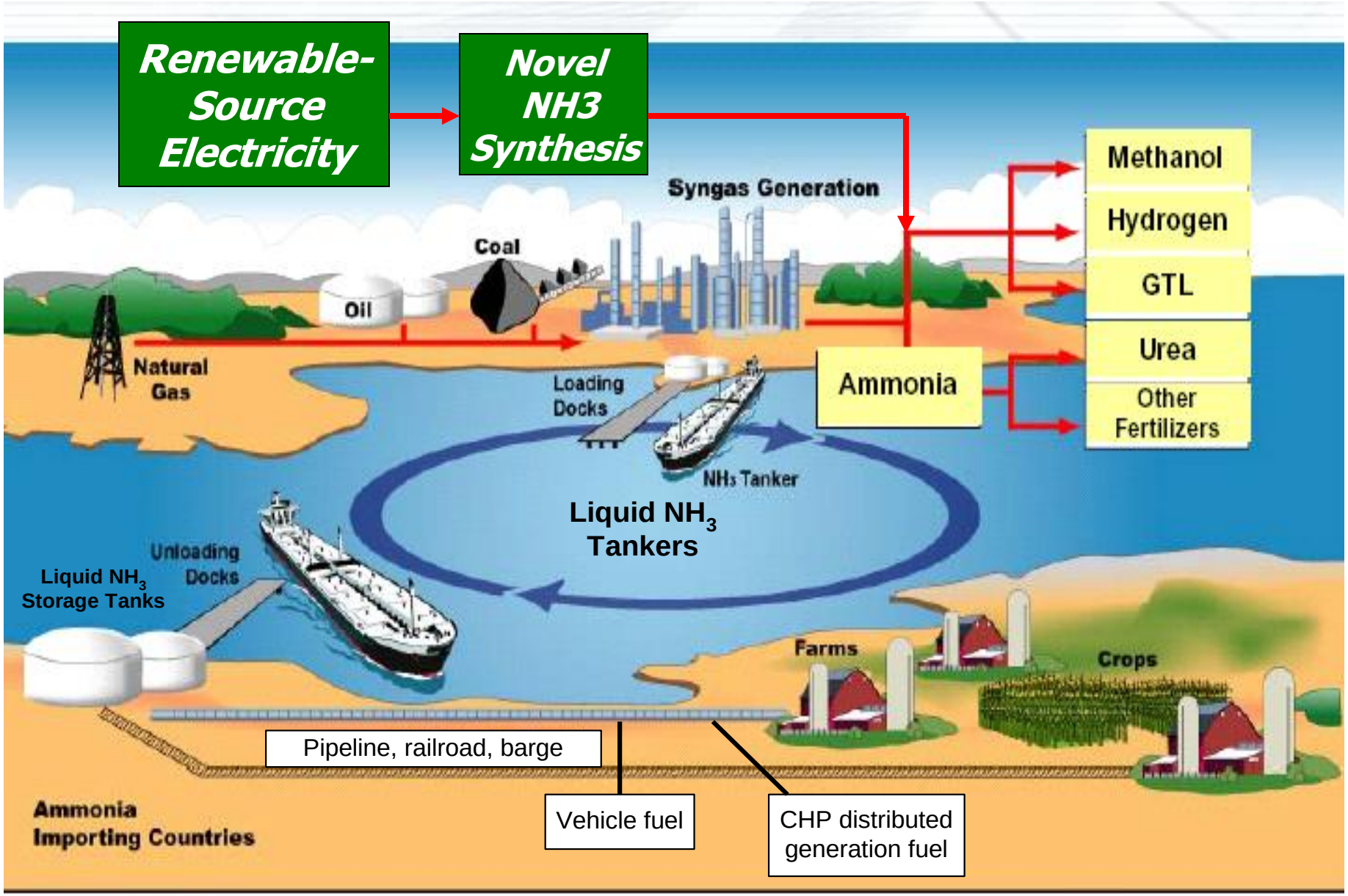
System Ratings



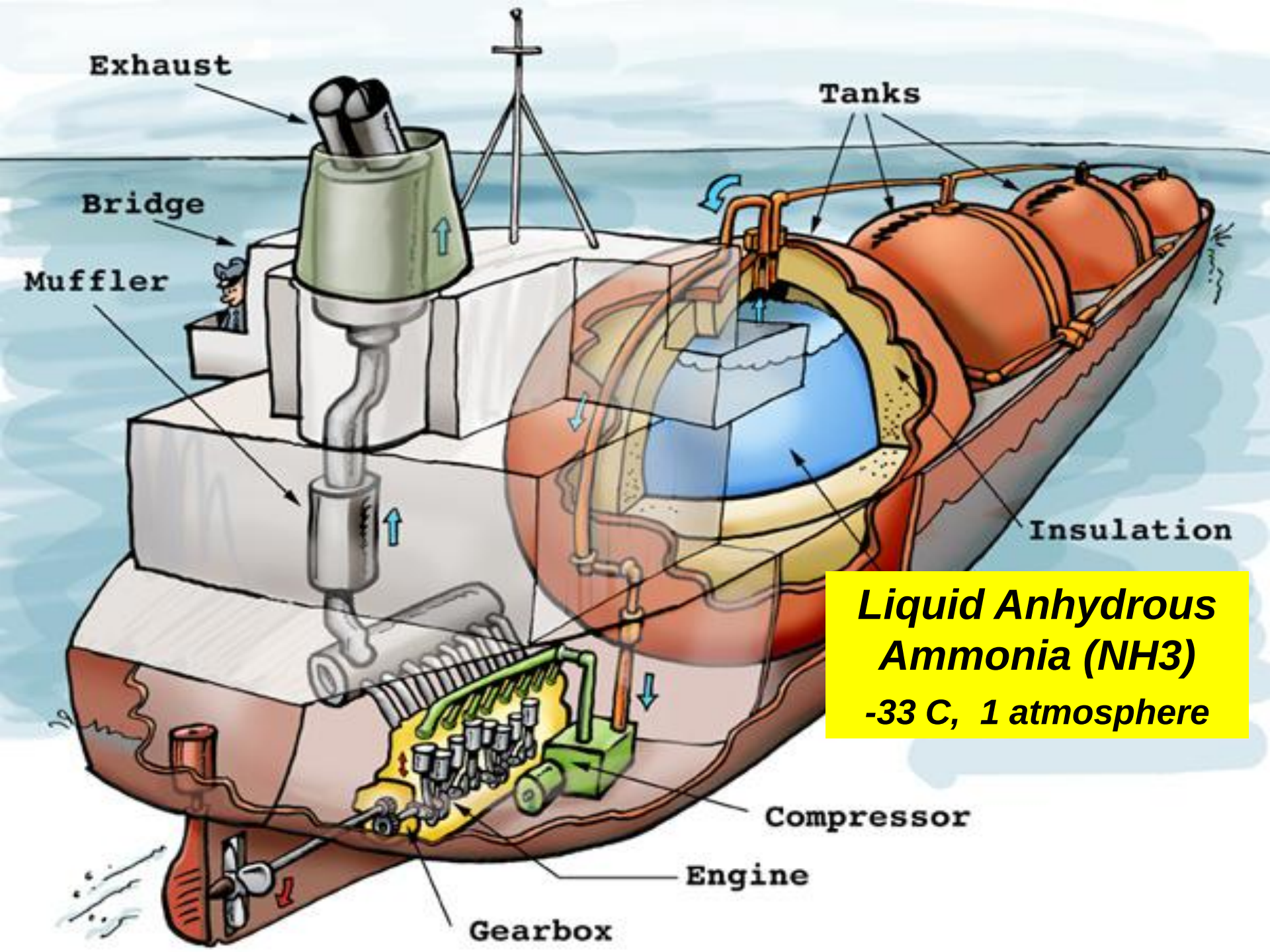

Capital Cost per Unit Energy - $/kWh-output
(Cost / capacity / efficiency)
10,000
1,000
100
10
High Power
E.C. Capacitors
High Power
Fly Wheels
Ni-Cd
Li-ion
Long Duration
Fly Wheels
NaS
Battery
Zinc-Air
Bat.
Rechargeable
Lead-Acid
Batteries
Long Duration
E.C. Capacitors
Flow Batteries
Pumped
Hydro
CAES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

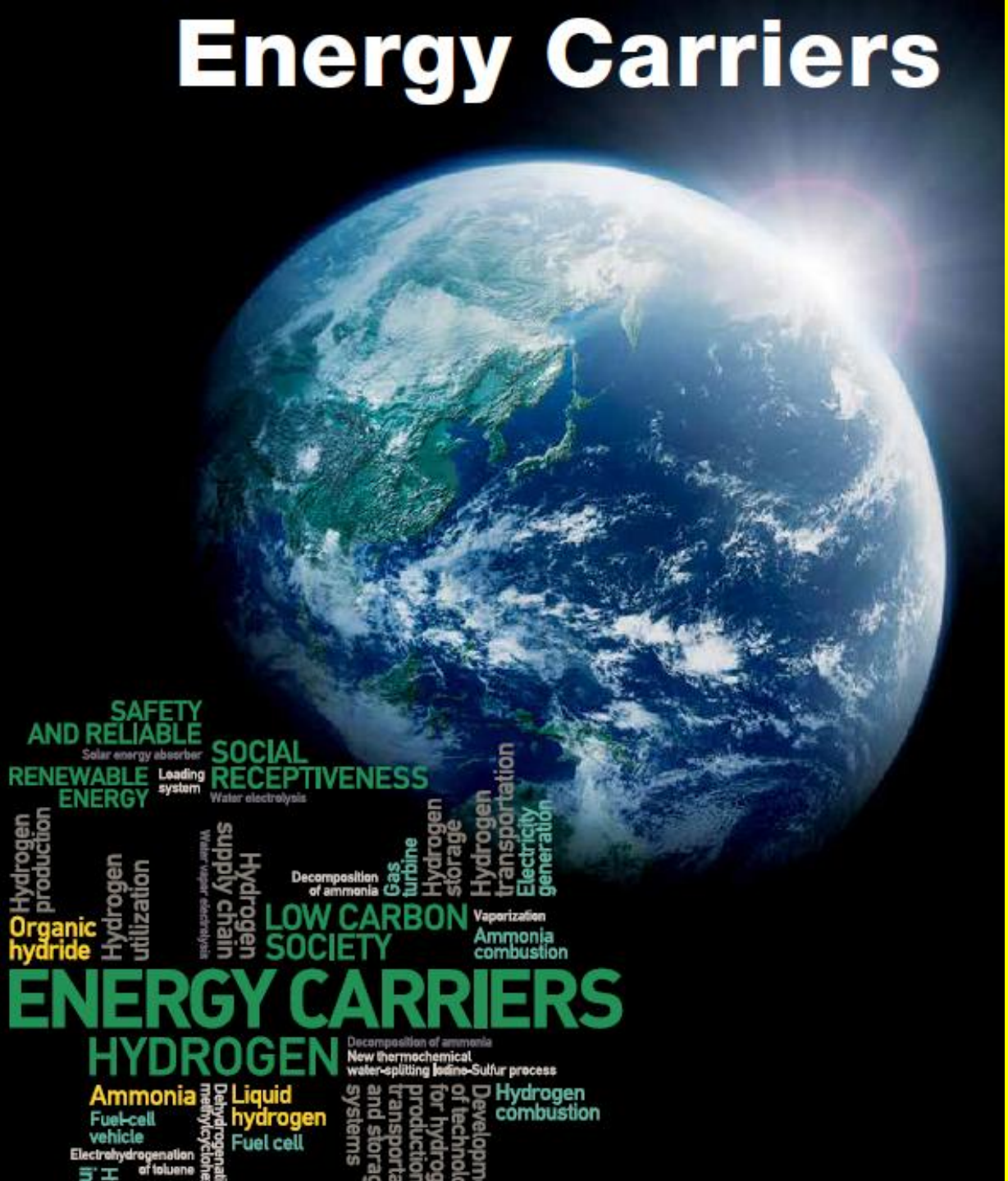
GH2 and NH_3


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



KBR
Energy and Chemicals


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

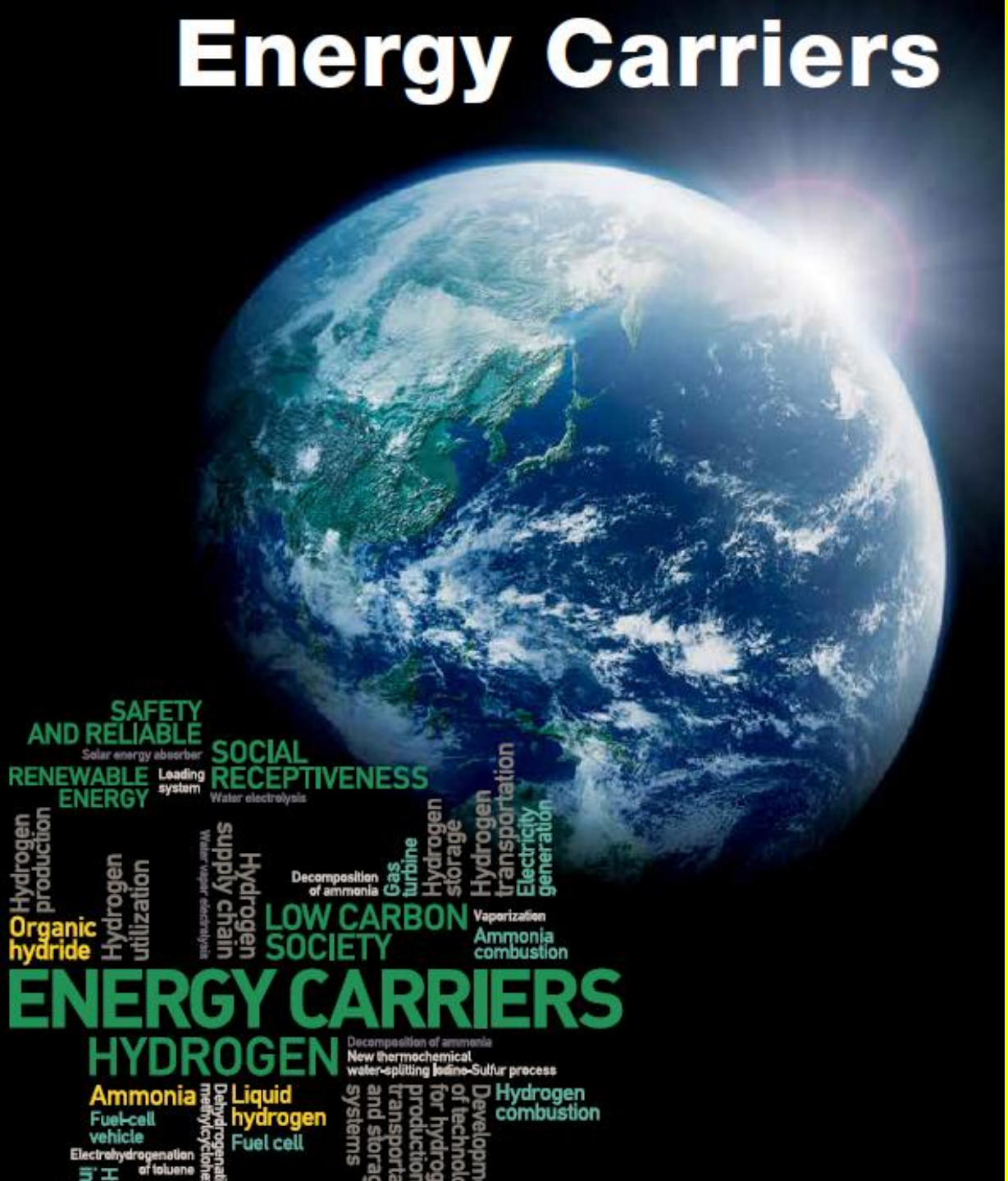


2016

Japan Science and Technology Agency

Strategic Innovation Promotion Program

SIP



2016

Strategic Innovation Promotion Program

SIP

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

Kawasaki LH2 ocean tanker, truck

World Smart Energy Week

Tokyo, 26 Feb 14

Japan
Chiyoda Chemical

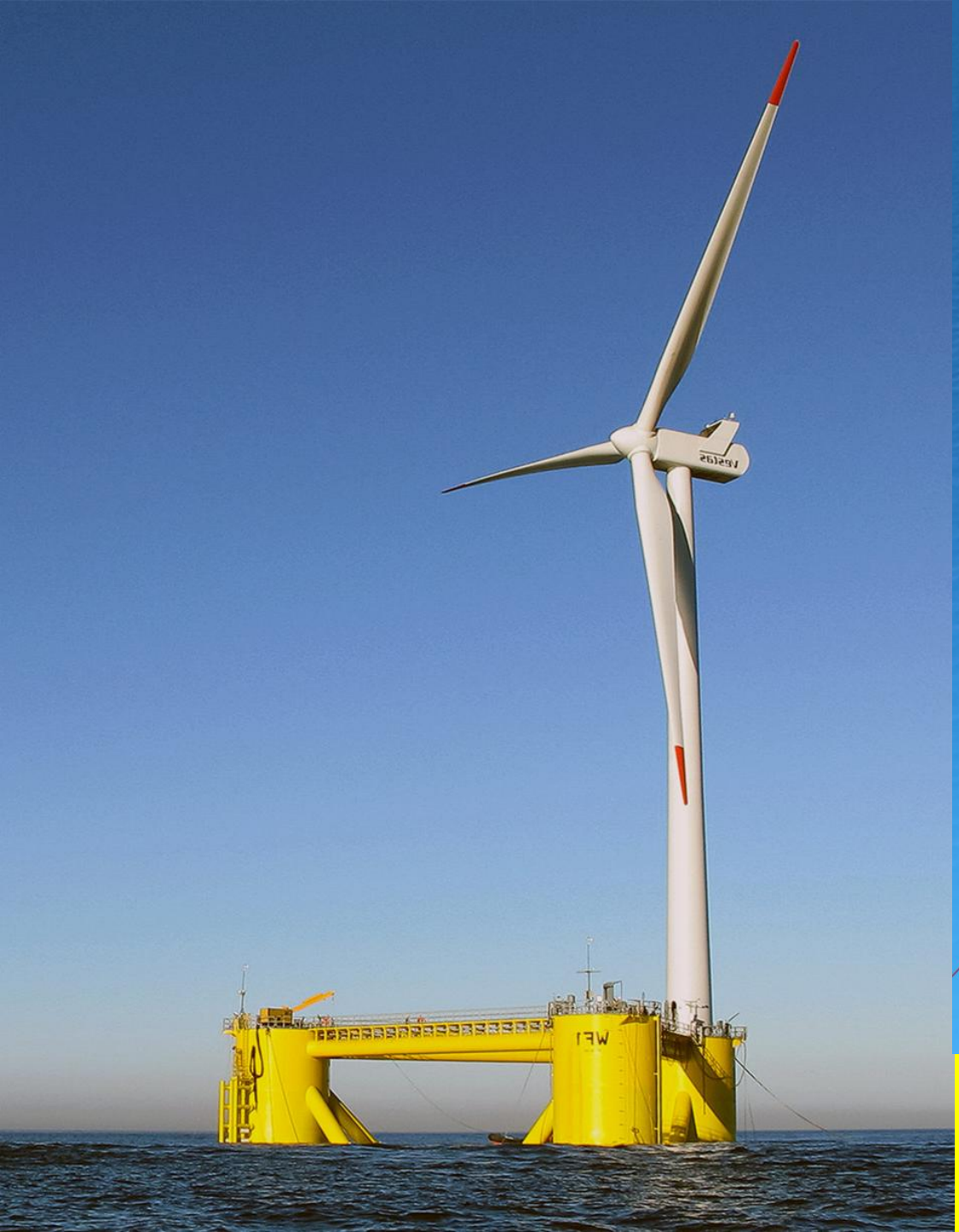
CHIYODA CORPORATION

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

"Spera": Latin for "hope"

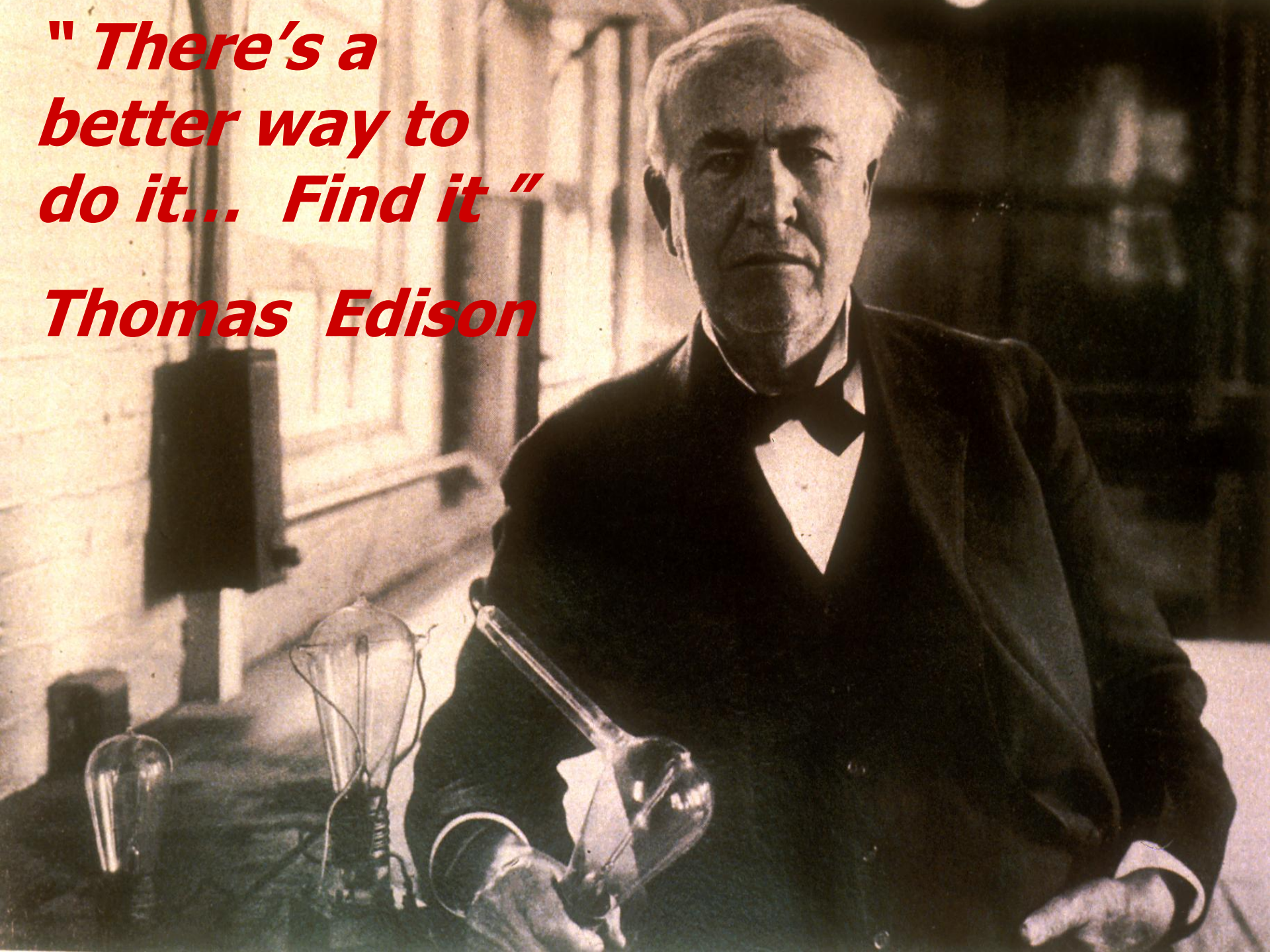
Spera Hydrogen

Chiyoda Chemical



Floating Offshore
Deep water, multi - MW

Aleutians wind to Japan via liquid fuel(s) tankers

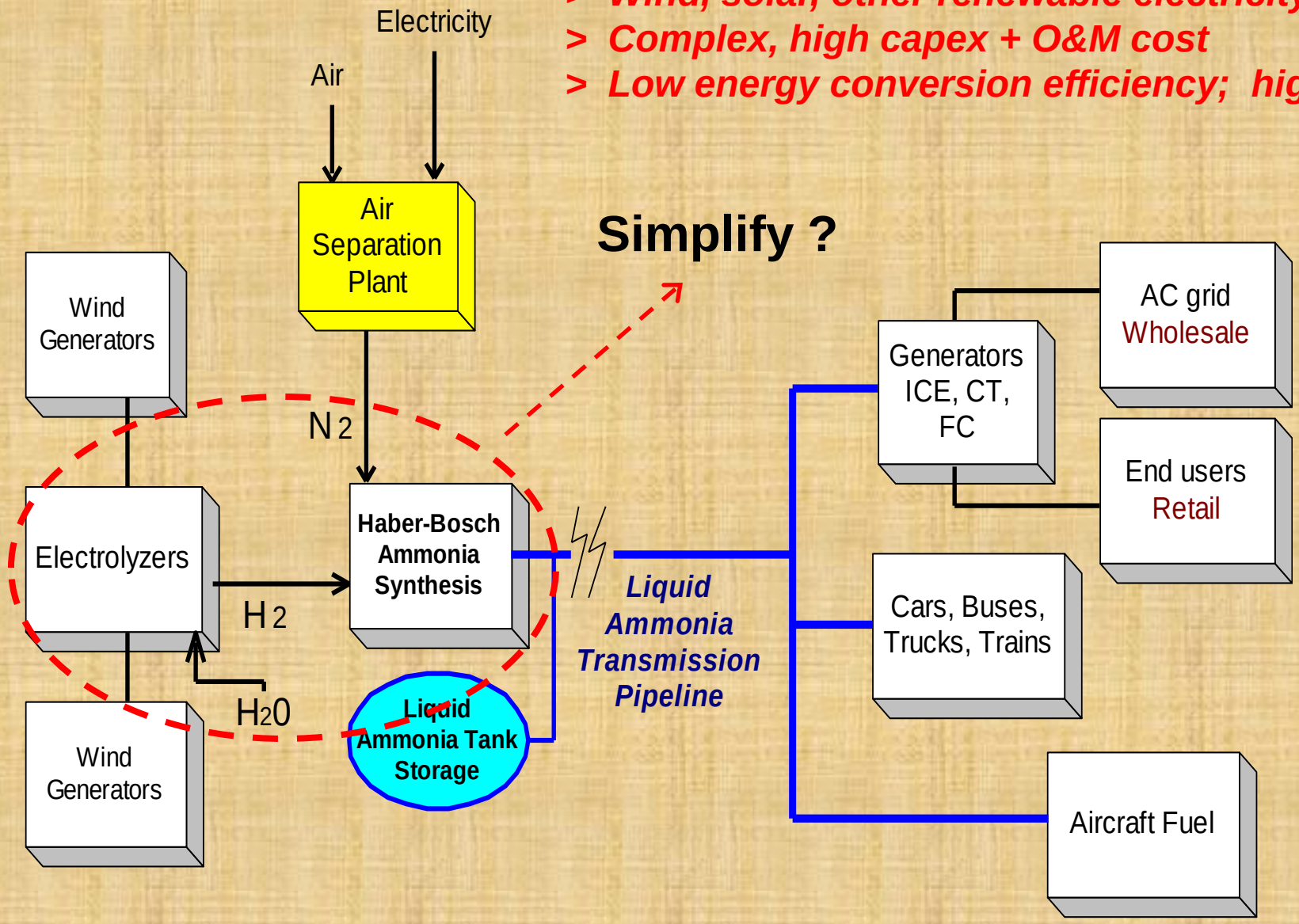

" There's a better way to do it... Find it "
Thomas Edison

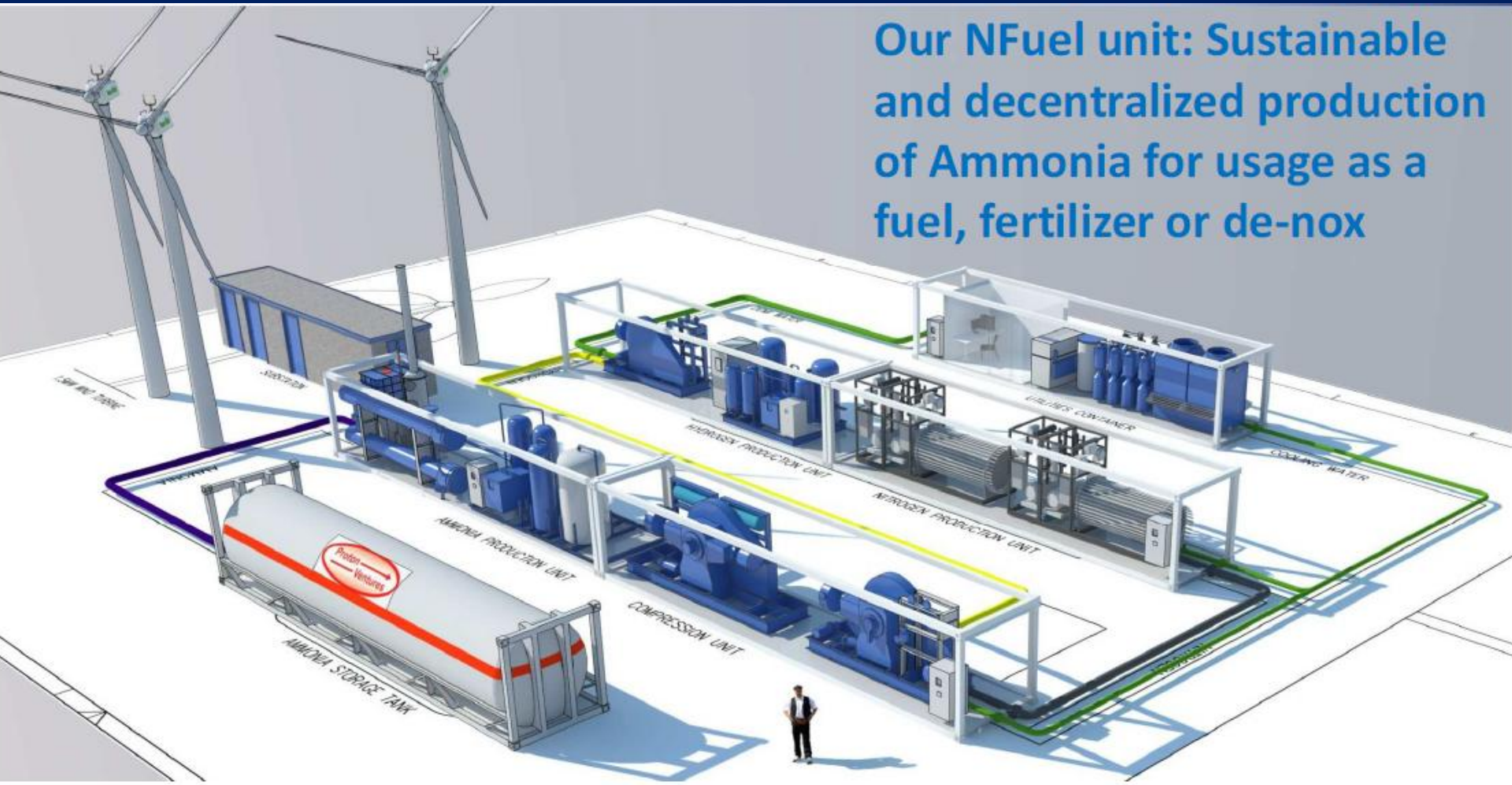
Now: Electrolysis + Haber – Bosch (EHB)

> Wind, solar, other renewable electricity

> Complex, high capex + O&M cost

> Low energy conversion efficiency; high T, P



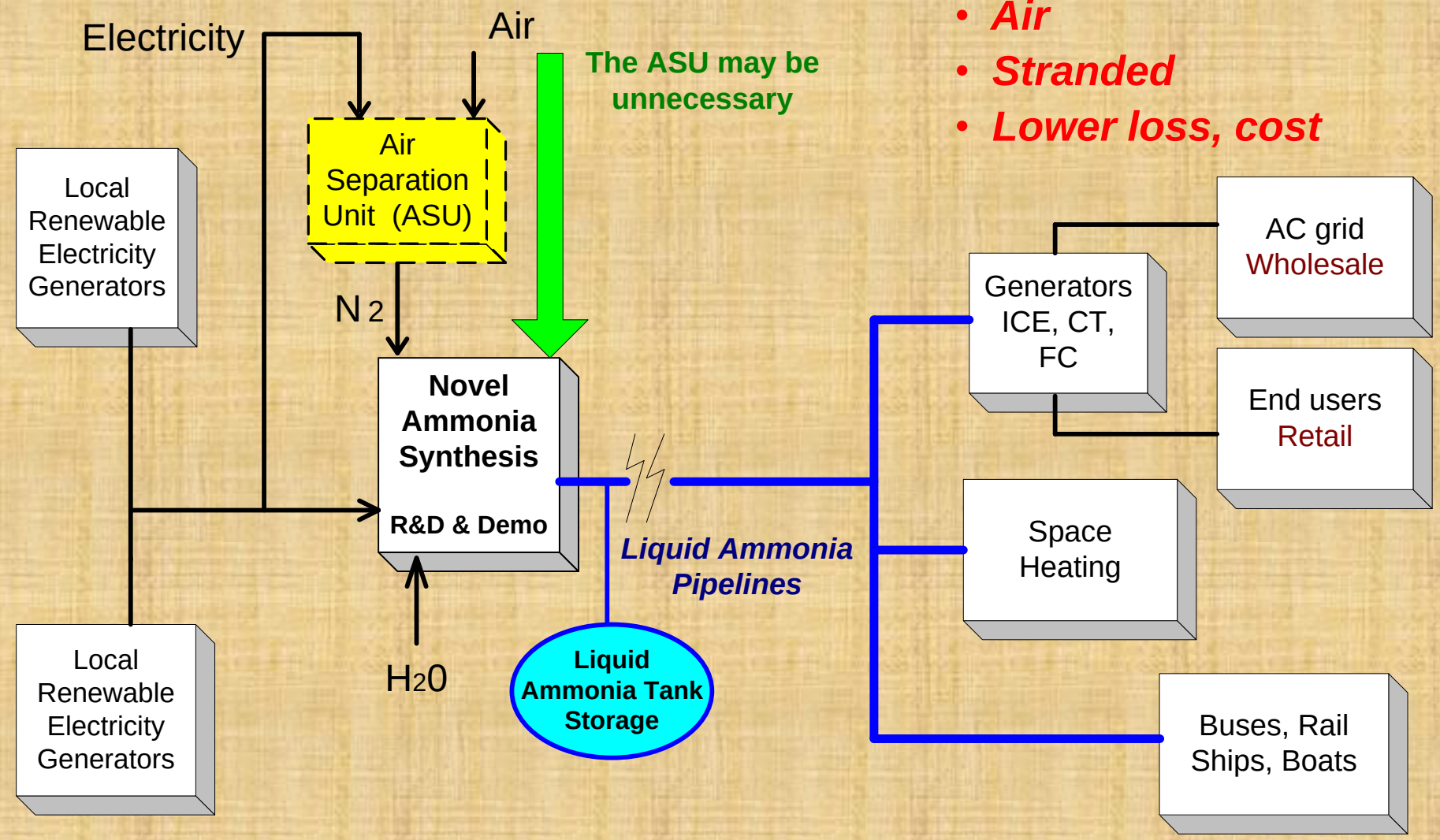


Proton Ventures BV, Netherlands

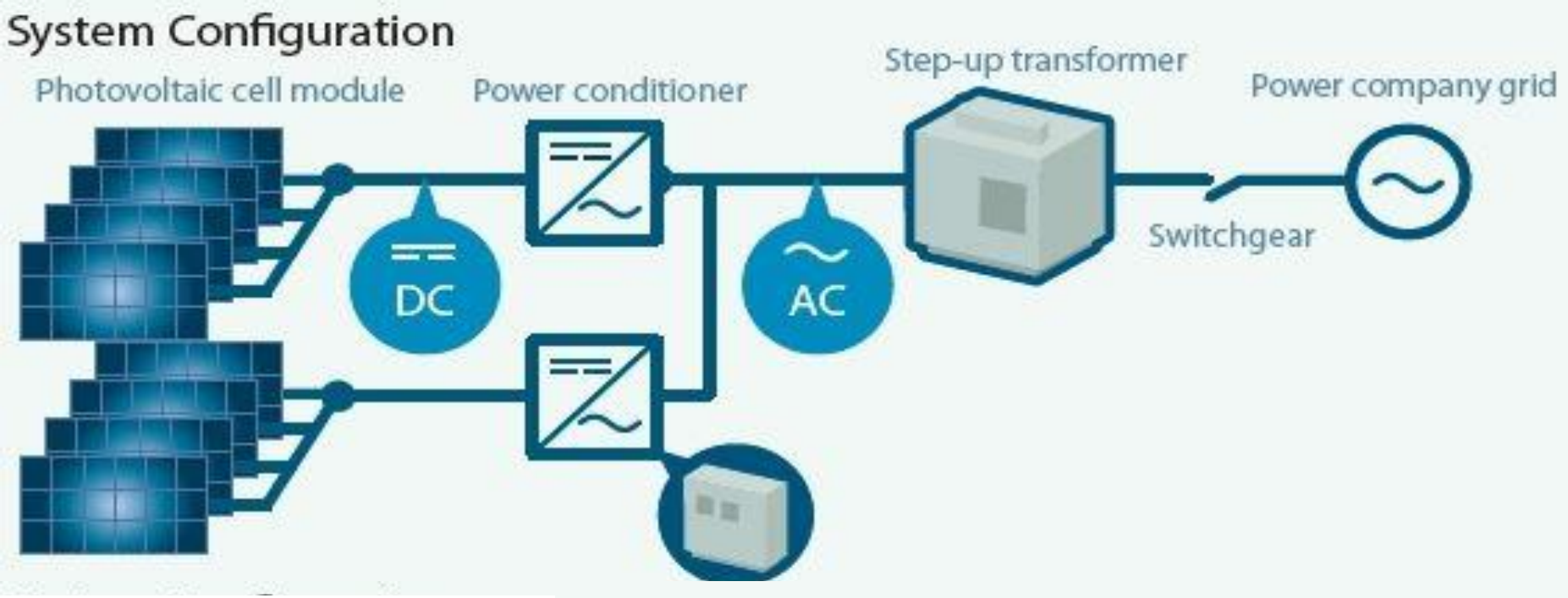
www.protonventures.com

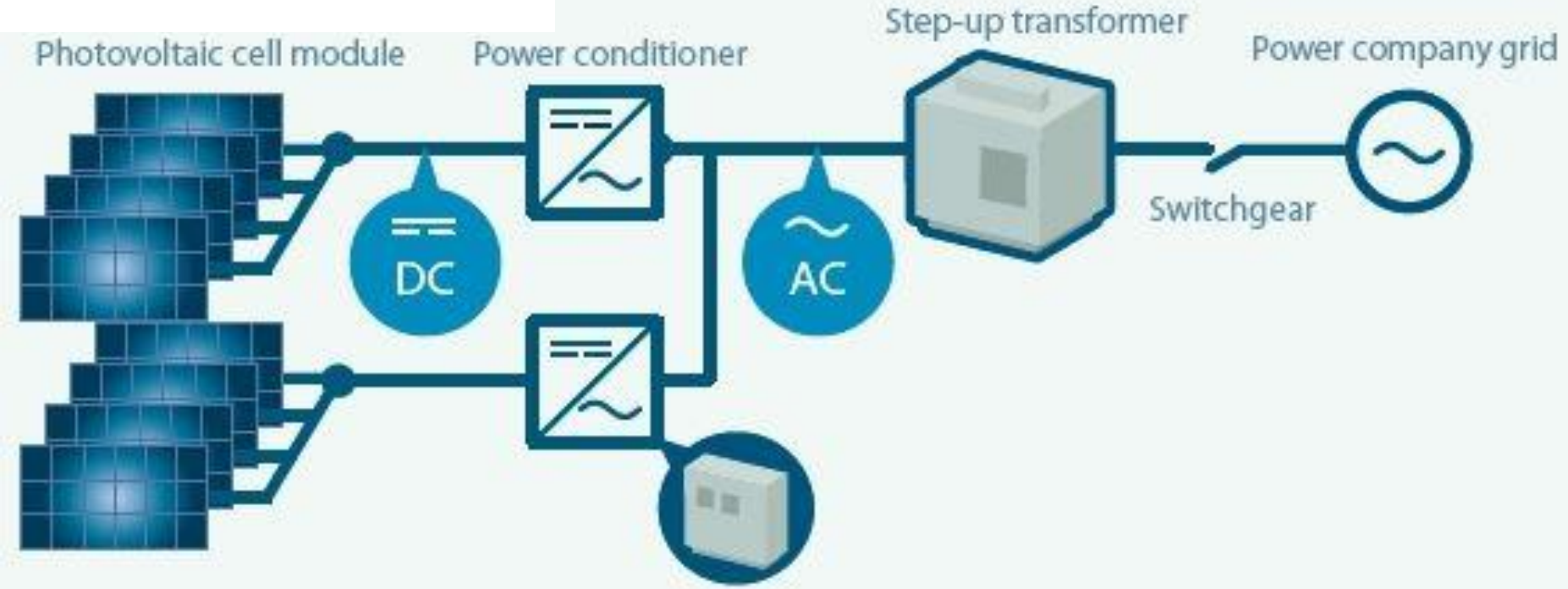
Novel Ammonia Synthesis

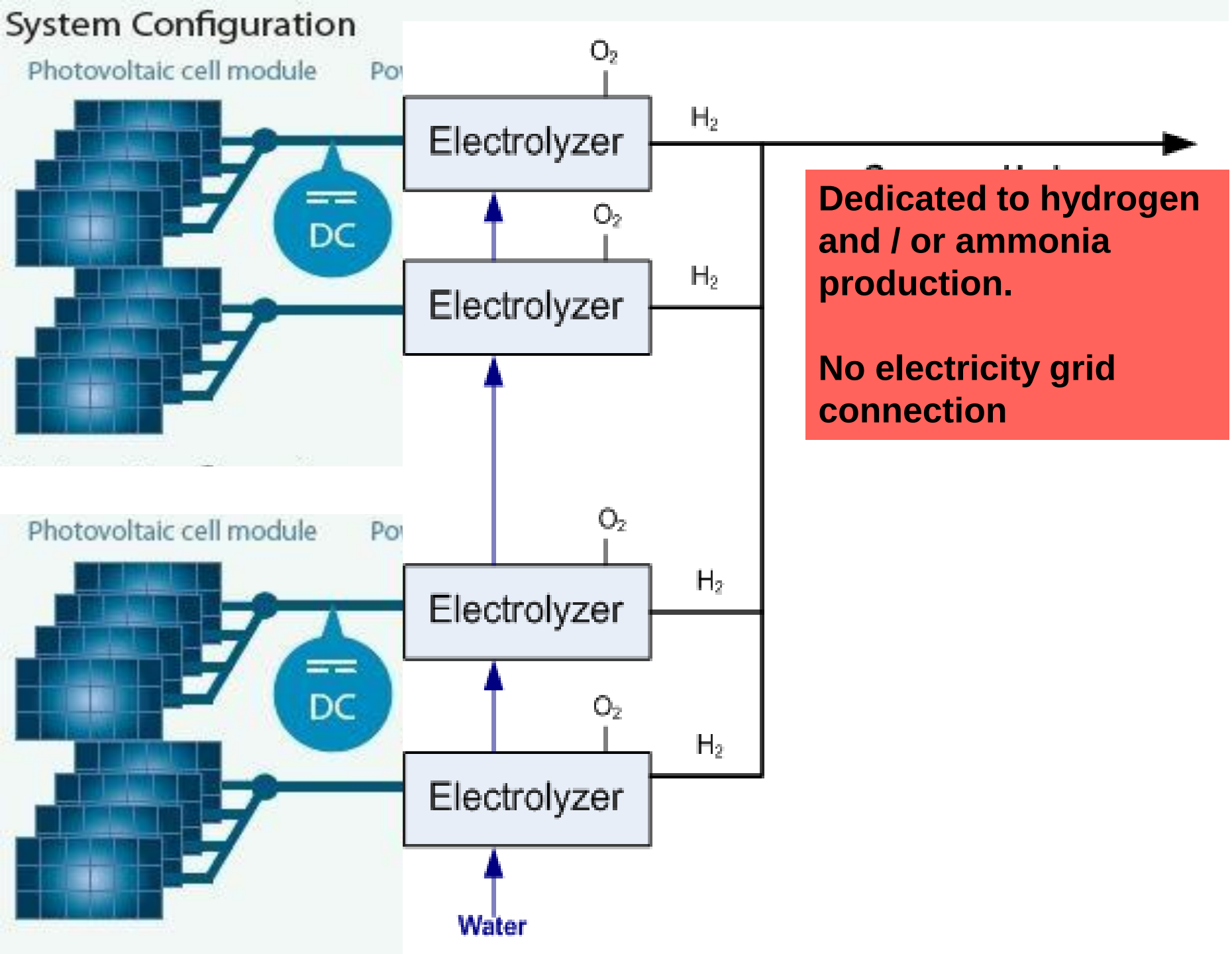
- ***Electricity***
- ***Water***
- ***Air***
- ***Stranded***
- ***Lower loss, cost***

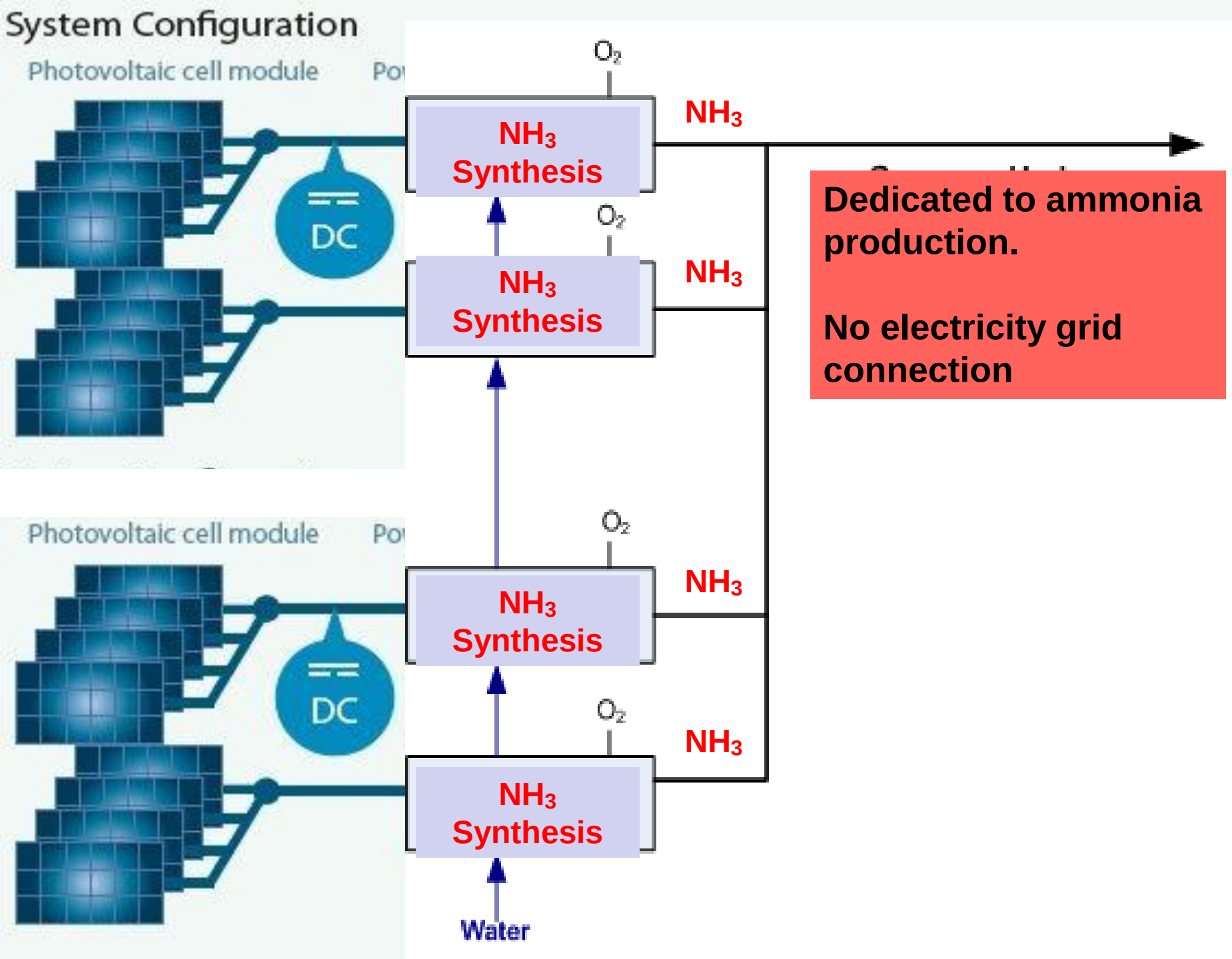


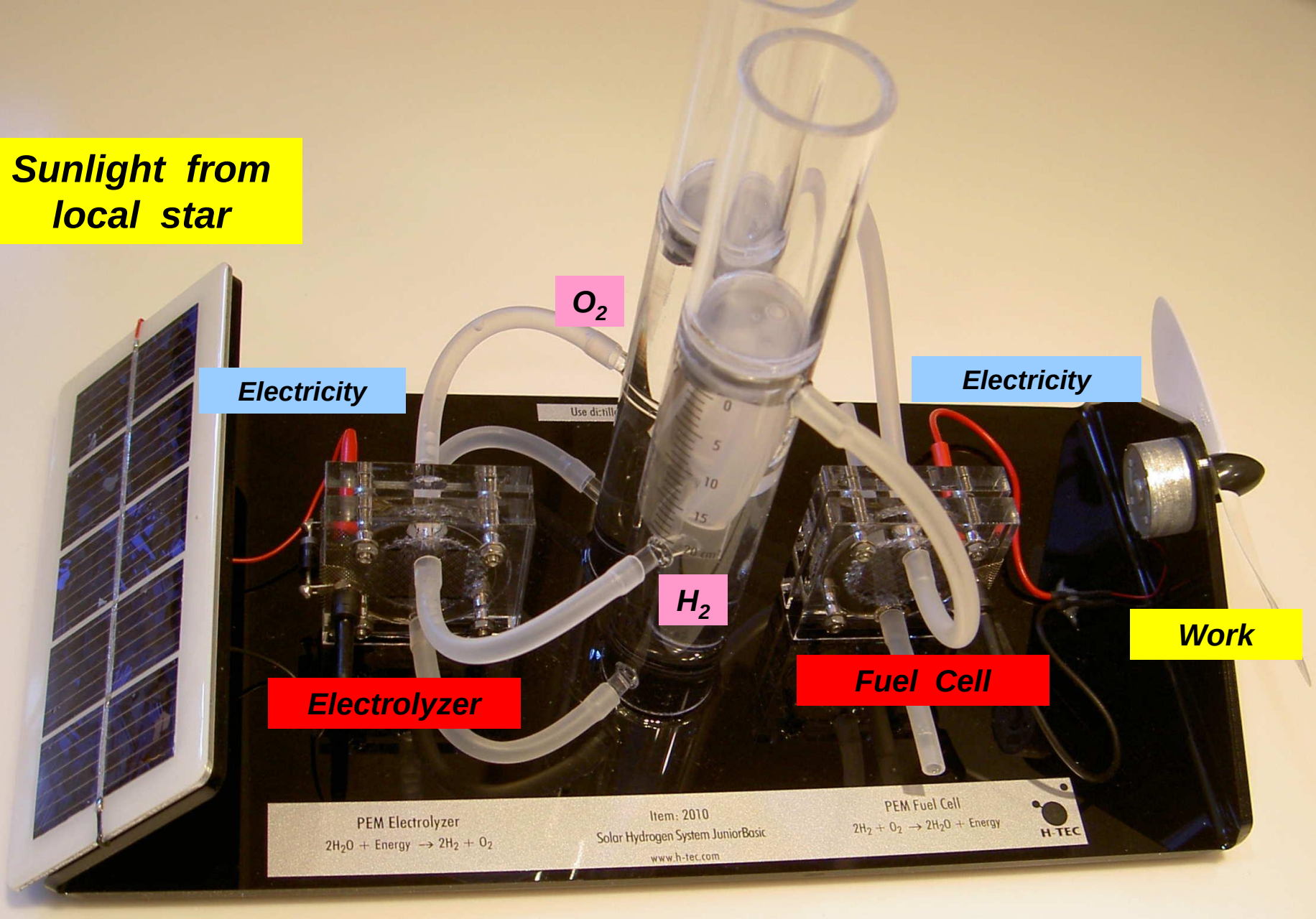
System Configuration



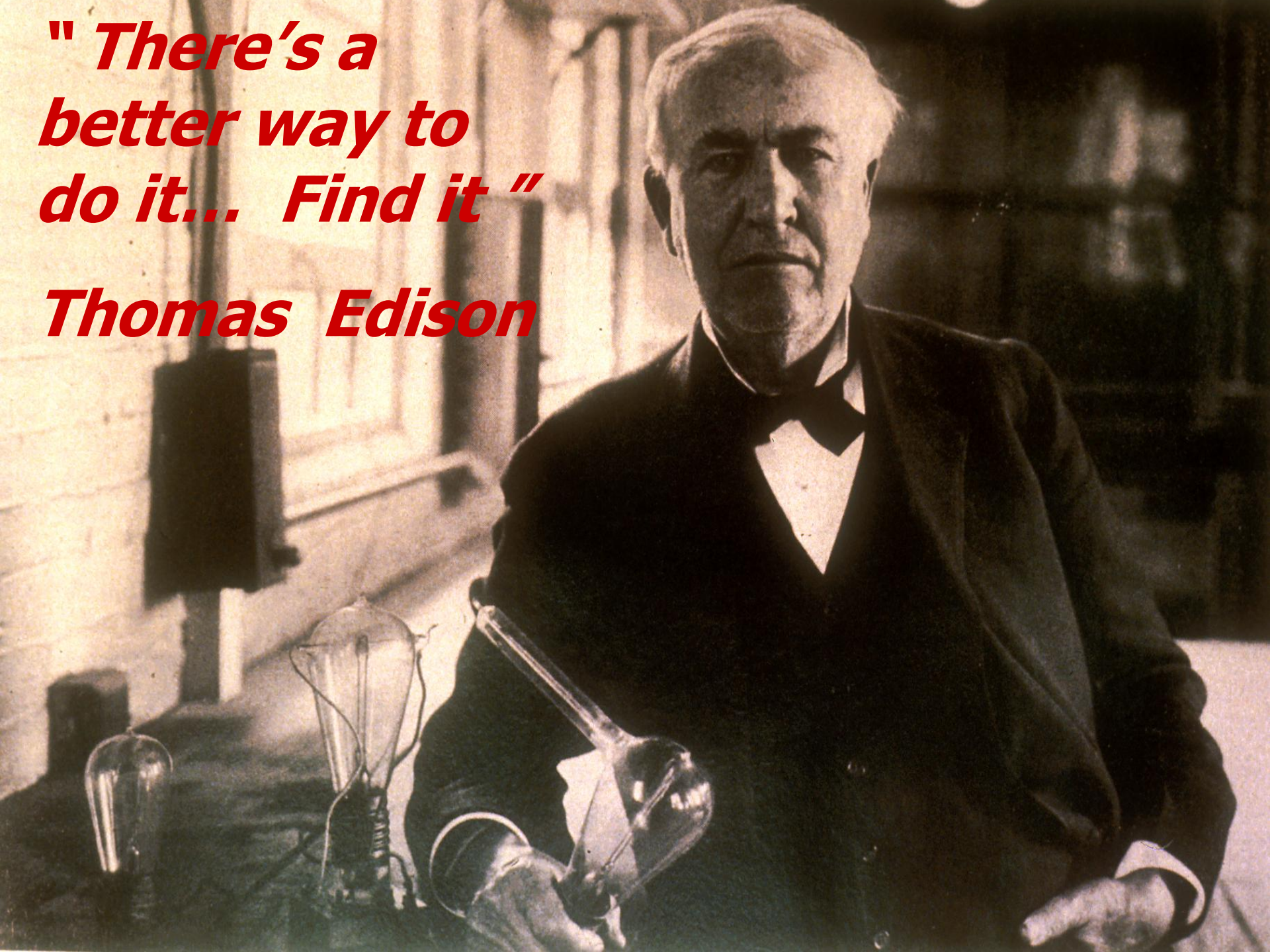


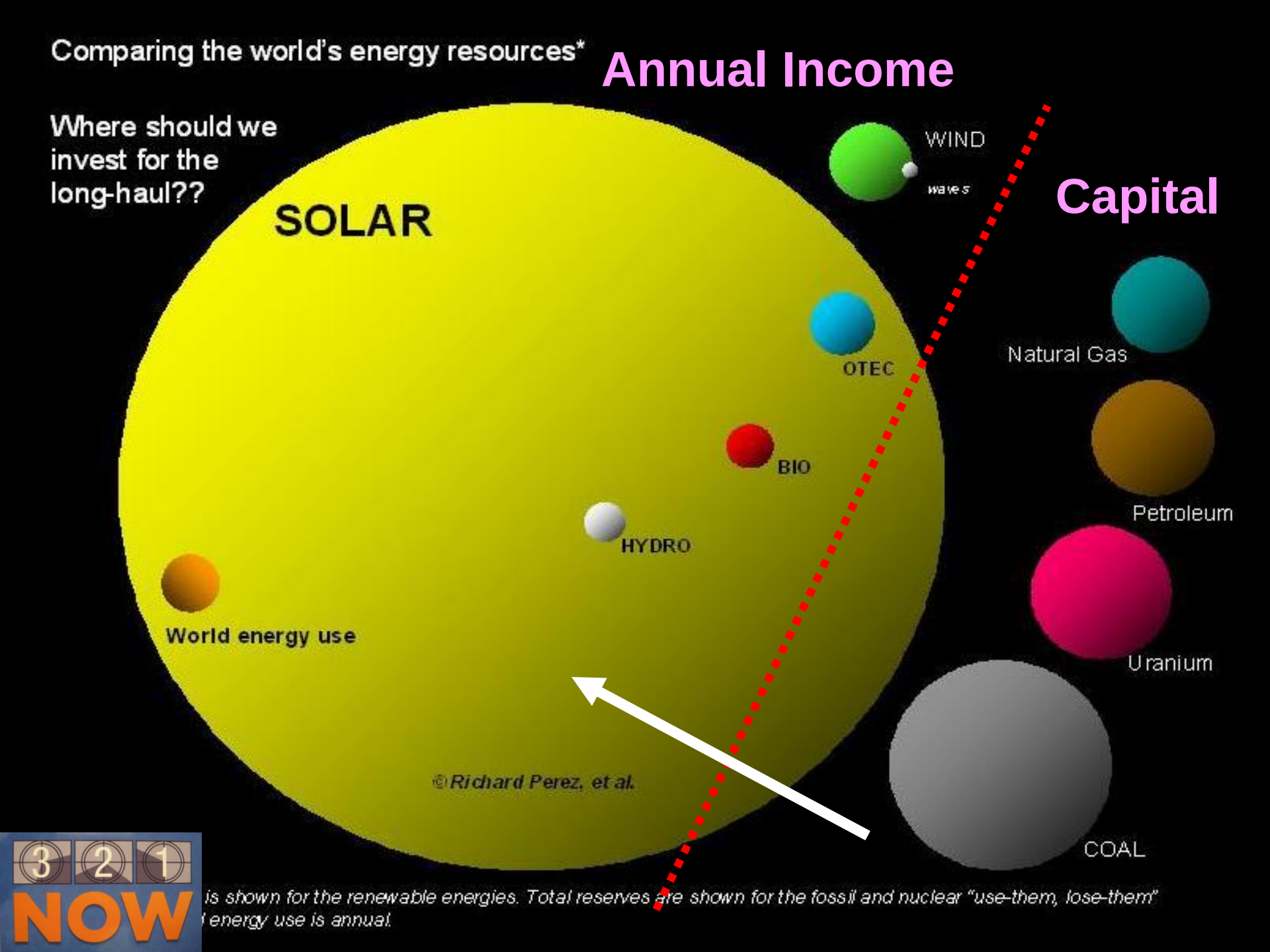

System Configuration
Photovoltaic cell module
Photovoltaic cell module
DC
DC
Electrolyzer
Electrolyzer
Electrolyzer
Electrolyzer
O2
O2
O2
O2
H2
H2
H2
H2
Water
Dedicated to hydrogen and / or ammonia production.
No electricity grid connection


System Configuration
Photovoltaic cell module
DC
O_2
NH_3
NH_3 Synthesis
NH_3
NH_3 Synthesis
O_2
NH_3
NH_3 Synthesis
O_2
NH_3
NH_3 Synthesis
Water
Dedicated to ammonia production.
No electricity grid connection

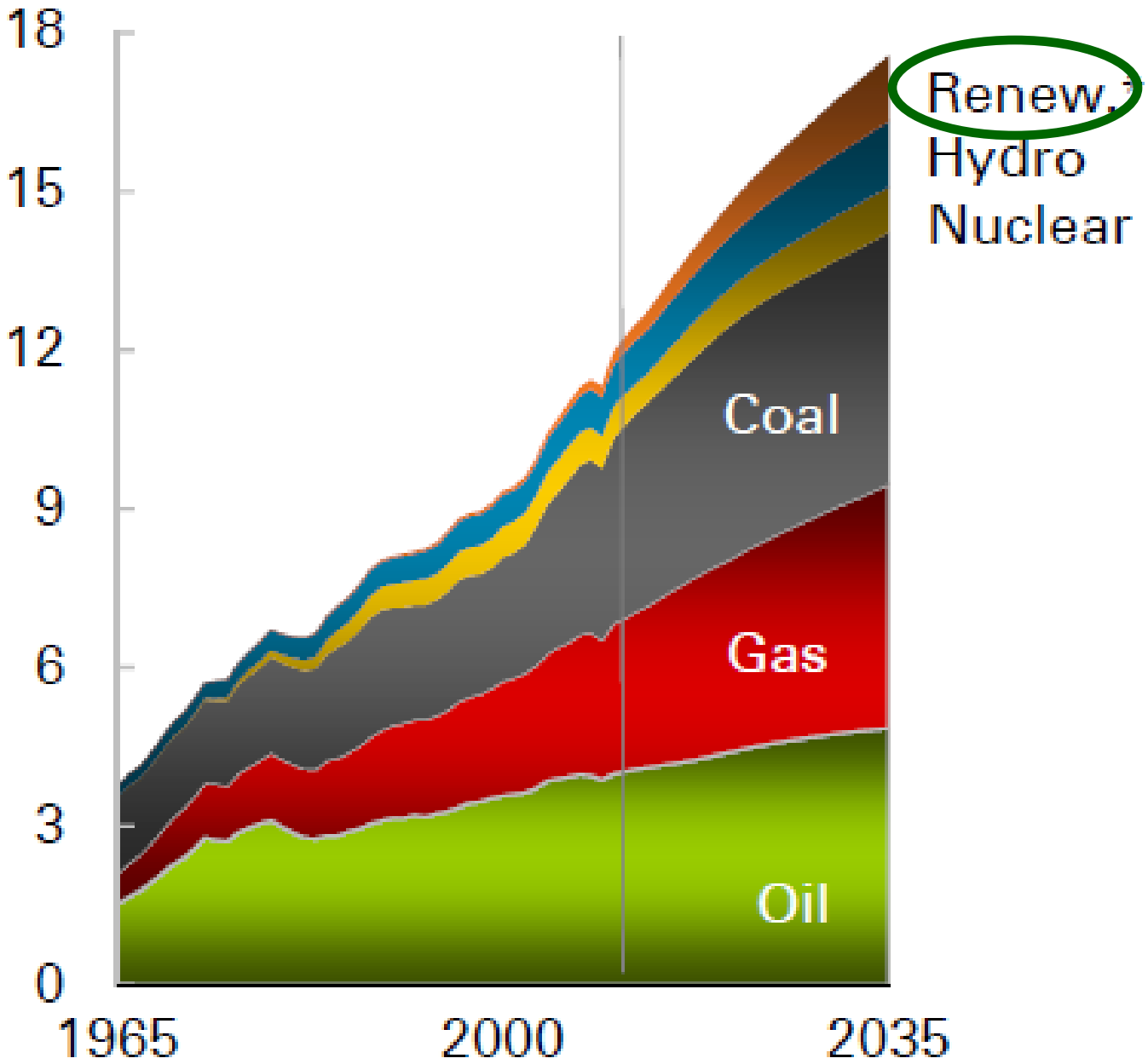


Solar Hydrogen Energy System


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


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

Billion tons of oil equivalent (toe)



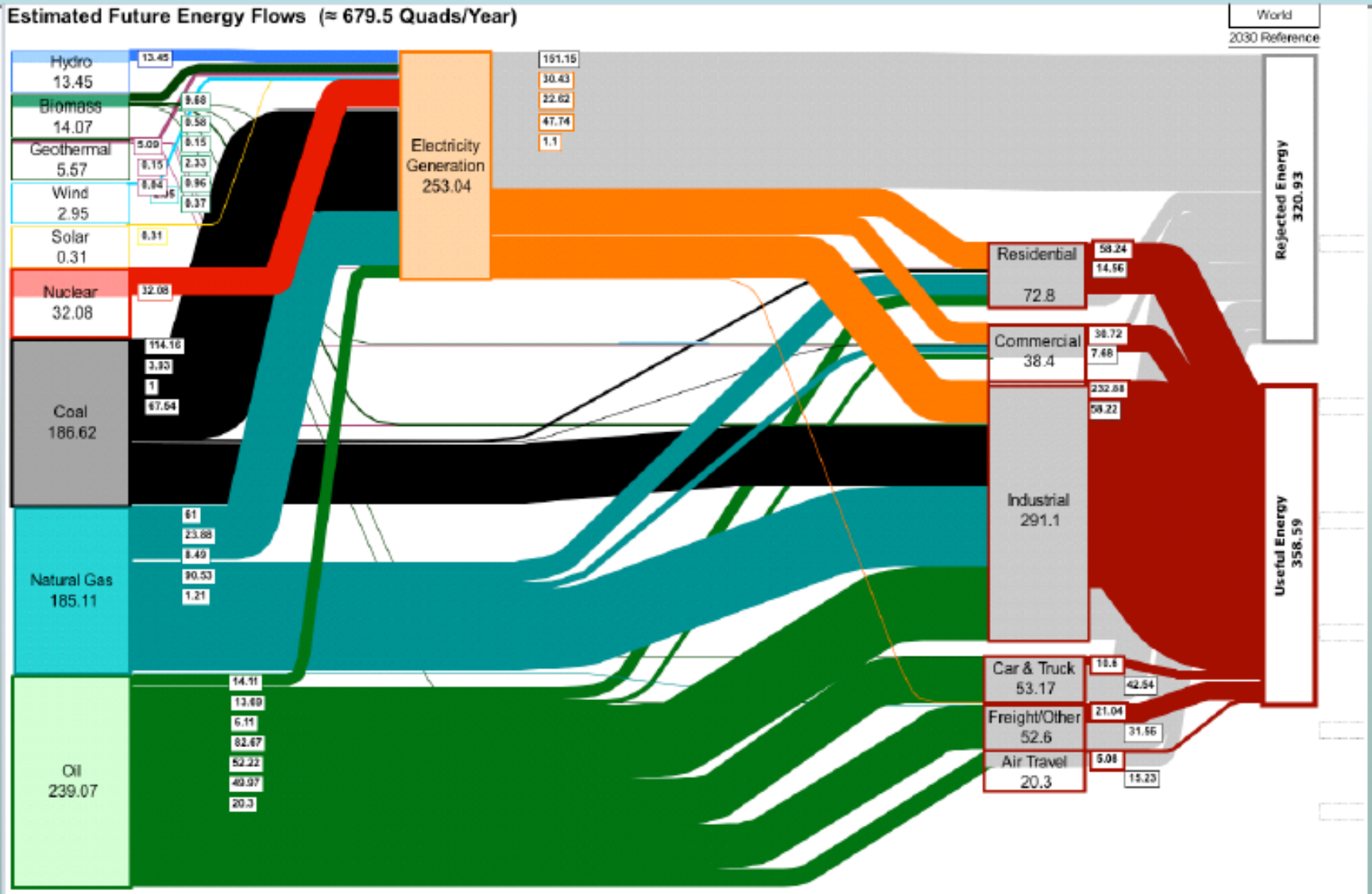
World Primary Energy Consumption

BP Energy Outlook 2035

January ‘14

Projected World Energy ~ 680 Quads/yr

2030 Reference Case (IEO 2006)



1 meter global sea level rise by 2100 ?

“ 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

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

Transform World's Largest Industry

Opportunity, Responsibility

~ 85 % fossil → →

~ 100% renewable,
CO2-emissions-free

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

Bigger Market for Renewables than the Electricity Grid: Carbon-Free Hydrogen Fuel for Transportation and CHP

Bill Leighty
Director, The Leighty Foundation, Juneau, AK

www.leightyfoundation.org/earth.php
wleighty@earthlink.net 206-719-5554

9B - Novel Non-Electric Energy Storage Technologies
Energy Storage II
Wednesday, December 6, 2017
0930 - 1130

Session Chair: Jeff Myles, Surrette Battery Co.
902-597-4012 Email: jeff@surrette.com

Notes:

1. In 2016, AES Energy Storage deployed the largest of these farms for San Diego Gas & Electric, connecting 400,000 individual batteries into 24 containers to store 120 MWh of electricity for up to four hours. [That's 5 MWh per container. What's capex and opex ? What are components of each ?] Source: http://www.power-eng.com/articles/print/volume-121/issue-11/features/implications-of-a-lithium-ion-storage-transformation.html?cmpid=enl_pe_power_engineering_e-newsletter_2018-01-23&pwhid=62c6b7f0ca76757d1273a31a0c9aeeeda30289eb2a5811ffa322380a5ea635ef4e14e58832bd1657ec3320fb5be4d3a1fed5c067f7af9111ba1a3928f57a710e&eid=326852561&bid=1981271
2. Bill comment on above: Quoting the article: " In 2016, AES Energy Storage deployed the largest of these farms for San Diego Gas & Electric, connecting 400,000 individual batteries into 24 containers to store 120 MWh of electricity for up to four hours."
3. What are capex and opex for this battery system, including interface switchgear and transformer(s) ? What are capex and opex for the two large Tesla batteries recently installed -- one in Ontario, CA for SCE, one in Australia ? Probably confidential. Have we any credible estimates ? We can store energy, as chemical energy, as gaseous hydrogen (GH2) in deep, solution-mined (man-made) salt caverns and as liquid anhydrous ammonia (NH3) in "atmospheric" surface tanks for < $ 1.00 / kWh capex. GH2 and NH3 transmission capex is < electricity per MW-km. Perhaps we should emulate the natural gas industry, which has affordable annual-scale firming storage, by basing our total-energy-decarbonization strategy on GH2 and NH3 rather than trying to stuff the square peg of variable generation (VG) PV and wind into the round hole of electricity. See: https://vimeo.com/251251415