Introduction to Power-to-Gas

Do We Really Need Hydrogen?

Renewable Gas 360

Sacramento, CA

National Fuel Cell Research Center
UCIrvine | University of California

Jack Brouwer, Ph.D., Director

January 23, 2020

How to Produce Hydrogen

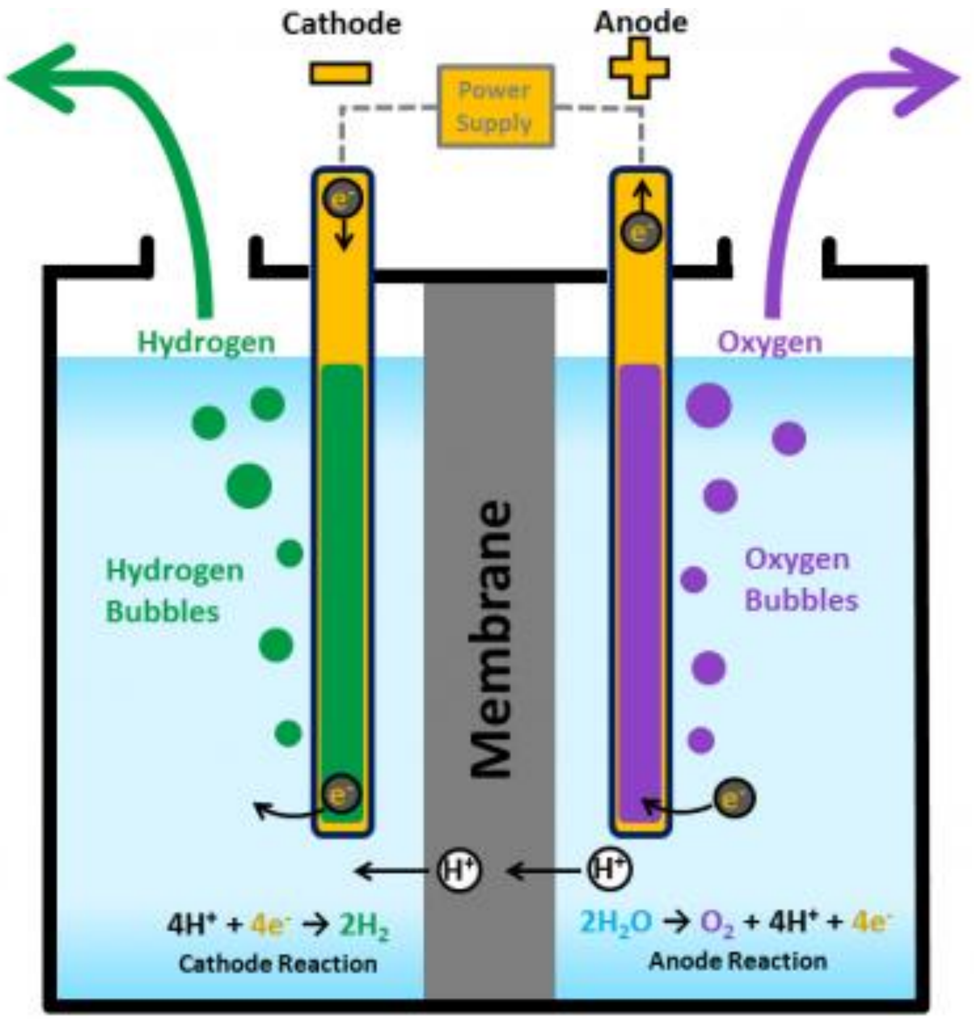
Electrolysis

- $2\ H_2O$ + Electricity → $2\ H_2 + 1\ O_2$
- 1 liter of Water yields ~ 1 $Nm^3\ H_2$
- Typical System Power Demand:

  4 – 7 kWh/Nm^3 or

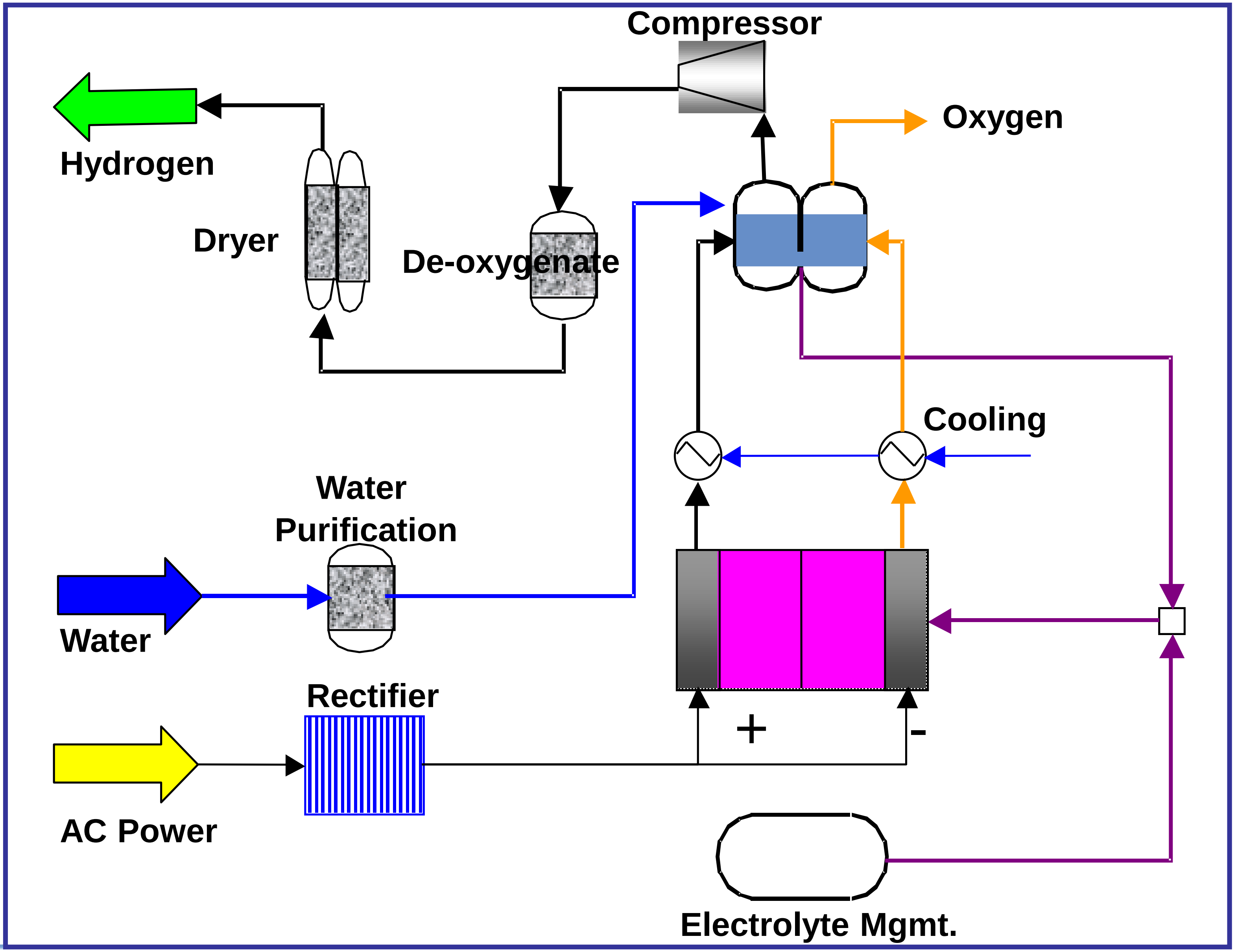
  45 – 78 kWh/kg

  (depending upon type)



from: energy.gov, 2020

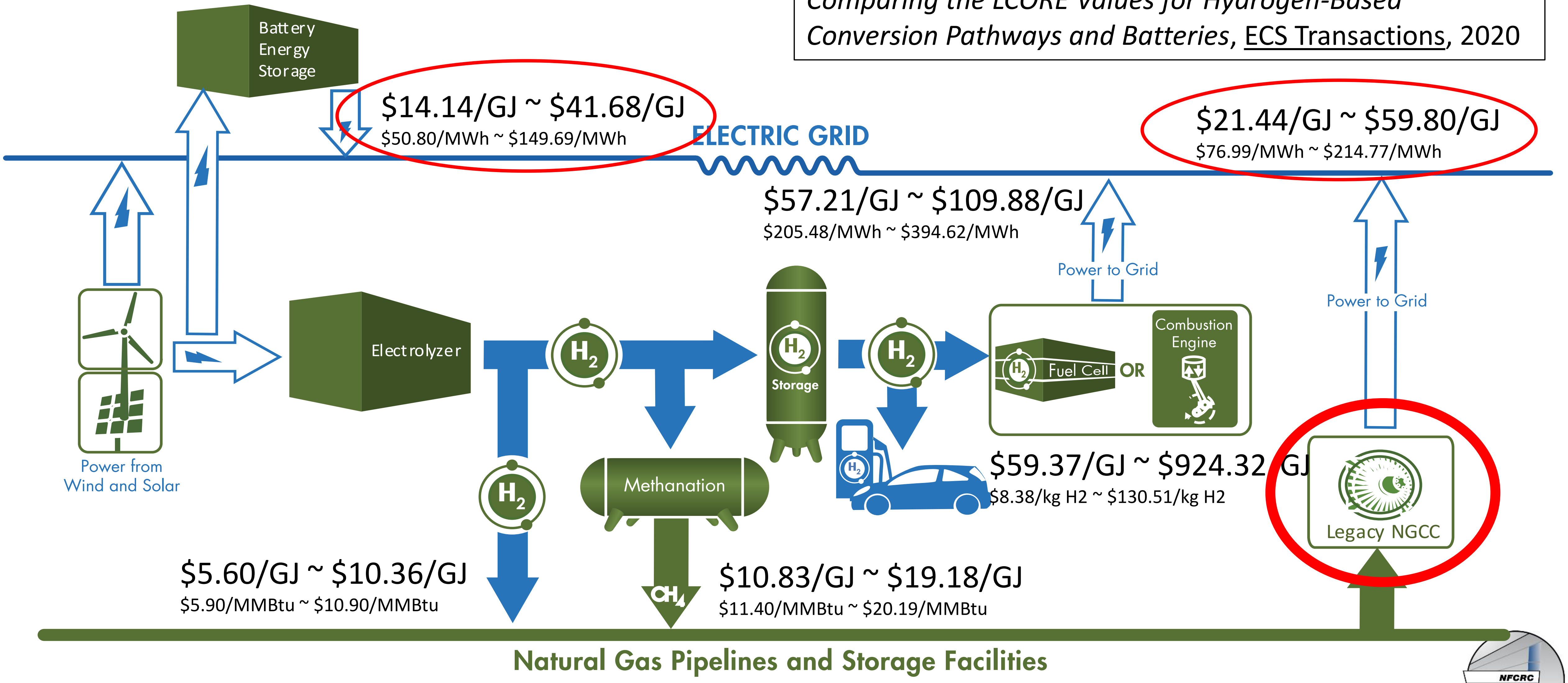
How to Produce Hydrogen



What is Power-to-Gas?

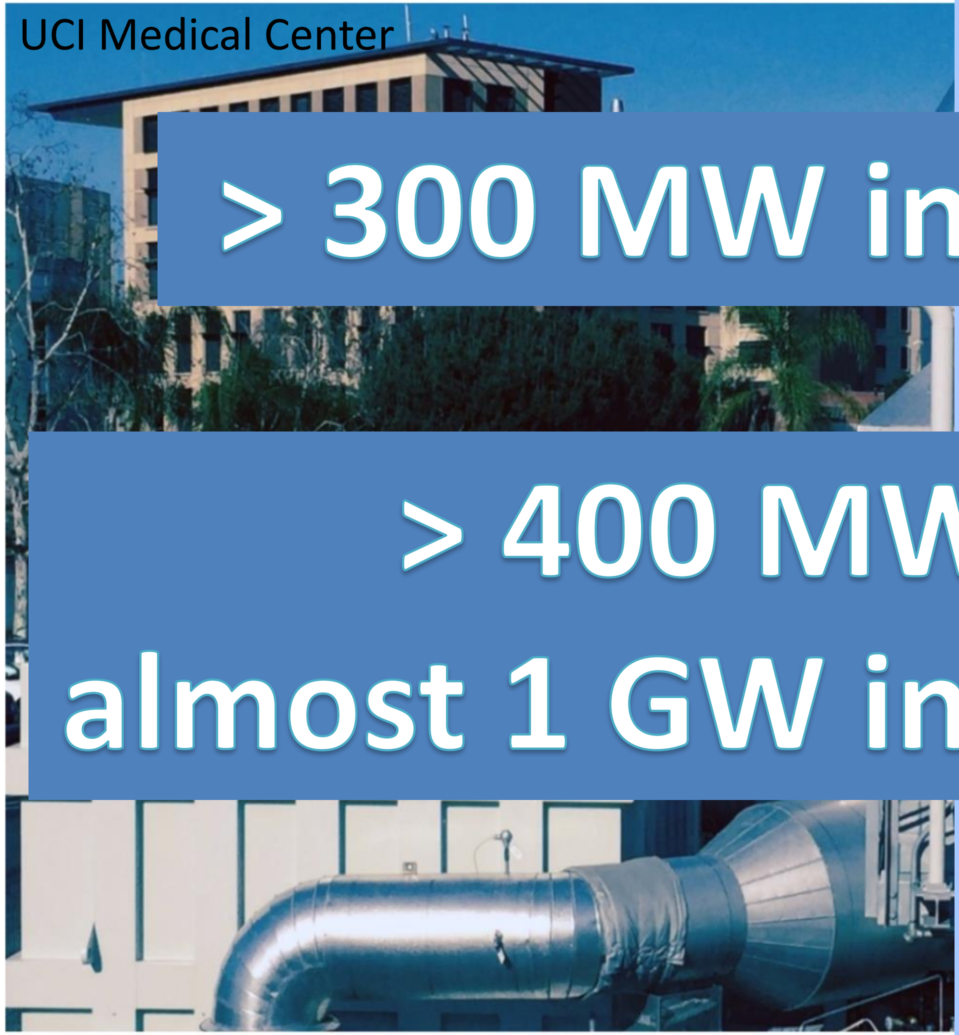
Levelized Cost of Returned Energy (LCORE)

Schell, L.S., Reed, J.G., Chao, L., Brouwer, J., Samuelsen, S., *Comparing the LCORE Values for Hydrogen-Based Conversion Pathways and Batteries*, ECS Transactions, 2020



Stationary Fuel Cells Required for Zero Emissions

- **Zero Criteria Pollutant Emissions TODAY & Forever**
- **Zero GHG emissions in proportion to Renewable Gas used**



> 300 MW in CA market

> 400 MW in Korea
almost 1 GW installed globally

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Popular Thinking & Arguments

Main Strategy:

- 100% renewable (solar, wind, geothermal, …) power generation
- Electrify ~~all~~ end-uses
- Use batteries to handle some intermittency on grid & for some end-uses

Arguments against hydrogen & fuel cells:

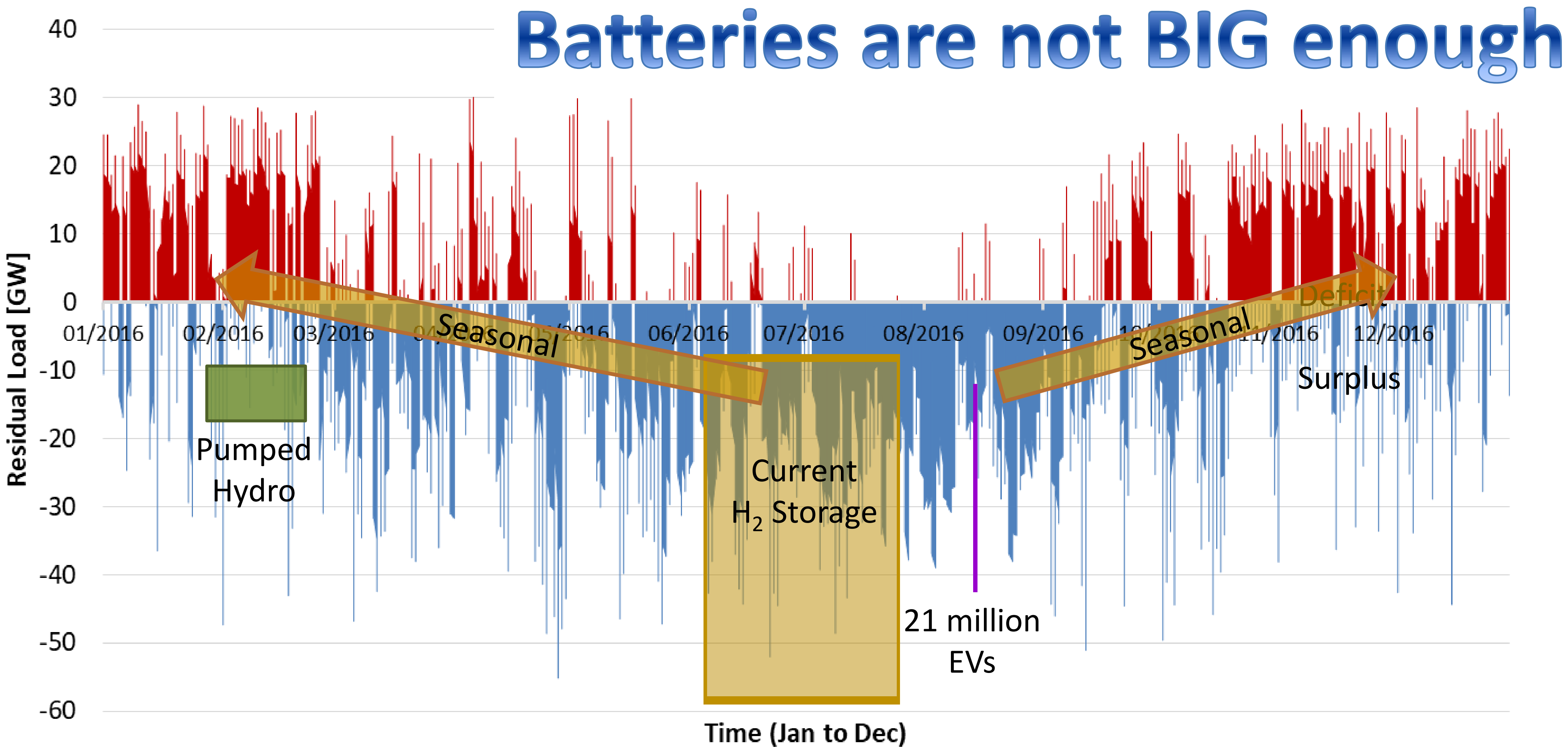
- Most hydrogen today is made from fossil fuels (natural gas)
- Making hydrogen from water & electricity is less efficient than charging a battery
- Making electricity from hydrogen in a fuel cell is less efficient than a battery (i.e., round-trip efficiency is lower than a battery except for long duration storage!)
- Hydrogen is difficult to store and move around in society

I agree with most of this!

Subtly untruthful - Not the whole story

Amount of Storage Required

- **Wind dominant case (37 GW solar capacity, 80 GW wind capacity)**



Energy Storage Need

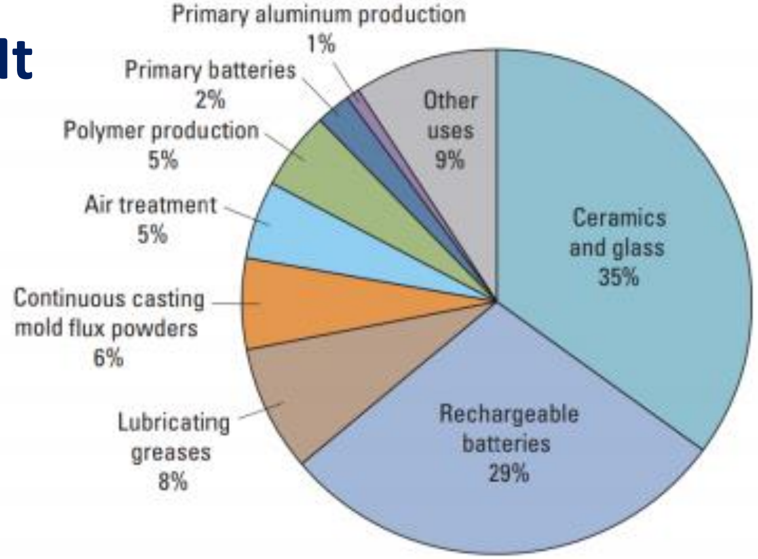
Simulate meeting of TOTAL world electricity demand w/ Solar & Wind

	Solar contribution	Wind contribution	Consumption and storage ratio	Consumption (TWh)	Storage (TWh)
Africa	0.70	0.30	8.39	9,123	1,088
America	0.45	0.55	7.83	38,541	4,919
Asia	0.50	0.50	7.95	80,866	10,178
Europe	0.30	0.70	7.50	26,951	3,592
Oceania	0.50	0.50	7.95	1,625	205
TOTAL				157,106	19,981 TWh

[Nuria Tirado, M.S. Thesis, 2018]

- To build one Li-ion battery requires: Li: 3,144 Mt Co: 25,815 Mt
- World Li resources: 53 Mt
- World Co resources: 25 Mt (terrestrial), 120 Mt (ocean floor)
- 40% of Co comes from the Democratic Republic of the Congo

There is not enough lithium or cobalt in the world



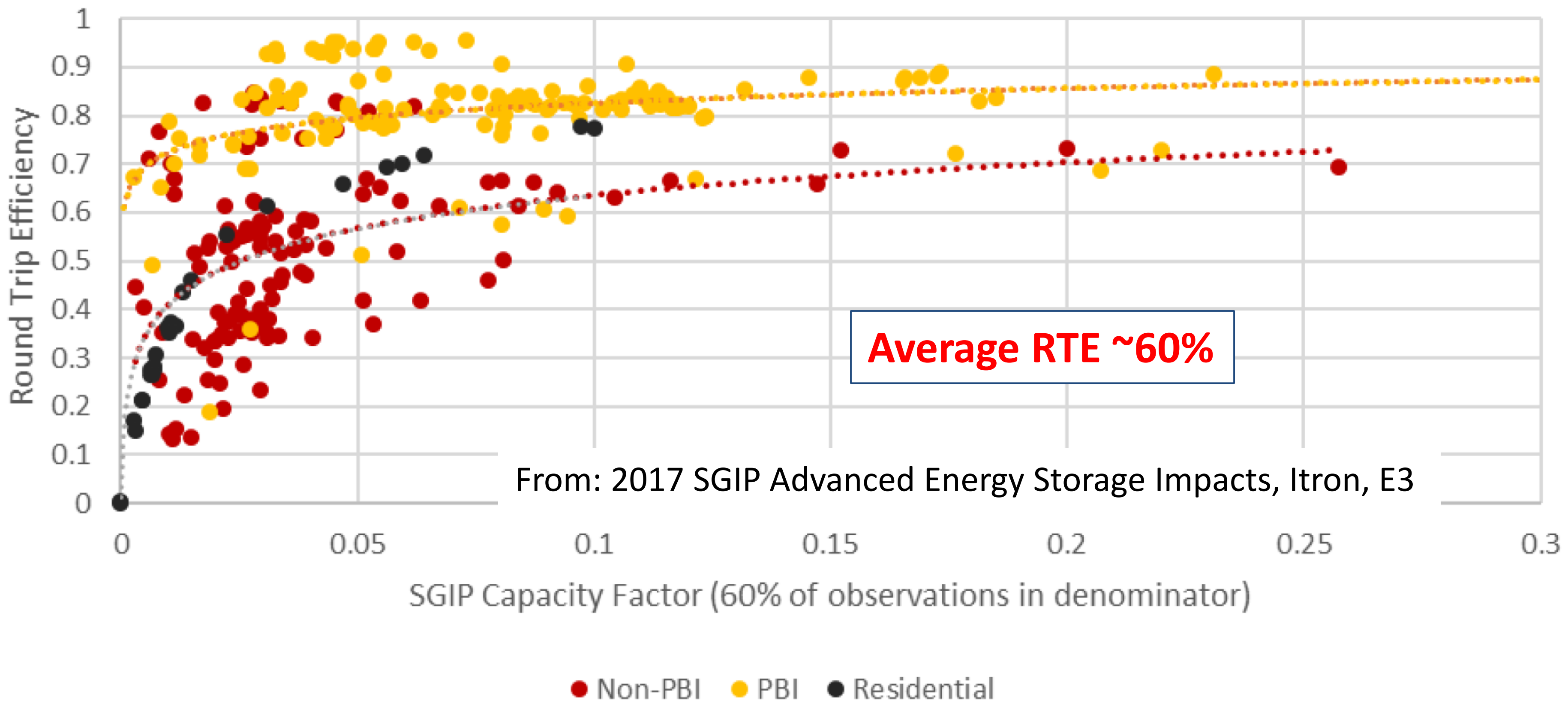
Source: U.S. Geological Survey, 2018

Lithium-Ion Batteries

Batteries not EFFICIENT enough & suffer SELF-DISCHARGE

Round-Trip Efficiency (>90% in Laboratory Testing)

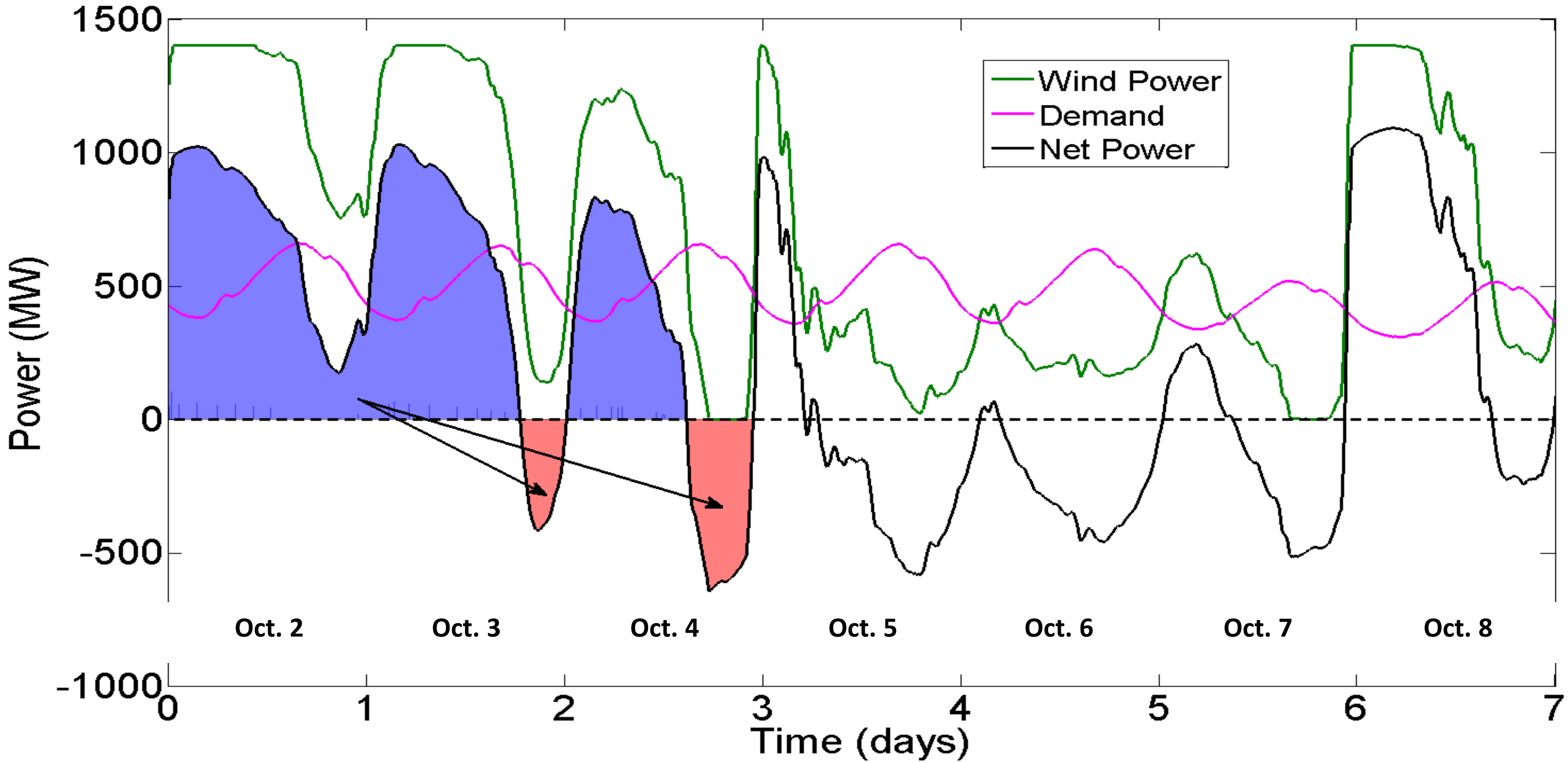
- **Measured battery system performance in Utility Applications**



- **Self-Discharge (the main culprit), plus cooling, transforming, inverting/converting, and other balance of plant**

Hydrogen Energy Storage Dynamics

- **Compressed Hydrogen Storage complements Wind & Power Demand Dynamics in Texas**

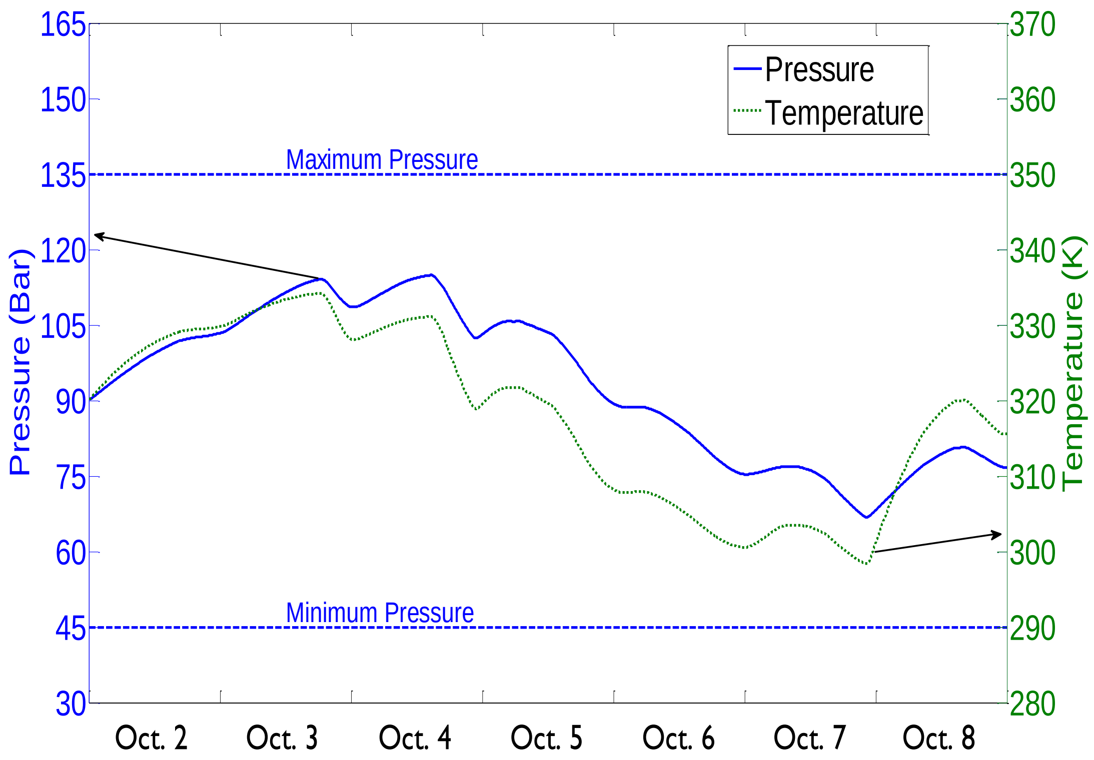


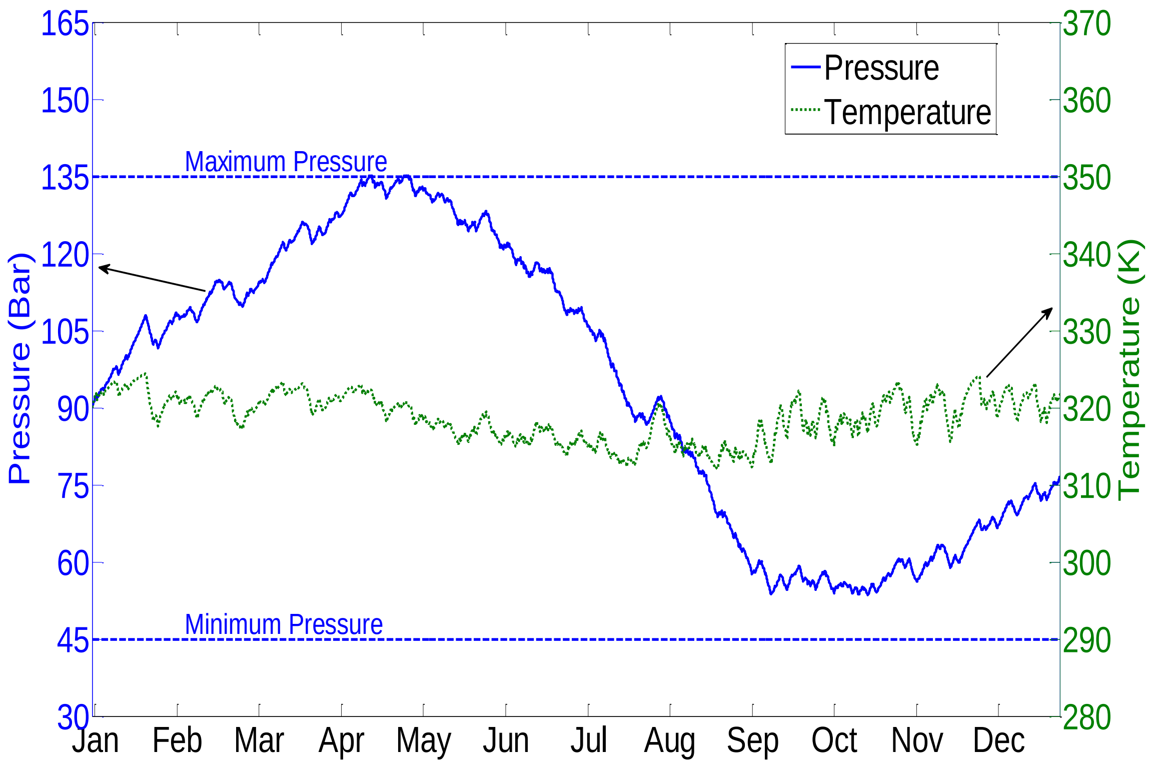
- **Load shifting from high wind days to low wind days**
- **Hydrogen stored in adjacent salt cavern**

Maton, J.P., Zhao, L., Brouwer, J., Int'l Journal of Hydrogen Energy, Vol. 38, pp. 7867-7880, 2013

Hydrogen Energy Storage Dynamics

- **Weekly storage and seasonal storage w/ H2, fuel cells, electrolyzers – all zero emissions!**
  - **Weekly** **Seasonal**



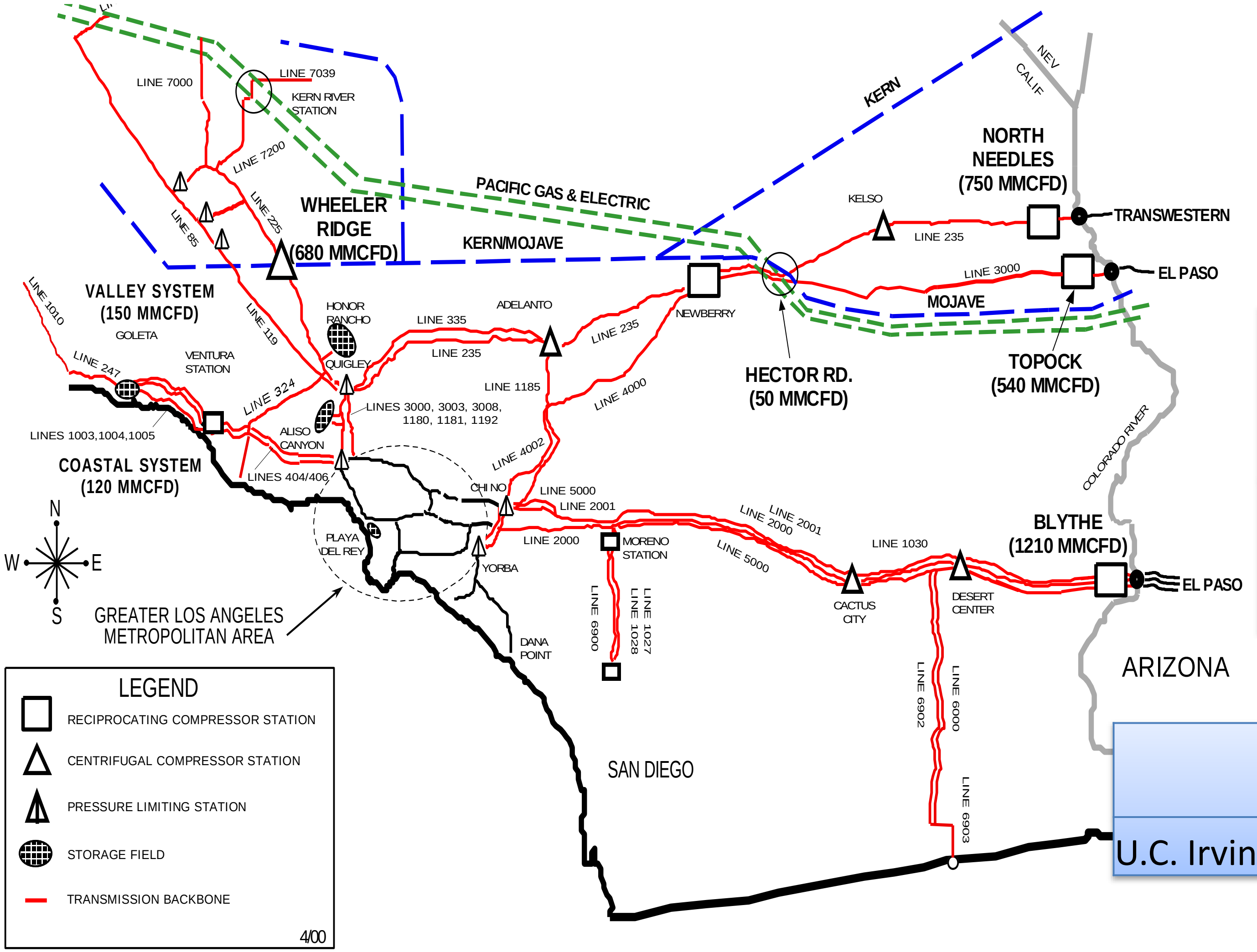


But what can we do if we don't have a salt cavern?

Maton, J.P., Zhao, L., Brouwer, J., Int'l Journal of Hydrogen Energy, Vol. 38, pp. 7867-7880, 2013

“Natural” Storage & Transmission/Distribution Resource

- **Natural Gas Transmission, Distribution & Storage System**



650 GWh if stored at 5% H2 in natural gas

$130 billion battery (DOE future cost)

$2.6 trillion battery (DOE future cost)

13 TWh of Equivalent Electricity Storage

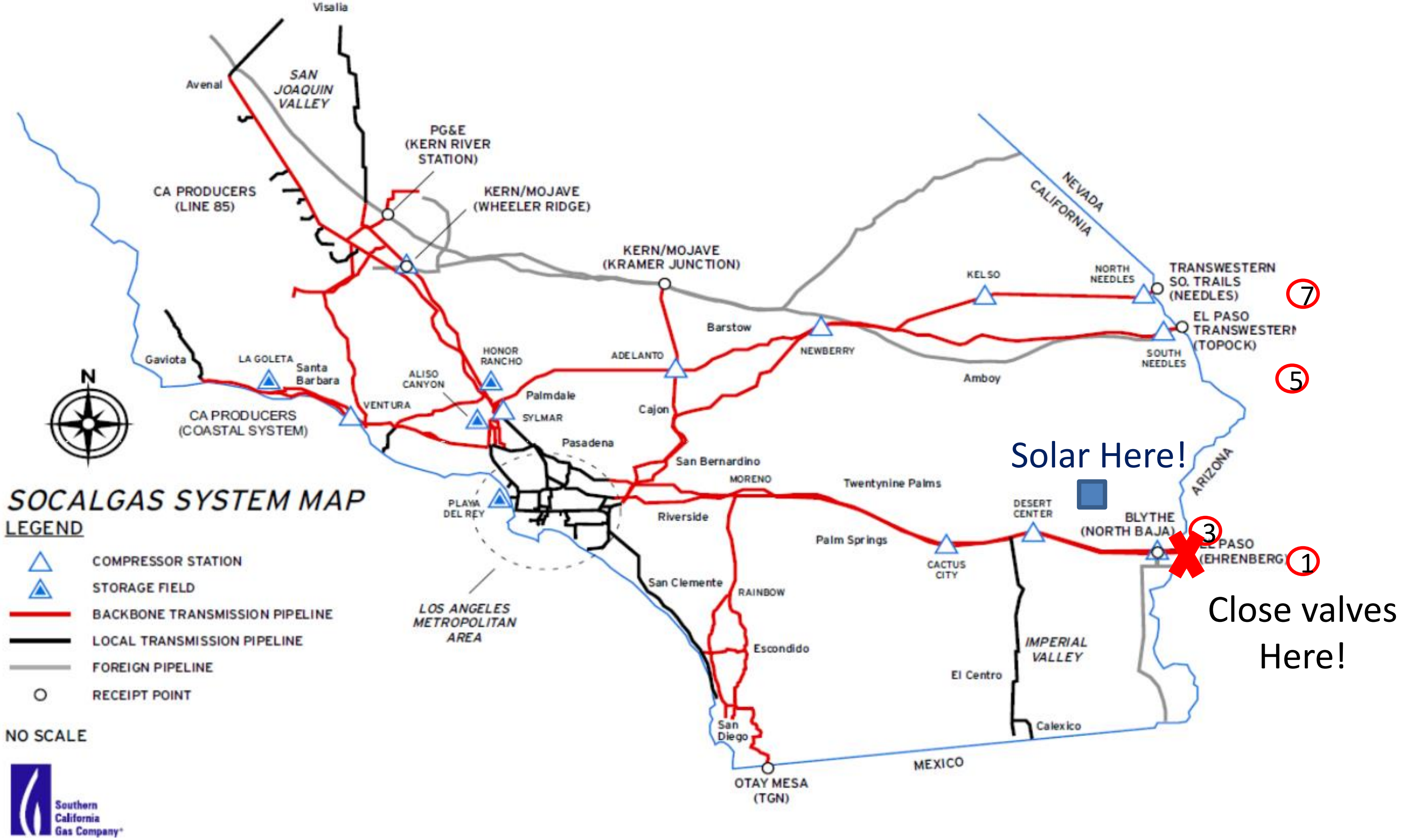
	Average Annual Tuition & Fees	Total Student Population	4 years for entire population
All University of California Schools	$ 17,800	265,000	$4.7 billion

	Annual Tuition & Fees	Total OC Population	4 years for entire population
U.C. Irvine	$ 17,331	2,246,000	$39 billion

Carmona, Adrian, M.S. Thesis Project, UC Irvine, J. Brouwer advisor, 2014.

Gas System – TREMENDOUS Resource for Zero Emissions

- **First mix up to X% – ADD grid renewables & transportation electrification**
- **Then piecewise conversion to pure hydrogen**

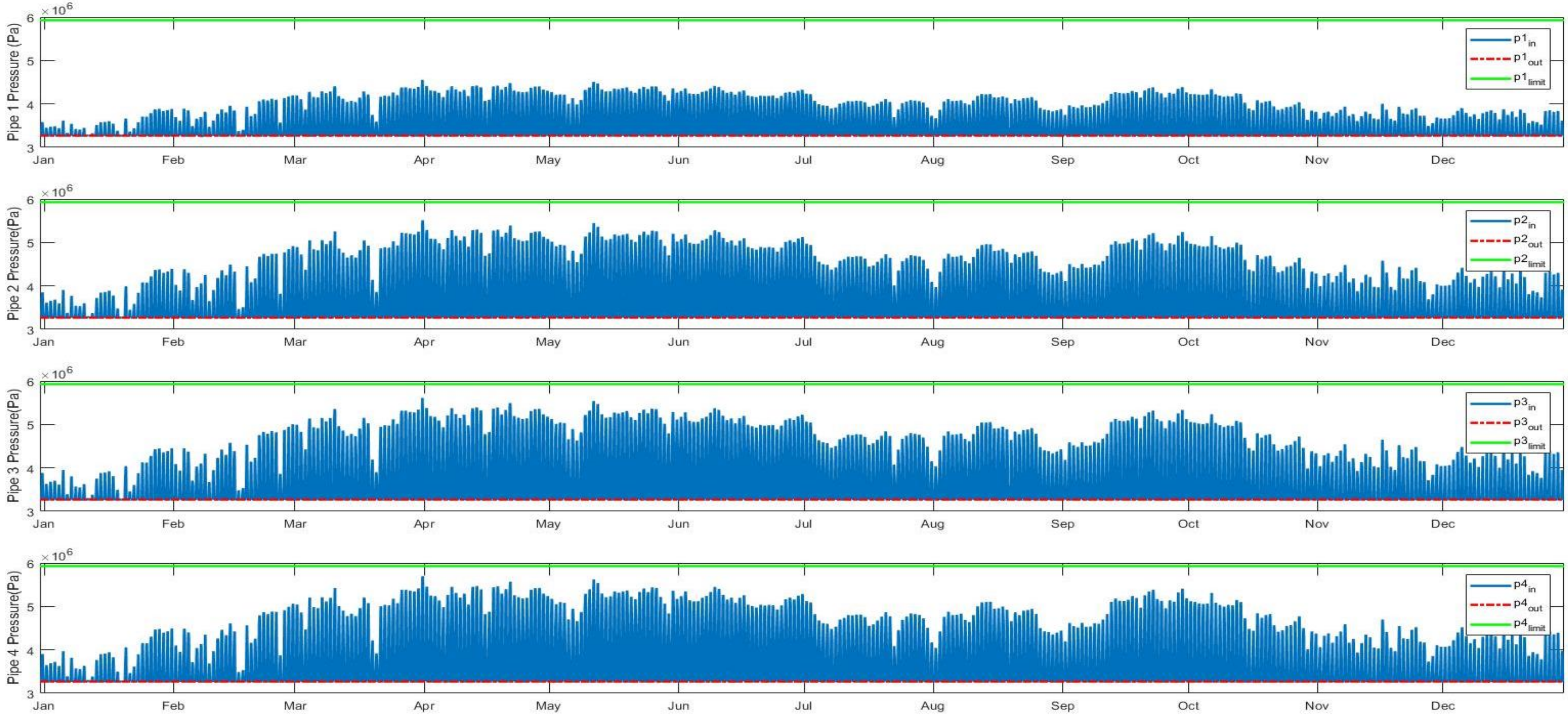


NFCRC

Gas System – MASSIVE Resource for Zero Emissions

- 40% of all electric demand – 20 sq. miles of solar, only gas system use for H_2 storage AND all T&D

20 sq. miles solar, H2 in gas system from 35% to 75% zero!



Role of Hydrogen as Zero Emissions Fuel

- Hydrogen most important/ubiquitous

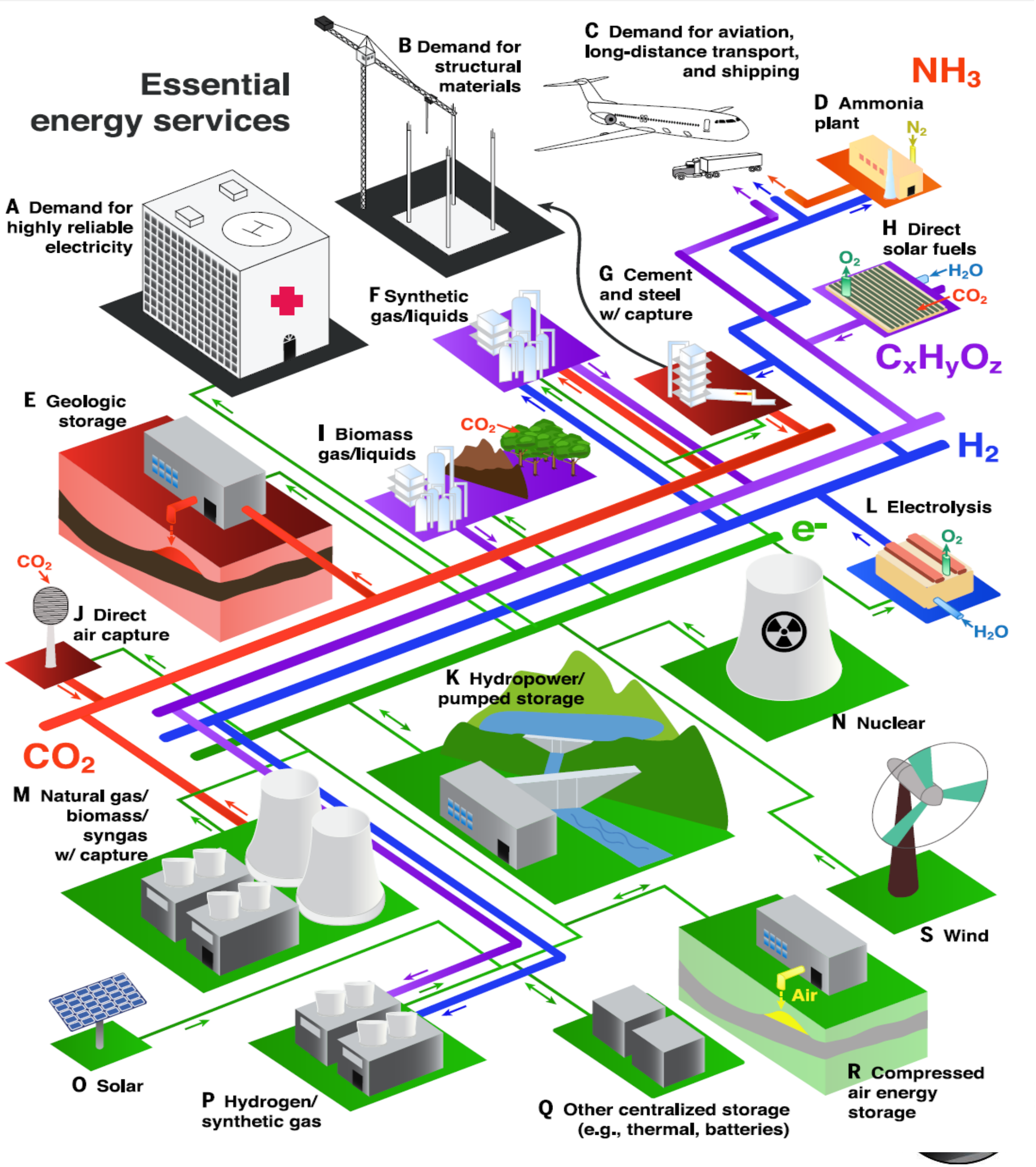
REVIEW SUMMARY

ENERGY

Net-zero emissions energy systems

Steven J. Davis*, Nathan S. Lewis*, Matthew Shaner, Sonia Aggarwal, Doug Arent, Inês L. Azevedo, Sally M. Benson, Thomas Bradley, Jack Brouwer, Yet-Ming Chiang, Christopher T. M. Clack, Armond Cohen, Stephen Doig, Jae Edmonds, Paul Fennell, Christopher B. Field, Bryan Hannegan, Bri-Mathias Hodge, Martin I. Hoffert, Eric Ingersoll, Paulina Jaramillo, Klaus S. Lackner, Katharine J. Mach, Michael Mastrandrea, Joan Ogden, Per F. Peterson, Daniel L. Sanchez, Daniel Sperling, Joseph Stagner, Jessika E. Trancik, Chi-Jen Yang, Ken Caldeira*

Davis *et al.*, *Science* **360**, 1419 (2018)   29 June 2018



Role of Hydrogen as a Zero Emissions Fuel

- **Provide zero emissions fuel to difficult end-uses**

Shipping

Aircraft

Fuel Cell Trains & Locomotives

Anything that requires: (1) long range, (2) fast fueling, (3) heavy payload

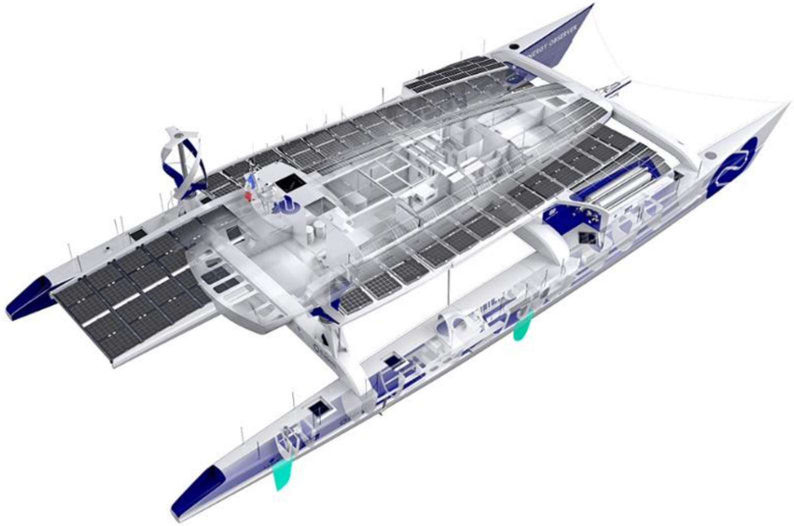
Fuel Cell Buses

Toyota Fuel Cell:
Zero Emissions Big Rig

NFCRC

Role of Hydrogen as Zero Emissions Fuel

- **2018: UNESCO, 101 stops, > 11,000 nautical miles traveled**



Role of Hydrogen as Zero Emissions Fuel

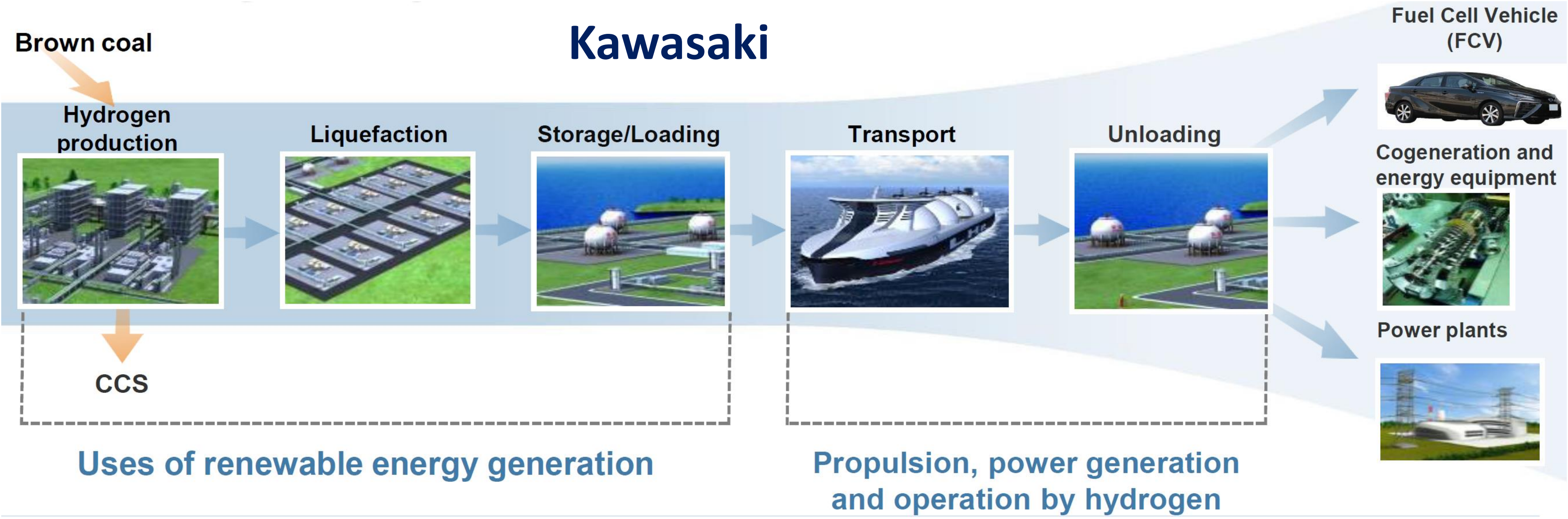
<u>Many recent announcements for Zero Emissions Shipping</u>

- **2017: Royal Caribbean Cruise Lines – all H2 Fuel Cell in certain classes by 2030 (first ships in 2022, 2024)**
- **2017: Viking Cruises, 4 ships ordered, 900 passengers, 500 crew, LH_2, hydrogen turbine powered first, Statoil H_2 production partner**
- **2018: GGZEM, Construction underway, America's first H_2 ferry, Bay Ship & Yacht, BAE, Hydrogenics, Red & White Fleet, Crowther, …**

Role of Hydrogen as Zero Emissions Fuel

Zero Emissions Ports are Technically Feasible - H2 Ecosystem Required

- **Kawasaki**



Sandia National Laboratories

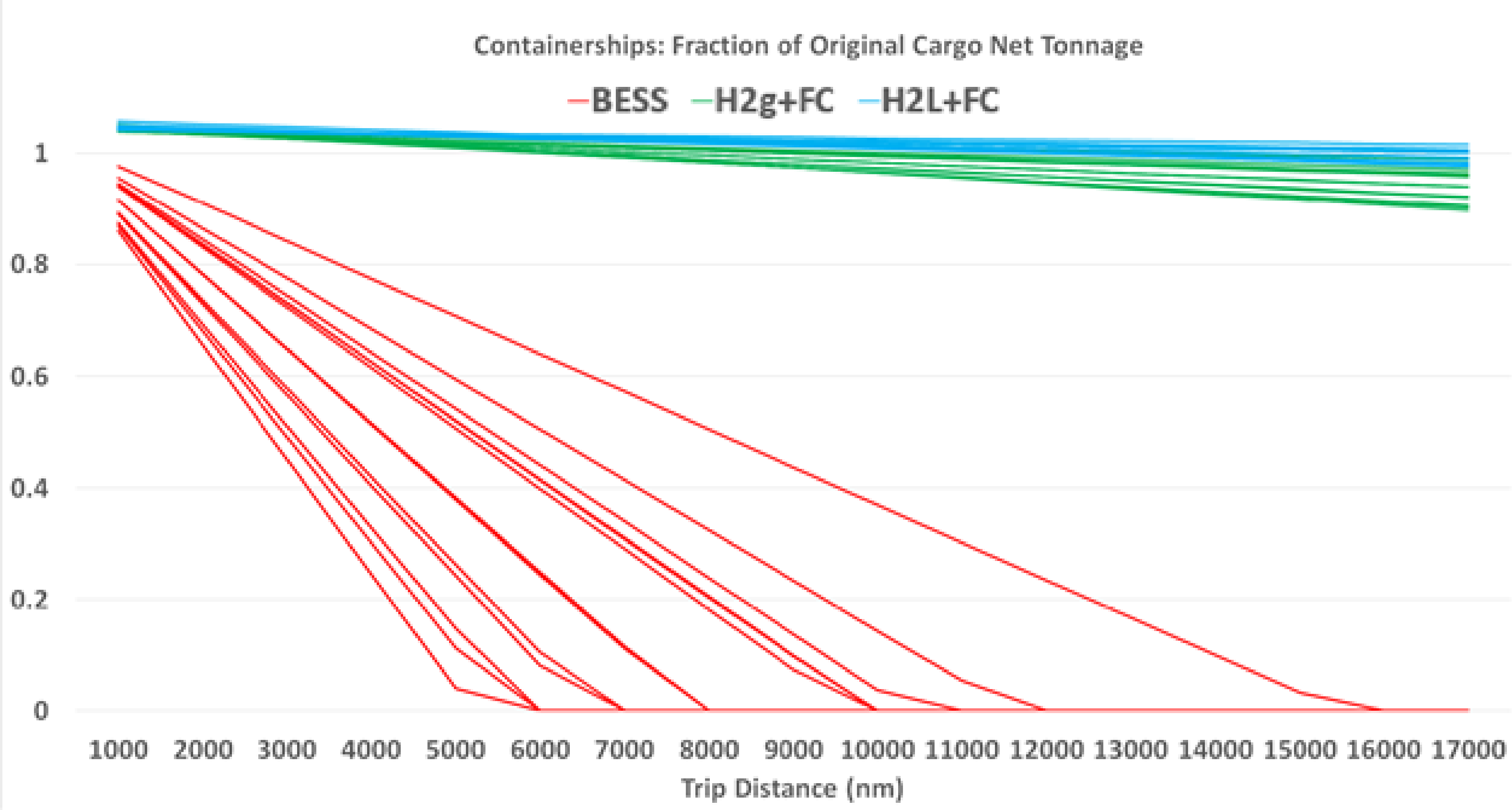
High-speed H_2 Ferry
- Zero-emission Hydrogen Fuel Cell Power
- 150 passenger, 35 kts

Dockside H_2 Station
- Serving vessels, cars, buses and trucks
- 2,500 kg/day capacity

Gedanken Experiment – Can LA/LB Port become Zero Emissions?

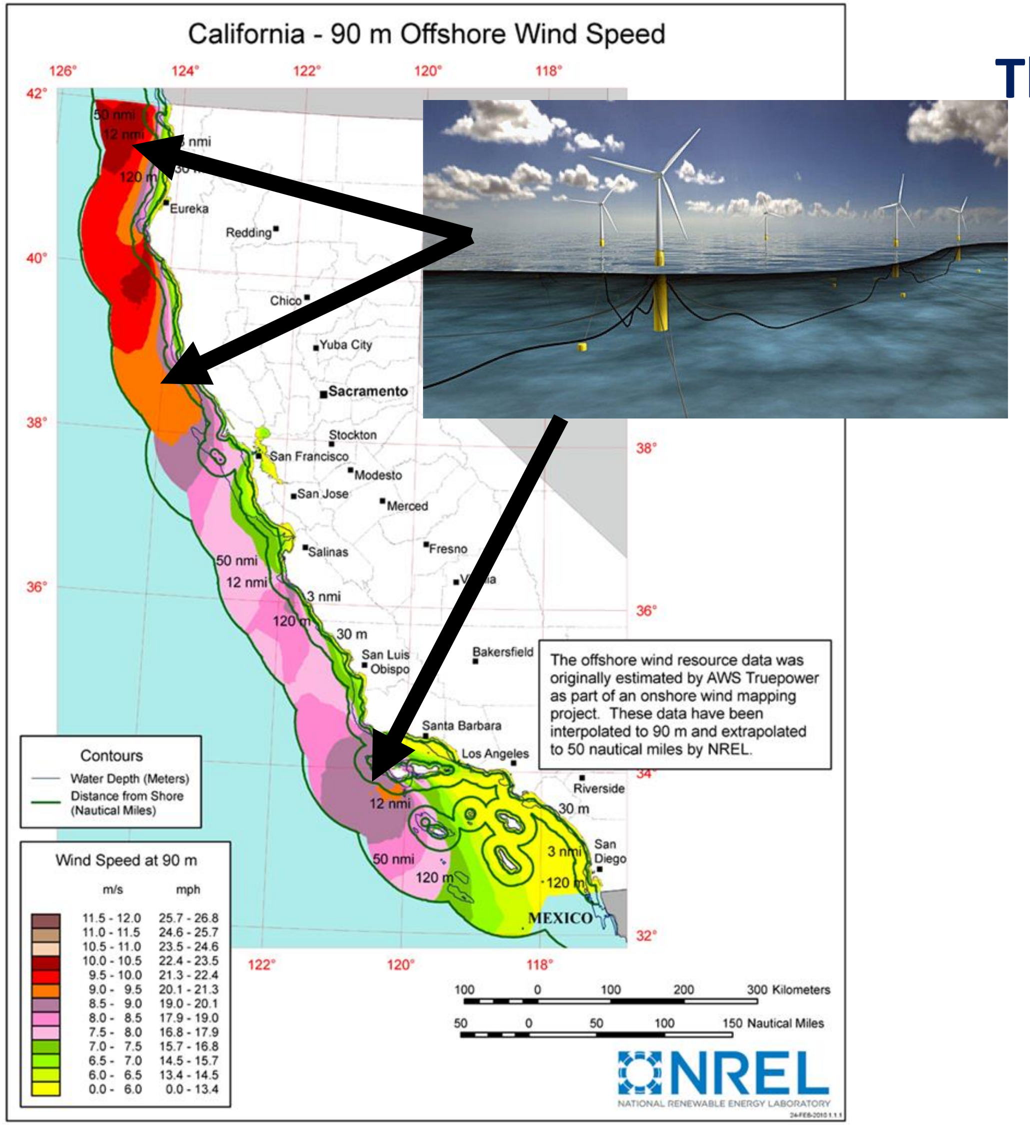
Preliminary Analyses

- **Batteries compared to Hydrogen & Fuel Cells for Container Ships**



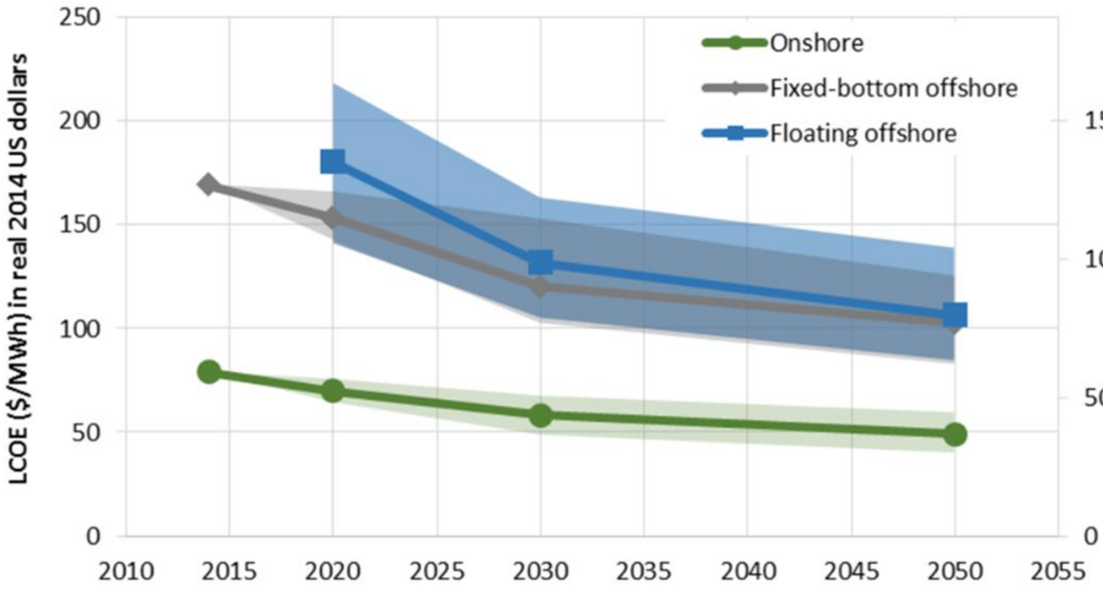
Gedanken Experiment – Can LA/LB Port become Zero Emissions?

Preliminary Analyses – All ships, trains, & trucks through LA/LB Port requires 8.88M tons H_2



The California coast an enormous resource for renewable energy!

Wind energy experts anticipate significant cost reductions in offshore wind technology:



Lines/markers indicate the median expert response for the **median LCOE scenario**
Shaded areas show the 1st-3rd quartiles of expert responses

Gedanken Experiment – Can LA/LB Port become Zero Emissions?

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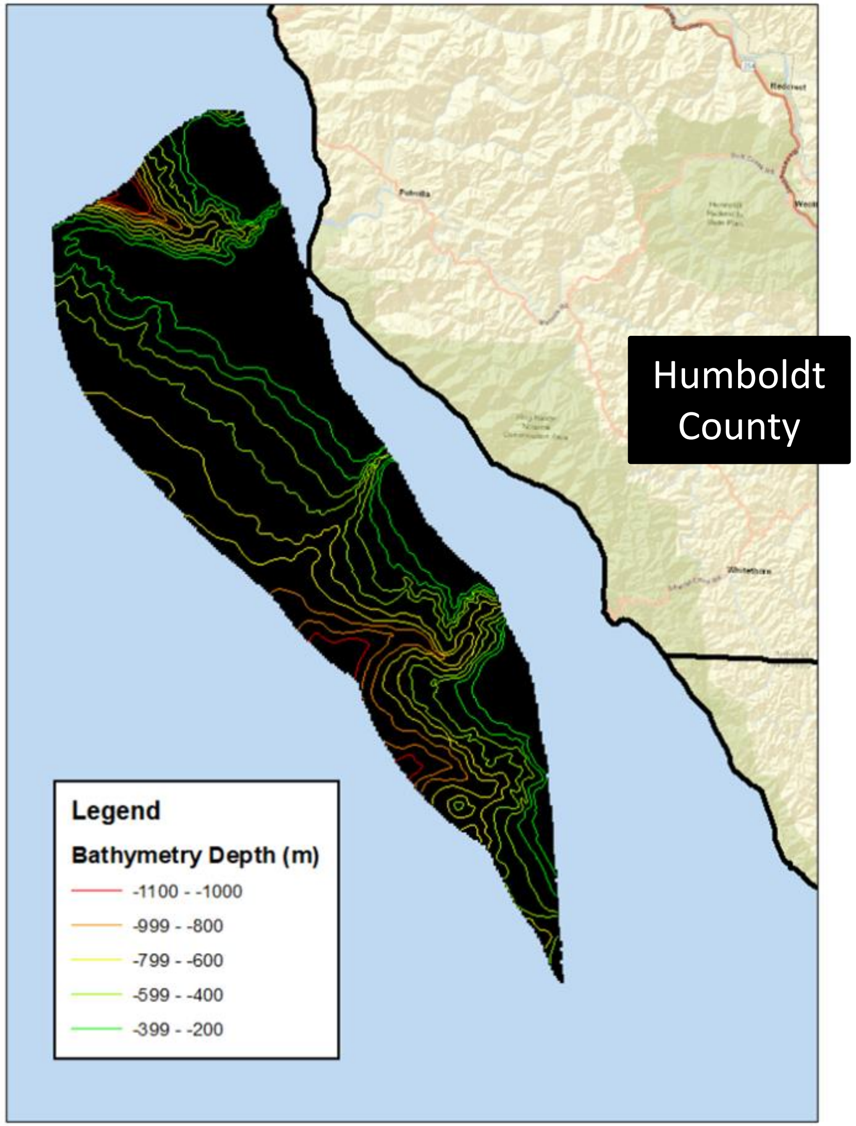


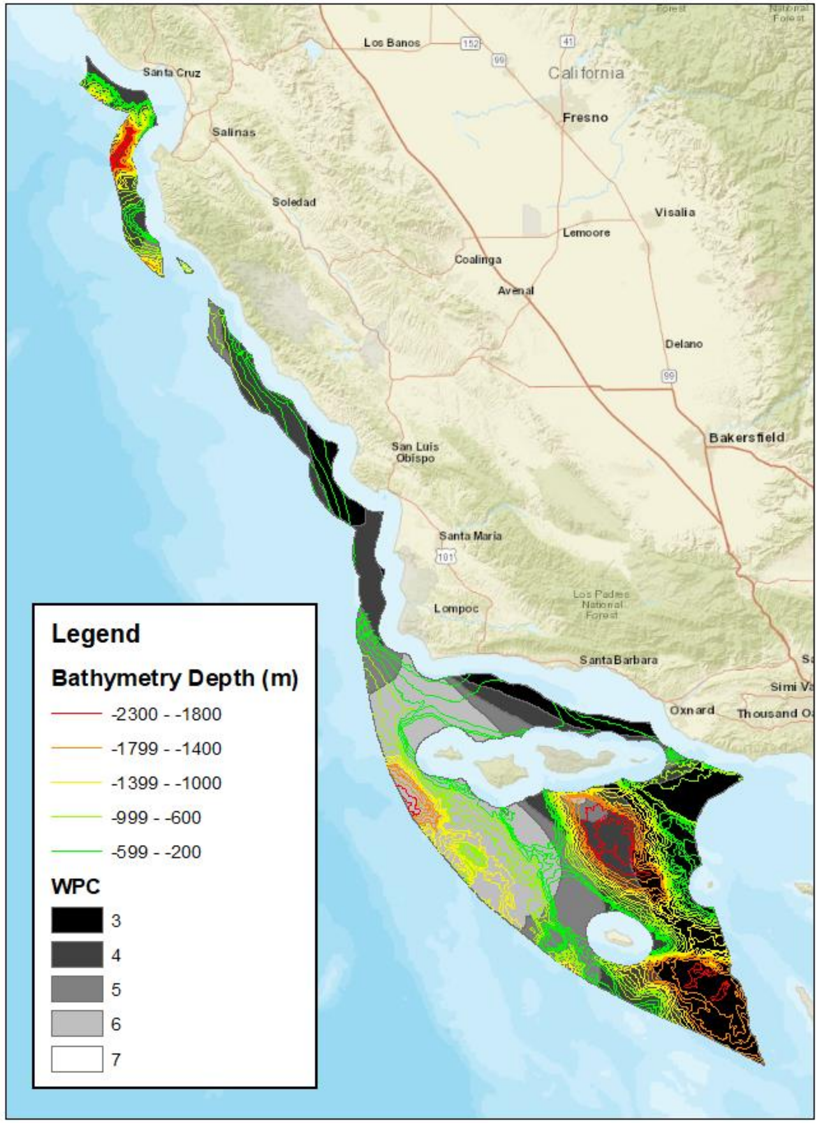
Service Layer Credits: Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, (c)

Northern California

WPC: 7 (8.84 – 11.96 m/s)
Distance to Shore: 0 -12 nm

# of Turbines	350
Diameter (m)	205
Prated (MW)	10
Area (km^2)	1470
Energy (TWh/ yr)	16 - 24
H_2 Gen (kg)	3.05×10^8 - 4.61×10^8

Gedanken Experiment – Can LA/LB Port become Zero Emissions?

- 

Service Layer Credits: Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, (c)

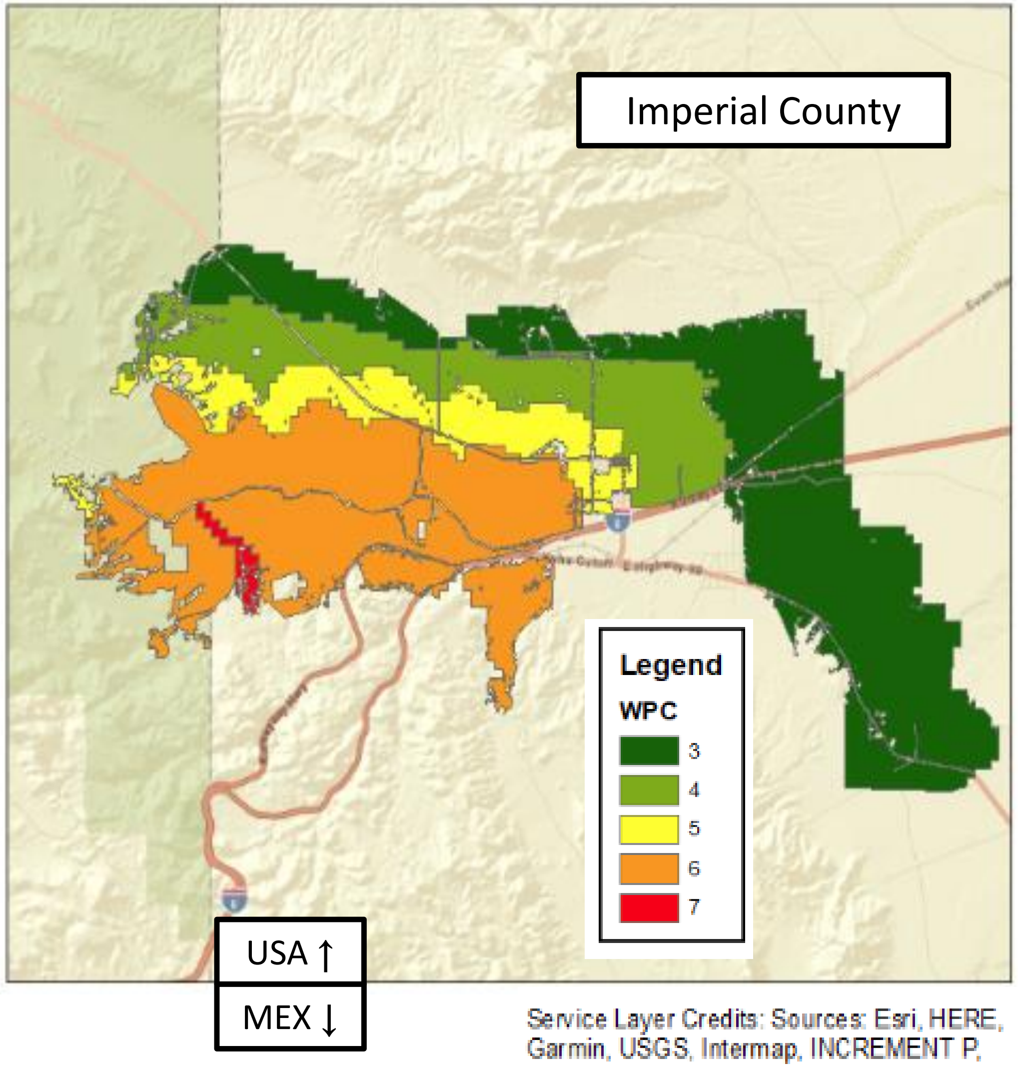
Southern California

WPC: 3 - 7 (6.43 – 11.96 m/s)
Distance to Shore: 5 – 77 nm

# of Turbines	5880
Diameter (m)	205
Prated (MW)	10
Area (km^2)	24,710
Energy (TWh/ yr)	201 - 229
H_2 Gen (kg)	$3.78 \times 10^9 - 4.29 \times 10^9$

Nearly **half** of the total H2 demand for freight in CA!

Preliminary Results for an onshore wind farm in Imperial County in Southern California (On-Shore)



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Wind power in 3 large wind farms can make LA/LB Port zero emissions!

WPC: 3 - 7 (6.43 – 11.96 m/s)

# of Turbines	72
Diameter (m)	150
Prated (MW)	5
Area (km^2)	162
Energy (TWh/ yr)	1.29 - 1.46
H_2 Gen (kg)	2.41×10^7 - 2.74×10^7

Hydrogen is Required for Zero Emissions!

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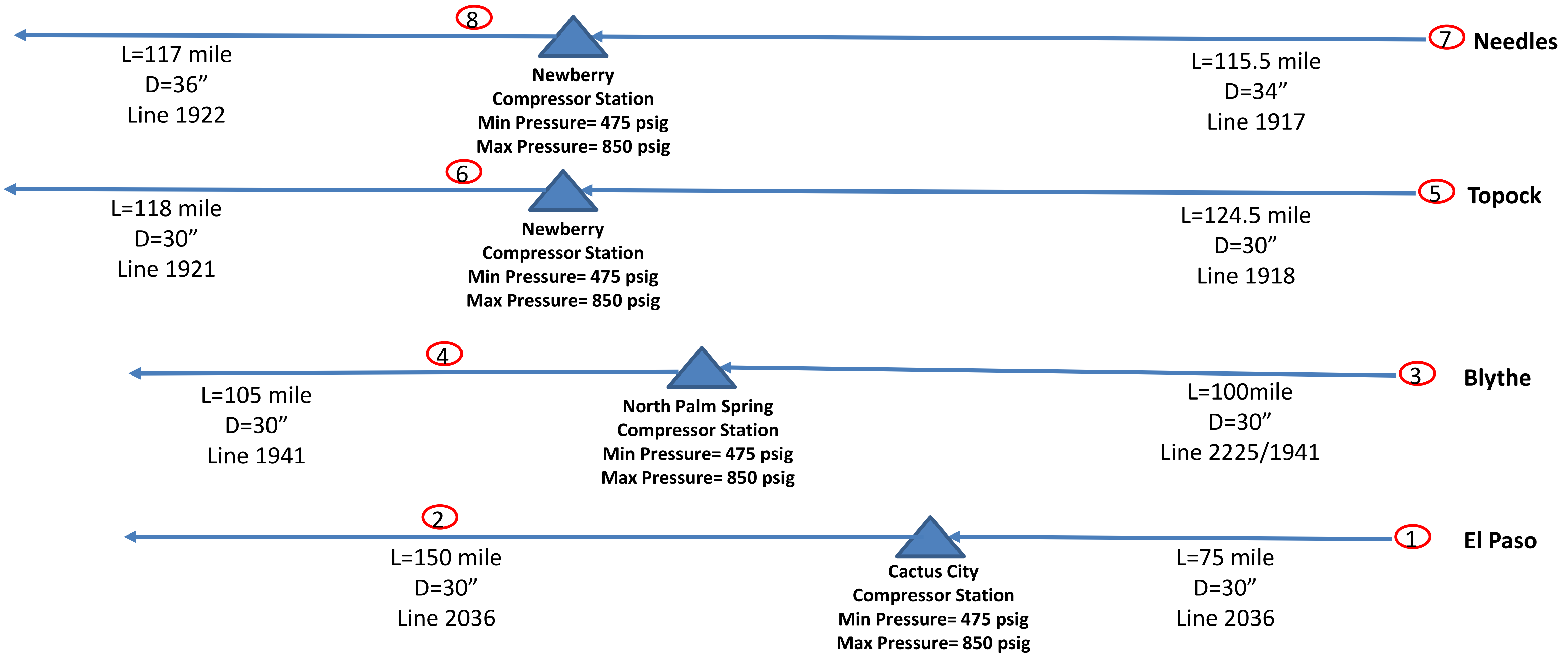
Pressure and Flow Dynamics

- **With renewable gas injection at border (in desert)**



Reference for pipe and compressor: stationhttps://www.arcgis.com/home/webmap/viewer.html?webmap=f8b54b821642463b8dc0becb2711093a