CALIFORNIA HYDROGEN
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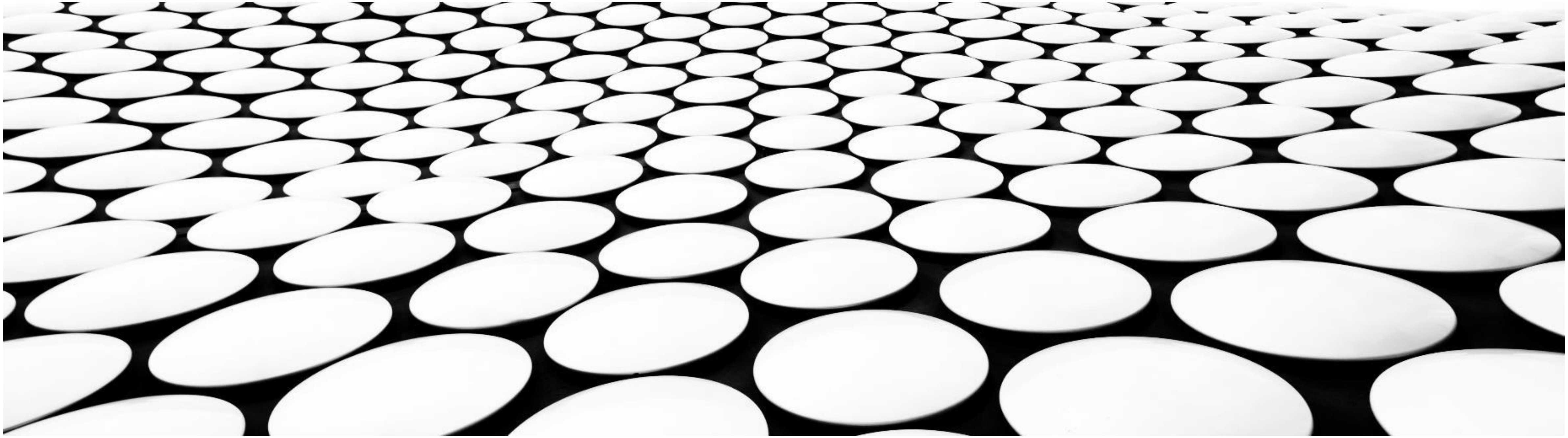

CHBC HYDROGEN 101 BRIEFING

JUNE 17, 2021

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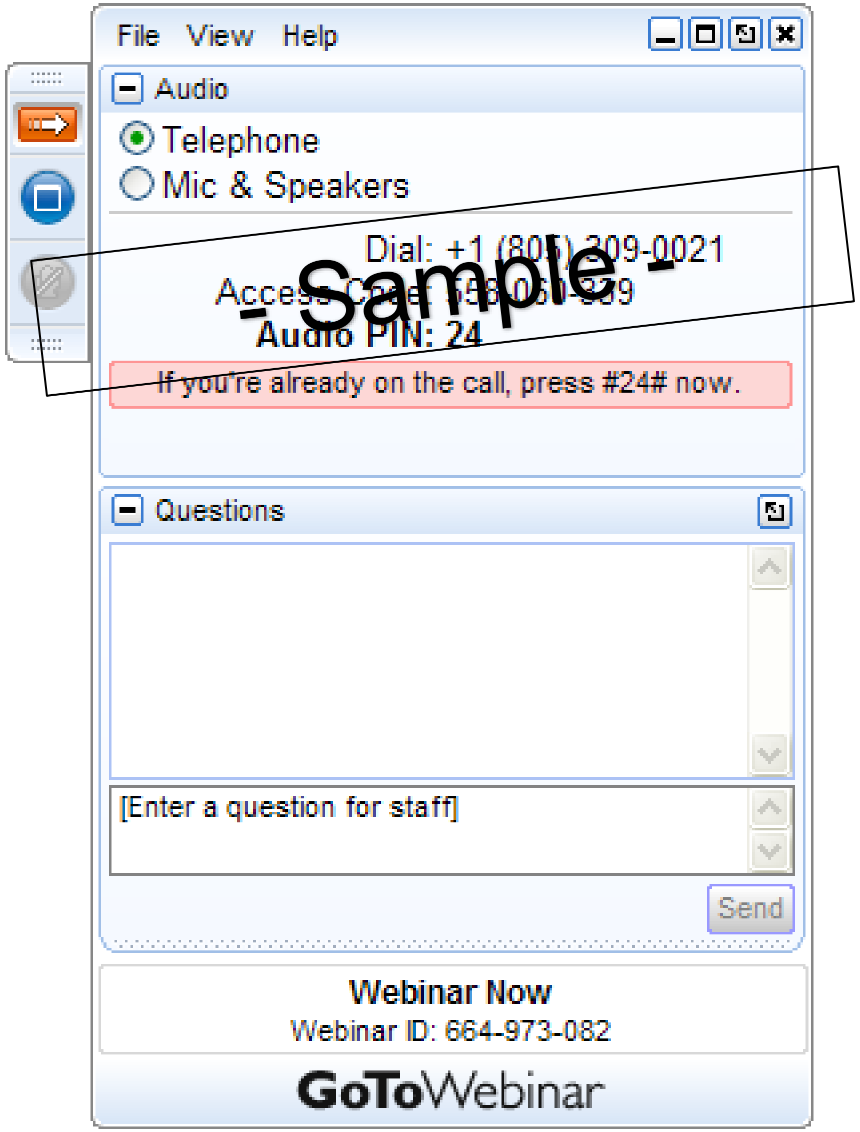

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FEATURED MODERATOR AND SPEAKER

William “Bill” Zobel
Executive Director,
California Hydrogen Business Council

Dr. Jack Brouwer
Director, National Fuel Cell Research Center, UC Irvine
Director, Advanced Power and Energy Program, UC Irvine
Professor of Mechanical and Aerospace Engineering

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ENERGY STORAGE AND RENEWABLE HYDROGEN

- **Our Vision:**
  - CHBC is committed to advancing the commercialization of hydrogen in the energy and transportation sectors to achieve California's climate, air quality, and decarbonization goals.
- **Our Mission:**
  - Provide clear value to our members and serve as an indispensable and leading voice in promoting the use of hydrogen in the utility and transportation sectors in California and beyond.
- **Our Principals:**
  - Leadership, Integrity, Teamwork and Inclusion.
- **Our Objectives:**
  - Enhance market commercialization through effective advocacy and education of policymakers and policy influencers
  - Be "the" trusted "go to" resource on Hydrogen and Fuel Cell technology for policymakers and policy influencers
  - Accelerate market growth via networking opportunities and information exchange for the industry and its customers

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Trillium A Love's Company
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WFT Winkelmann Flowform Technology Fuel Systems
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- A trusted and knowledgeable industry resource
- Access to policymakers, policy influencers and industry
- Track record of success
- Platform for industry collaboration
- Learn more: www.californiahydrogen.org

BECOME A MEMBER AND MAKE A DIFFERENCE
TOGETHER WE CAN INFLUENCE PUBLIC POLICY AND GROW YOUR BOTTOM LINE

SPEAKER

Dr. Jack Brouwer
Director, National Fuel Cell Research Center, UC Irvine
Director, Advanced Power and Energy Program, UC Irvine
Professor of Mechanical and Aerospace Engineering

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NATIONAL FUEL CELL RESEARCH CENTER

Hydrogen 101 – Myths vs. Facts

Jack Brouwer

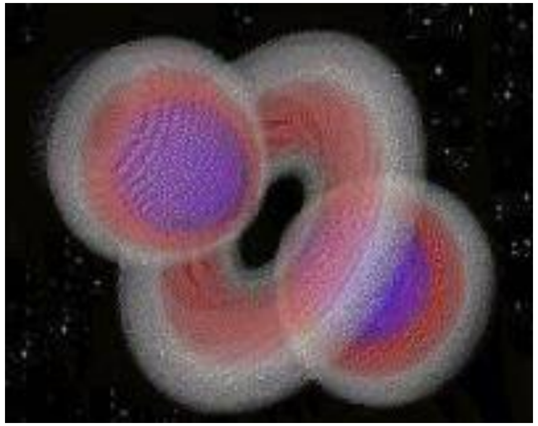
June 17, 2021

California Hydrogen Business Council
Webinar Series

Hydrogen Properties

Molecular Hydrogen Properties

- Gaseous specific gravity of 0.0695 at atmospheric pressure
  - H_2 molecular weight = 2
- Boiling point of -423°F (-252.8°C) at atmospheric pressure
- Colorless
- Odorless
- Tasteless
- Non-toxic
- *Flammable* gas
  - Higher heating value (HHV) = 60,958 BTU/lb (141,670 kJ/kg)
  - Lower heating value (LHV) = 51,571 BTU/lb (119,855 kJ/kg)



Some Hydrogen Myths

- Hydrogen is not safe
- Hydrogen is fossil
- Hydrogen will be more expensive than other zero emission options
- Hydrogen is less efficient than other zero emission options
- Hydrogen leaks too much
- Hydrogen is not compatible in current infrastructure

Hydrogen Safety

- Risk scenarios must consider: (1) flammability, (2) density, (3) diffusivity, (4) ignition energy, (5) total energy available

Density:

- Hydrogen is the lightest element and molecule.
- H_2 is 8 times lighter than natural gas. Per unit of energy contained, H_2 weighs 64% less than gasoline or 61% less than natural gas.
- Hydrogen is 14.4 times lighter than air. Natural gas is only 1.7 times lighter than air.

Diffusivity:

- Hydrogen is four time more diffusive than natural gas and 11 times more diffusive than gasoline fumes. H_2 is most diffusive fuel.

Total Available Energy:

- 1 kg of hydrogen has about the same energy as 1 gallon of gasoline which weighs 2.8 kg. Gasoline has 22 times the explosive power per unit of volume than gaseous hydrogen.

Hydrogen Safety

- Risk scenarios must consider: (1) flammability, (2) ~~density,~~ (3) ~~diff~~ tion energy, (5) ~~total energy available~~

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Diffusivity:

- Hydrogen is four time mo al gas and 11 times more diffusive than gasoline fumes el.

Total Available En

- 1 kg of hyd ame energy as 1 gallon of gasoline which weighs 2.8 kg the explosive power per unit of volume than gaseous hydro

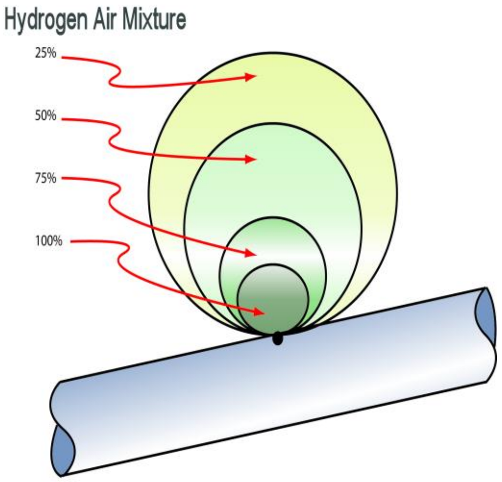
Density, Diffusivity, Available Energy metrics

H_2 unequivocally safer than current fuels!

Hydrogen Safety – Flammability Limits

Property	**Hydrogen**	**Methane**	**Propane**	**Gasoline**
Lower Flammability Limit	4%	5.3%	1.7%	1.0%
Lower Detonation Limit	18.3%	6.3%	3.1%	1.1%
Upper Detonation Limit	59%	13.5%	9.2%	3.3%
Upper Flammability Limit	75%	17%	10.9%	6.0%
Auto Ignition Temperature	585 C	537 C	450 C	228-471 C
Minimum Ignition Energy	0.017 mJ	0.274 mJ	0.240 mJ	0.240 mJ

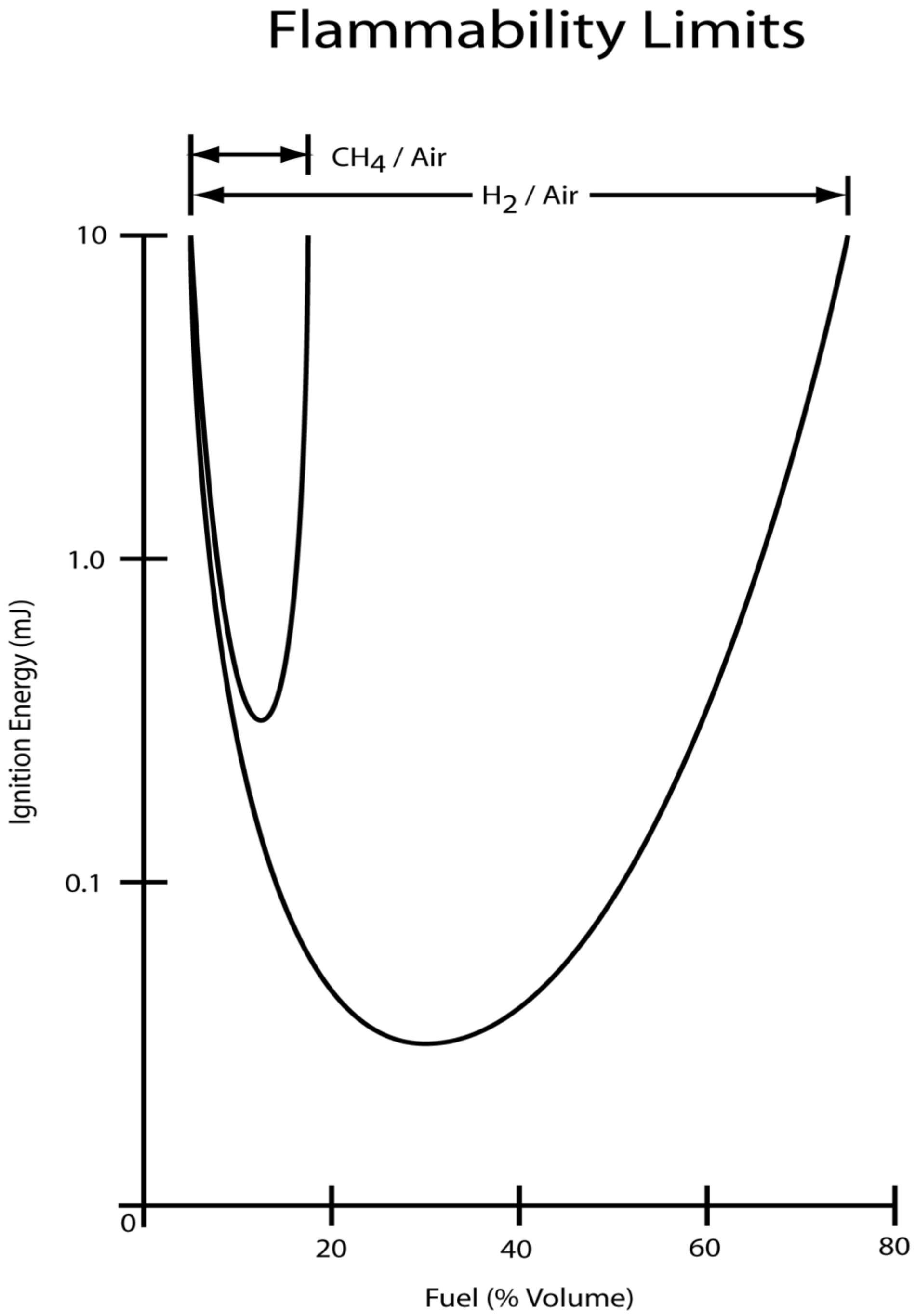
- Upper Flammability Limit is of less practical consequence
- Radius of concern is defined by LFL
- Safety sensors design for % of LFL
- 4 times higher concentration than gasoline required to get flammability yet it disperses 11 times faster. It is only half as likely as gasoline to ignite in open air.



Hydrogen Safety – Ignition Energy

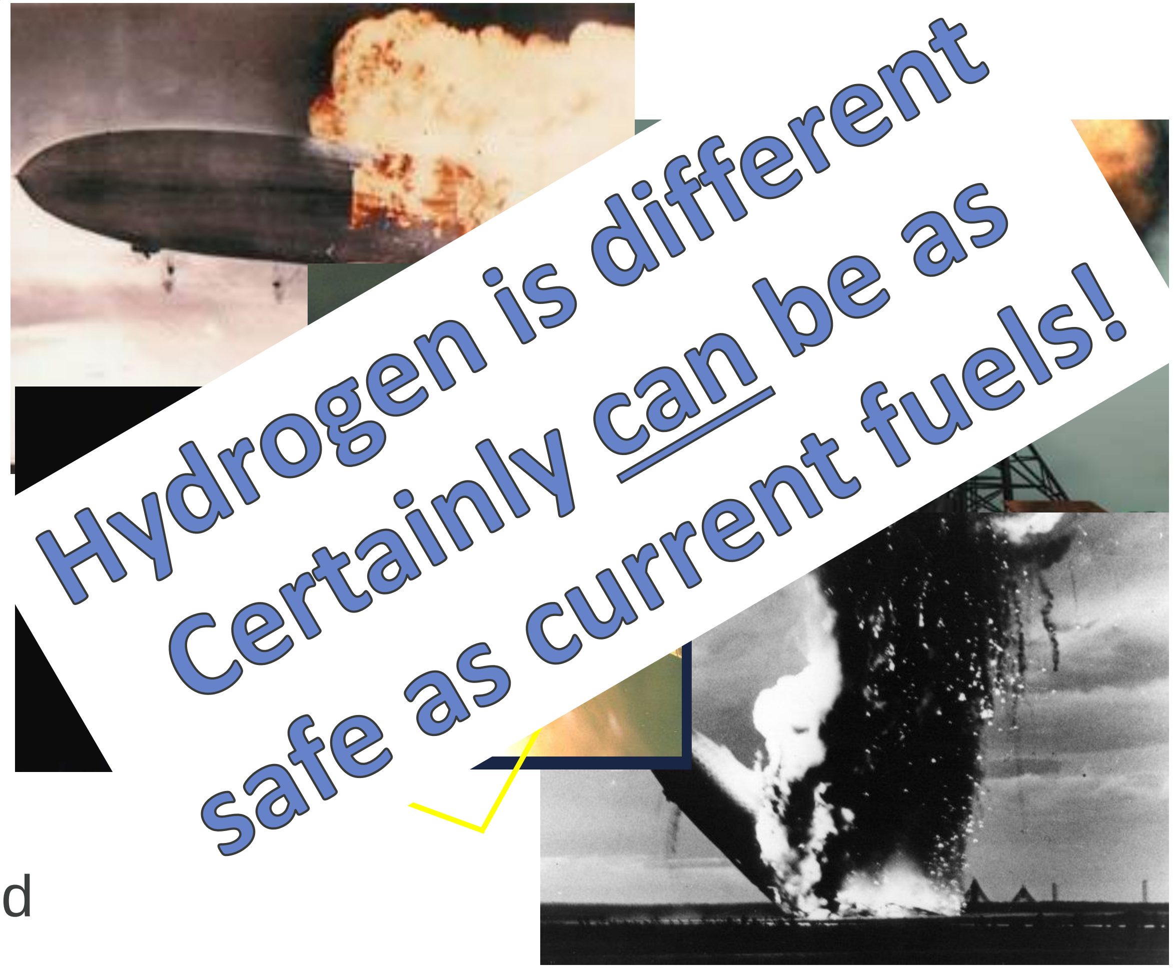
- Lowest ignition energy at stochiometric point.
- At 4-10% concentrations (at LFL, common leak scenario), ignition energy of H_2 is comparable to natural gas.
- Tendency to ignite and burn before large energy accumulation occurs.
- Typical static shock is 10 mJ. It could ignite methane, propane, gasoline and hydrogen.

Figure from: Air Products via Jay Keller, ICHS, 2009



Hydrogen saved lives in the Hindenburg disaster

- 36 out of 97 died mostly trapped by the fire of fabric, diesel fuel, furniture, … or jumping (not hydrogen)
- The craft did not explode but burned & while burning stayed aloft (hydrogen still in the nose)
- The craft fell to the ground tail first – the nose was still full of hydrogen
- Radiation from the flame was red, orange and yellow – hydrogen flames emit in the near UV (mostly blue in color)
- Main Cause: The covering was coated with cellulose nitrate or cellulose acetate -- both flammable materials. Furthermore, the cellulose material was impregnated with aluminum flakes to reflect sunlight. -- Dr. Addison Bain
- A similar fire took place when an airship with an acetate-aluminum skin burned in Georgia & it used **helium** (not hydrogen)



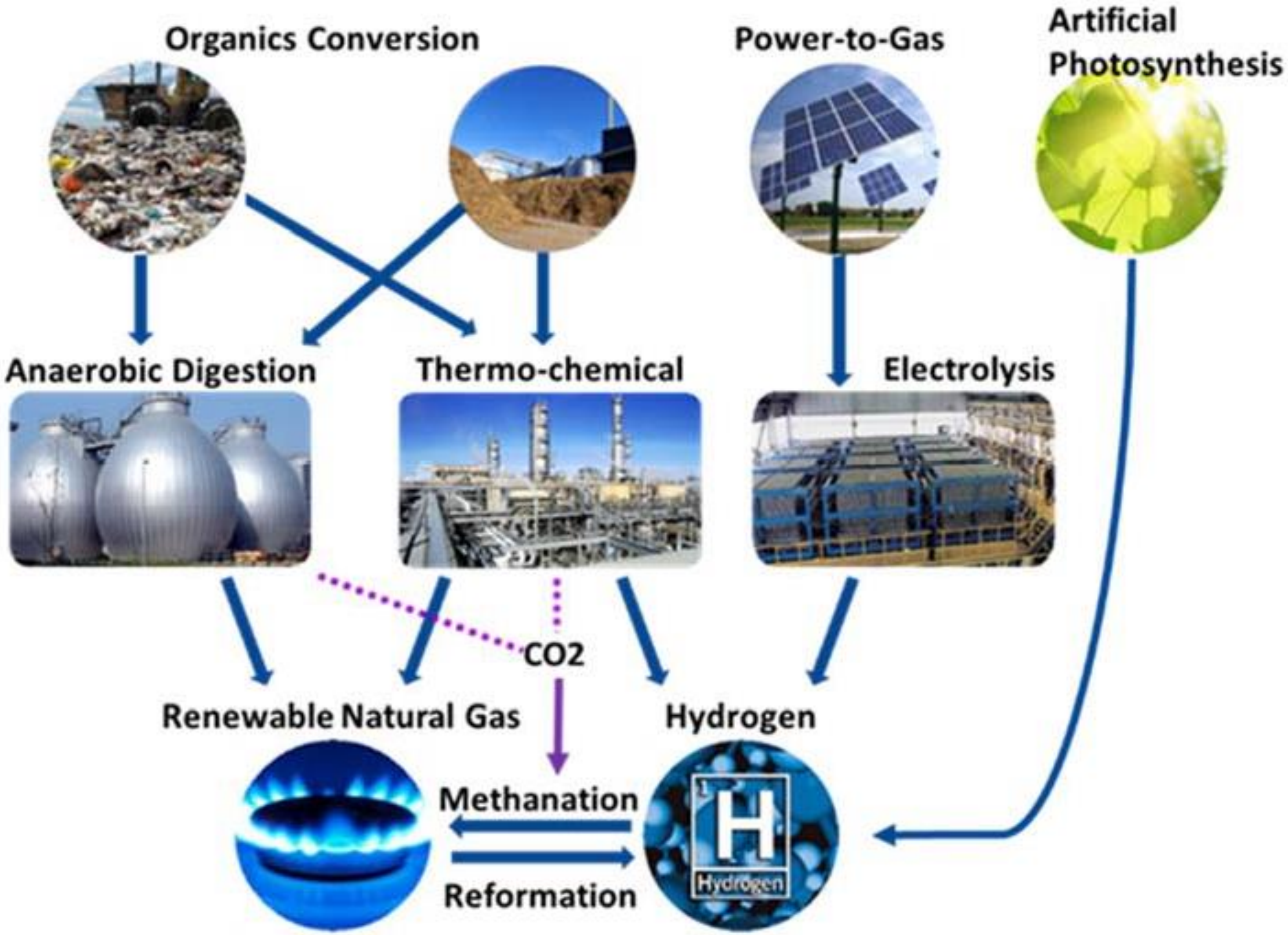
Hydrogen is different

Certainly can be as safe as current fuels!

From: Jay Keller, ICHS, 2009

Hydrogen is NOT Fossil – Energy Carrier

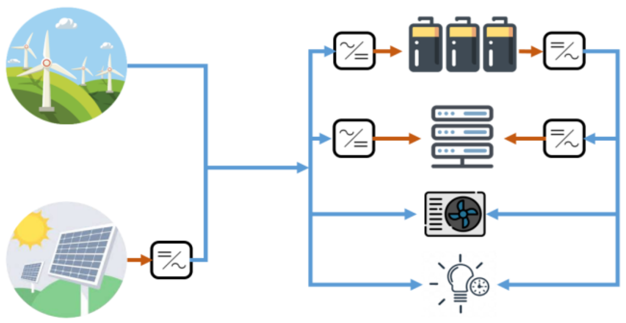
Many Important Renewable Pathways



Cost of Hydrogen for 100% Zero Emissions

Data Center Configurations/Locations Modeled

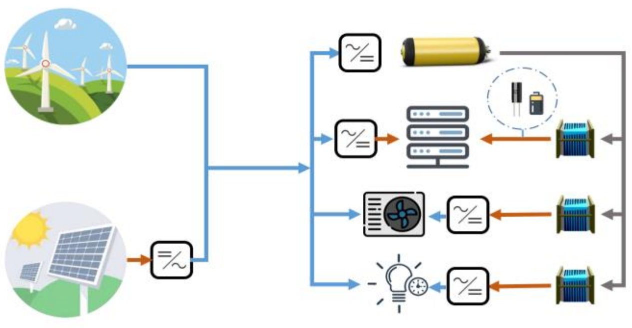
Battery - Central Storage



Data Center powered directly from renewable generators when available. Excess of electricity stored in batteries.

Wyoming
Iowa
Virginia
Texas

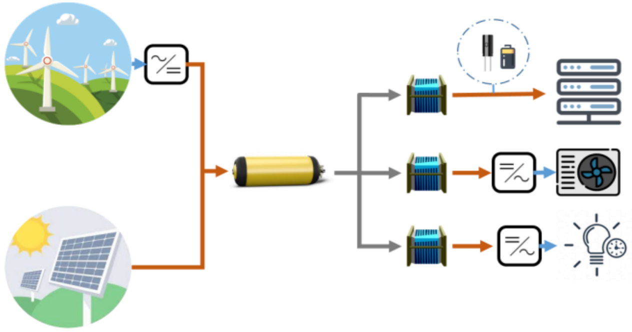
Excess power to gas



Data Center powered directly from renewable generators when available. Excess of electricity converted to hydrogen and used when required.

Wyoming
Iowa
Virginia
Texas

Power to gas



All renewable electricity generation converted to hydrogen. Data Center powered from hydrogen.

Wyoming
Iowa
Virginia
Texas

Cost of Hydrogen for 100% Zero Emissions

Excess P2G & Battery Cases – Wyoming (optimal mix of solar/wind)

	Hydrogen Case					**Battery Case**		
	Wind Onshore	**Solar PV**	**Electrolyzer**	**Fuel Cell**	**LH2 Storage + Liquefaction**	**Wind onshore**	**Solar PV**	**Battery**
Size, MW (MWh)	48	271	100	55		31	177	21,781
Dewar, ton					520.6			
Liquefier, kg/s					0.57			
OM fixed, M$/yr	0.43	1.19	0.31	0.18	0.335	0.28	0.78	306.5
OM var, $/MWh	-	-	39.14	154.7				
Cooling cost, $/h					23.6			
Energy cost, $/h					799.2			
Capital, M$	43.40	196.01	62.25	35.35	67.0	28.43	128.43	6224.1
Cell capex, M$								3396.5
Power conversion capex, M$								2823.4
BOS capex, M$								2.12
Dewar cost, M$					13.8			
Liquefier cost, M$					53.2			
WACC_{inf}	6.86E-2	6.86E-2	6.86E-2	6.86E-2	7.06E-2	6.86E-2	6.86E-2	7.06E-2
LCOH(E), $/MWh	29.57	67.05	131.5	371.2	23.2	29.57	67.05	4,744.5
LCOH, $/kg (EZ+stor)			5.16					
LCOE, \$/MWh$_e$	119.82					4,798.20		

Cost of Hydrogen for 100% Zero Emissions

Excess P2G & Battery Cases – Wyoming (optimal mix of sola

Every H2 case for 100% renewable w/ all storage is significantly cheaper!

	Hydrogen Case					tery Case		
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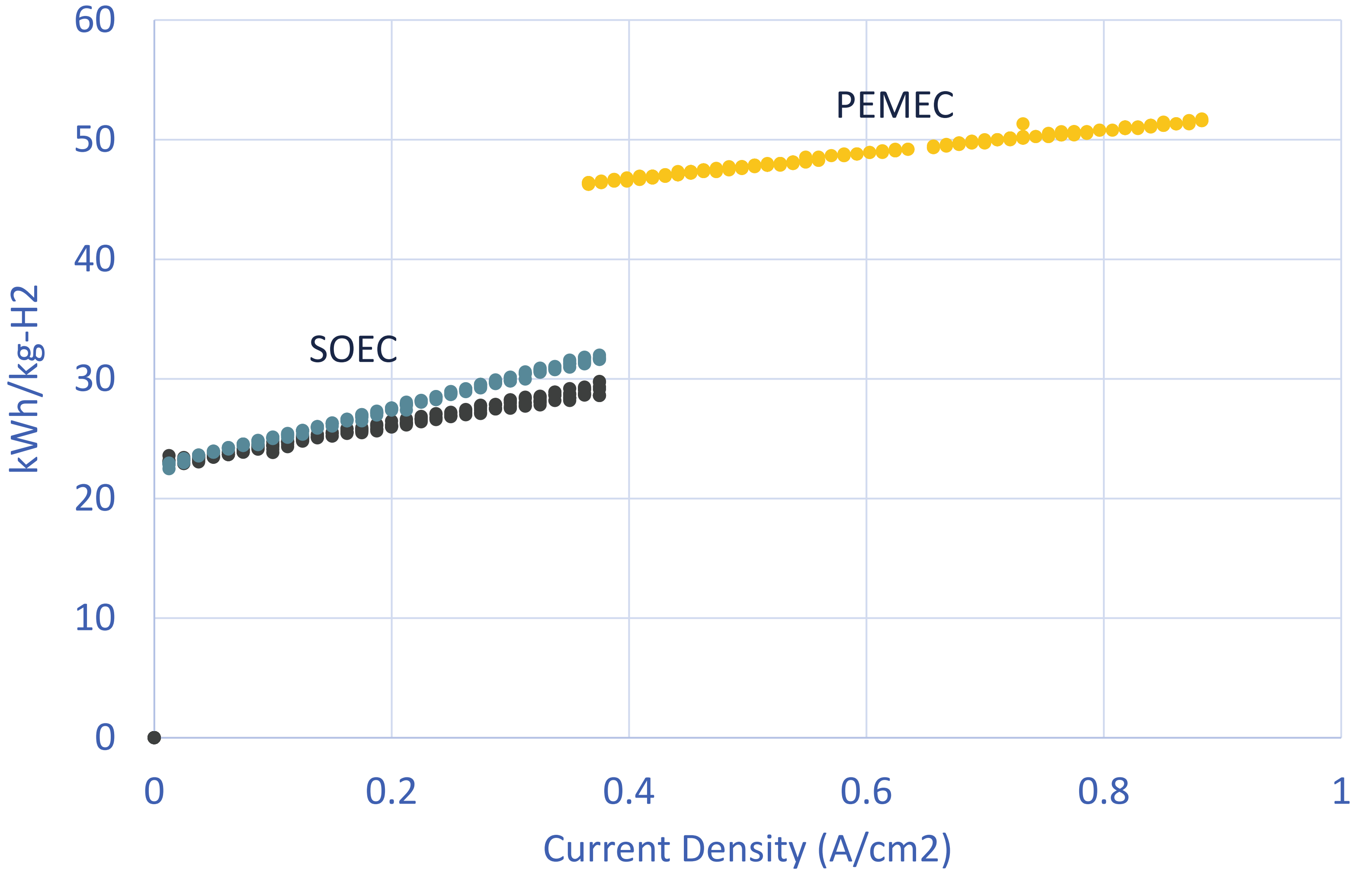
LCOH, $/kg (E			5.16					
LCOE, $/MW			119.82				4,798.20	

Efficiency of Emerging Electrolysis Systems

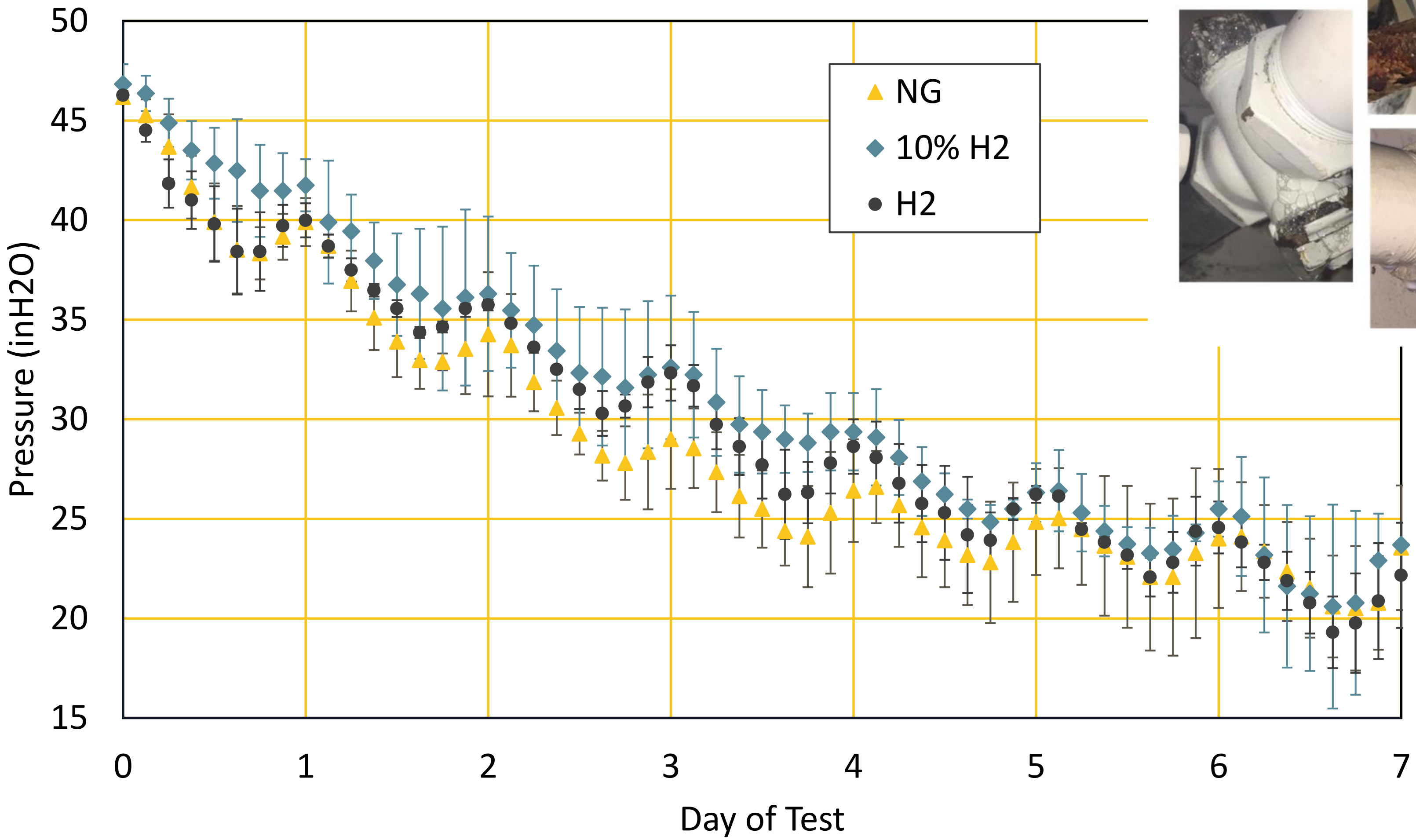
- Can achieve much higher round-trip efficiency



H_2 leakage from NG Infrastructure

H2 injection into existing natural gas infrastructure (low pressure)

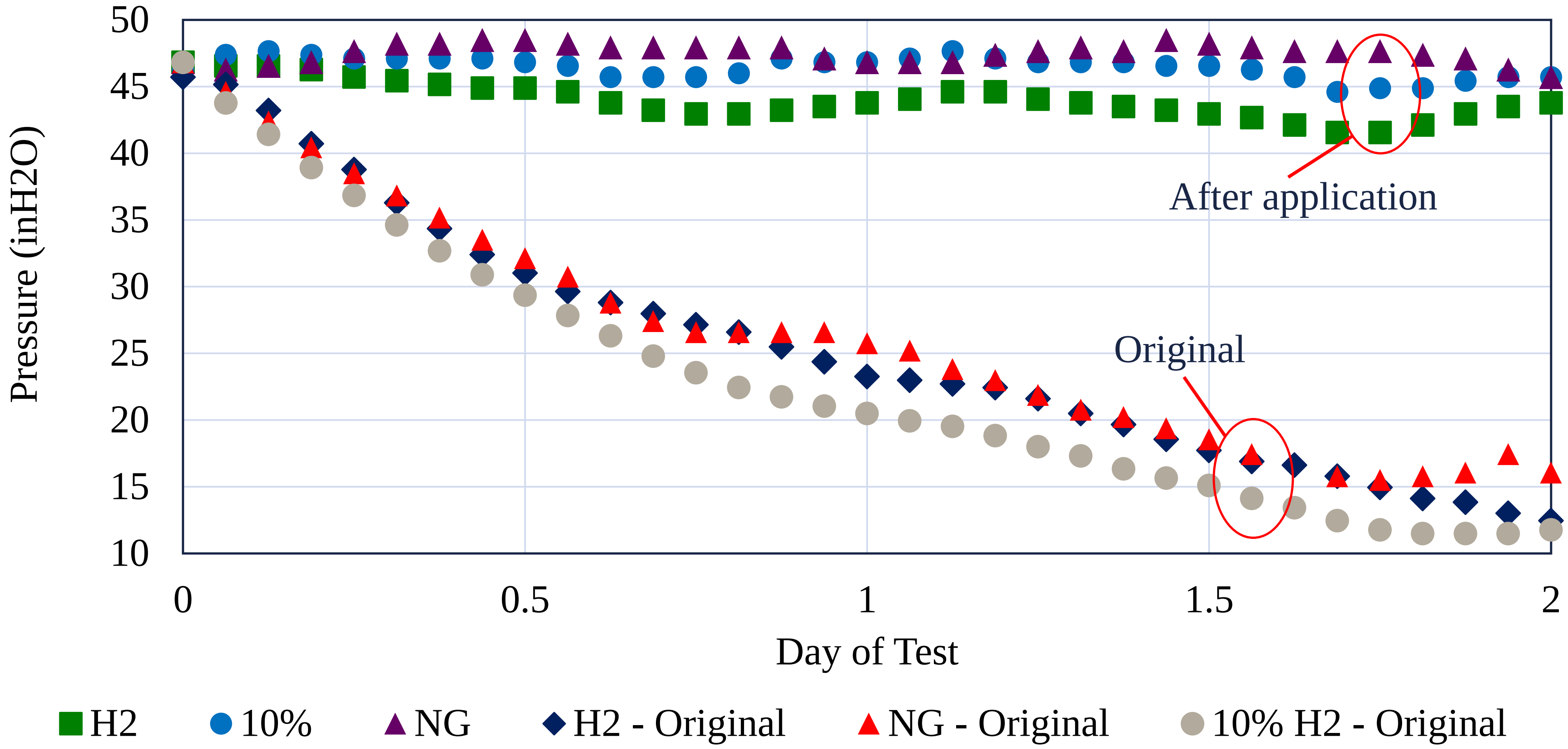
- NG, H_2/NG mixtures, H_2 leak at same rate



H_2 leakage mitigation technologies

H2 injection into existing natural gas infrastructure (low pressure)

- Copper epoxy applied (Ace Duraflow®) to mitigate H_2 leaks

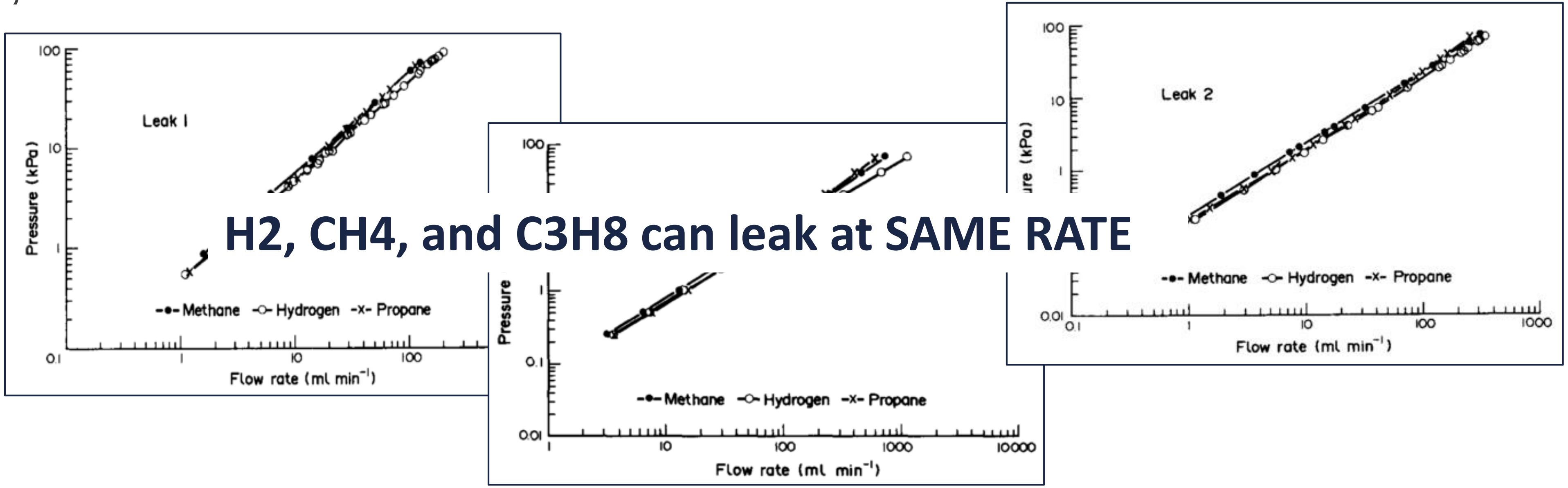


H_2 Leakage Rates

- Results from a previous study (1992) support our recent findings!

Leakage Flow Regime	Ratio of flow between H2 and CH4
~~Diffusion (diffusion constant)~~	~~3.15~~
~~Laminar (viscosity)~~	~~1.29~~
~~Turbulent (density)~~	~~2.83~~

- First publication on this topic: Swain & Swain, Int'l J. Hydrogen Energy, Vol. 17, pp. 807-815, 1992.



H2, CH4, and C3H8 can leak at SAME RATE

H_2 Leakage Rates

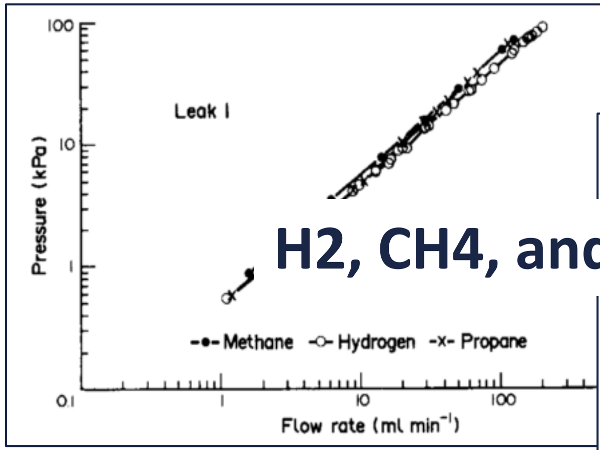
- Results from a previous study (1992) support our rec findings!

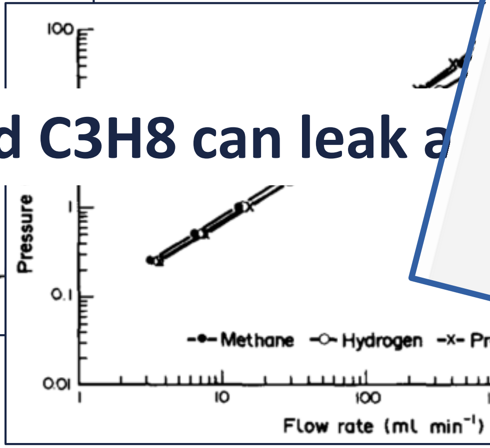
Leakage Flow Regime	Ratio of flow be

Entrance effects?

Compressibility?

- First publication on this topic: Swain & Swain, In 807-815, 1992.





H2, CH4, and C3H8 can leak a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International Journal of Hydrogen Energy

Volume 45, Issue 15, 18 March 2020, Pages 8810-8826

Hydrogen leaks at the same rate as natural gas in typical low-pressure gas infrastructure

Alejandra Hormaza Mejia [a], Jacob Brouwer [a], Michael Mac Kinnon [b]

Show more

https://doi.org/10.1016/j.ijhydene.2019.12.159

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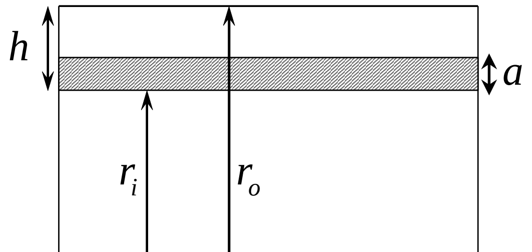
Highlights

- H_2 and CH_4 leak rates are measured in unmodified low pressure gas infrastructure.
- Experiments show H_2 leaks at the same rate as CH_4 under these conditions.

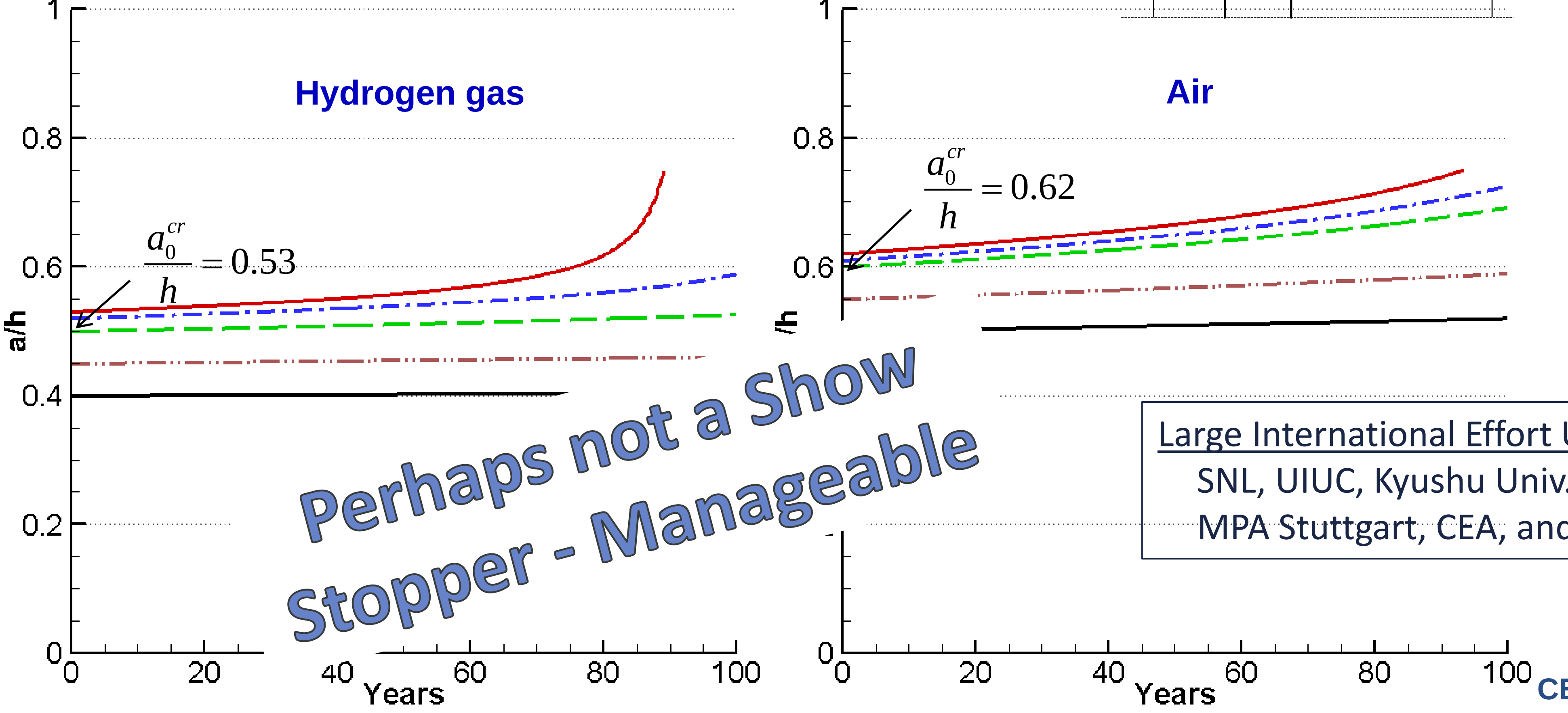
Hydrogen Steel Pipeline Embrittlement

Simulation of H2 embrittlement and fatigue crack growth with UIUC

- Fatigue crack growth in 6” SoCalGas pipeline



0.188” wall thickness: $(h = 0.188'' = 4.8\ \text{mm})$

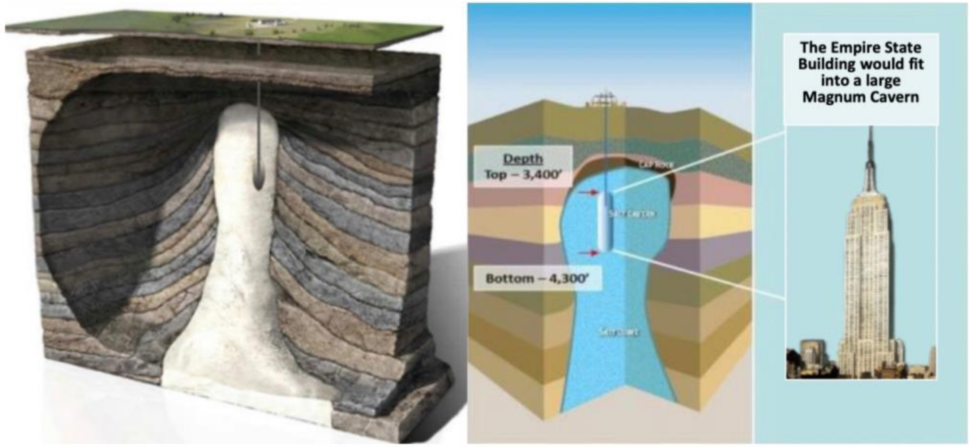


Perhaps not a Show Stopper - Manageable

Large International Effort Underway

SNL, UIUC, Kyushu Univ.,
MPA Stuttgart, CEA, and others

Hydrogen Massive Storage Facility Transformation



Plan for storing hydrogen in Utah salt caverns

Images: Los Angeles Department of Water and Power

Salt Caverns already widely used and proven

- Air Liquide & Praxair operating H_2 salt cavern storage in Texas since 2016
    - Very low leakage rate
    - Massive energy storage
    - Safe & Low-cost storage
- Similar success in Europe
- Magnum working with LADWP to adopt similar salt cavern H_2 storage in Utah

Current CA depleted oil and gas fields not yet used or proven for H_2 use

- Several research and development needs
    - H2 leakage
    - H2 reaction with petroleum remnants
    - H2 biological interactions
    - H2 storage capacity
    - H2 safety

Some Hydrogen Subtle Untruths – Popular Thinking

Zero Emissions 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 compared to fossil fuels!

I agree with most of this!

Subtly untruthful - Not the whole story

Hydrogen Facts – Unique Zero Emissions Features

Hydrogen: 11 features required for 100% zero carbon & pollutant emissions

- Massive energy storage potential
- Rapid vehicle fueling
- Long vehicle range
- Heavy vehicle/ship/train payload
- Seasonal (long duration) storage potential
- Sufficient raw materials on earth
- Water naturally recycled in short time on earth
- Feedstock for industry heat
- Feedstock for industry chemicals (e.g., ammonia)
- Pre-cursor for high energy density renewable liquid fuels
- Re-use of existing infrastructure (lower cost)

Saeemanesh, A., Mac Kinnon, M., and Brouwer, J., *Hydrogen is Essential for Sustainability*, Current Opinion in Electrochemistry, 2019.

Hydrogen Facts – Unique Zero Emissions Features

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Current Opinion in Electrochemistry

Review Article

Hydrogen is essential for sustainability

Alireza Saeedmanesh, Michael A. Mac Kinnon and Jack Brouwer*

Sustainable energy conversion requires zero emissions of greenhouse gases and criteria pollutants using primary energy sources that the earth naturally replenishes quickly, like renewable resources. Solar and wind power conversion technologies have become cost effective recently, but challenges remain to manage electrical grid dynamics and to meet end-use requirements for energy dense fuels and chemicals. Renewable hydrogen provides the best opportunity for a zero emissions fuel and is the best feedstock for production of zero emission liquid fuels and some chemical and heat end-uses. Renewable hydrogen can be made at very high efficiency using electrolysis systems that are dynamically operated to complement renewable wind and solar power dynamics. Hydrogen can be stored within the existing natural gas system to provide low cost massive storage capacity that (1) could be sufficient to enable a 100% zero emissions grid; (2) has sufficient energy density for end-uses including heavy duty transport; (3) is a building block for zero emissions fertilizer and chemicals; and (4) enables sustainable primary energy in all sectors of the economy.

Address
National Fuel Cell Research Center, University of California, Irvine, 92697-3550, United States

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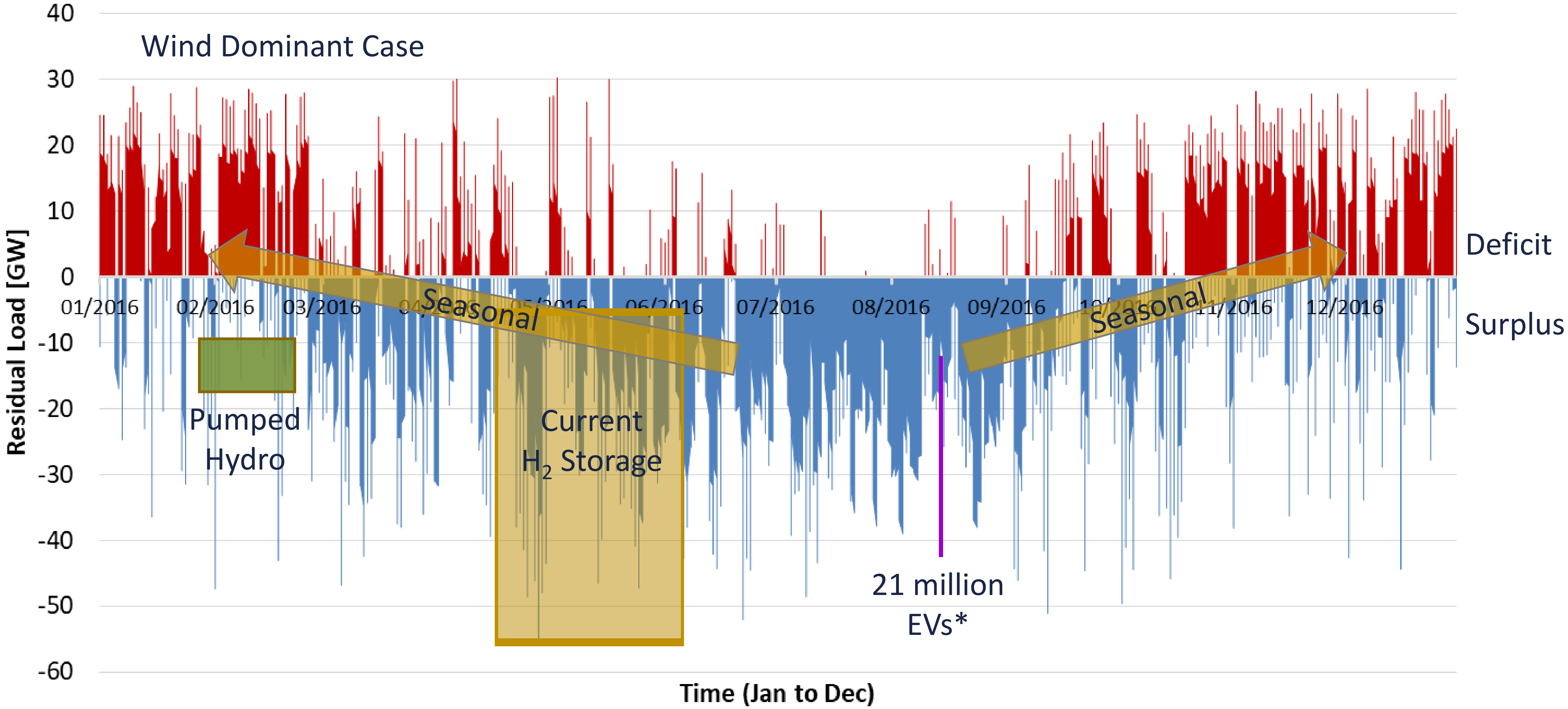
electricity generation, and industrial applications, will increase substantially over this century [7–14].

Since the Industrial Revolution, the vast majority of energy converted in society has been obtained from fossil fuels – coal, natural gas, and petroleum – which require tremendously long times for earth and the power of the sun to produce. This trend is widely expected to continue in coming decades [15–18]. Although the available global quantity of these fuels is extremely large, they are nevertheless finite and so will inevitably 'run out' at some near future time as we consume them much faster than the earth produces them [19]. A primary reason for their continued use is economics – energy from fossil fuels has been more cost effective than most other sustainable forms of energy, including renewable resources.

In addition, the continued use of fossil fuels is associated with increased criteria pollutant and greenhouse gas emissions [20]. Emissions from fossil fuel combustion degrade air quality, pose human health risks, and drive global climate change. In 2017, global energy-related CO_2 emissions reached an historic high of 32.5 Gt as a result of

Saeemanesh, A., Mac Kinno
Hydrogen is Essential for Sustainability, Curr
Opinion in Electrochemistry, 2019.

Massive Storage Required for 100% Renewable – CA



* Nissan Leaf Equiv. – 62 kWh

Saeedmanesh, A. Mac Kinnon, M. Brouwer, J., Current Opinion in Electrochemistry, Vol. 12, pp. 166-181, 2018

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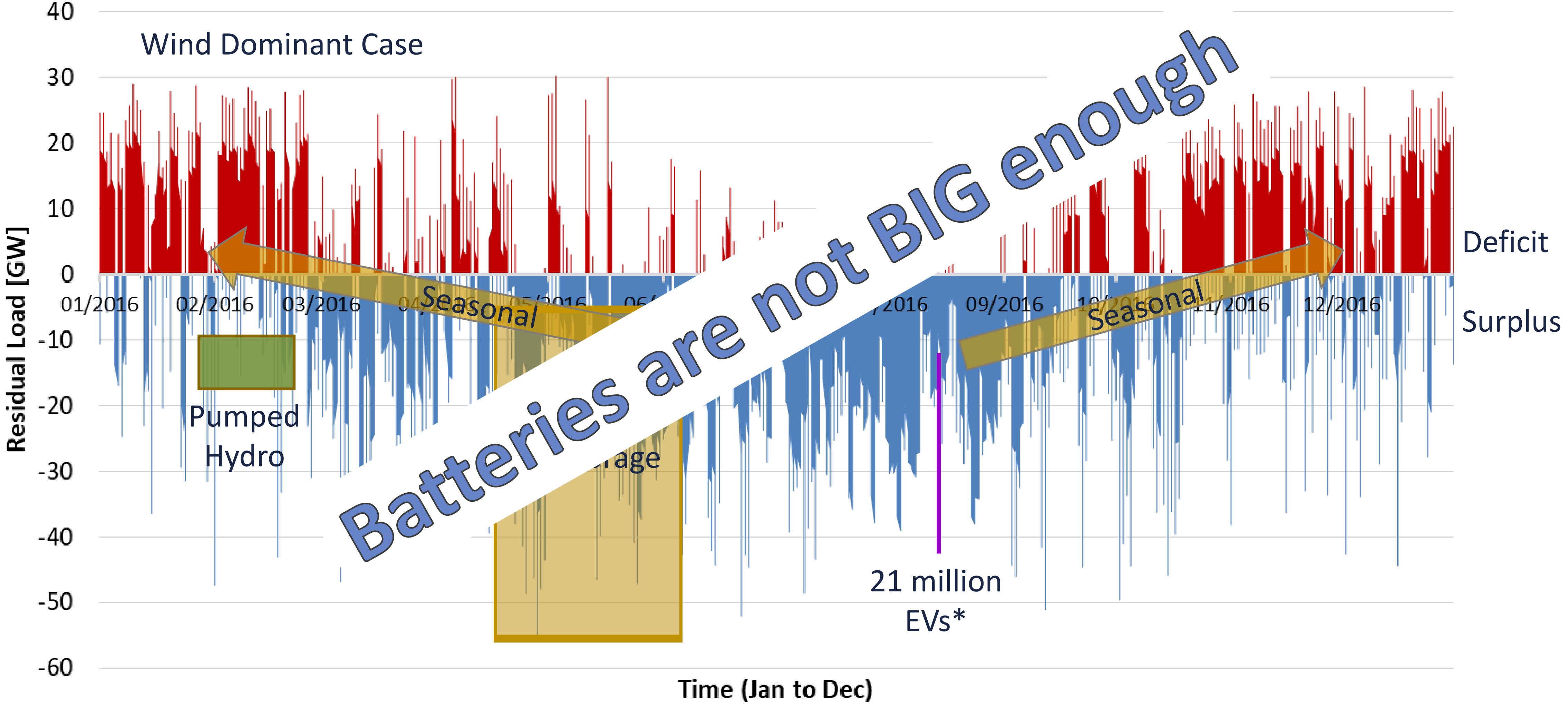
Massive Storage Required for 100% Renewable – CA



Batteries are not BIG enough

* Nissan Leaf Equiv. – 62 kWh

Saeedmanesh, A. Mac Kinnon, M. Brouwer, J., Current Opinion in Electrochemistry, Vol. 12, pp. 166-181, 2018

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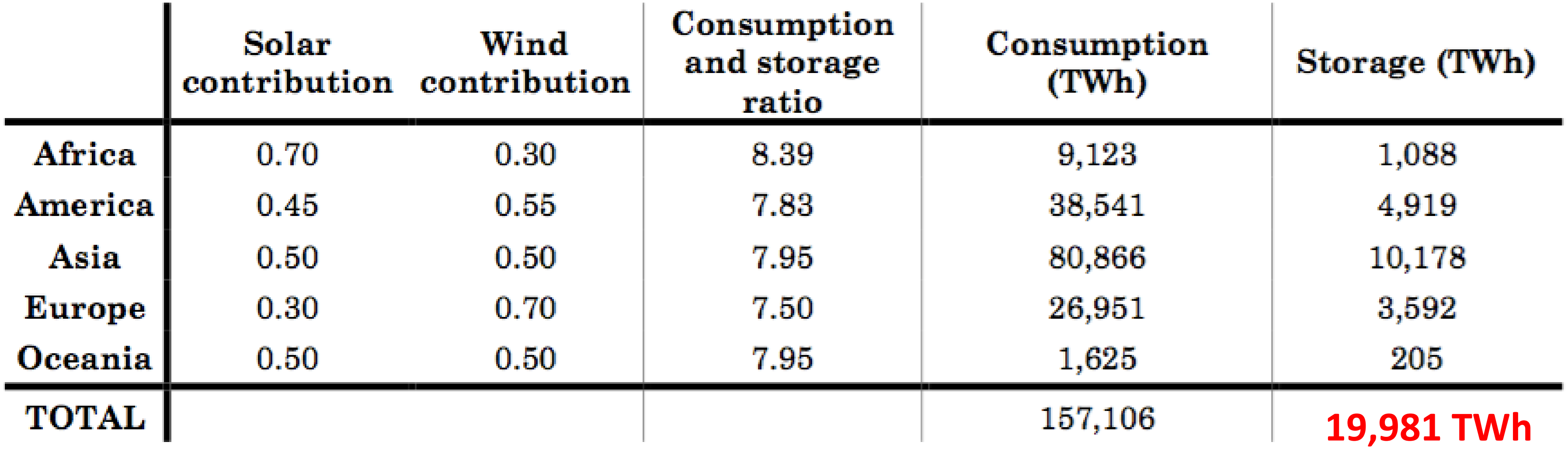
Energy Storage Need - World

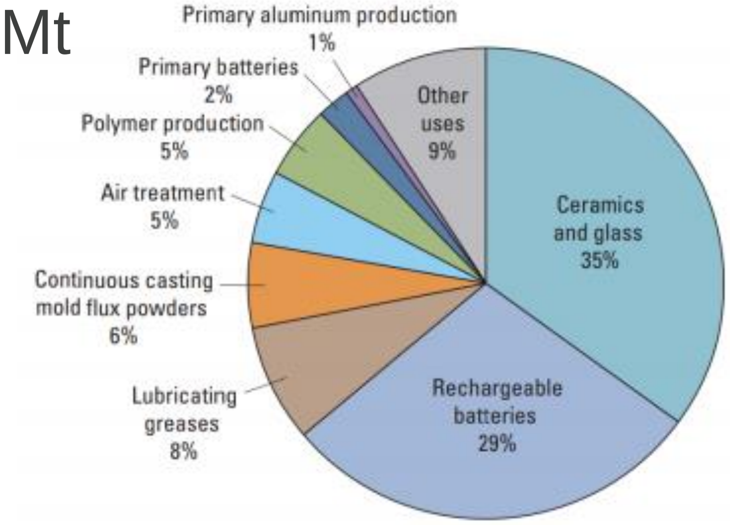
Simulate meeting of total world energy demand w/ Solar & Wind



	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)
- > 60% of Co comes from the Democratic Republic of Congo



Source: U.S. Geological Survey, 2018

Energy Storage Need - World

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Oceania	0.50	0.50	[illegible]	[illegible]	205
TOTAL					19,981 TWh

. Thesis, 2018]

There is not enough lithium or cobalt in the world

- To build one Li-ion batter [illegible] Co: 25,815 Mt
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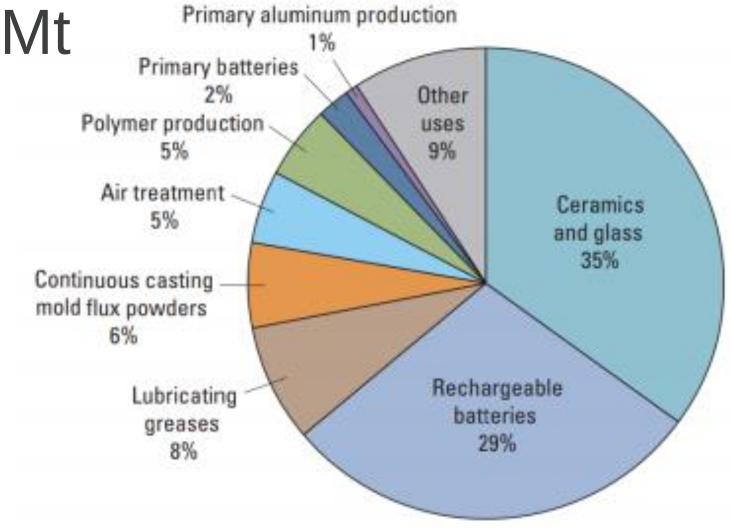
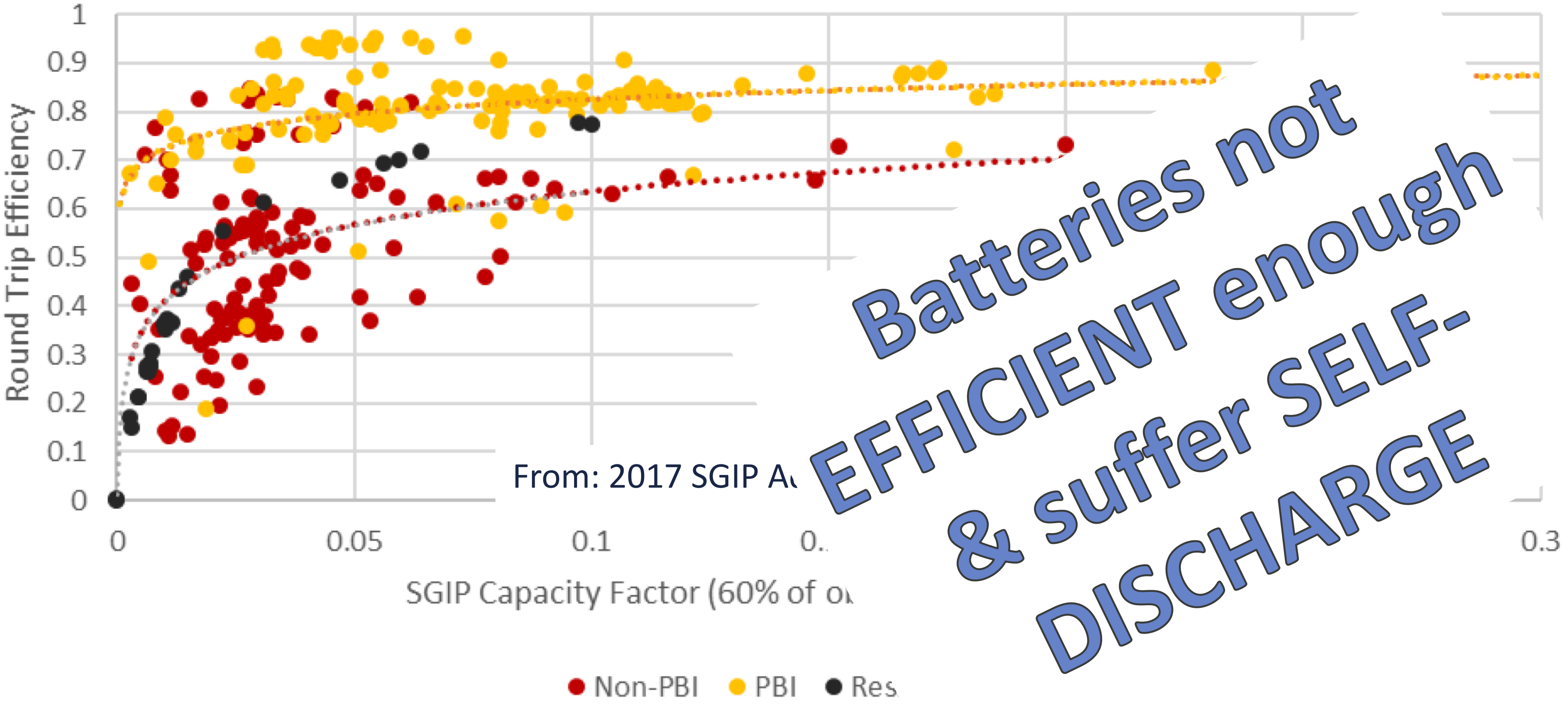


Source: U.S. Geological Survey, 2018

Efficiency for Long Duration Storage

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

- Measured battery system performance in Utility Applications



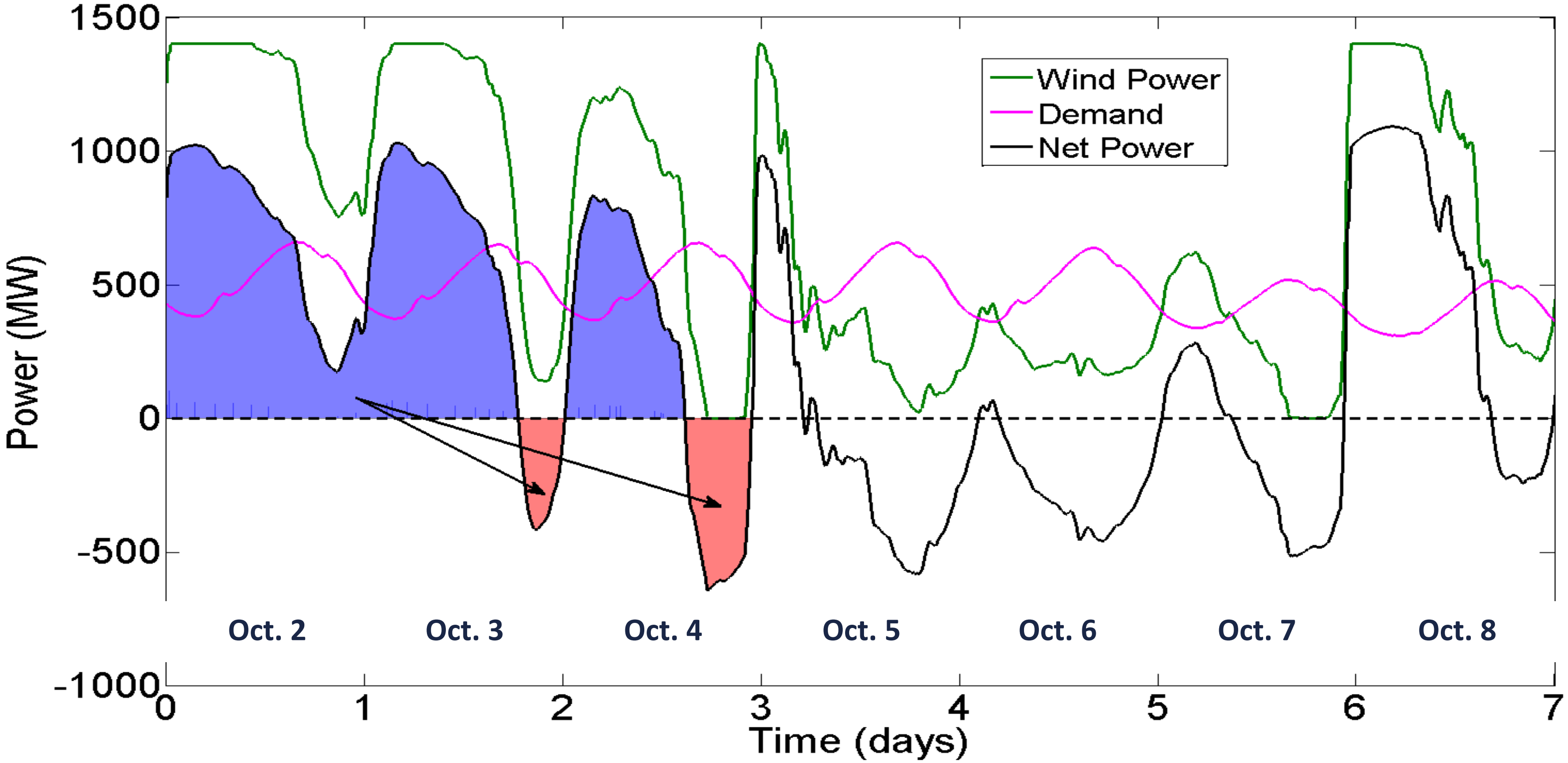
From: 2017 SGIP A

Batteries not EFFICIENT enough & suffer SELF-DISCHARGE

- Self-Discharge (the main culprit), plus cooling, t sforming, inverting/converting, ...

Hydrogen Energy Storage Dynamics

- Hydrogen Storage complements Texas Wind & Power Dynamics



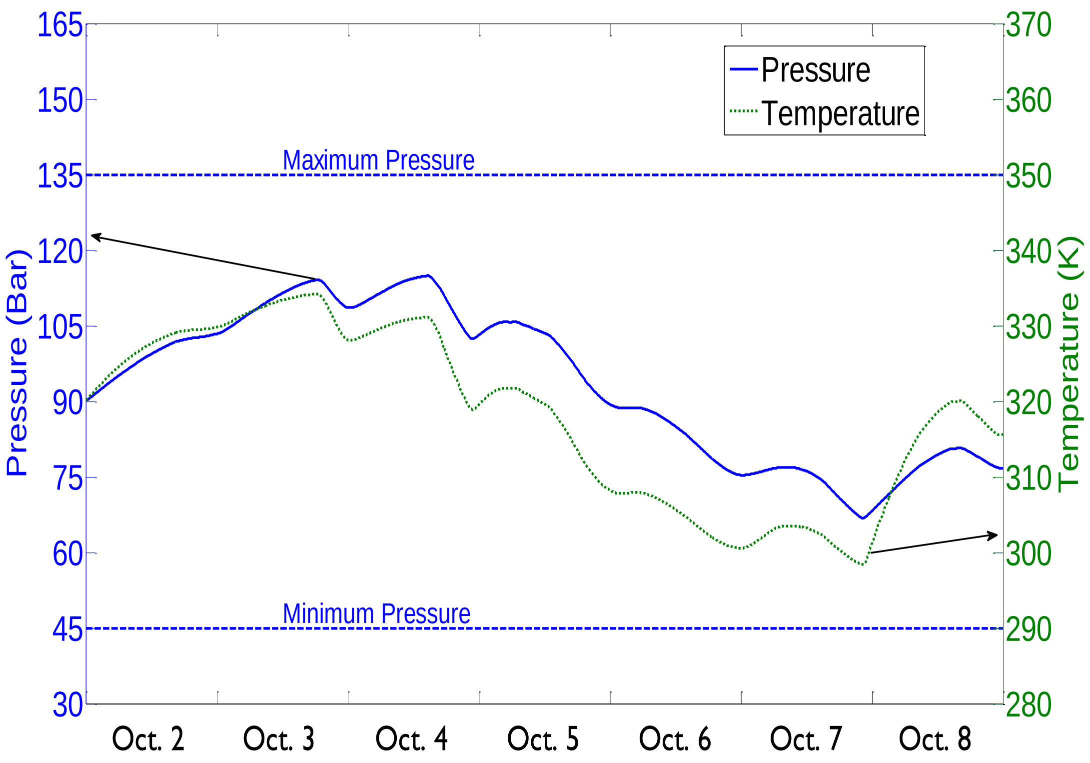
- Load shifting from high wind days to low wind days
- Hydrogen stored in adjacent salt cavern

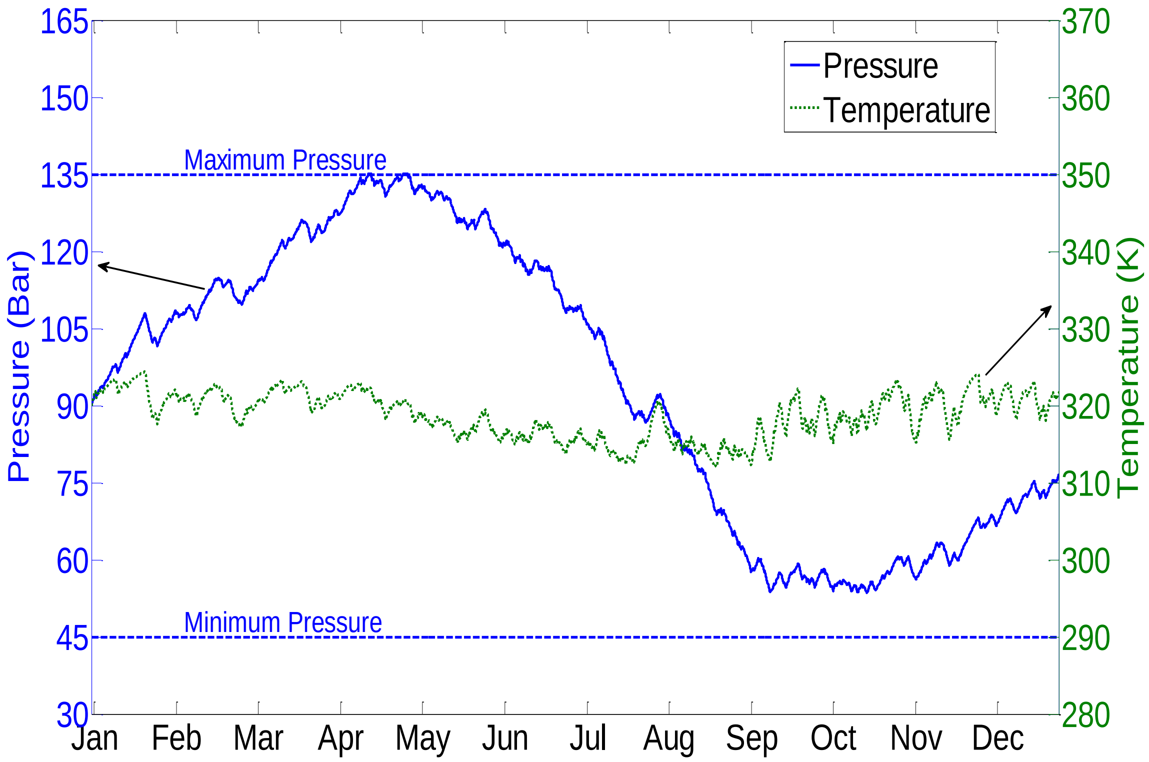
Maton, J.P., Zhao, L., Brouwer, J., Int'l Journal of Hydrogen Energy, Vol. 38, pp. 7867-7880, 2013

Hydrogen Energy Storage Dynamics

- Weekly and seasonal storage w/ H_2, fuel cells, electrolyzers
  - 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

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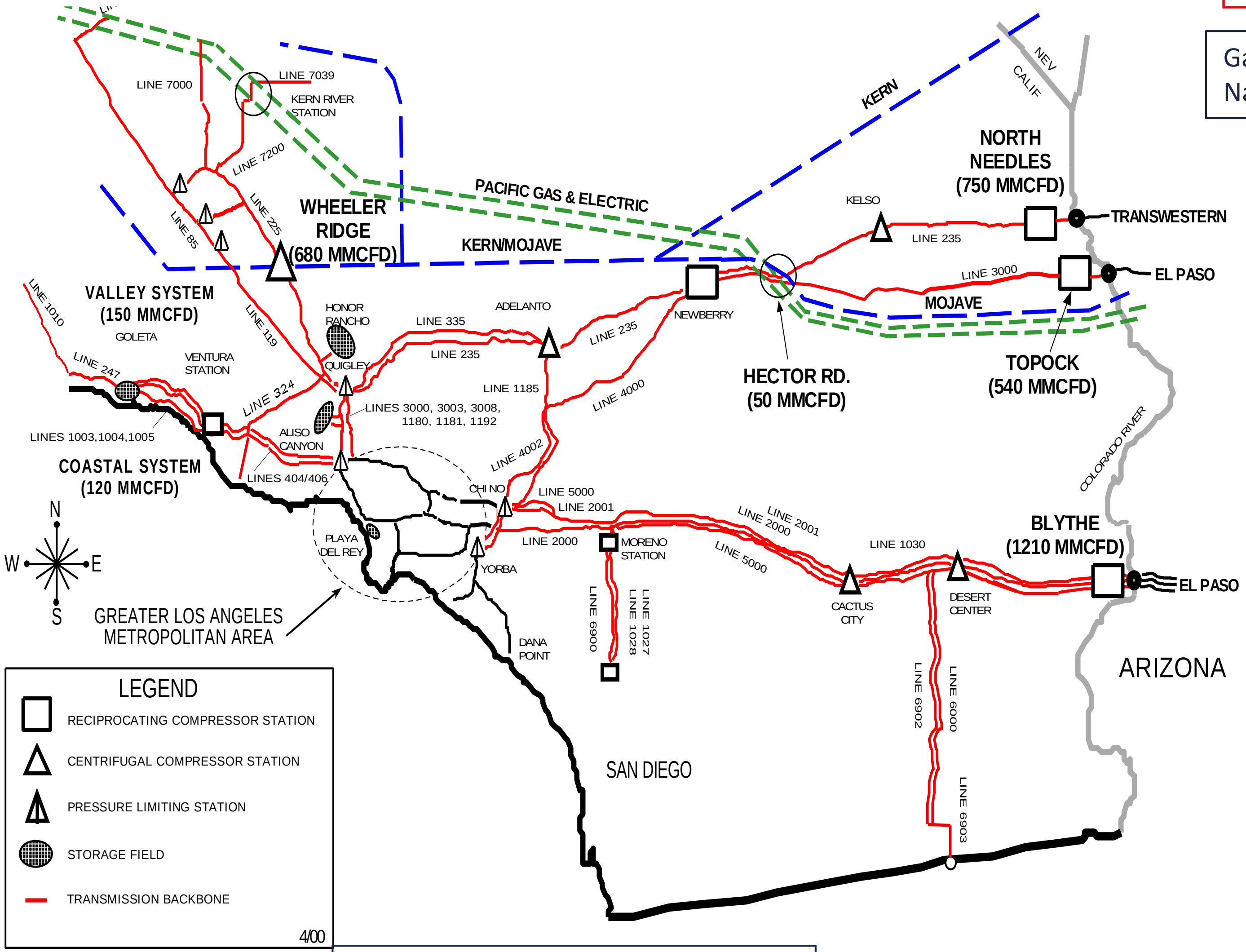
Resilient Storage & Transmission/Distribution Resource

- Natural Gas Transmission, Distribution & Storage System

> 99.999% available

Gas Technology Institute, Assessment of Natural Gas … Service Reliability, 2018.



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

Resilient Storage & Transmission/Distrib Resource

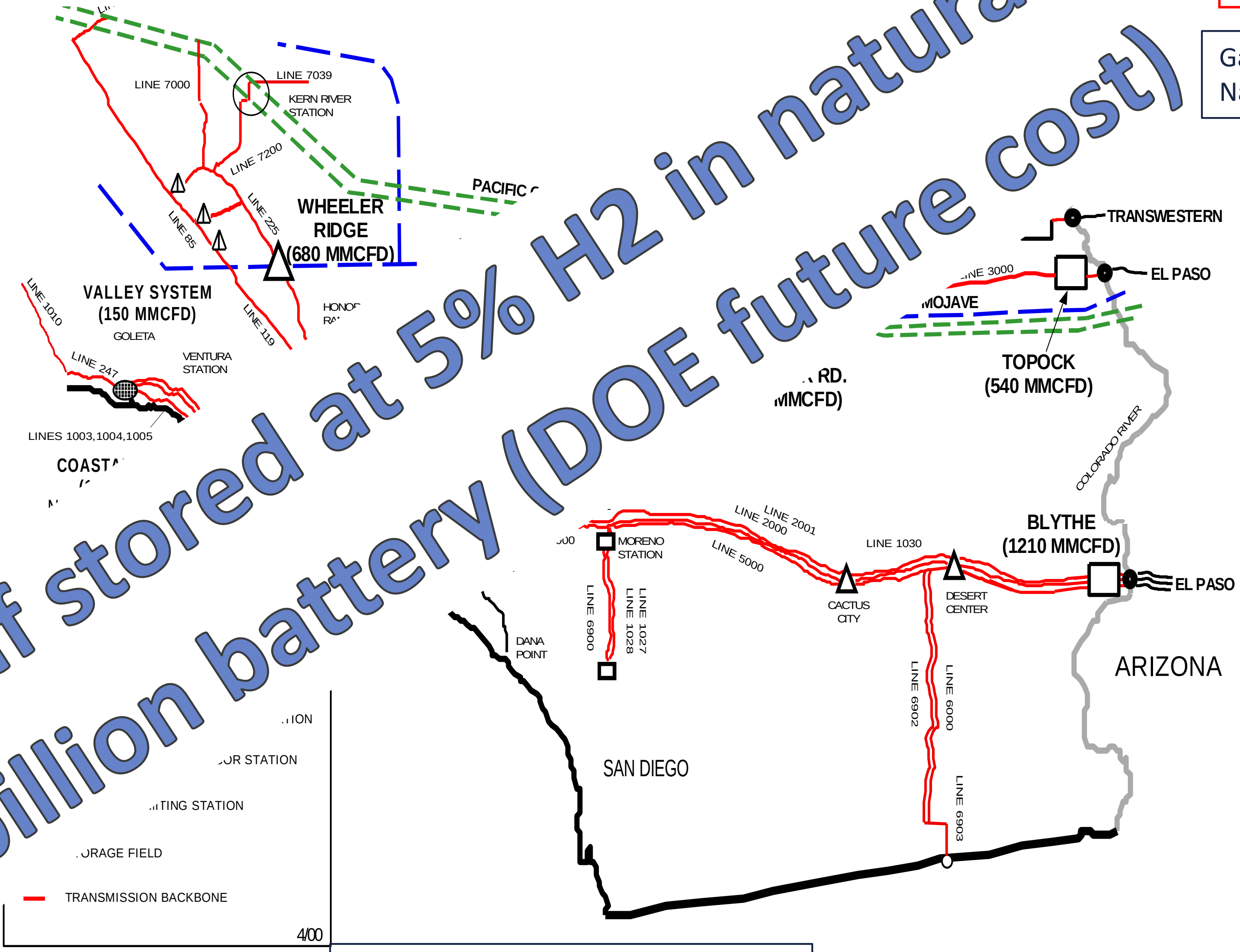
- Natural Gas Transmission, Distribution & Storage Syste

> 99.999% available

Gas Technology Institute, Assessment of Natural Gas … Service Reliability, 2018.

650 GWh if stored at 5% H2 in natural gas

$130 billion battery (DOE future cost)



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Resilient Storage & Transmission/Distrib… Resource

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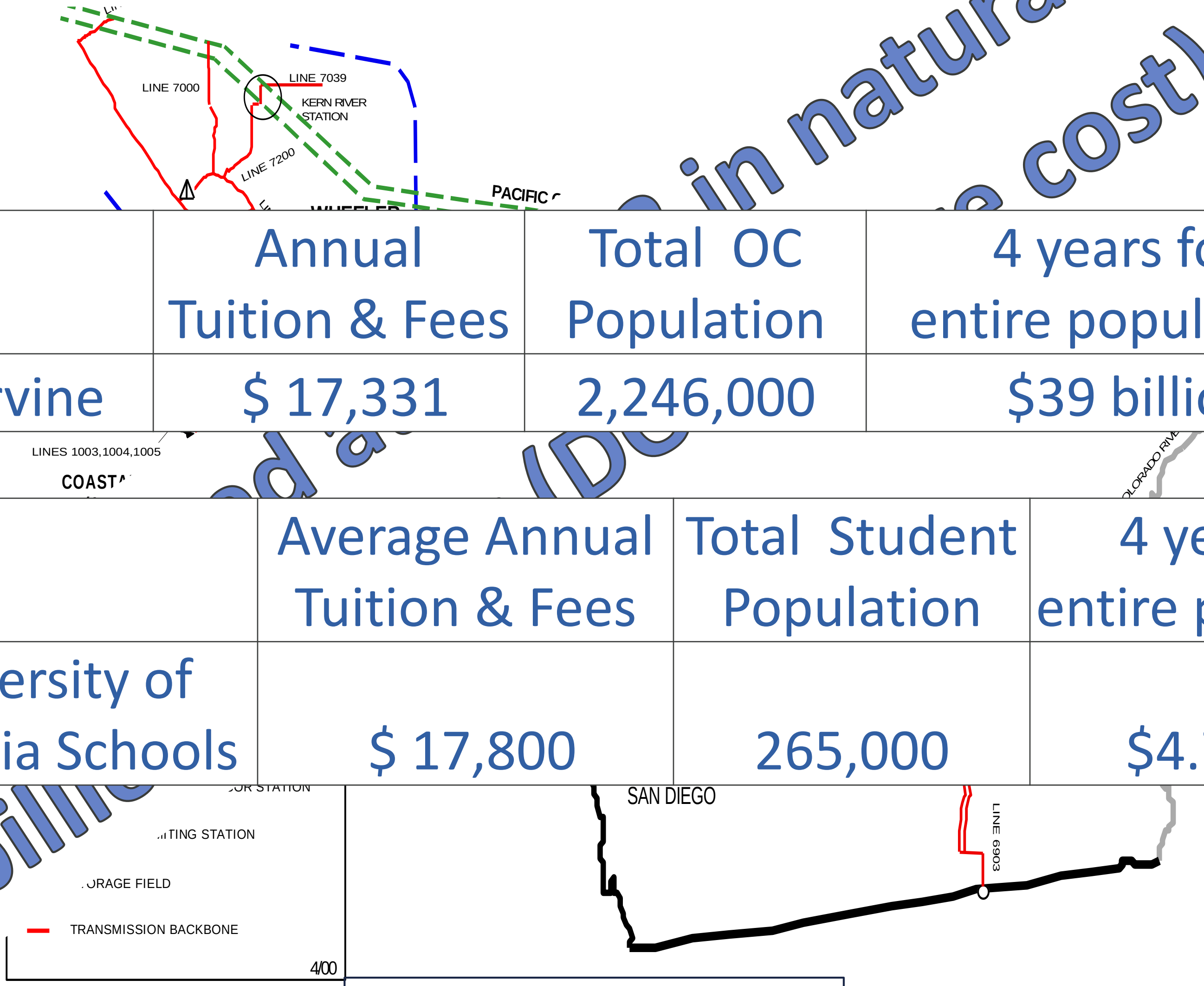
cost)



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

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

650 G

$130 billi

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

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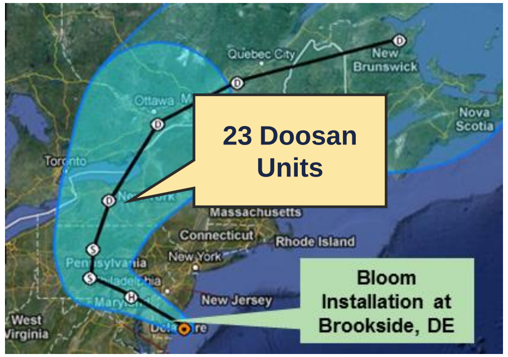
Demonstrated Resilience of Fuel Cells and Gas System

San Diego Blackout, 9/28/11

Winter Storm Alfred, 10/29/11

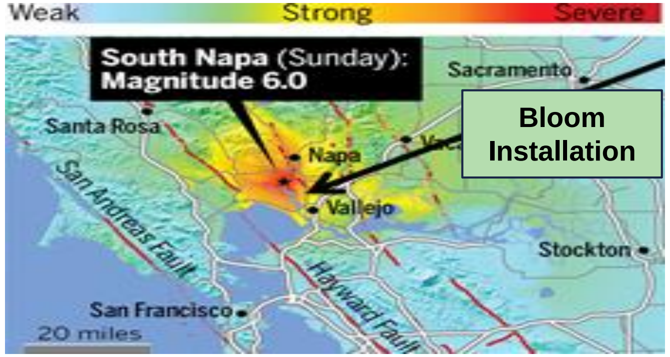
Hurricane Sandy, 10/29/12



23 Doosan Units

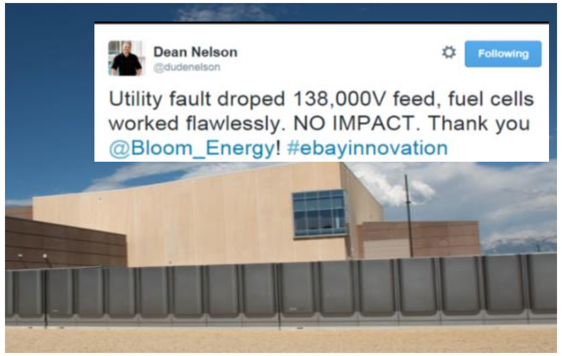
Bloom Installation at Brookside, DE

CA Earthquake, 8/24/14



Bloom Installation

Data Center Utility Outage, 4/16/15



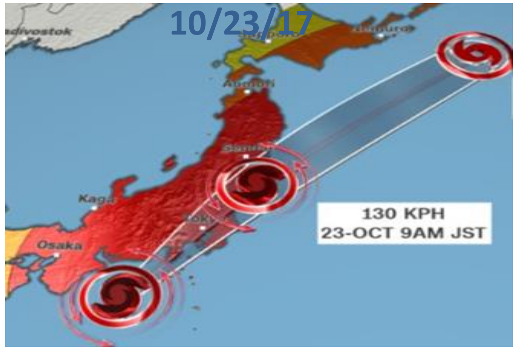
Dean Nelson
@dudenelson

Utility fault droped 138,000V feed, fuel cells worked flawlessly. NO IMPACT. Thank you @Bloom_Energy! #ebayinnovation

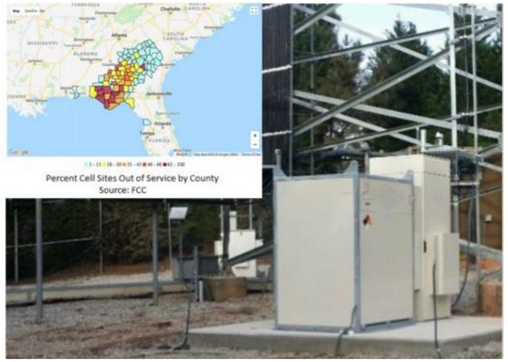
Hurricane Joaquin, 10/15/15

Napa Fire, 10/9/17

Japanese Super-Typhoon, 10/23/17

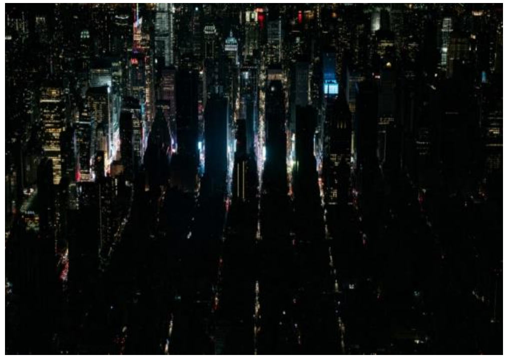


Hurricane Michael, 10/15/18

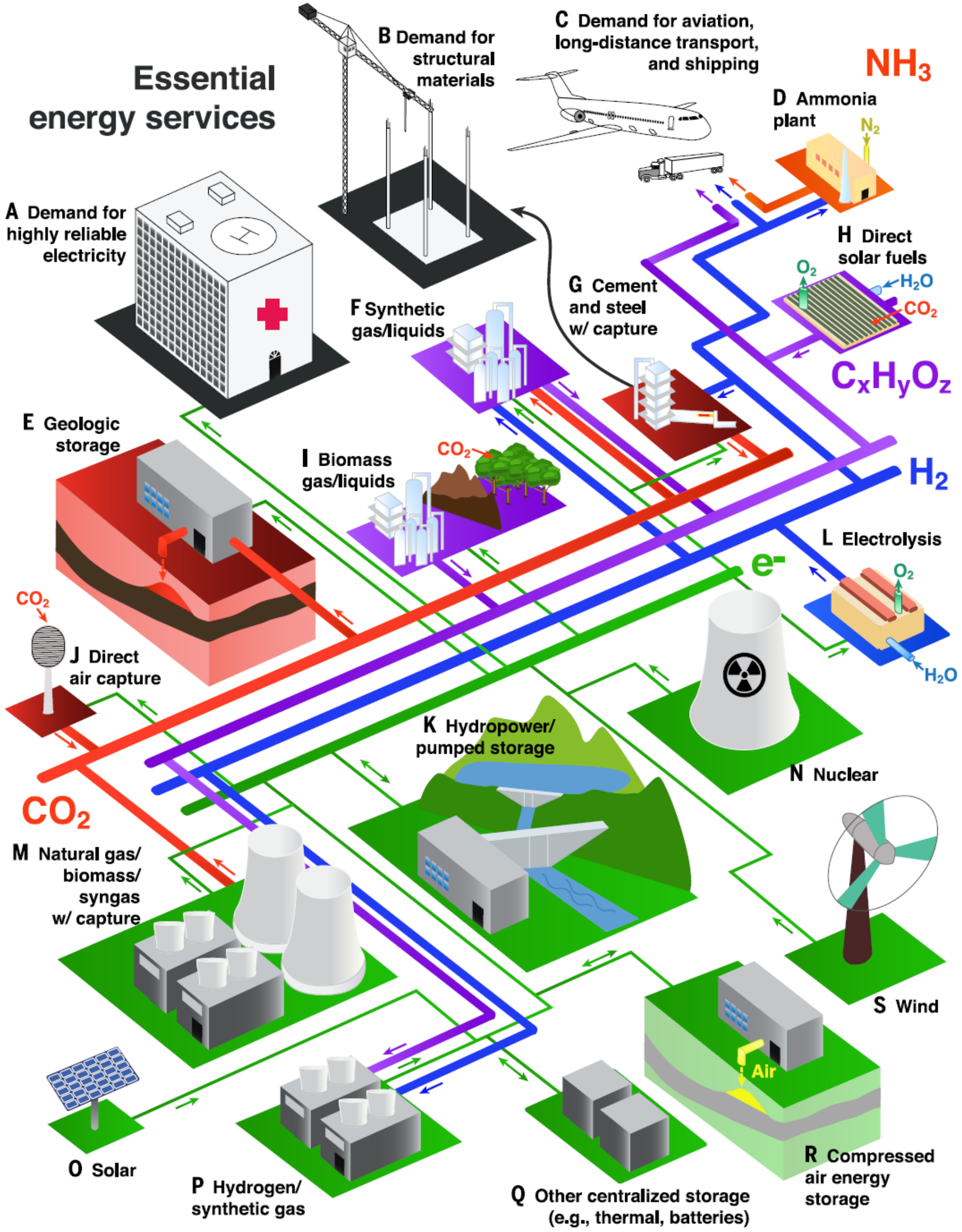


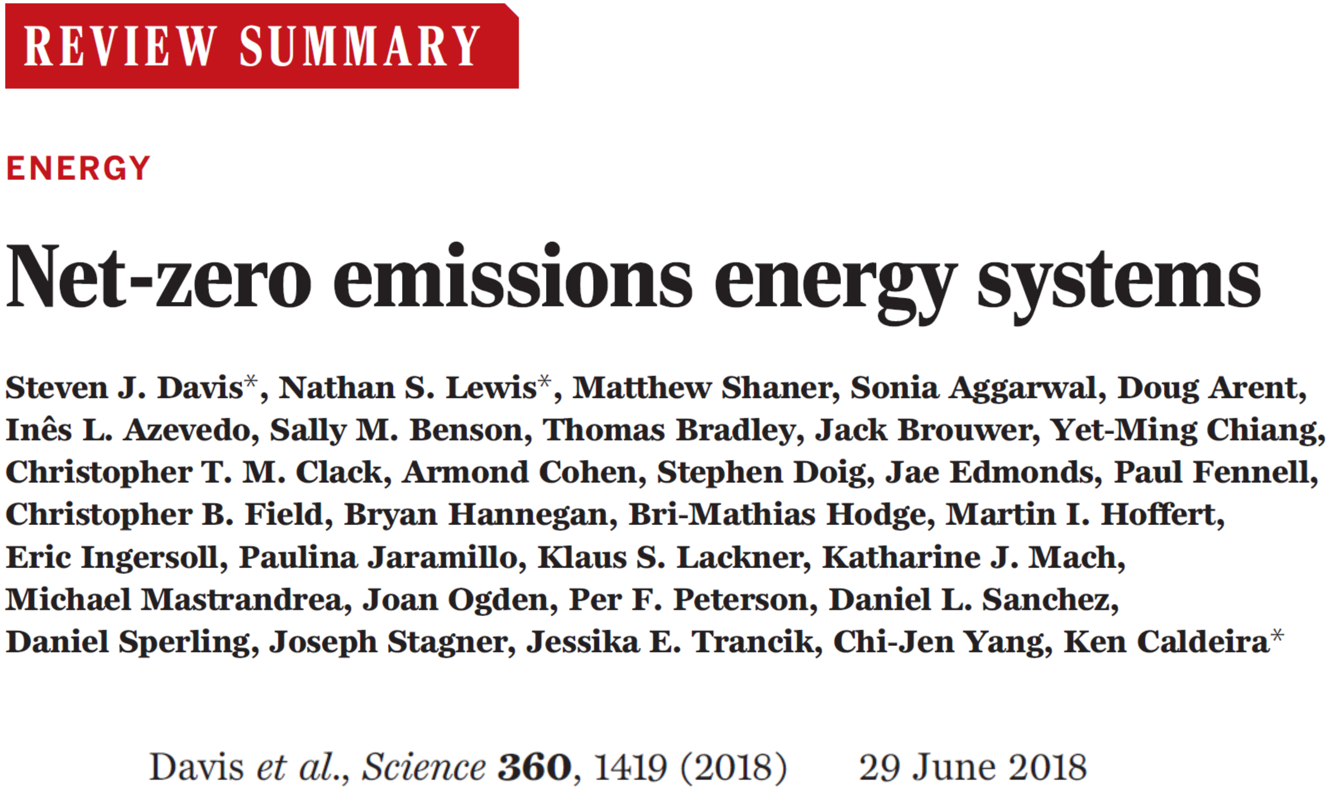
Ridgecrest Earthquakes, 7/4-5/19

Manhattan Blackout, 7/13/19



Why Hydrogen? Required for completely zero emissions





REVIEW SUMMARY

ENERGY

Net-zero emissions energy systems

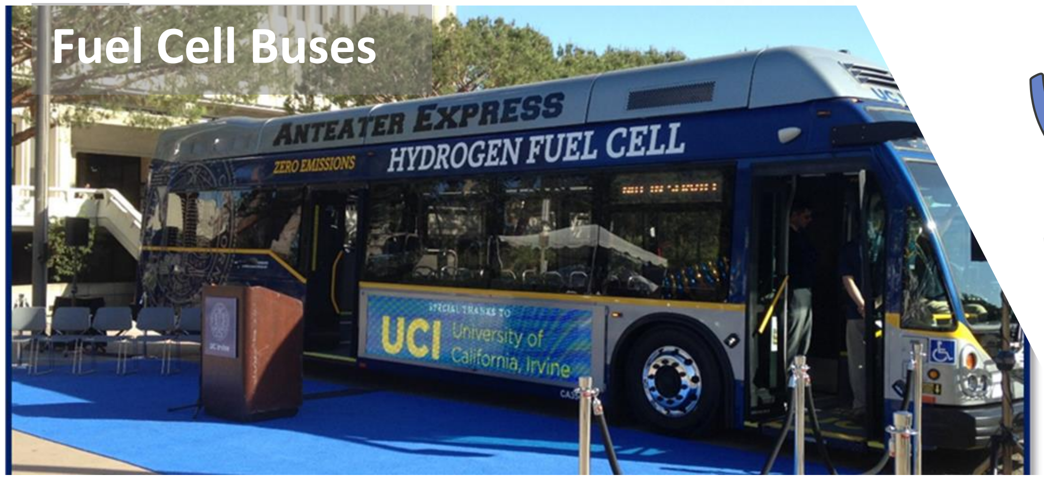
Steven J. Davis*, Nathan S. Lewis*, Matthew Shaner, Sonia Aggarwal, Doug Arent, Inês L. Azevedo, Sally M. Benson, Thomas Bradley, Jack Brouwer, Yet-Ming Chiang, Christopher T. M. Clack, Armond Cohen, Stephen Doig, Jae Edmonds, Paul Fennell, Christopher B. Field, Bryan Hannegan, Bri-Mathias Hodge, Martin 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

Why Hydrogen? Zero Emission Fuels Required

- Provide zero emissions fuel to difficult end-uses

Anything that requires (1) rapid fueling,
(2) long range,
(3) large payload



Toyota Fuel Cell:
Zero Emissions Big Rig

Why Hydrogen? Industry Requirements for Heat, Feedstock,

- Many examples of applications that cannot be electrified

Steel Manufacturing & Processing

Cement Production

(Photo: ABB Cement)

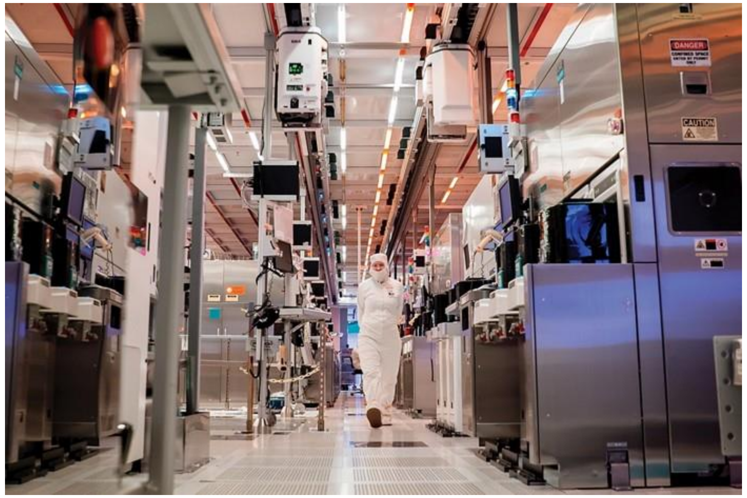
Plastics

(Photo: DowDuPont Inc.*)*

Ammonia & Fertilizer Production

(Photo: Galveston County Economic Development)

Computer Chip Fabrication



(Photo: American Chemical Society)

Pharmaceuticals

(Photo: Geosyntec Consultants)

Summary

- We must and will inevitably increasingly depend upon solar power and its more direct derivatives (e.g., wind)
  - Air quality
  - Greenhouse gas emissions & climate
  - Energy, environment, & geopolitical sustainability
  - Environmental Justice

- The DYNAMICS of such a future are challenging – require complementary dispatch, massive storage, and seasonal storage
  - Batteries, hydro, power-to-gas (P2G), hydrogen energy storage (HES)

- HYDROGEN will become the indispensable zero emissions fuel and energy storage medium to enable this future – unique features
  - Long duration energy storage
  - Massive energy storage amount
  - Hydrogen & its derivative fuels
  - Will be lower cost (separate power/energy scaling)
  - High round-trip efficiency possible
  - Reliability & resilience (underground infrastructure)

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Hydrogen 101 – Myths vs. Facts

Jack Brouwer

June 17, 2021

California Hydrogen Business Council
Webinar Series

Q&A

- Submit your question in the Q&A Panel on your right.

Dr. Jack Brouwer
Director, National Fuel Cell Research Center, UC Irvine
Director, Advanced Power and Energy Program, UC Irvine
Professor of Mechanical and Aerospace Engineering

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