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NATIONAL FUEL CELL RESEARCH CENTER

Can Energy Conversion be 100% Zero Emissions?

Midwest Hydrogen Summit

from: San Diego Union Tribune

Prof. Jack Brouwer, Ph.D., Director

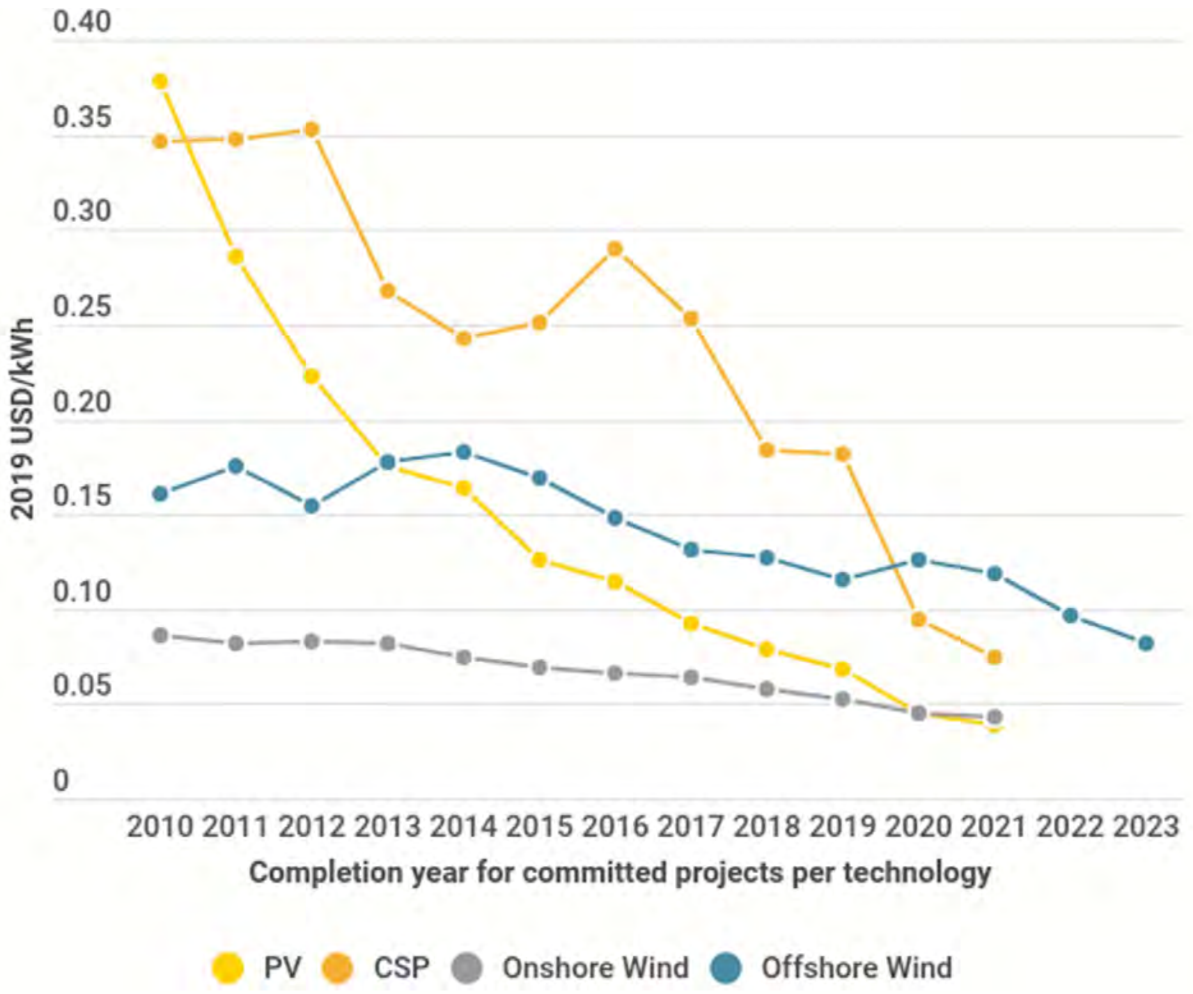
July 7, 2022

Adopt More Solar & Wind and Use It Directly

We must increasingly adopt energy conversion that is sustainable & naturally replenished quickly

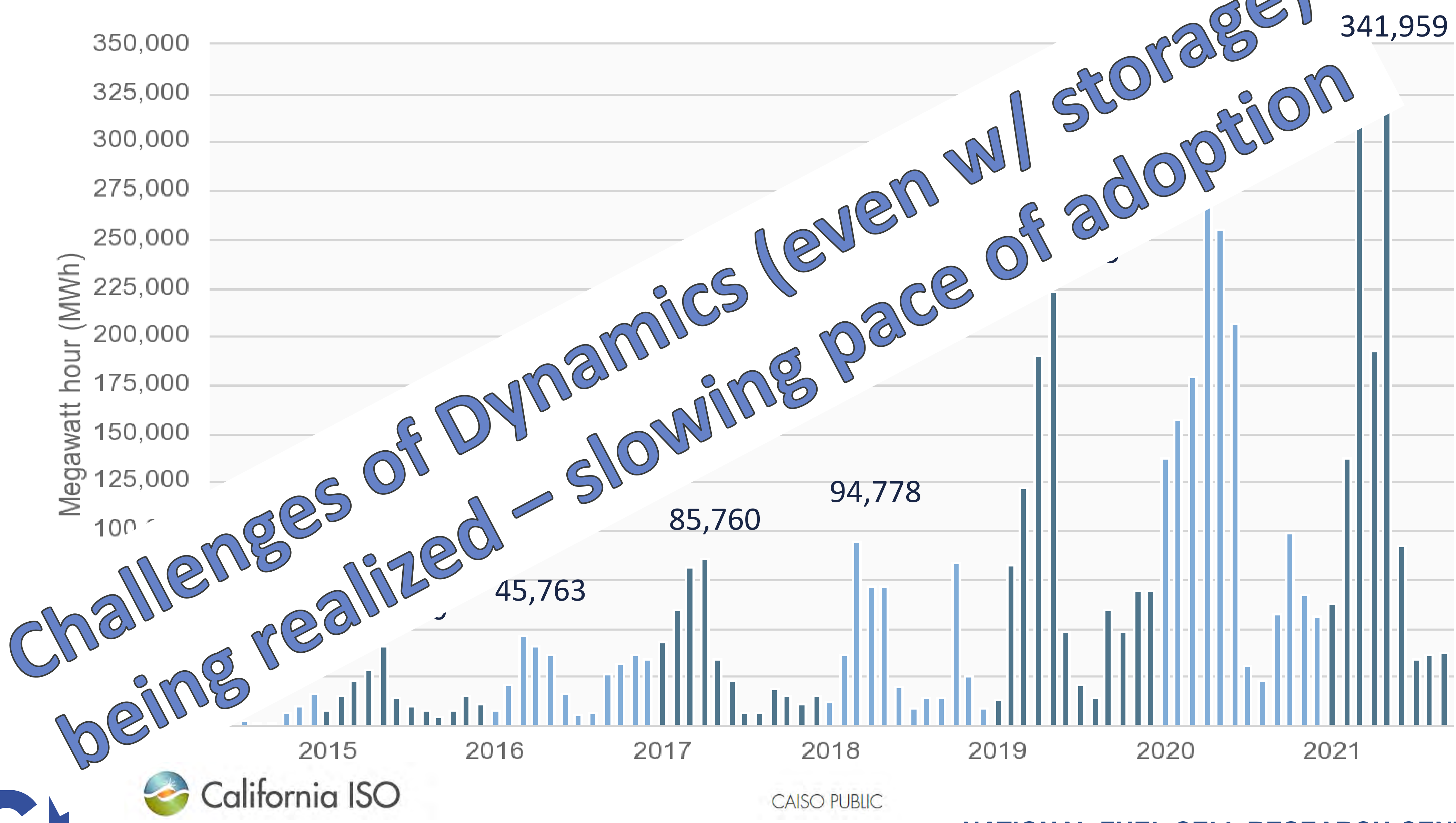
<u>Good News!</u>

- Widely & equitably available around world
- Now typically cheapest form of primary energy
- Electrify all amenable end-uses
- Control loads to match renewable dynamics



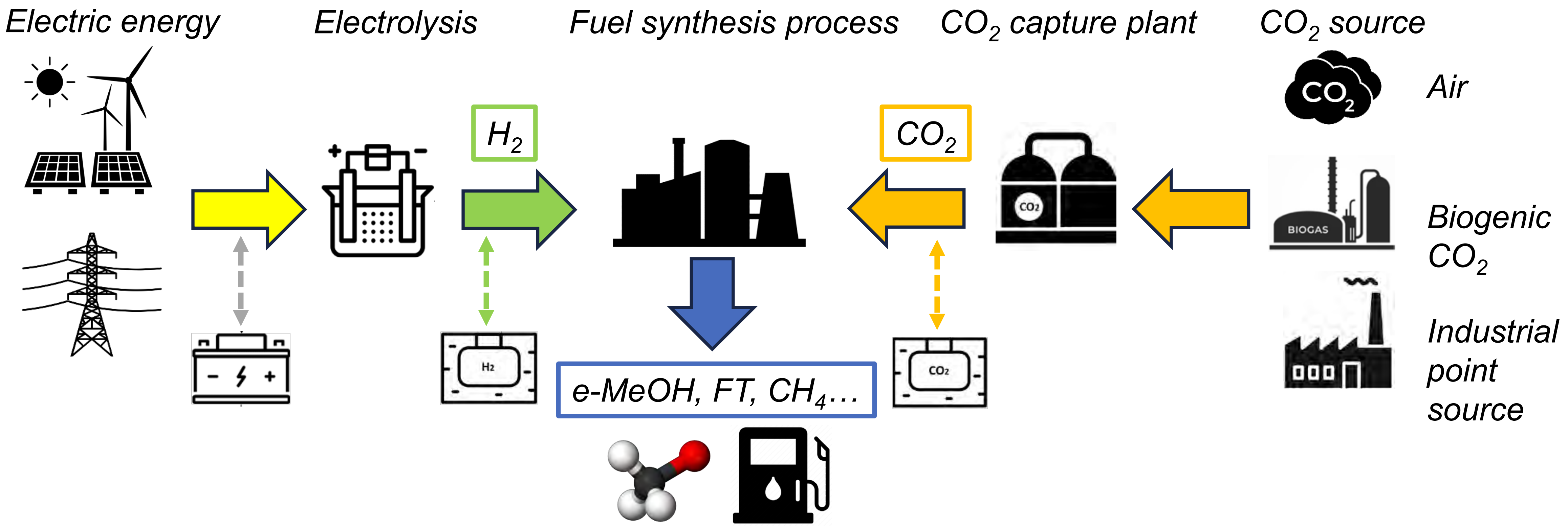
From: IRENA, www.irena.org/newsroom/pressreleases/2020/Jun , 2020

High Renewable Use is Challenging (Curtailmen... CA)



Then Use E-Fuels & Renewable Fuels

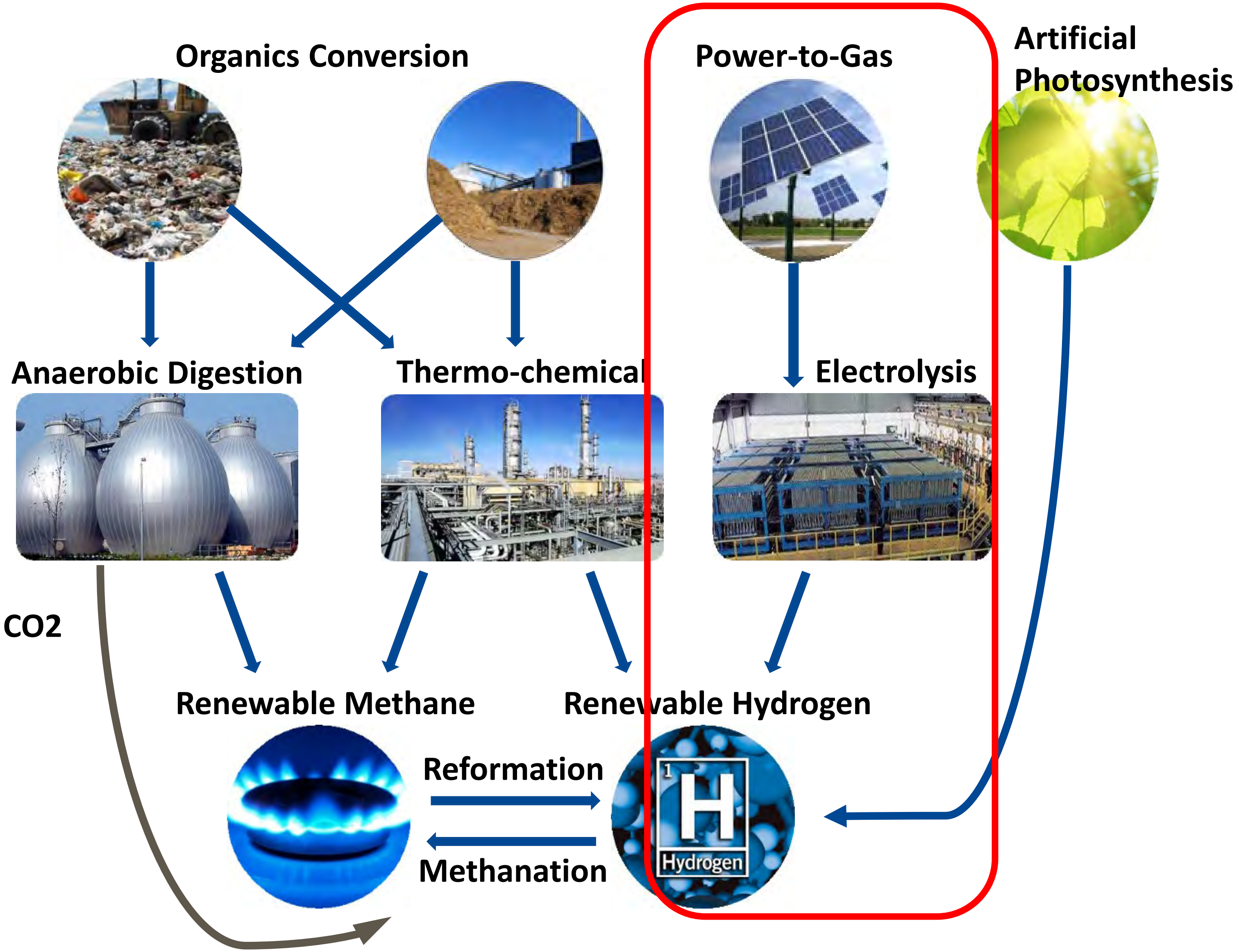
- e-fuels: synthetic fuels produced from electricity
- Each process has a certain efficiency (loss of energy)



From: Matteo Romano, Politécnico di Milano, 2022

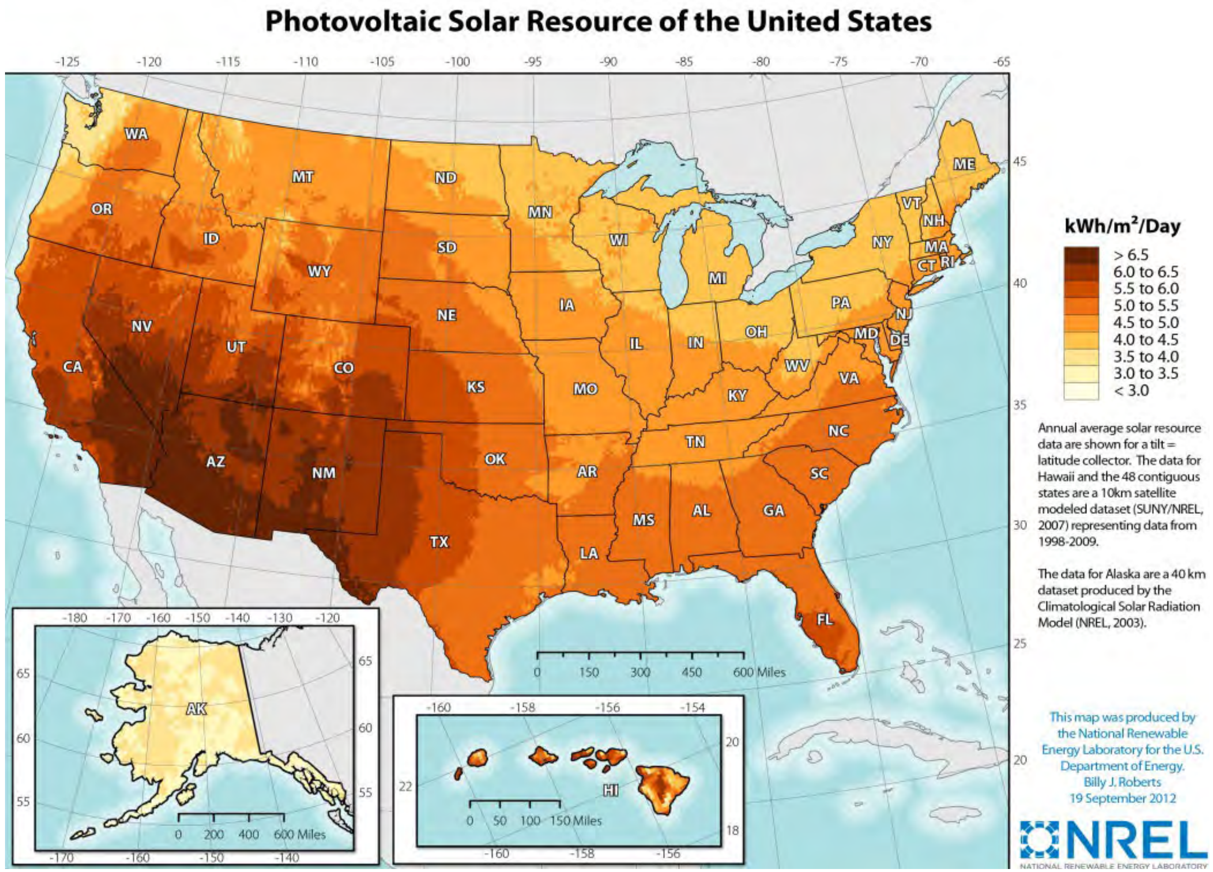
Renewable and Zero-carbon Gaseous Fuel Pathways

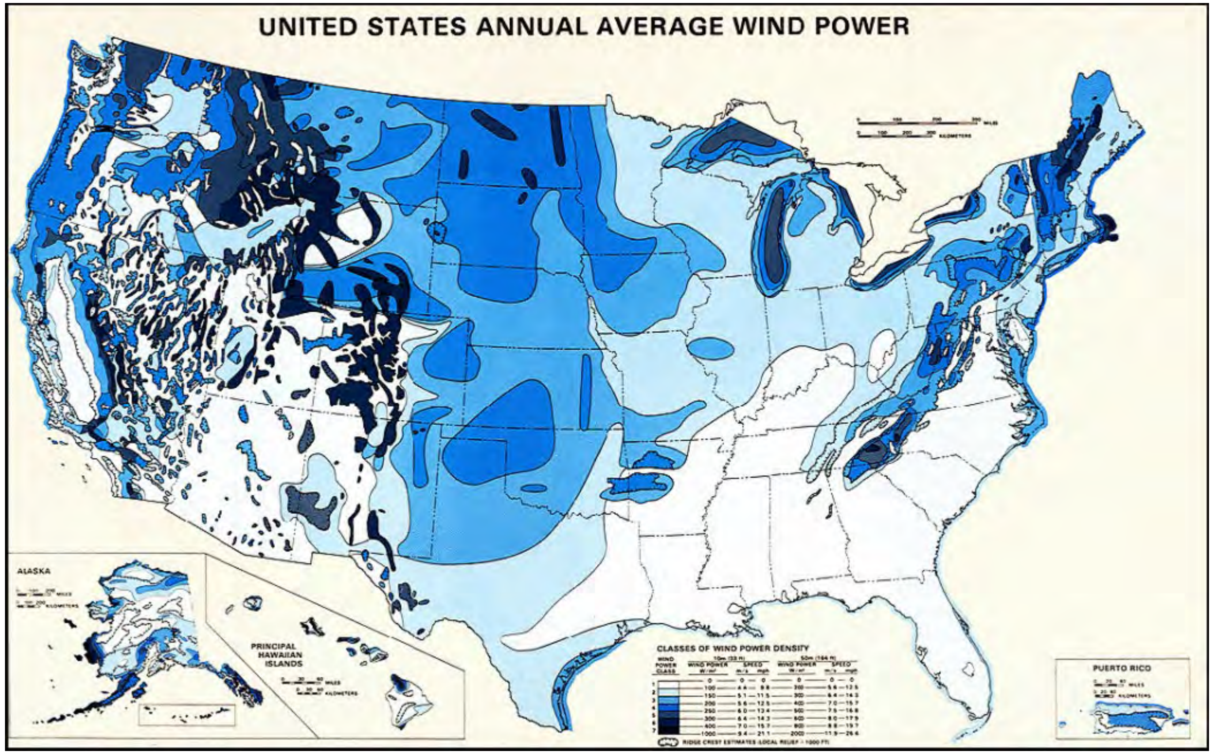
- "**Green**" in the traditional sense of environmentally sensitive, sustainable and desirable



Solar & Wind Power – most widely available resources

- Renewable future will be more equitable all around the world

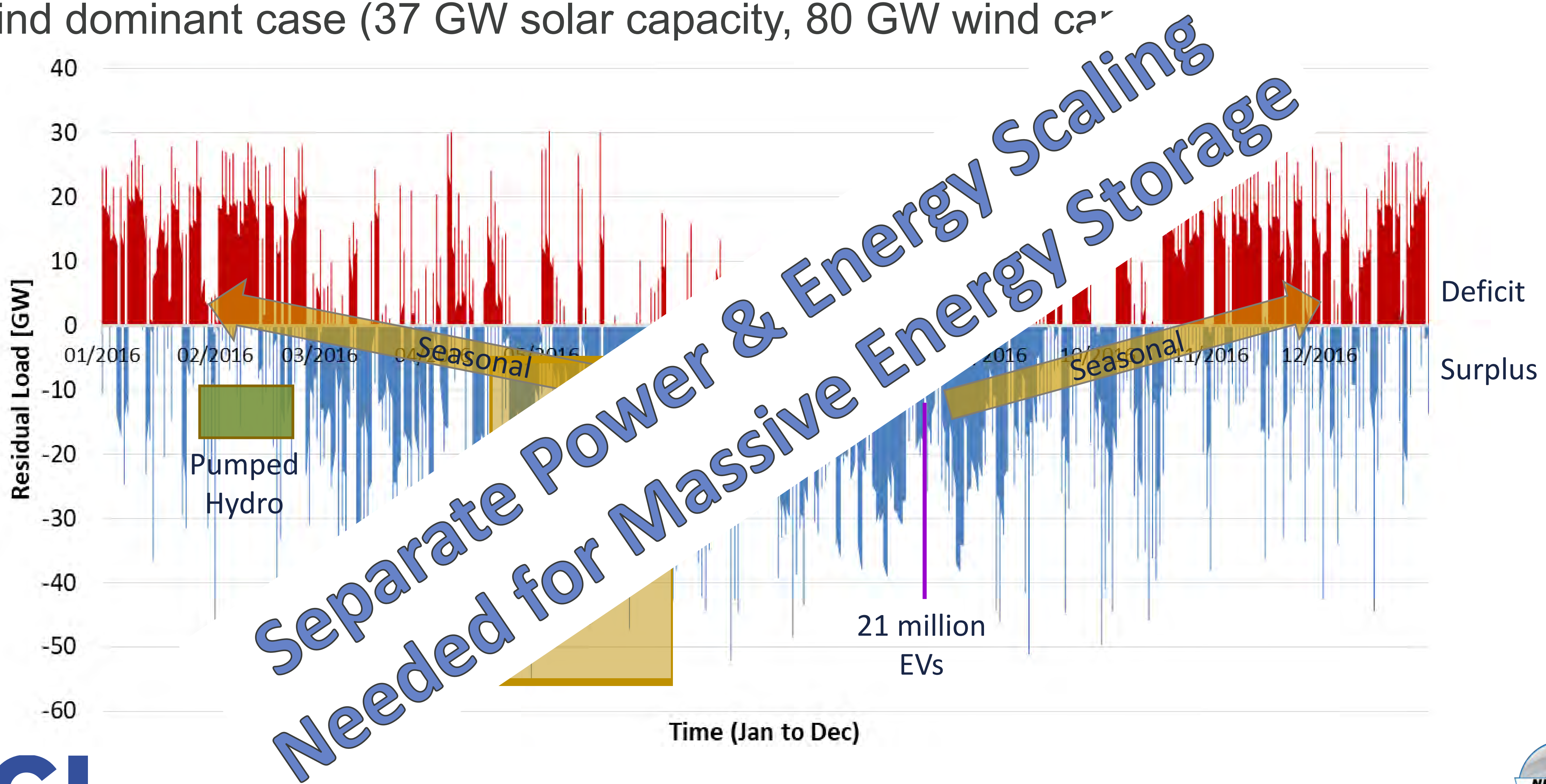




NREL, 2018

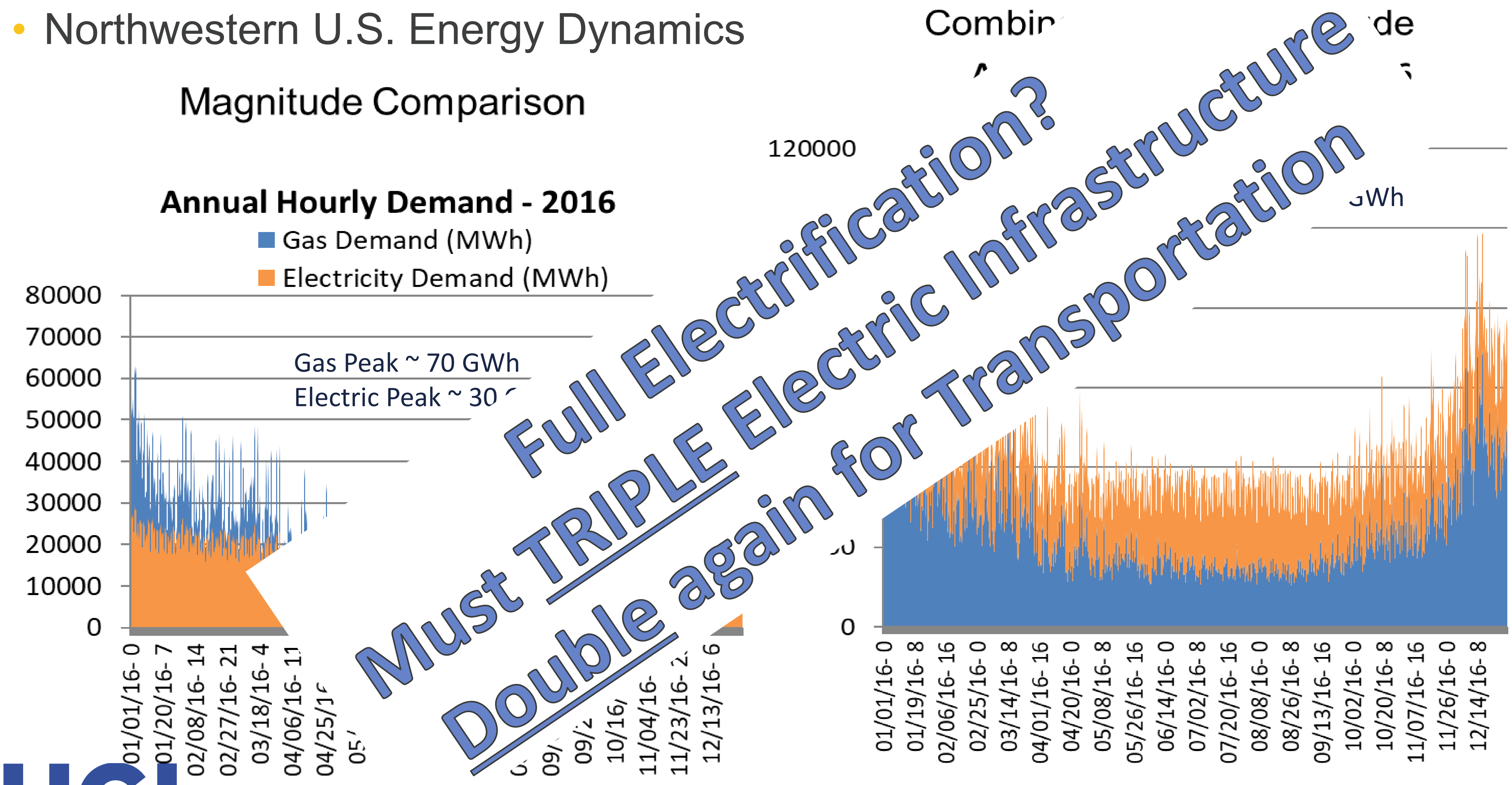
Dynamics of Renewable Future are Challenging

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



We Must Transform the Gas System

- Northwestern U.S. Energy Dynamics



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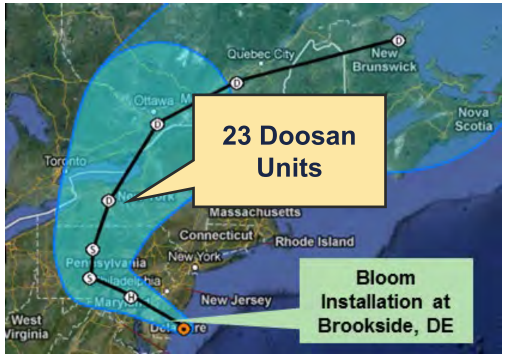
Demonstrated Resilience of Fuel Cells and Gas System

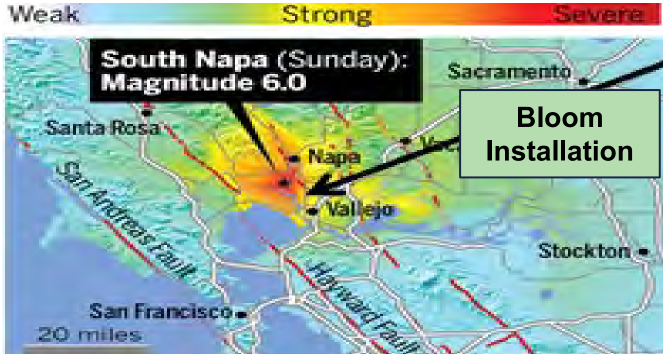
San Diego Blackout, 9/28/11

Winter Storm Alfred, 10/29/11

Hurricane Sandy, 10/29/12



CA Earthquake, 8/24/14



Data Center Utility Outage, 4/16/15

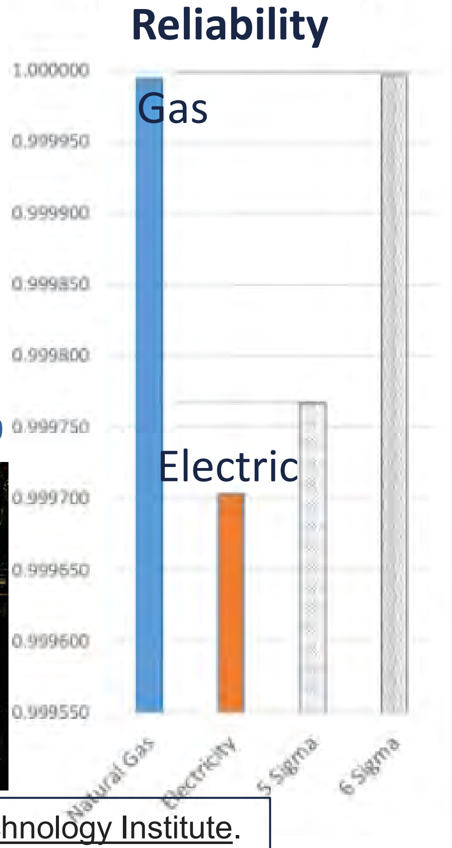
Hurricane Joaquin, 10/15/15

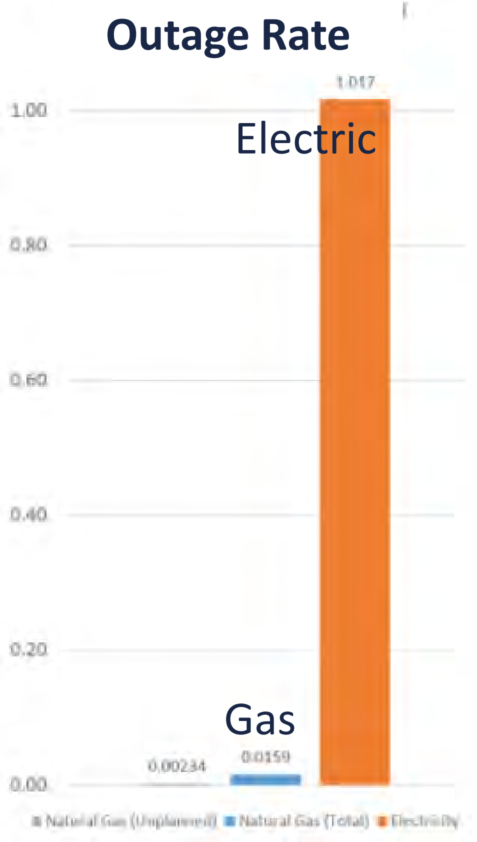
Napa Fire, 10/9/17

Hurricane Michael, 10/15/18

Ridgecrest Earthquakes, 7/4-5/19

Manhattan Blackout, 7/13/19





Liss, W., & Rowley, P. (2018). *Assessment of natural gas and electric distribution service reliability*. Gas Technology Institute.

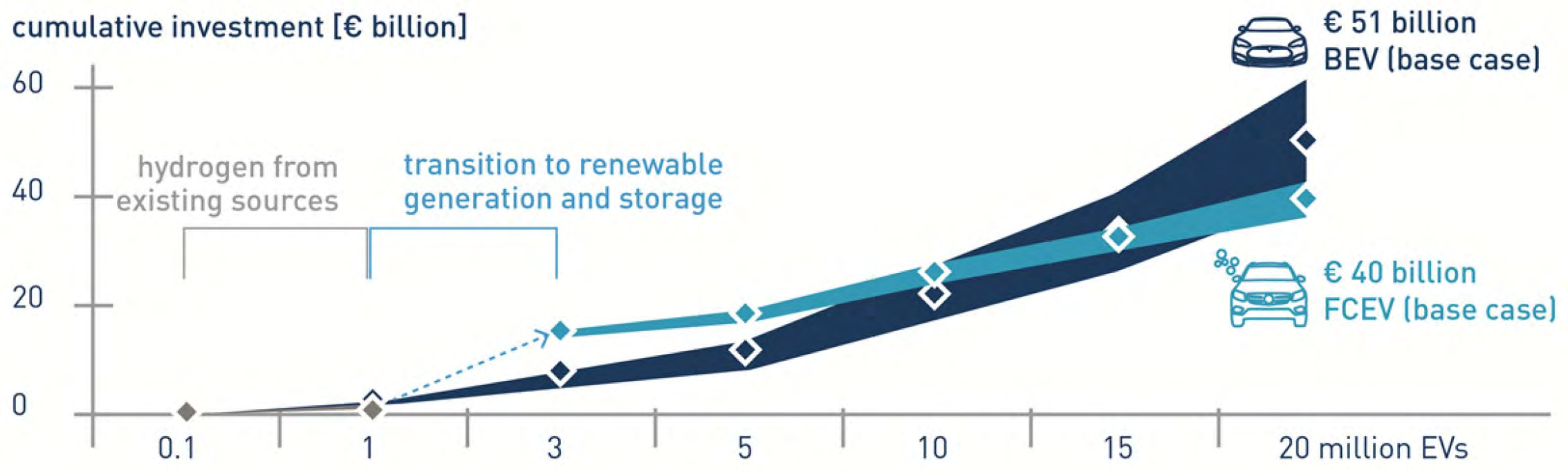
Why Hydrogen? Zero Emission Fuels Required

- Provide zero emissions fuel to difficult end-uses

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

Infrastructure Limits Require both FCEV & BEV

Comparative Analysis of Infrastructures: H2 & FCEV vs. Grid & BEV



Robinius, Martin, Jochen Franz Linßen, Thomas Grube, Markus Reuß, Peter Stenzel, Konstantinos Syranidis, Patrick Kuckertz, and Detlef Stolten. *Comparative analysis of infrastructures: hydrogen fueling and electric charging of vehicles*. Forschungszentrum Jülich GmbH, Zentralbibliothek, Verlag, 2018.

Why Hydrogen? Industry Requirements for Heat, Feedstock,

- Many examples of applications that cannot be electrified

Steel Manufacturing & Processing

Cement Production

(Photo: ABB Cement)

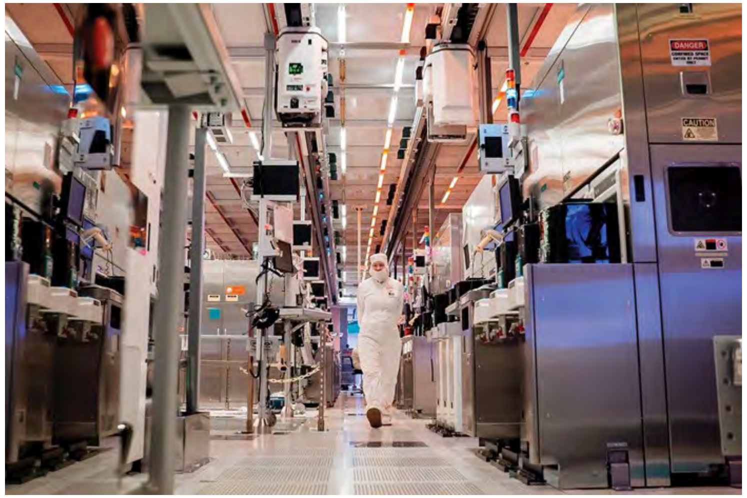
Plastics

(Photo: DowDuPont Inc.*)*

Ammonia & Fertilizer Production

(Photo: Galveston County Economic Development)

Computer Chip Fabrication



(Photo: American Chemical Society)

Pharmaceuticals

(Photo: Geosyntec Consultants)

Solid Oxide Electrolysis Cells (SOEC) integrated with Direct Reduced Iron (DRI) plants for producing green steel

Luca Mastropasqua, Jack Brouwer

http://www.apep.uci.edu/H2GS/

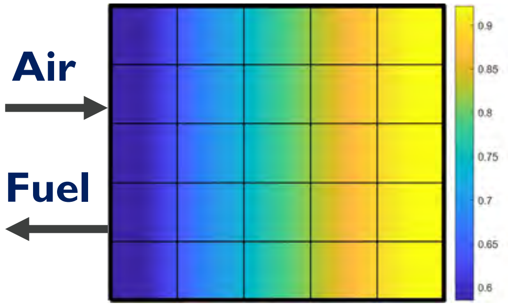
H2GS

UCI ADVANCED POWER AND ENERGY PROGRAM

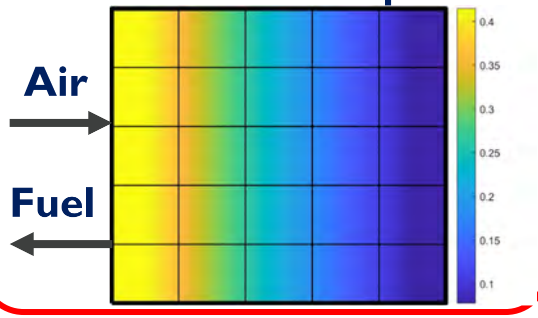
Hydrogen Direct Reduction (HDR) of Steel

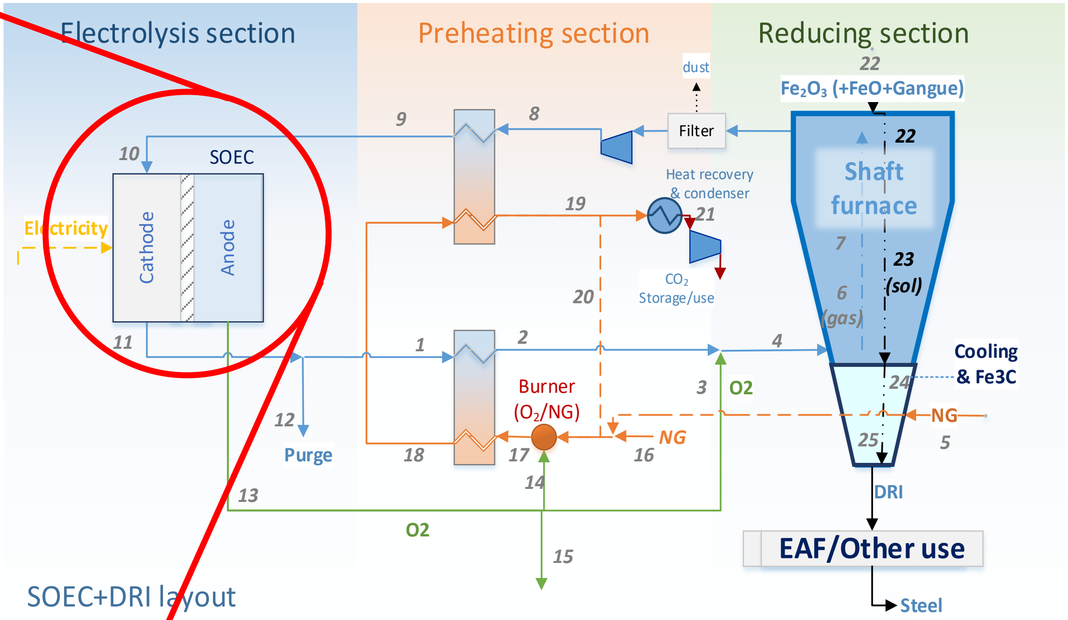
- Voltage = 1.206 V
- Current Density = 829 A/m2
- Operating Power = 495 MW
- Steam Utilization = 0.8936
- Pressure = 7 bar
- Efficiency = 95%

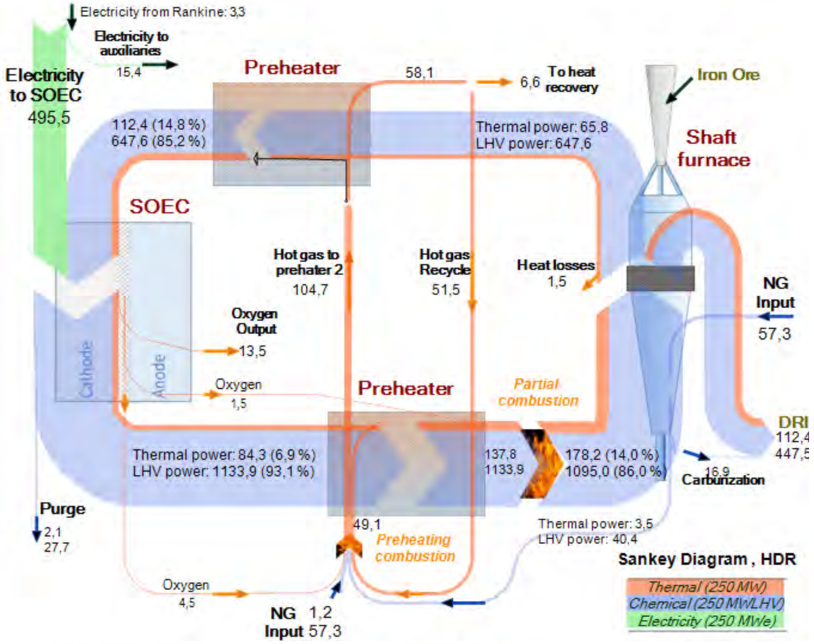
Hydrogen map



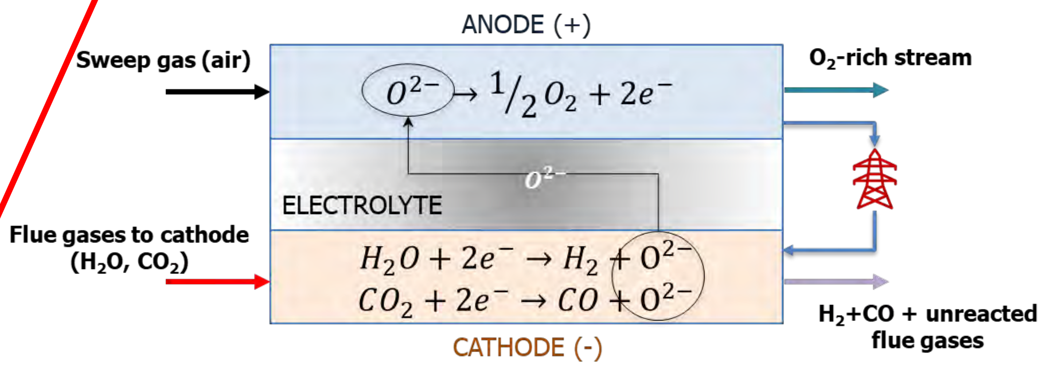
Steam map

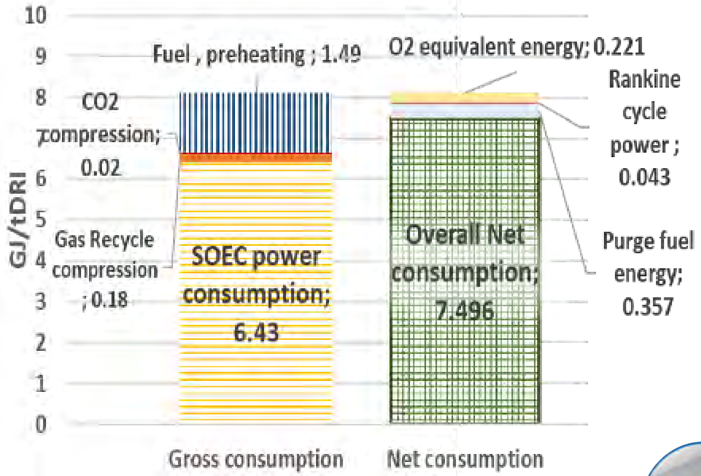






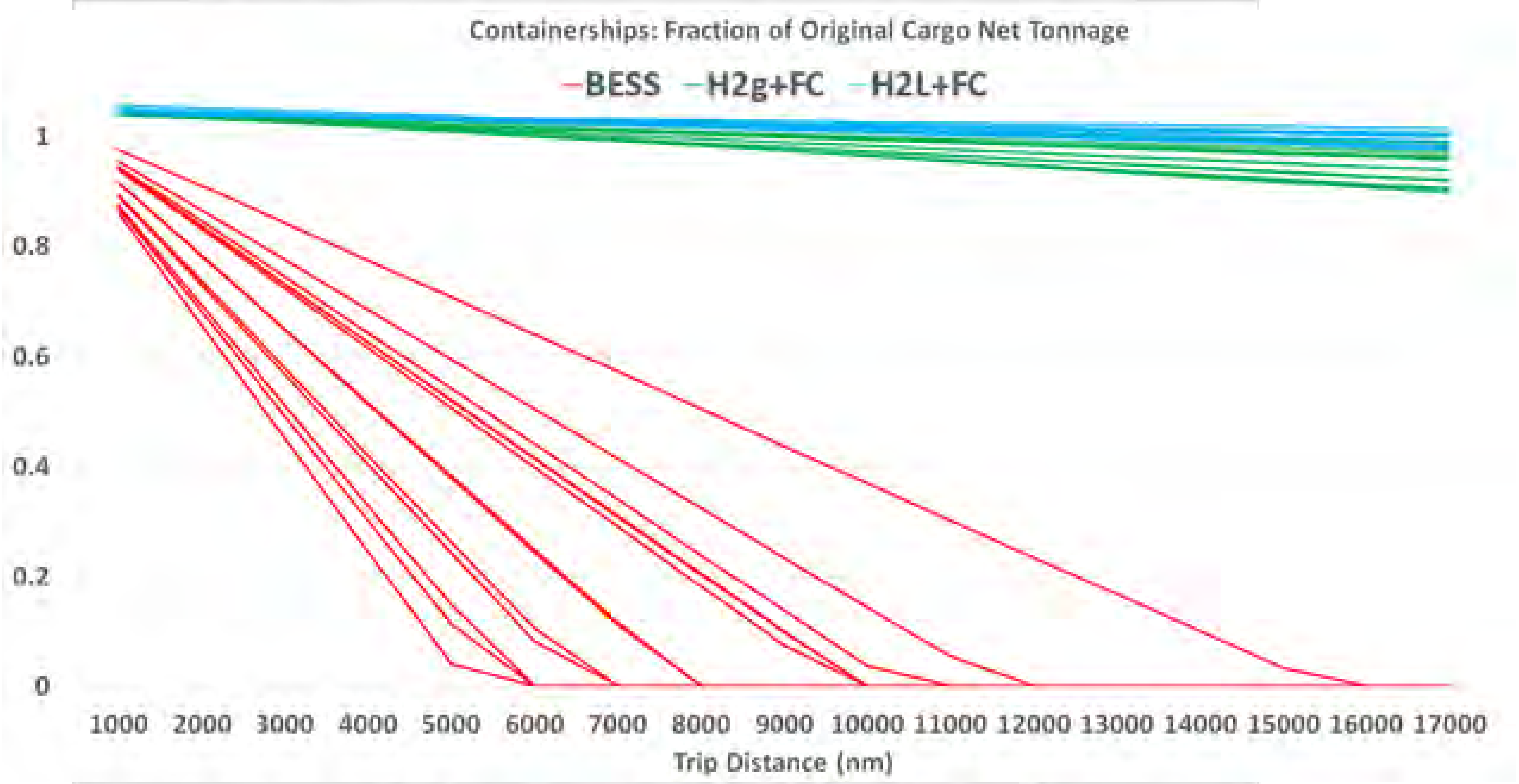
Steam and co-electrolysis





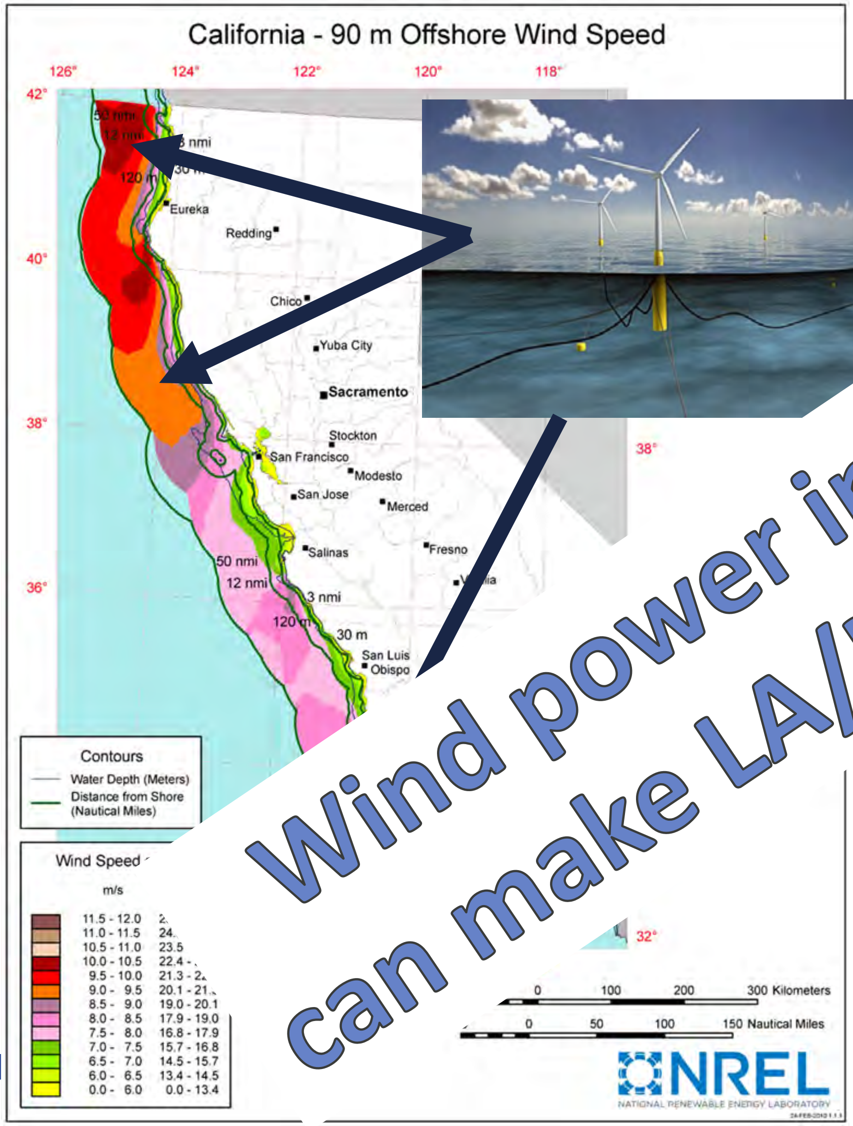
Decarbonization of Ships & Ports

Batteries compared to Hydrogen & Fuel Cells for Container Ships



Decarbonization of Ships & Ports

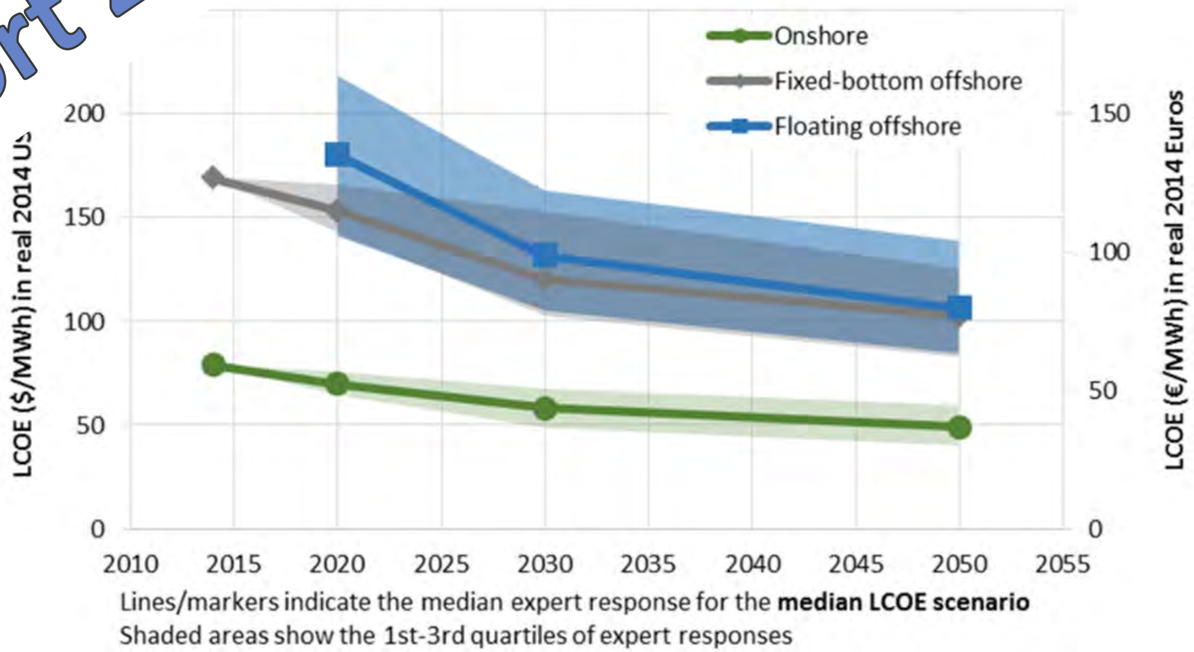
All ships, trains, & trucks through LA/LB Port: 8.89M tons '



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

The C… …nous resource for … energy!

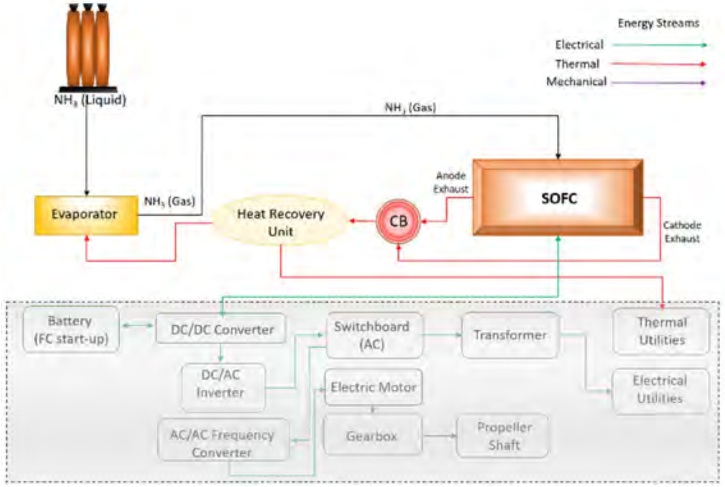
…perts anticipate significant cost …ns in offshore wind technology:

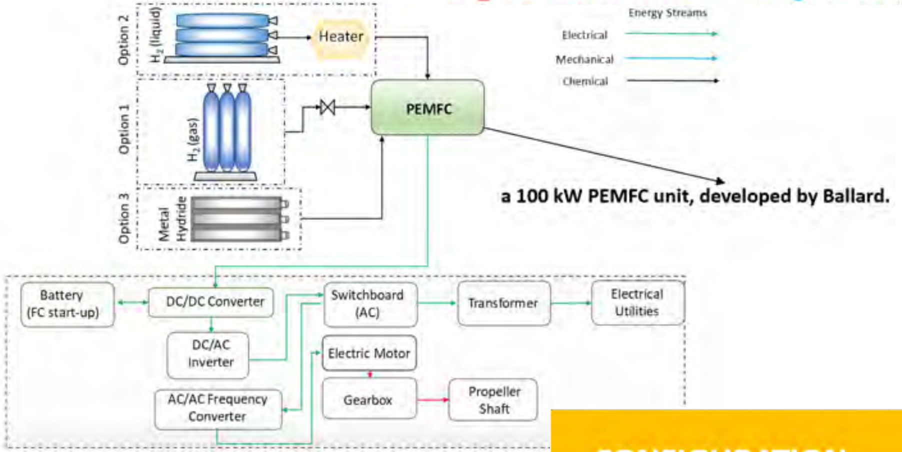


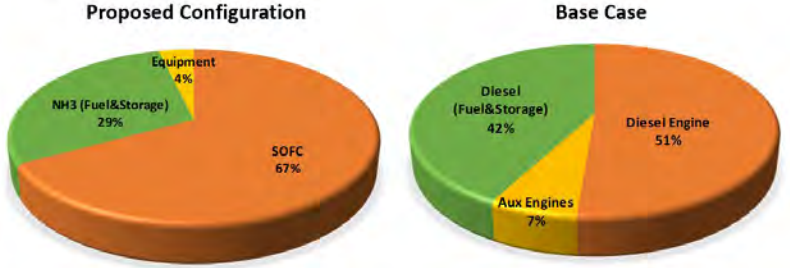
Physical Modeling of Ships

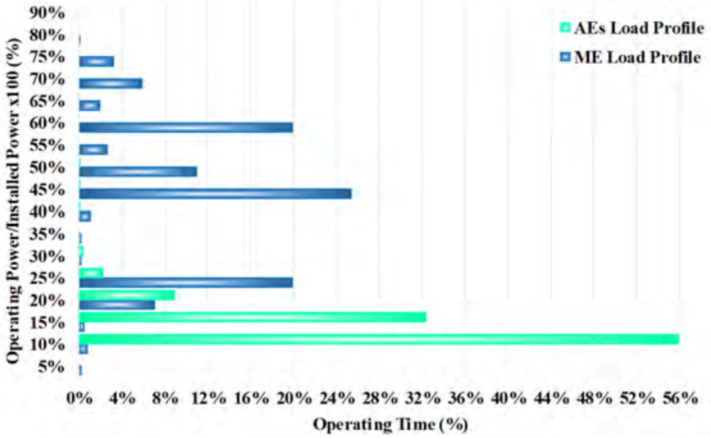
- Collaboration w/ U. Naples-Parthenope

H_2-based PEMFC | NH_3-based PEMFC | NH_3-H_2 based ENGINE | NH_3-based SOFC









CONFIGURATION	FUEL AND STORAGE WEIGHT (TONS)				CARGO REDUCTION			
H_2-based PEMFC	LH2	GH2 (350 bar)	GH2 (700 bar)	MH	LH2	GH2 (350 bar)	GH2 (700 bar)	MH
	353.5	896.7	810.3	4369.3	0.1%	1.3%	1.1%	9%
NH3-based PEMFC with Pd-Membrane	852.3				1.6%			
NH3-based PEMFC with PSA as purification system	872.8				1.3%			
NH3-H2 based ENGINE with H2 STORED on-board	NH3-LH2	NH3-GH2 (350 bar)	NH3-GH2 (700 bar)		NH3-LH2	NH3-GH2 (350 bar)	NH3-GH2 (700 bar)	
	590.1	721.1	712.2		0.8%	1.08%	1.06%	
NH3-H2 based ENGINE with H2 PRODUCED on-board	Pd-Membrane	PSA			Pd-Membrane	PSA		
	706.5	711.3			1.4%	1.09%		
NH_3-based SOFC	244				2.88%*			

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Light Water Reactor Integrated Energy Systems Hydrogen End Use Demonstration

Pathway 1 - First of a Kind Nuclear Demonstration Readiness Projects

Luca Mastropasqua, Jack Brouwer

Project Goal

- U.S. light water reactor (LWR) nuclear power plants (NPP) comprise 8.5% of electric generation capacity
- But … these provide 20% of all U.S. electric power – carbon free
- Transition to flexible operation of LWR NPP may reduce economic viability

Support the advancement of integrated low temperature electrolysis (LTE) and high temperature electrolysis (HTE) at commercial NPPs, as well as increase the scale of integrated hydrogen generation at nuclear plants

Demonstrate end uses of hydrogen as part of an integrated energy system that provides responsive load that **minimizes** or alleviates demand for nuclear plant **curtailment**

During high demand periods hydrogen can be used to generate additional power, or it can provide market value as an **energy vector**, through its synthesis into value-added non-electric energy products

Water Use for Hydrogen via Electrolysis

- Future "Hydrogen Economy" uses less water than current fossil fuel energy conversion economy
- Anecdotes:
  - All Southern California cars could be powered by less than 1% of CA aqueduct flow
  - Any home could be hydrogen powered with 1 additional toilet flush (1.6 gallons) / day

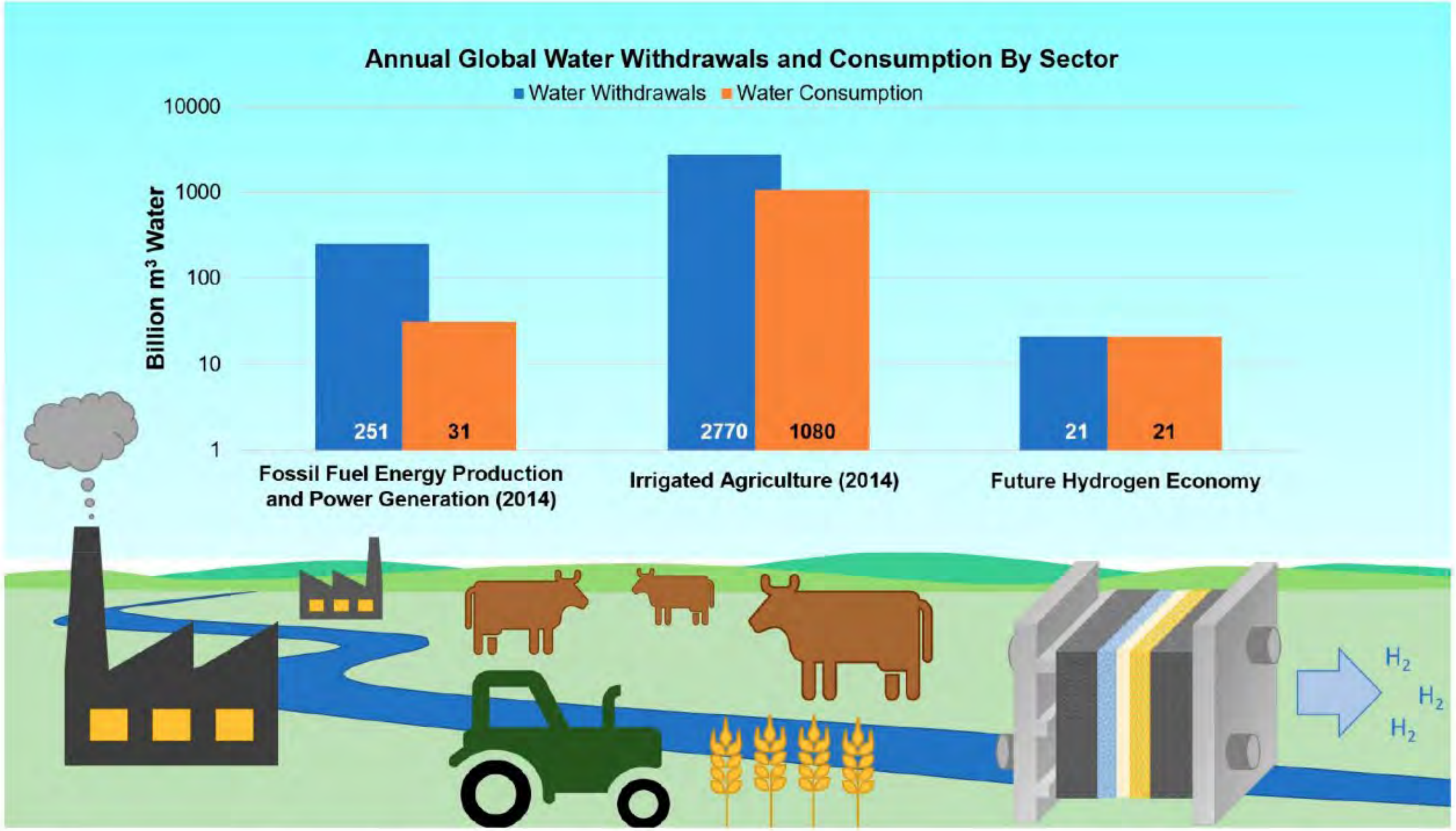

Figure 1. Comparison of the global freshwater withdrawal and consumption of three different sectors: fossil fuel energy production and power generation, agriculture, and the implementation of a global hydrogen economy. Note that the bar chart is on a log scale.[3,5]

Rebecca R. Beswick, Alexandra M. Oliveira, and Yushan Yan, *ACS Energy Letters* **2021** *6* (9), 3167-3169, DOI: 10.1021/acsenergylett.1c01375

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Water Use for Hydrogen via Electrolysis

- Amount of water is not a problem

Water Consumption for Green Hydrogen

… "The water consumption of electricity gen ossil electricity compared to solar and wind power … Us olytic hydrogen has an overall water consumption of ~130 l hydrogen production powered by solar or wind has a gH_2 (Shi et al., 2020). With a 30 L/kgH_2 water consumption Mt/yr demand for hydrogen using green H_2 would consu which is three orders of magnitude less than global freshw ion m^3/yr (UNESCO, 2019), making the water footprint of g gible from a global perspective."

resh water to produce hydrogen (Bhardwaj et al. 2021;

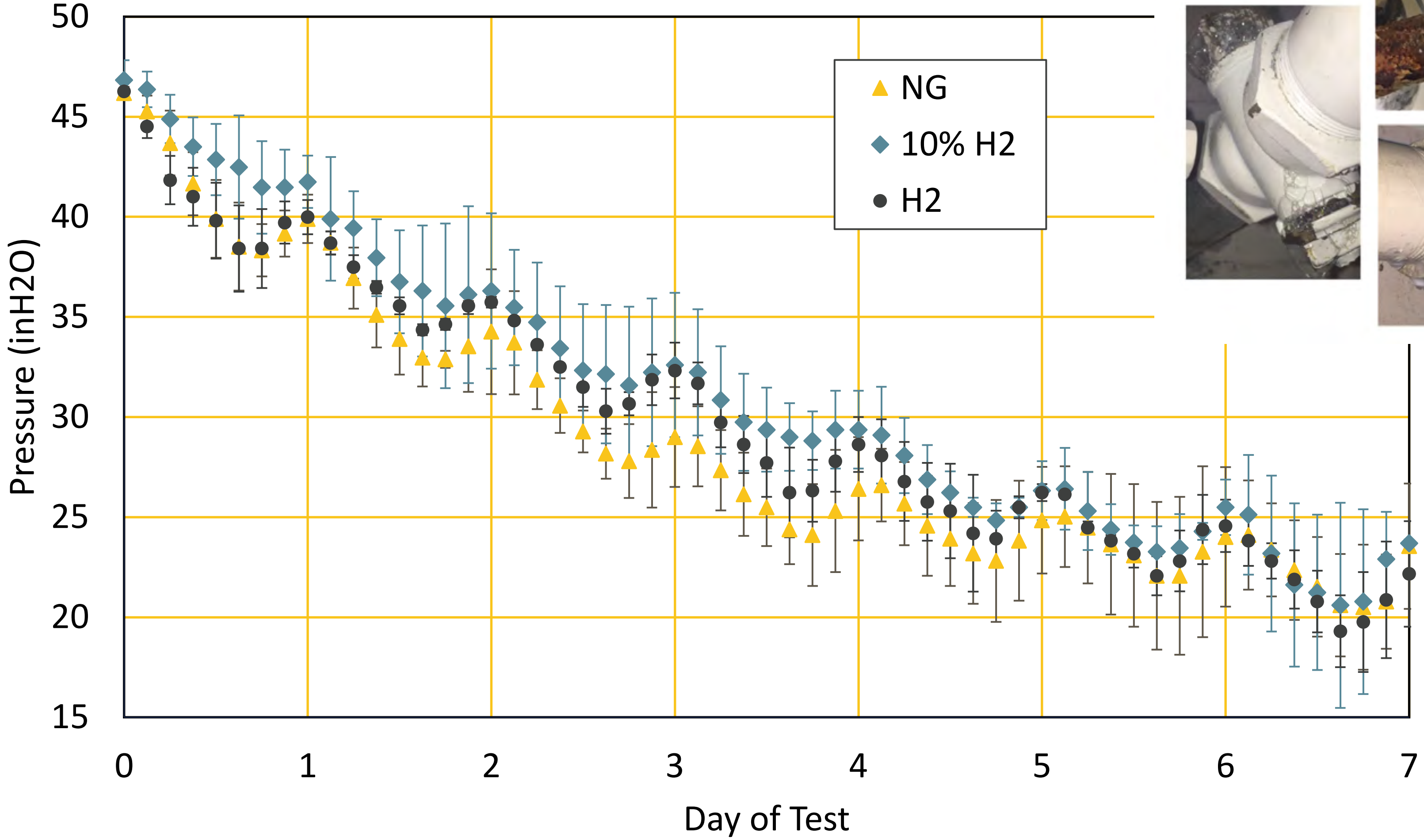
Challenges remain w.r.t. locations of water availability & distributed/desert environments of renewables

, E., Braverman, S., Lou, Y., Smith, G., Bhardwaj, er, J., McCormick, C. and Friedmann, J., 2021. hydrogen in a circular carbon economy: Opportunities nd limits. *Columbia Center for Global Energy Policy*.

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



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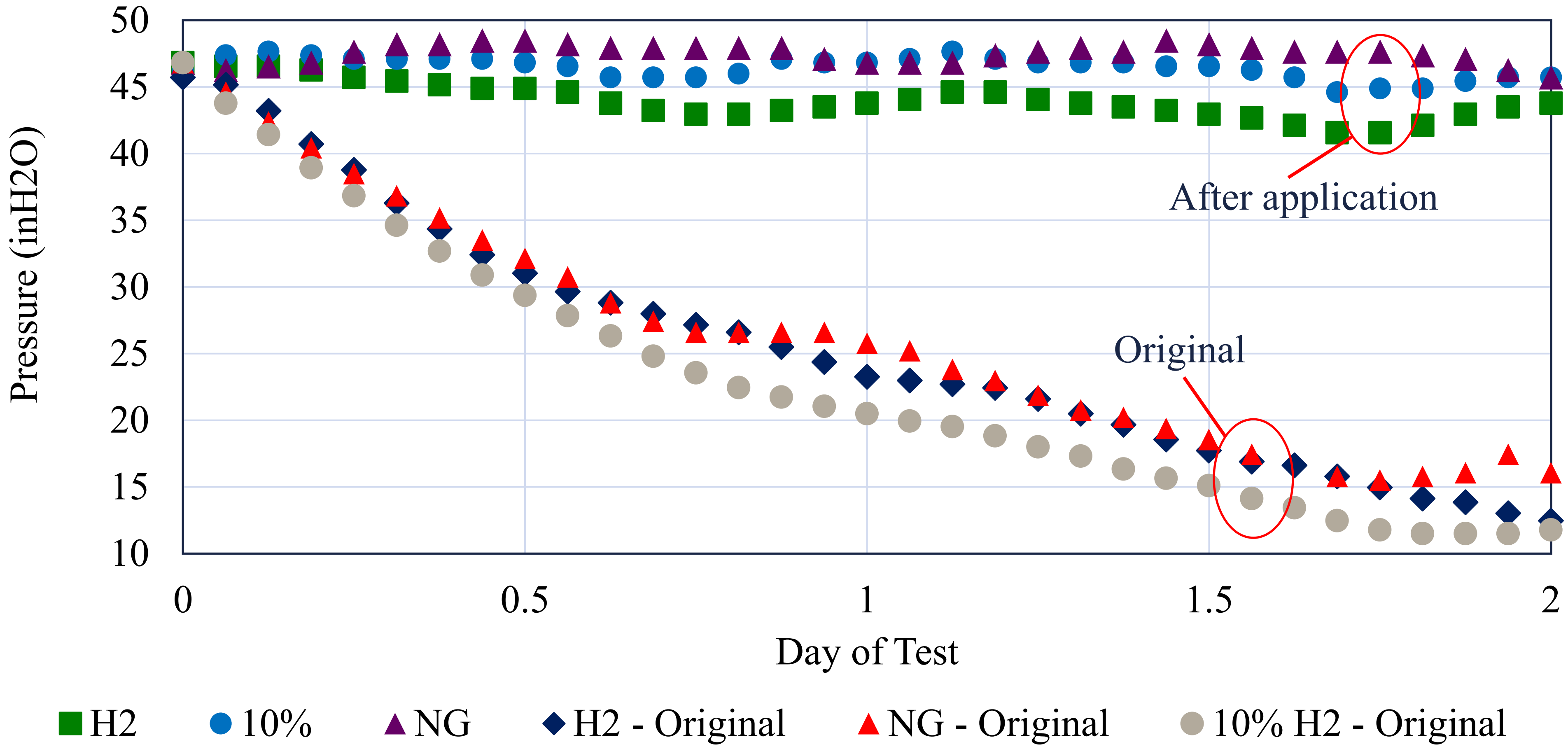
H_2 leakage from NG Infrastructure

H2 injection into existing natural gas infrastructure (low pressure)

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



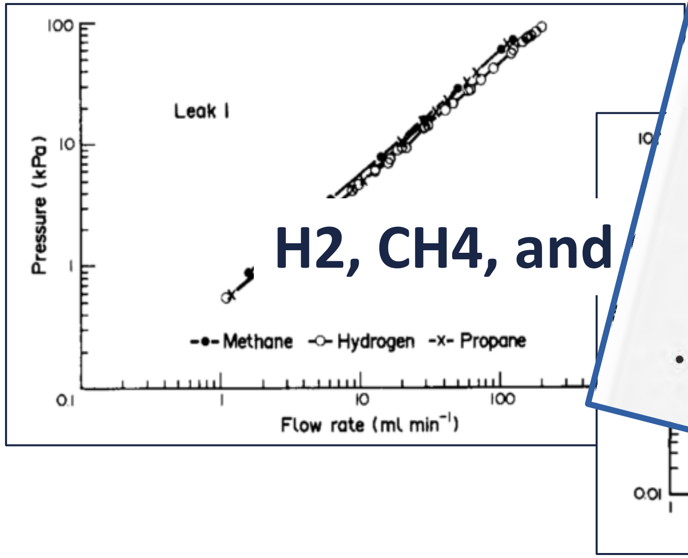
H_2 leakage from NG Infrastructure

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

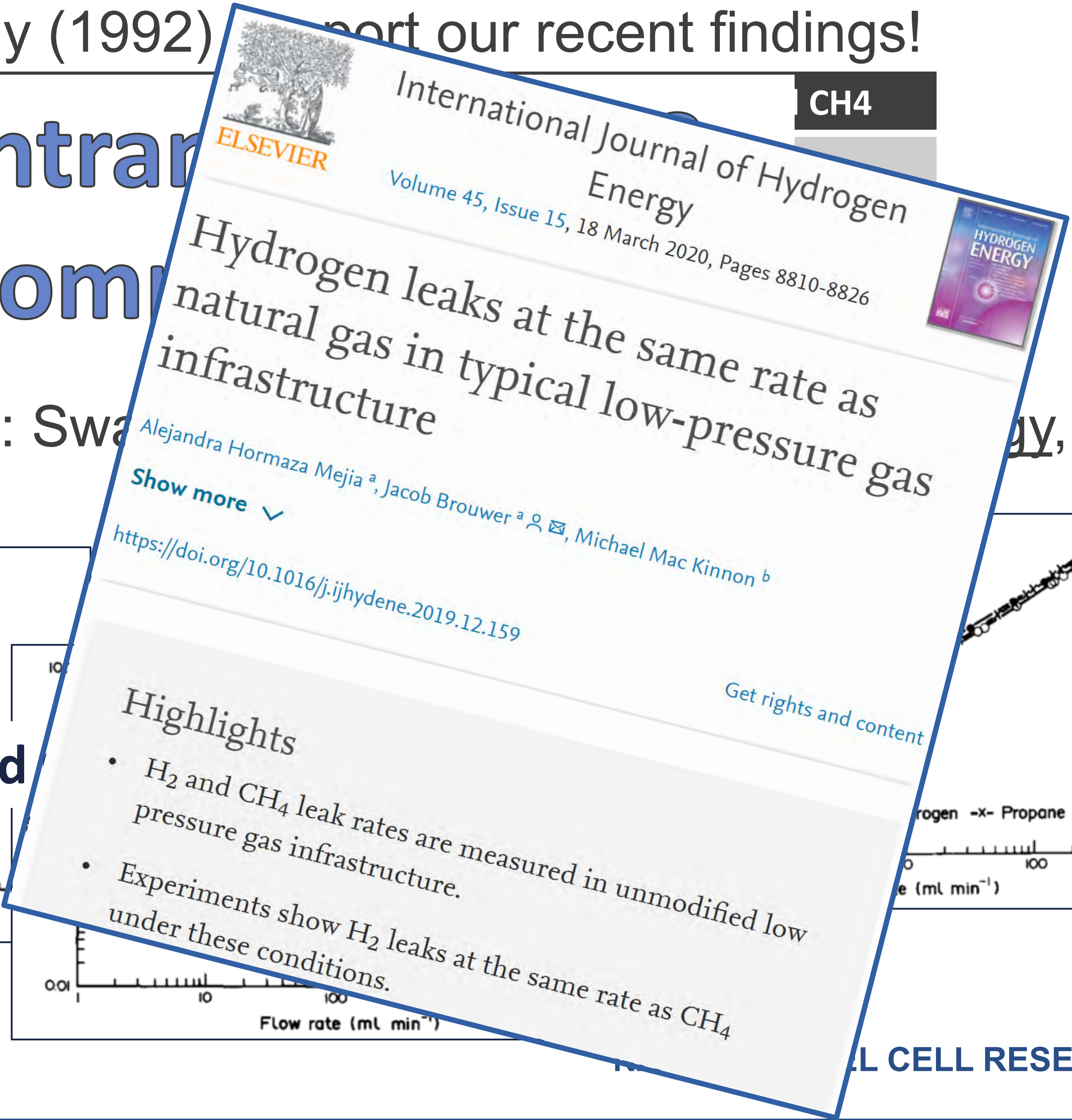
Lea...		CH4
~~Diffusi...~~		
~~La...~~		
~~Tu...~~		

Entrai... Com...

- First publication on this topic: Swa... ...gy, Vol. 17, pp. 807-815, 1992.



H2, CH4, and ...



ELSEVIER
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

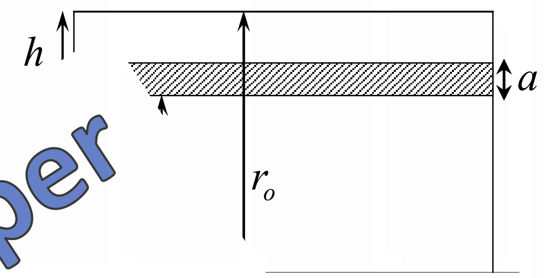
Get rights and content

Highlights

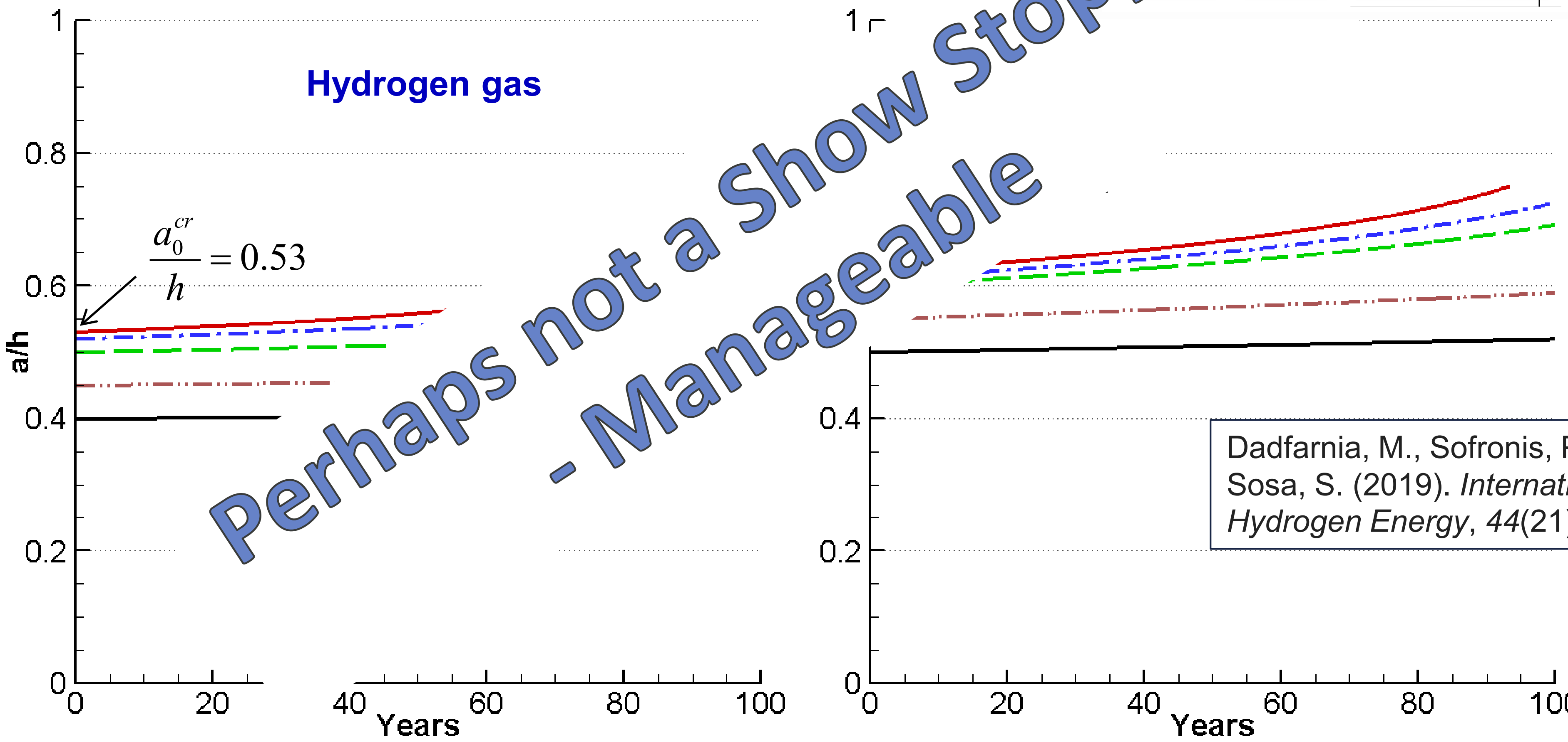
- H_2 and CH_4 leak rates are measured in unmodified low pressure gas infrastructure.
- Experiments show H_2 leaks at the same rate as CH_4 under these conditions.

Existing Pipeline Embrittlement – mostly in Transmission

- Simulation of H_2 embrittlement and fatigue crack growth with UIUC
- Fatigue crack growth in 6" SoCalGas pipeline



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

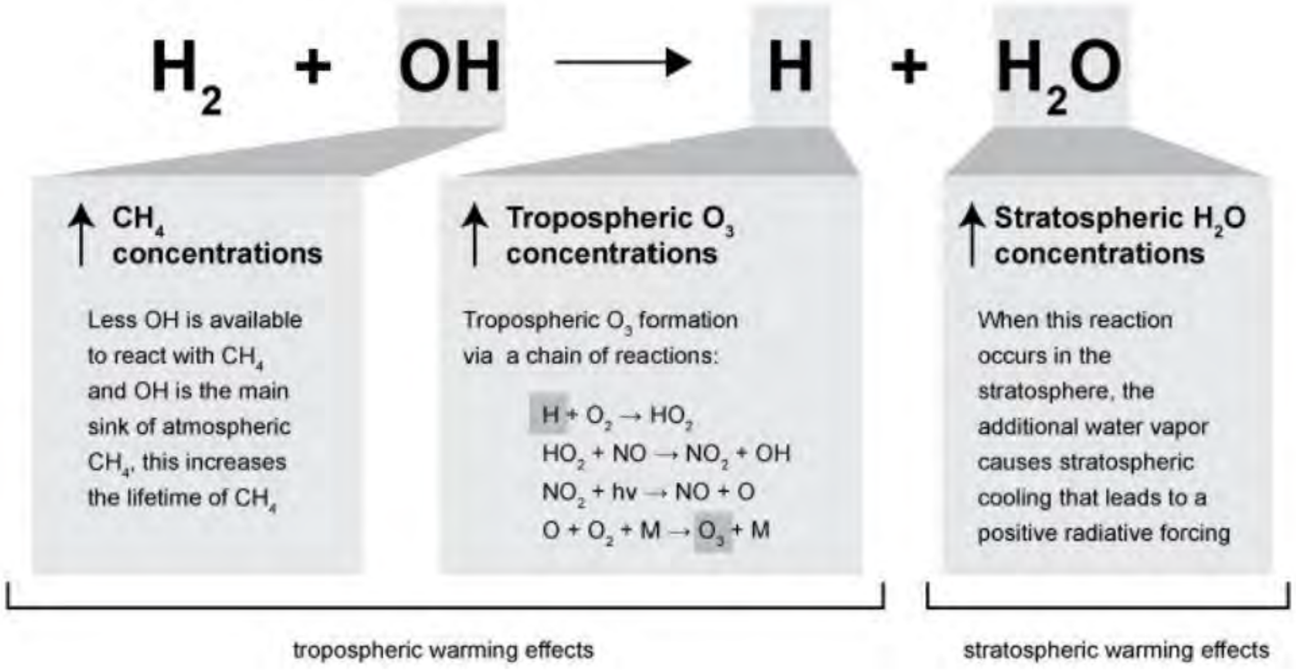


Dadfarnia, M., Sofronis, P., Brouwer, J., & Sosa, S. (2019). *International Journal of Hydrogen Energy*, *44*(21), 10808-10822.

Hydrogen Leakage – Climate Impacts

- Recent EDF study: Hydrogen an indirect climate pollutant
- Reduces OH radical pool, leaving methane in atmosphere longer
- Makes water in stratosphere, which has warming effect

Good Atmospheric Chemistry



<u>Study Could be Improved</u>:

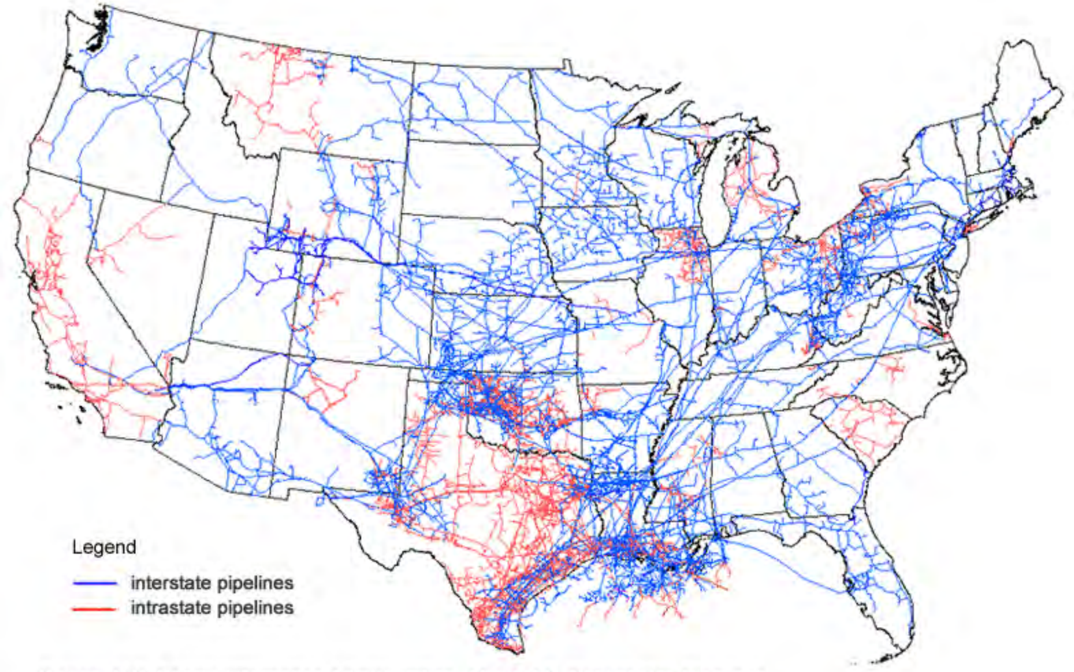
(1) Better analysis/assumptions for H_2 leakage rate

(2) Corresponding reduction in methane (CH_4) emissions

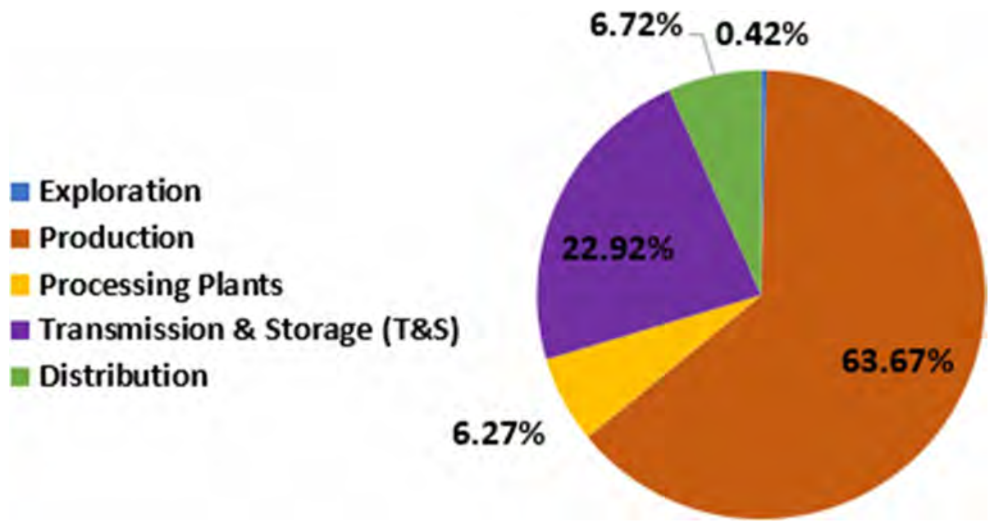
Ocko, I. B. and Hamburg, S. P.: Climate consequences of hydrogen leakage, Atmos. Chem. Phys. Discuss. [preprint], https://doi.org/10.5194/acp-2022-91, in review, 2022.

Fossil Methane – Very Different System vs. Renewable H_2

- Methane emissions: 87% in production, transmission/storage (many super-emitters)
- Distribution systems – mostly plastic pipe with quite low leakage rates
- Hydrogen will be mostly made from local renewable electricity & require distribution
- Fossil natural gas requires production/extraction & interstate transmission



Source: U.S. Energy Information Administration, *About U.S. Natural Gas Pipelines*



Natural gas leaks in Sectors of NG system

Heydarzadeh, Z., Mac Kinnon, M., Thai, C., Reed, J., & Brouwer, J. (2020). Marginal methane emission estimation from the natural gas system. *Applied Energy*, *277*, 115572.

Combustion Emissions – Appliances

Summary

- Hydrogen addition improves emissions for most un-modified burners
  - Those using ~80% NG / 20% H_2
- Understanding established to propose modifications to accommodate even more hydrogen


Cooktop Burner


Oven Burner


Broiler Burner


Storage Water Heater


Ultra-Low NOx SWH


Tankless Water Heater


Central Furnace Burner


Ventless Space Heater


Gas Grill Burner


Gas Fireplace Burner


Pool Heater


Laundry Dryer

CFD
Experiment Test + CFD

Burner Performance Reports Available for each—Appendices for Final Report

	1. Cooktop			2. Oven			3. Gas Fireplace			4. Low NO_x SWH			5. Tankless WH		
Fuel Mixture	NO_x	CO	Upper Limit	NO_x	CO	Upper Limit	NO_x	CO	Upper Limit	NO_x	CO	Upper Limit	NO_x	CO	Upper Limit
CH_4 - H_2	-23%	-14%	55%	0%	-38%	30%	3966%	-100%	100%	0%	+27%	10%	-20%	-10%	>20%
CH_4 - CO_2	-51%	+58%	35%	-92%	+114%	15%	-76%	- 99.9%	45%	-46%	+334%	15%	-45%	+350%	15%

	6. Space Heater			7. Pool Heater			8. Outdoor Grill			9. Laundry Dryer		
Fuel Mixture	NO_x	CO	Upper Limit	NO_x	CO	Upper Limit	NO_x	CO	Upper Limit	NO_x	CO	Upper Limit
CH_4 - H_2	-4%	-14%	45%	-96%	+762%	NA	+128%	-94%	>40%	-62%	-34%	NA
CH_4 - CO_2	-47%	+898%	30%	-99%	+2400%	20%	-100%	-78%	40%	-81%	+118%	15%

Key (NO_x/CO)
% Increase
% Decrease
No Change

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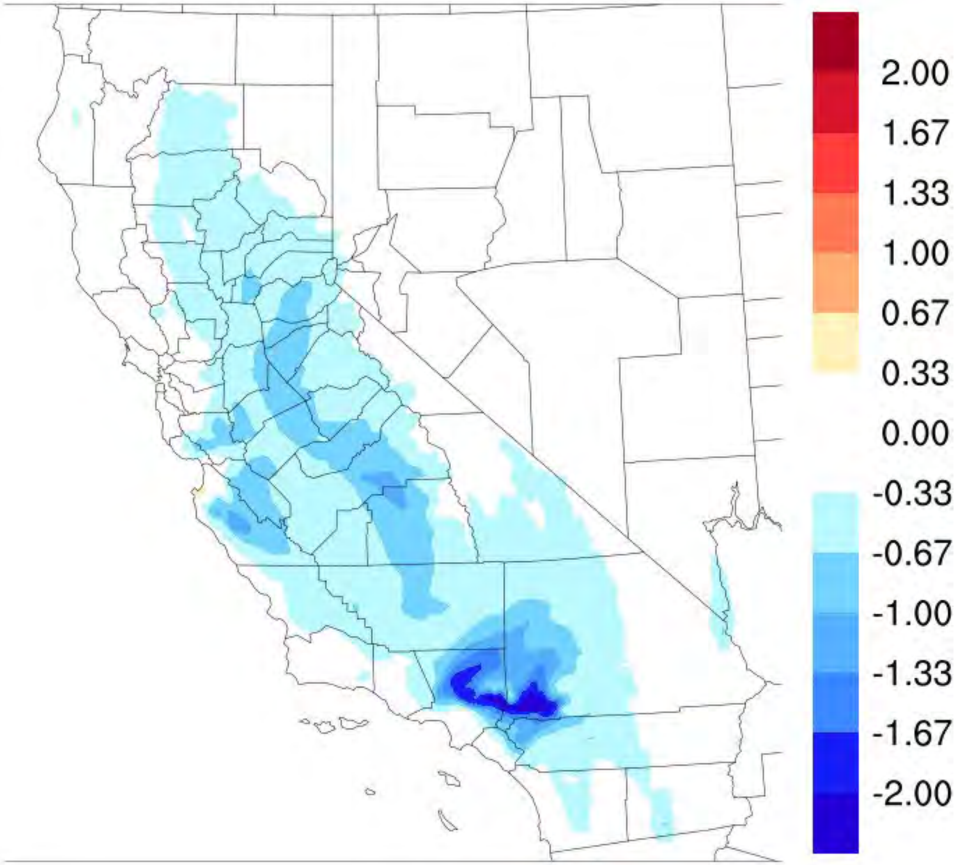
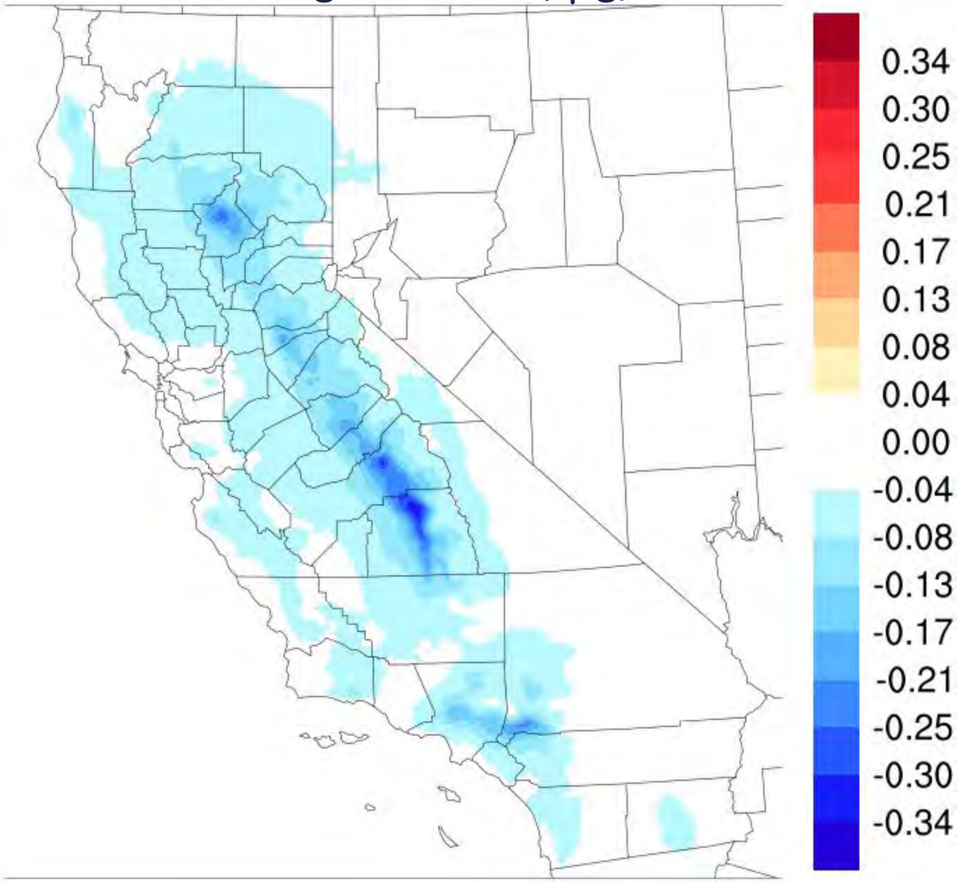
Air Quality Implications

- Example: Adaptation of preferred equipment @ 20% hydrogen addition, summer
  - Using measured/simulated changes in NOx emissions from Appliances, Industrial burners and Gas turbines

Change in Ozone, ppb



Change in PM2.5, $\mu g/m^3$



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NFCRC

Can Energy Conversion be 100% Z missions?

Midwest Hydrogen Su

from: San Diego Union Tribune

Yes – features of hydrogen are essential!

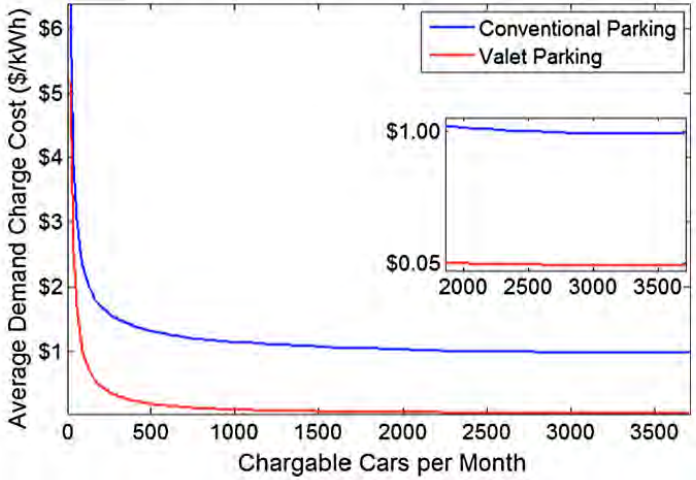
Prof. Jack Brouwer, Ph.D., Director

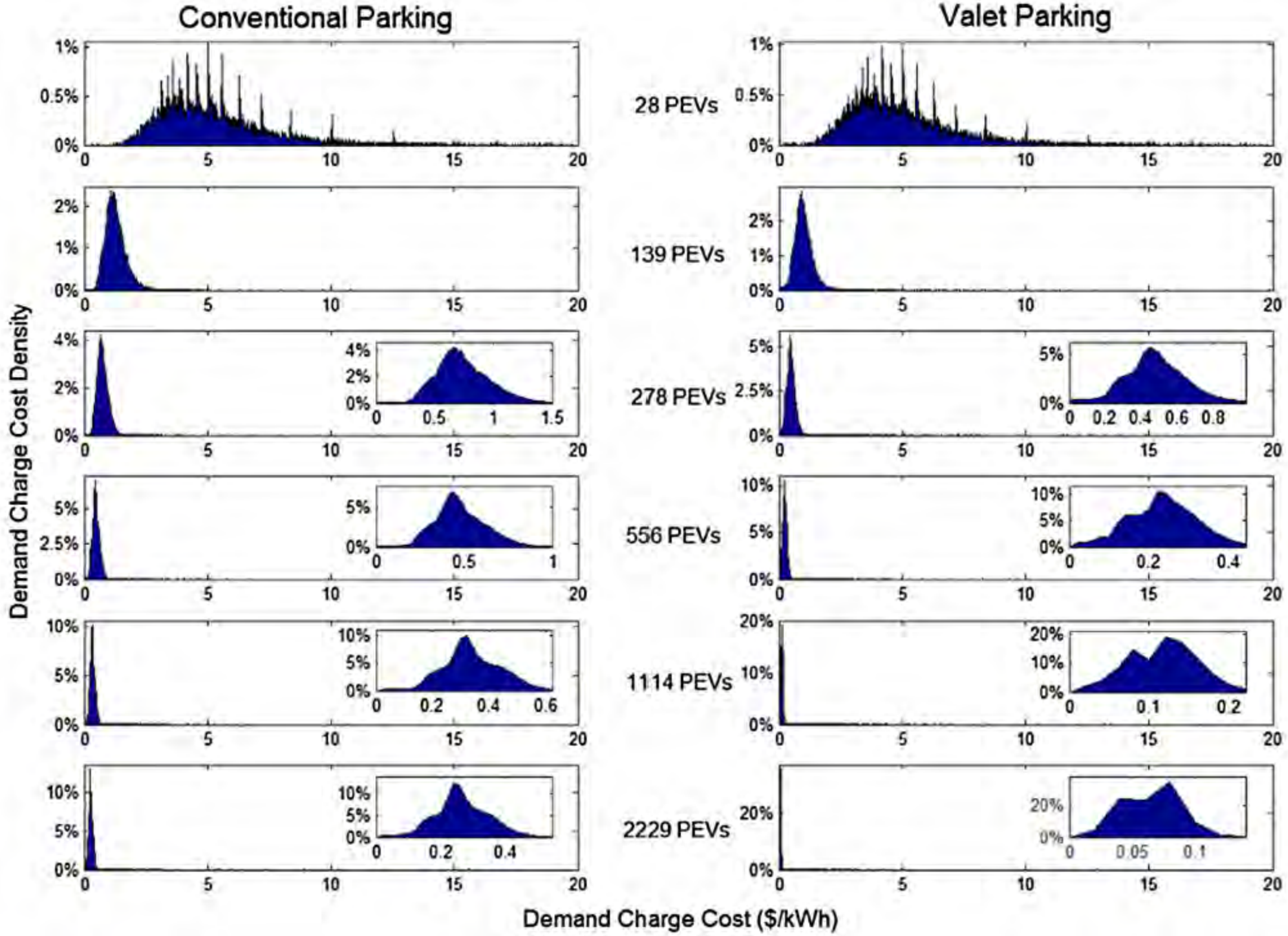
July 7, 2022

Backup Slides

BEV "Only" Case Will be Too Expensive

- At low levels of PEV use, demand charges are extremely high (>$1.00 per kWh).
- Increasing the number of available EVSE can increase the number of PEVs refueled & lower costs.
- Increasing refueling power increases demand charges in all scenarios. Increasing charger power from 44 kW to 120 kW ~ doubles demand charges

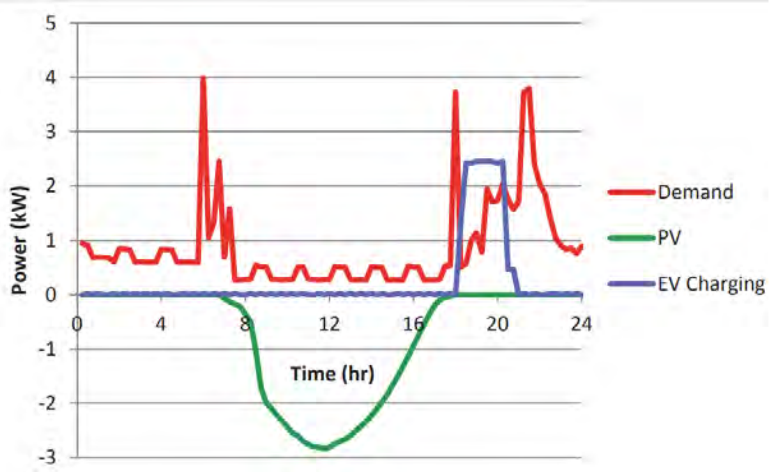


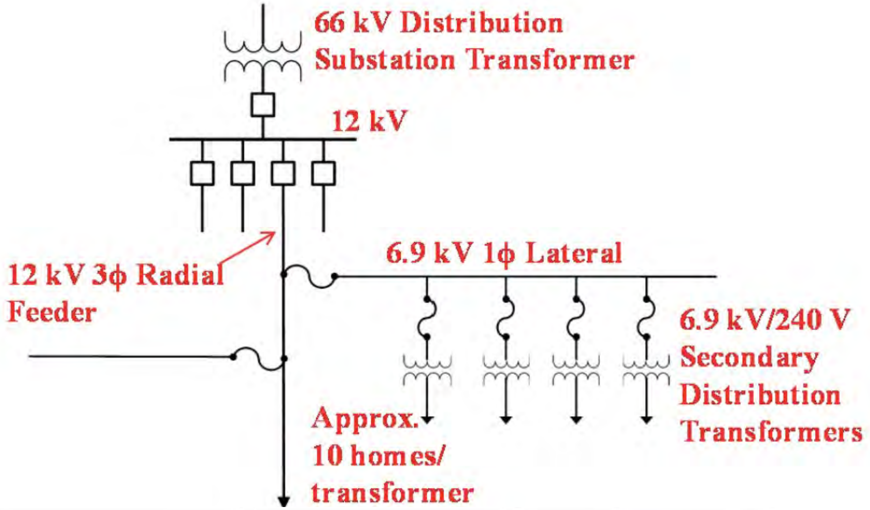


Flores, Robert J., Brendan P. Shaffer, and Jacob Brouwer. "Electricity costs for an electric vehicle fueling station with Level 3 charging." *Applied Energy* 169 (2016): 813-830.

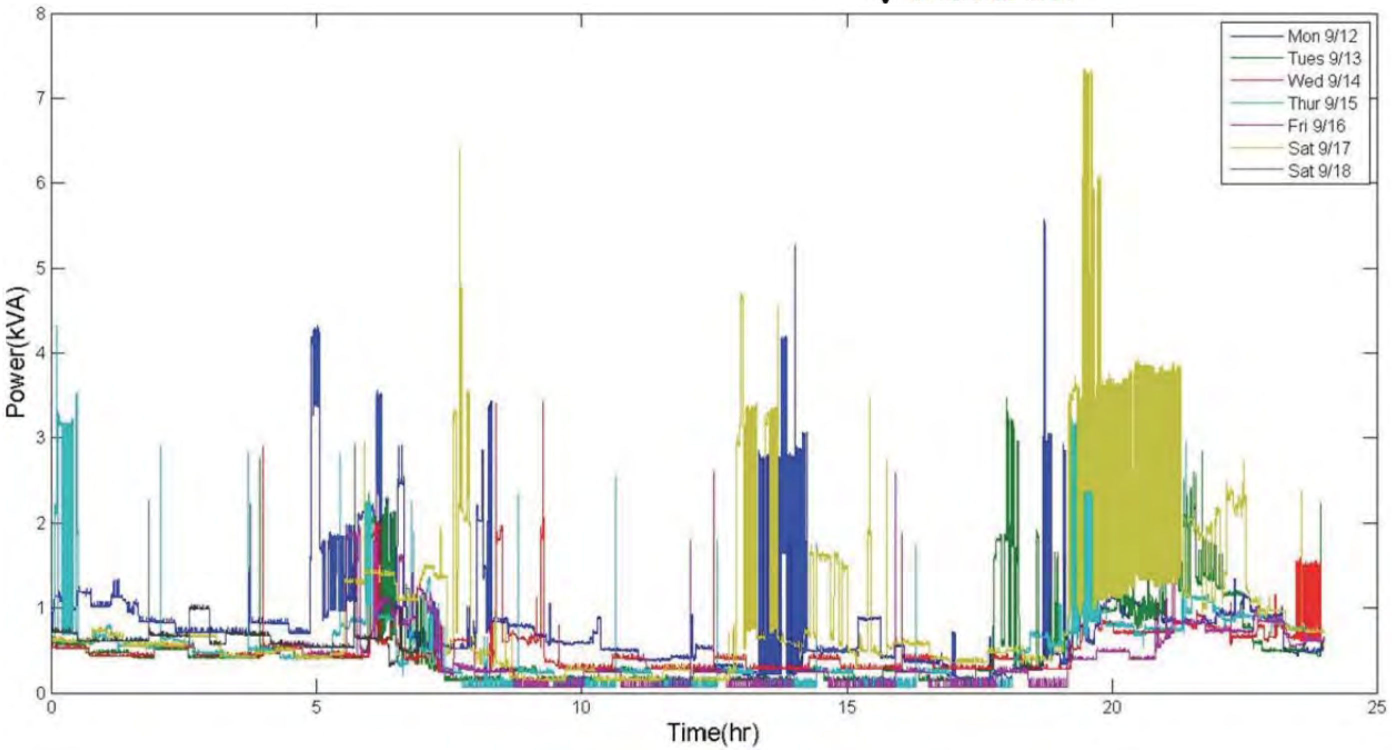
Residential Circuits Cannot Support 100% BEV

- Level 1 charging
  - 20A, 120V, 2.4kW
  - On average only 7/10 homes on the circuit can accommodate level 1 EV charging





- Level 2 charging
  - Up to 80A, 240V, 19.2kW
  - On average only 2/10 homes on the circuit can accommodate level 2 EV charging unless scheduled/controlled



Cinar, R. G. (2014). Applying Smart Grid Technologies to the Secondary Distribution System. University of California, Irvine.

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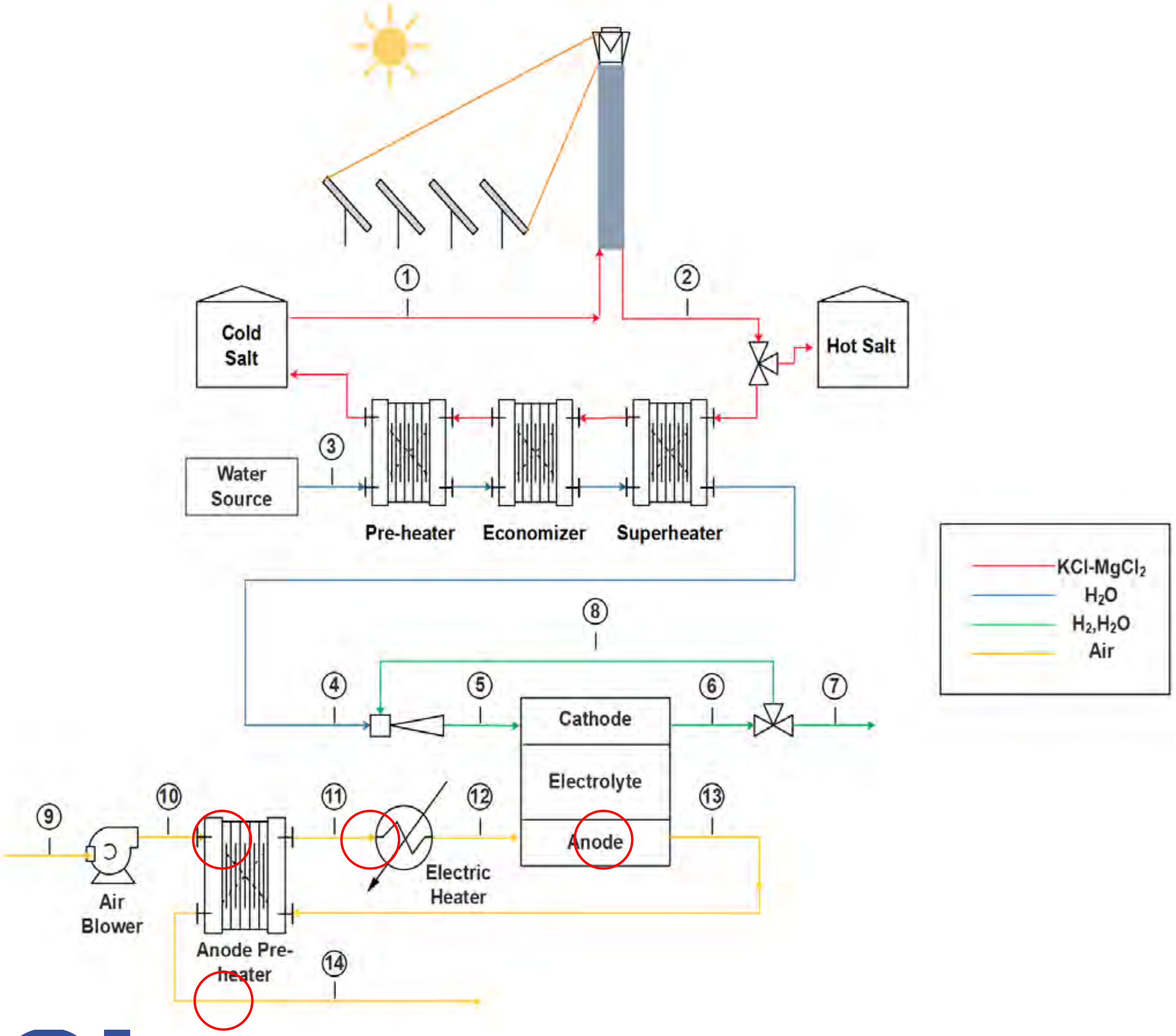
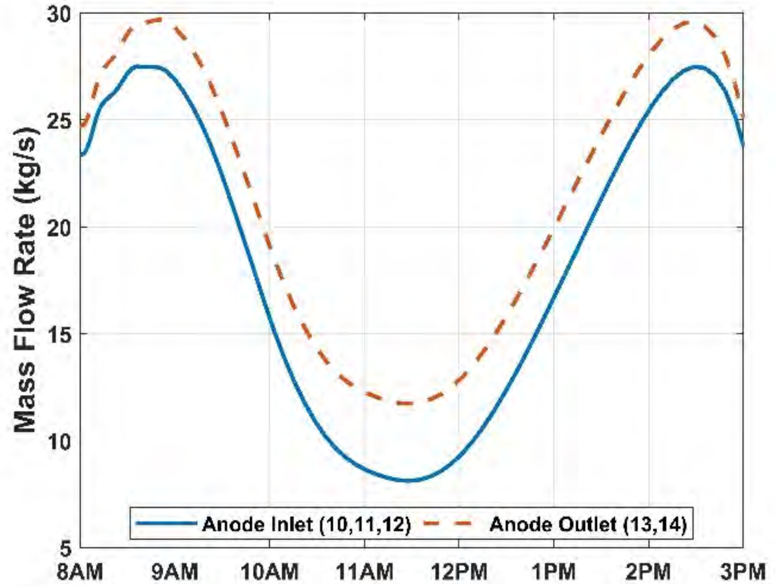
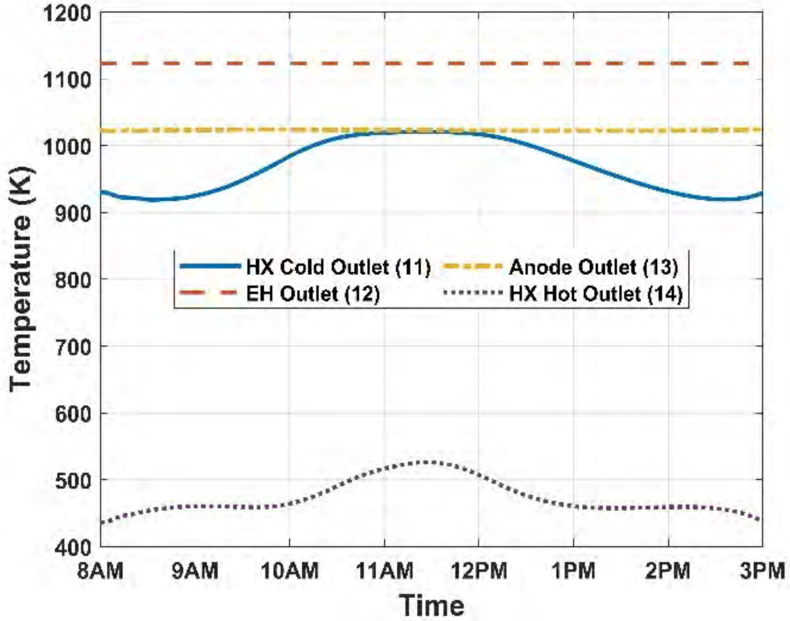
Integrated CSP-SOEC for Hydrogen Production







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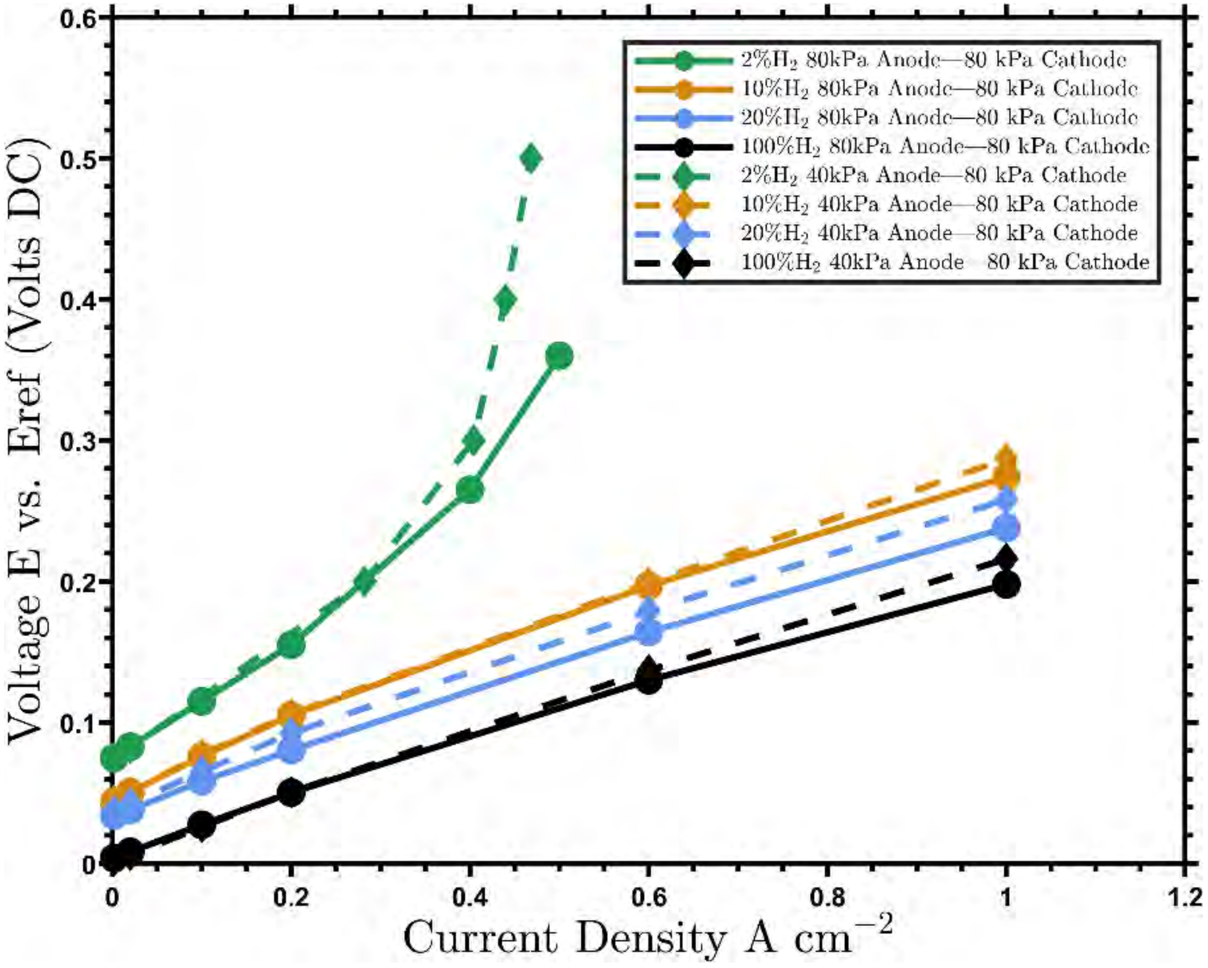
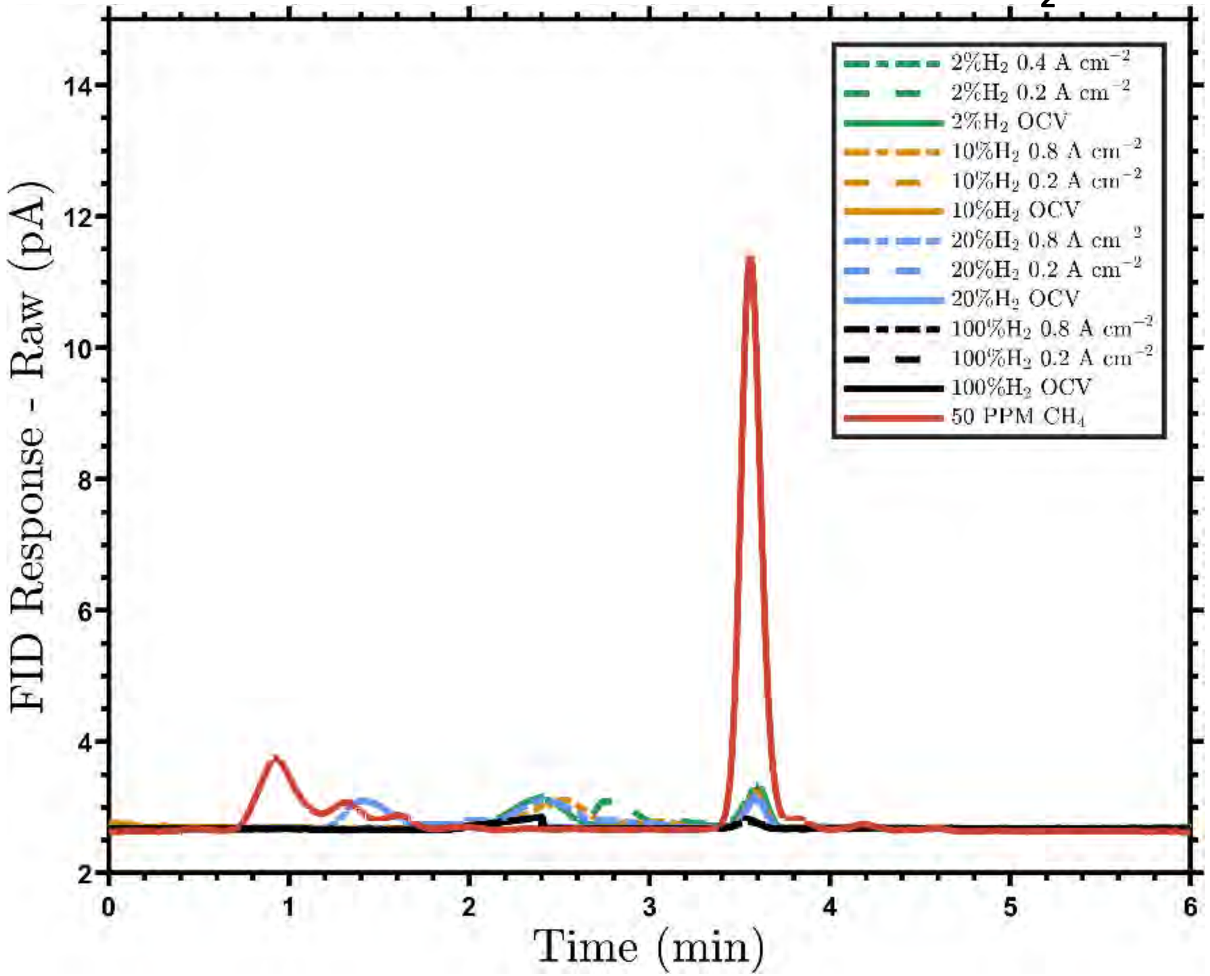
Electrochemical H_2 Separation from Methane

- Performance and Purity



>99.995% vol. H_2



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FCEV fueling requirements: 99.99% H_2 (SAE J-2719 and ISO/PDTS 14687-2)

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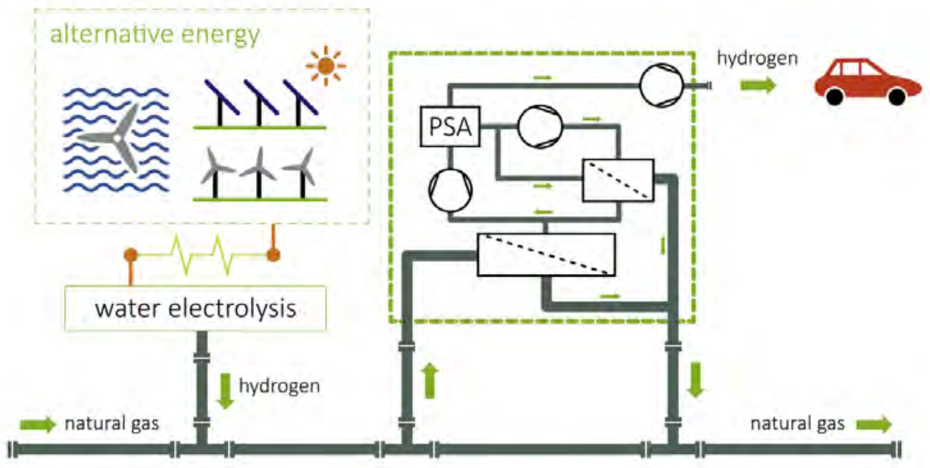
Comparison to State-of-the-Art

- We can efficiently separate hydrogen from very low % volume H_2/CH_4 mixtures
- EHC able to produce fuel cell quality H_2 (>99.995%) while compressing outlet H_2

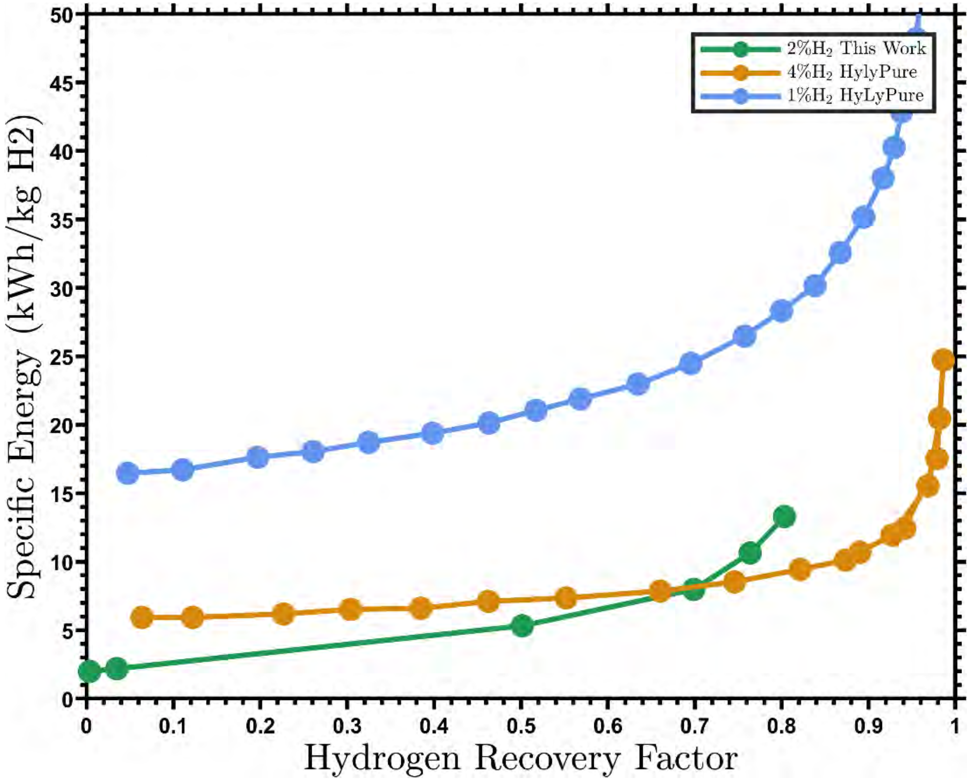
HylyPure

Modelled process optimization of hybrid PSA and membrane separation



>99.97% vol. H_2 Purity
51 bar feed pressure | 25 bar outlet

Source: Liemberger et al. "Efficient extraction of hydrogen transported as co-stream in the natural gas grid – The importance of process design". Applied Energy 233-234 (2019).



>99.995% vol. H_2 Purity
0.4 barg inlet | 0.8 barg outlet

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U.S. DOE "Hydrogen Energy Earthshot"

- Accelerate breakthroughs of more abundant, affordable, and reliable clean energy solutions within the decade - $9.5 billion in federal funding allocated

Office of Energy Efficiency & Renewable Energy » Hydrogen Shot

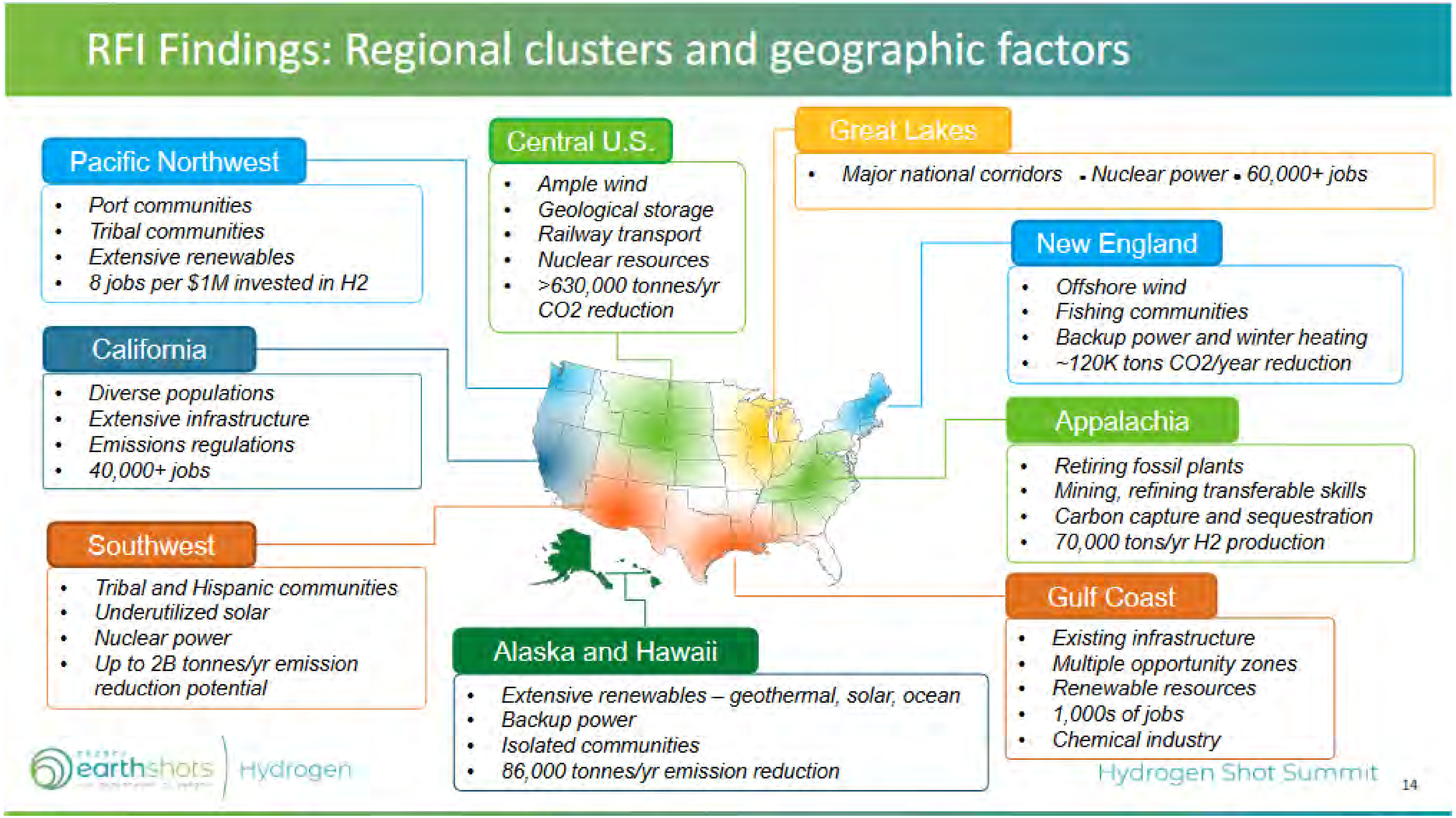
ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

- Reduce RH_2 cost from ~$5/kg to $1/kg to unlock new markets for hydrogen, including steel manufacturing, ammonia, energy storage, and heavy-duty trucks

1 Dollar | 1 Kilogram | 1 Decade

Federal Opportunity: US $8B for 4-8 Regional Hydrogen Hubs

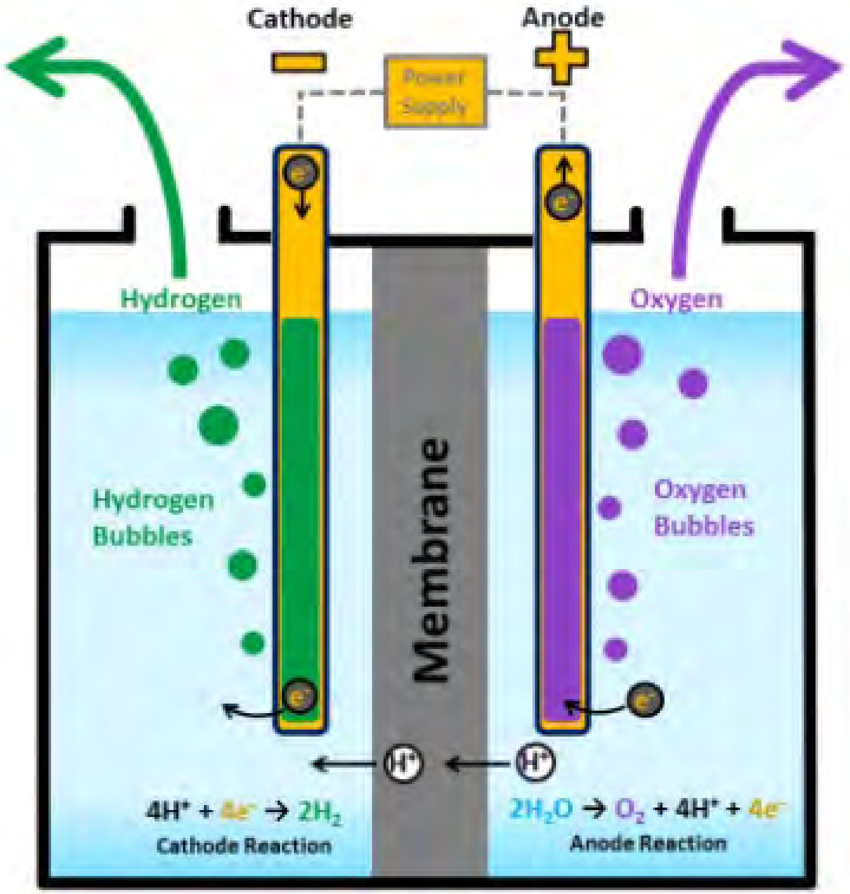
“Hydrogen Shot, RFI Results, and Summary of Hydrogen Provisions in the Bipartisan Infrastructure Law”



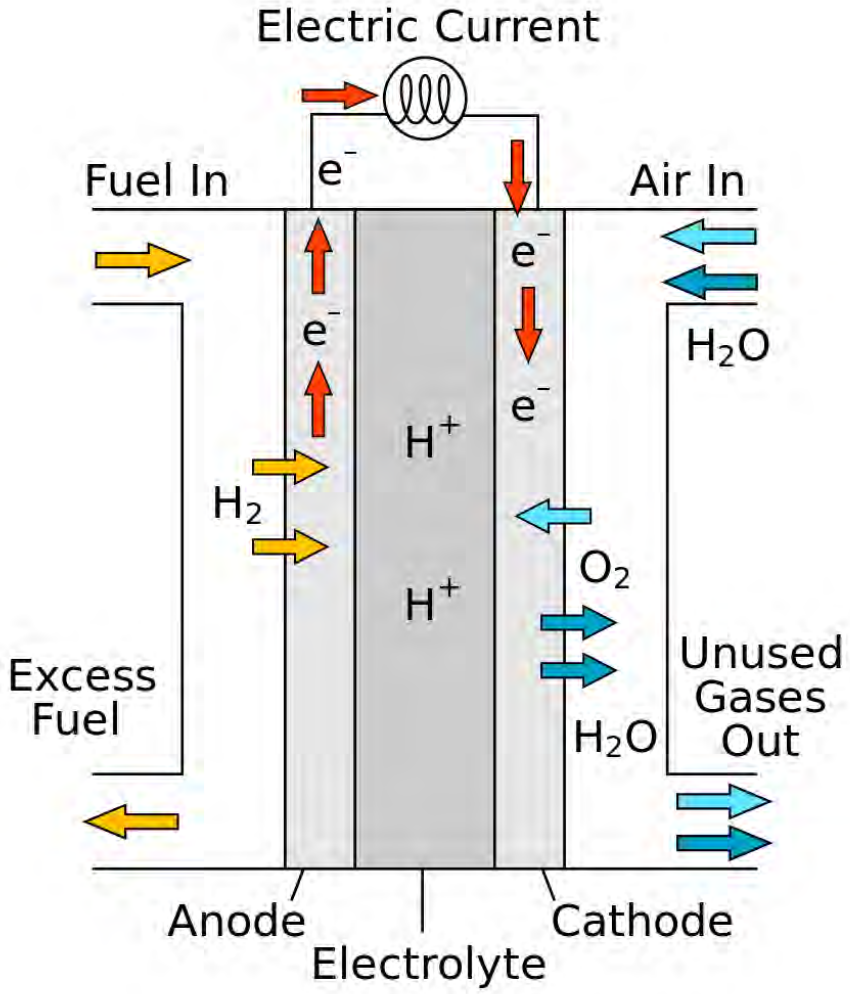
https://www.federalregister.gov/documents/2022/02/16/2022-03324/notice-of-request-for-information-rfi-on-regional-clean-hydrogen-hubs-implementation-strategy

Fuel Cells & Electrolyzers

Electrolyzer (make H_2 from power)

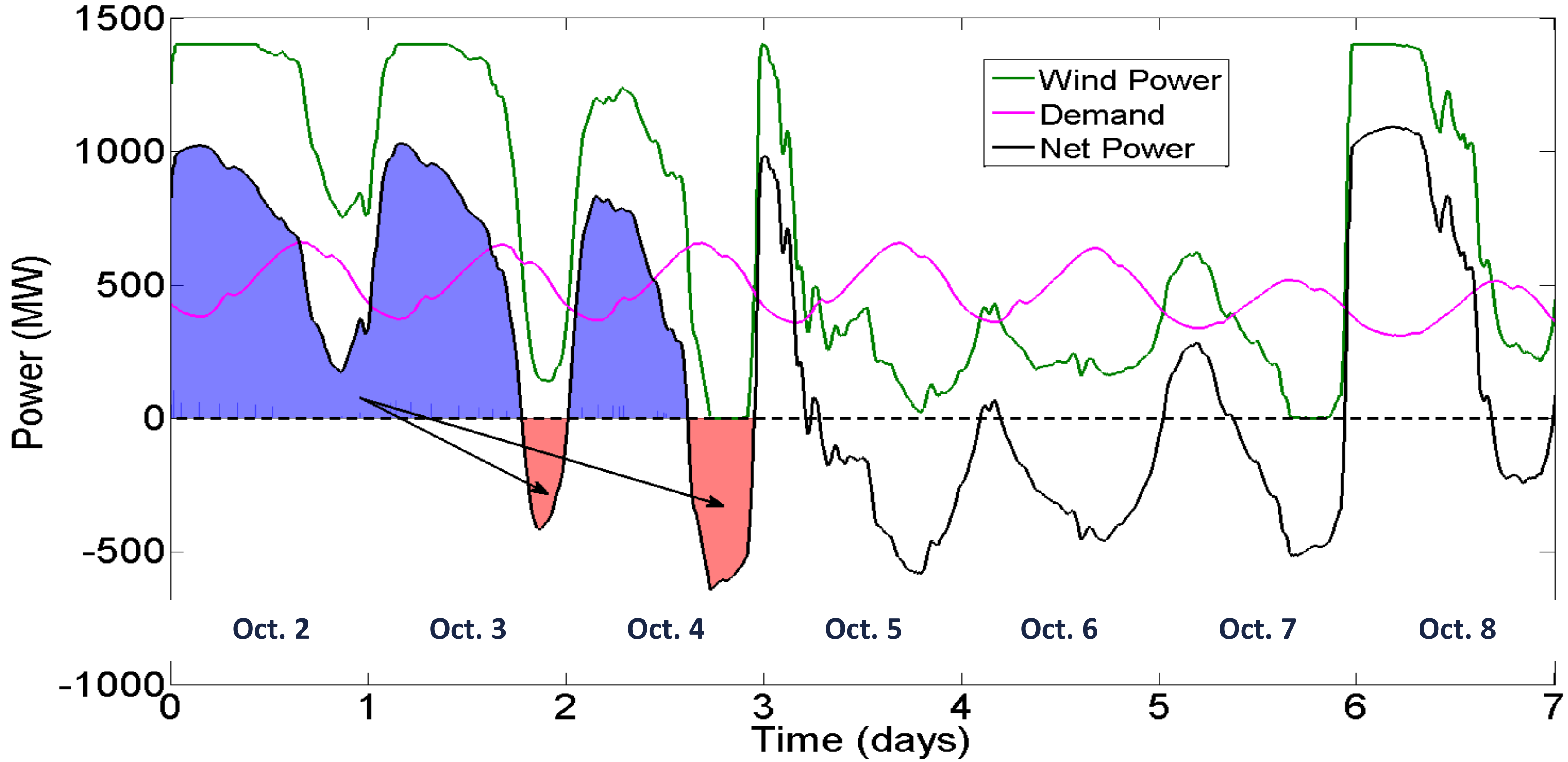


Fuel Cell (make power from H_2)



Hydrogen Energy Storage Dynamics

- Hydrogen Storage complements Texas Wind & Power Dynamics

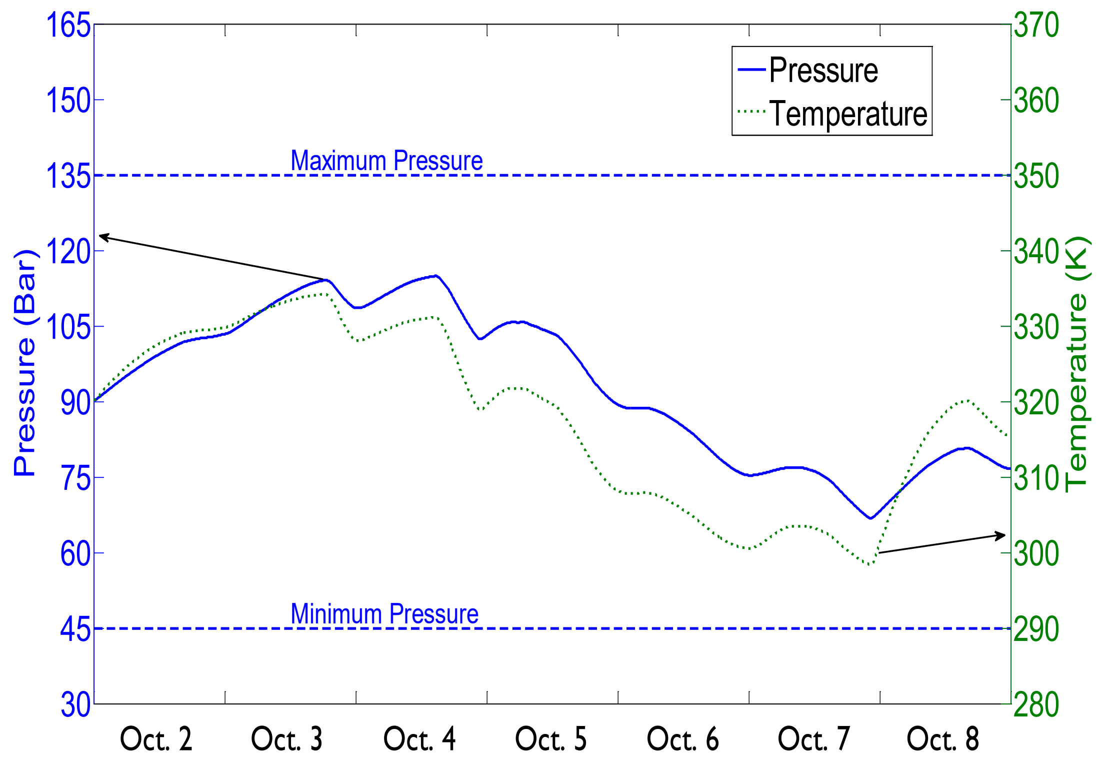


- Load shifting from high wind days to low wind days
- Hydrogen stored in adjacent salt cavern

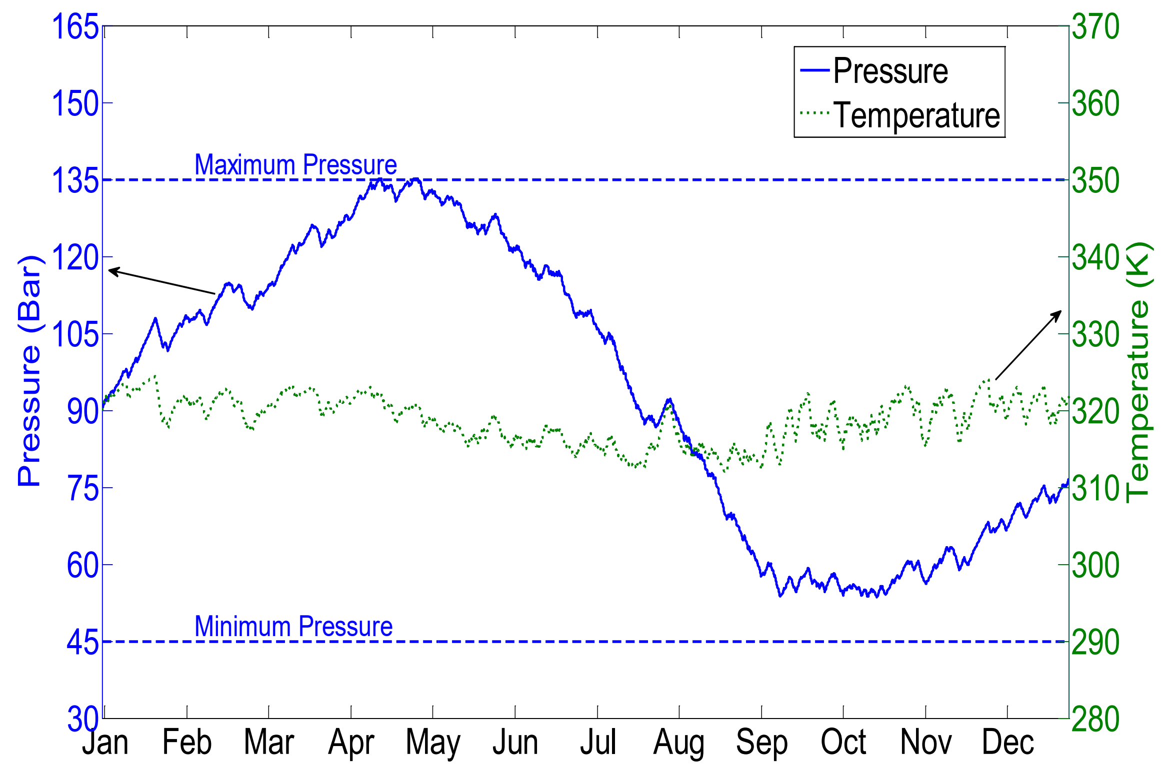
Maton, J.P., Zhao, L., Brouwer, J., Int'l Journal of Hydrogen Energy, Vol. 38, pp. 7867-7880, 2013

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?

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

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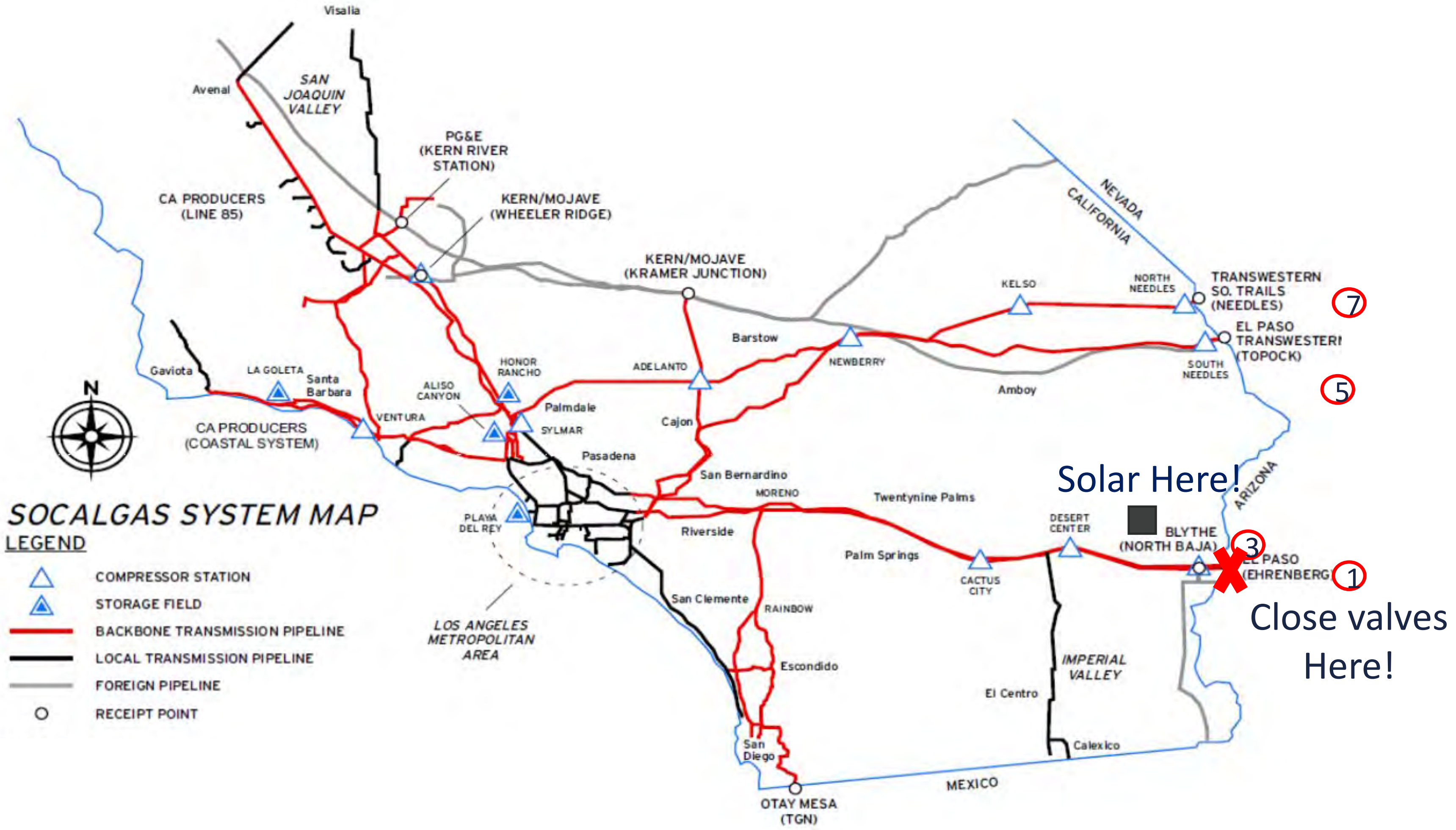
Gas System – Resource for Zero Emissions & Resilience

- First mix X% – HUGE Resource for grid renewables & transportation electrification
- Then piecewise convert to pure hydrogen



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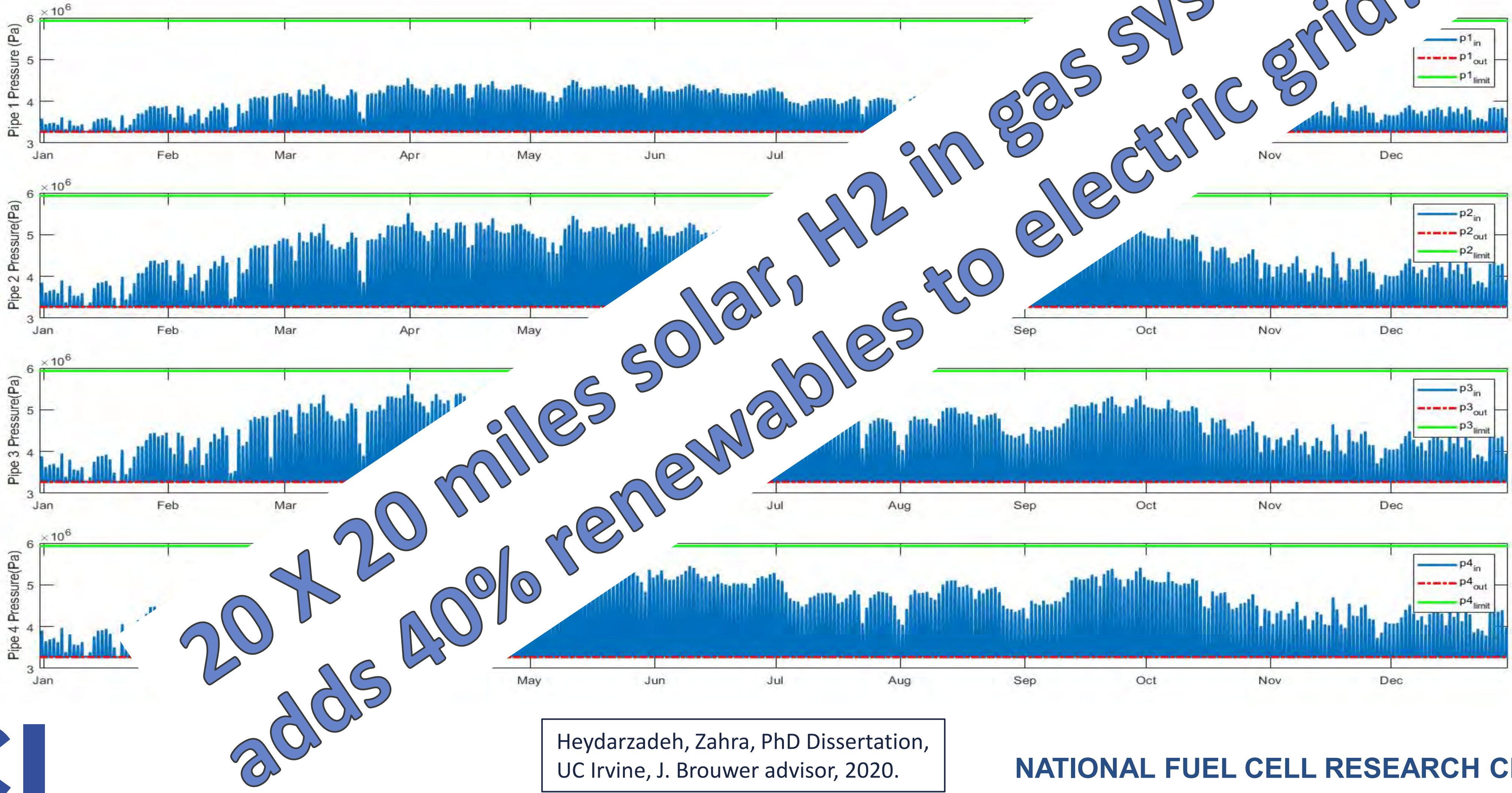
NFCRC

Gas System – Resource for Zero Emissions & R^silience

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



Heydarzadeh, Zahra, PhD Dissertation,
UC Irvine, J. Brouwer advisor, 2020.

Hydrogen Leakage – Climate Impacts

- 2006 study: “Hydrogen is therefore an indirect greenhouse gas with a GWP of 5.8 over a 100-year time horizon. A future hydrogen economy would therefore have greenhouse consequences and would not be free from climate perturbations.”
- But with reasonable assumptions: “If a global hydrogen economy replaced the current fossil fuel-based energy system and exhibited a leakage rate of 1%, then it would produce a climate impact of 0.6% of the current fossil fuel based system.” (or if 10% H_2 leaked it would have 6% of the impact)

Derwent, R., Simmonds, P., O'Doherty, S., Manning, A., Collins, W., & Stevenson, D. (2006). Global environmental impacts of the hydrogen economy. *International Journal of Nuclear Hydrogen Production and Applications*, 1(1), 57-67.

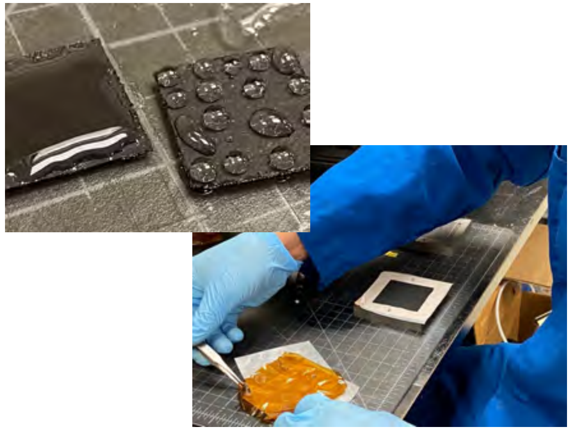
Hydrogen Leakage – Climate Impacts

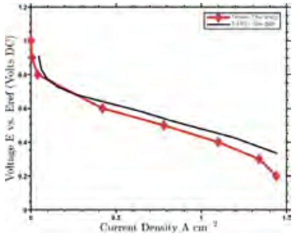
- 2021 study: “The GWPs of methane and hydrogen were estimated using a global chemistry-transport model as 29.2 ± 8 and 3.3 ± 1.4, respectively, over a 100-year time horizon. The current natural gas leakage rates from the distribution system have been estimated for the UK by the ethane tracer method to be about 0.64 Tg CH4/year (2.3%) and for the US by literature review to be of the order of 0.69e2.9 Tg CH4/year (0.5e2.1%). On this basis, with the inclusion of carbon dioxide emissions from combustion, replacing natural gas with green hydrogen in the domestic sectors of both countries should reduce substantially the global warming consequences of domestic sector energy use both in the UK and in the US, provided care is taken to reduce hydrogen leakage to a minimum.”

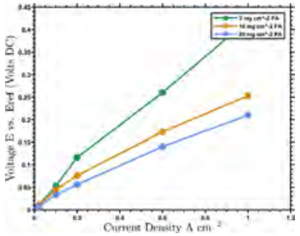
Field, R. A., & Derwent, R. G. (2021). Global warming consequences of replacing natural gas with hydrogen in the domestic energy sectors of future low-carbon economies in the United Kingdom and the United States of America. International Journal of Hydrogen Energy, 46(58), 30190-30203.

Electrochemical Separation Research

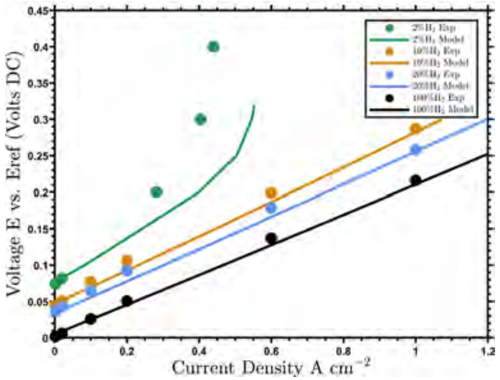
MEA Bench Testing

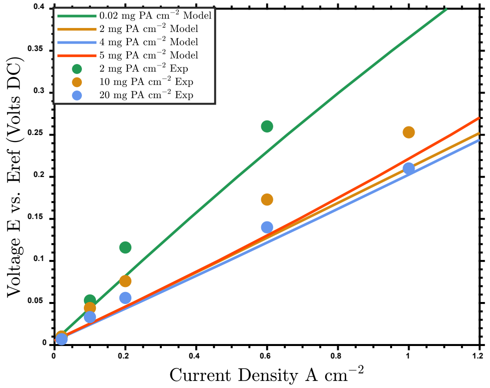




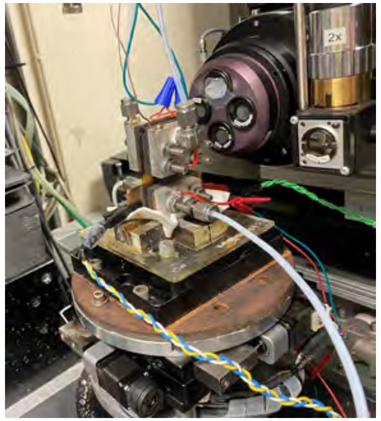


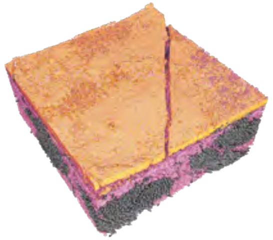
Physical Modelling

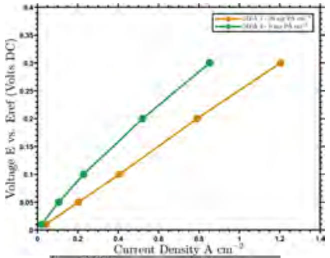




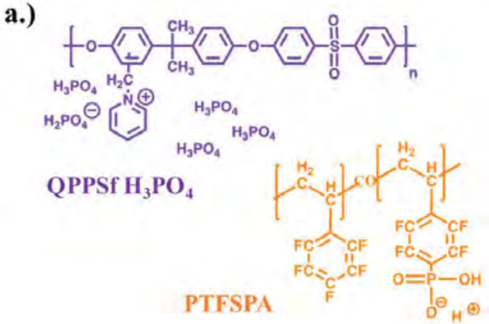
Materials Characterization

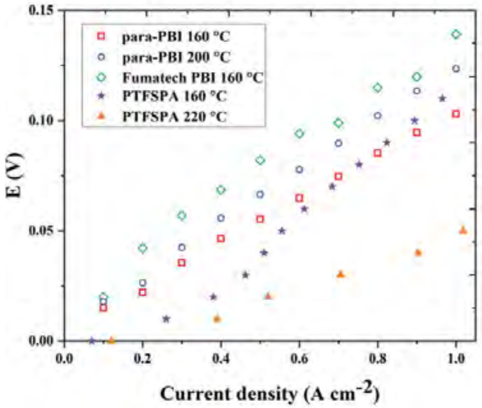






Novel materials





Source: Arges Group. LSU.

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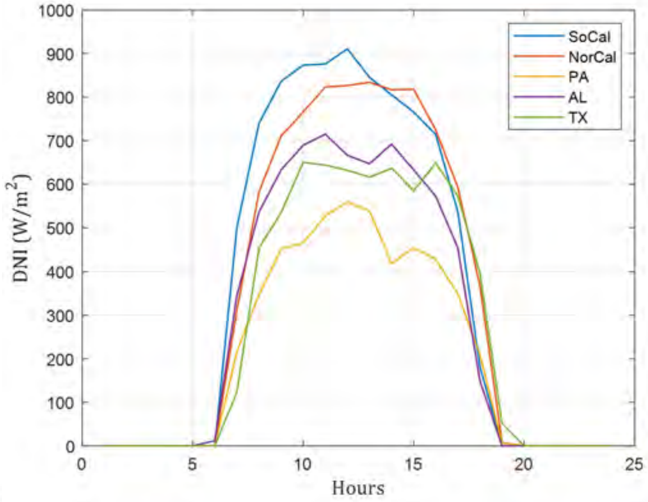
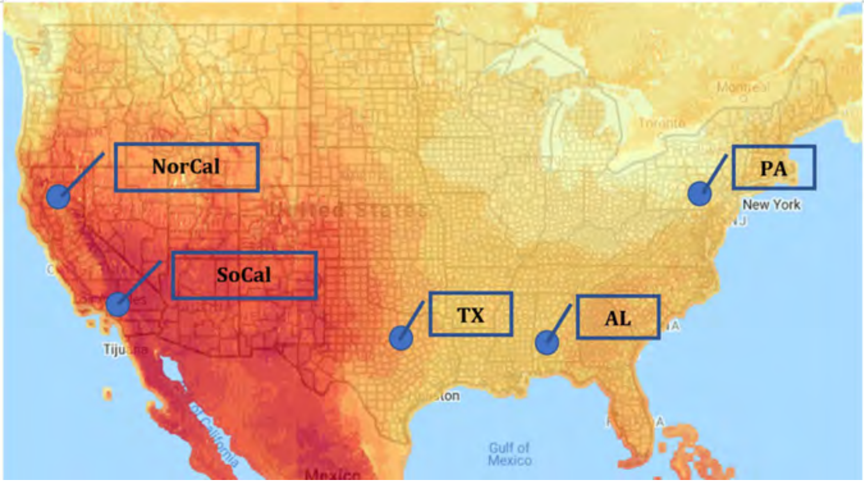
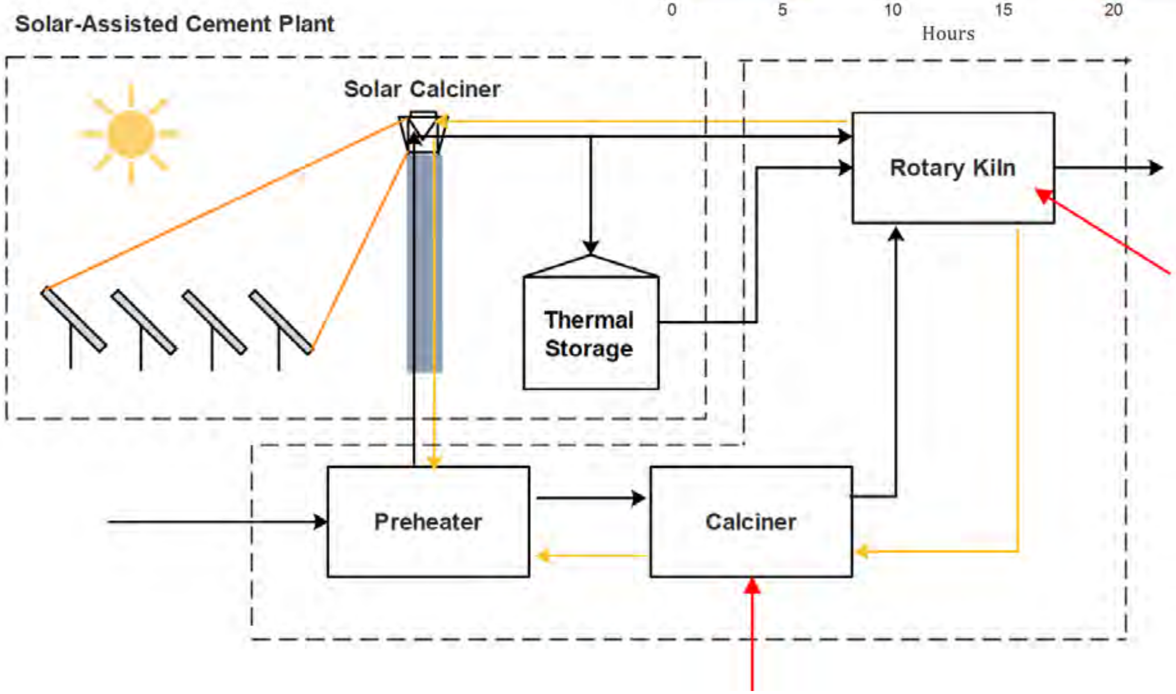
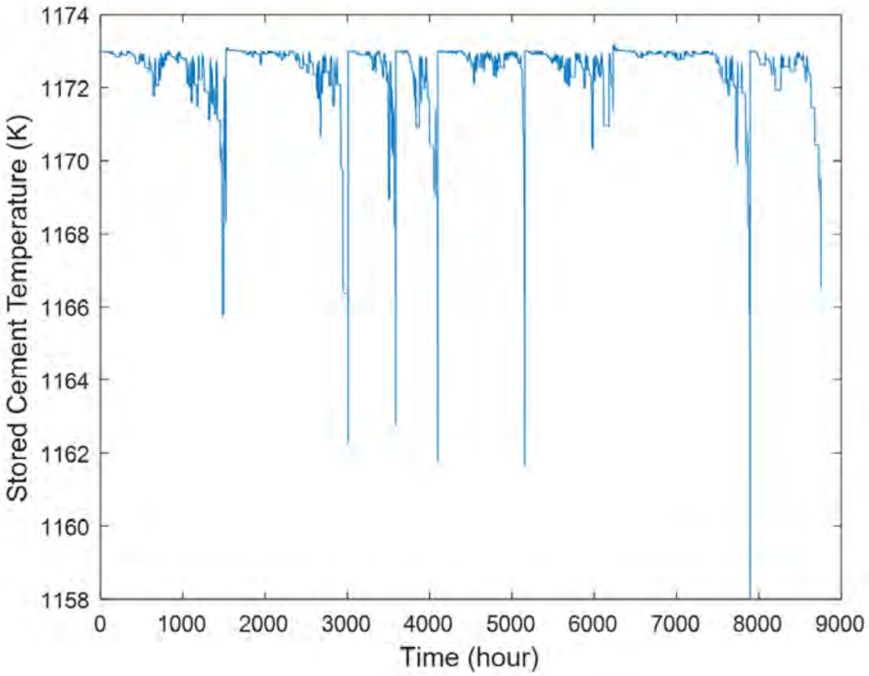
Concentrated Solar Calcination

- Solar-Assisted Cement Plant



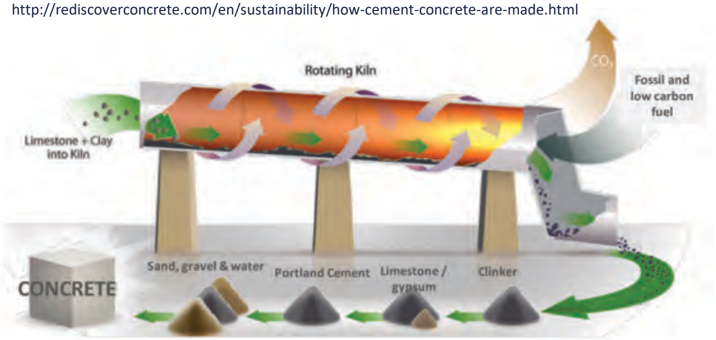




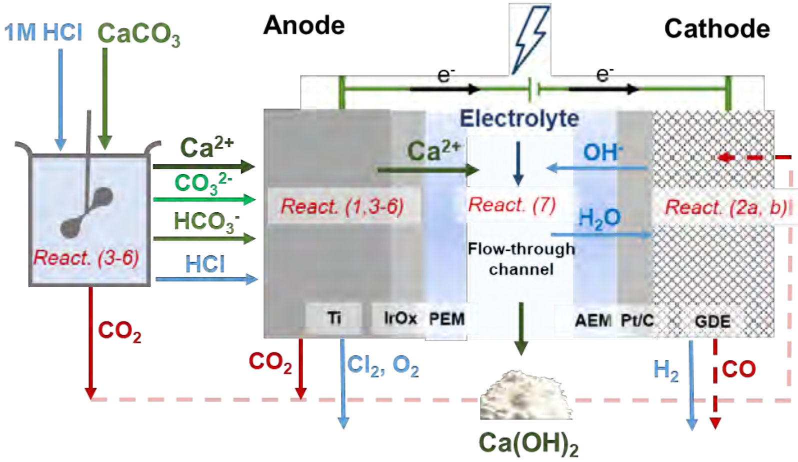


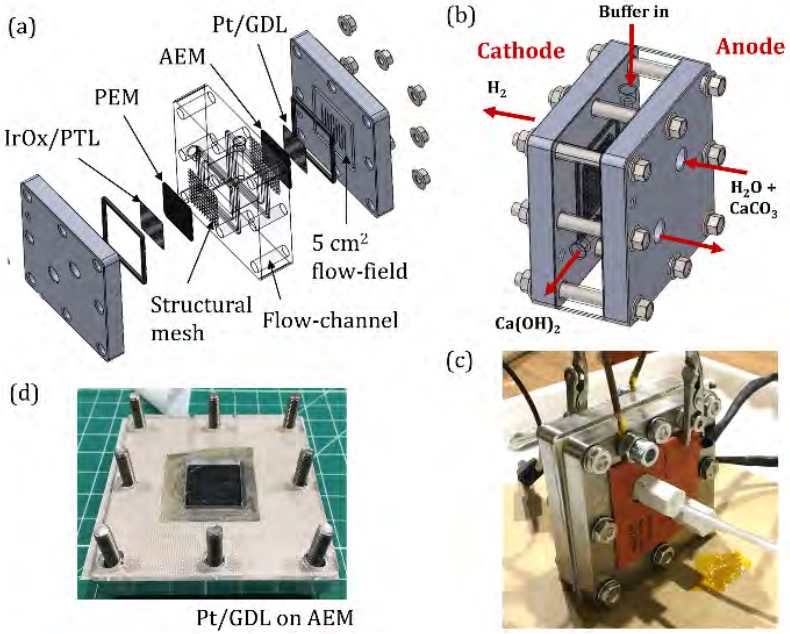
Decarbonization of Cement Production via Electrochemistry

http://rediscoverconcrete.com/en/sustainability/how-cement-concrete-are-made.html

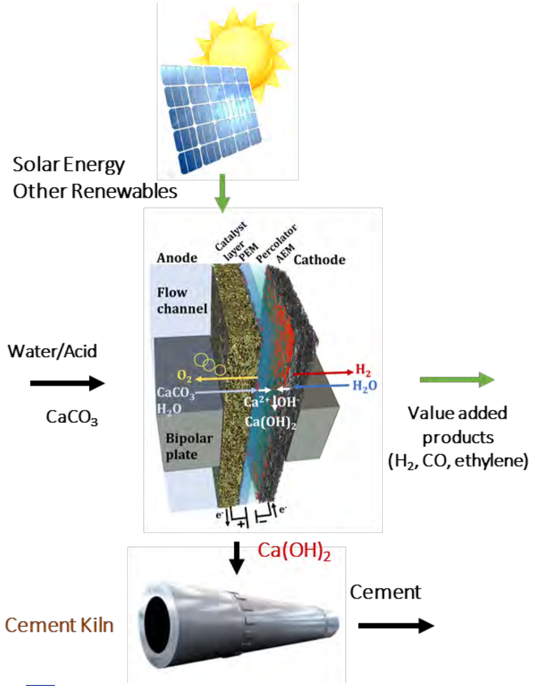


- **Low temperature process (40-80°C)** vs. **cement kiln (1500°C)**
- Compatible with **renewable electricity** sources
  - **Lower CO_2 emissions**
  - Lower consumption of fossil fuel
- Possibility to perform **CO_2 capture** on all stage of the process

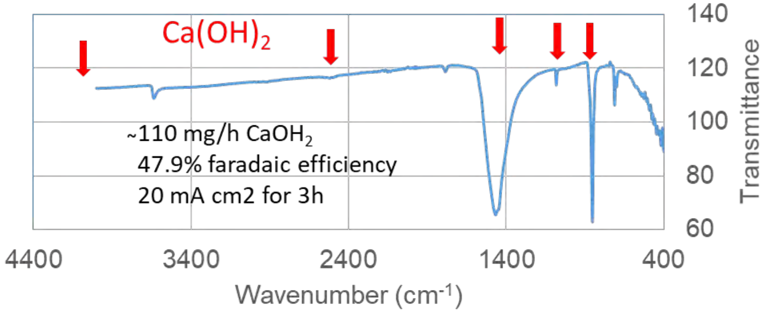




Pt/GDL on AEM




Prof. Iryna V.Zenyuk



	Existing/emerging cement manufacturing technology	Proposed technology
Energy intensity	4.9 GJ/ton (fossil-fuels)	7.2 – 10.8 GJ/ton (electricity)
CO_2 emissions	0.972 ton CO_2/ton of cement	Reduced (Case 1), 0 or negative (Case 2)
Cost per ton	\$100-\$110 OPC \$600 Mg cements \$230- \$490 Wollastonite \$132 Geopolymers	\$197.5 - \$310 for $Ca(OH)_2$ \$12.9- \$22.7 to convert $Ca(OH)_2$ to cement **\$210.4 - \$332.7 total**

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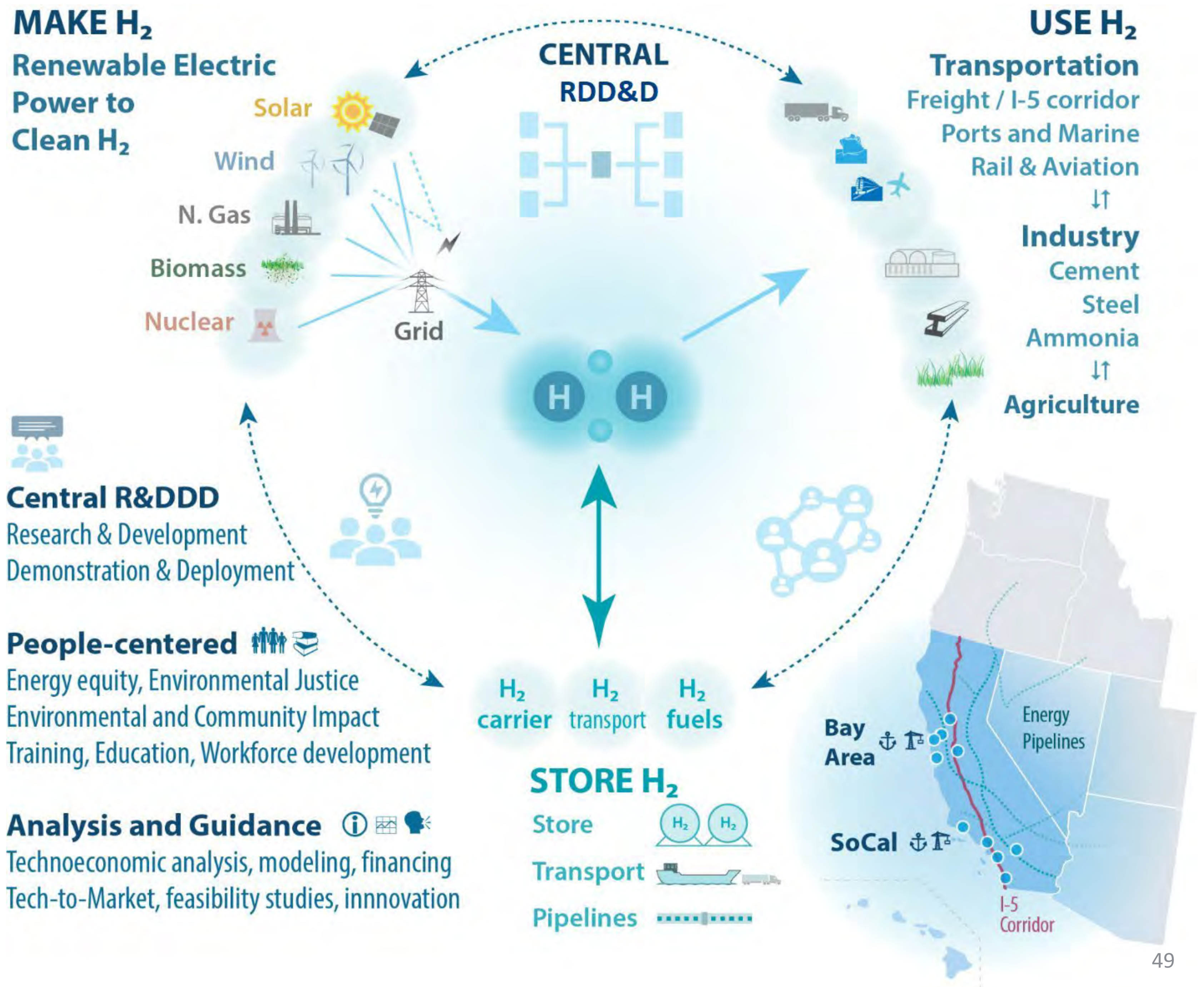
[1] Zenyuk I.V., Perego A., Li M., Kulkarni D.S., PCT/US2020/067531

ARCHES

Alliance for Renewable Clean Hydrogen Energy Systems

A Public/Private Partnership

For a Clean California H_2 Ecosystem



Colors of Hydrogen – Carbon Intensity & Emissions!

- No accepted/agreed-to standard (example below)
- Emissions vary within colors; picking colors stymies market; other negative outcomes
- Should rather use "Carbon Intensity" and "Emissions" metrics for hydrogen

Color	Technology	Feedstock
Gre[illegible]	Electrolysis	Solar, Wind, Hydro, Geothermal, Tidal
Gree[illegible]	[illegible]am reforming, Gasification, Digestion	Biogas, Biomass, Waste
Pink/Purple	Electr[illegible]	Nuclear
Yellow	Electrolysis	[illegible]ower
Blue	Steam reforming or Gasification [illegible]	[illegible]atural Gas, Coal
Turquoise	Pyrolysis w/ solid ca[illegible]oduct	[illegible]
Grey	Steam[illegible]	Natural Gas
Brown	[illegible]ification	Brown Coal
Blac[illegible]	Gasification	Black Coal

University of California, Irvine
Home to the National Fuel Cell Research Center

36,000+ students

#1 Best College in the U.S.
— *MONEY*

#9 Public University in the U.S.
— *U.S. News & World Report 2020*

#1 Cool School in the U.S. for sustainability
Top 10 for 10 years
— *Sierra* magazine

200,000+
Anteater alumni

Most applied to UC campus for California's aspiring freshmen for a second year in a row

82 majors — **75** minors

$133 million
private donor support in 2018-19

$5 billion
annual economic impact in Orange County

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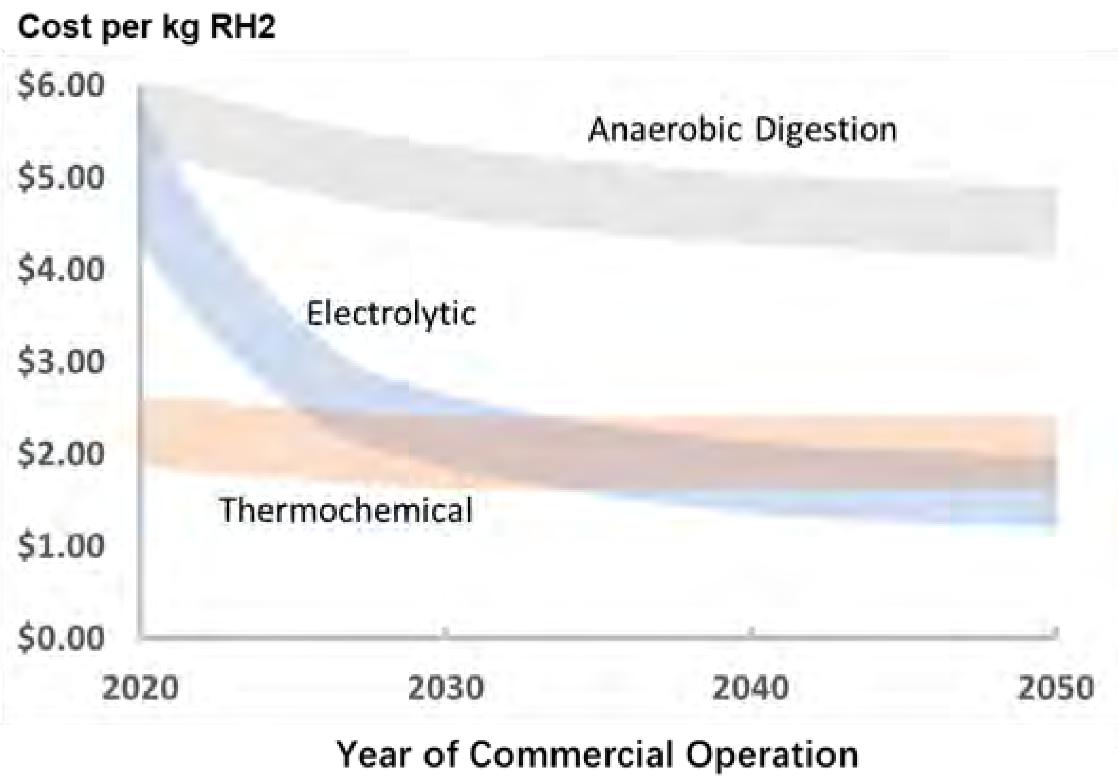
one of the 10 campuses of
the University of California

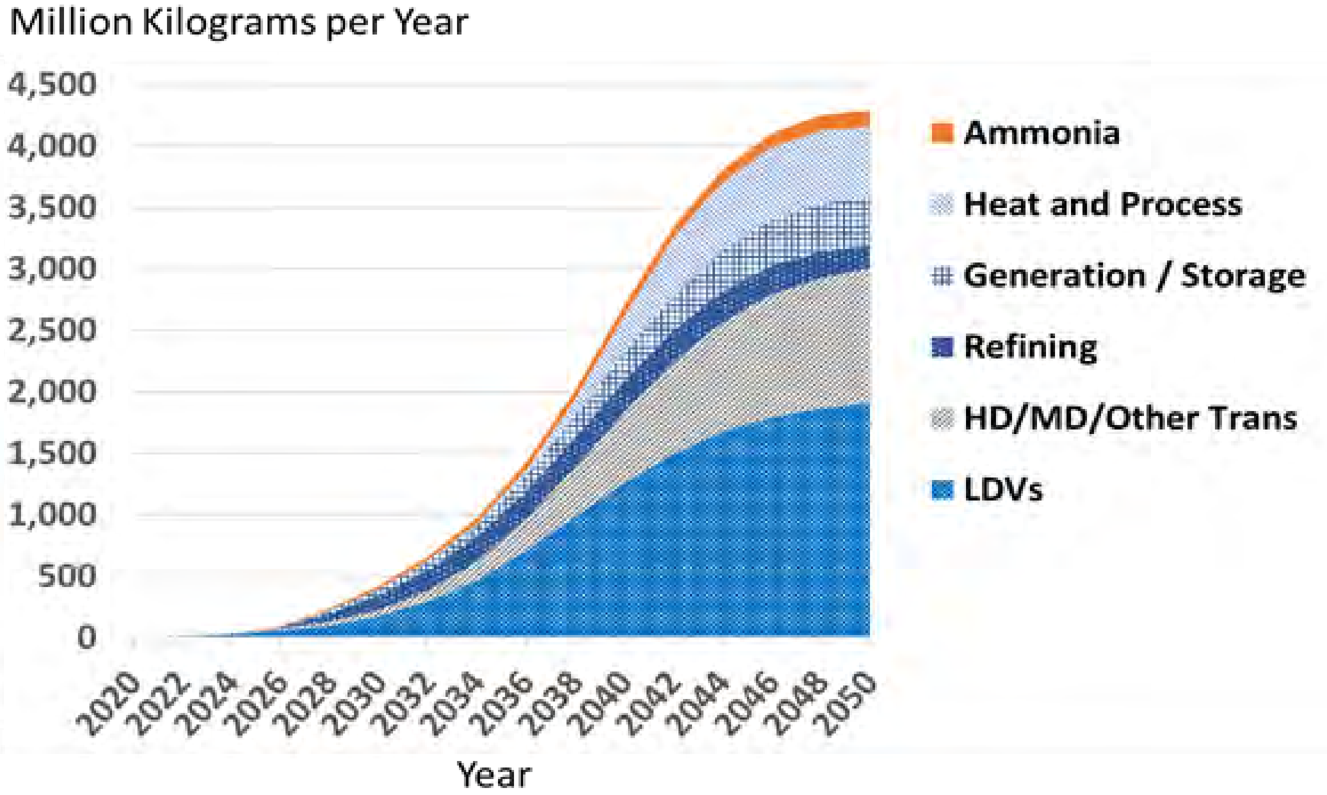
… and, our mascot is – Peter, the…

UCI-APEP: Renewable & Sustainable Energy Systems Dynamics

California Renewable Hydrogen Roadmap

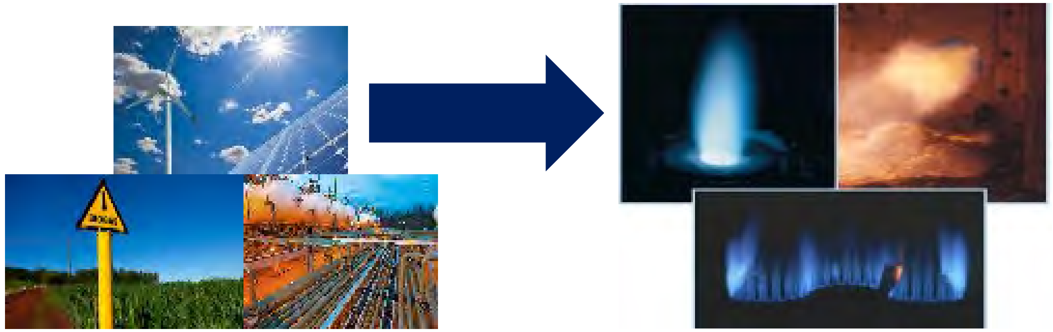
- Developed by APEP (Dr. Jeff Reed, PI) in 2018 – 2020 timeframe for CEC





Reed, J.G., Dailey, E.F., Shaffer, B.P., Lane, B.A., Flores, R.J., Fong, A.F., Samuelsen, G.S., "Roadmap for the Deployment and Buildout of Renewable Hydrogen Production Plants in California," CEC-600-2020-002, 2020

Combustion Emissions – Industrial Burners



Quantified NO_x and CO emissions relative to operation on 100% Natural Gas (CH_4)

- **Variation for burners, pollutants, and fuels**

	1. LSB		2. SSB		3. MTC		4. Oxygas		5. HSJ	
Fuel Mixture	NO_x	CO	NO_x	CO	NO_x	CO	NO_x	CO	NO_x	CO
76% CH_4 - 24% H_2	111%	-40%	-64%	-40%	200%	-50%	16%	-20%	48%	-11%
98% CH_4 - 2% CO_2	-5%	11%	-3%	3%	-17%	1%	-4%	3%	-2%	3%
94% CH_4 - 6% C_2H_6	5%	8%	2%	3%	3%	4%	5%	8%	3%	4%
95% CH_4 - 5% C_3H_8	9%	3%	3%	6%	5%	4%	4%	6%	8%	5%

	6. GTC		7. RT		8. IRB		9. SB	
Fuel Mixture	NO_x	CO	NO_x	CO	NO_x	CO	NO_x	CO
76% CH_4 - 24% H_2	-20%	-50%	233%	-35%	-60%	-10%	58%	-13%
98% CH_4 - 2% CO_2	-3%	0%	-2%	2%	-3%	-3%	-2%	5%
94% CH_4 - 6% C_2H_6	3%	3%	0%	4%	2%	-5%	3%	4%
95% CH_4 - 5% C_3H_8	3%	3%	5%	4%	1%	-5%	8%	6%

Key (NO_x/CO)
% Increase
% Decrease
No Change

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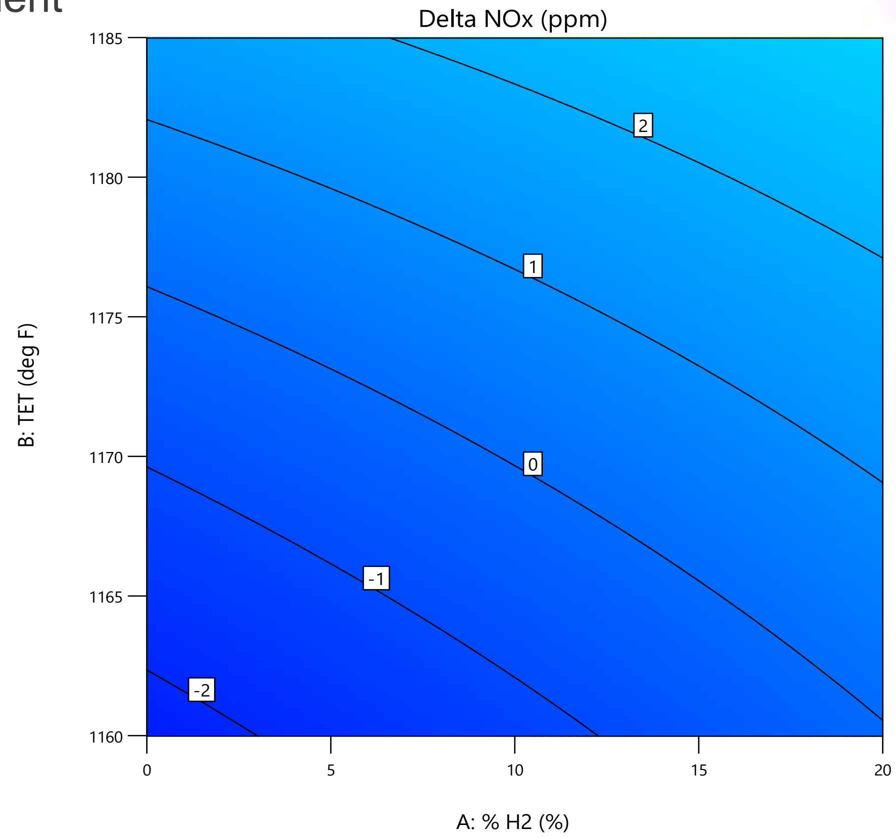
Colorado, Andres; McDonell, Vincent. 2016. *Effect of Variable Fuel Composition on Emissions and Lean Blowoff Stability Limits.* California Energy Commission. Publication number: 500-13-004

NFCRC

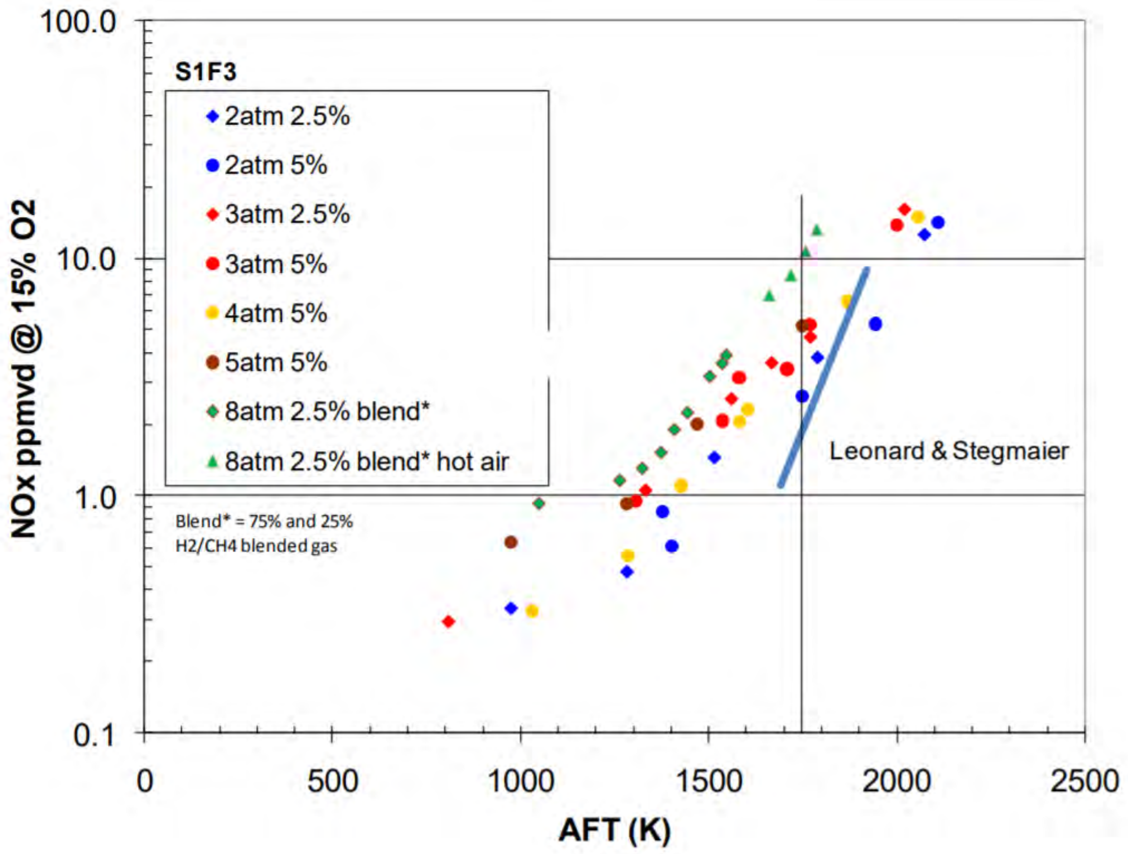
Combustion Emissions – Gas Turbines

- OEMs are conservative in their developments and targets
  - "Slight increase in NOx may result"
  - This has been the case for decades
    - Original NOx limits were 42 ppm, then 25 ppm, then 9 ppm and now 2.3 ppm
      - ~20x reduction attained through technology development
  - Combustion science guides the development
    - Well established
    - Optimization of local combustion temperatures via flow split adjustments
  - UCI measurements on commercial 60kW engine illustrate that NOx can actually be reduced when adding hydrogen
    - Modification of air distribution within the combustion system can take advantage of the wider flammability limits offered by hydrogen
  - UCI currently testing a 200kW version

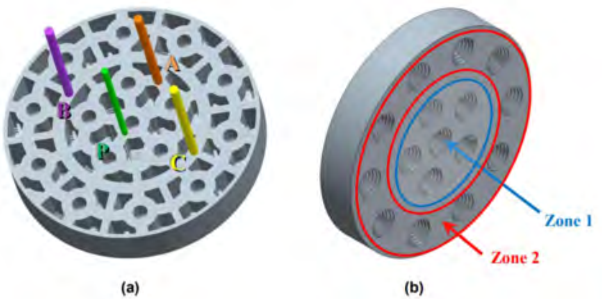


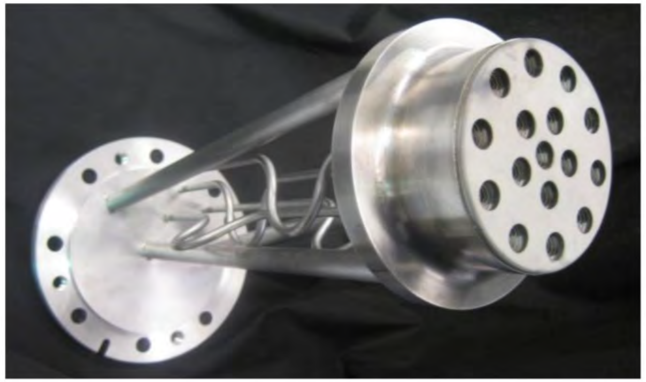
Combustion Emissions – Gas Turbines

- Hydrogen faster flame speed allows more lean operation
- Micro-mixing full-scale GT design



Parker





https://www.osti.gov/servlets/purl/1030641

Directly Use More Renewable Electricity

- Electrify buildings, especially residential new construction – but not all built environment demand is amenable and some infrastructure upgrades are too costly
- Always use renewable electricity directly whenever possible (demand management)
- Store in electrochemical battery energy storage systems first (most efficient storage) – but some uses require rapid fueling, long range, heavy payload (fuel cells)
- Battery electric vehicles (BEV) & fuel cell electric vehicles (FCEV) are important








Proposed New SoCalGas Infrastructure: Angeles Link

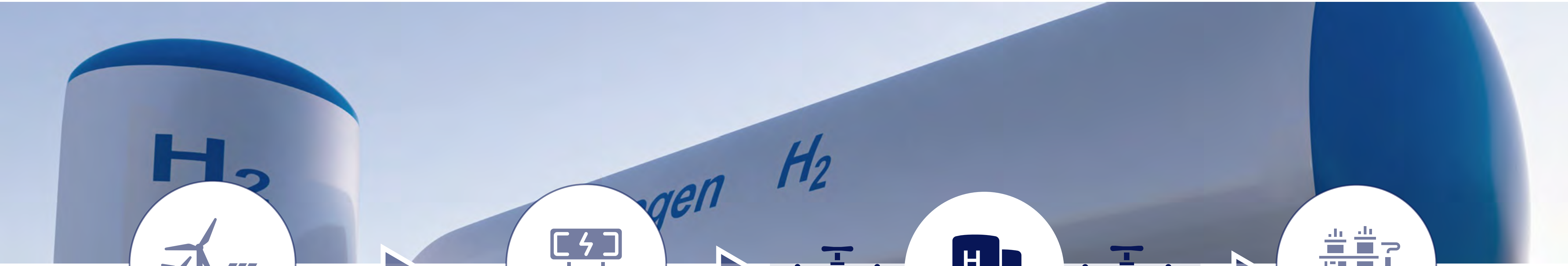
- Proposal to develop what would be the nation's largest green hydrogen energy infrastructure system to deliver clean, reliable energy to the Los Angeles region
- When built, the Angeles Link green hydrogen system could reduce greenhouse gas emissions, improve local air quality, and help SoCalGas serve California's energy needs for generations to come.
- Angeles Link can drive deep decarbonization of heavy-duty transportation, dispatchable electric generation, industrial processes and other hard-to-electrify sectors of the SoCal economy
- **Timing: Memo account application filed with California Public Utilities Commission in February 2022**

ANGELES LINK

Shaping the Future with Green Hydrogen.

From: Yuri Freedman, Southern California Gas Company, 2022.

SoCalGas' Angeles Link: How Could it Work?



25-35 GW Curtailed/New/Solar/Wind
2 GW Batteries

Start with 100% renewable electricity

Utilize renewable electricity that is on the grid or being curtailed to provide power to electrolyzer

10-20 GW Electrolyzers

Convert it into green hydrogen with advanced electrolyzers

Electrolysis splits water into hydrogen and oxygen -- with virtually zero greenhouse gas and criteria pollutant emissions

Hydrogen infrastructure

*Deliver it into LA Basin by pipeline

SoCalGas will use its expertise in pipeline infrastructure and potential rights-of-way to safely deliver hydrogen from outside of LA Basin to industries that need it most

14.3 million tons of CO_2 emissions eliminated

Use it to decarbonize sectors that can't be plugged in

Dispatchable electric generation and hard-to-electrify sectors like manufacturing and heavy-duty transportation are the missing links to solving the most challenging aspect of decarbonization; green hydrogen offers the solution

From: Yuri Freedman, Southern California Gas Company, 2022.

SoCalGas' Angeles Link: Project Benefits

Could provide **zero-carbon green hydrogen** to assist LADWP's conversion of its natural gas electric generation facilities

+

Displace **3 million gallons of diesel per day** reducing NOx **(24,721 tons per year)**, $PM_{2.5}$ and other hazardous air pollutants associated with diesel emissions

=

Could significantly reduce regional natural gas demand to potentially remove **14.3 million metric tons of CO_2**

→

Equivalent to eliminating 57% of LA County's large stationary source CO_2 emissions

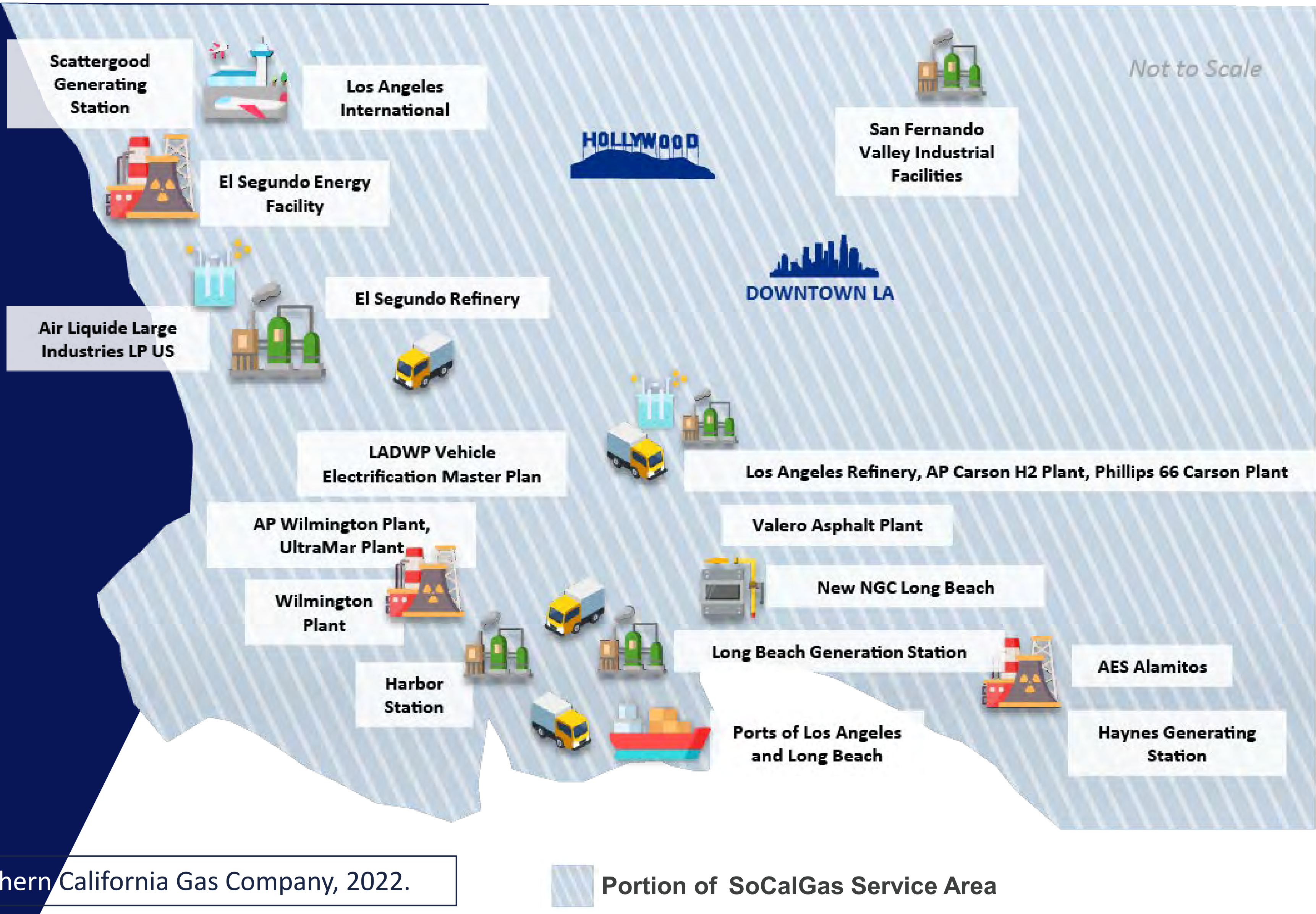
From: Yuri Freedman, Southern California Gas Company, 2022.

Green Hydrogen Could Anchor LA Basin Hub

Reliable and scalable delivery of green hydrogen as demand grows

---

Focuses on large emitters such as electric generation, aviation, cement, chemical manufacturing, shipping and trucking



From: Yuri Freedman, Southern California Gas Company, 2022.

Opportunity for California to be First-Mover

Secures California's legacy as a true world leader in accelerating green energy transition —while growing the economy and local, union workforce

Supports California's bid to pursue significant portion of more than
$9 billion in US Dept. of Energy funding made available by Infrastructure Investment and Jobs Act to build-out hydrogen hubs

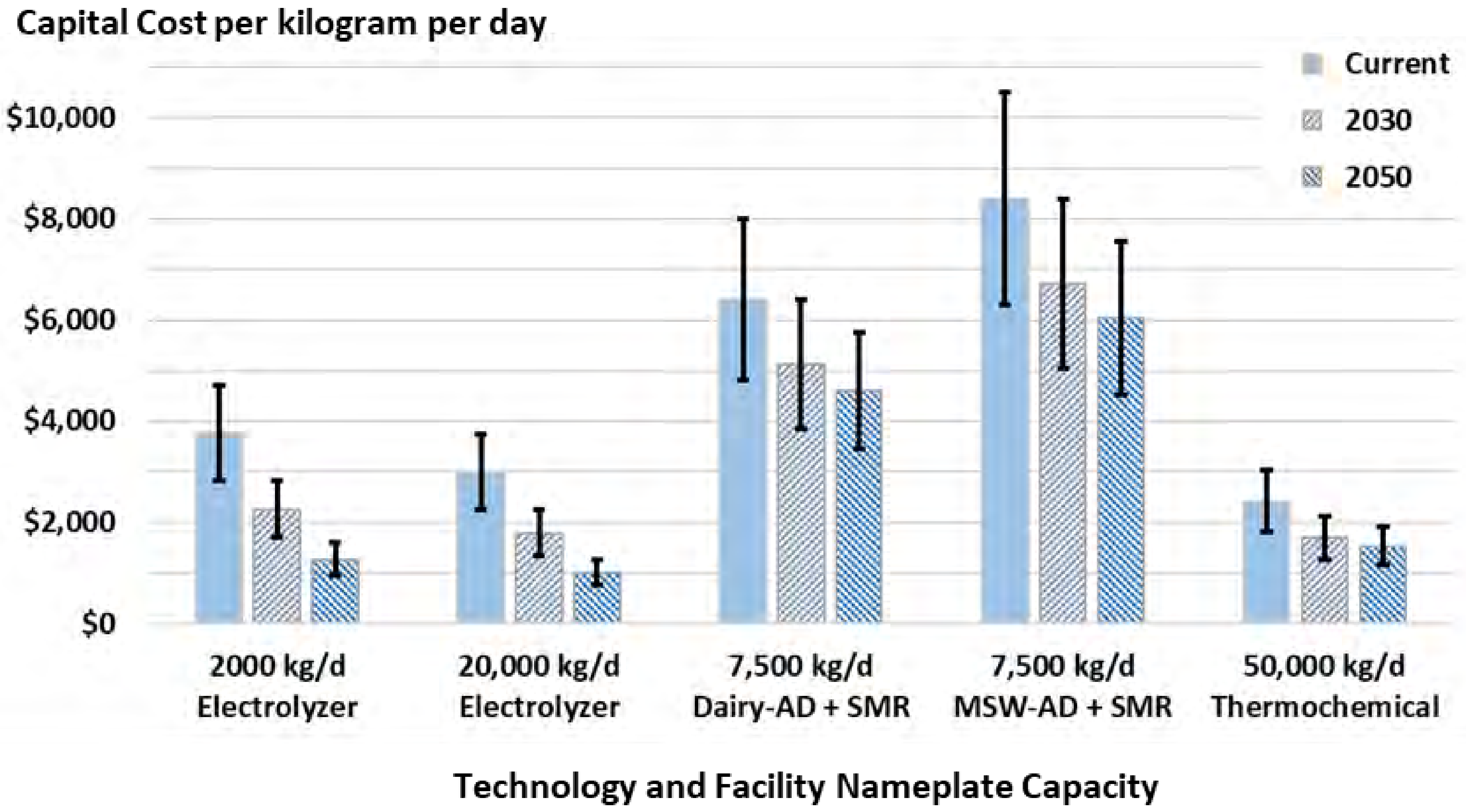
Bring green hydrogen into the LA Basin and advance climate goals and support current and future hydrogen end users, including heavy industry, electric generation, and the heavy-duty transportation sector, such as ports

Make LA Basin the country's leading center for clean fuels and catalyze green hydrogen industry here and abroad

From: Yuri Freedman, Southern California Gas Company, 2022.

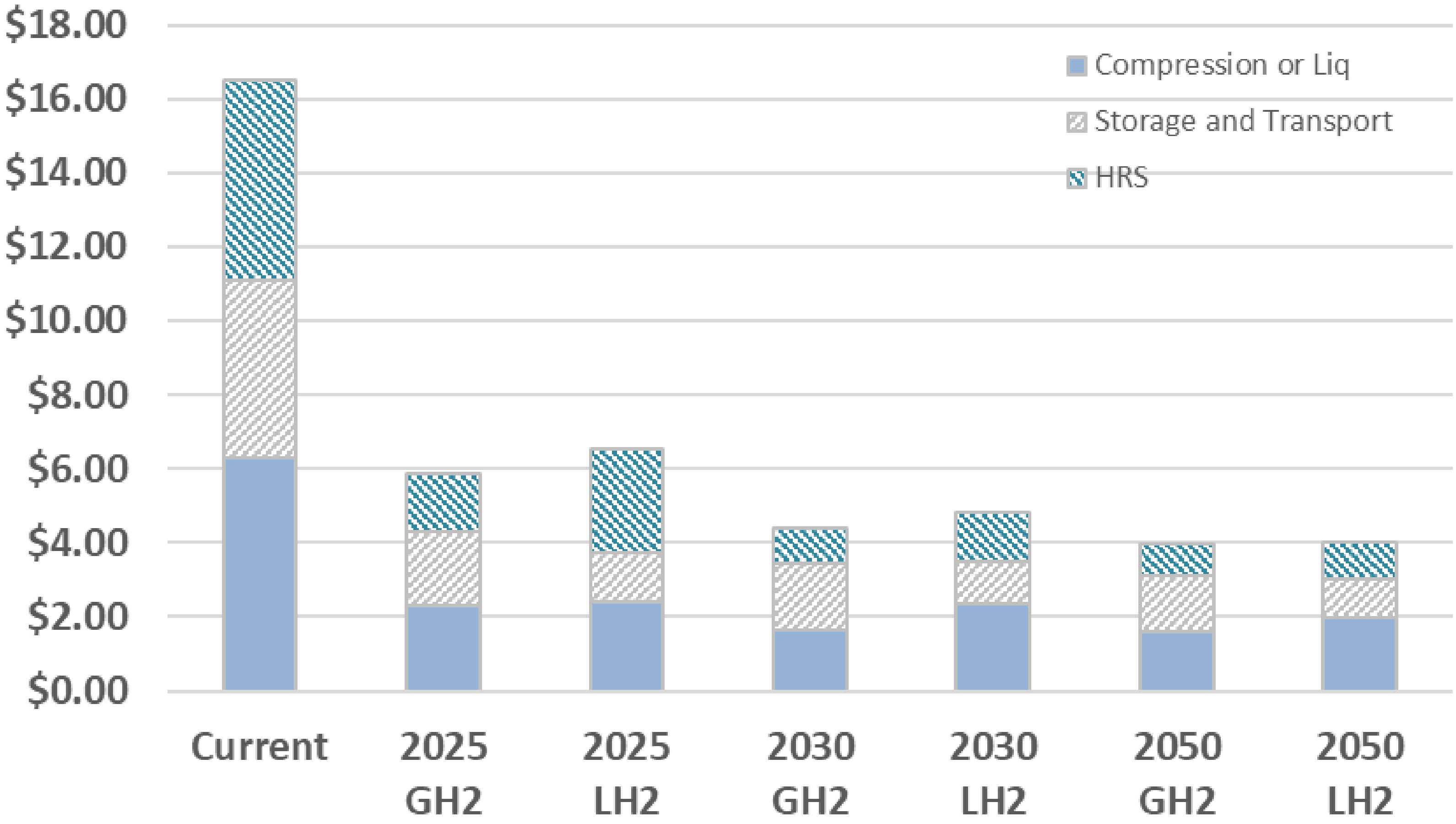
Learning Curve & Other Methods Project Significant Cost Reduction for all RH2 Production Technologies

Electrolyzers show the greatest reduction – nearly 70% by 2050



Hydrogen Supply-chain Costs Forecast to Decline Rapidly

Increased station network use & economies of scale are most significant

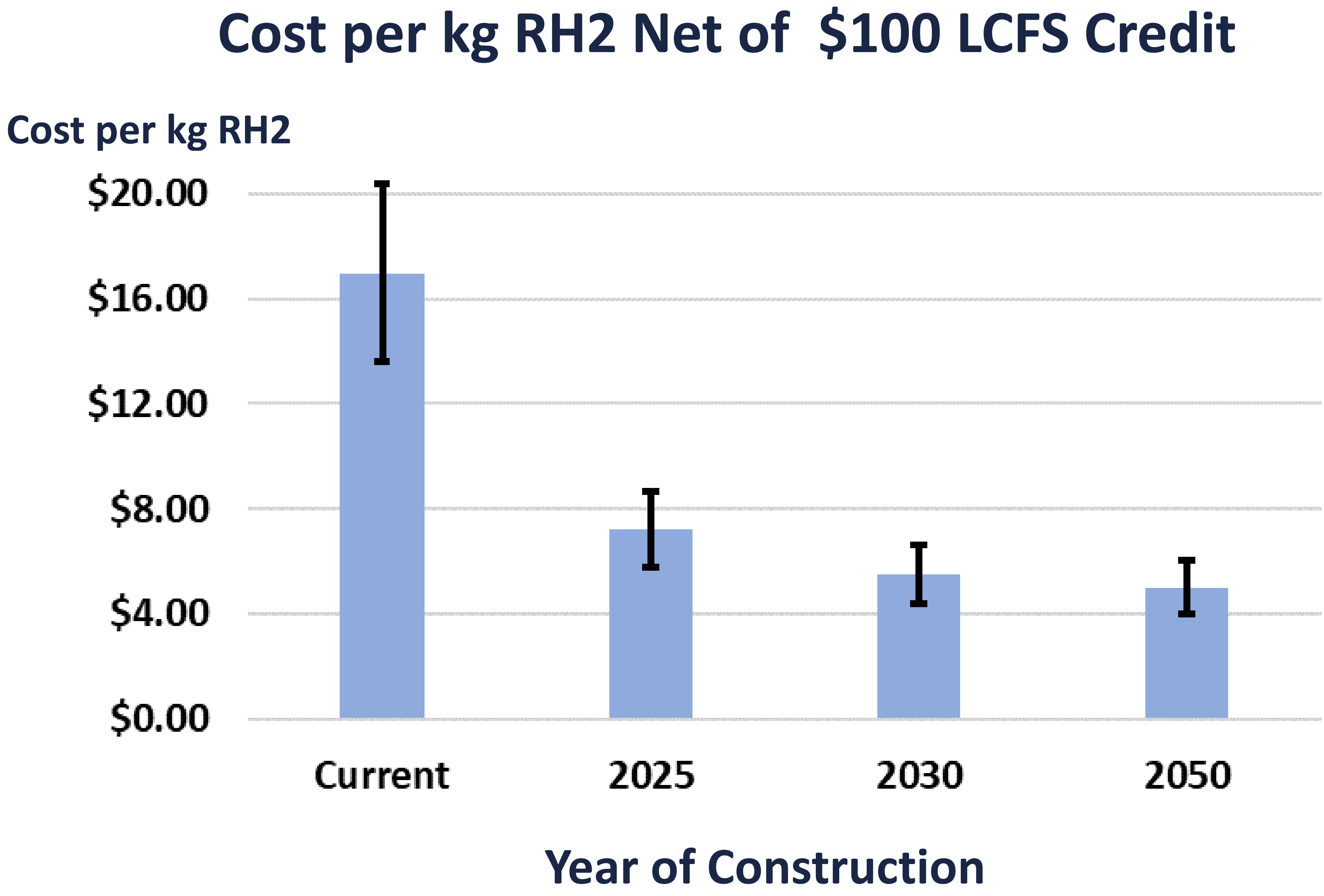


Input Assumptions

	Current	2025	2030	2050
Station Size Kg/d	300	600	1200	1500
Utilization	40%	70%	80%	80%
Production Volume	Low	Medium	High	High

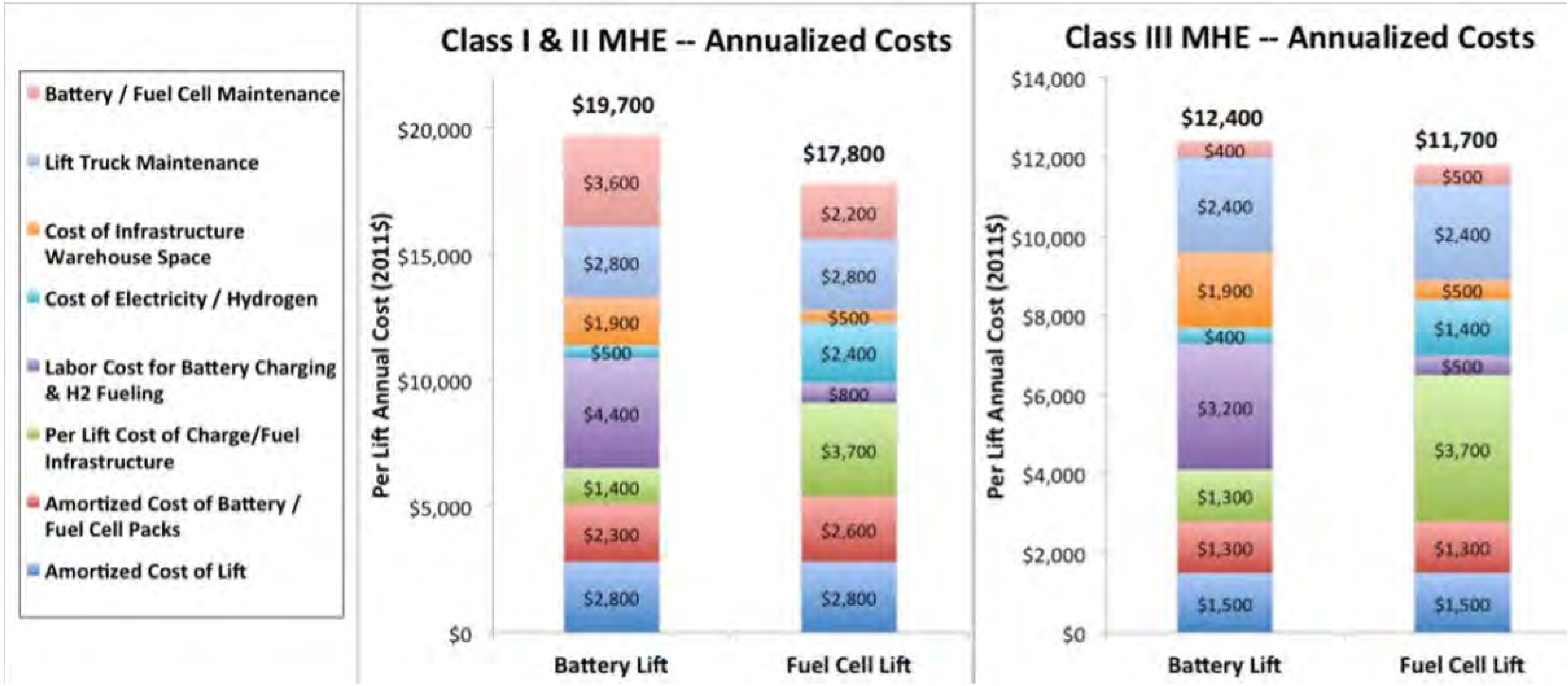
Source: UCI APEP using HDSAM 3.1

Potential Evolution of Pump Price of Renewable Hydrogen



An Evaluation of the Total Cost of Ownership of Fuel Cell-Powered Material Handling Equipment

- Fuel cells provide a cheaper cost of ownership compared to batteries-for class I, II, and III forklifts. Fuel cells reduce ownership costs by 5% to 10%, these costs include the infrastructure costs in the annual costs as well (pg.v)



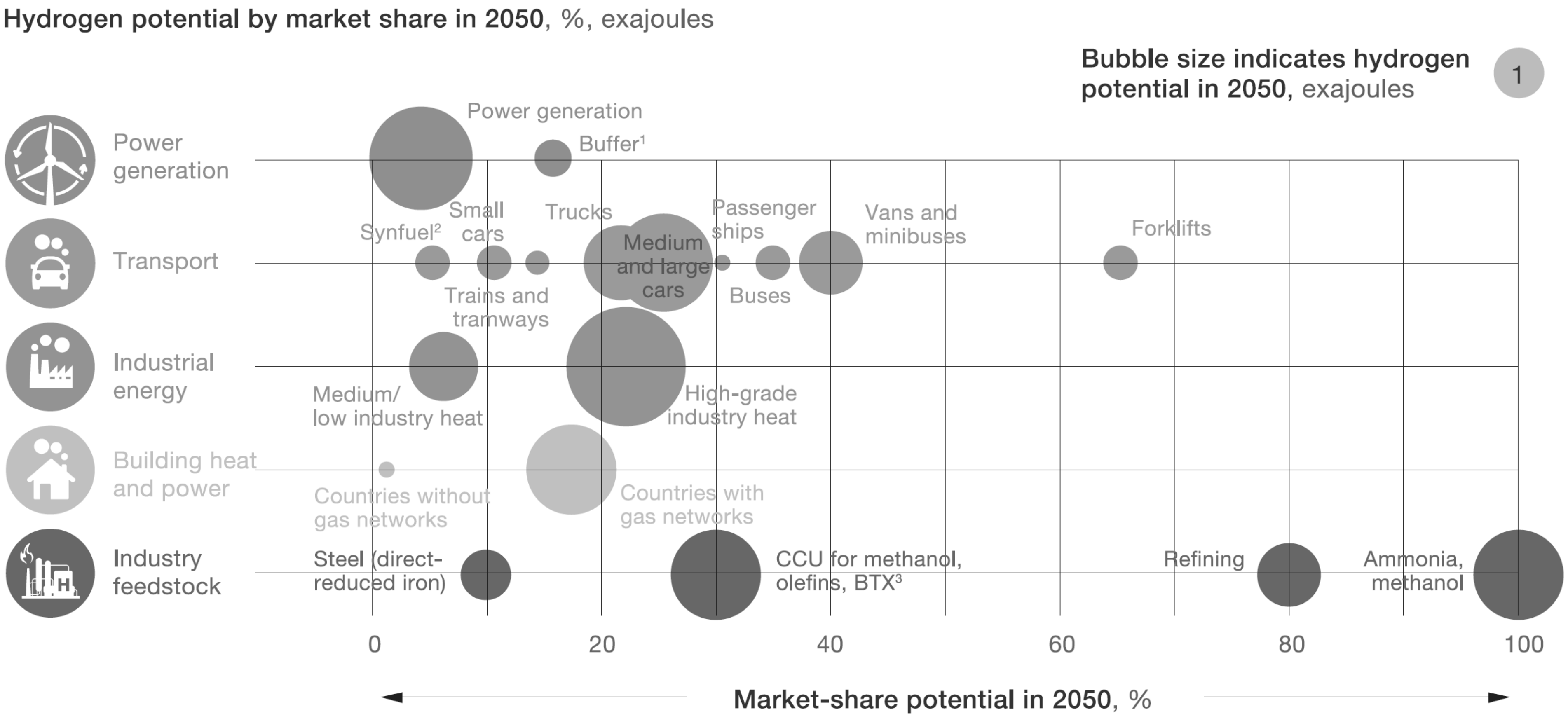
- Fuel cells have higher fuel costs and more expensive infrastructure compared to batteries; however, fuel cells drastically reduced labor and space costs in these tests (pg.27)

Ramsden, T. (2013). *An Evaluation of the Total Cost of Ownership of Fuel Cell Powered Material Handling Equipment*. https://www.nrel.gov/docs/fy13osti/56408.pdf

Role of Green Hydrogen in Markets

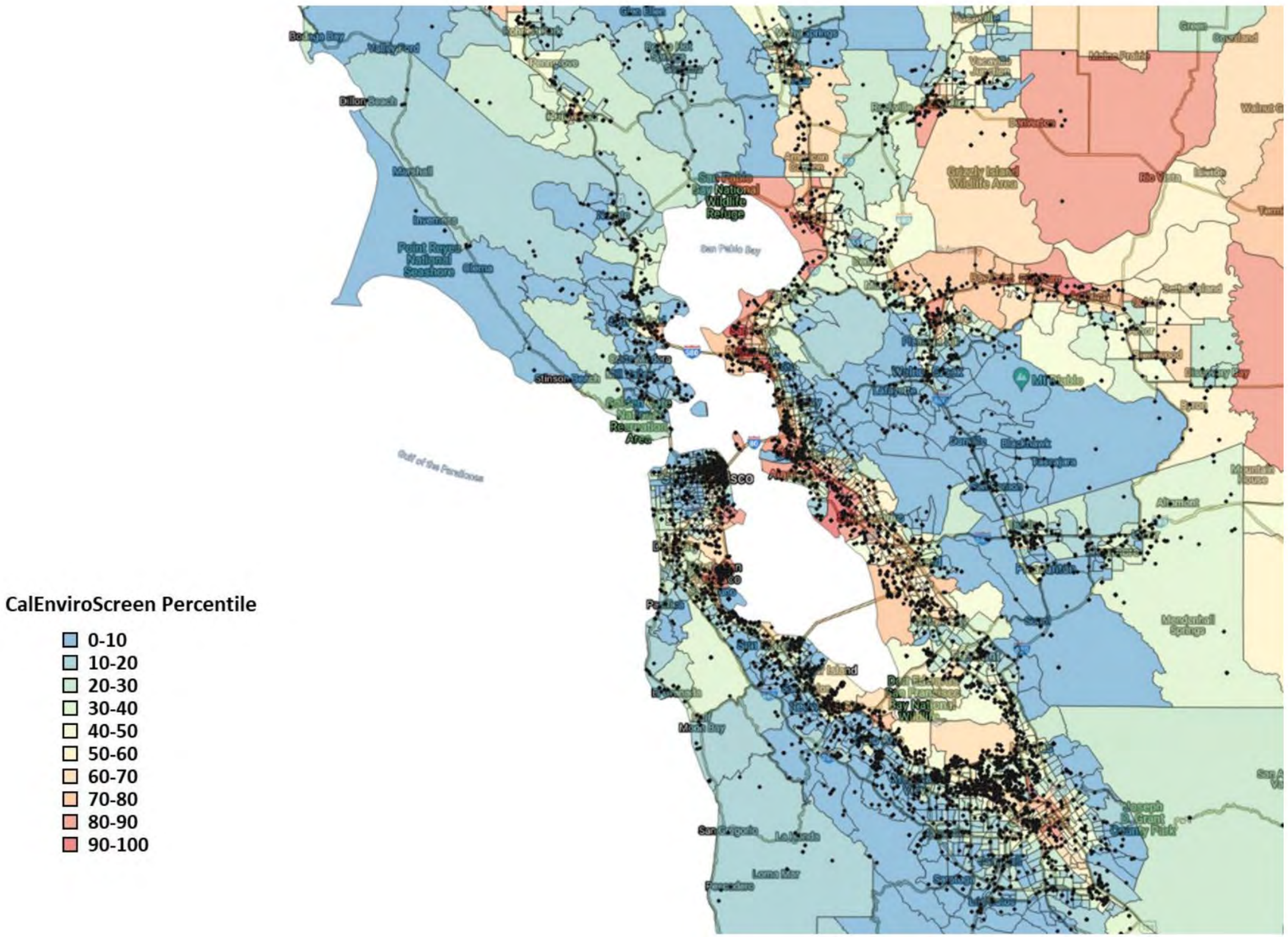
Comparative Analysis: H2 & FCEV vs. Grid & BEV

- Bernd Heid, Martin Linder, Anna Orthofer, Markus Wilthaner
- McKinsey & Company



Recent Increase in Fossil Back-up Generator Deployment

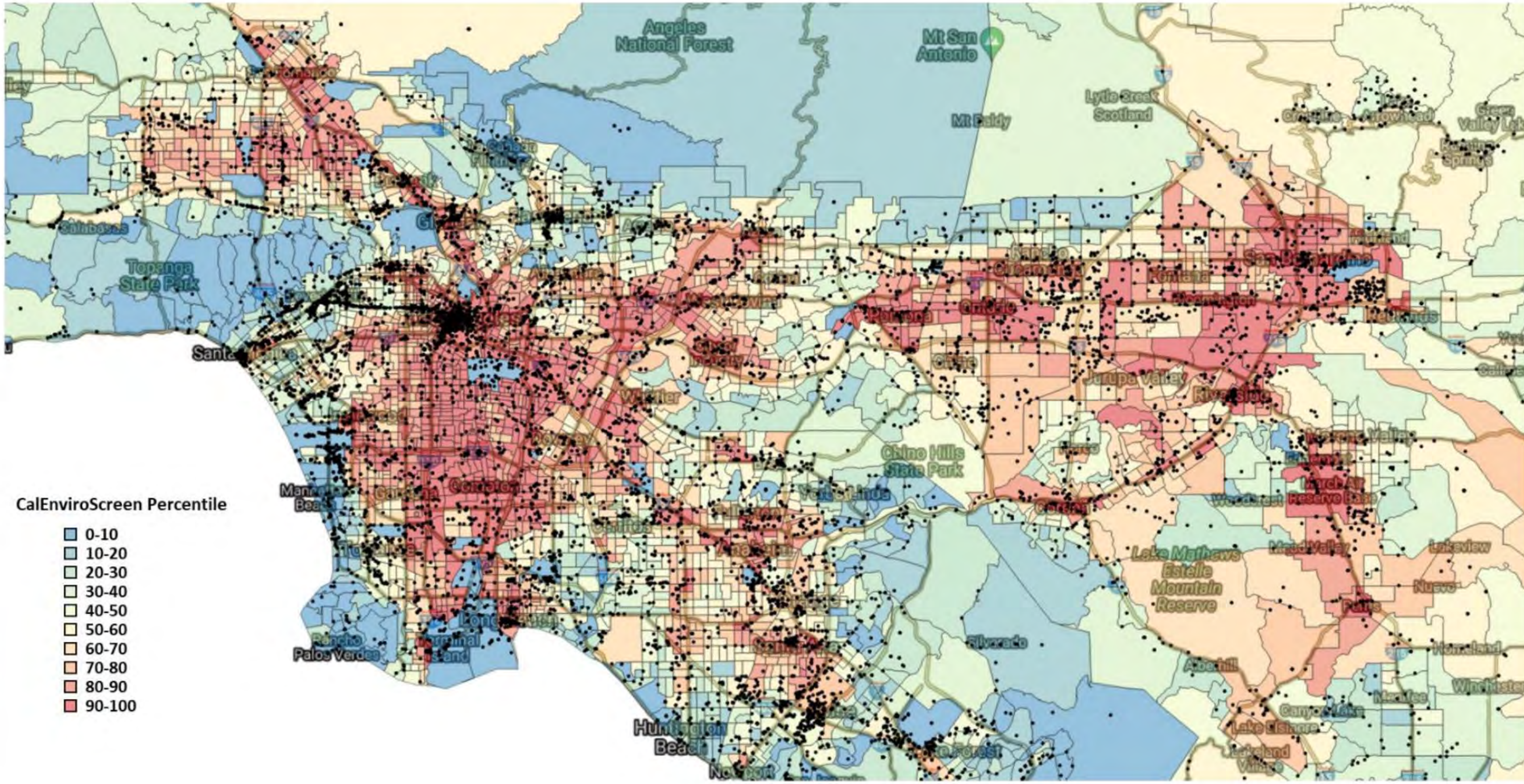
- 34% increase in Bay Area from 2018 - 2021
- > 8,700 deployed
- Capable of > 4.8 GW
- Disproportionately located in disadvantaged communities (CalEnviroScreen 3.0 percentiles shown)



https://www.bloomenergy.com/wp-content/uploads/diesel-back-up-generator-population-grows-rapidly.pdf

Recent Increase in Fossil Back-up Generator Deployment

- 22% increase in SoCAB
- > 14,00 deployed
- Capable of > 7.3 GW
- Disproportionately located in disadvantaged communities (CalEnviroScreen 3.0 percentiles shown)



https://www.bloomenergy.com/wp-content/uploads/diesel-back-up-generator-population-grows-rapidly.pdf

Recent Increase in Fossil Back-up Generator Deployment

M.Cubed study found significant health & economic impacts of BUGs

- Used U.S. EPA's CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA)
- Estimated annual economic benefits of reducing BUG emissions
  - $3.5 to $7.9 million annually for a 25% reduction
  - $7.0 to $15.9 million for a 50% reduction
  - $14.1 to $31.8 million for a 100% reduction

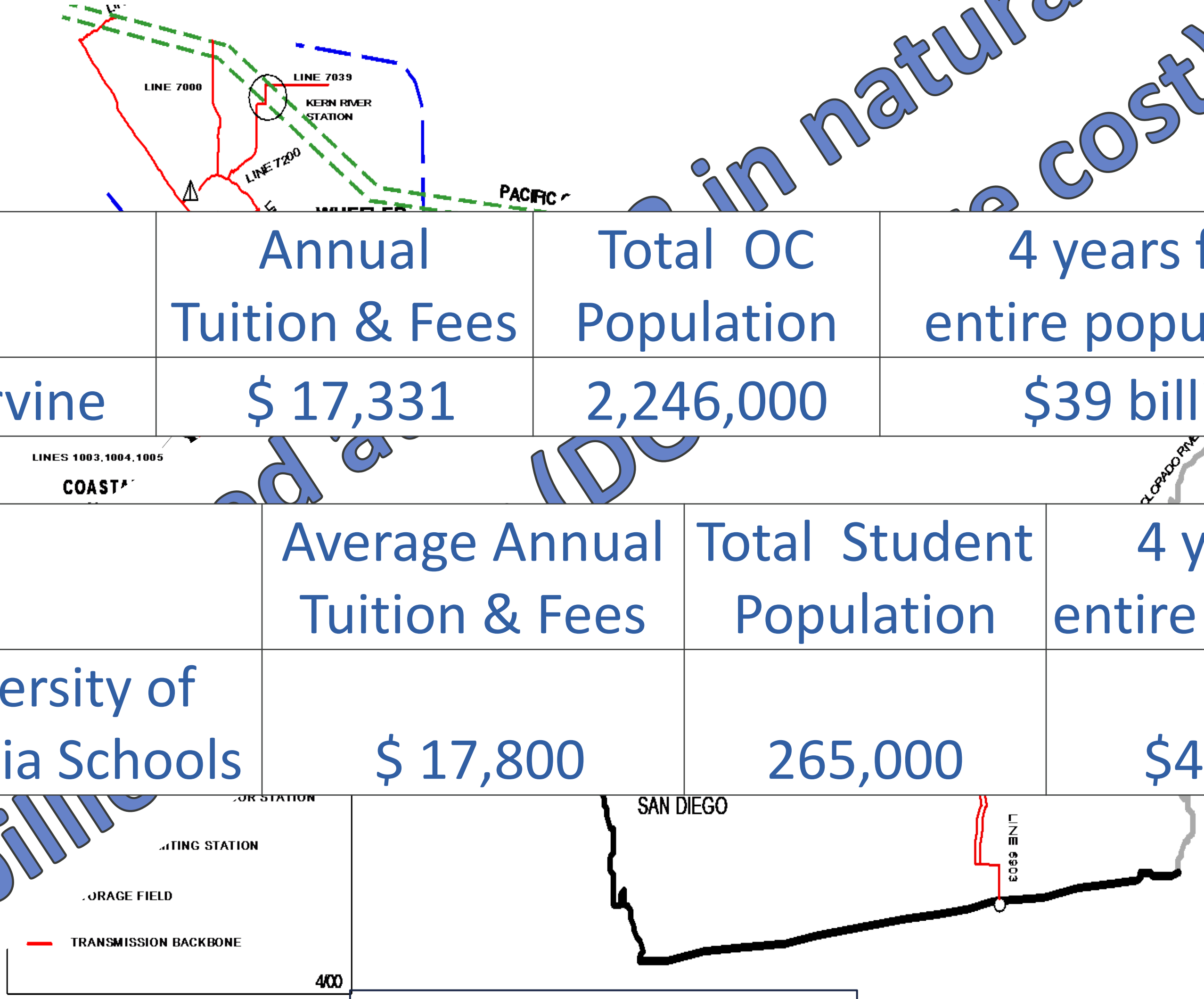
https://www.bloomenergy.com/wp-content/uploads/diesel-back-up-generator-population-grows-rapidly.pdf

Resilient Storage & Transmission/Distrib… Resource

- Natural Gas Transmission, Distribution & Storage Syster…

> 99.999% available

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



	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

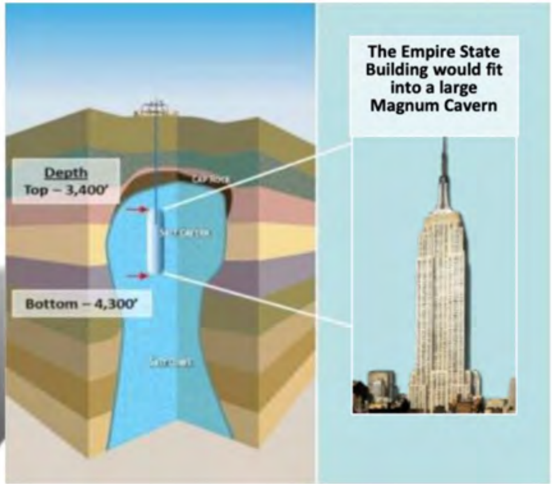
650 G… in natural gas

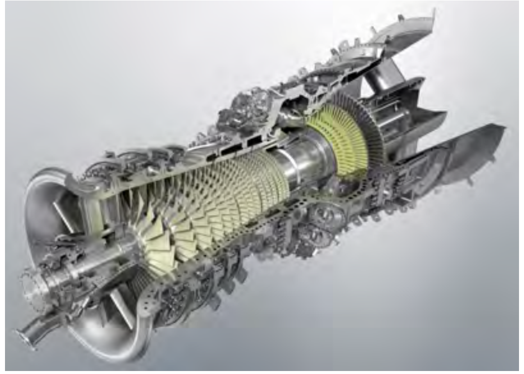
$130 billi… cost)

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

Example: Renewable H_2 Production & Use by LADWP

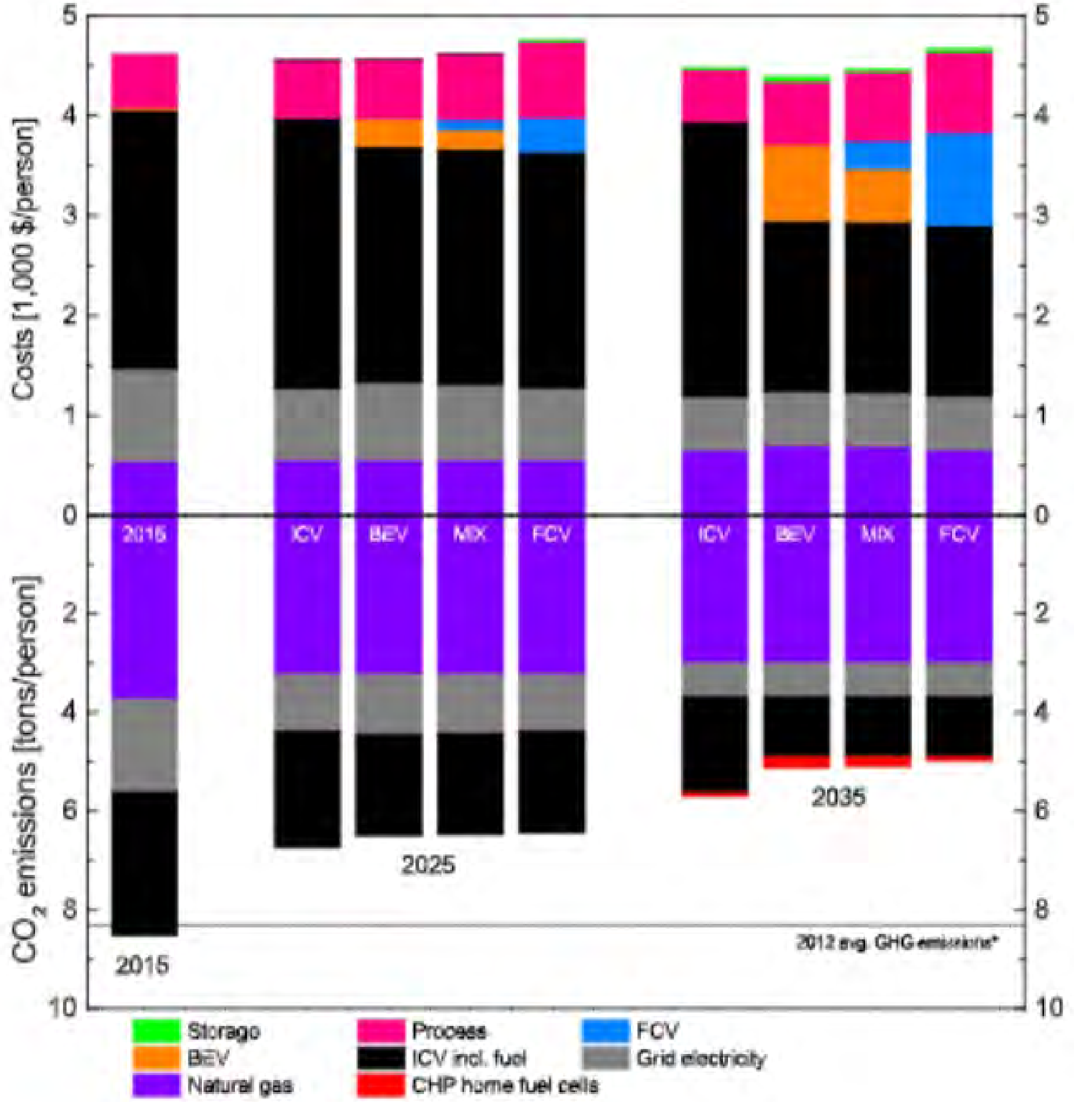
- Salt Caverns & other facilities proven to safely store massive amounts of hydrogen
- Magnum working with LADWP to adopt similar salt cavern H_2 storage in Utah
- Gas turbines – colleagues & competitors
  - state-of-the-art for large scale power generation
- All gas turbine manufacturers evolving H_2-use
  - GE, Mitsubishi, Siemens, Solar, others





Evaluating co-benefits of battery and fuel cell vehicles in a community in California

- The cost for an initial hydrogen refueling system would cost ~$450M (pg.360)
- “”producing and selling hydrogen was found to be much more valuable than producing and storing hydrogen to later produce electricity”” (pg.361)
- A mix of FCEVs and BEVS (30% and 70% respectively) is the only way to have lower costs and emissions (pg.364)
- FCEVs may have lower emissions but cost “significantly” more (pg.364), BEVs have a lower overall cost—study is conducted for light-duty vehicles.
- For FCEVs “the economic benefits of grid storage…are not sufficient” to justify the “significantly higher” hydrogen infrastructure costs (pg.367)



Felgenhauer, M., Pellow, M., Benson, S., & Hamacher, T. (2016). *Evaluating co-benefits of battery and fuel cell vehicles in a community in California*. Energy, 114, 360–368.

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Gas Transformation Key Findings from Literature Review

- Converting to a system that relies solely on hydrogen is the "most cost-effective end state for a deeply decarbonized gas system" (pg.1)
- Being able to use existing natural gas lines for hydrogen infrastructure would be 80% cheaper than building an entirely new hydrogen infrastructure system (pg.7)
- An equal mix of hydrogen, batteries, and biomethane is ~10% cheaper than the 100% battery infrastructure system (pg.10)
- In 2050 it is projected that over 50% of buildings will rely on hydrogen

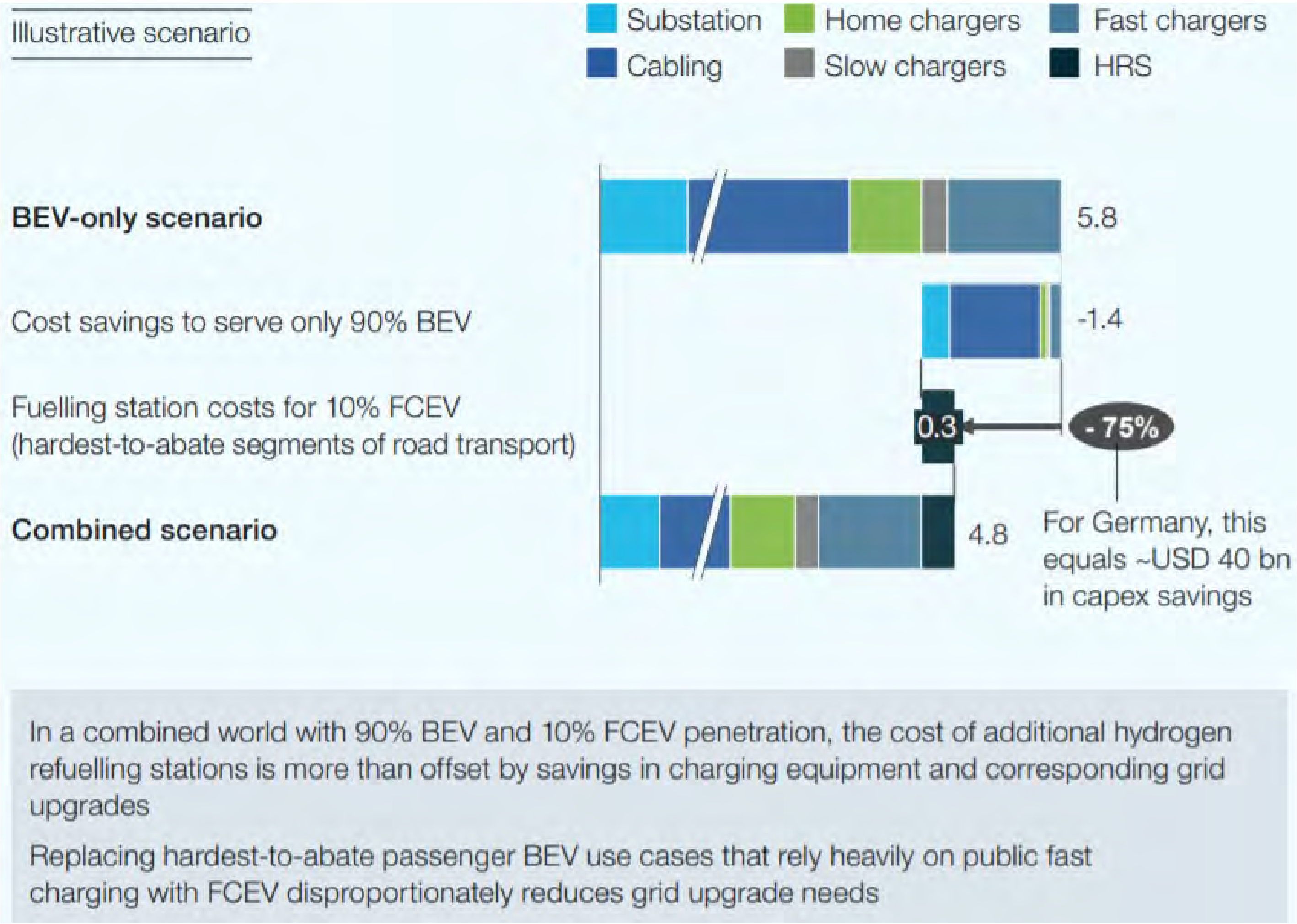
		Low	Medium	High
Pipeline cost	€ billion	33	41	51
Compression cost	€ billion	10	15	30
Total investment cost	**€ billion**	**43**	**56**	**81**
OPEX (excluding electricity)	€ billion/year	0.8	1.1	1.8
Electricity costs	€ billion/year	0.9	1.1	2.0
Total OPEX	**€ billion/year**	**1.7**	**2.2**	**3.8**

Chart shows capital and operating costs for European hydrogen system

Gas Transformation project. (2021). Gas Transformation Key Findings from Literature Review.

Roadmap towards zero emissions

- The cost for FCEV infrastructure versus BEV infrastructure is highly dependent on the location and available resources (pg.20)
- Building both FCEV and BEV infrastructure is cheaper than just building one or the other this is because upgrading to higher power electricity in remote and high-demand places is very expensive. Hydrogen can better suit the needs of these areas(pg.23)



Hydrogen Council. (2021). Roadmap towards zero emissions. https://hydrogencouncil.com/wp-content/uploads/2021/10/Transport-Study-Full-Report-Hydrogen-Council-1.pdf

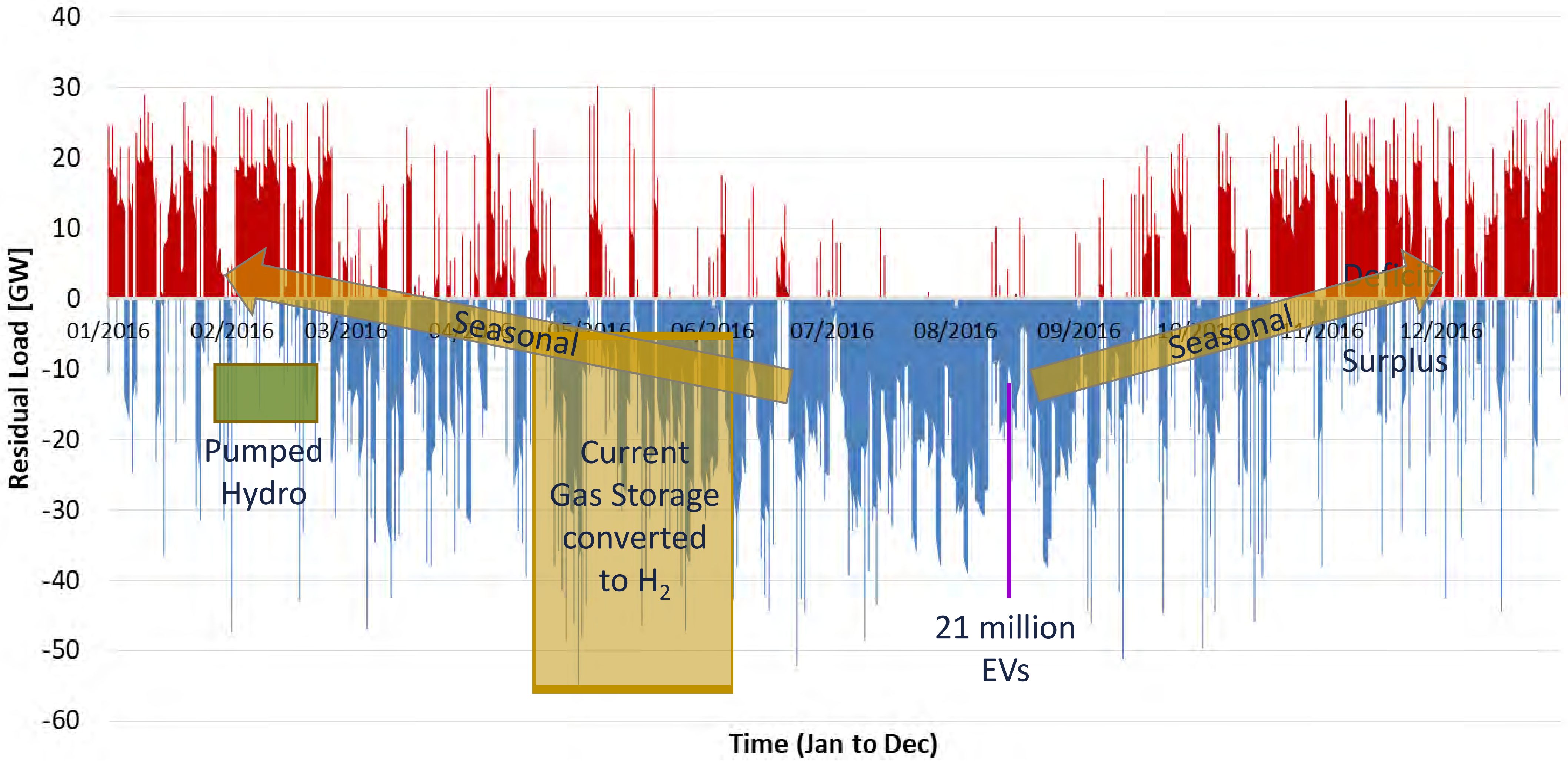
Orange County Transportation Authority's Zero-Emissions Bus Rollout Plan

- The infrastructure costs for both FCEBs and BEBs is "comparable…in cost with unit discount for large purchases" (pg.7)
- A mixed fleet consisting of 61% FCEBs, 15% depot-only BEBs, and 24% depot/ on-route charging BEBs has a TCO/mile that is 1% cheaper than a 100% FCEB fleet. The mixed fleet also requires 9% less upfront capital but from an operations standpoint the mixed fleet is 12% more expensive. This makes the 100% FCEB fleet the cheaper overall option, these include acquisition, infrastructure, and fuel costs.

Johnson, D. (2020). *Orange County Transportation Authority's Zero-Emission Bus Rollout Plan*. https://ww2.arb.ca.gov/sites/default/files/2020-09/OCTA ZEB Rollout Plan_ADA08122020.pdf

Dynamics of Renewable Future are Challenging

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



Assessment of Natural Gas and Electric Distribution Service Reliability

- Electricity "is considerably more vulnerable" to being damaged compared to natural gas (pg.17)
- Considering that hydrogen could be distributed in the same way as natural gas, hydrogen infrastructure could be the more reliable power distribution method in times of extreme weather

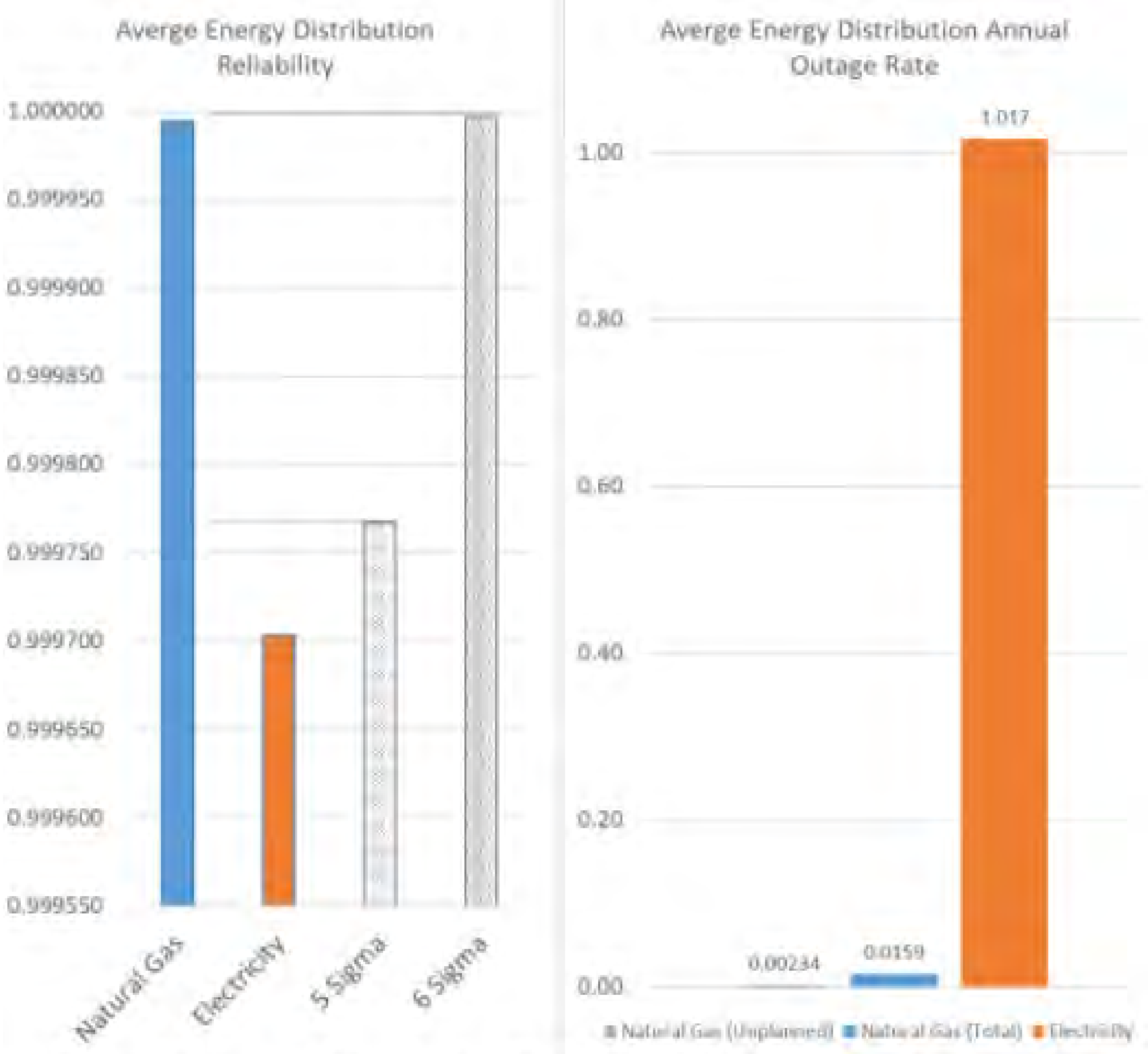


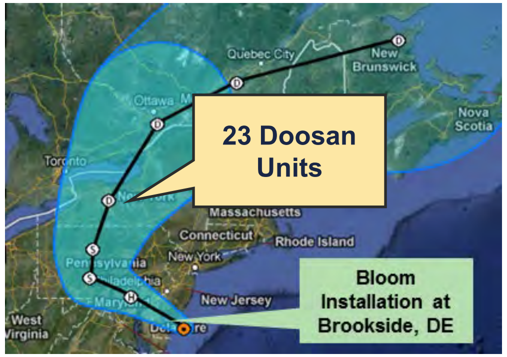
Figure 18: Energy Distribution Reliability and Outage Rate Comparison

Demonstrated Resilience of Fuel Cells and Gas System

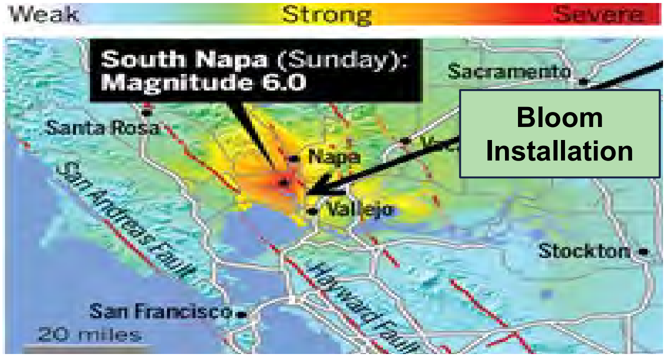
San Diego Blackout, 9/28/11

Winter Storm Alfred, 10/29/11

Hurricane Sandy, 10/29/12



CA Earthquake, 8/24/14

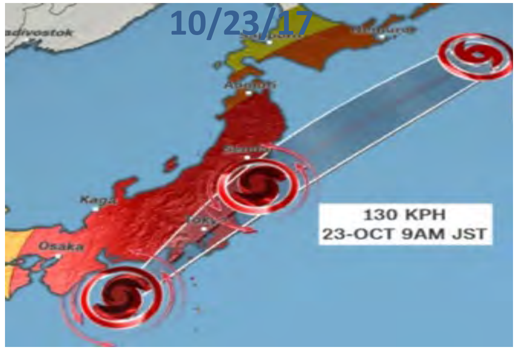


Data Center Utility Outage, 4/16/15

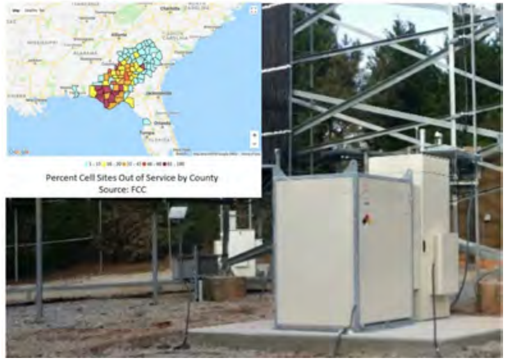
Hurricane Joaquin, 10/15/15

Napa Fire, 10/9/17

Japanese Super-Typhoon, 10/23/17



Hurricane Michael, 10/15/18

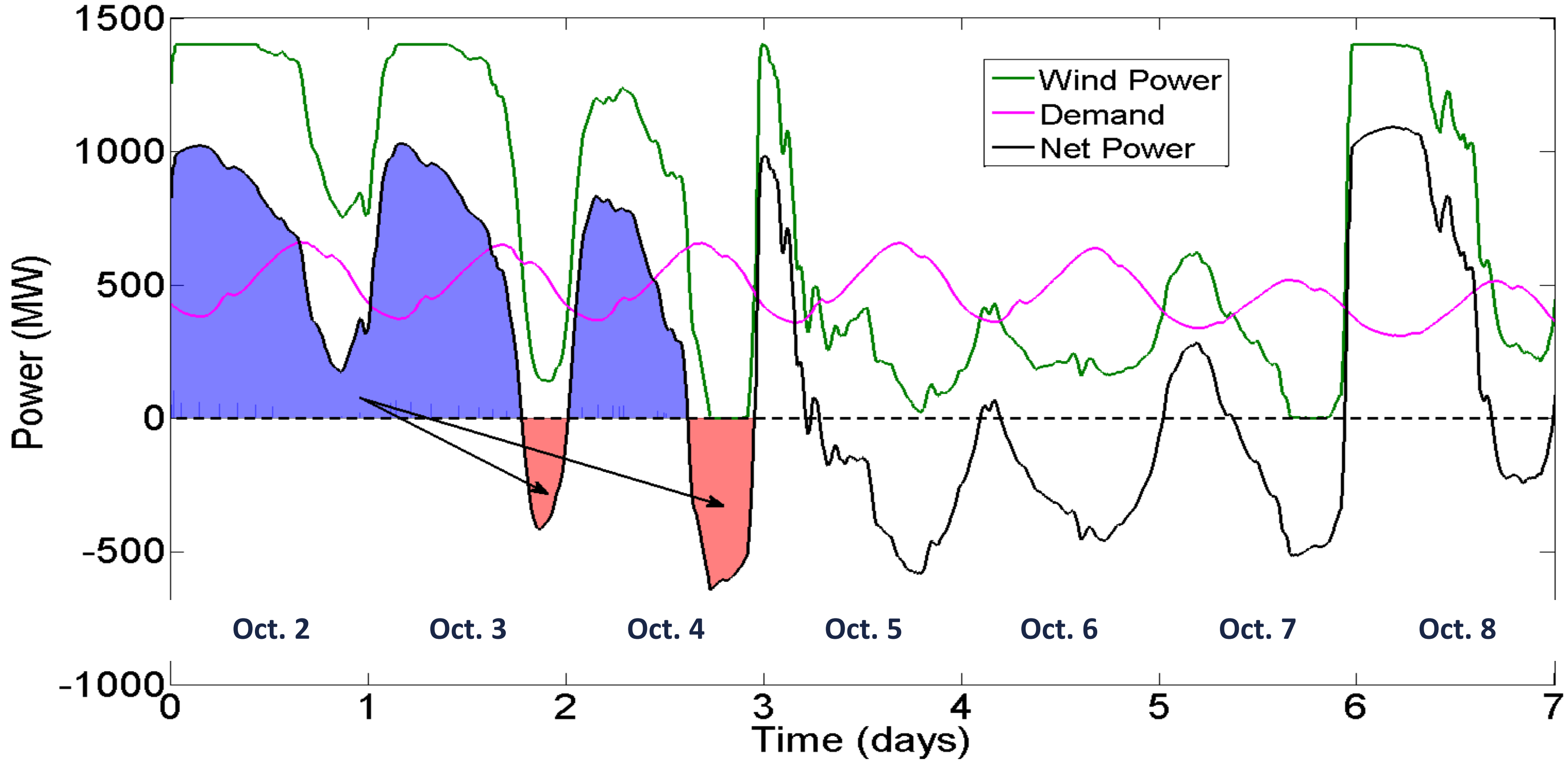


Ridgecrest Earthquakes, 7/4-5/19

Manhattan Blackout, 7/13/19

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

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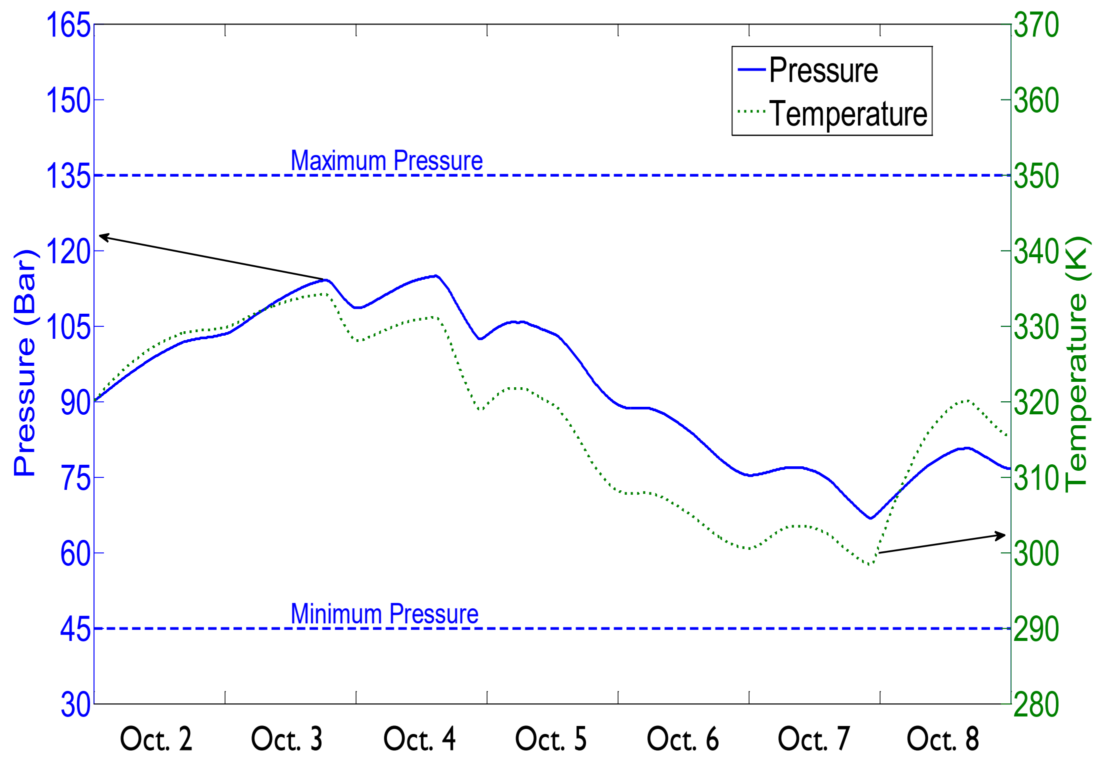
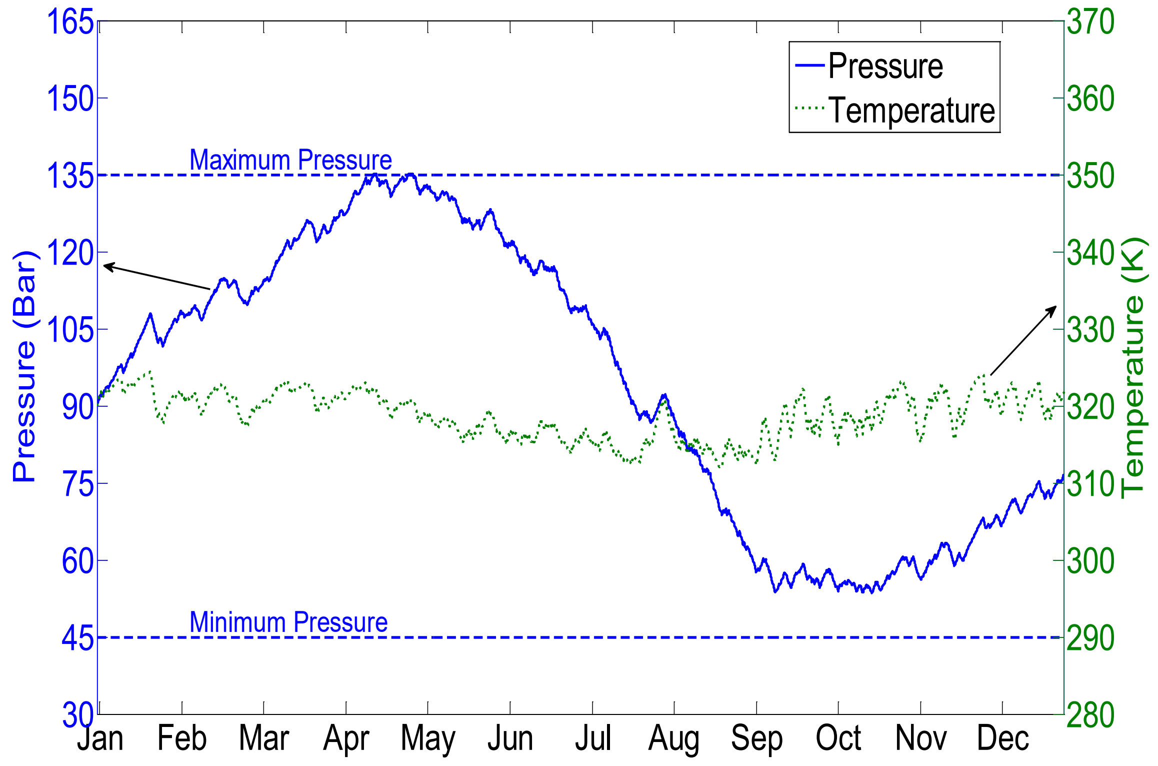
Hydrogen Energy Storage Dynamics

- 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?

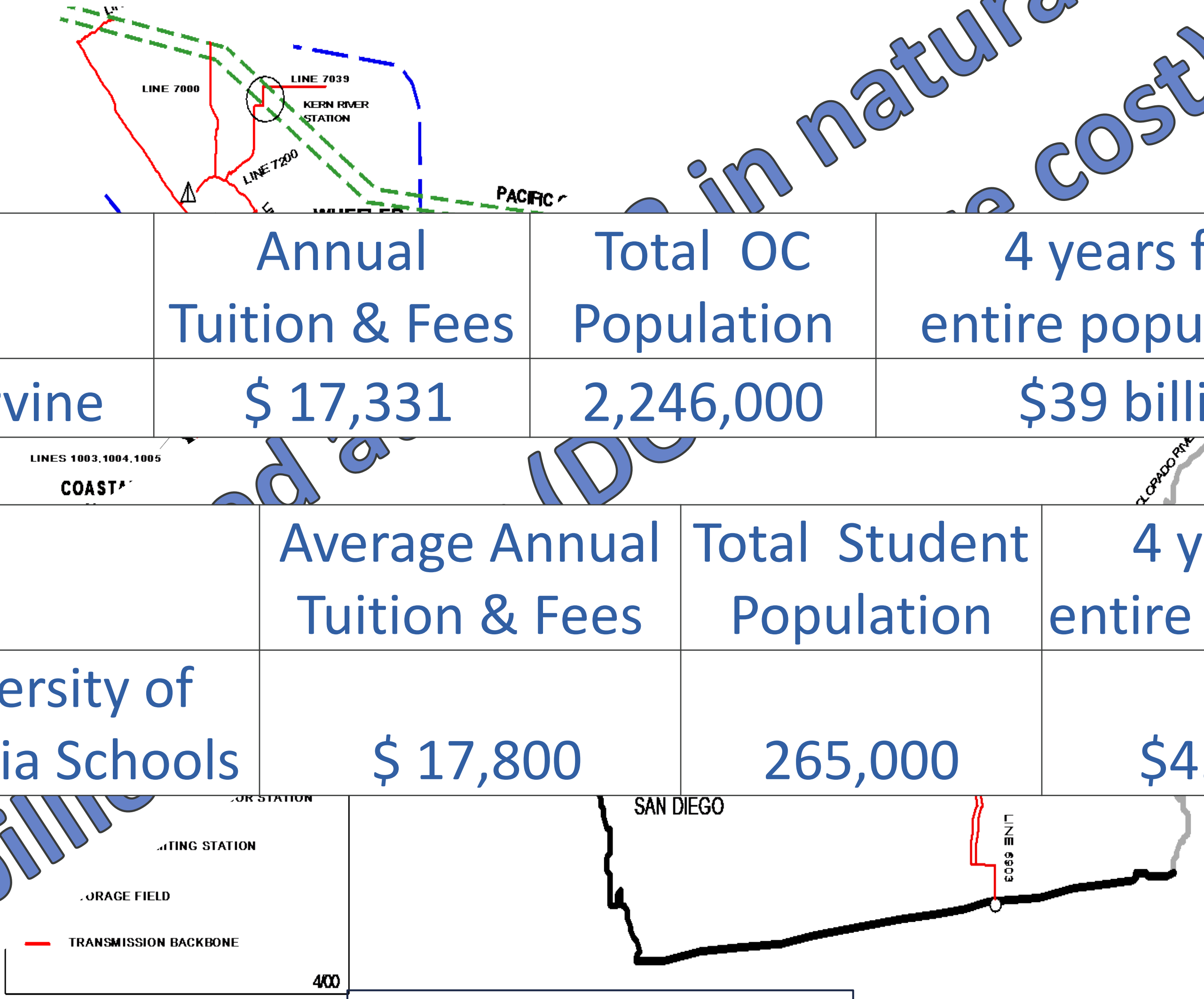
Maton, J.P., Zhao, L., Brouwer, J., Int'l Journal of Hydrogen Energy, Vol. 38, pp. 7867-7880, 2013

Resilient Storage & Transmission/Distrib... Resource

- Natural Gas Transmission, Distribution & Storage System

> 99.999% available

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



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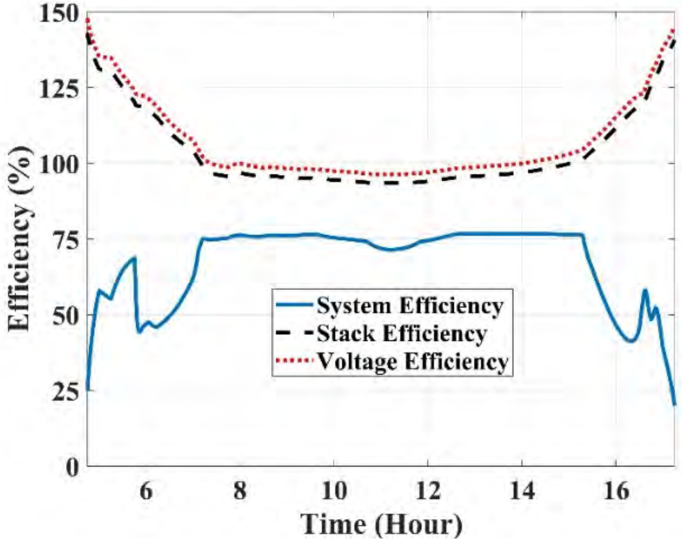
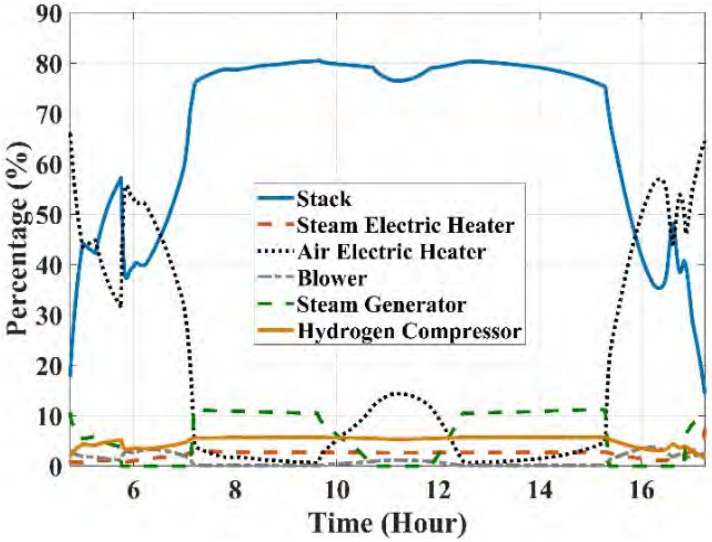
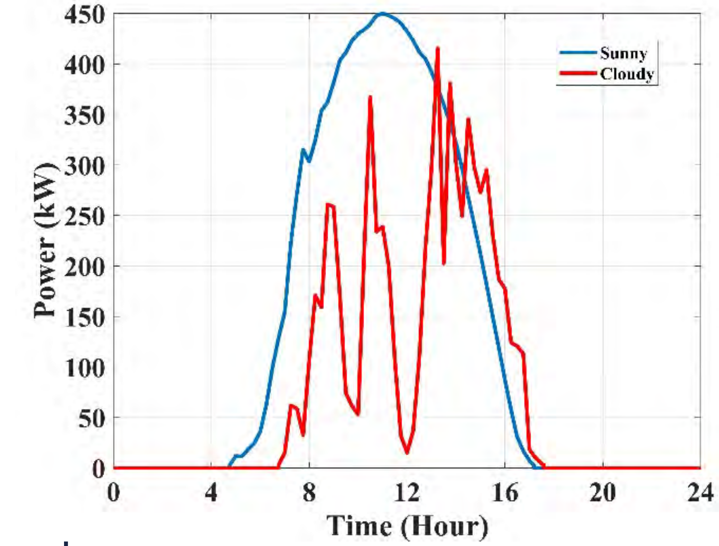
Carmona, Adrian, M.S. Thesis Project, UC Irvine, J. Brouwer advisor, 2014.

Dynamic Operation of SOEC System

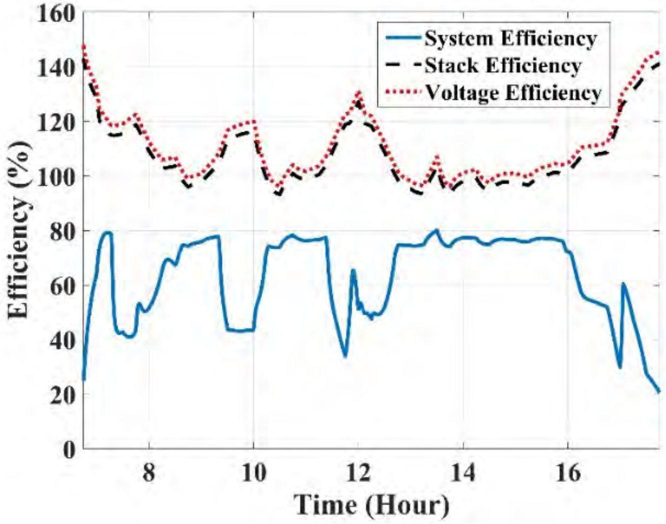


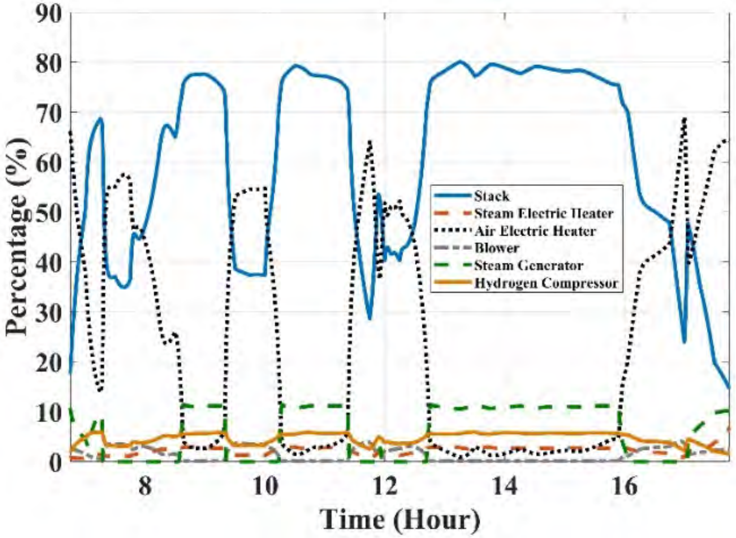


Sunny



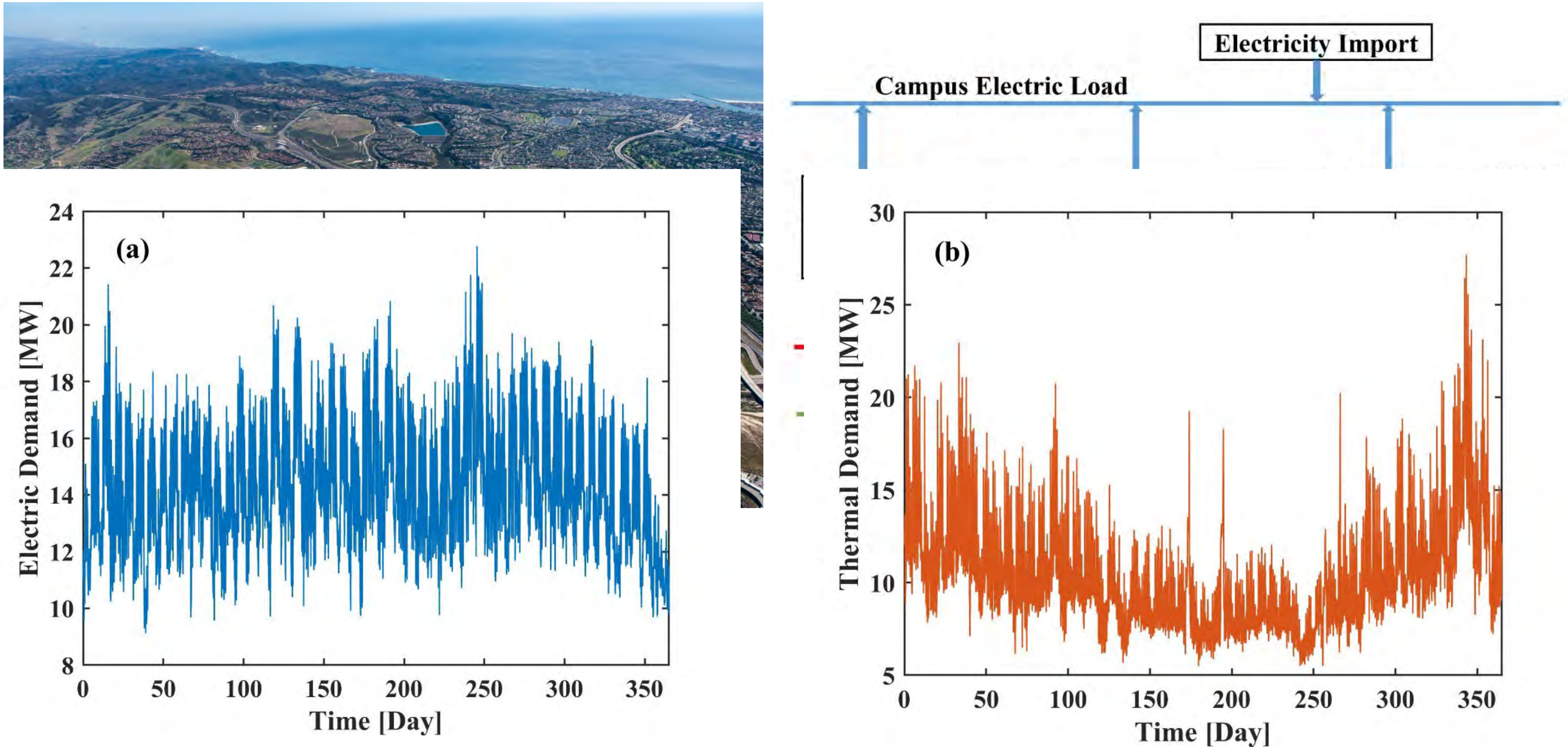
Cloudy





Saeedmanesh, A., Colombo, P., McLarty, D. and Brouwer, J., Journal of Electrochemical Energy Conversion and Storage, 2019.

UCI Microgrid Simulation



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Colombo, P., Saeedmanesh, A., Santarelli, M. and Brouwer, J., Energy Conversion and Management, 2019.

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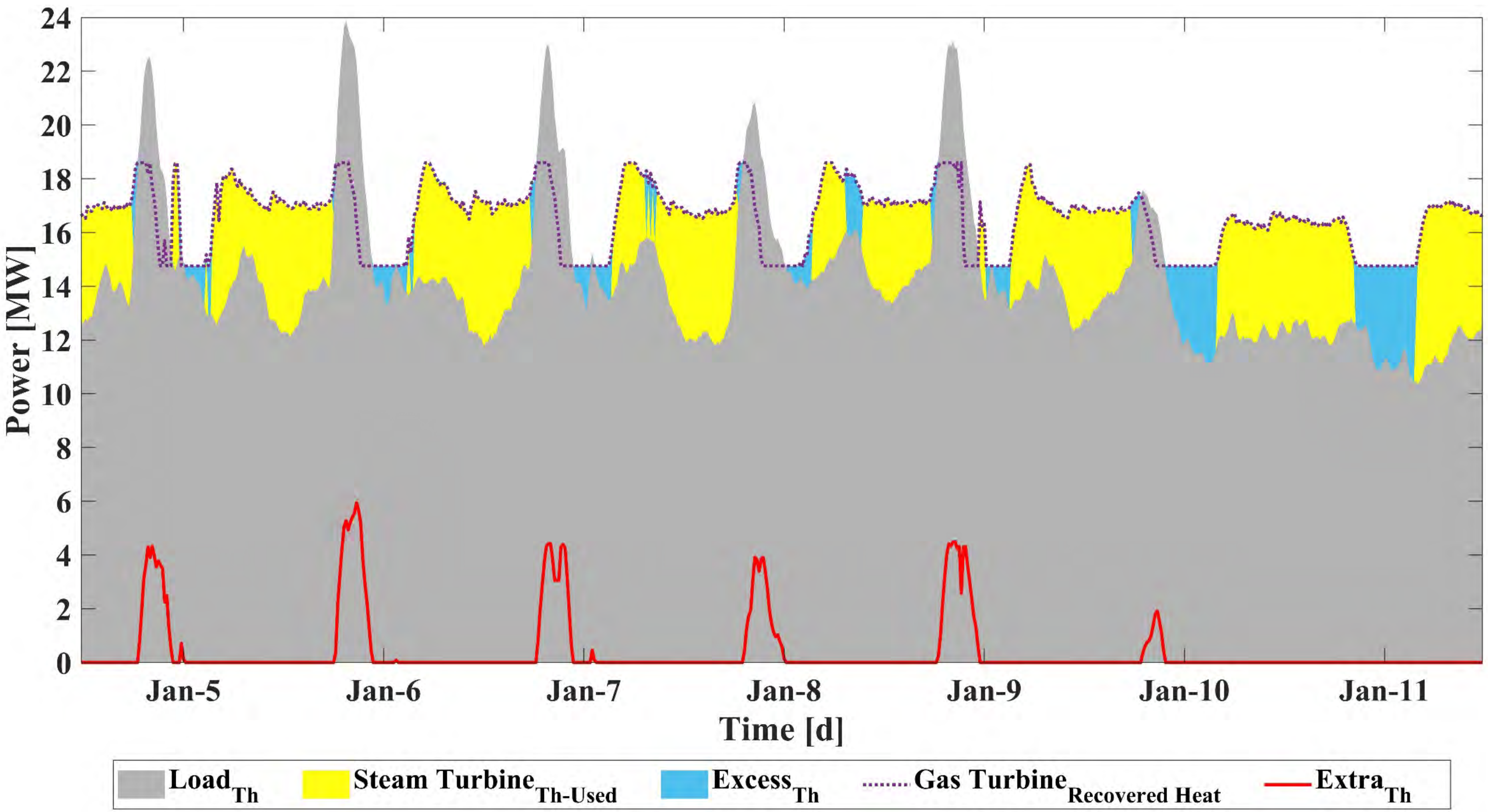
UCI Microgrid Results in High Renewable Use Cases



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Colombo, P., Saeedmanesh, A., Santarelli, M. and Brouwer, J., Energy Conversion and Management, 2019.

Hydrogen is Essential for Sustainability

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 potent
- Sufficient raw materials on earth
- Water naturally recycled in short time o
- Feedstock for industry heat
- Feedstock for industry chemicals (e.g.
- Pre-cursor for high energy density ren
- Re-use of existing infrastructure (lowe

Available online at www.sciencedirect.com

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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

CrossMark

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.

UCI

RD&D Topic #2: Hydrogen Safety & Sensing

Tests for Hydrogen Safety

Fire

Mechanical Damage

Courtesy: BMW Group, 2000
and Garrity, Murdoch Univ., 2002

Excessive Tank Pressure (Blocking all safety valves)

Hydrogen Leak **Gasoline Leak**

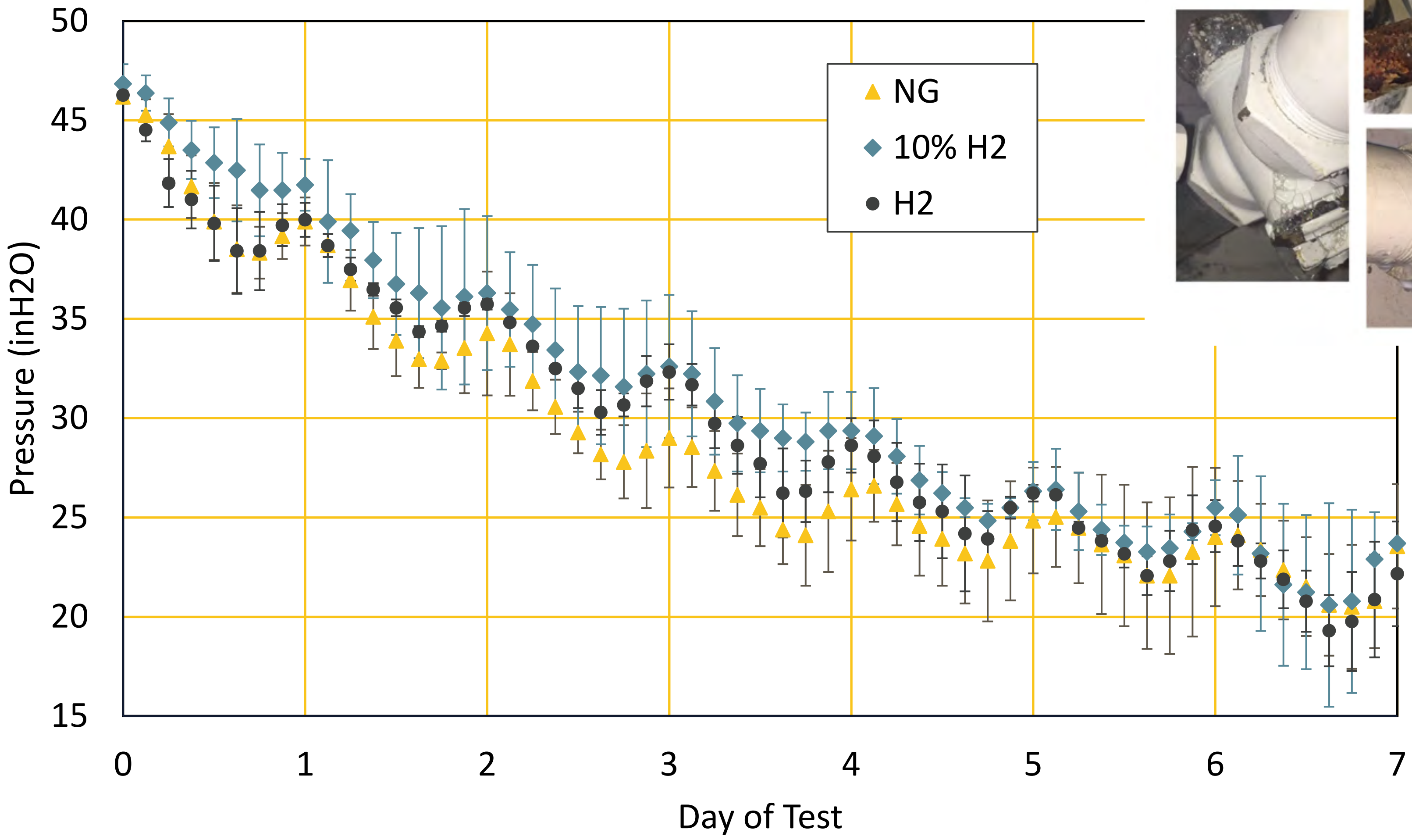
RD&D Topic #2: Hydrogen Safety & Sensing

- Hindenburg and the Hydrogen Bomb
  - No nuclear reactions
  - Hindenburg disaster caused by paint and skin
- H_2 characteristics
  - Broadest flammability limits
  - Low ignition energy (at stoichiometric)
  - Highest diffusivity
  - Lowest density
- Can be safer than gasoline & natural gas, but different!
  - In the event of an accident/leak – creation and ignition of a flammable mixture is less likely with hydrogen than with gasoline, perhaps more likely than with NG
- But, fire marshals, codes, standards, regulations, are not currently friendly
- Recently – disinformation

RD&D Topic #3: 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



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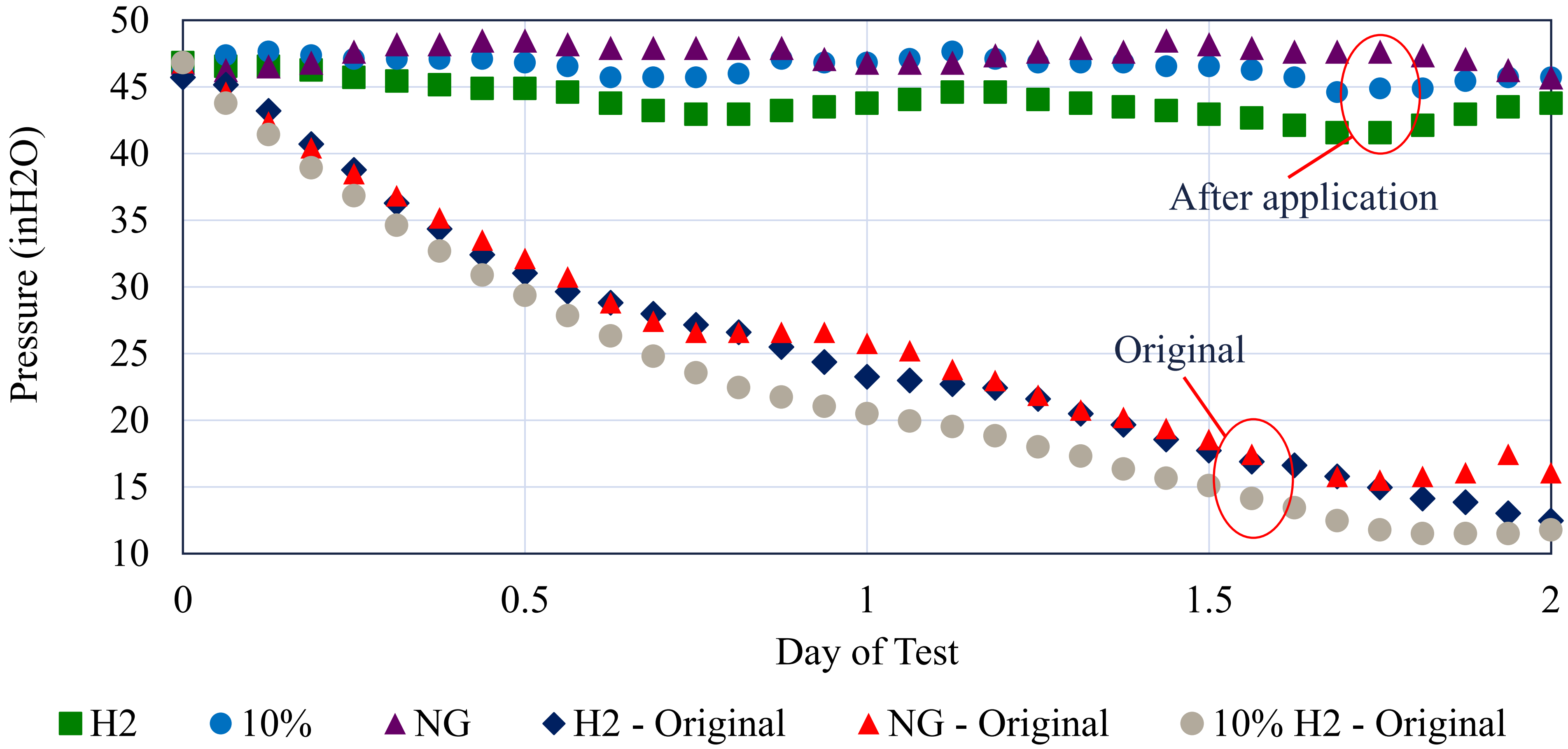
RD&D Topic #3: H_2 leakage from NG Infrastructure

H2 injection into existing natural gas infrastructure (low pressure)

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



RD&D Topic #3: H_2 leakage from NG Infrastructure

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

Lea...	CH4
~~Diffusi...~~	
~~La...~~	
~~Tu...~~	

Entran...

Com...

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

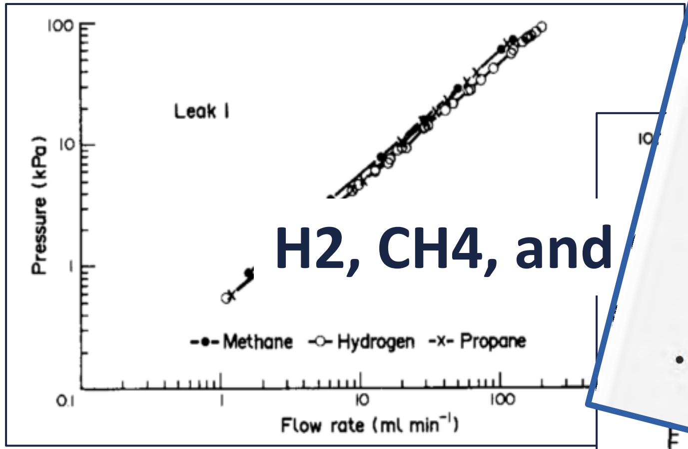
Alejandra Hormaza Mejia [a], Jacob Brouwer [a], Michael Mac Kinnon [b]

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

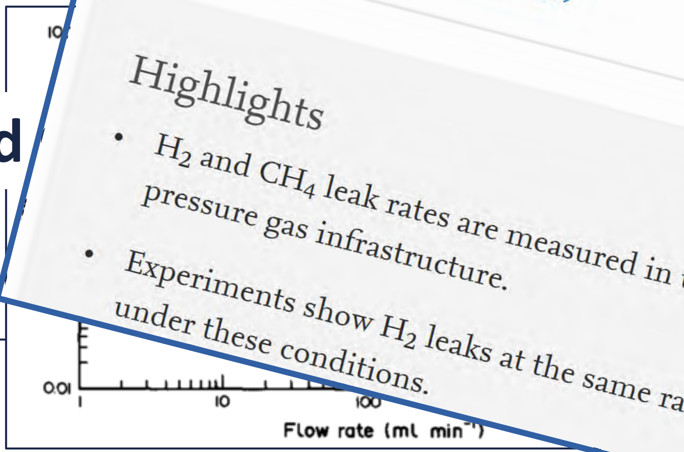
Highlights

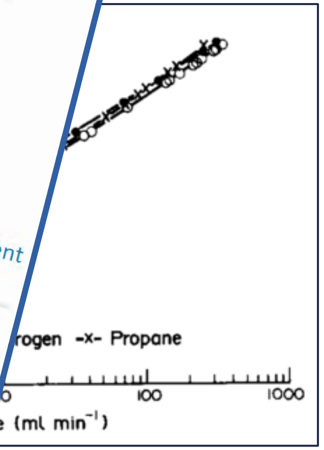
- H_2 and CH_4 leak rates are measured in unmodified low pressure gas infrastructure.
- Experiments show H_2 leaks at the same rate as CH_4 under these conditions.

- First publication on this topic: Swa... ...gy, Vol. 17, pp. 807-815, 1992.



H2, CH4, and ...





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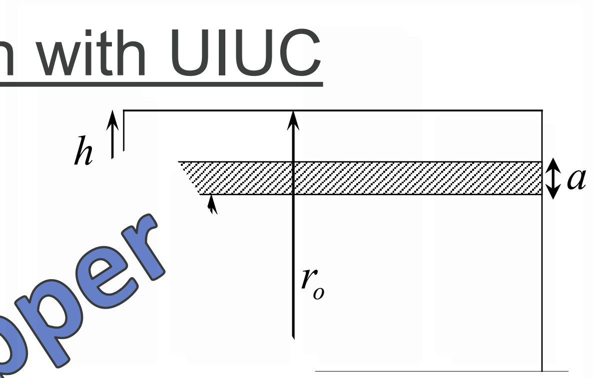
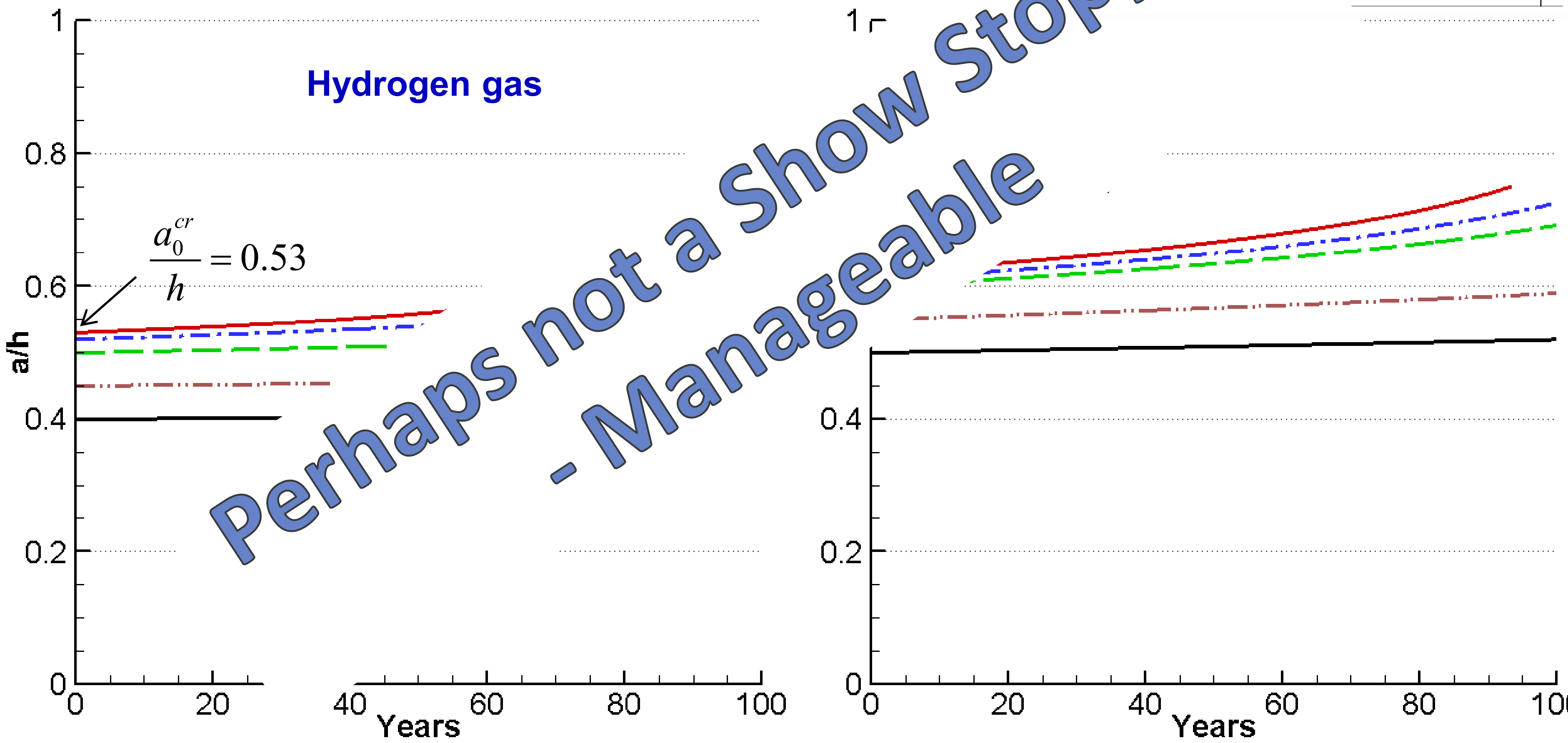
RD&D Topic #4: Existing Pipeline Embrittlement

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

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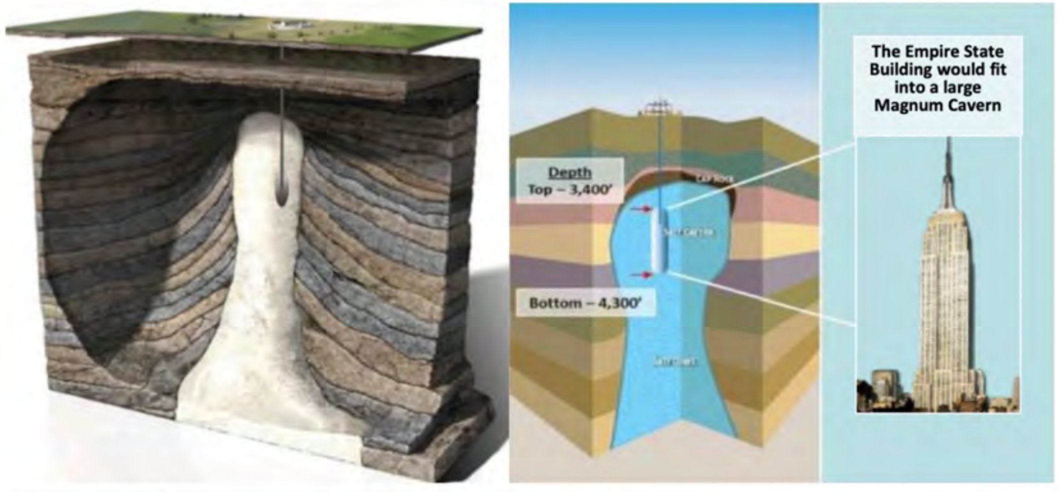
RD&D Topic #5: Massive Storage Facility Transformation



Plan for storing hydrogen in Utah salt caverns

Images: Los Angeles Department of Water and Power

<u>Salt Caverns already widely used and proven</u>

- 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

<u>Current CA depleted oil and gas fields not yet used or proven for H_2 use</u>

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

NG utilities must participate

RD&D Topic #6: End-Use Impacts of H_2/NG mixtures & variability

Meter-sets
- Physical flow/measurement characteristics
- Heating value and Wobbe Index
- …

Consumer appliances
- Stove-top, oven, space heater, water heater, …
  - UCI investigations, European studies exist
  - Up to 20% H_2 in NG likely manageable

Power plants
- Already capable of significant H_2/NG blends (e.g., 30%)
- R&D for higher H_2/NG blends
- Locations where high H_2 (up to 100%) can be evaluated

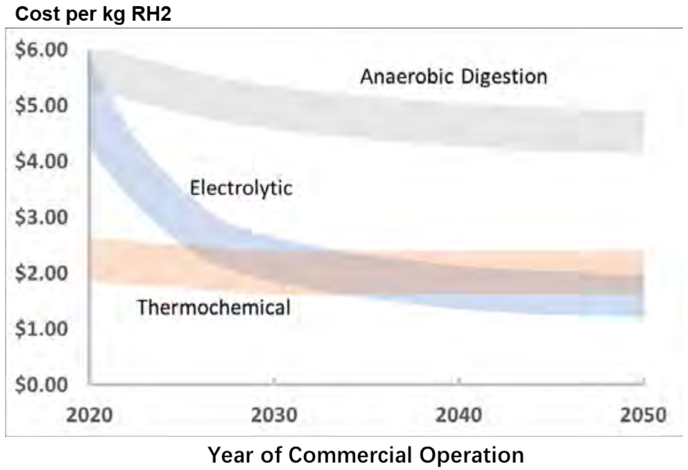
NG utilities must participate

Industry
- Ammonia, refining, glass, …

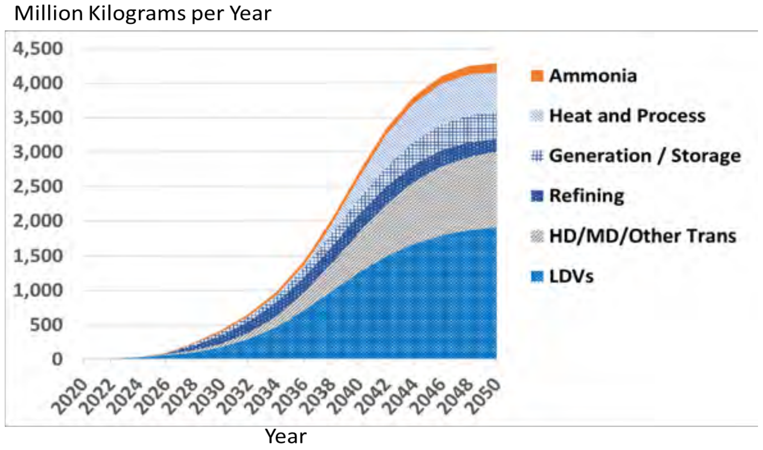
UC Decarbonization

- Most sister campuses deciding to electrify everything & purchase renewable electricity
  - Does not achieve a solution that can scale to all other communities
  - Neglects responsibility for achieving true zero emissions
  - Depends upon current market that is only ~40% decarbonized
  - Inequitably asks all ratepayers to subsidize UC decarbonization
- APEP desires to work with our campus to achieve “true zero” solutions that could be applied to all communities throughout U.S. and world
- APEP research is directly contributing to “true zero” solutions that can scale
- Integration of the research enterprise/solutions with campus infrastructure is essential for demonstrating these solutions to the world
- Grateful/Fortunate for historical and current support of Division of Finance and Administration & especially Facilities Management
  - Best in the world

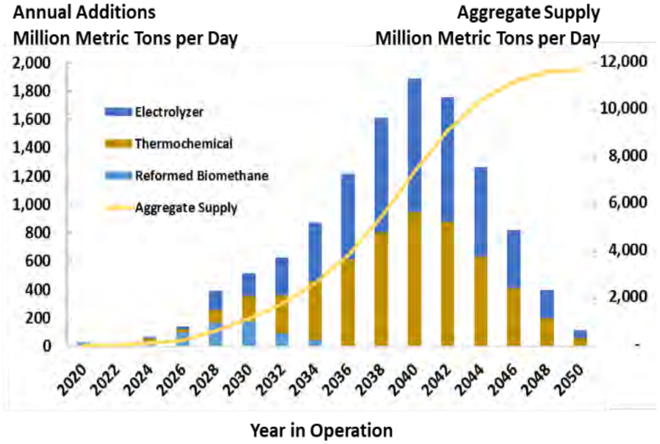
Roadmap for the Deployment and Buildout of Renewable Hydrogen (RH_2) Production Plants in California



Renewable Hydrogen Cost Evolution

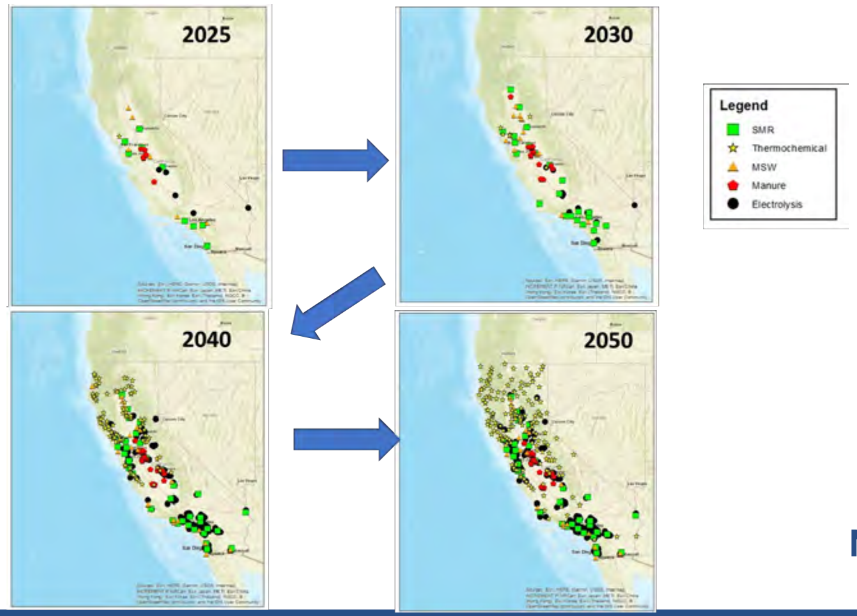


Renewable Hydrogen Demand Growth



Renewable Hydrogen Production Additions

Renewable Hydrogen Production Geospatial Build-out



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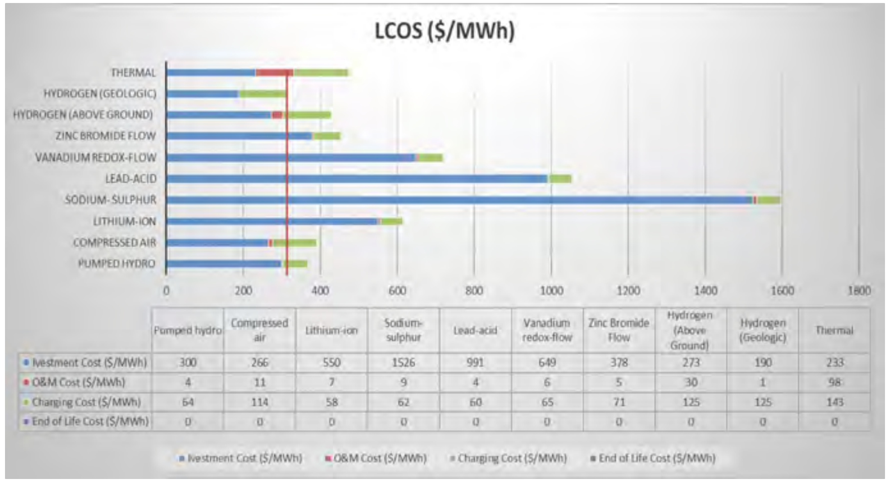
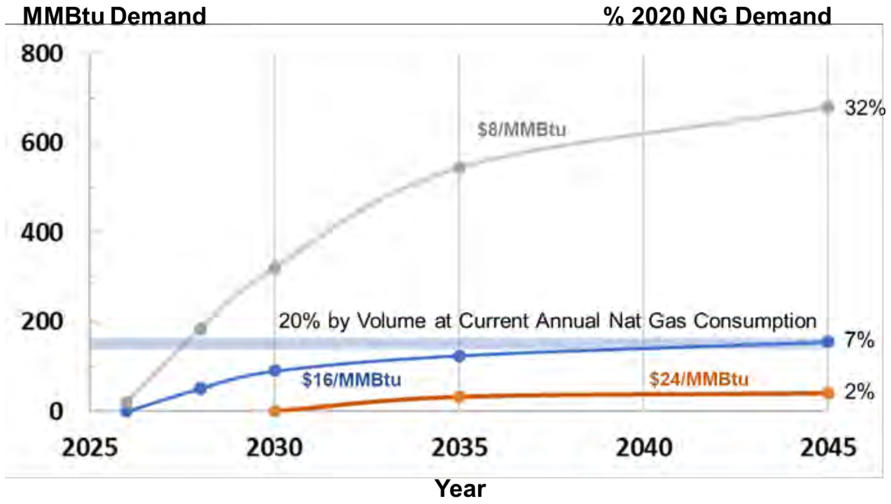
Electrolytic Hydrogen as a Long-Duration Storage Resource



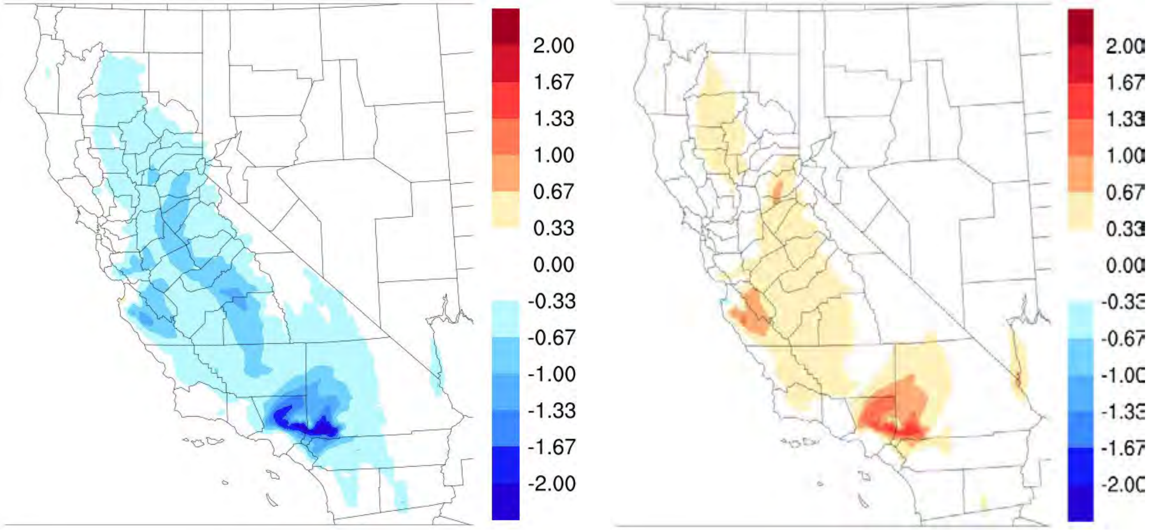
	Pumped hydro	Compressed air	Lithium-ion	Sodium-sulphur	Lead-acid	Vanadium redox-flow	Zinc Bromide Flow	Hydrogen (Above Ground)	Hydrogen (Geologic)	Thermal
Ivestment Cost ($/MWh)	300	266	550	1526	991	649	378	273	190	233
O&M Cost ($/MWh)	4	11	7	9	4	6	5	30	1	98
Charging Cost ($/MWh)	64	114	58	62	60	65	71	125	125	143
End of Life Cost ($/MWh)	0	0	0	0	0	0	0	0	0	0

Levelized Cost of Storage – 100 Hours



Demand for Renewable Fuel for Firming

Practical Limits on Hydrogen Injection



Air Quality Impacts

Optimal Strategies for Decarbonizing the Gas Grid – Hydrogen or Renewable Methane?