UCI

Hydrogen & Fuel Cells for Zero Emissions Electricity

CARB Scoping Plan Electricity Workshop

from: San Diego Union Tribune

Jack Brouwer

November 2, 2021

Outline

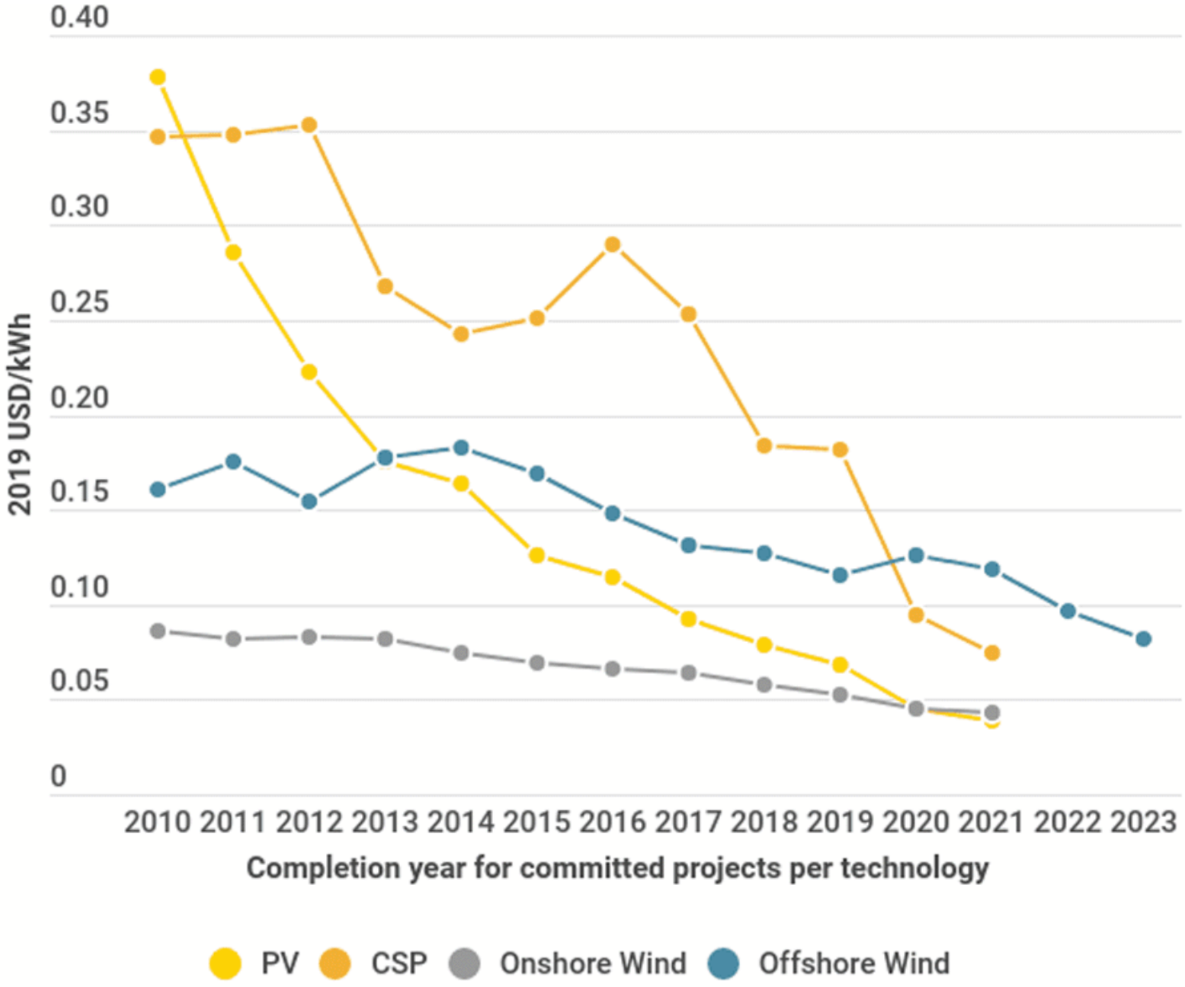
- Electric sector decarbonization opportunities for hydrogen & fuel cells
  - Fuel for dispatchable resources
  - Long-duration and massive energy storage
  - Resilience & reliability via pipelines & wires
- Air quality improvements of hydrogen & fuel cells
  - Fuel cells vs. backup diesel generator AQ impacts
- Hydrogen production pathways
- Emissions and air quality impacts of hydrogen blends with natural gas
  - Appliances
  - Industrial Burners
  - Power Plants

Renewable Energy Conversion (Solar & Wind)

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

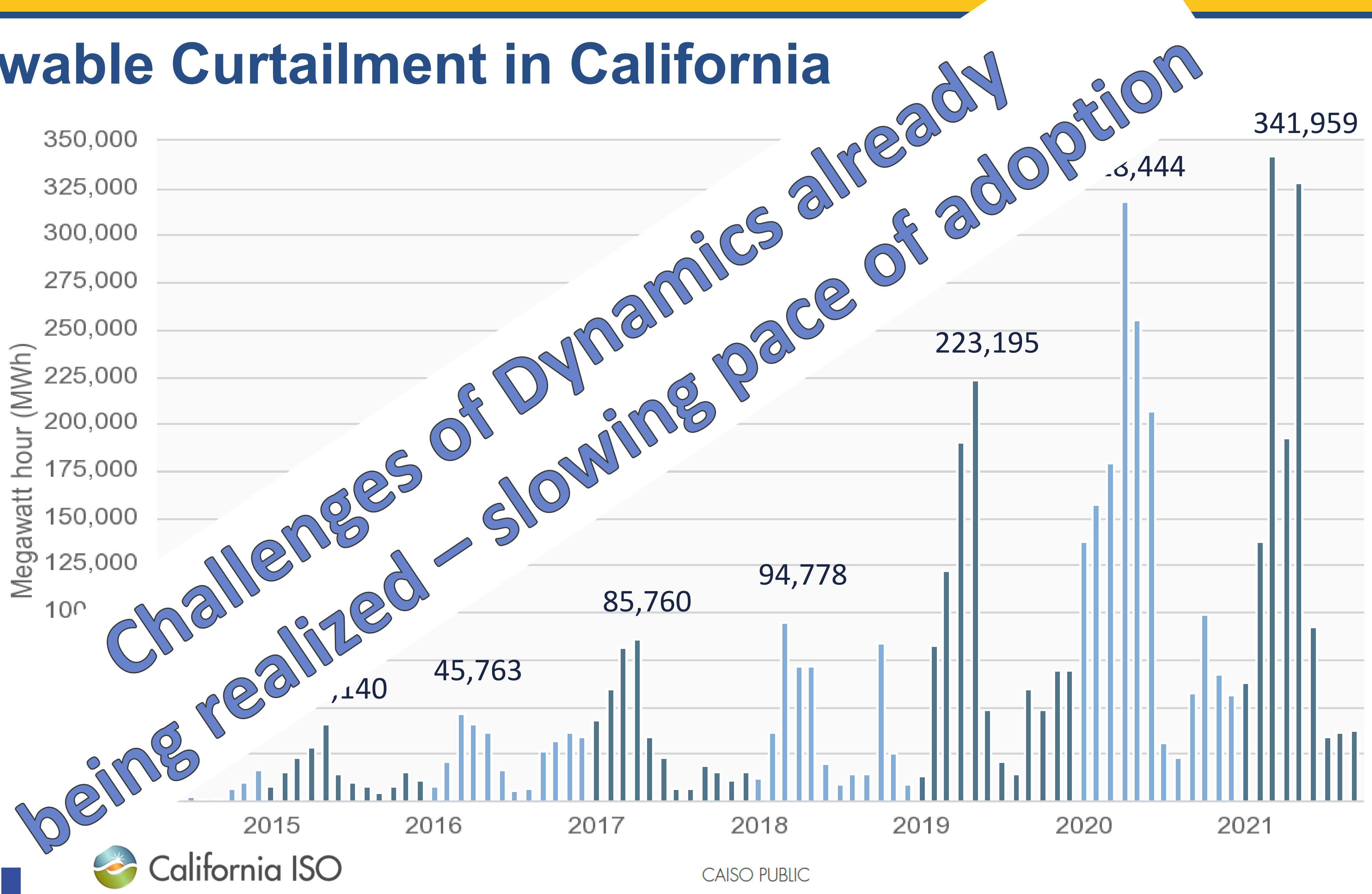
Good News!

- Widely available around world
- Now typically cheapest form of primary energy



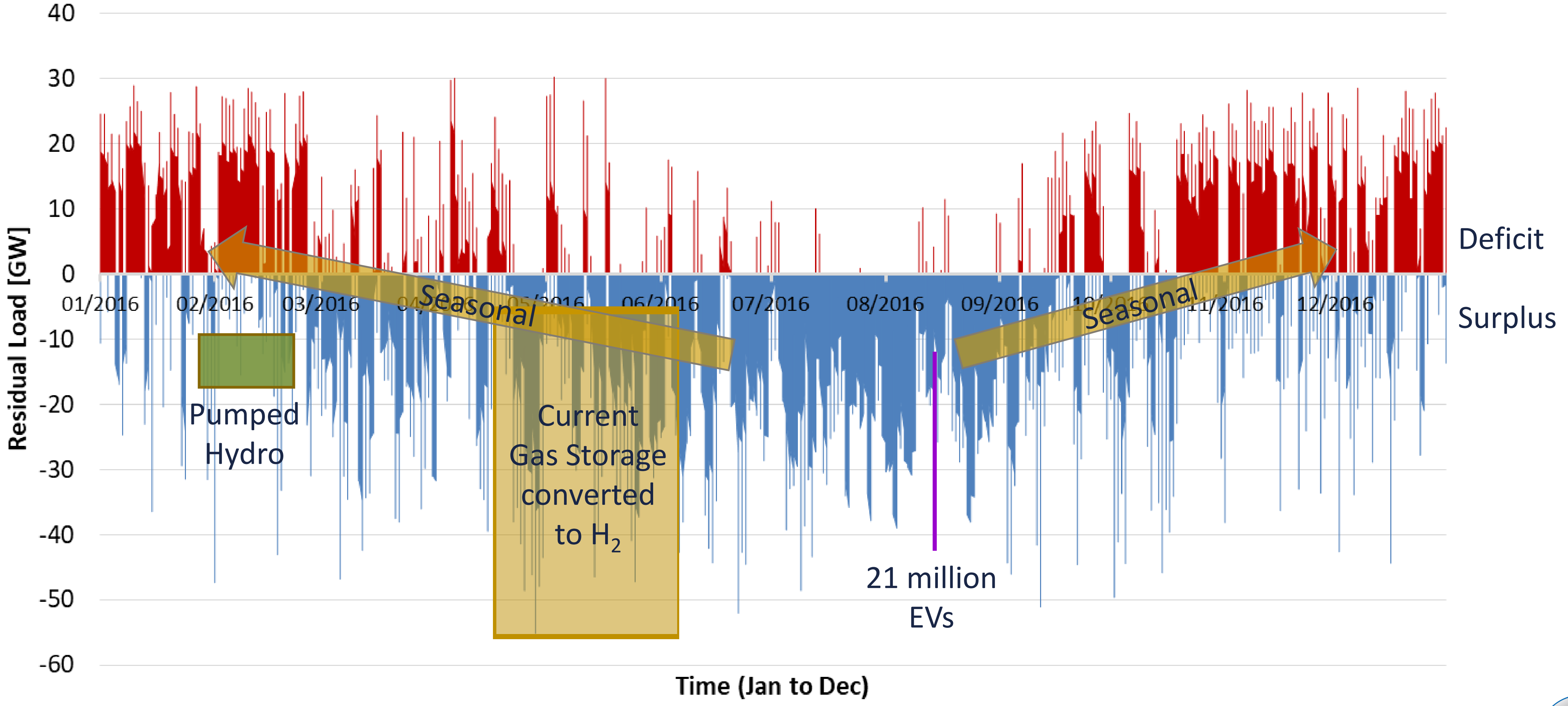
From: IRENA, www.irena.org/newsroom/pressreleases/2020/Jun , 2020

Renewable Curtailment in California



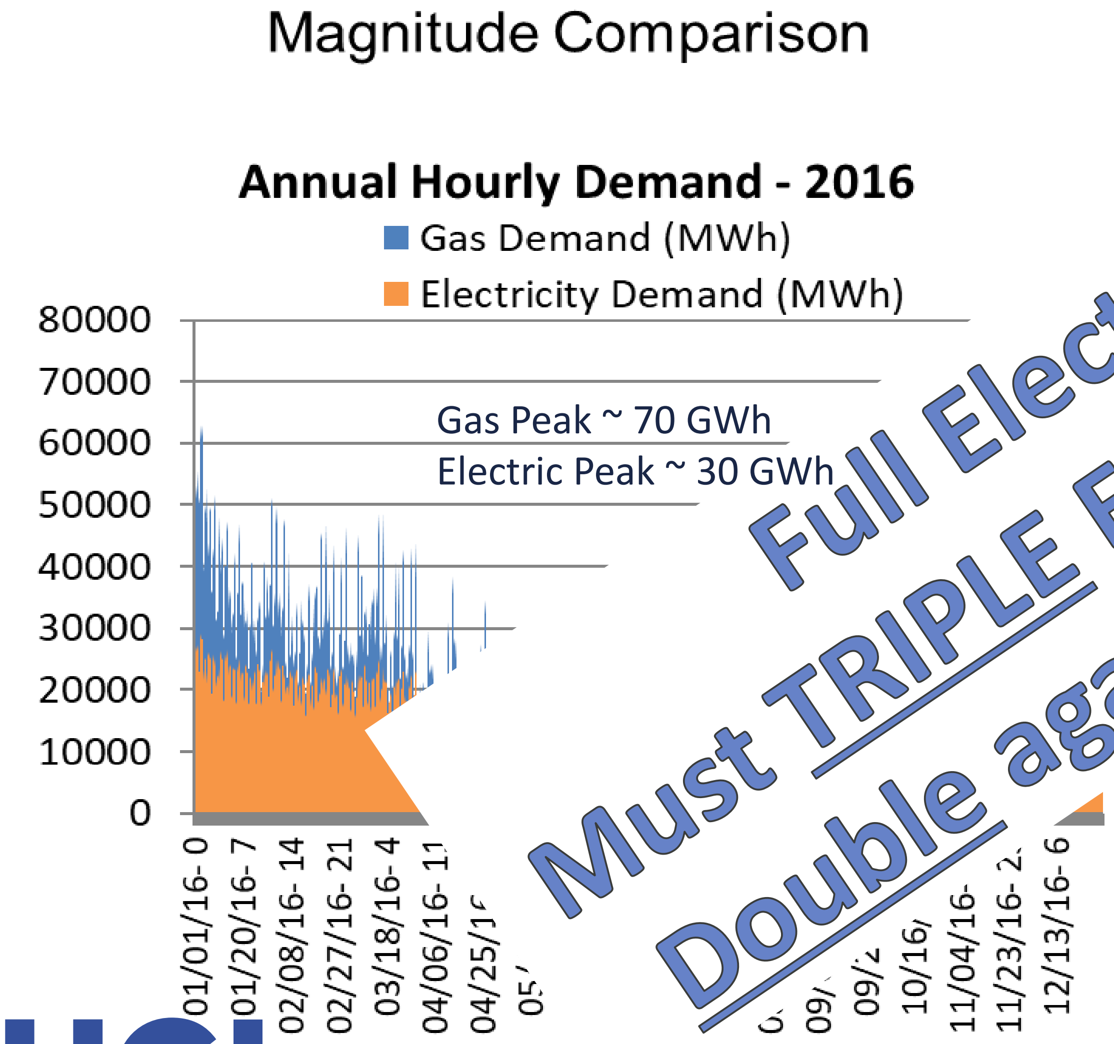
Dynamics of Renewable Future are Challenging

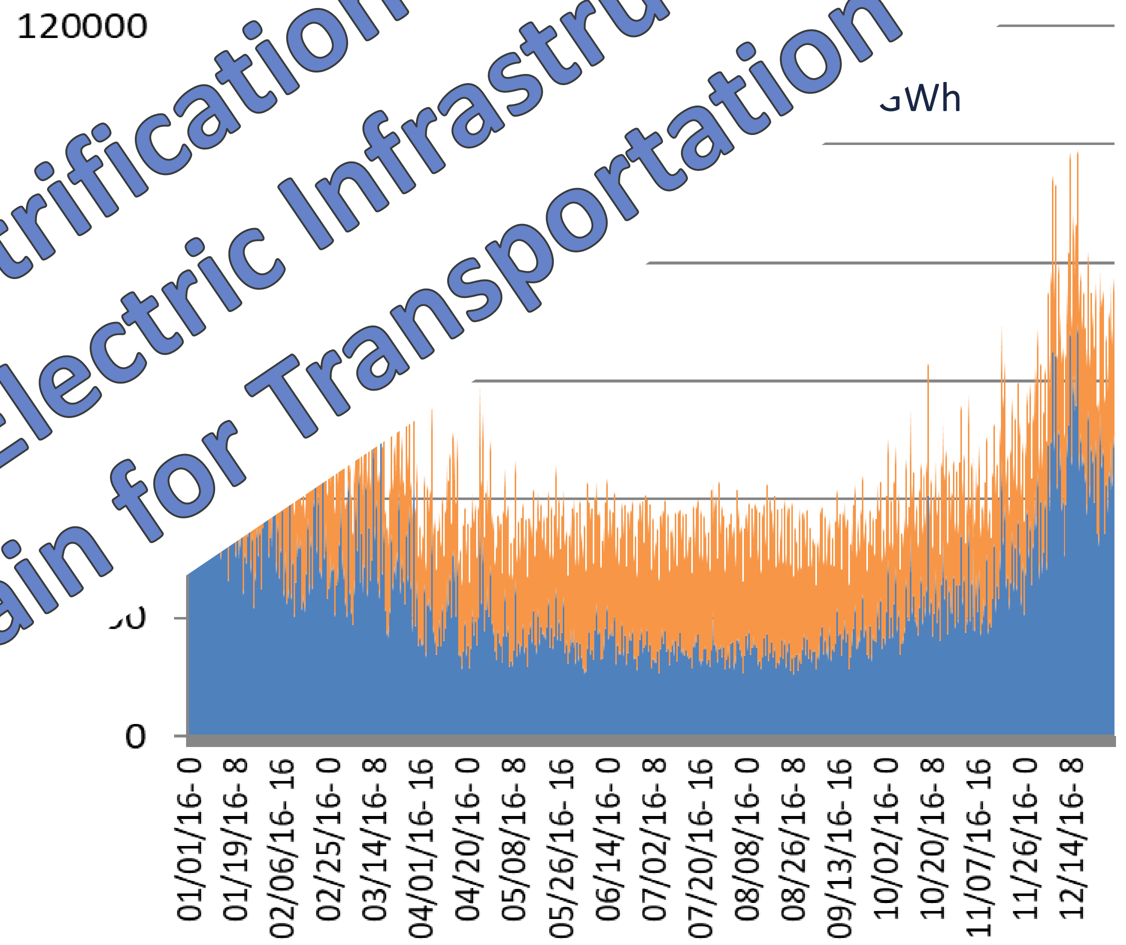
- Wind dominant case (37 GW solar capacity, 80 GW wind capacity)



We Must Transform the Gas System

- Northwestern U.S. Energy Dynamics





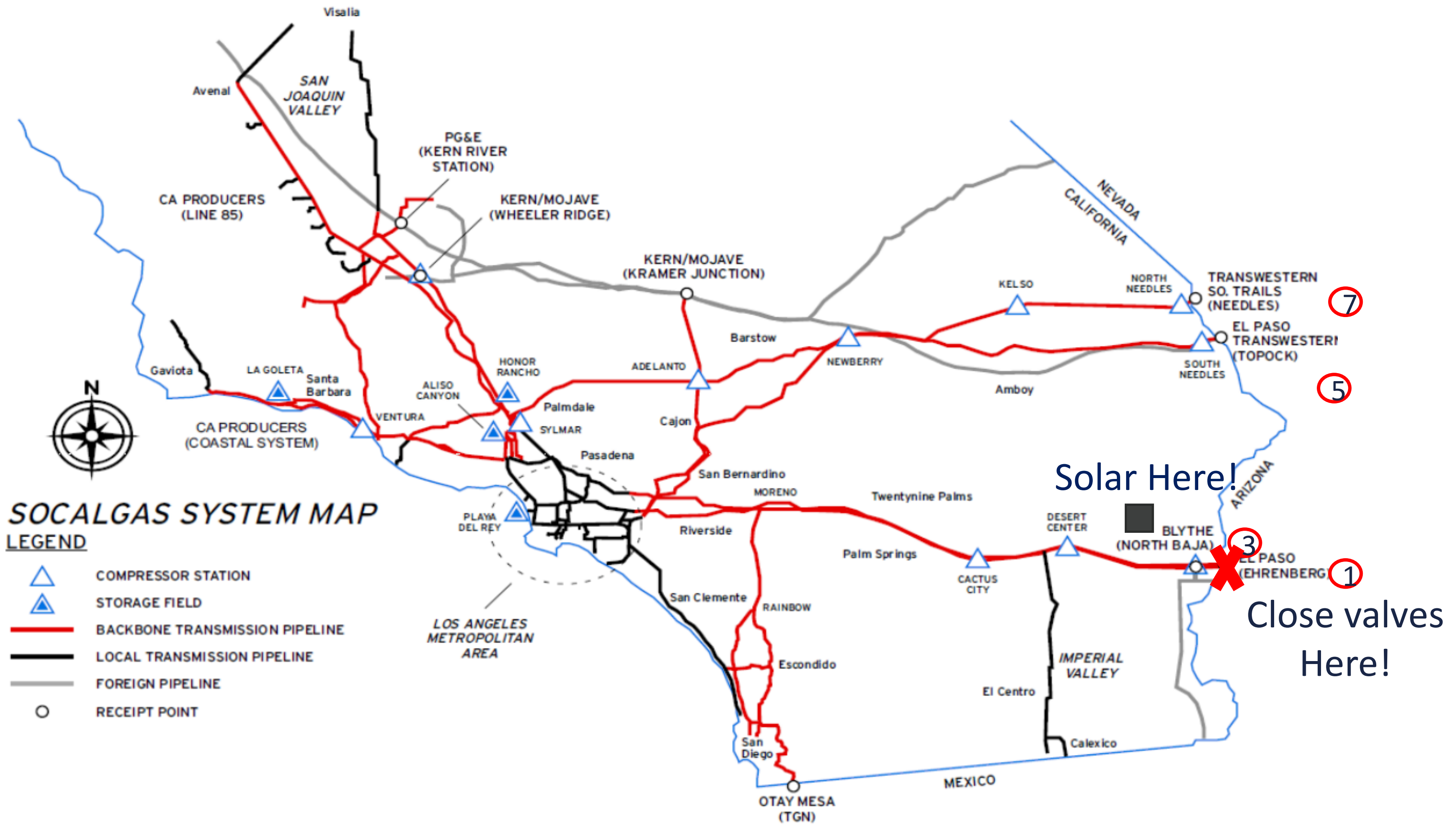
Full Electrification?

Must TRIPLE Electric Infrastructure

Double again for Transportation

Gas System – Resource for Zero Emissions & Resilience

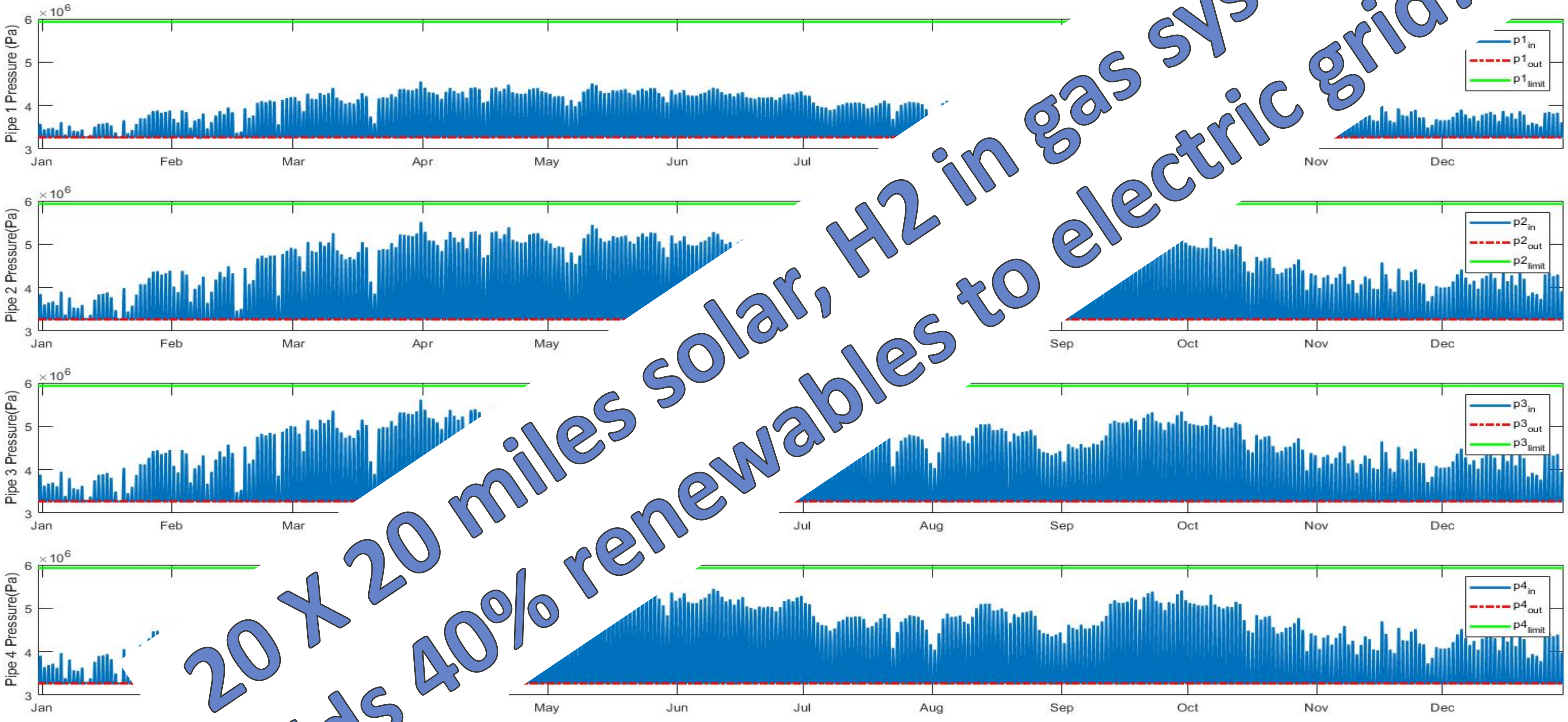
- First mix X% – HUGE Resource for grid renewables & transportation electrification
- Then piecewise convert to pure hydrogen



NATIONAL FUEL CELL RESEARCH CENTER

Gas System – Resource for Zero Emissions & Resilience

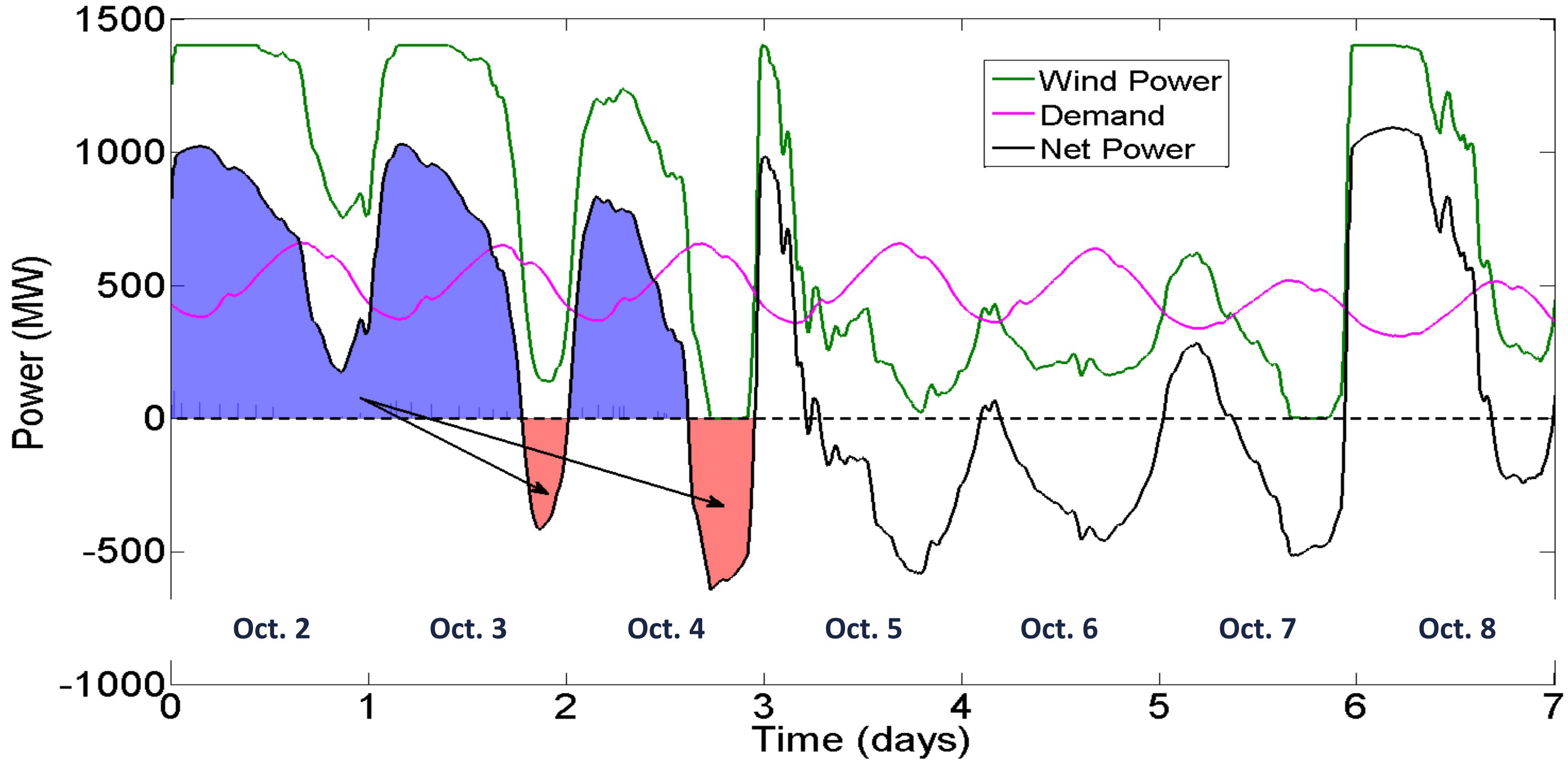
- 40% of all electric demand – 20 sq. miles of solar, only gas sy... for H_2 storage AND all T&D for resilience



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

Hydrogen Energy Storage Dynamics

- Hydrogen Storage complements Texas Wind & Power Dynamics

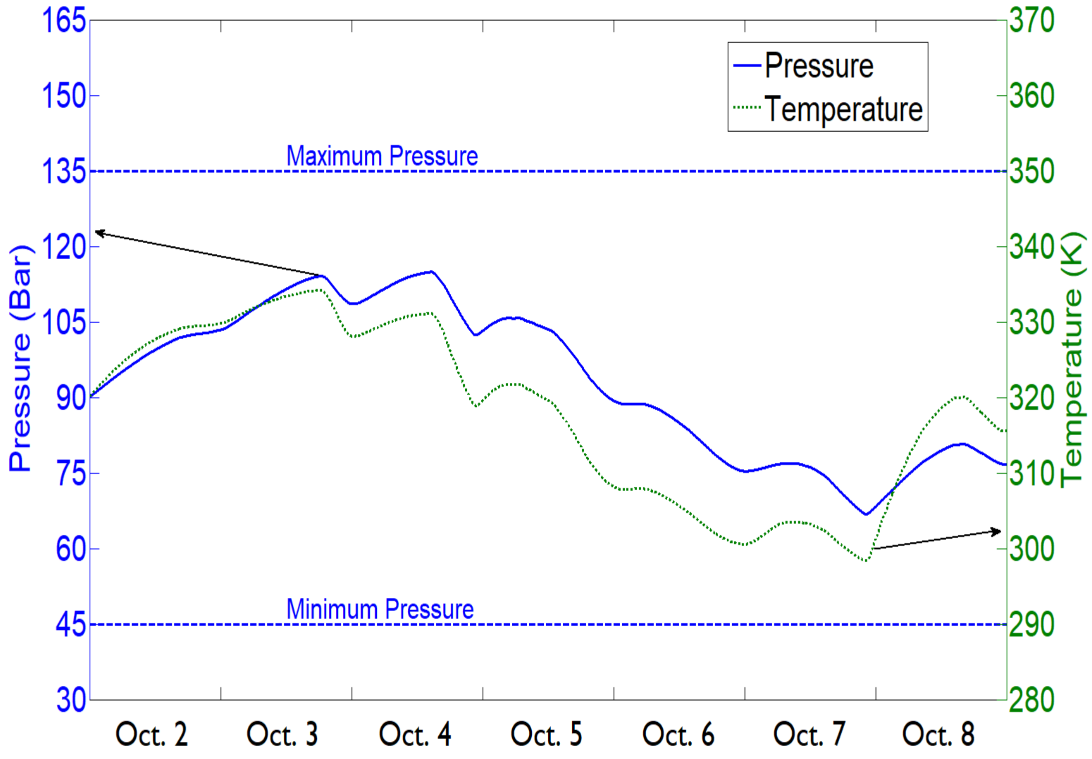


- Load shifting from high wind days to low wind days
- Hydrogen stored in adjacent salt cavern

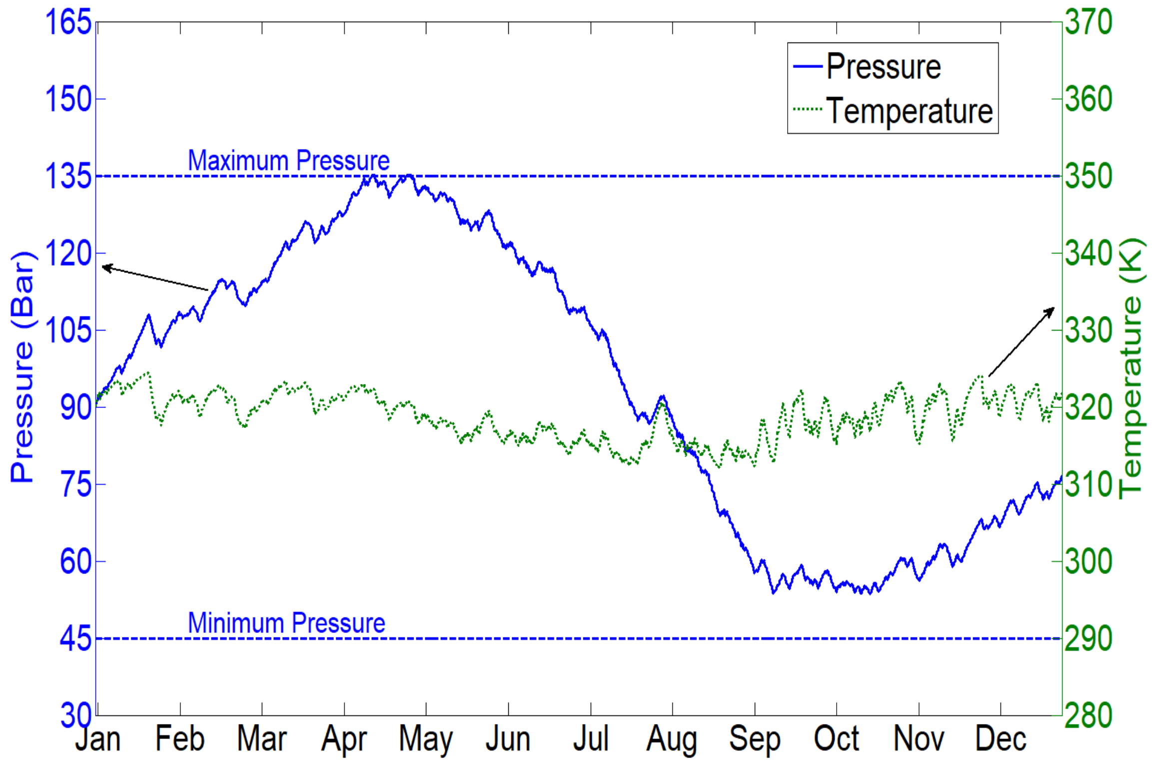
Maton, J.P., Zhao, L., Brouwer, J., Int'l Journal of Hydrogen Energy, Vol. 38, pp. 7867-7880, 2013

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?

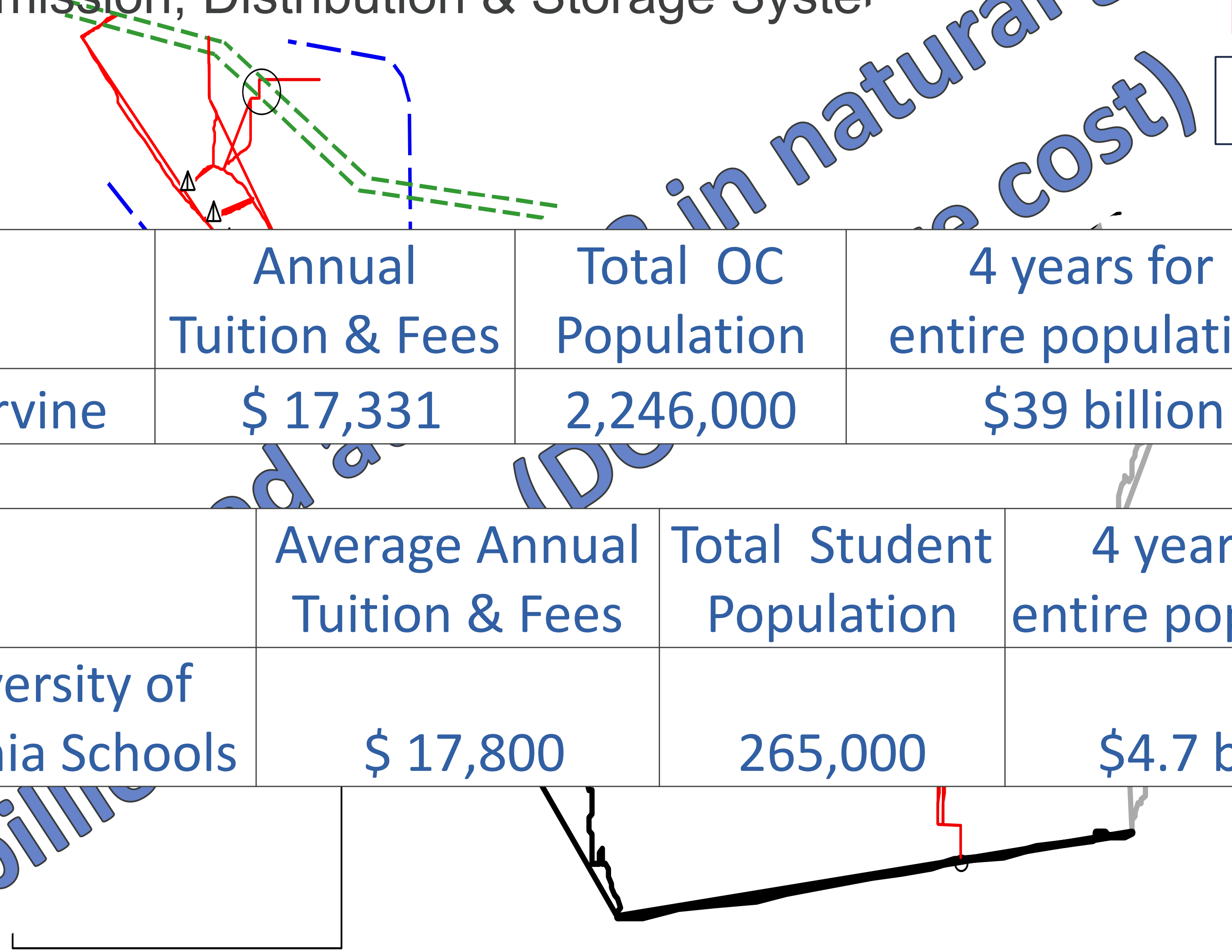
Maton, J.P., Zhao, L., Brouwer, J., Int'l Journal of Hydrogen Energy, Vol. 38, pp. 7867-7880, 2013

Resilient Storage & Transmission/Distrib… Resource

- Natural Gas Transmission, Distribution & Storage System

> 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

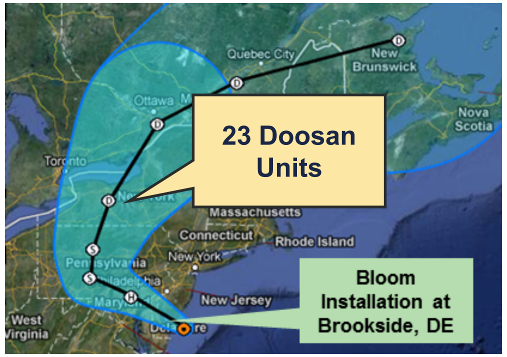
Carmona, Adrian, M.S. Thesis Project, UC Irvine, J. Brouwer advisor, 2014.

Demonstrated Resilience of Fuel Cells and Gas System

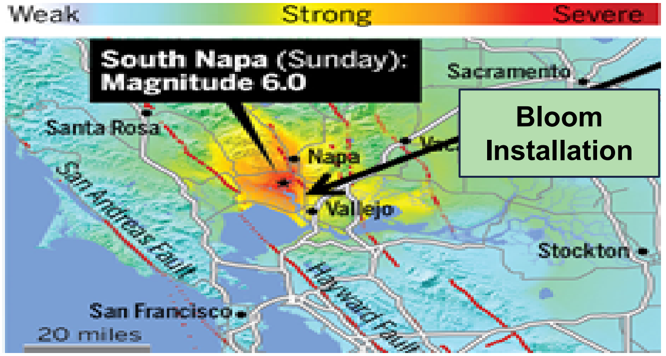
San Diego Blackout, 9/28/11

Winter Storm Alfred, 10/29/11

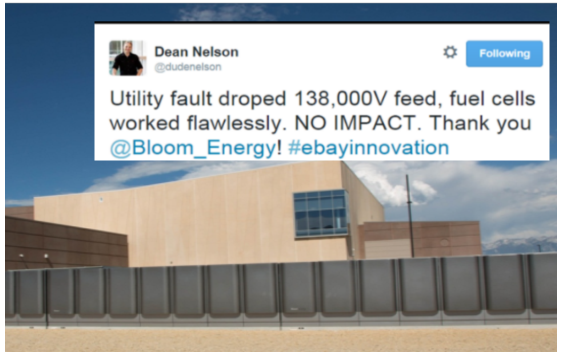
Hurricane Sandy, 10/29/12



CA Earthquake, 8/24/14



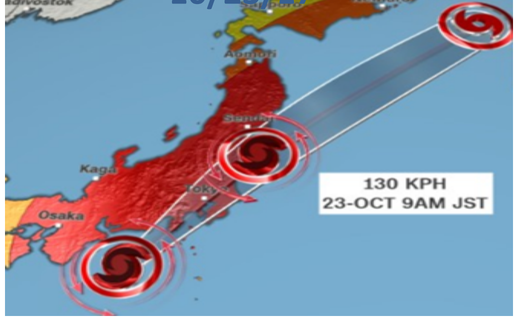
Data Center Utility Outage, 4/16/15



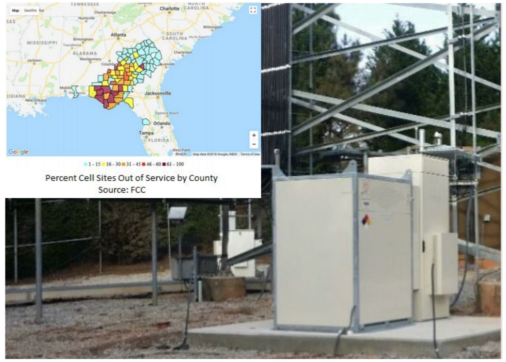
Hurricane Joaquin, 10/15/15

Napa Fire, 10/9/17

Japanese Super-Typhoon, 10/23/17

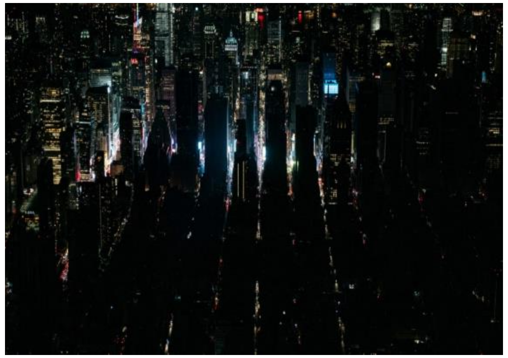


Hurricane Michael, 10/15/18

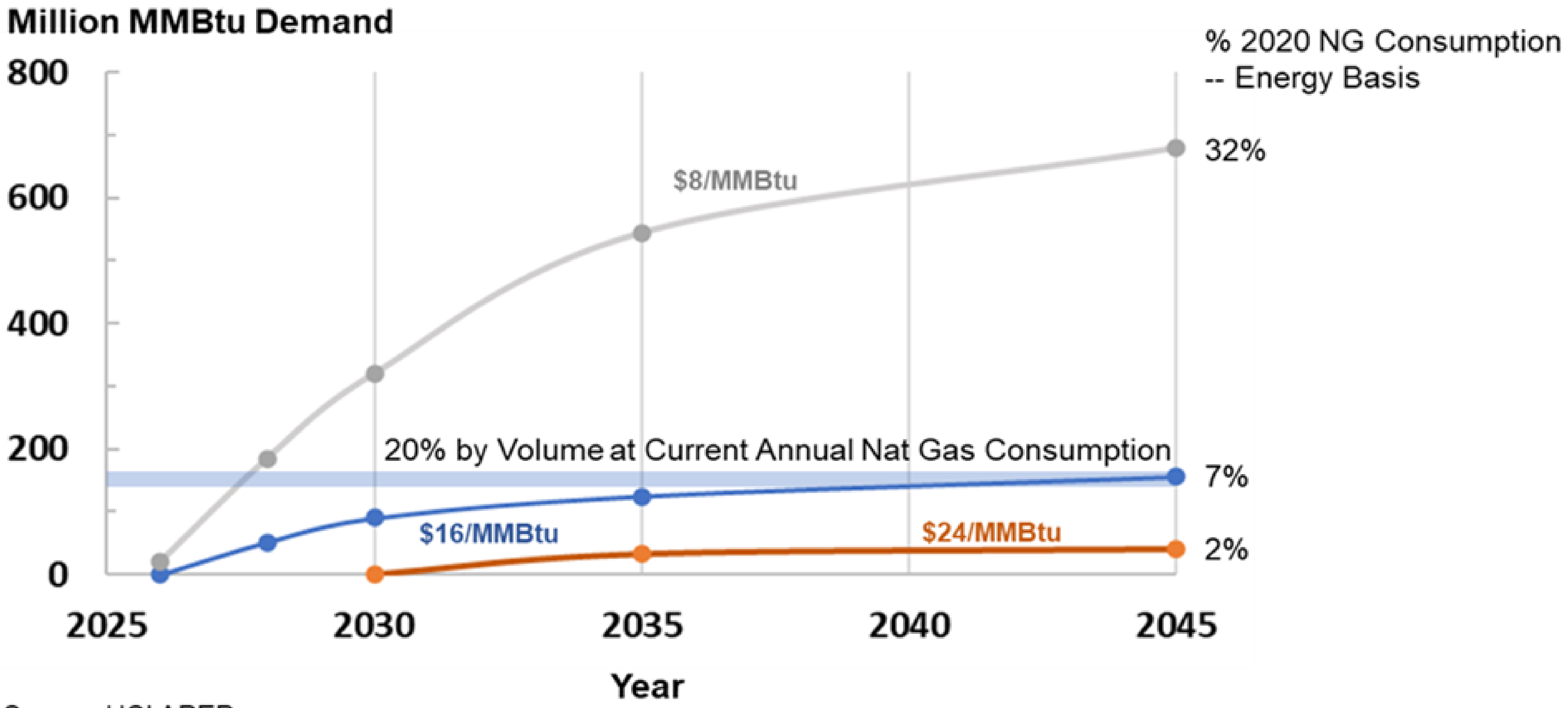


Ridgecrest Earthquakes, 7/4-5/19

Manhattan Blackout, 7/13/19



Grid Dispatch Modeling



Source: UCI APEP

Grid dispatch modeling using CPUC RESOLVE model shows that use of renewable hydrogen for VER firming becomes cost optimal in some hours beginning at a cost of $24/MMBtu (just over $3/kg).

U.S. DOE "Hydrogen Energy Earthshot"

- Accelerate breakthroughs of more abundant, affordable, and reliable clean energy solutions within the decade

Office of Energy Efficiency & Renewable Energy » Hydrogen Shot

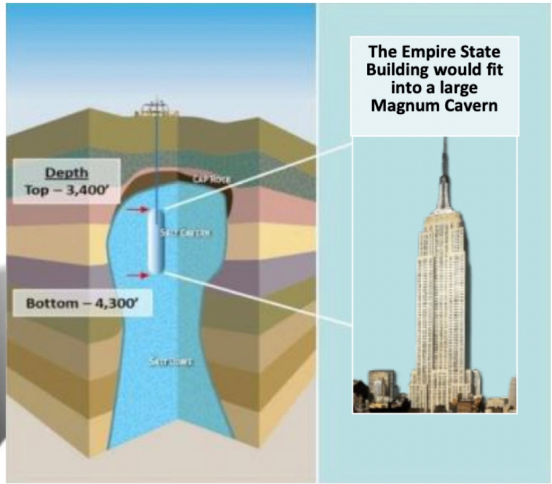
ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

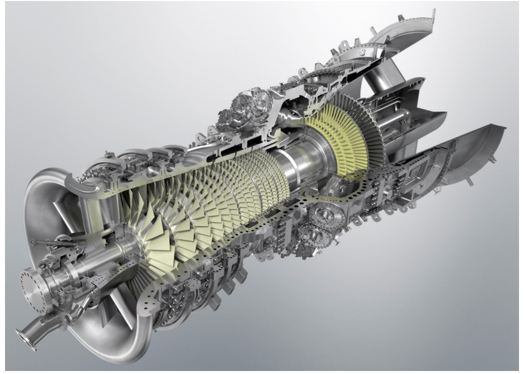
- Reduce RH_2 cost from ~\$5/kg to \$1/kg to unlock new markets for hydrogen, including steel manufacturing, ammonia, energy storage, and heavy-duty trucks

1 Dollar | 1 Kilogram | 1 Decade

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





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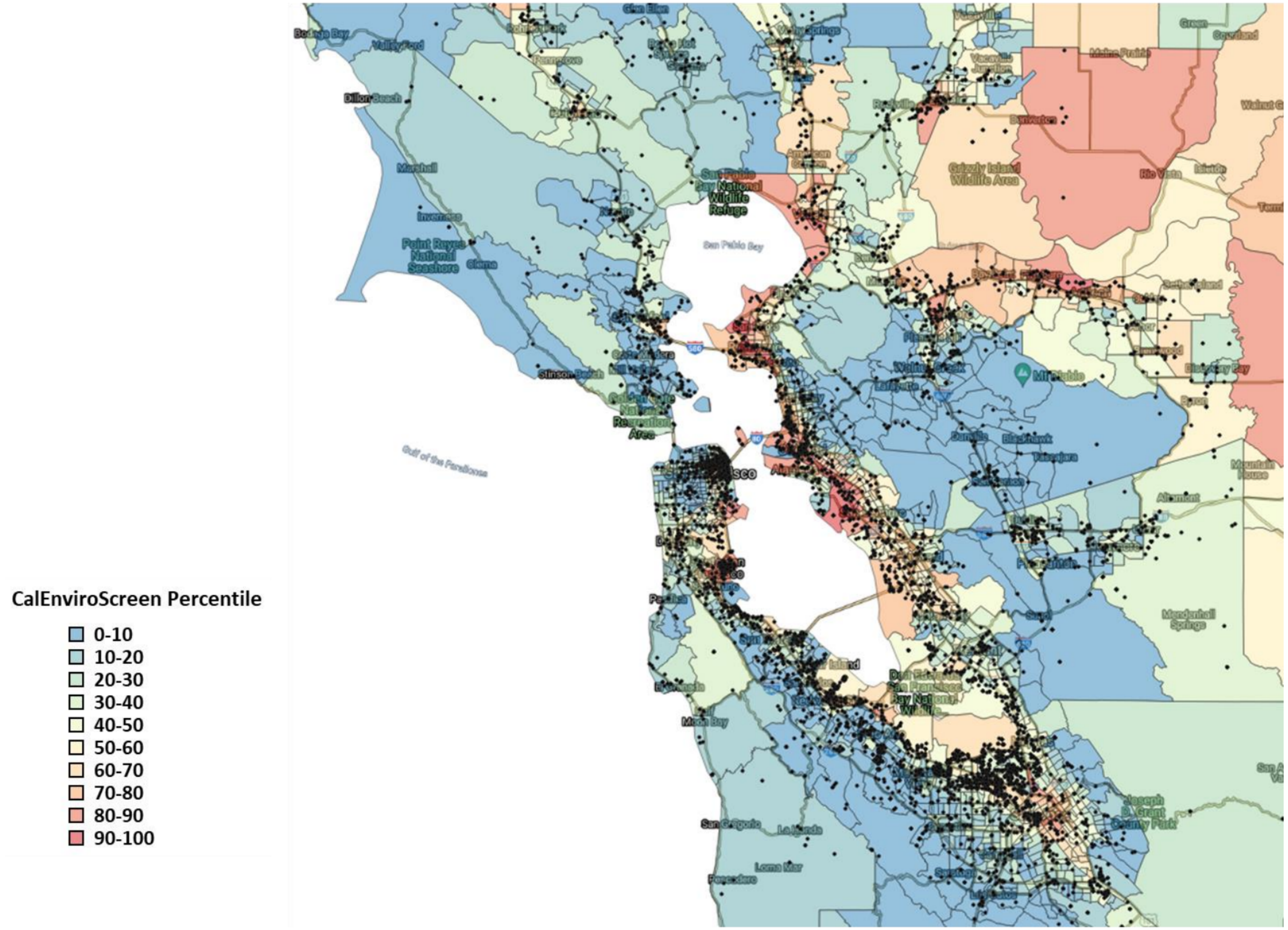
Recent Increase in Fossil Back-up Generator Deployment

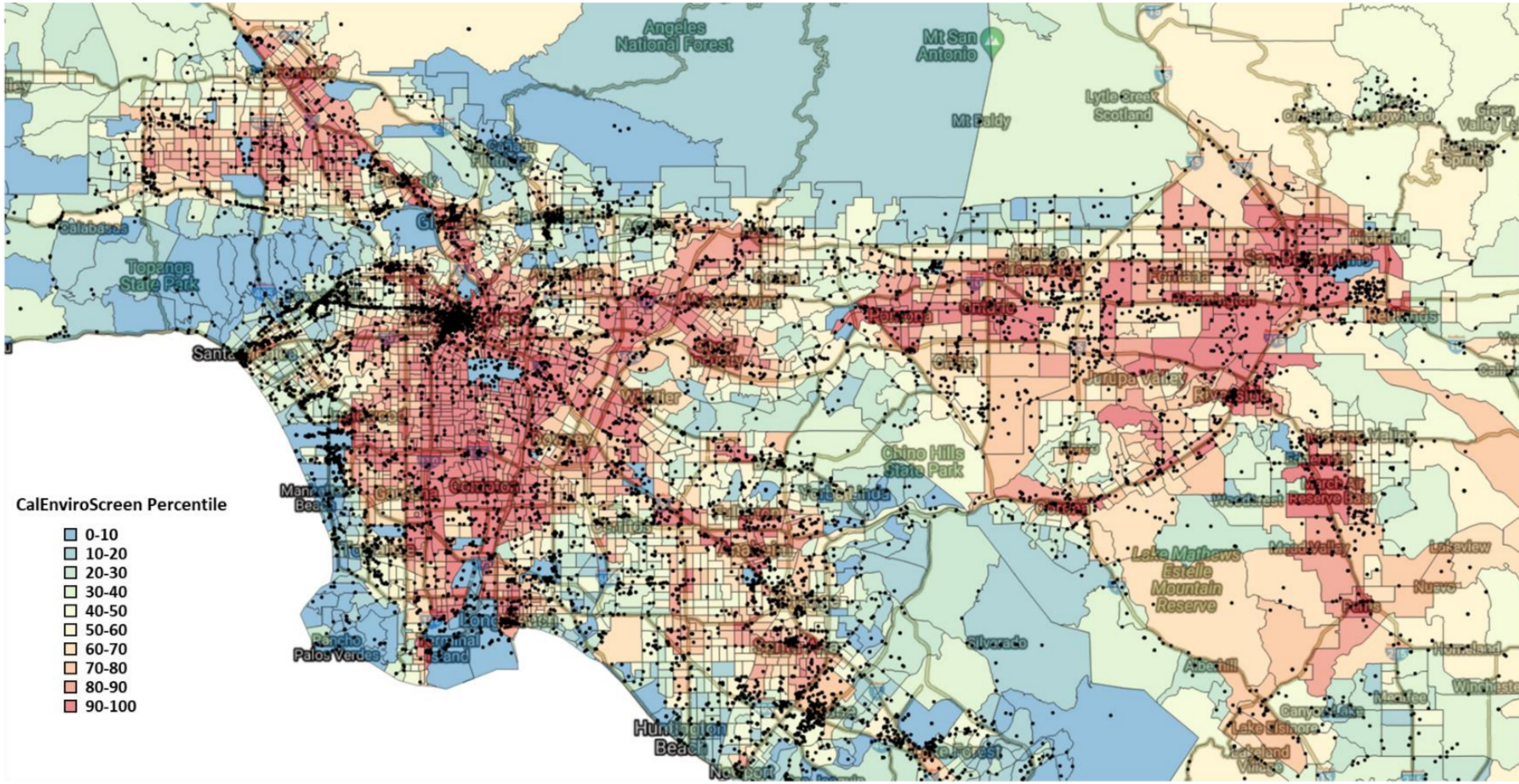
- 34% increase in Bay Area from 2018 - 2021
- > 8,700 deployed
- Capable of > 4.8 GW
- Disproportionately located in disadvantaged communities (CalEnviroScreen 3.0 percentiles shown)



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

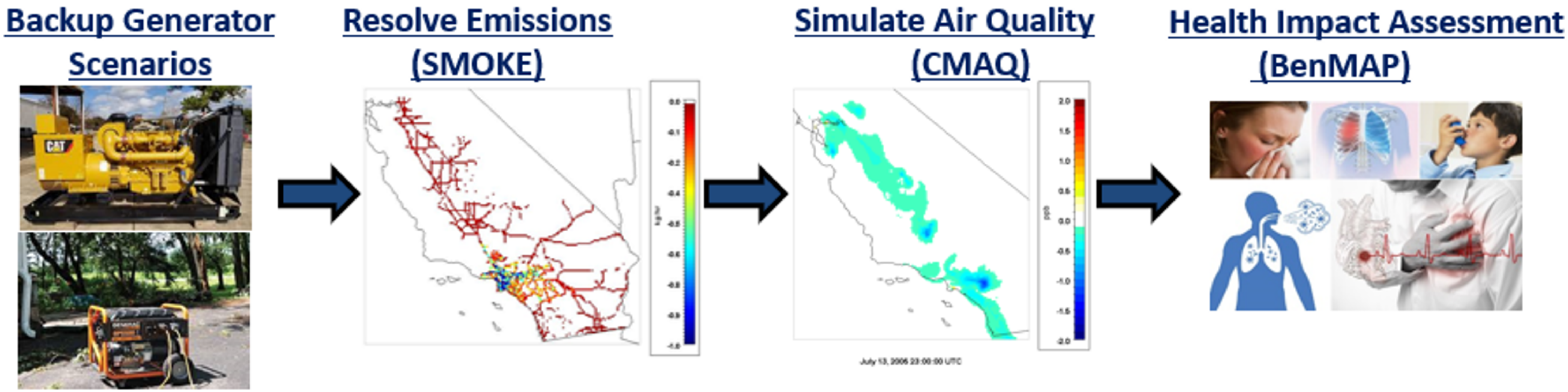
M.Cubed study found significant health & economic impacts of BUGs

- 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

Air Quality Impacts of H_2 & Fuel Cell Alternatives

- The only alternative to H2 & Fuel Cells that is currently available and being widely implemented to deal with reliability and resilience (e.g., for wildfires & PSPS events) is diesel backup generation
- Recent APEP study

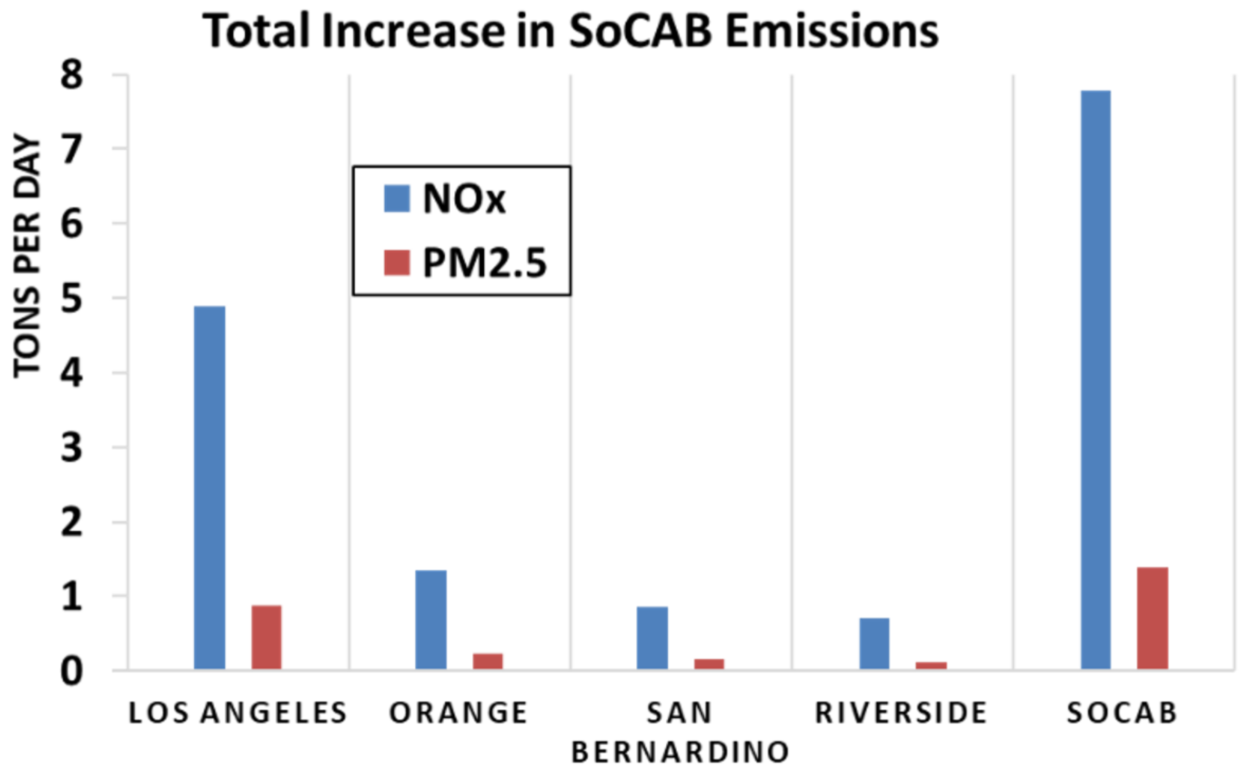


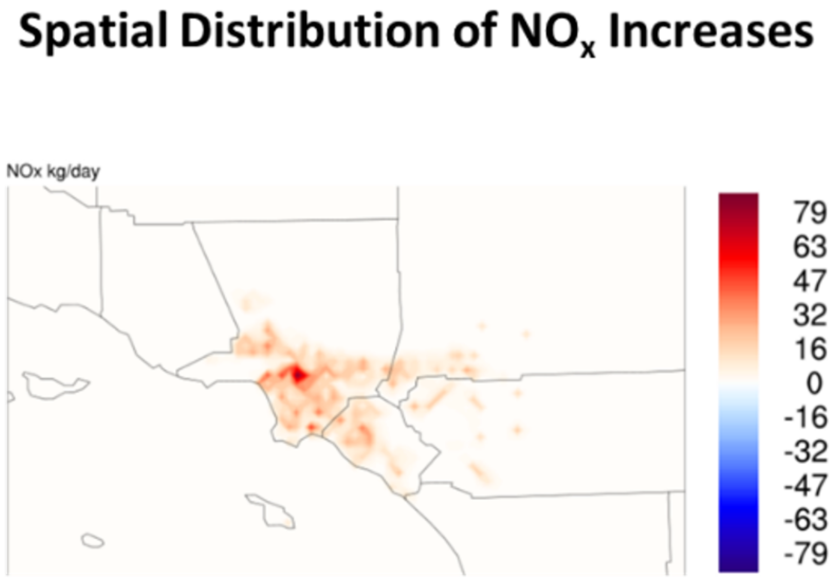
Overview of study methodology

http://apep.uci.edu/PDF/Potential_Public_Health_Costs_from_Air_Quality_Degradation_During_Grid_Disruption_Events_070921.pdf

Air Quality Impacts of H_2 & Fuel Cell Alternatives

- Total increases of NOx and $PM_{2.5}$ and spatial location of NOx emissions increases of the Grid Disruption Scenario

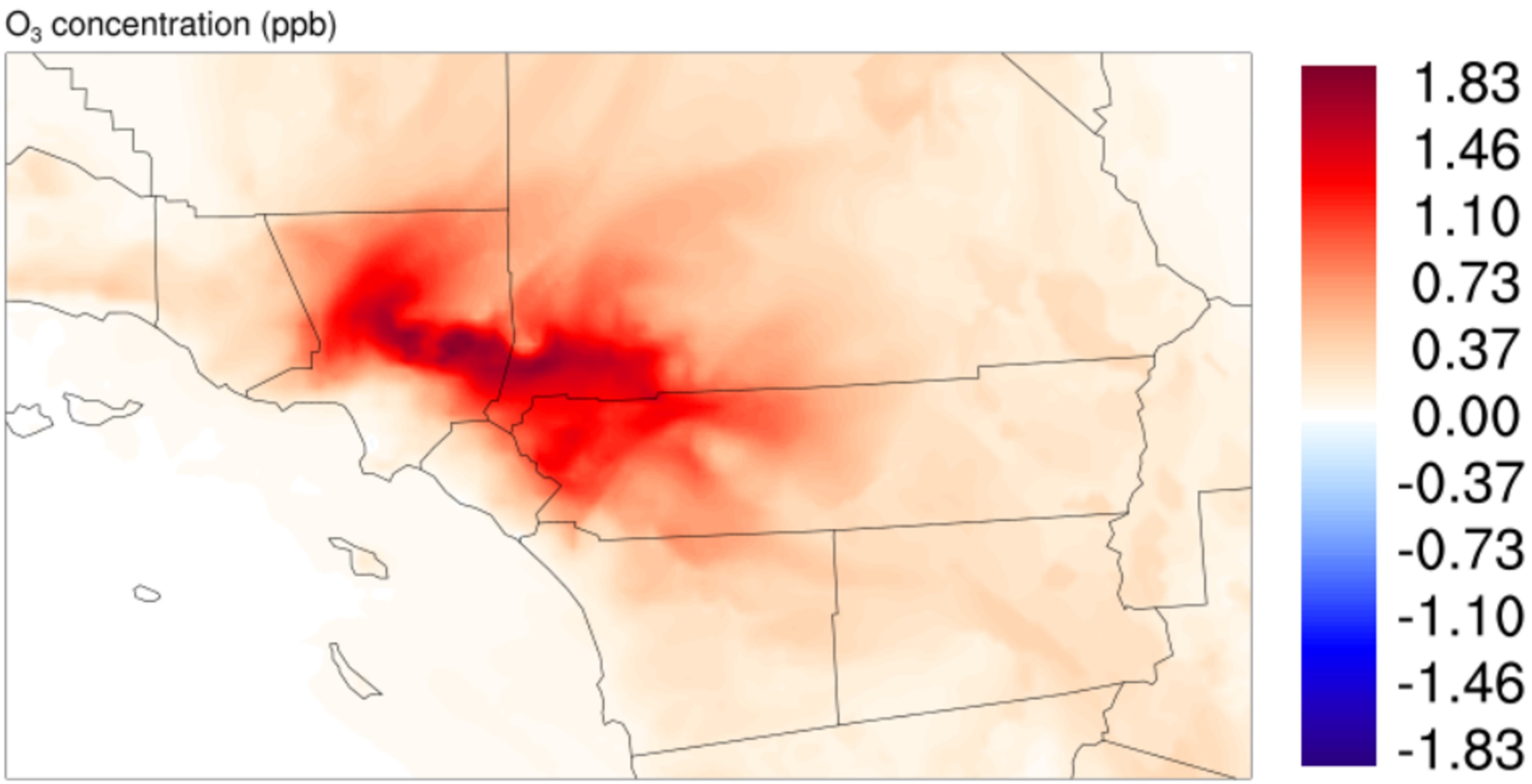




http://apep.uci.edu/PDF/Potential_Public_Health_Costs_from_Air_Quality_Degradation_During_Grid_Disruption_Events_070921.pdf

Air Quality Impacts of H_2 & Fuel Cell Alternatives

- Changes in ground-level ozone (O_3) due to grid disruption scenario



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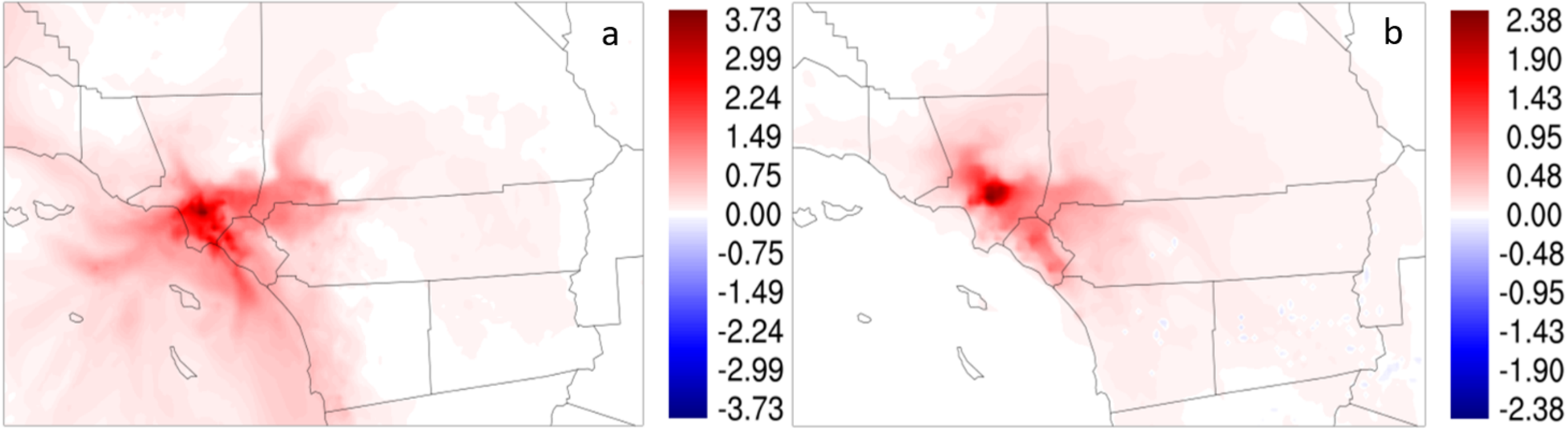
Air Quality Impacts of H_2 & Fuel Cell Alternatives

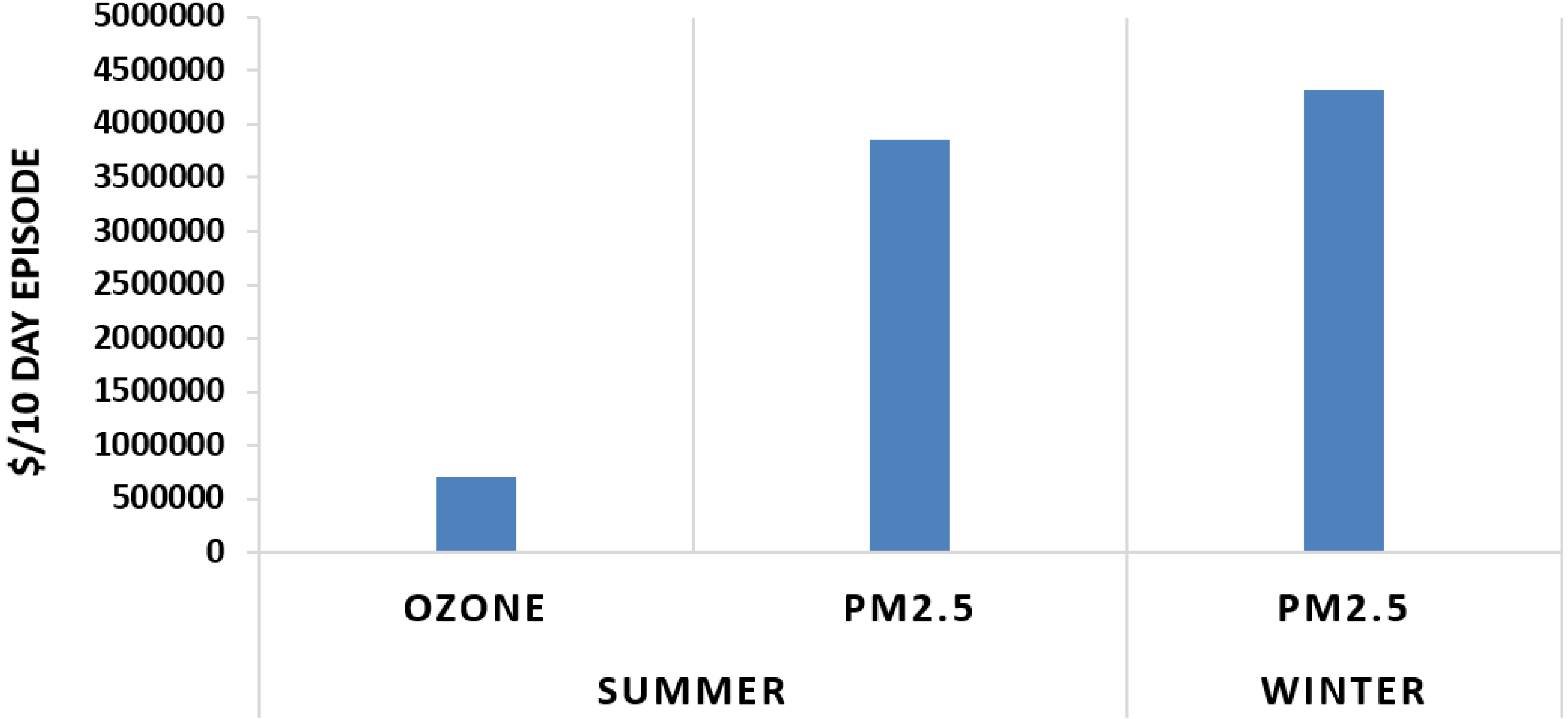
- Increases in ground level MD24H $PM_{2.5}$ from the widespread use of fossil backup generators during a grid disruption for winter (a) and summer (b) with units in µg/m^3



http://apep.uci.edu/PDF/Potential_Public_Health_Costs_from_Air_Quality_Degradation_During_Grid_Disruption_Events_070921.pdf

Air Quality Impacts of H_2 & Fuel Cell Alternatives

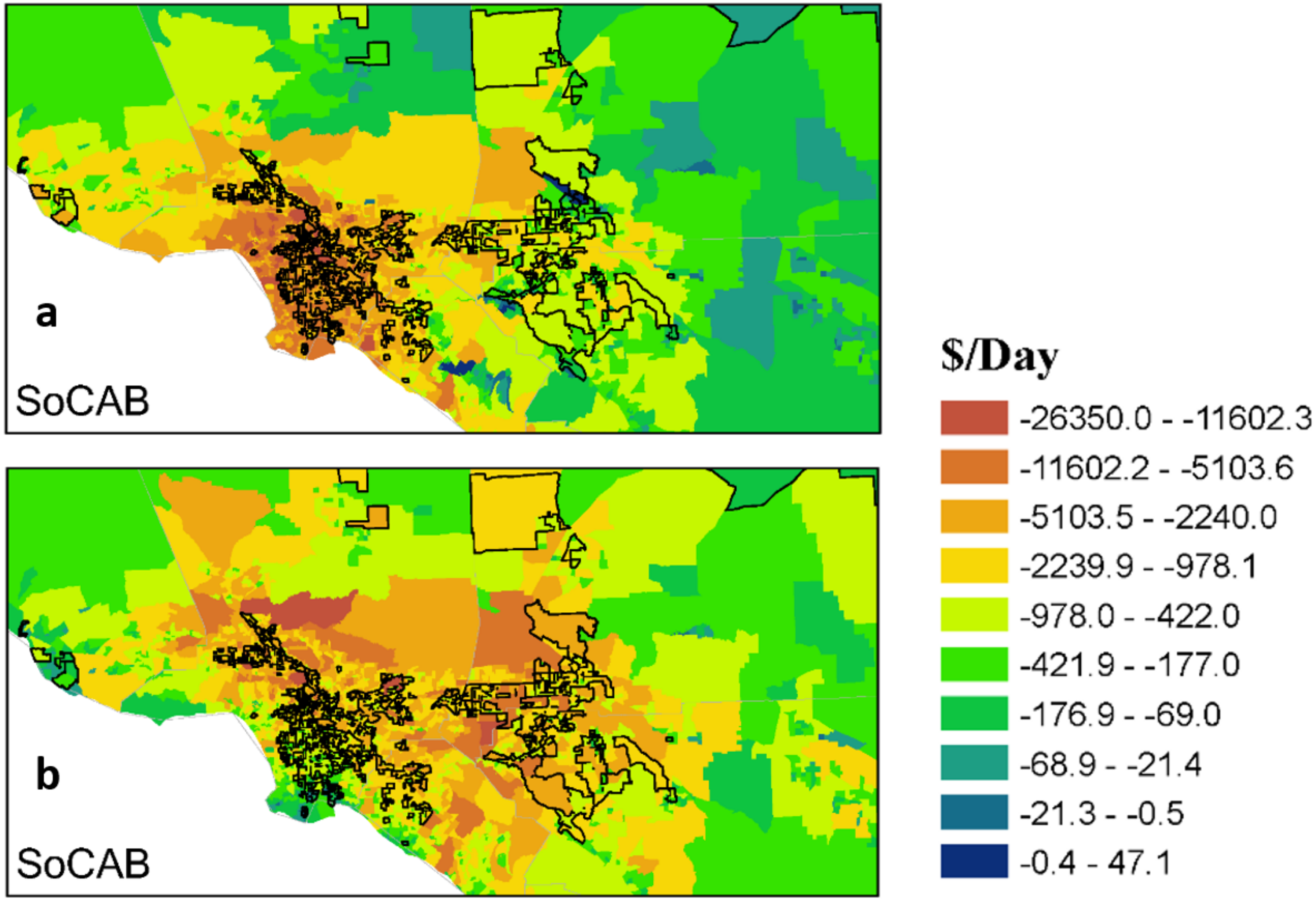
- Public health costs estimated from increased short-term exposure to ozone and $PM_{2.5}$ that results from fossil back-up generators operating during a grid disruption



http://apep.uci.edu/PDF/Potential_Public_Health_Costs_from_Air_Quality_Degradation_During_Grid_Disruption_Events_070921.pdf

Air Quality Impacts of H_2 & Fuel Cell Alternatives

- Spatial distribution of public health costs from AQ degradation in (a) winter and (b) summer
- Boundaries for socially disadvantaged communities (DAC) according to CalEnviroScreen 3.0 are outlined
- DACs are disproportionately impacted



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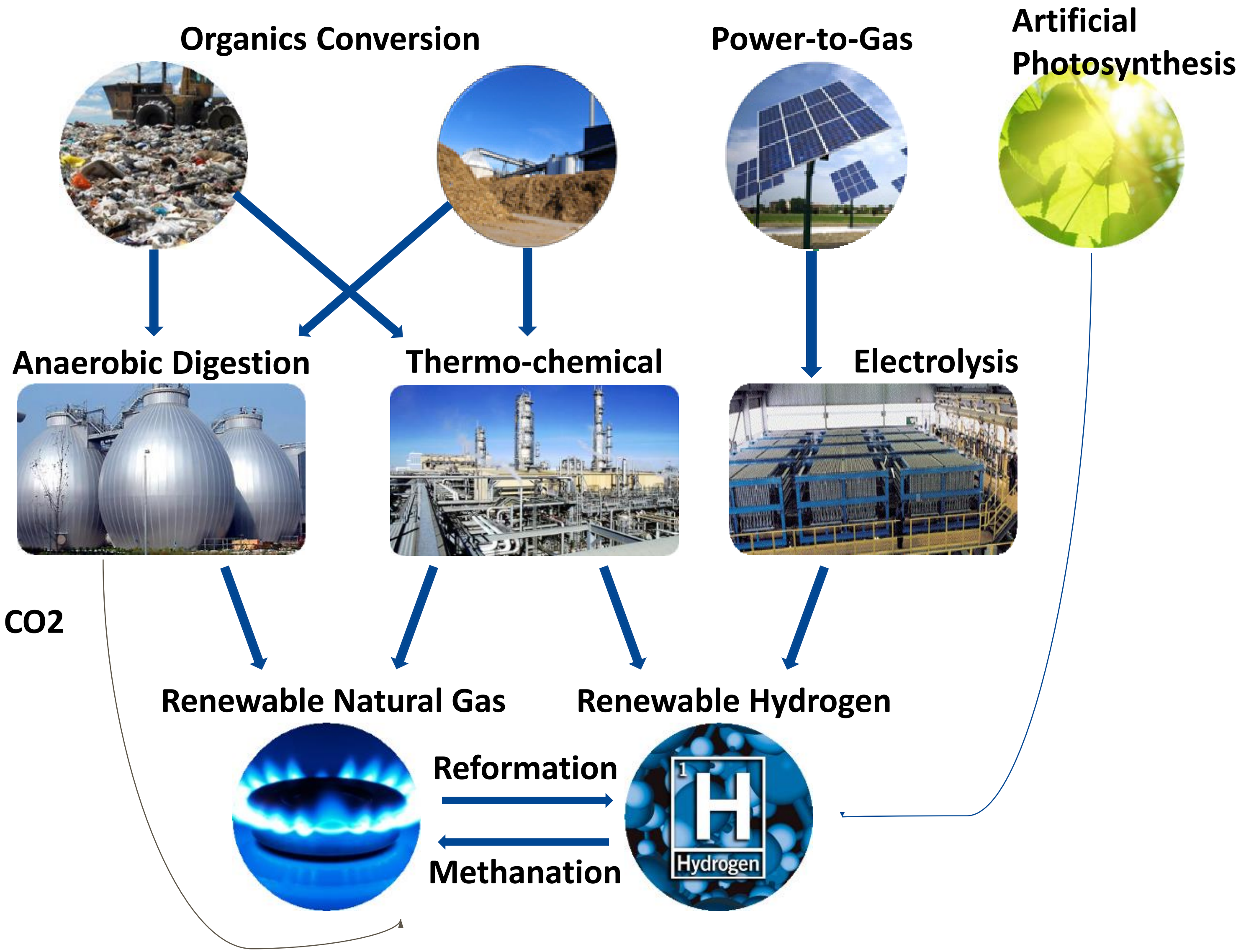
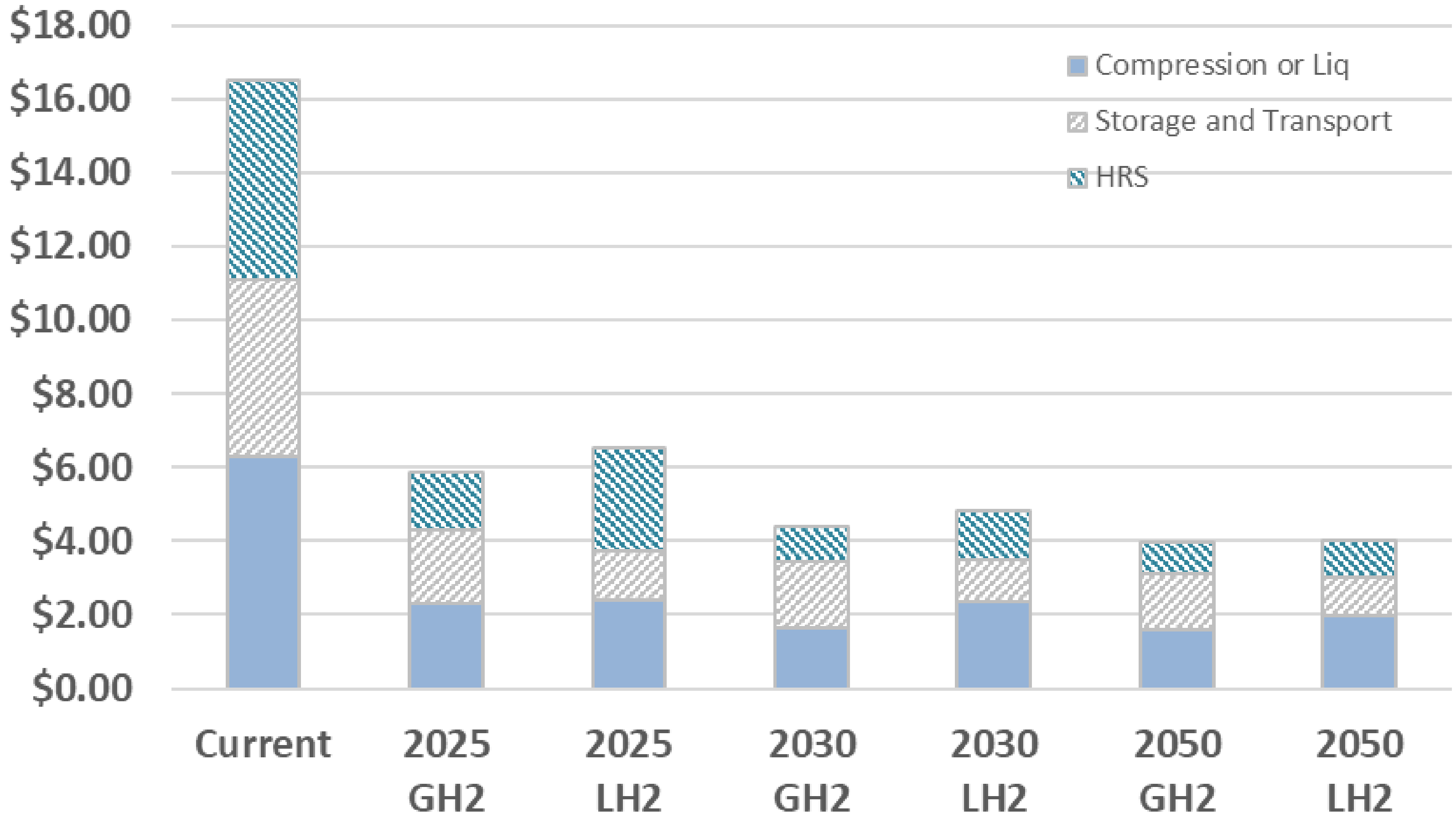
Renewable and Zero-carbon Gaseous Fuel Pathways



Hydrogen Supply-chain Costs Forecast to Decline Rapidly

Increased station network use & economies of scale are most significant



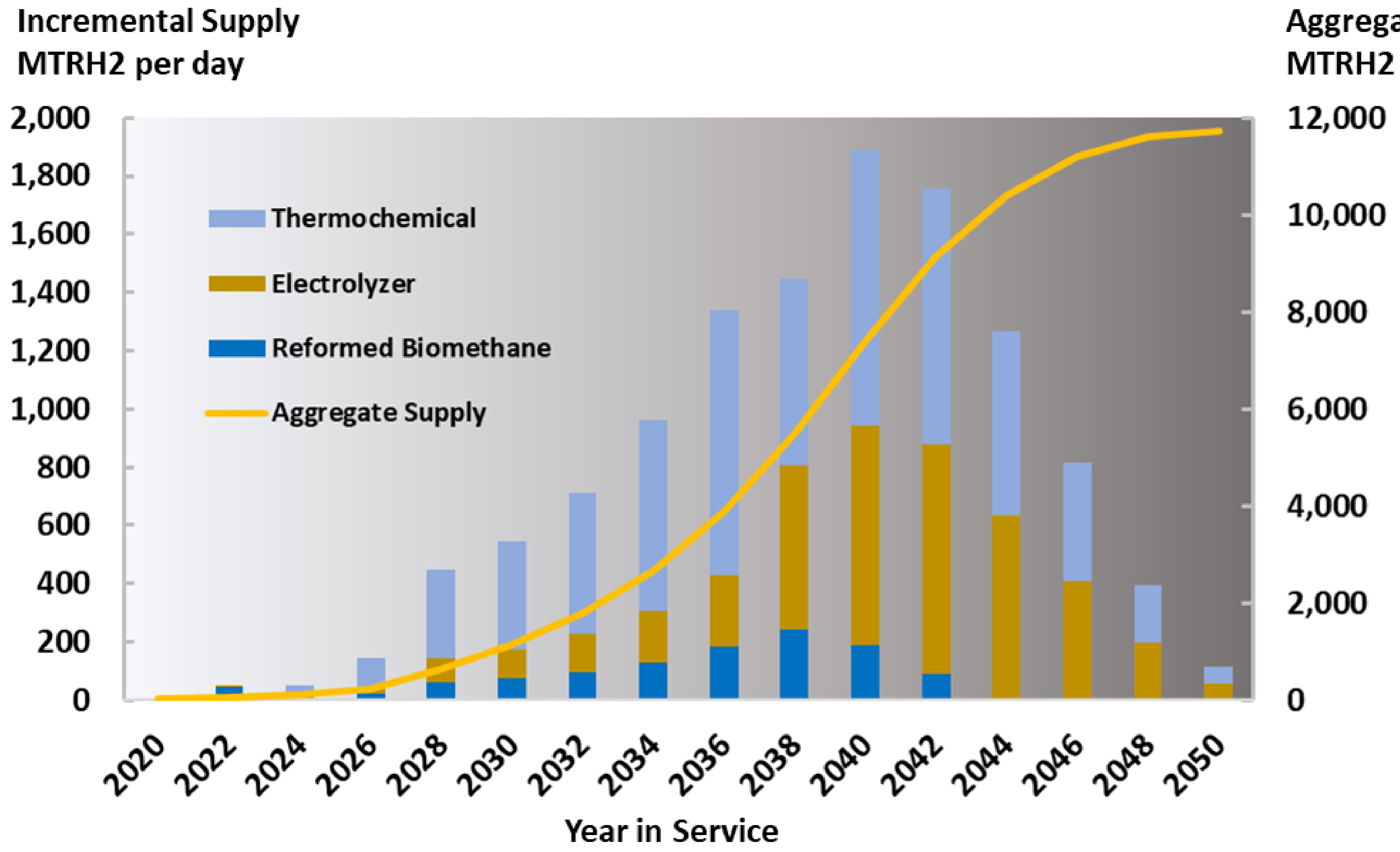
Input Assumptions

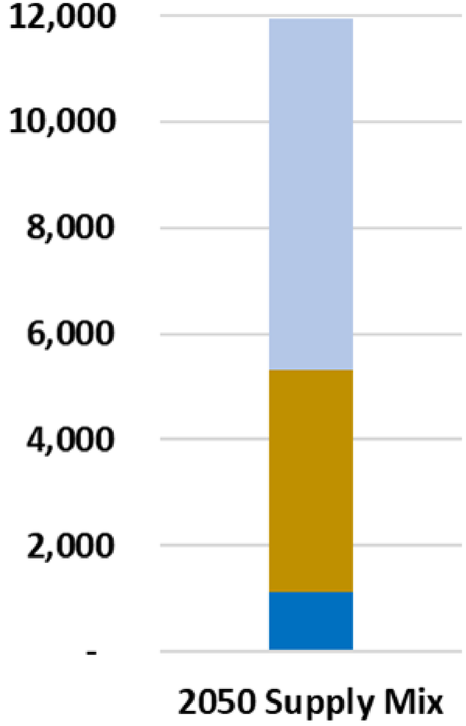
	Current	2025	2030	2050
Station Size Kg/d	300	600	1200	1500
Utiliza-tion	40%	70%	80%	80%
Produc-tion Volume	Low	Medium	High	High

Source: UCI APEP using HDSAM 3.1

Build-out to Serve High-demand Case

- ~500 new facilities needed – more than 25 new facilities in peak year
- Aggregate investment of $30 - $50 billion





Source: UCI APEP, CEC Renewable H2 Roadmap, 2020

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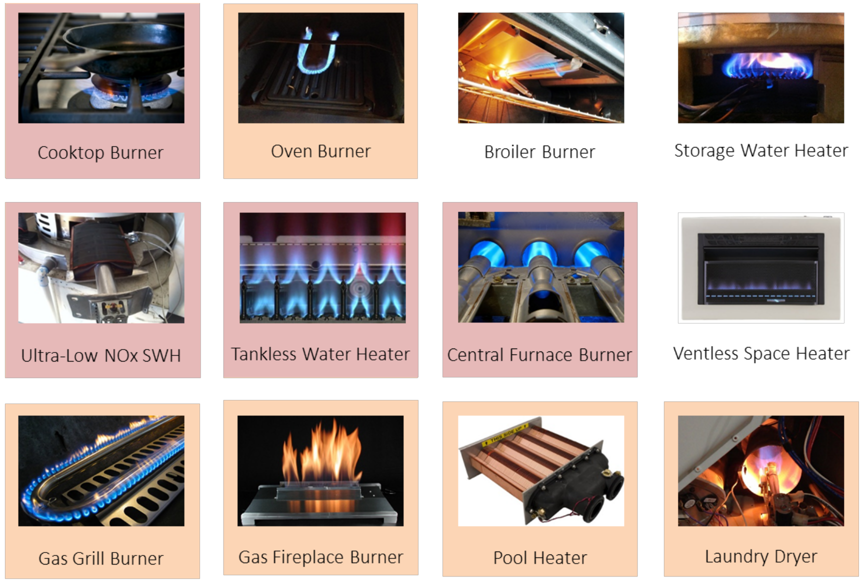
Appliances

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



CFD
Experiment Test + CFD

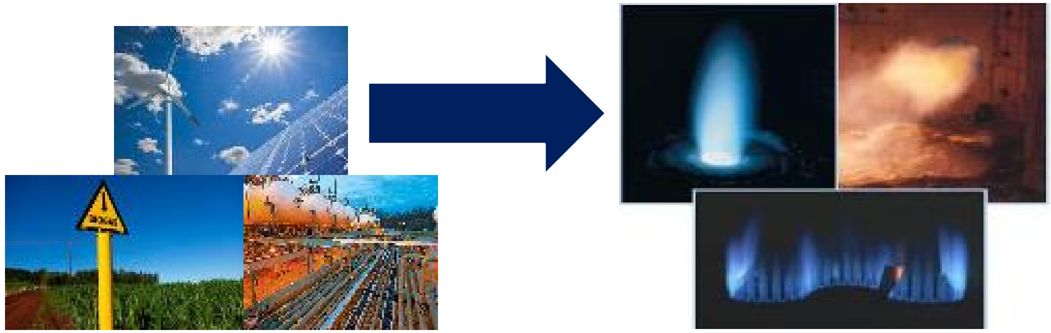
Burner Performance Reports Available for each—Appendices for Final Report

	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

Industrial Burners



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

- Variation for burners, pollutants, and fuels

Fuel Mixture	1. LSB NOx	1. LSB CO	2. SSB NOx	2. SSB CO	3. MTC NOx	3. MTC CO	4. Oxygas NOx	4. Oxygas CO	5. HSJ NOx	5. HSJ 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%

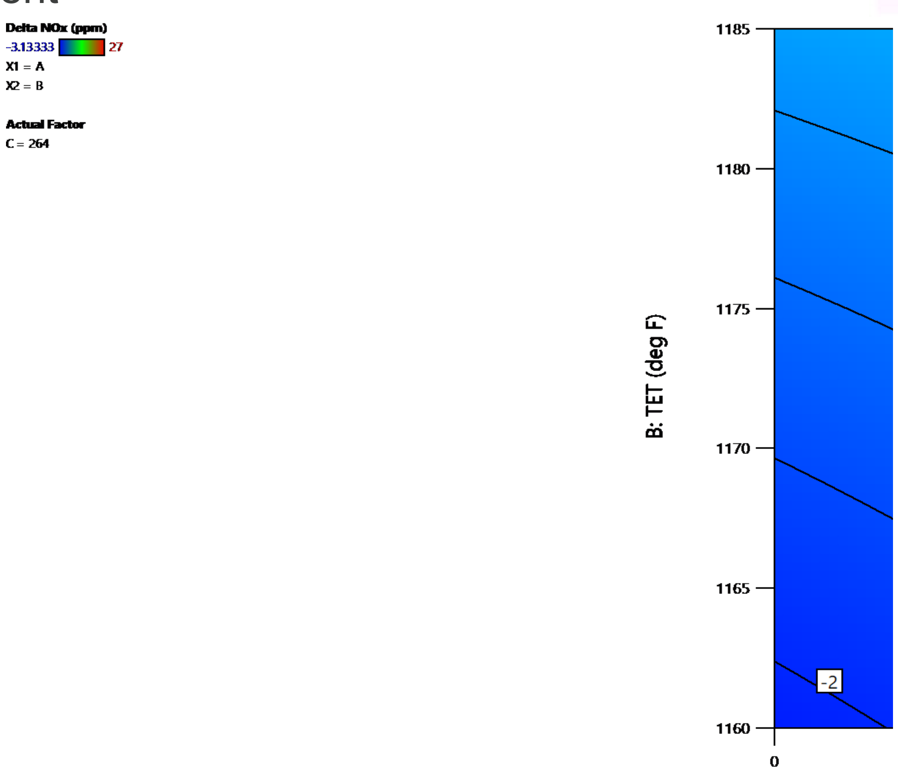
Fuel Mixture	6. GTC NOx	6. GTC CO	7. RT NOx	7. RT CO	8. IRB NOx	8. IRB CO	9. SB NOx	9. SB CO
76% CH_4 - 24% H_2	-20%	-50%	233%	-35%	-60%	-10%	58%	-13%
98% CH_4 - 2% CO_2	-3%	0%	-2%	2%	-3%	-3%	-2%	5%
94% CH_4 - 6% C_2H_6	3%	3%	0%	4%	2%	-5%	3%	4%
95% CH_4 - 5% C_3H_8	3%	3%	5%	4%	1%	-5%	8%	6%

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

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

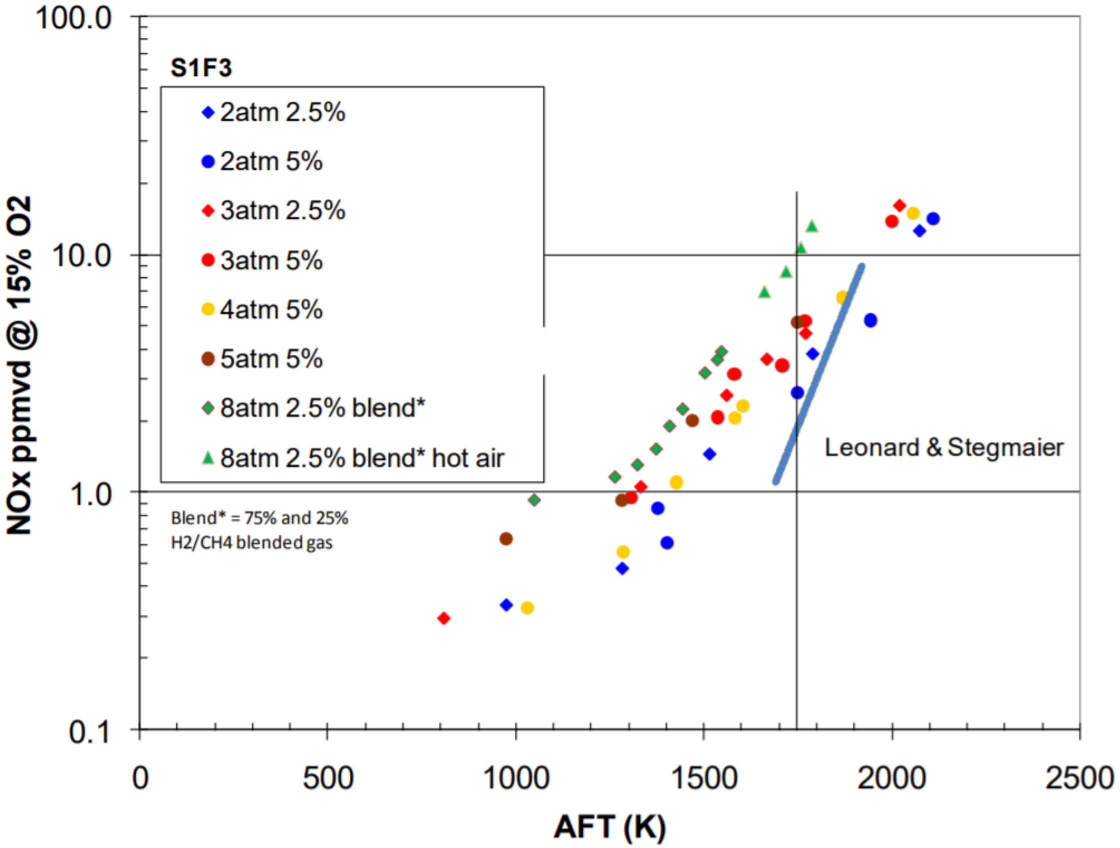
Gas Turbines

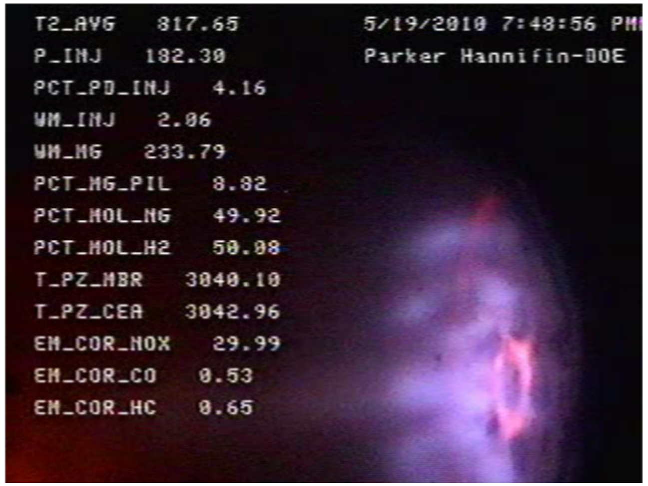
- OEMs are conservative in their developments and targets
  - "Slight increase in NOx may result"
  - This has been the case for decades
    - Original NOx limits were 42 ppm, then 25 ppm, then 9 ppm and now 2.3 ppm
      - ~20x reduction attained through technology development
  - Combustion science 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

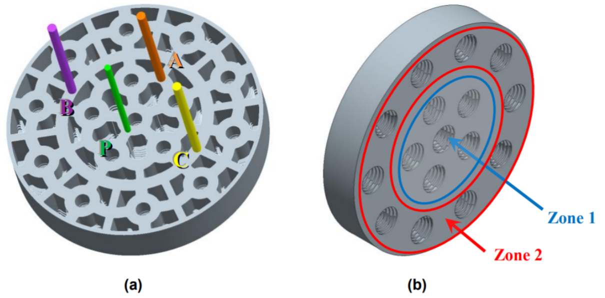


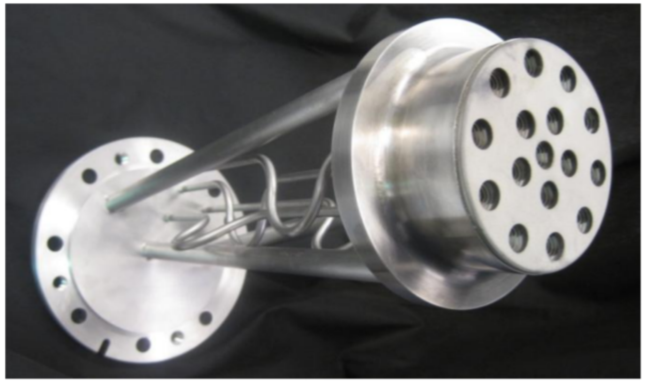
Gas Turbines

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







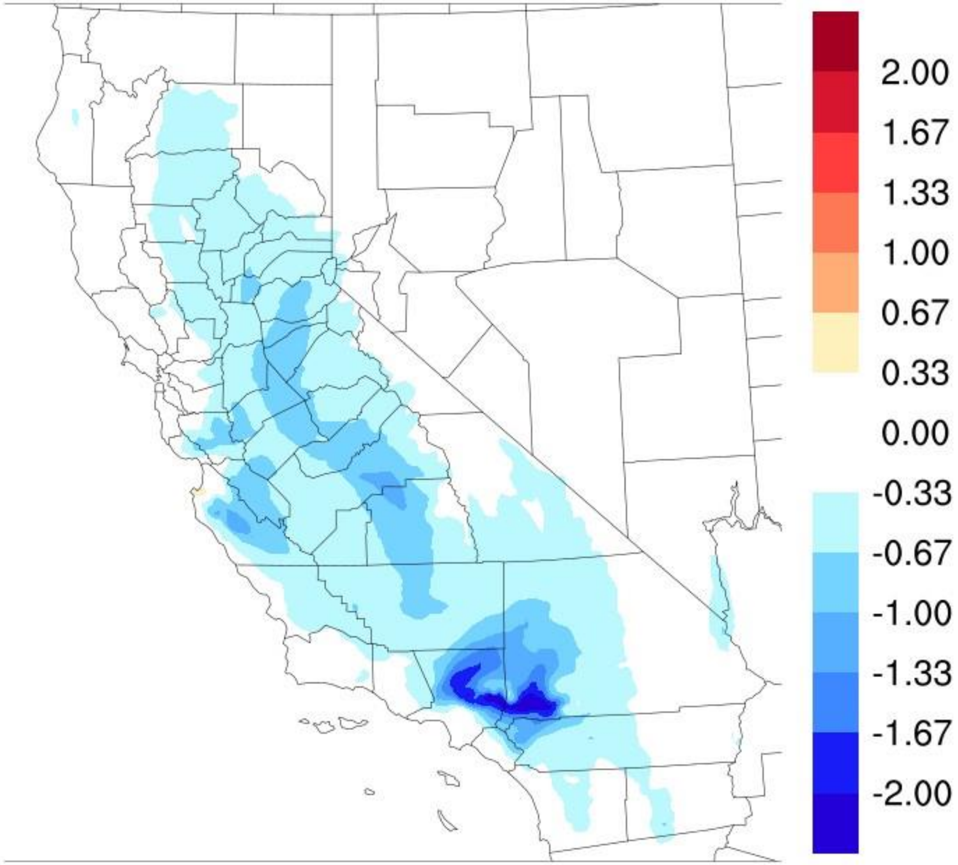


https://www.osti.gov/servlets/purl/1030641

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, μg/m³