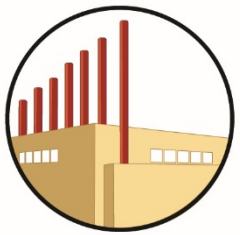
What happens when we use low carbon fuels in applications like water heating and cooking?



UCI Combustion Laboratory

UCIrvine | University of California

CalPlug Workshop
17 April 2023, Irvine, CA

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Content

- **25 minutes total (20 + 5)**

- **Background**
- **Goals**
- **Experimental Results**
  - **Storage Water Heater**
  - **Tankless Water Heater**
- **Summary/Outlook**

Building Use
--Space Heating
--Hot Water
--Cooking

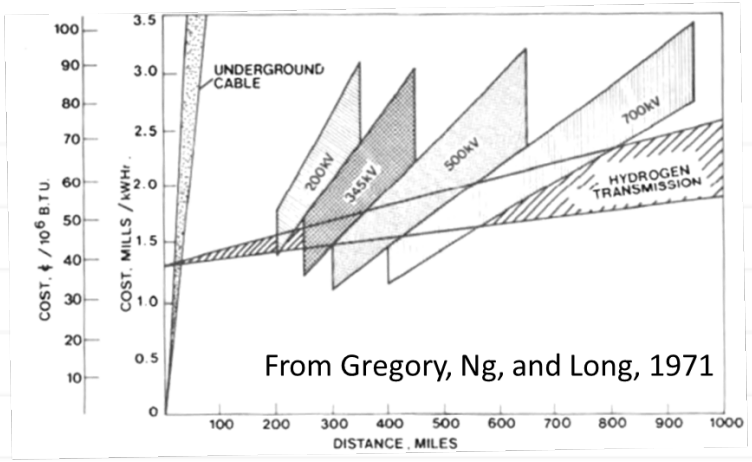
Can touch on each and summarize?

Answer question at end—
NOx goes down, CO goes down
GHGs go down.

CEC benefits analysis

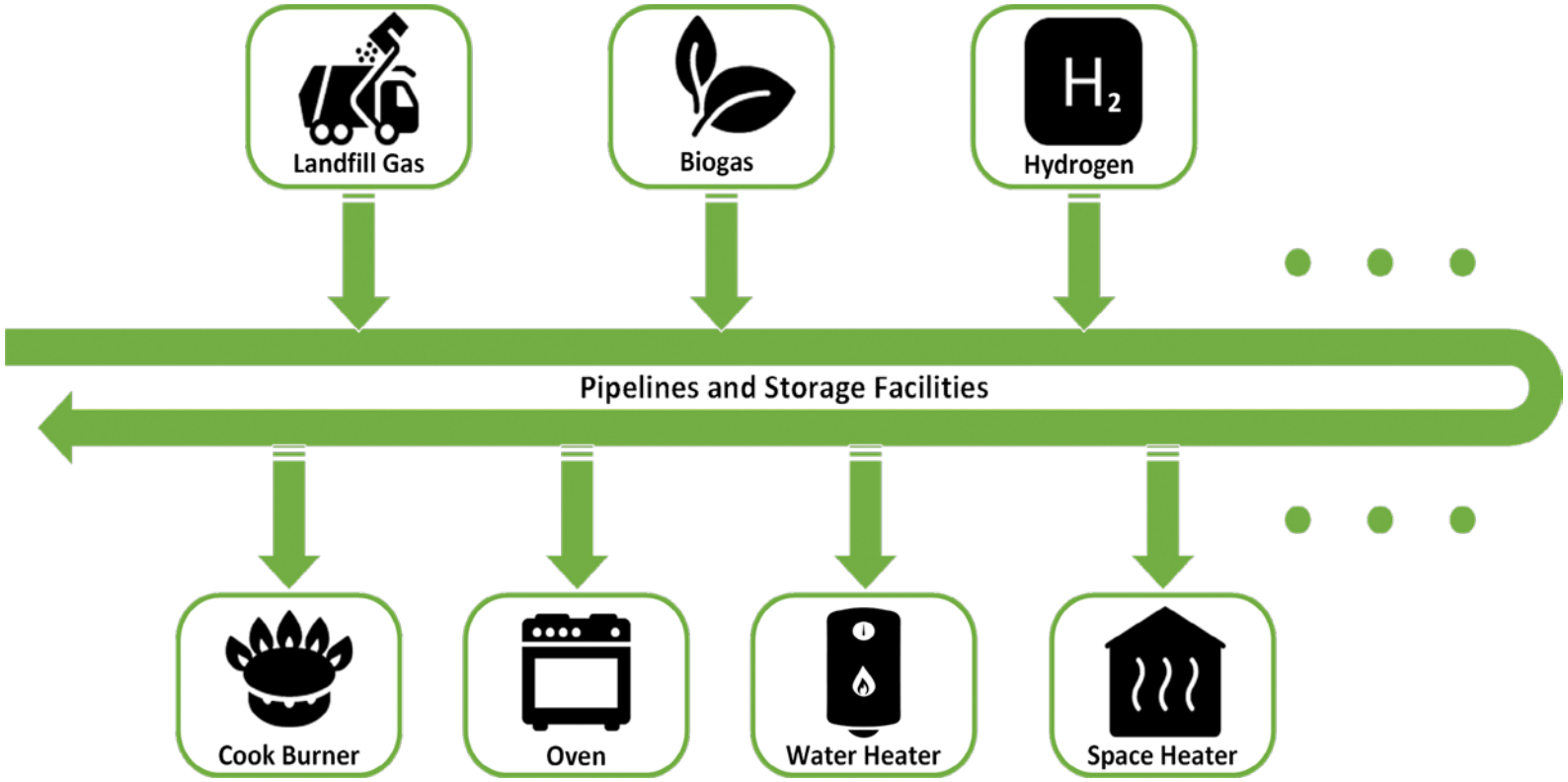
Hydrogen Economy?

- **Ngram Viewer**



Background

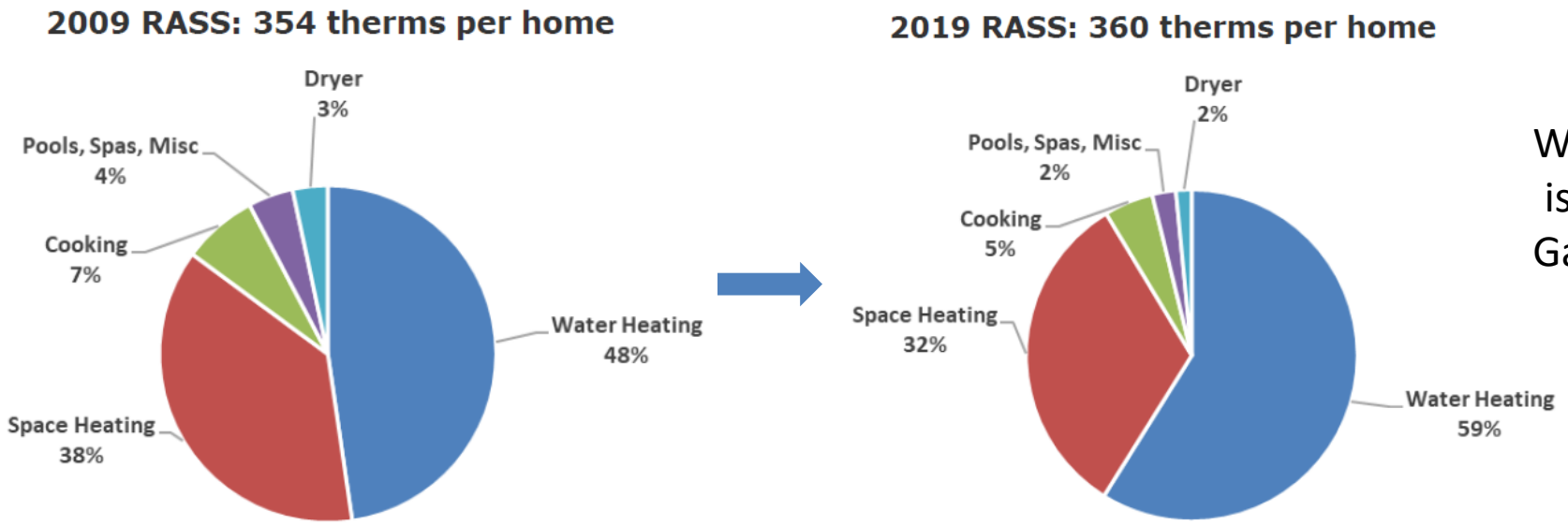
- **Blending towards decarbonization**



Background

- **California is targeting reducing GHG by 40% of 1990 level of emissions by 2030 –California Assembly Bill 398, July 2017**

- **California Residential Natural Gas Consumption**



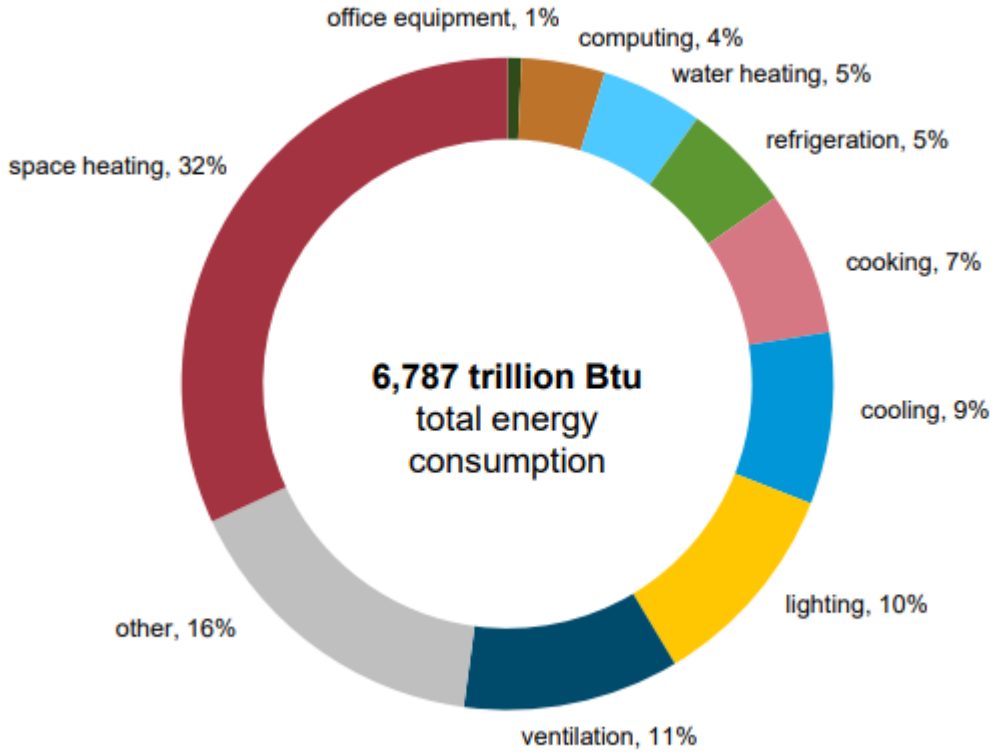
Water Heating is the Largest Gas Consumer

Source: 2019 California Residential Appliance Saturation Survey

Background

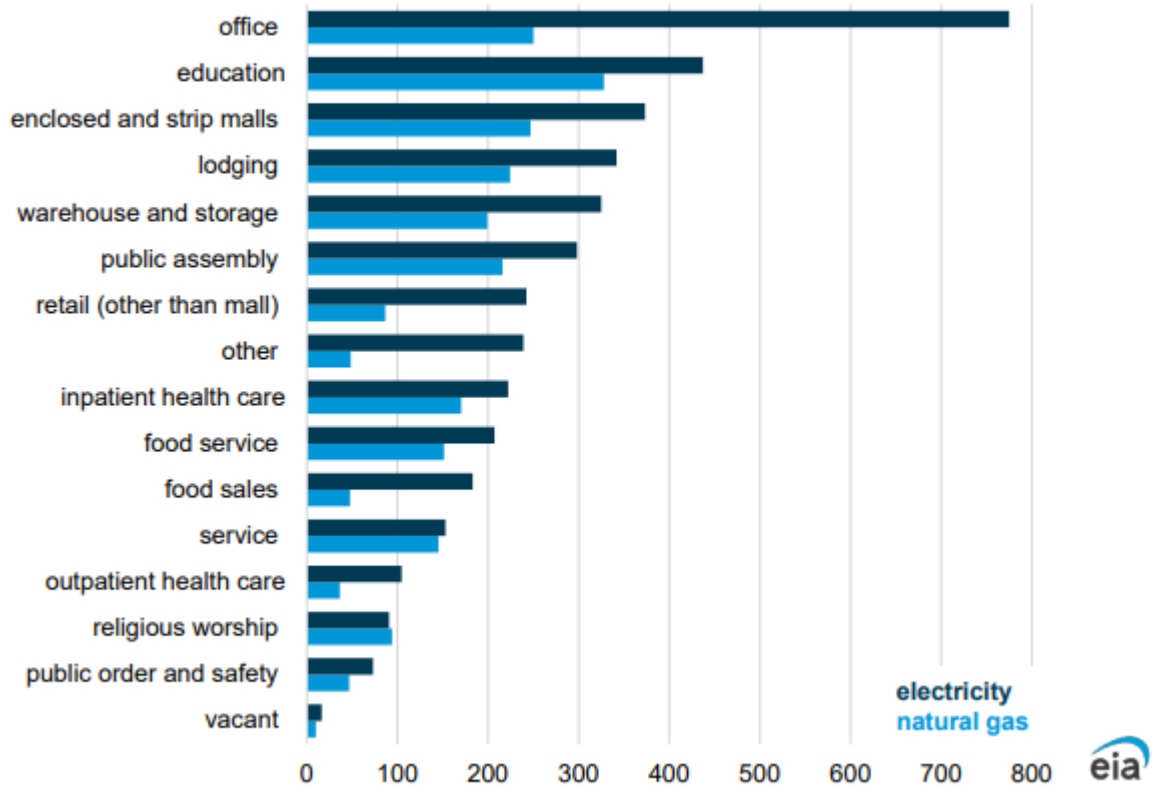
- US Energy Use

Major fuels consumption by end use, 2018
share of total



Data source: U.S. Energy Information Administration, *Commercial Buildings Energy Consumption Survey*
Note: Btu = British thermal units

Electricity and natural gas consumption by principal building activity, 2018
trillion British thermal units



Data source: U.S. Energy Information Administration, *Commercial Buildings Energy Consumption Survey*

Background

- California Commercial Building End Use
  - HVAC Boilers
    - ~53,000 units
  - Gas Furnaces
    - ~750,000 units
  - Cooking Appliances

What happens to these devices when hydrogen is added?

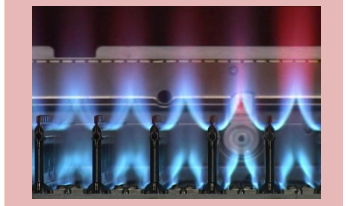
Cooktop Burner

Oven Burner

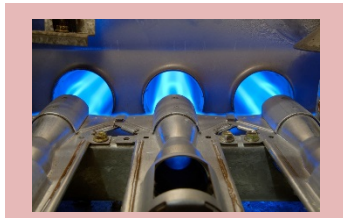
Broiler Burner

Storage Water Heater

Ultra-Low NOx SWH



Tankless Water Heater

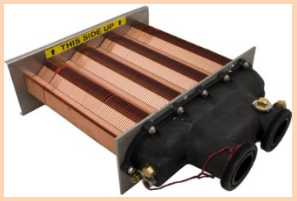


Central Furnace Burner

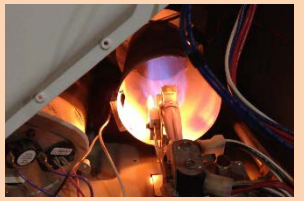
Ventless Space Heater

Gas Grill Burner

Gas Fireplace Burner



Pool Heater



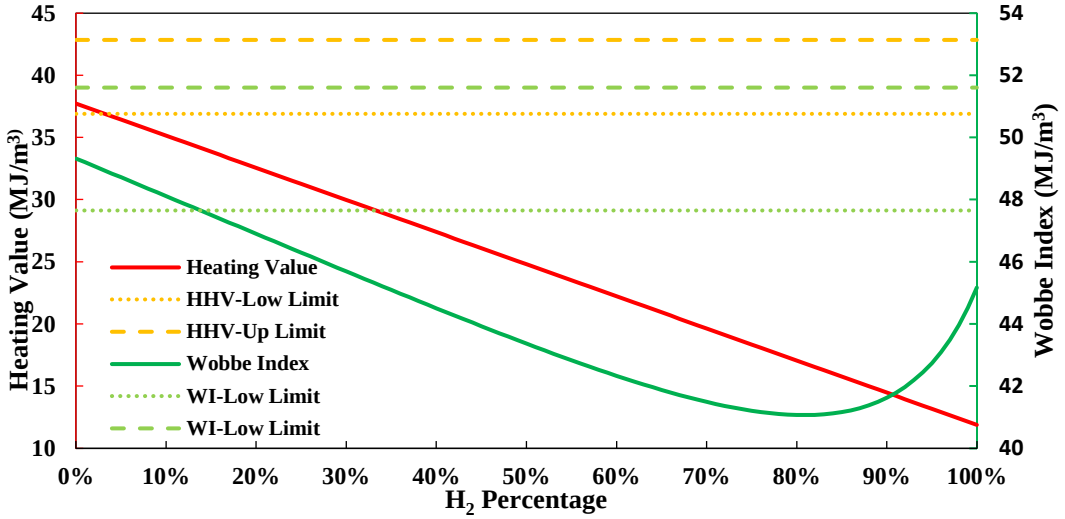
Laundry Dryer

Simulation

Experiment Test + Simulation

Relevant Thermodynamics

- **Similar Wobbe Index**
- **Hydrogen requires 24% less air volume to react compared to NG**



$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2$$

$$H_2 + 0.5(O_2 + 3.76N_2) \rightarrow 2H_2O + 1.88N_2$$

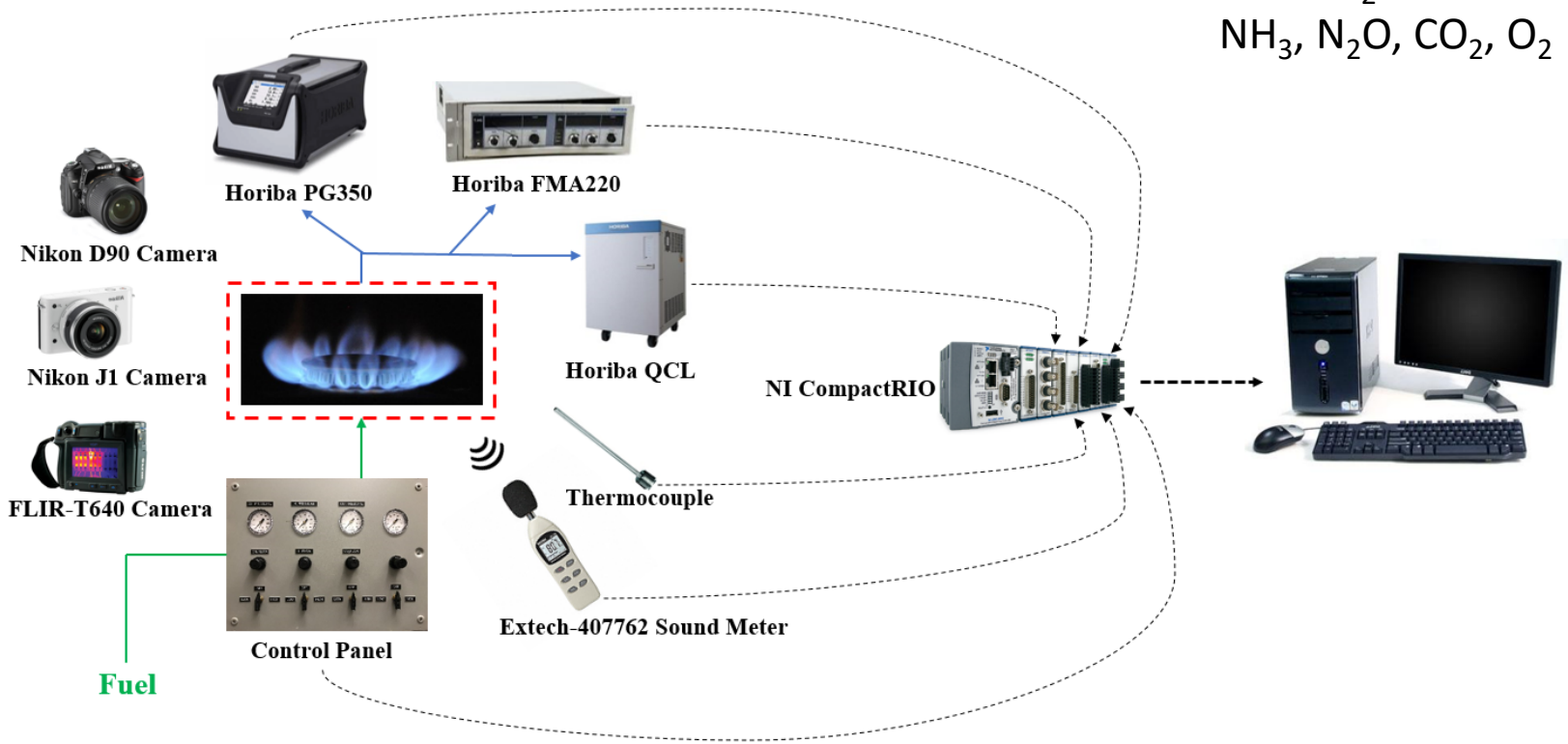
3x difference in heating value—need 3x higher fuel volume flow for hydrogen…

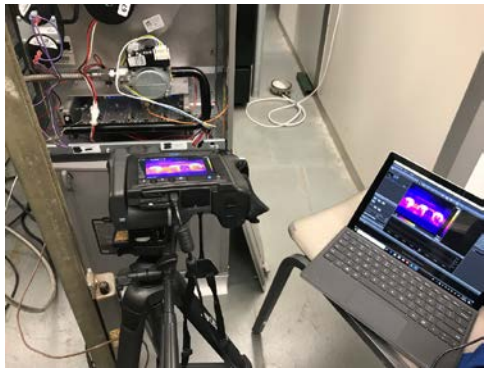
$$\frac{\dot{V}_{air,H_2,st}}{\dot{V}_{air,CH_4,st}} = \frac{HHV_{CH_4}}{HHV_{H_2}} * \frac{0.5}{2} \approx 0.76 < 1$$

- **Natural Draft water heater draws ~ same air regardless of fuel type**
- **Forced Draft has more control over excess air→target of this effort**

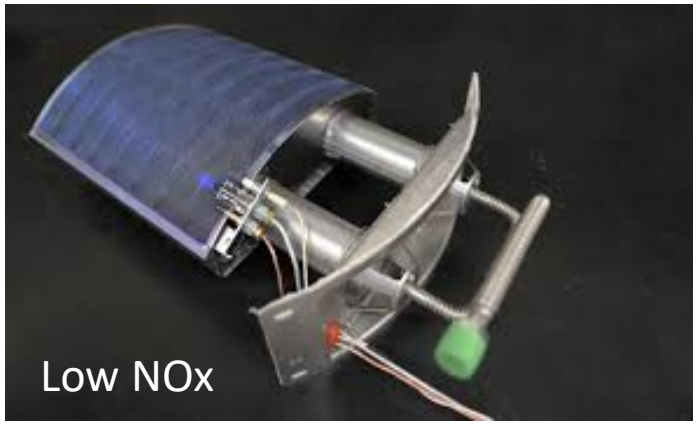
Experiment Setup

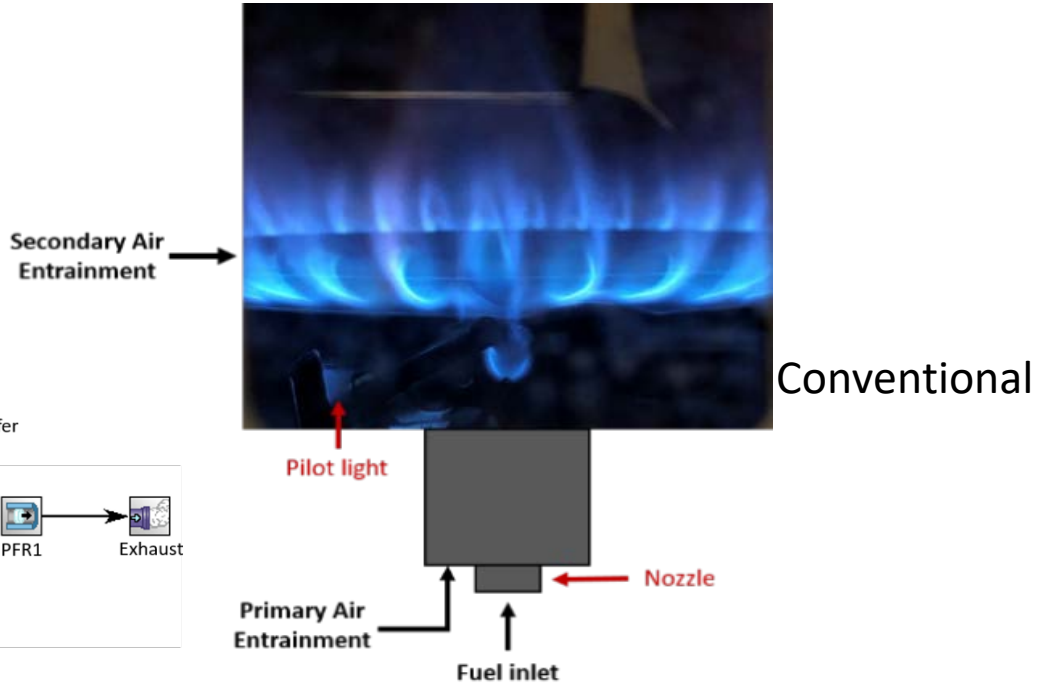
NO, NO_2, CO, UHC,
NH_3, N_2O, CO_2, O_2





Storage Water Heater

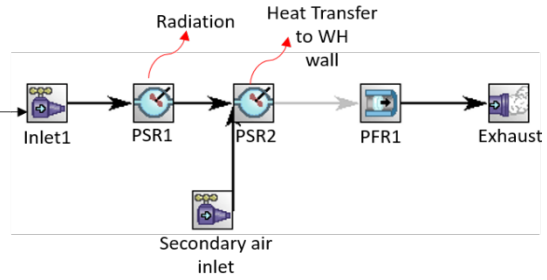




Conventional

Premixed air-fuel mixture

- CH_4
- CH_4+CO_2
- CH_4+H_2



Water Heater Emissions

- **Emissions and hydrogen limits (experimental)**

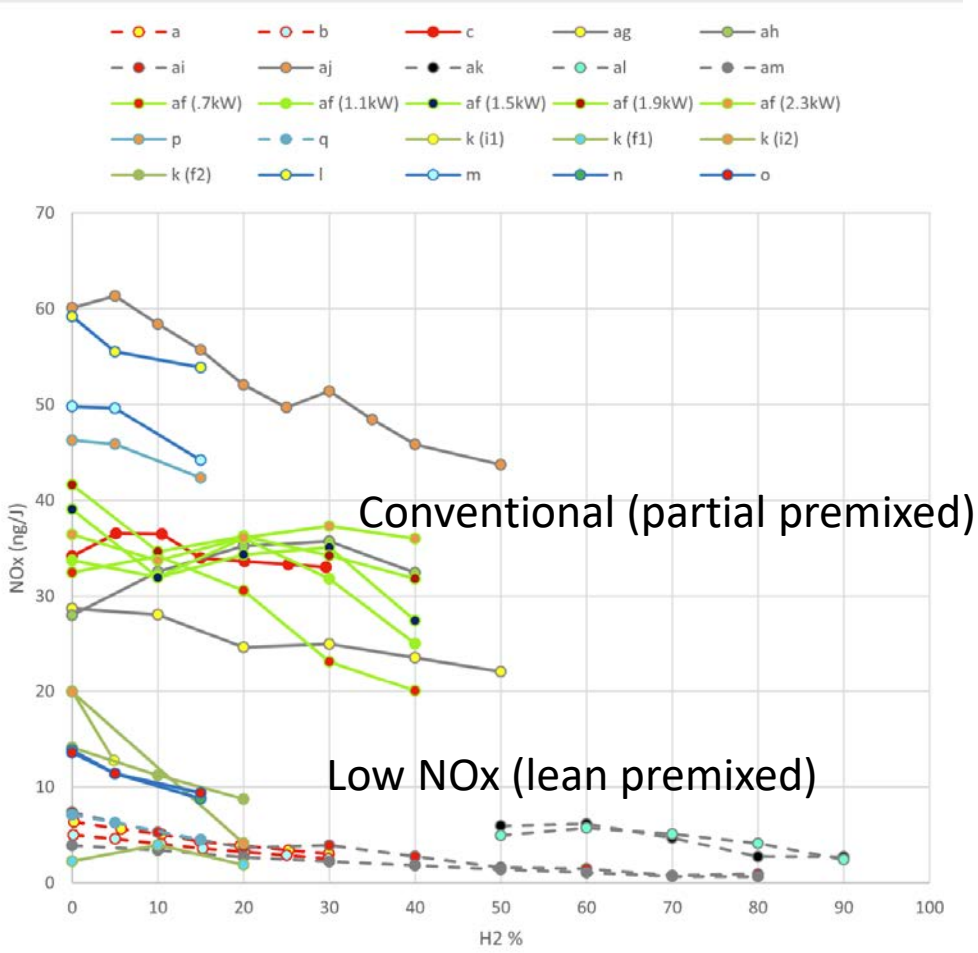


Fig. 12 – ng/J of NOx vs hydrogen concentrations in natural gas for all water heaters.

- **Adding Hydrogen Reduces NOx**
- **40-50% limit for conventional units**
- **70-80% limit for low NOx**

- **Major changes above 80% H2 (flame speed, etc)—most of challenge**

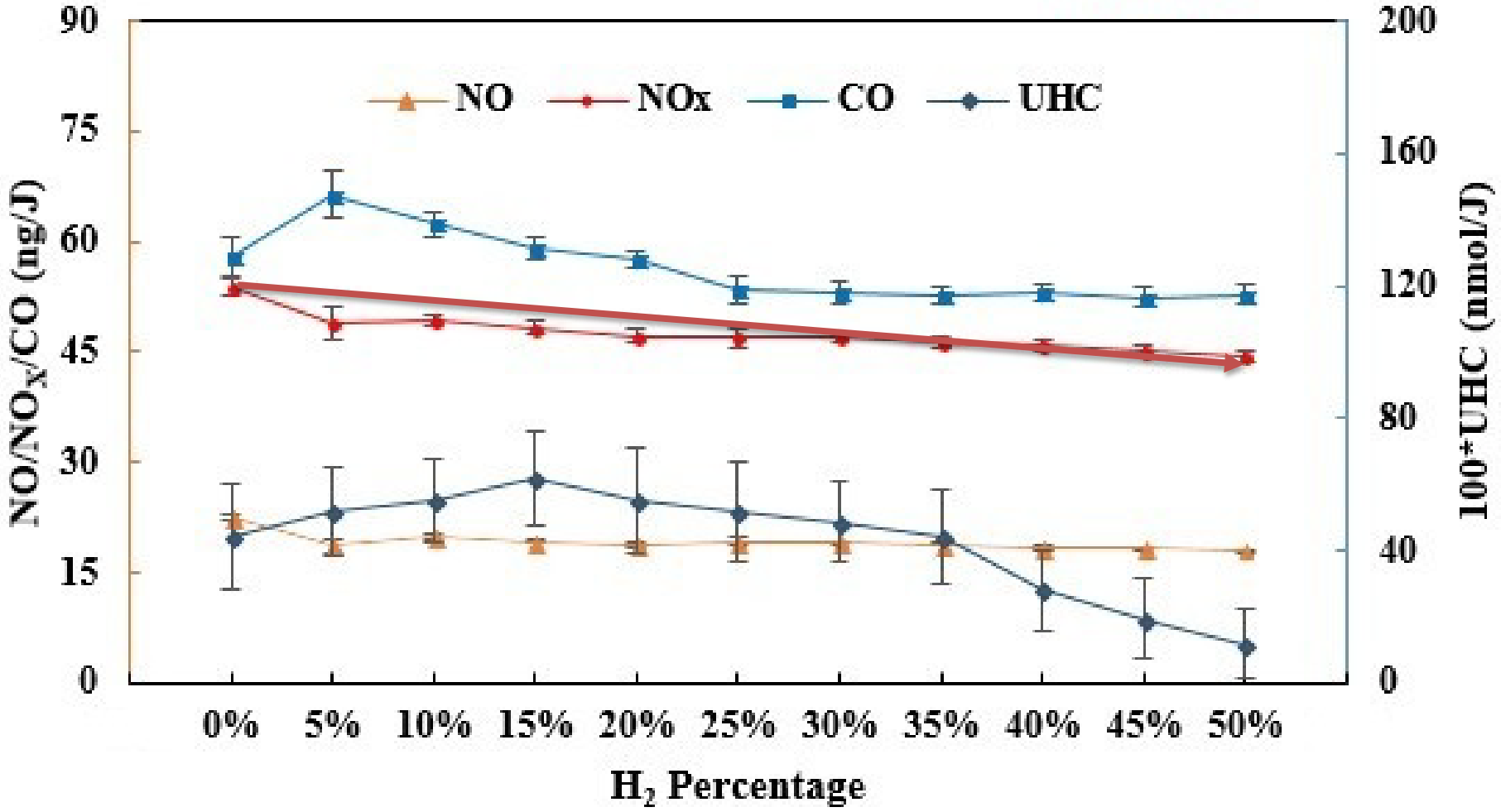
Cooking


Cooktop Burner

*Hood Positioning per ANSI Z21.1-2016

Cooking


Cooktop Burner

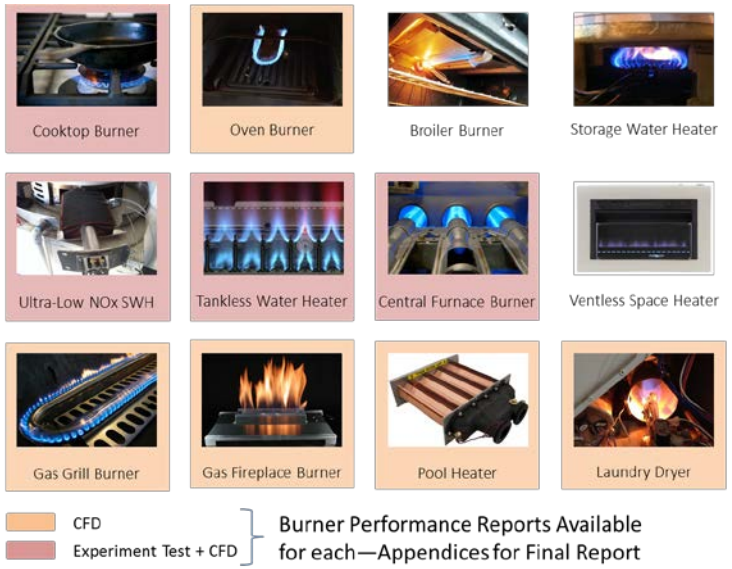


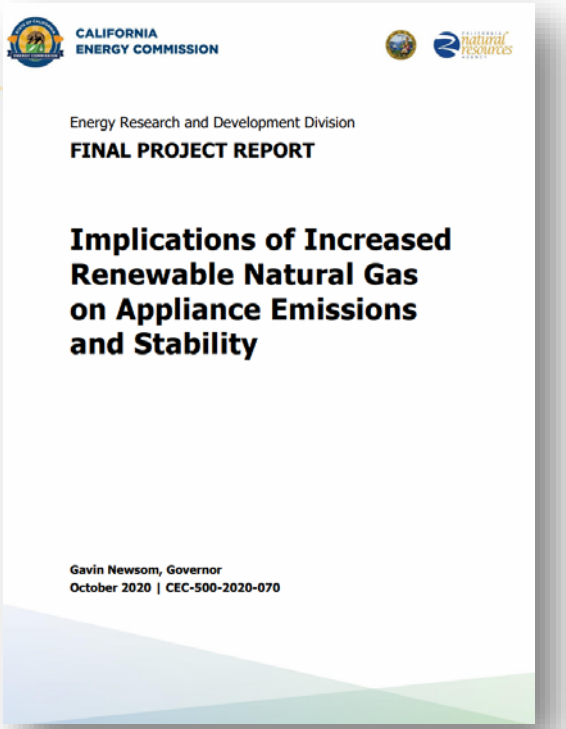
- Generally, H_2 addition reduces NOx emissions

$$[Emi]_{ng/J} = \frac{0.1 * [Emi]_{meas,ppm}}{[CO_2]_{meas,\%} - [CO_2]_{air,\%}} \frac{mol\ CO_2}{MJ\ Fuel} M_{Emi,g/mol}$$

Summary

- NOx decreases for most legacy burners
  - Those using ~80% NG in CA
- Understanding established to propose modifications to accommodate more hydrogen



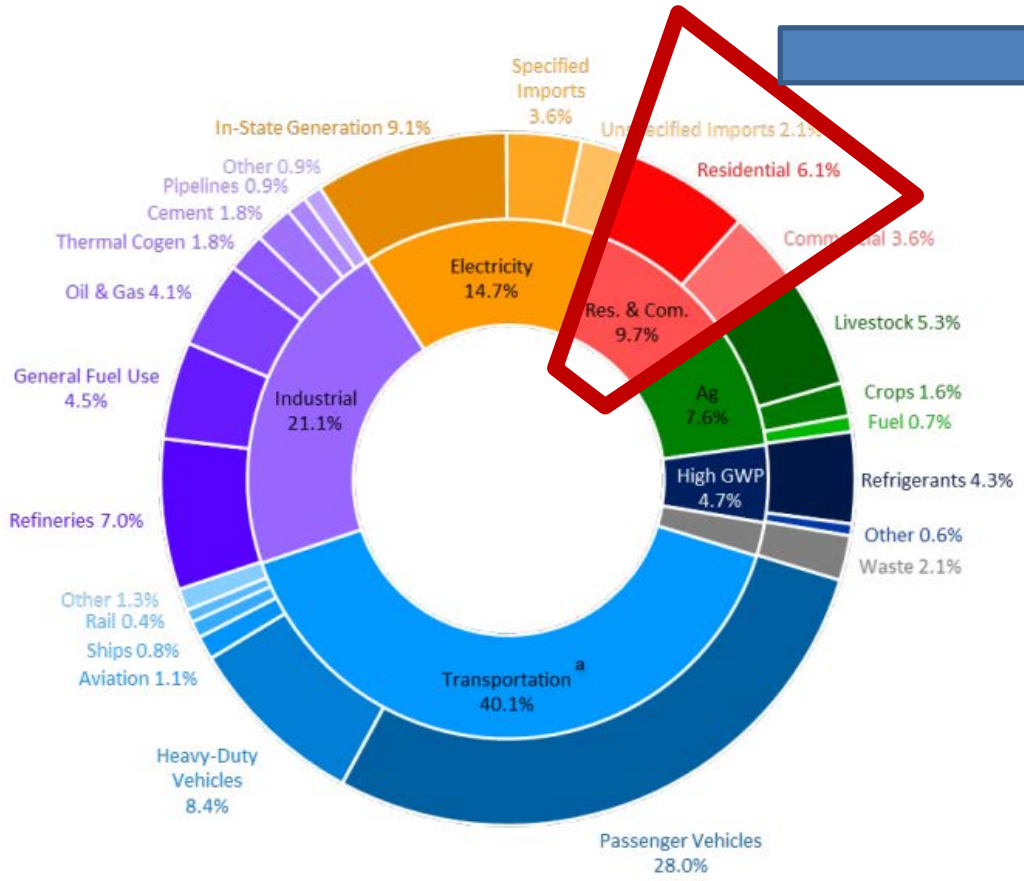


	1. Cooktop			2. Oven			3. Gas Fireplace			4. Low NO_x SWH			5. Tankless WH		
Fuel Mixture	**NO_x**	**CO**	**Upper Limit**	**NO_x**	**CO**	**Upper Limit**	**NO_x**	**CO**	**Upper Limit**	**NO_x**	**CO**	**Upper Limit**	**NO_x**	**CO**	**Upper Limit**
80 CH_4 – 20 H_2	-23%	-14%	55%	0%	-38%	30%	3966%	-100%	100%	0%	+27%	10%	-20%	-10%	>20%
(by volume)															
	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**			
80 CH_4 – 20 H_2	-4%	-14%	45%	-96%	+762%	NA	+128%	-94%	>40%	-62%	-34%	NA			

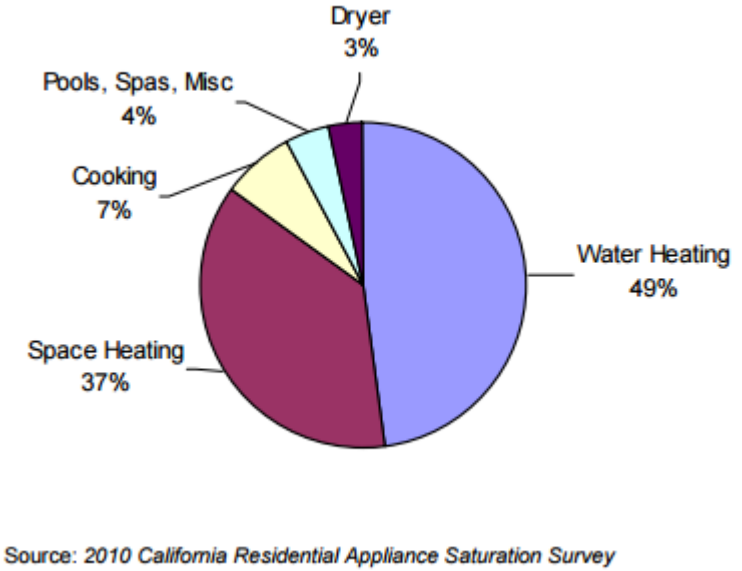
Key (NO_x/CO)
% Increase
% Decrease
No Change

McDonell, Vincent, Zhao, Yan, Choudhury, Shiny. 2020. ***Implications of Increased Renewable Natural Gas on Appliance Emissions and Stability.*** California Energy Commission. Publication number: CEC-500-2020-070

Emission Reduction



California GHG Emissions by Sector of 2017 (CARB)

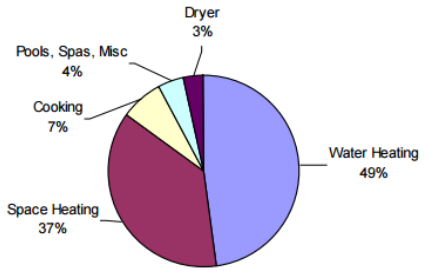


Source: *2010 California Residential Appliance Saturation Survey*

California Appliance Mix 2017 (EIA)

Decarbonization (CO_2 Reduction)

		5% H_2	10% H_2	15% H_2	20% H_2	Percentage	Reduction of Vehicles
1	Cooktop	2.83%	5.75%	8.75%	11.9%	Part of 7%	• 2017 California GHG emissions (converted to CO_2): 424 million tons. • GHG reduction by replacing 10% pipeline natural gas with H_2: 1.63 million tons, which is 0.38% of the total California GHG emissions. • The GHG reduction from the residential sector is equivalent to around 354,000 gasoline vehicles removed from the road.
2	Oven Burner	2.83%	5.75%	8.75%	11.9%	Part of 7%	
3	Gas Fireplace	2.83%	5.75%	8.75%	11.9%	Part of 37%	
4	Low NO_X WH	2.83%	5.75%	8.75%	11.9%	Part of 49%	
5	Tankless WH	1.67%	3.46%	5.38%	7.46%	Part of 49% (10-15%)	
6	Space Heater	2.83%	5.75%	8.75%	11.9%	Part of 37%	
7	Pool Heater	1.67%	3.46%	5.38%	7.46%	Part of 4%	
8	Outdoor Grill	2.83%	5.75%	8.75%	11.9%	Part of 7%	
9	Laundry Dryer	2.83%	5.75%	8.75%	11.9%	Part of 3%	



NOx Reduction

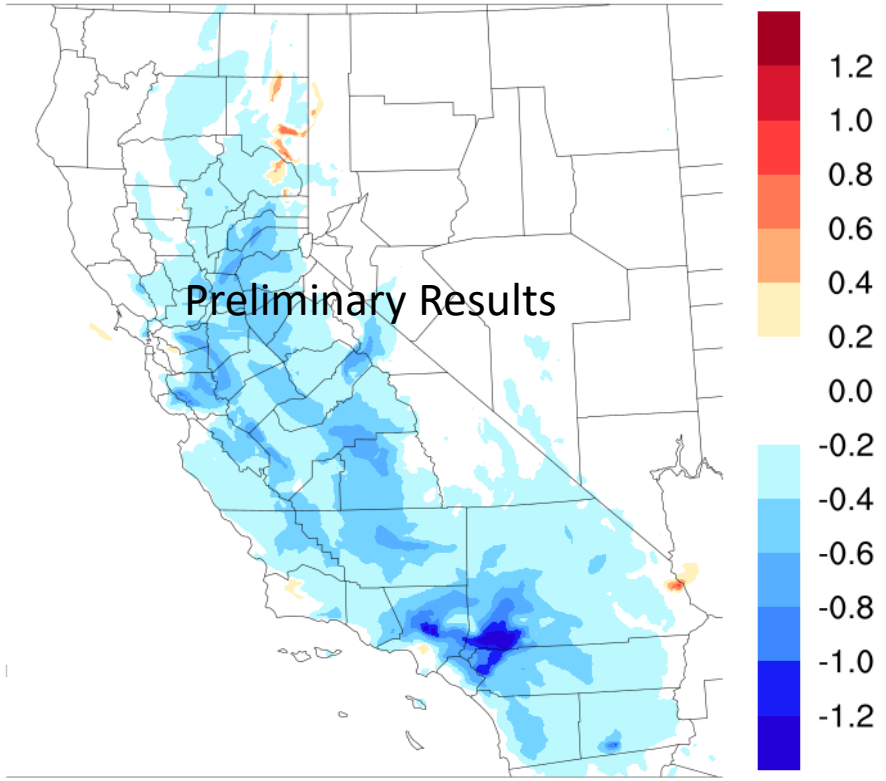
		5% H_2	10% H_2	15% H_2	20% H_2	Percentage
1	Cooktop	19.2%	18.6%	19.7%	22.4%	Part of 7%
2	Oven Burner	+1.7%	+1.1%	+1.1%	+1.8%	Part of 7%
3	Gas Fireplace	+10.4%	+17.7%	+19.3%	+20.7%	Part of 37%
4	Low NO_X WH	12.8%	---	---	30-50%	Part of 49%
5	Tankless WH	7.5%	12.0%	16.0%	20.3%	Part of 49% (10-15%)
6	Space Heater	+2.6%	+2.3%	+2.3%	+1.2%	Part of 37%
7	Pool Heater	32.2%	47.8%	52.2%	57.8%	Part of 4%
8	Outdoor Grill	+34.4%	+112.8%	+141.4%	+161.1%	Part of 7%
9	Laundry Dryer	20.8%	33.0%	38.6%	44.7%	Part of 3%

"+" indicates NOx Increase

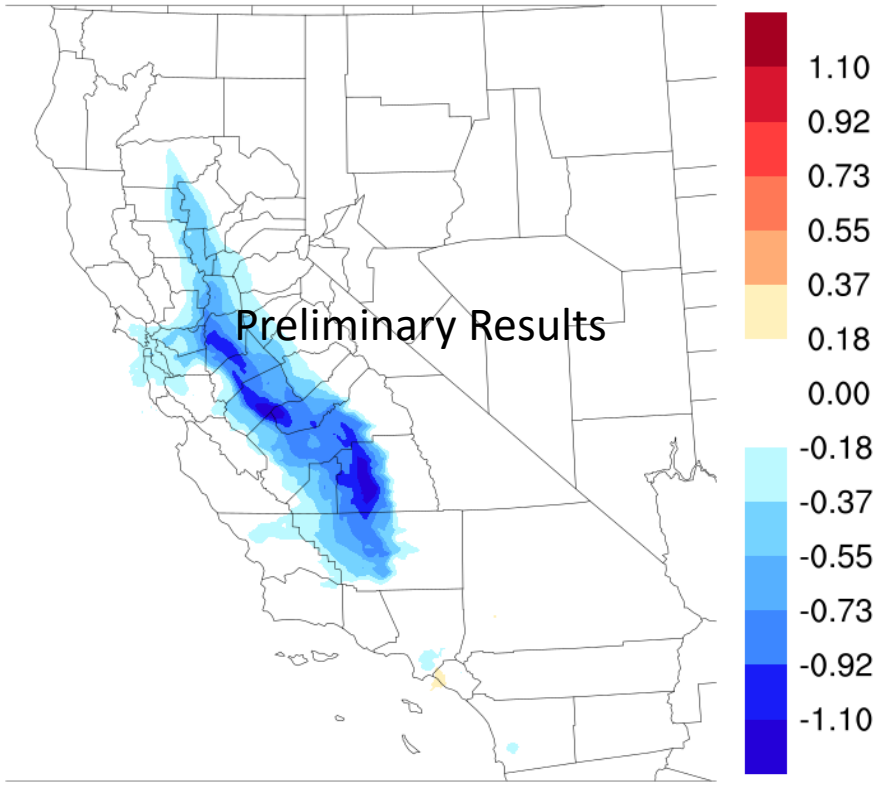
Air Quality Impacts?

- **Data Input for AQ Simulation Work (SCAQMD funding)—20% hydrogen addition senario**
  - **Major assumption regarding boiler emissions, future cases will explore alternatives that could dramatically change results including in sign and intensity**

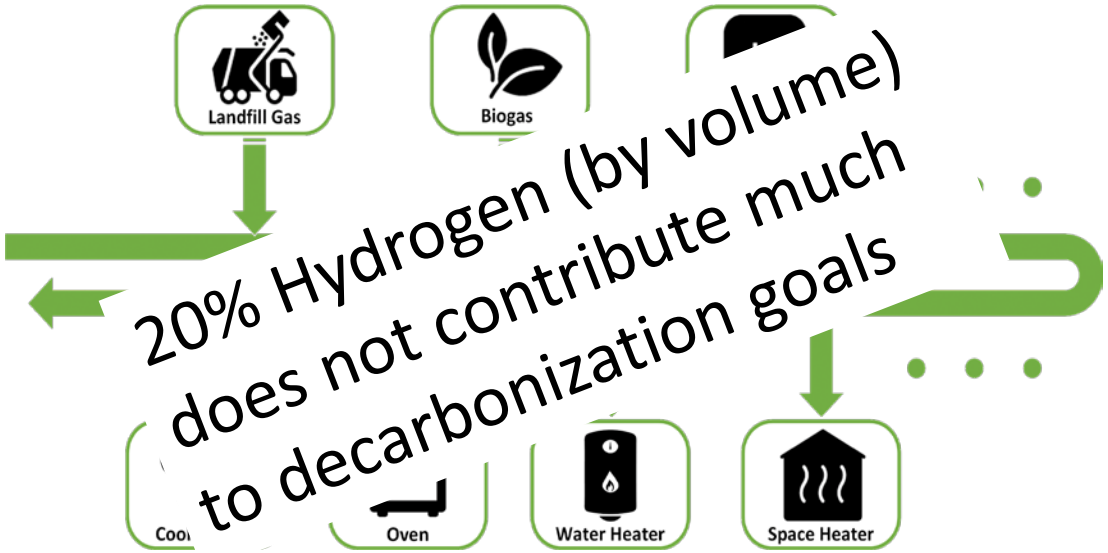
Δ Summer MD8H Ozone : -1.4 to +0.84 ppb



Δ Winter $PM_{2.5}$: - 1.3 to +0.32 µg/m³



Beyond Blending

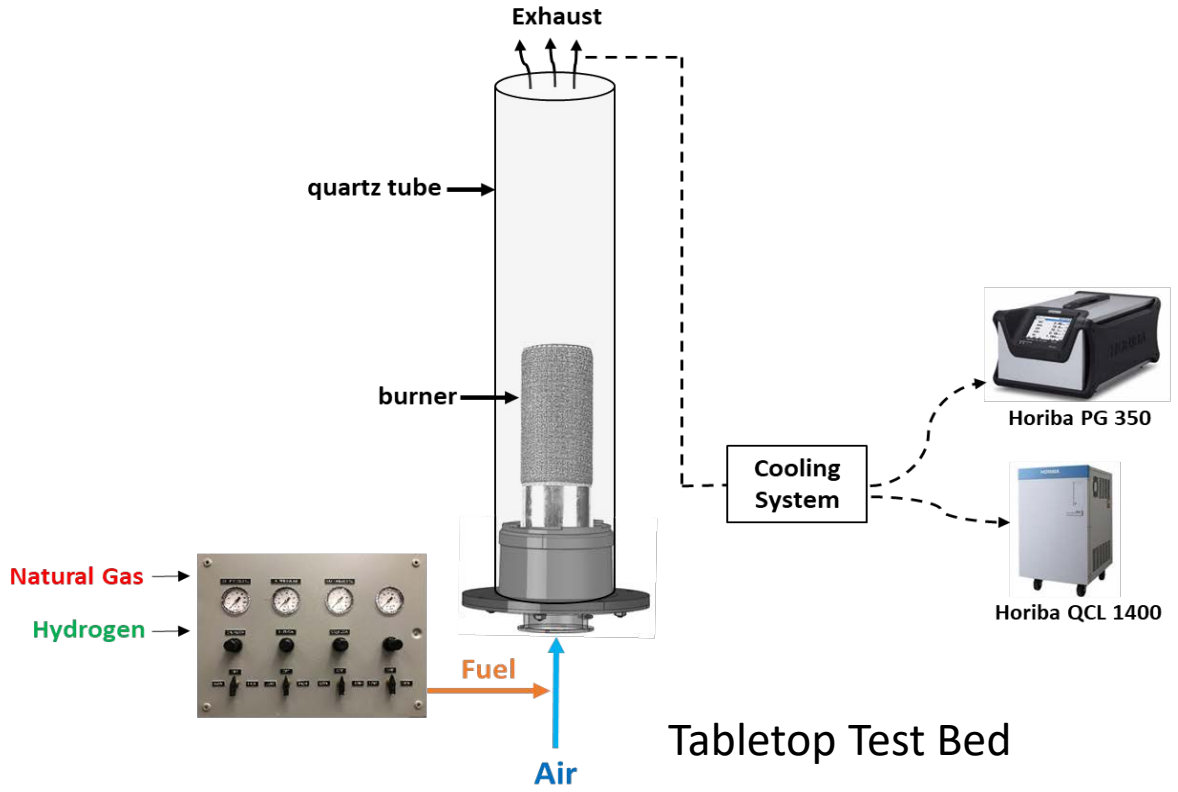


Beyond Blending: 100% Hydrogen

- **Can a retrofittable burner system capable of operating on 100% hydrogen be developed?**
- **Two test beds**

Programmable Blower

Prototype Forced Draft Waterheater

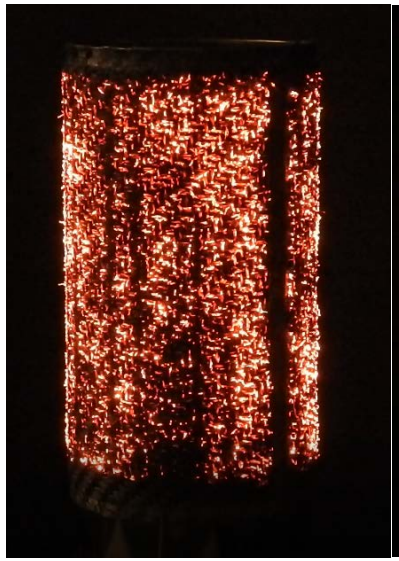


Tabletop Test Bed

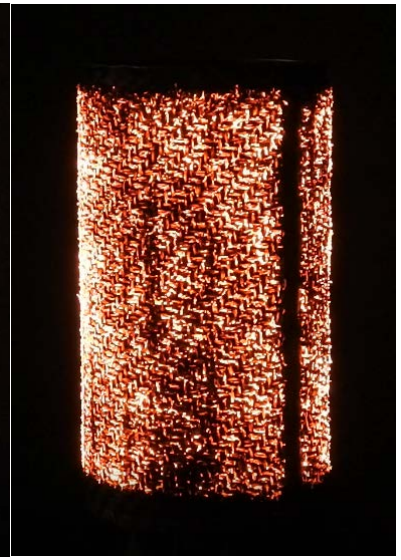
Beyond Blending: 100% Hydrogen

- **Images**

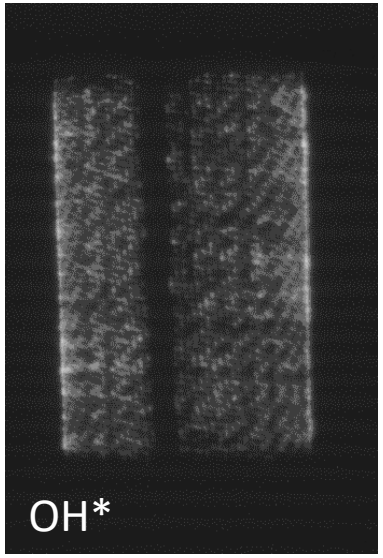
Hydrogen @ 100% Excess Air



50 kBTU/hr

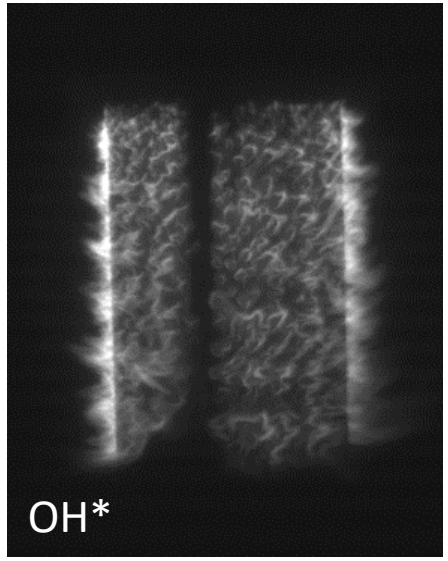


100 kBTU/hr

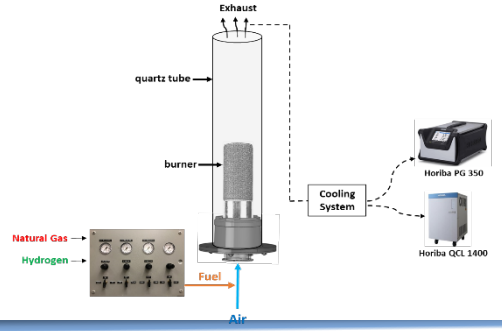


100 kBTU/hr

NatGas @ 30% Excess Air



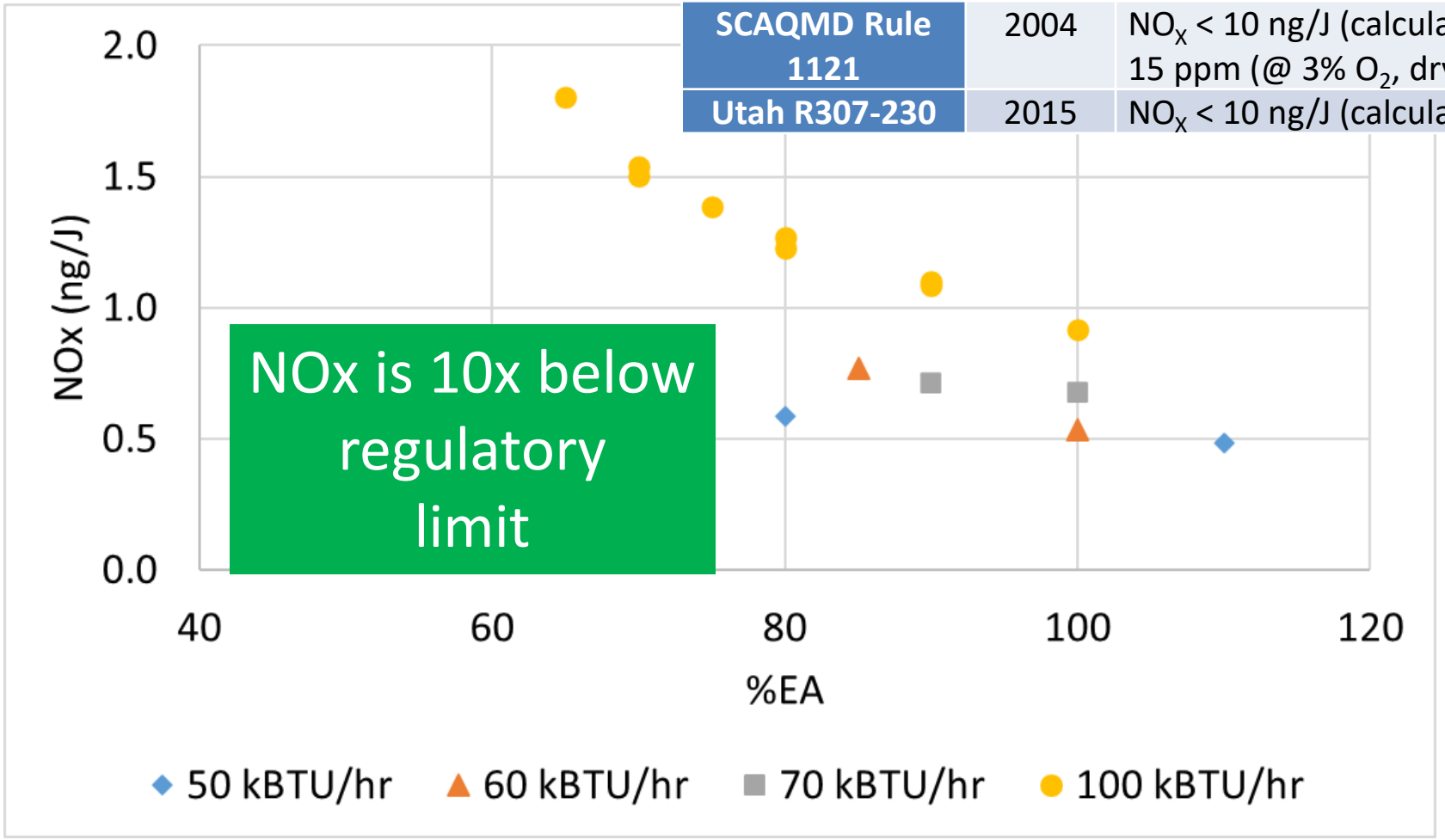
100 kBTU/hr



Beyond Blending: 100% Hydrogen

- **Emissions**

Regulation Titles	Year	Key contents
ANSI Z21.10.1/CSA 4.1	2017	Air-free sample: CO < 400 ppm
SCAQMD Rule 1121	2004	NO_X < 10 ng/J (calculated as NO_2) or NO_X < 15 ppm (@ 3% O_2, dry)
Utah R307-230	2015	NO_X < 10 ng/J (calculated as NO_2)

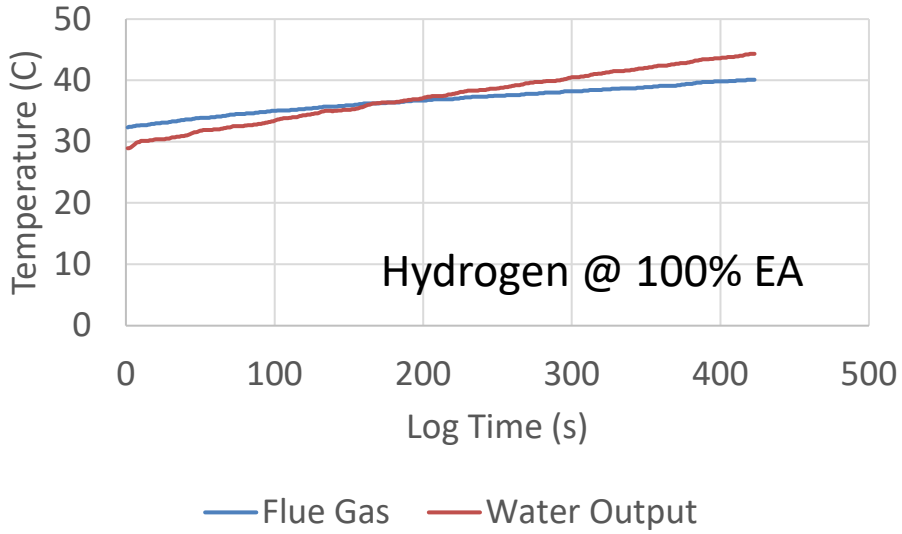


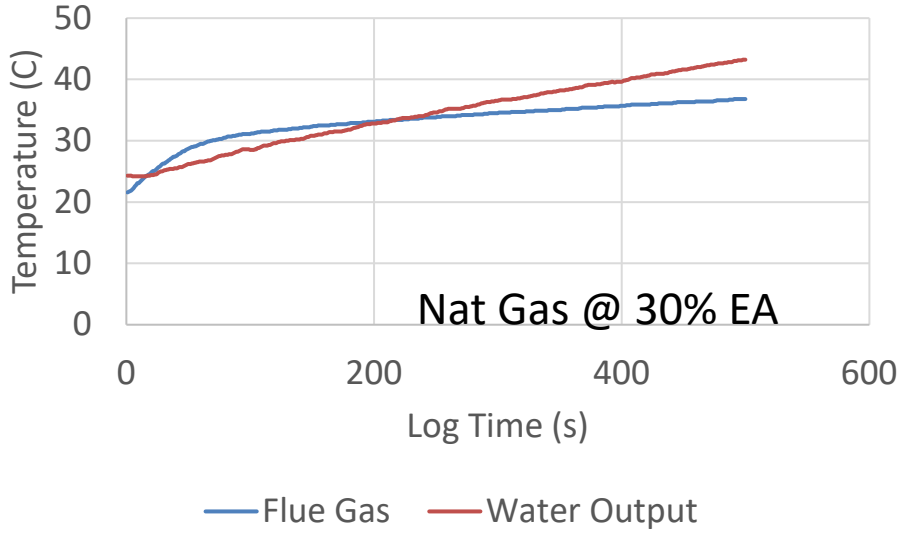
NOx is 10x below regulatory limit

SCAQMD needs 68% reduction in NOx emissions to reach attainment

Beyond Blending: 100% Hydrogen

- **Water Heating Performance**



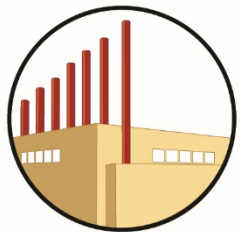


Fuel	Heatload (kBTU/hr)	%EA	Water flowrate (gpm)	Heating Rate (°C/s)	Condensation rate (g/s)
Natural Gas	100	30	1.5	0.0397	0.8
Hydrogen	100	70	1.5	0.0395	1.4

Similar Heating Performance Attained

What happens when we use low carbon fuels in applications like water heating and cooking?

NOx decreases for legacy devices on blends
(with H_2 specific devices even more decrease possible)
Air quality improves
We can significantly decarbonize buildings



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CalPlug Workshop
17 April 2023, Irvine, CA

What's Next?

- Hydrogen???
- Electrification???
- All in?

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EU Commission charts path towards 100% renewable hydrogen

6 minute read · March 2, 2023 8:50 AM PST · Last Updated 6 days ago

Europe takes steps toward developing hydrogen pipeline network

By Paul Day

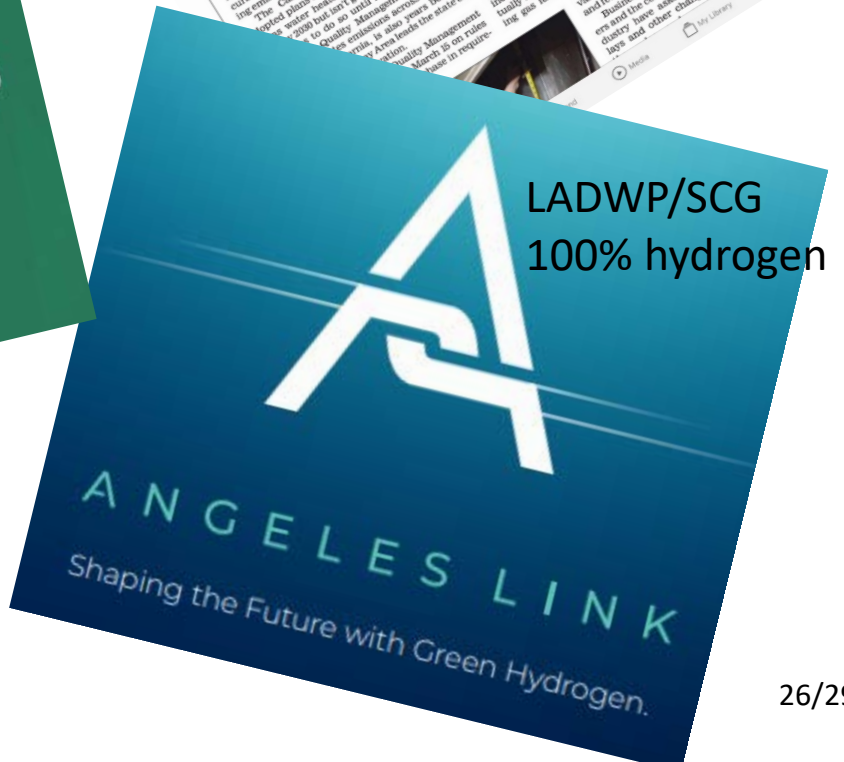
3 Mar 23—LA Times

BAAQMD..ban gas water heaters by 2027..

Department of Energy

Biden-Harris Administration Announces Historic $7 Billion Funding Opportunity to Jump-Start America's Clean Hydrogen Economy

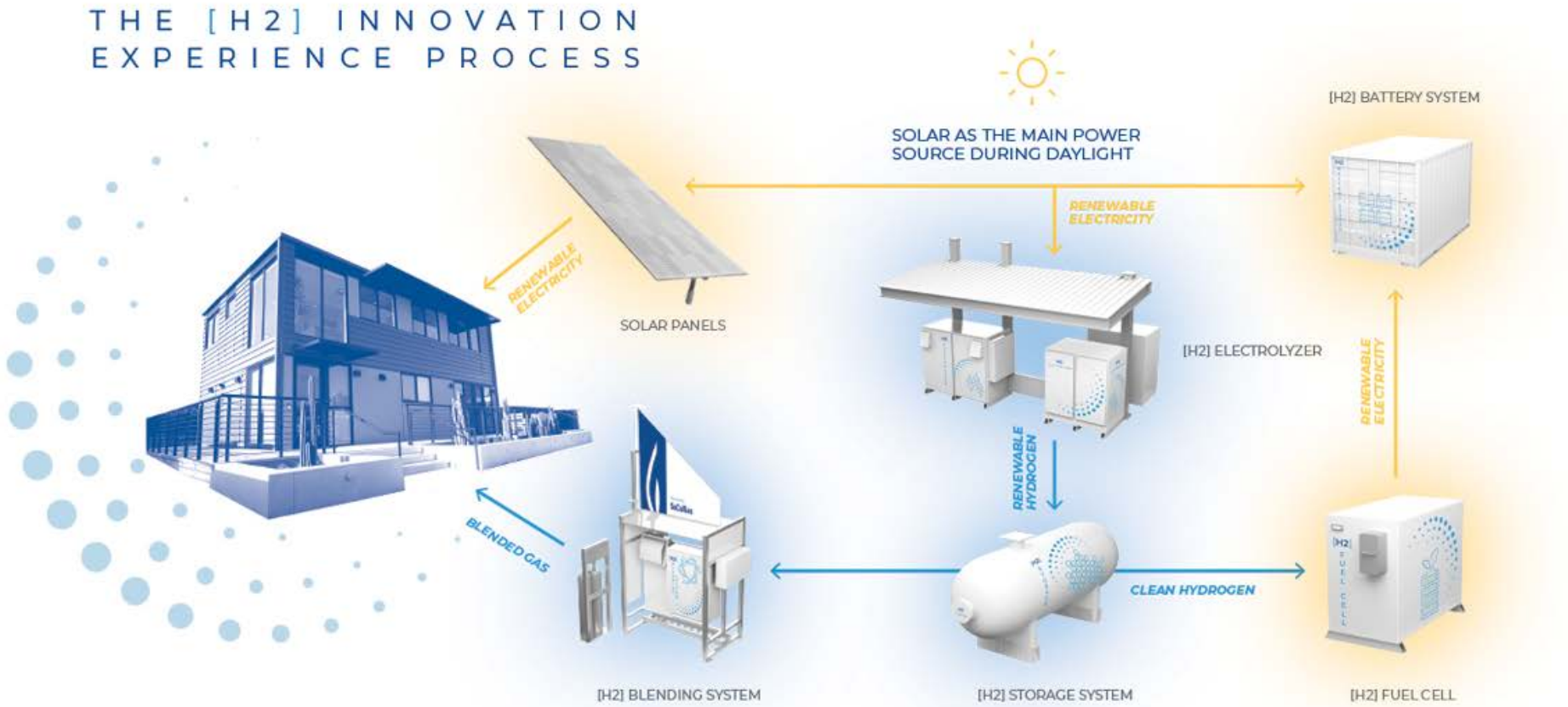
SEPTEMBER 22, 2022



LADWP/SCG
100% hydrogen

Demonstration

- **Hydrogen Microgrid (SoCalGas)**



Demonstration

- Wagenborgen (NLD)—June 2023
- Goal: Assess impact of hydrogen in combination with insulation, hybrid heat pump relative to bio-methane and/or electrification
- 33 homes volunteered for participation

Demonstration

Hydrogen Production adjacent to town

Inject into local gas grid

Heating system:
--Hydronic heater: 100% Hydrogen boiler small heat pump
--Domestic Hot Water: 100% Hydrogen tankless water heater

Building type:
Typical rental housing build in the 1970's.

Heat pump

Hydrogen boiler