Welcome to our SwRI Webinar!

The Webinar will begin at 12:00 noon.

All attendees will be muted during the presentation to reduce background interference.

Questions can be submitted using the Q&A or Chat box.

A PDF copy of the presentation slides will be emailed to all attendees after the conclusion of the Webinar.

For any questions, please contact Herminia Mares @ herminia.mares@swri.org

Hydrogen Gas Turbines

What You Need to Know

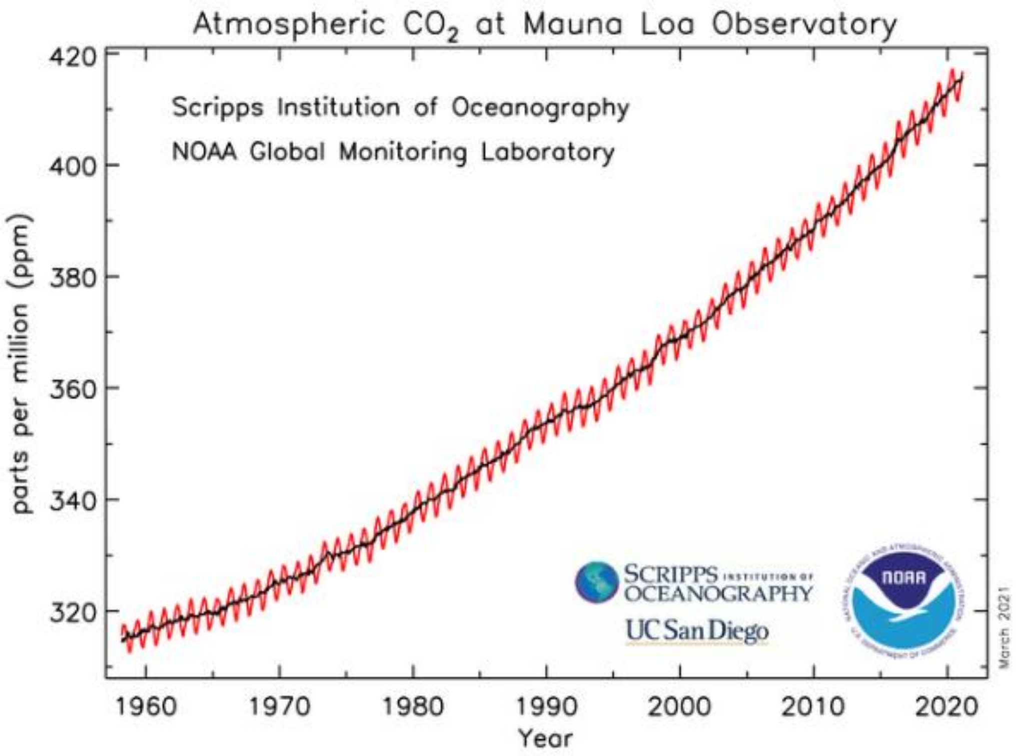
Presented by

Griffin Beck
Manager – R&D
Propulsion & Energy Machinery
Southwest Research Institute
griffin.beck@swri.org
(210) 522-2509

Brian Connolly, Ph.D
Research Engineer
Propulsion & Energy Machinery
Southwest Research Institute
brian.connolly@swri.org
(210) 522-3618

April 26, 2023

Multiple initiatives in recent years set decarbonization goals.

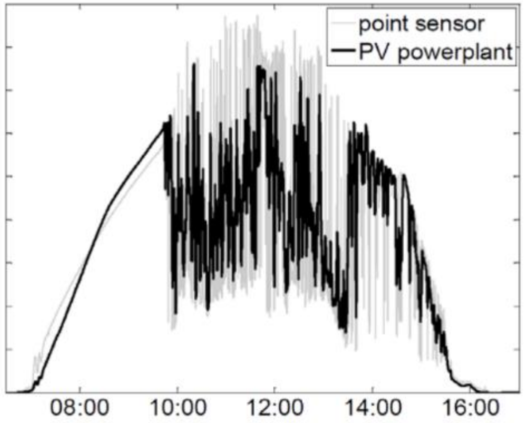


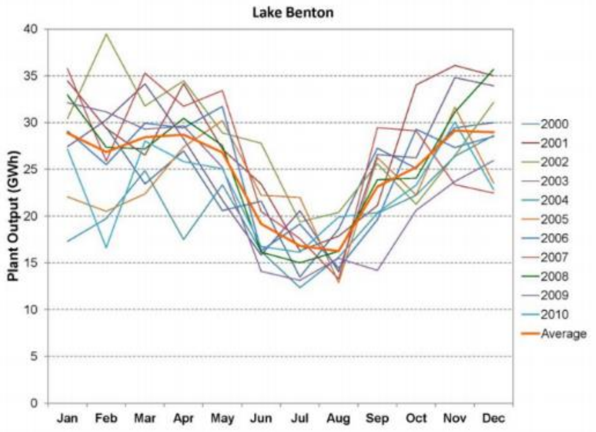
BRIEFING ROOM

Executive Order on Tackling the Climate Crisis at Home and Abroad

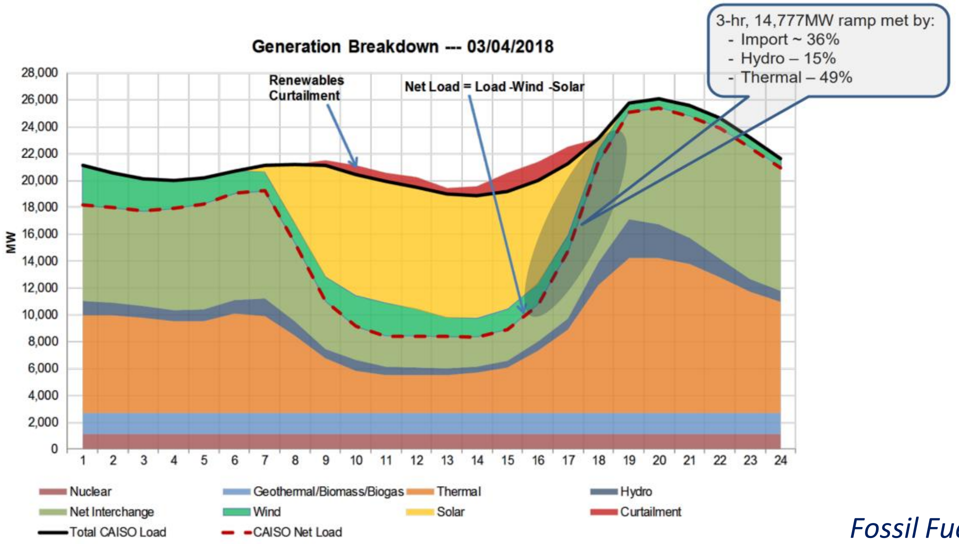
- November 2016 Paris Agreement limits climate change impact to <2 °C , requiring deep decarbonization across all sectors, typically with significant electrification.
- January 2021 White House Executive Order targets:
  - Carbon pollution-free electricity sector in U.S. by 2035
  - Net-zero emissions, economy-wide, by no later than 2050
- Likely to require multiple technology paths including fossil + carbon capture as well as renewables.

Increased renewables will require carbon-free thermochemical energy storage.

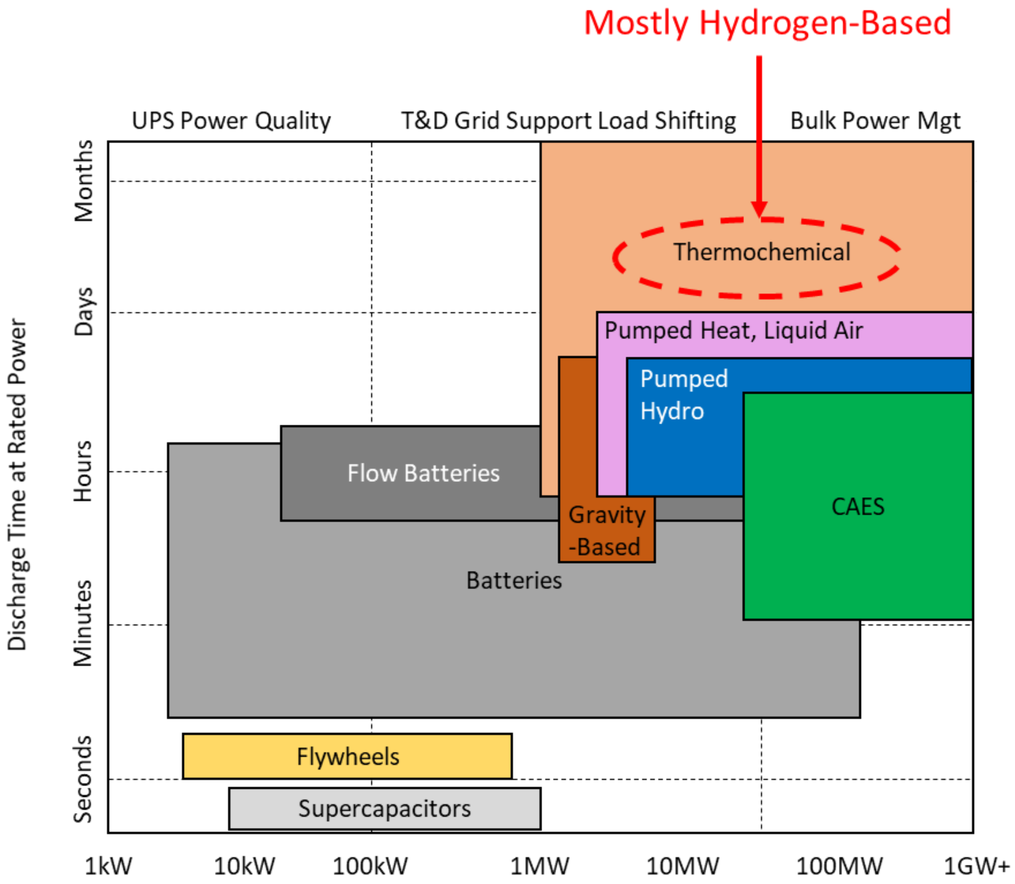




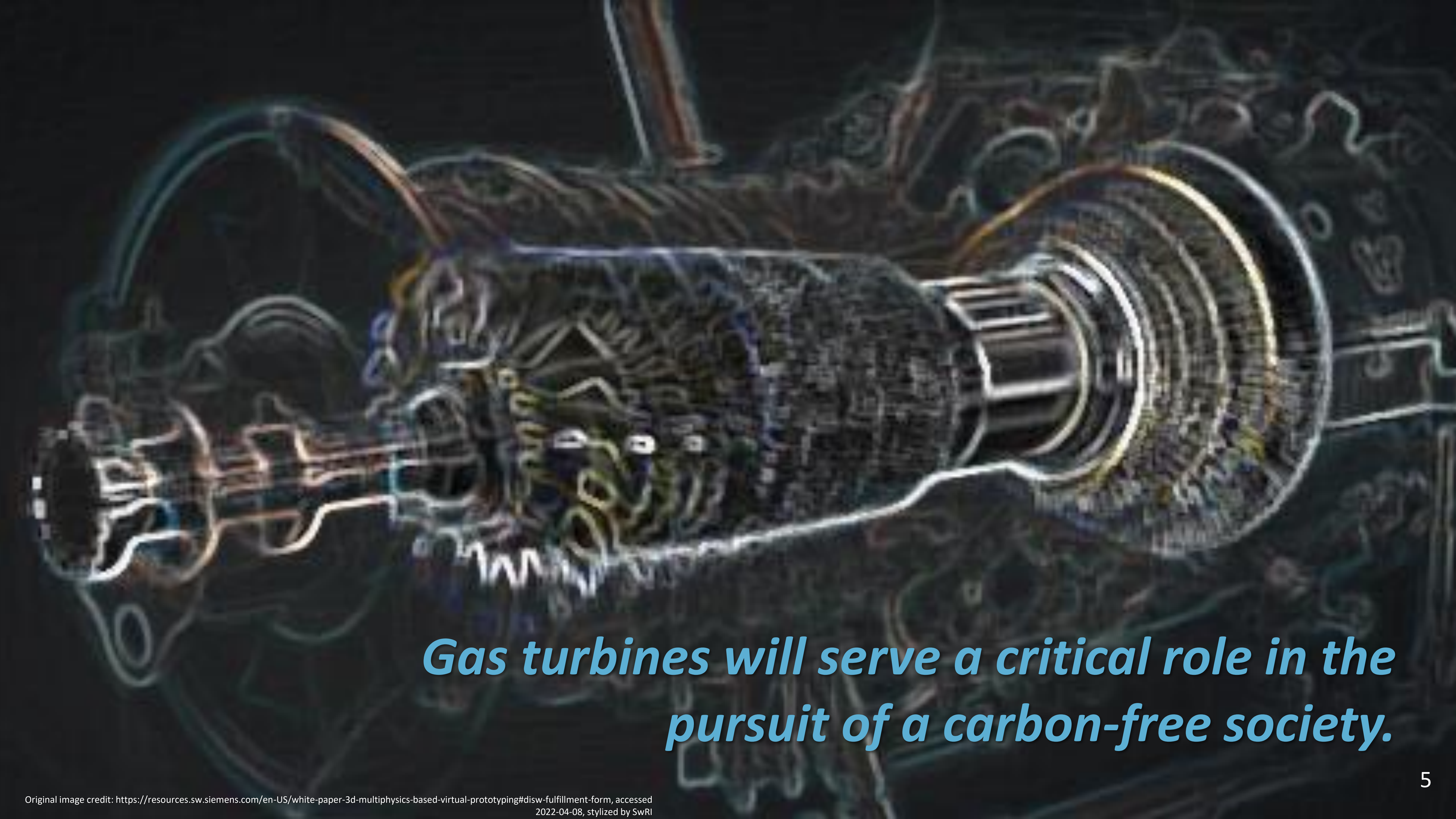
Solar PV Daily Variability (top left) and Wind Farm Annual Variability (top right)



More Electrification
More Renewables
More Grid Storage



Fossil Fuels Used to Firm Renewables (CAISO's "Duck Curve")

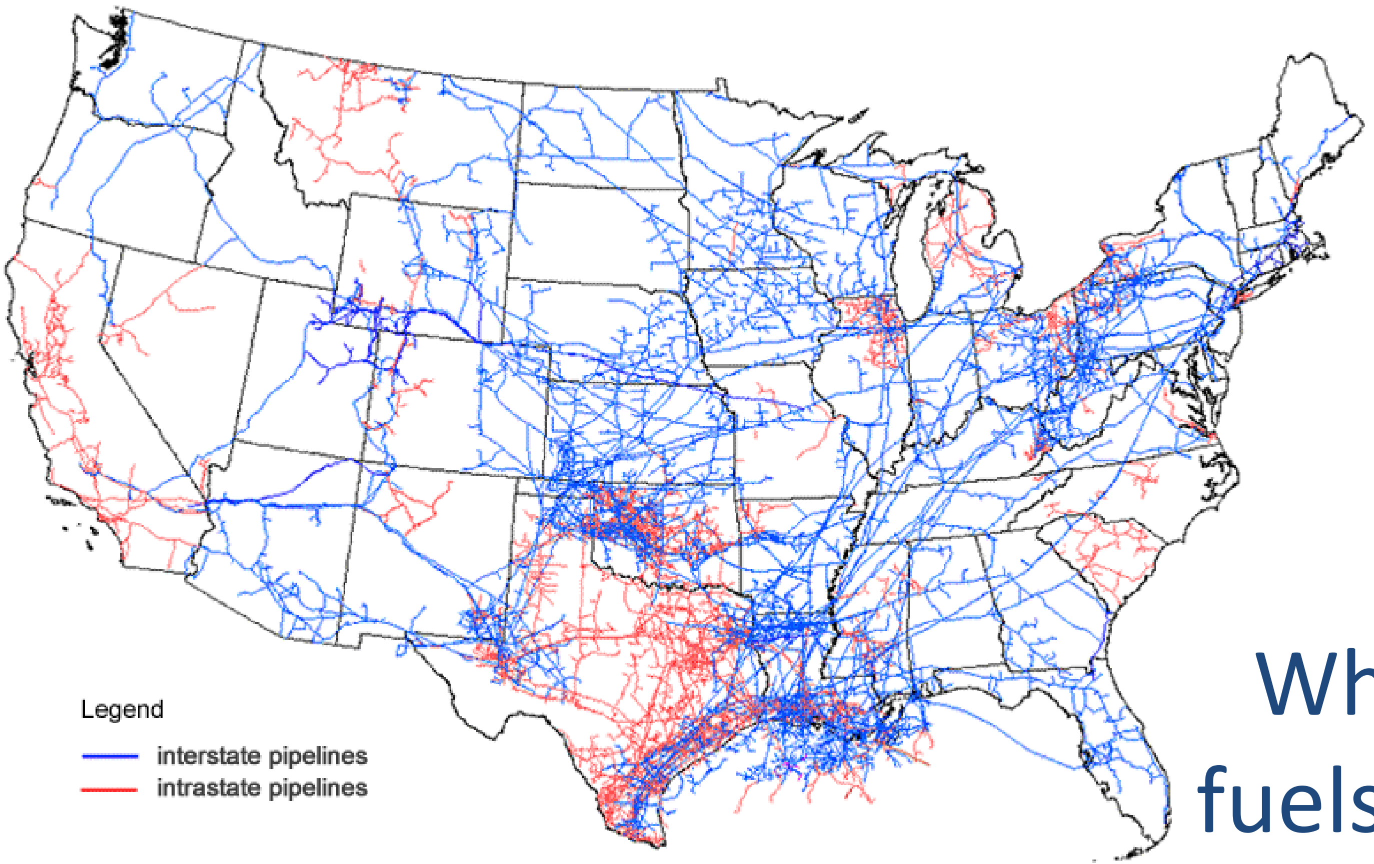


Gas turbines will serve a critical role in the pursuit of a carbon-free society.

Original image credit: https://resources.sw.siemens.com/en-US/white-paper-3d-multiphysics-based-virtual-prototyping#disw-fulfillment-form, accessed 2022-04-08, stylized by SwRI

Hydrogen blending is a compelling option to gradually introduce hydrogen into existing infrastructure.

Map of U.S. interstate and intrastate natural gas pipelines

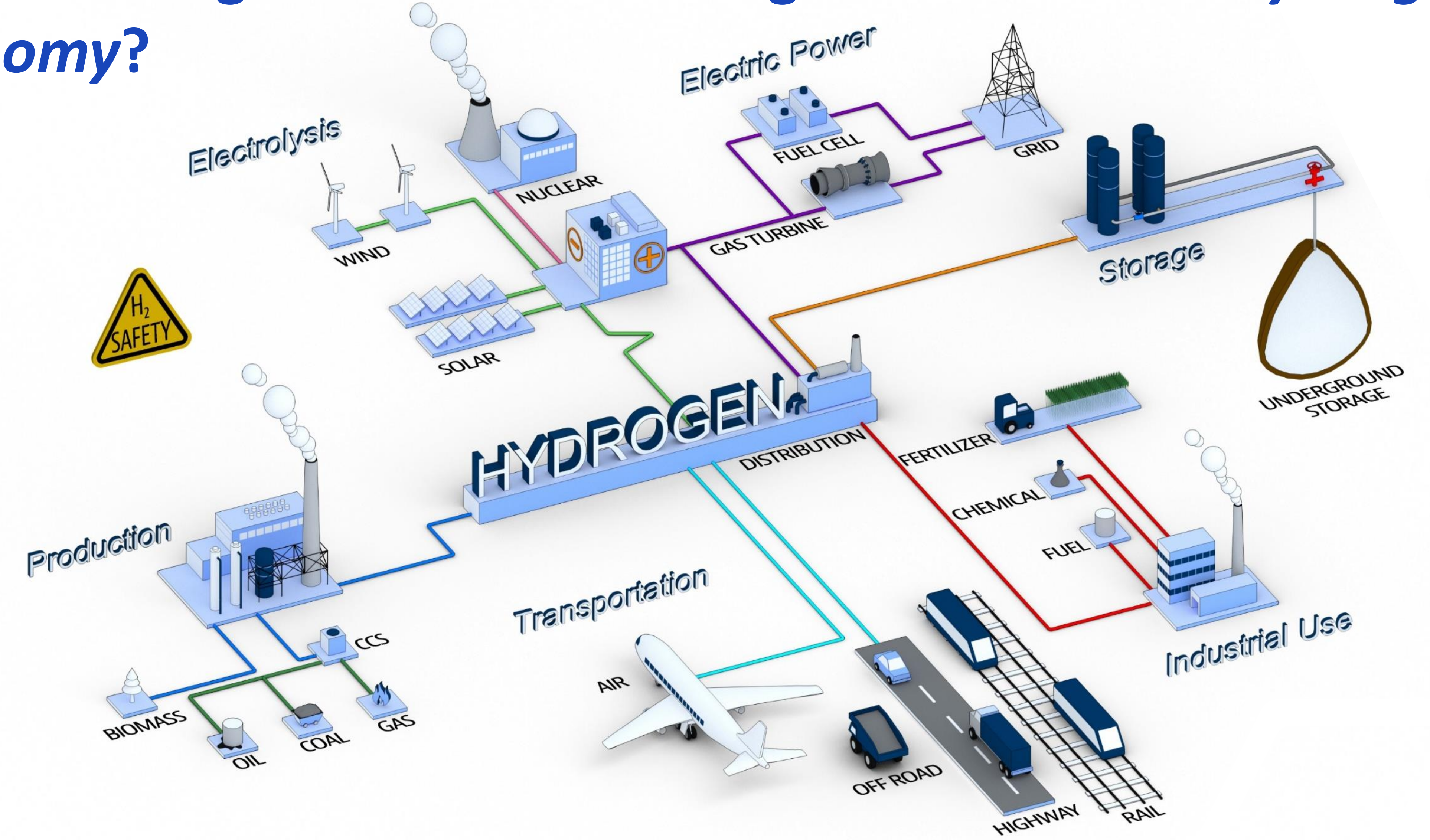


Source: U.S. Energy Information Administration, *About U.S. Natural Gas Pipelines*

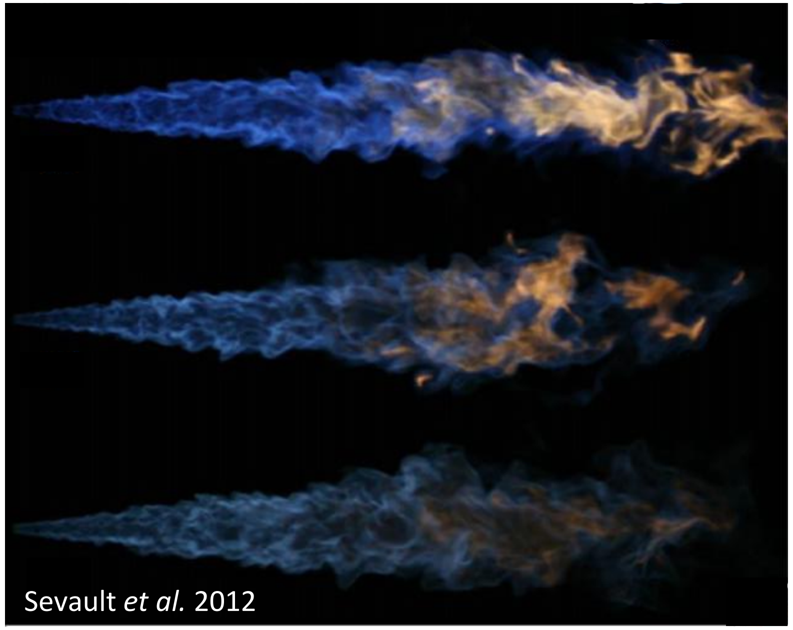
- Leverages existing infrastructure to decarbonize electric generation and industry
- 2.3 million miles @ ~\$5M/mile = \$11.5 Trillion
- Blending allows for gradual/phased introduction of hydrogen
- We already transport gas, right?

What is the impact of NG/H_2 fuels on existing gas turbines?

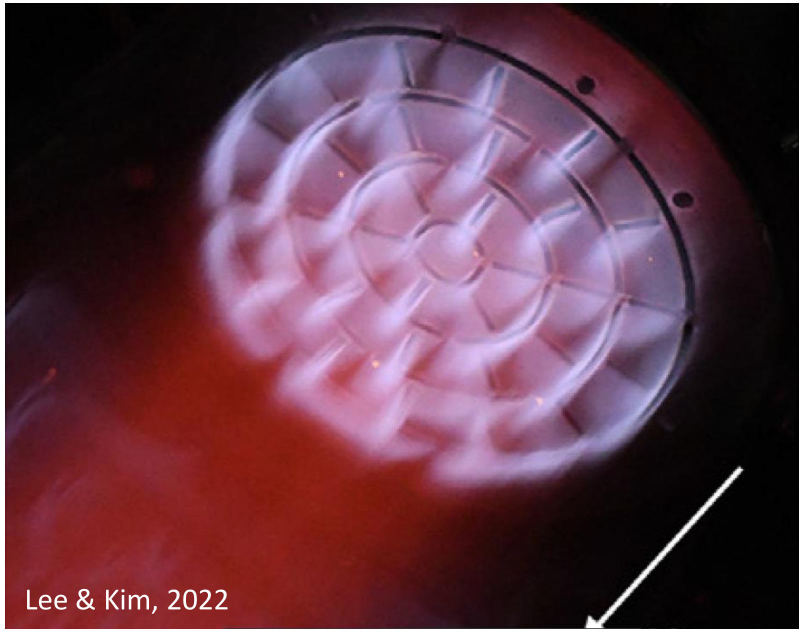
What is being done to transition gas turbines to a *hydrogen economy*?



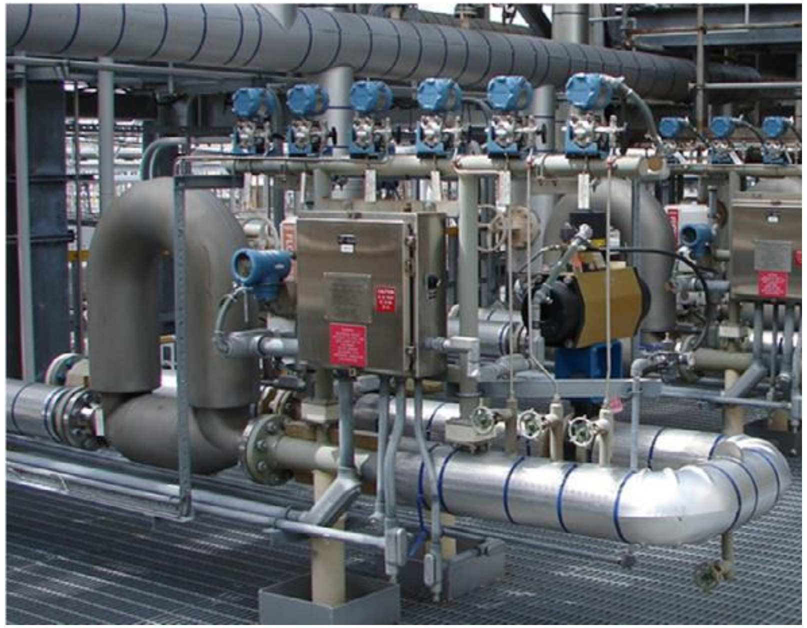
This presentation provides some key considerations related to the use of pure or blended H_2 fuels in industrial gas turbines.



H_2 Combustion Fundamentals



H_2 in Gas Turbines



Package Impacts

Fundamentals of H_2 Combustion

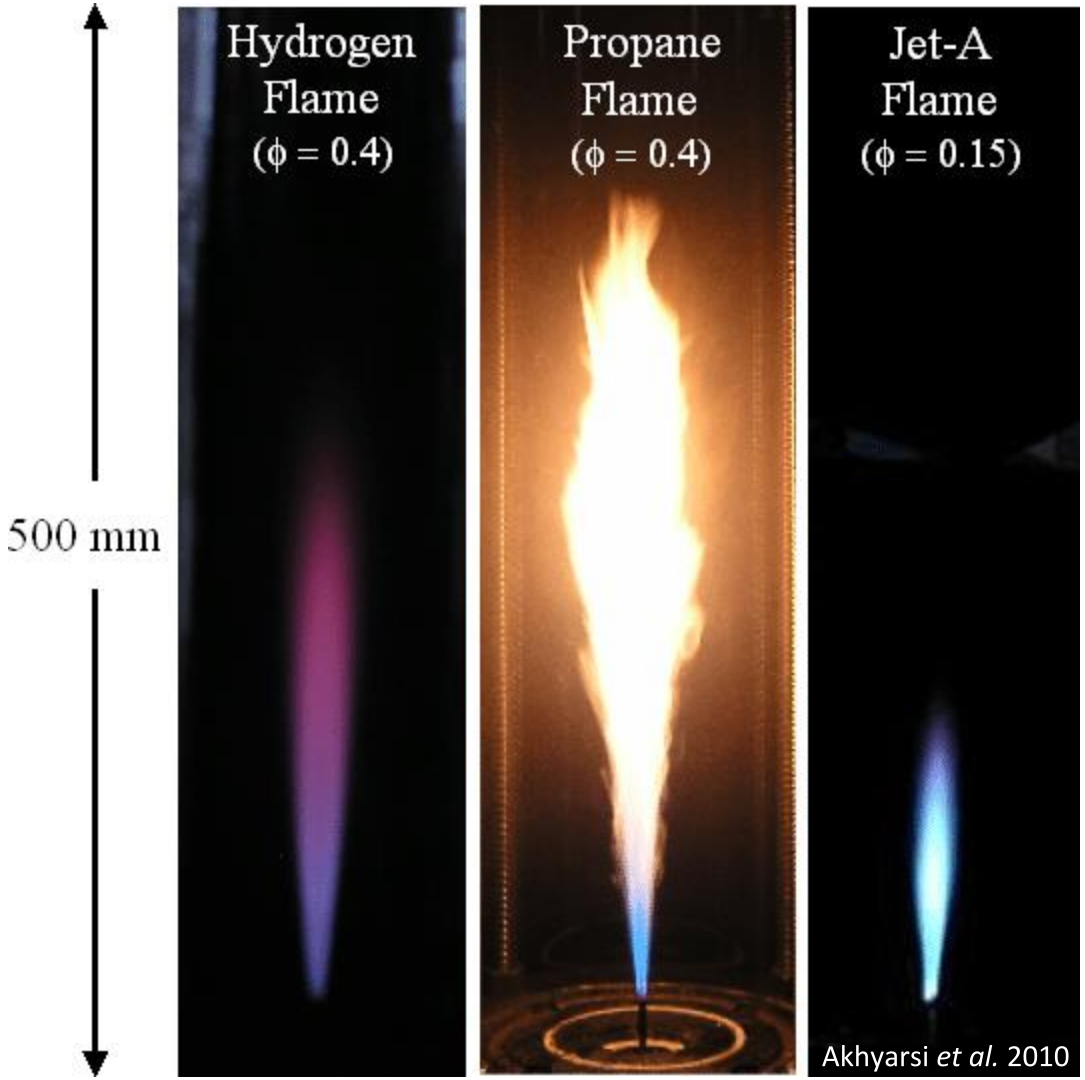
What are the key differences between hydrocarbon flames and hydrogen flames?

Physical considerations

- Heat release is different
- Fuel mixing is different
- Flame speed is different

Design questions

- Will it burn?
- Is it safe?
- Does it, in fact, pollute less?



Akhyarsi *et al.* 2010

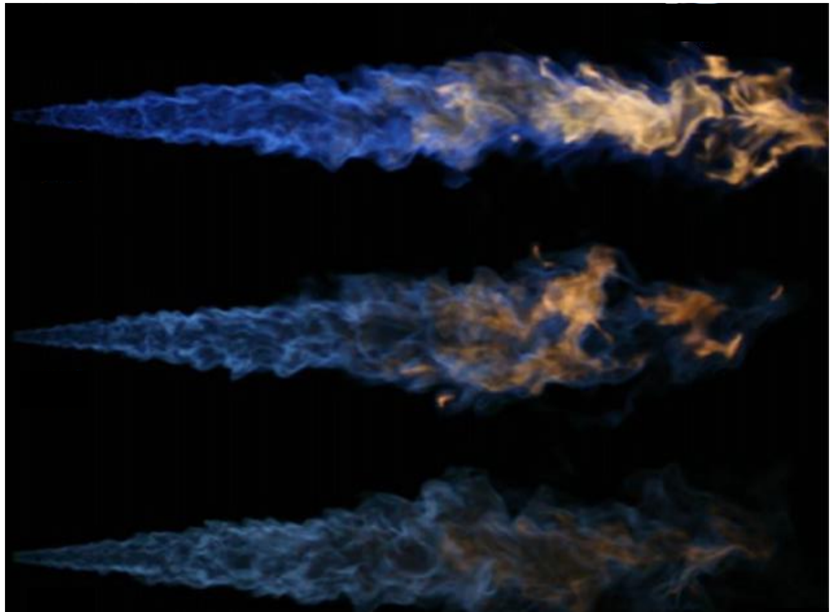
Physics Considerations

- Hydrogen has a much lower density than natural gas.
- Hydrogen burns much faster.
- Fuel momentum ratios, mixing efficiencies, and flammability envelopes all change.
- Premixing designs that work well for natural gas may simply explode with hydrogen.

37% H_2

45% H_2

55% H_2



Sevault *et al.* 2012

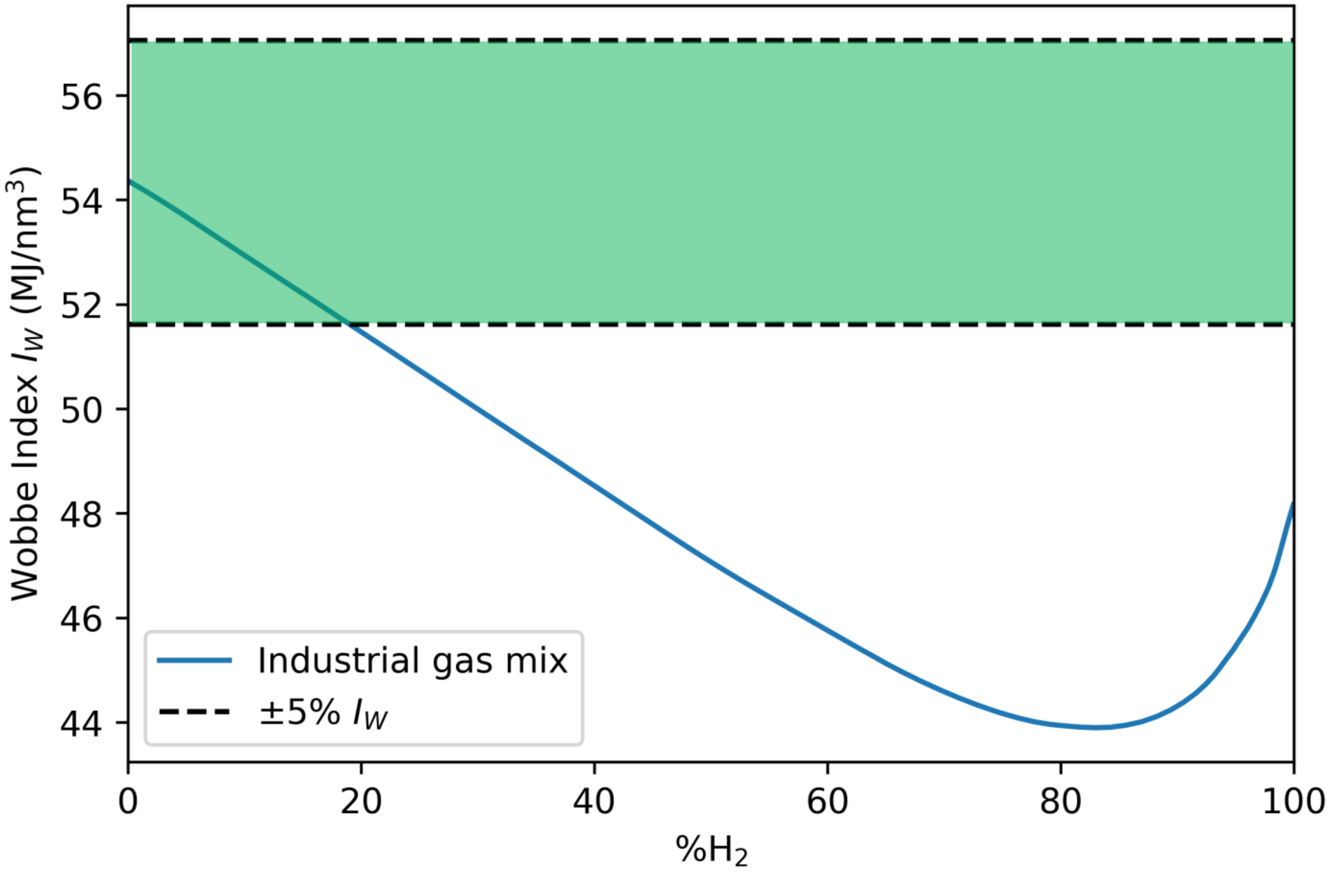
slower flame
longer ignition region
slower heat release

faster flame
shorter ignition region
faster heat release

A note on Wobbe index

$$I_W = \frac{\text{HHV}}{\sqrt{G_s}} = \frac{\text{HHV}}{\sqrt{\frac{\rho_{\text{STP}}}{\rho_{\text{air,STP}}}}}$$

- Measure of energy output of a fuel gas, good for comparing energy output of natural gas mixtures.
- Burner designs impose limits on calorific/heating value ranges and Wobbe indices.
- Necessary but not sufficient: other problems can arise.
- Acceptable range of I_w for GT varies between units but generally ± 2% to 5%



Adapted from deWit *et al.* 2006

Safety: flammability limits

Pacific Northwest National Lab, 2021

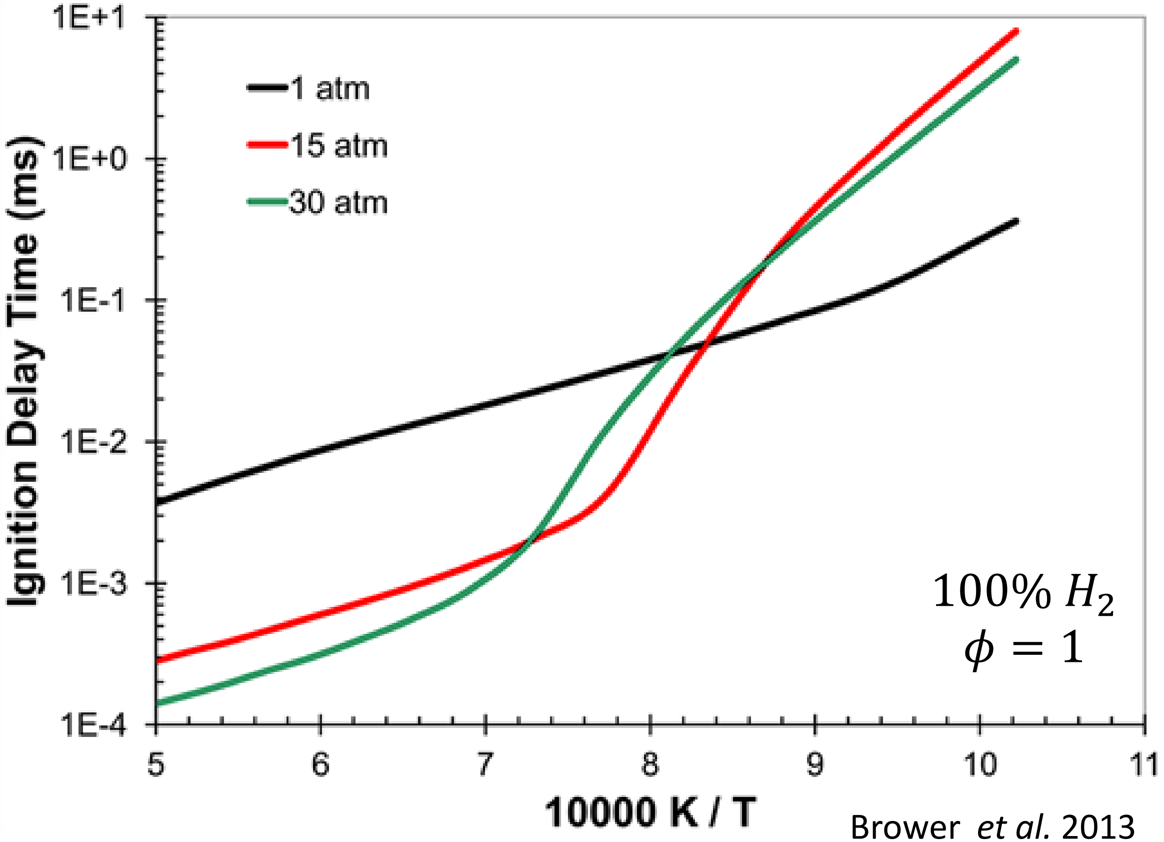
NG safety precautions alone are insufficient

Leaks can easily lead to autoignition

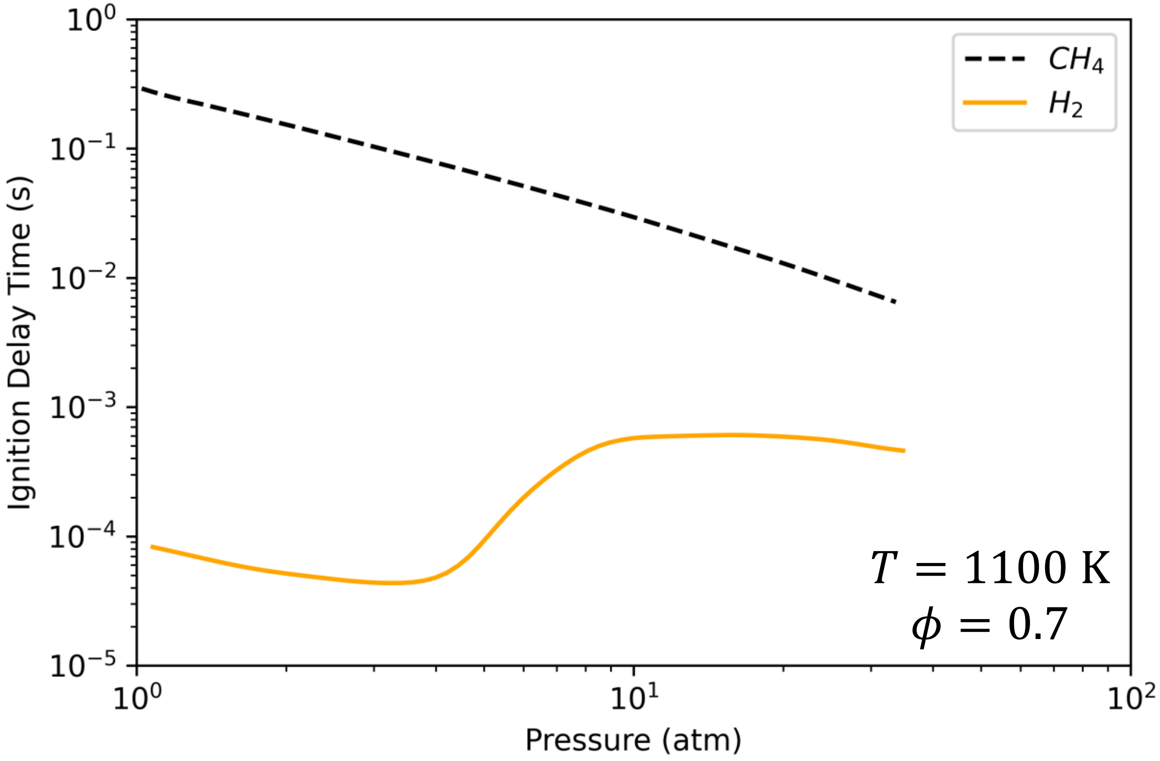
	Hydrogen	Gasoline Vapor	Natural Gas
Flammability Limits (in air)	4-74%	1.4-7.6%	5.3-15%
Explosion Limits (in air)	18.3-59.0%	1.1-3.3%	5.7-14%
Ignition Energy (mJ)	0.02	0.20	0.29
Flame Temp. in air (°C)	2045	2197	1875
Stoichiometric Mixture (most easily ignited in air)	29%	2%	9%

DoE

Autoignition hazards



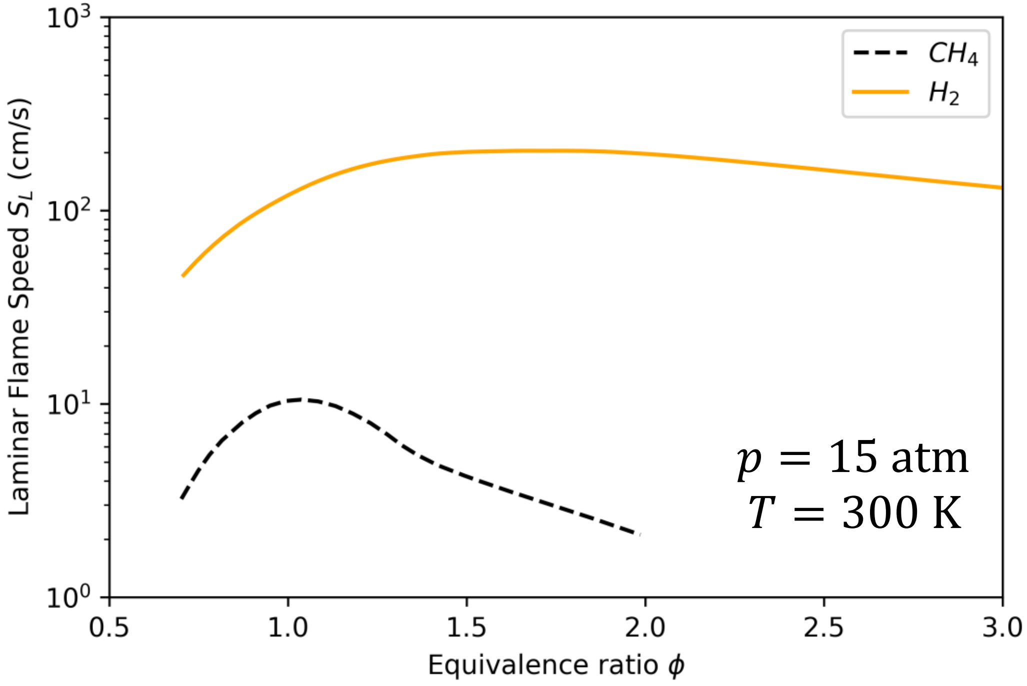
Brower *et al.* 2013



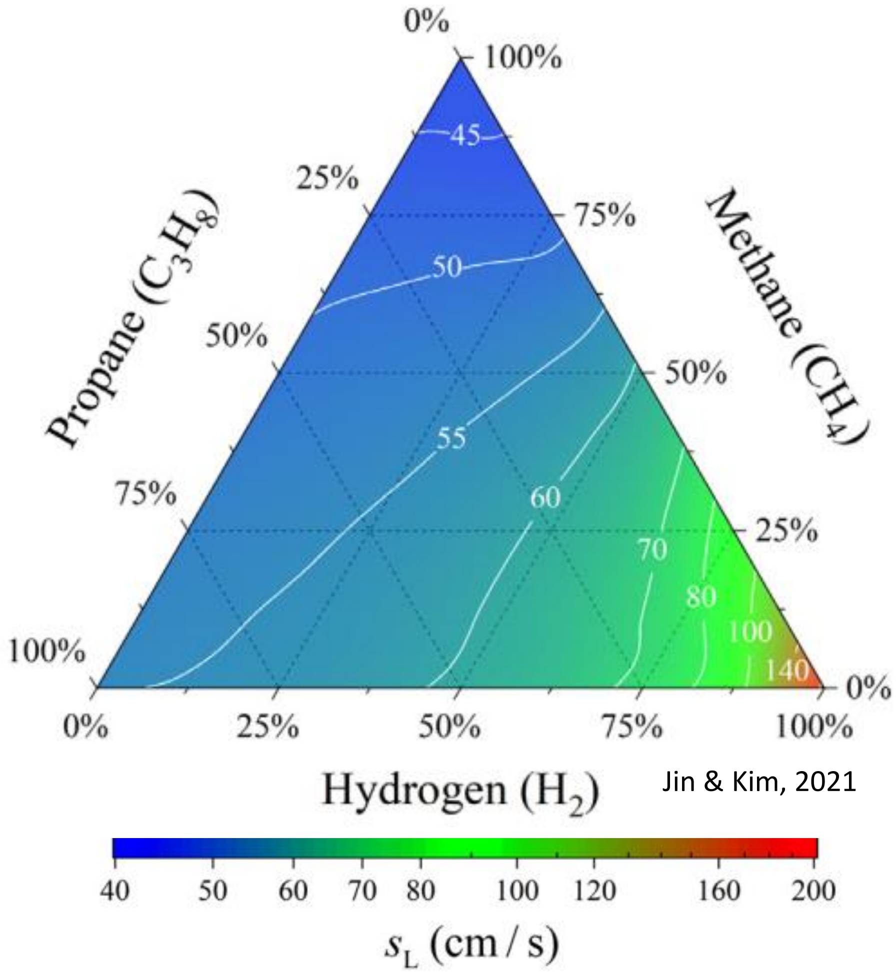
Adapted from Brower *et al.* 2013

Increasing Temperature

Laminar flame speed is much higher for hydrogen blends, and especially for pure hydrogen

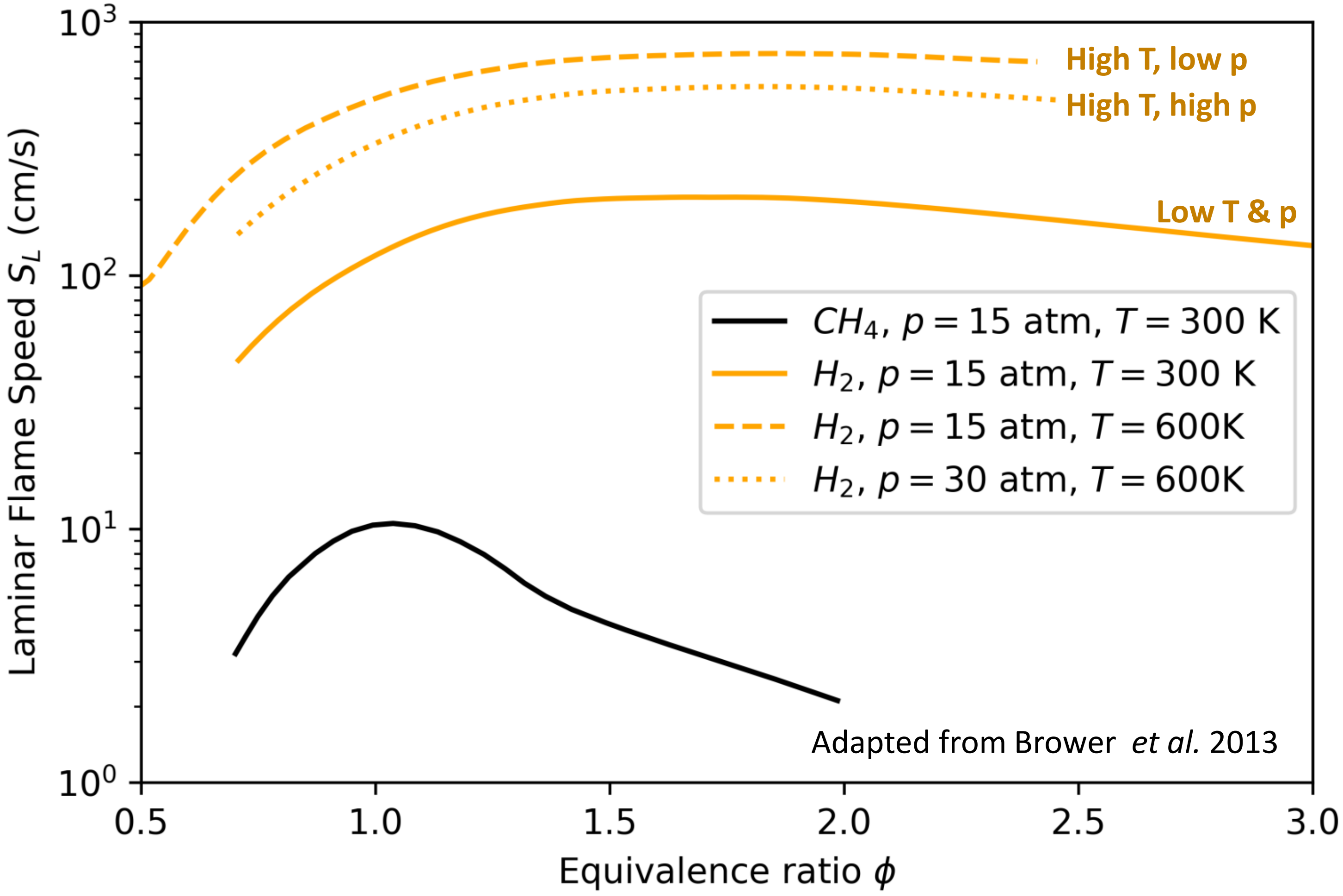


Adapted from Brower *et al.* 2013



Jin & Kim, 2021

Hydrogen fuel blend and temperature are more important than operating pressure



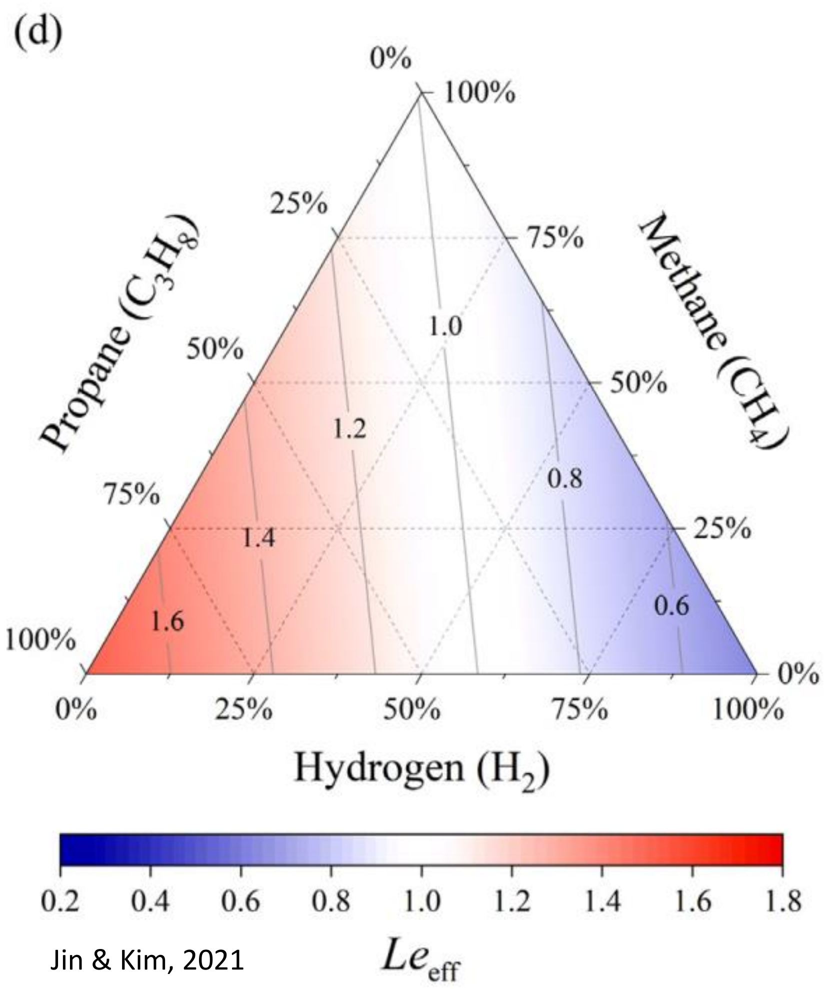
Lewis number is much lower for hydrogen

Lewis number: Ratio of thermal diffusivity to mass diffusivity

$$\mathrm{Le} = \frac{\alpha}{D}$$

Hydrogen has high mass diffusivity, leading to lower Lewis numbers.

Flamelet models may make numerous assumptions based on Lewis numbers near or above unity, and may not be appropriate for hydrogen without significant modification



Jin & Kim, 2021

Combustion emissions must still be considered

$$2H_2 + O_2 \rightarrow 2H_2O + \text{energy}$$

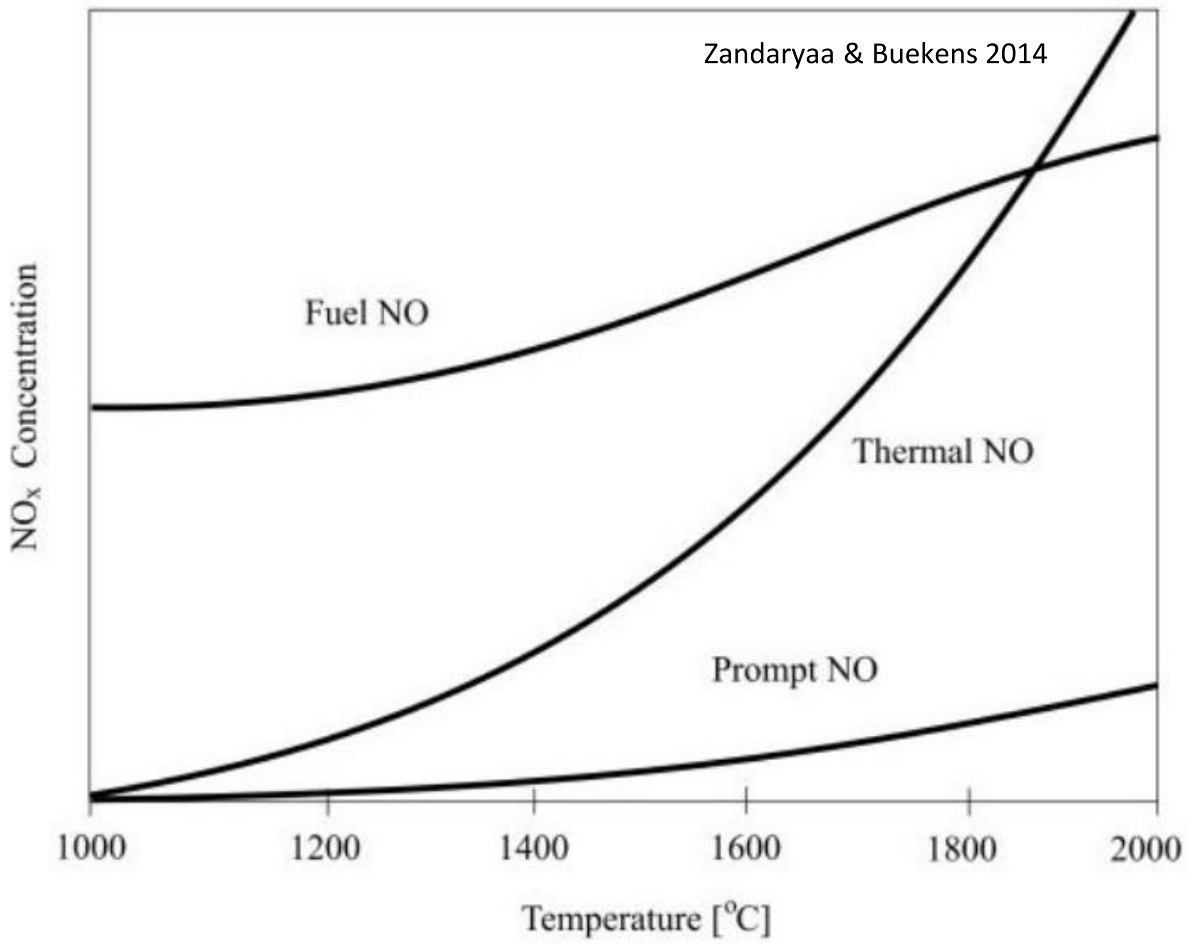
isn't the whole story

N_2 in the air dissociates

No fuel NO_x for H_2 but

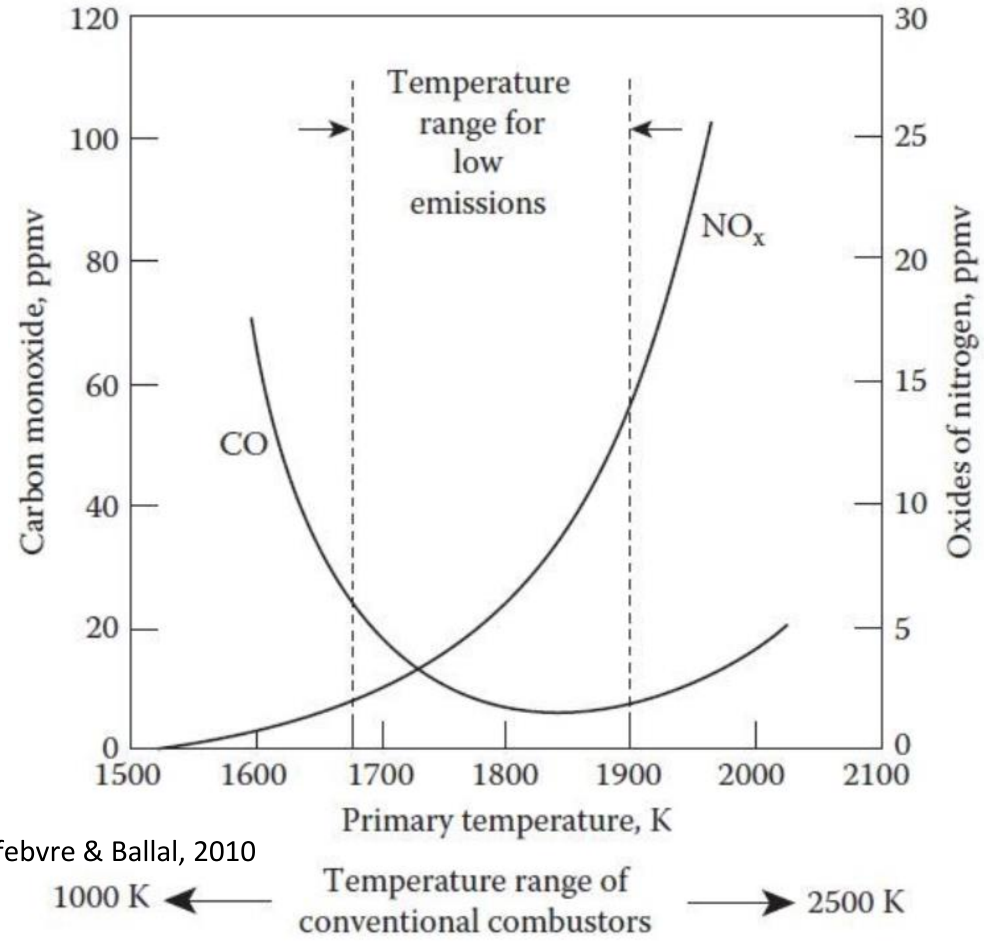
Thermal NO_x: Temperature dependent

Prompt NO_x: Reaction/Temperature dependent



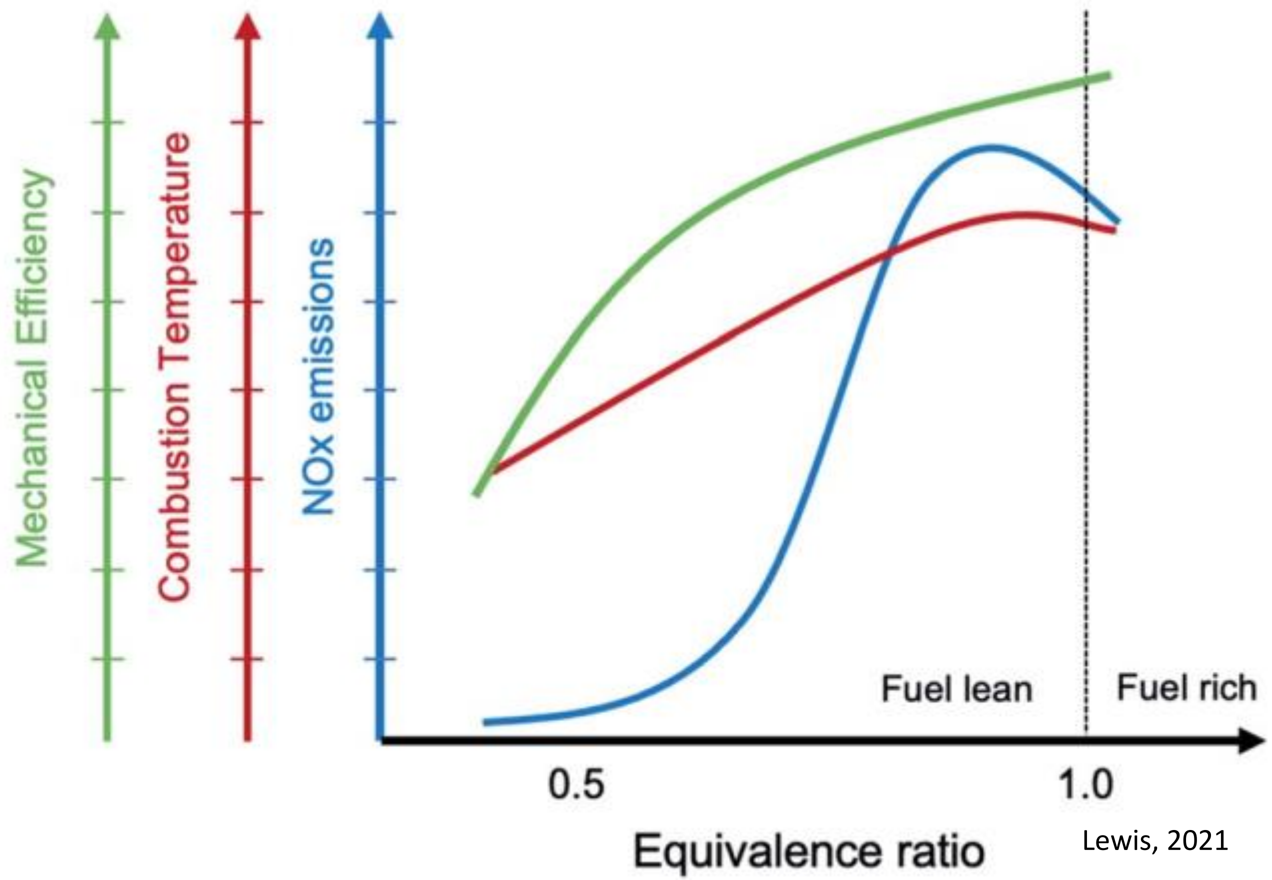
Combustion emissions vary with operation, application

Typical emissions curves for fossil-fueled gas turbines



Lefebvre & Ballal, 2010

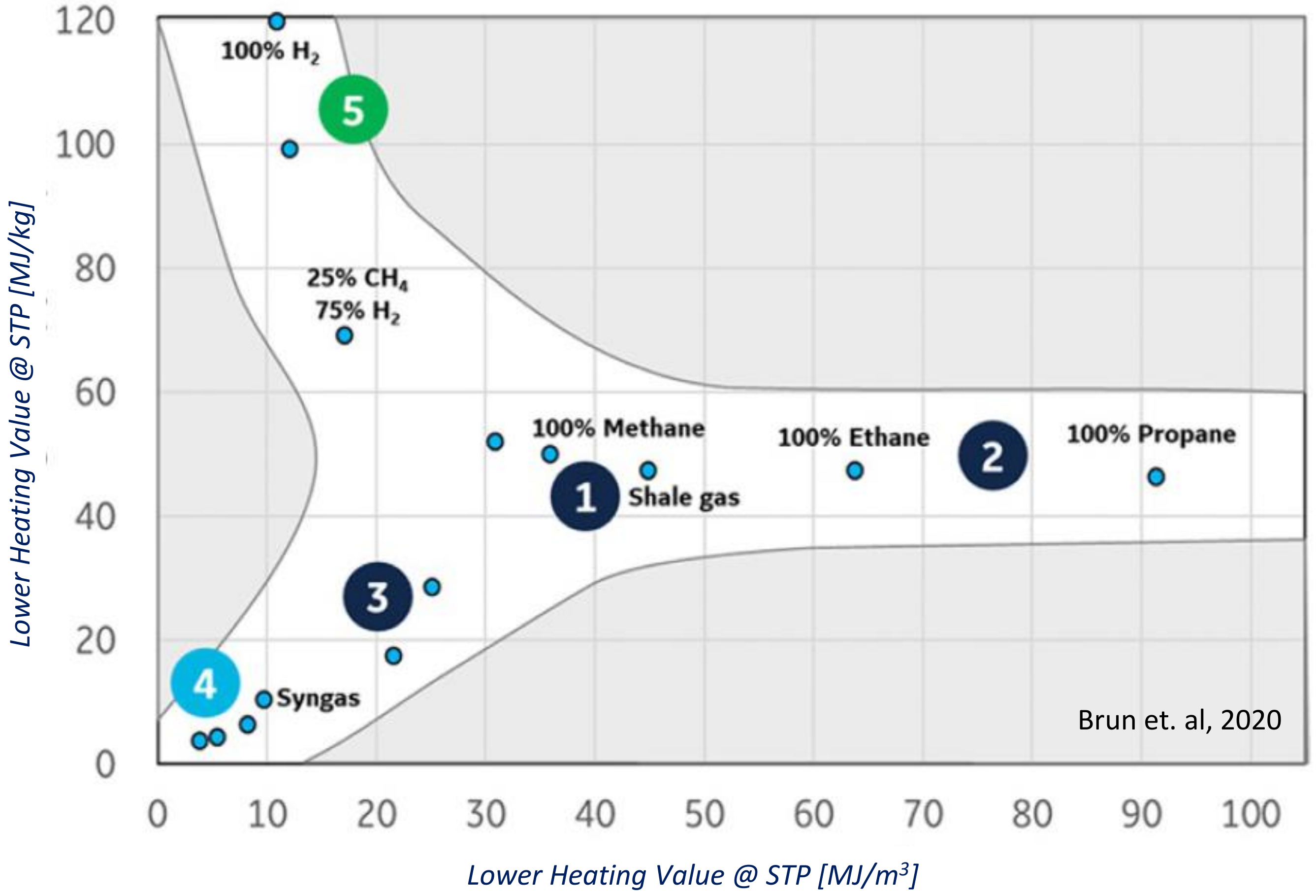
Example operating range for a H2-fueled internal combustion engine

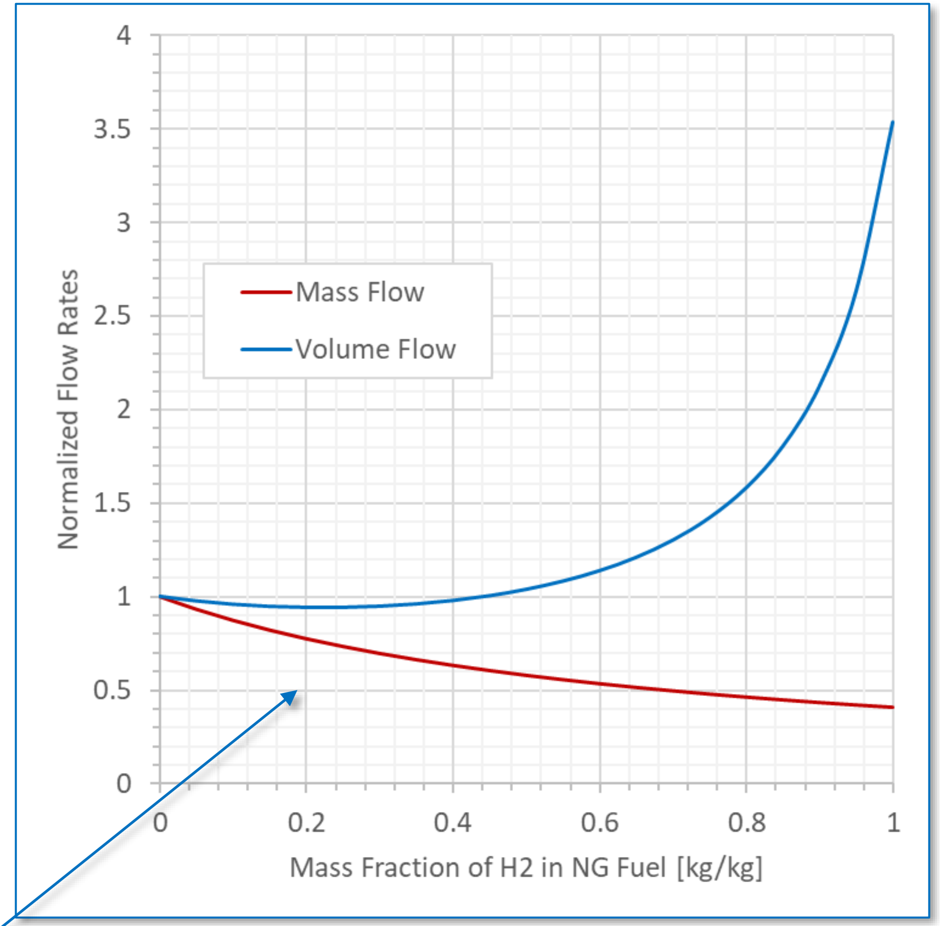


Lewis, 2021

H_2 in Gas Turbines

Fuel flow requirements are impacted with the addition of H_2.



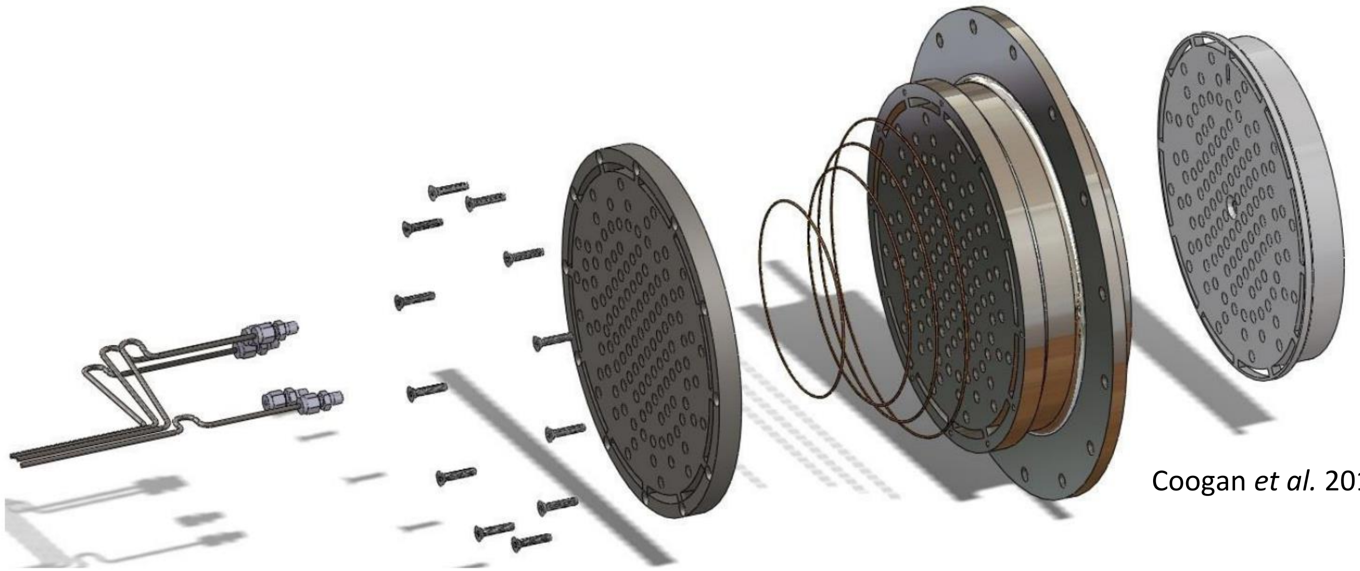


- 234.3 MW combined cycle plant
- Heat Rate: 6,261 kJ/kWh
- Assumed fuel conditions: 50°C, 2.19 MPa

To maintain an equivalent thermal energy input to a particular gas turbine, the mass flow will decrease with the addition of H2. However, the volume flow will increase significantly at mass fractions of 50% and more.

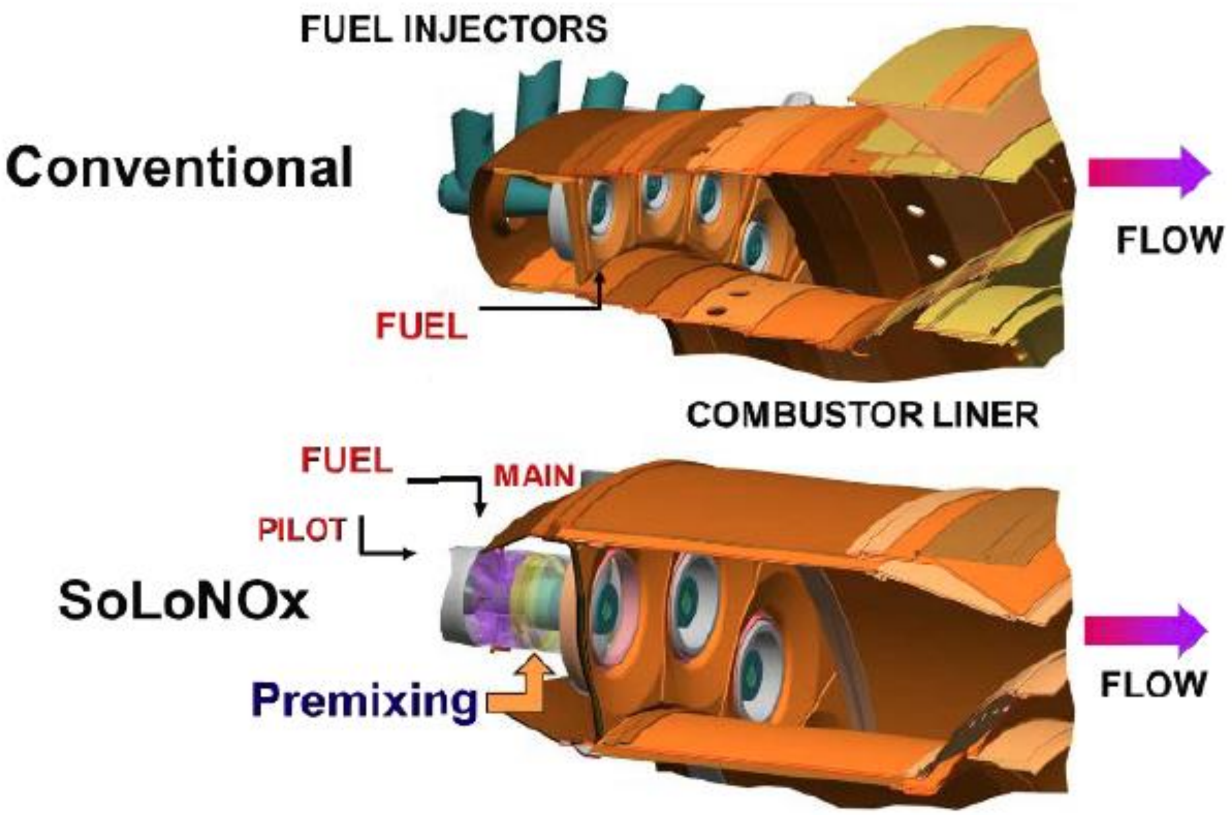
What are some design challenges for H2 combustors?

- Flashback – flame can travel upstream and briefly enter the fuel injector or fuel line.
- Hot spots – poor mixing can lead to high NO_x and nonuniform combustor heating.
- Volume – hydrogen requires more oxygen, so more air or oxy-fuel combustion needed.
- Autoignition – hydrogen can autoignite at a wide range of concentrations.
- Joule-Thomson Effect – at process temperatures, hydrogen heats when expanding.



Coogan *et al.* 2014

GTs use *conventional* or *lean pre-mixed* combustion systems.

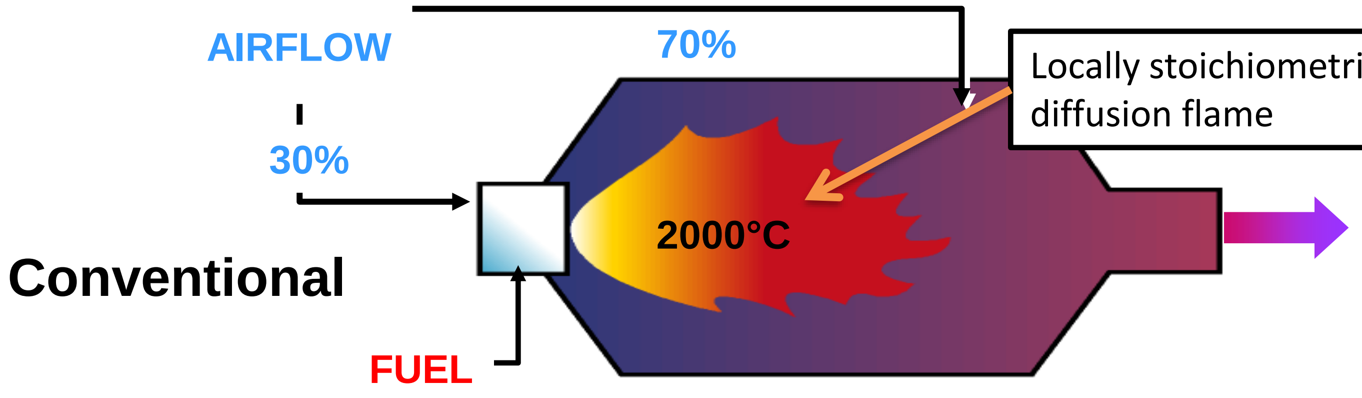


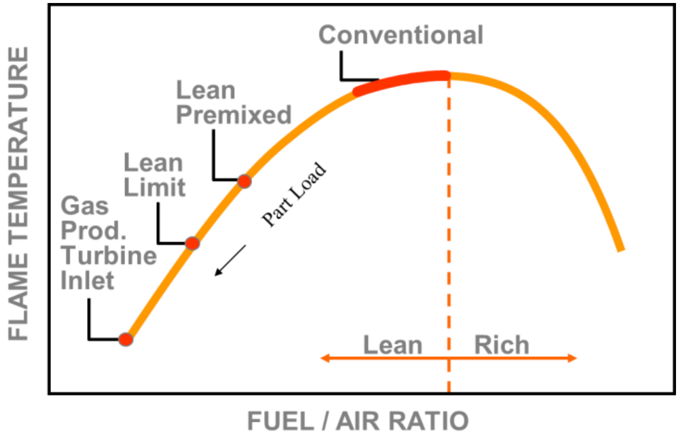
Kurz et. al, 2020

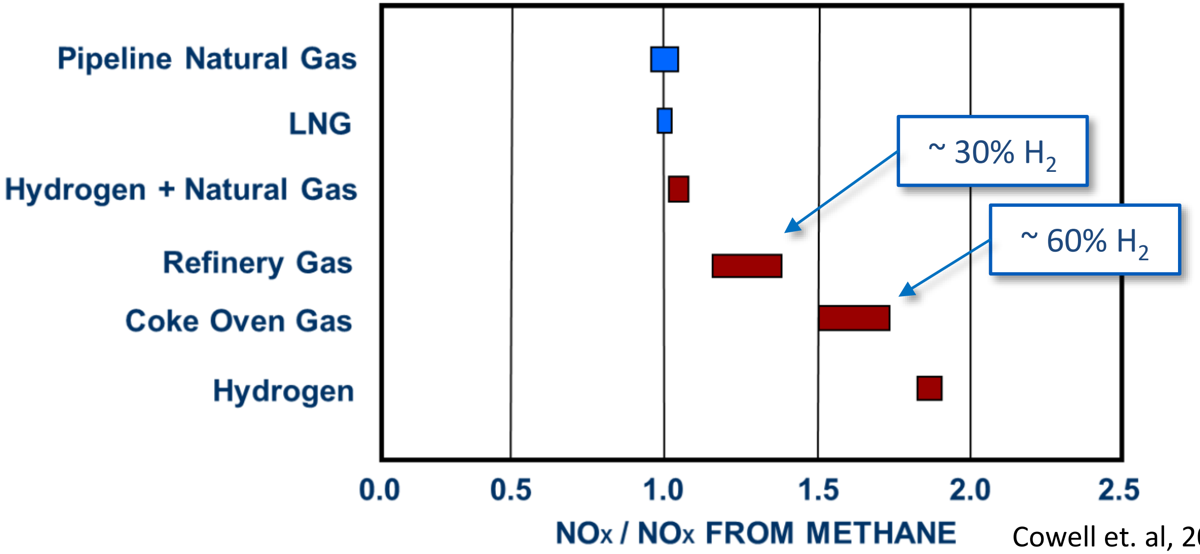
- Fuel/air mix immediately downstream of nozzles/injectors (at flame front)
- Addition of H_2 (up to 100%) is established technology
- Primary challenges higher NO_X and combustor operational life, both due to increased flame temperature

- Fuel/air mixed upstream of combustion zone
- Lean, premixed air/fuel yields lower NOx
- Addition of H2 at small concentrations not likely to impact performance significantly
- Continued research/development needed to achieve high-H2 nozzle designs

Conventional combustion systems are already operating with high-H_2 fuels.



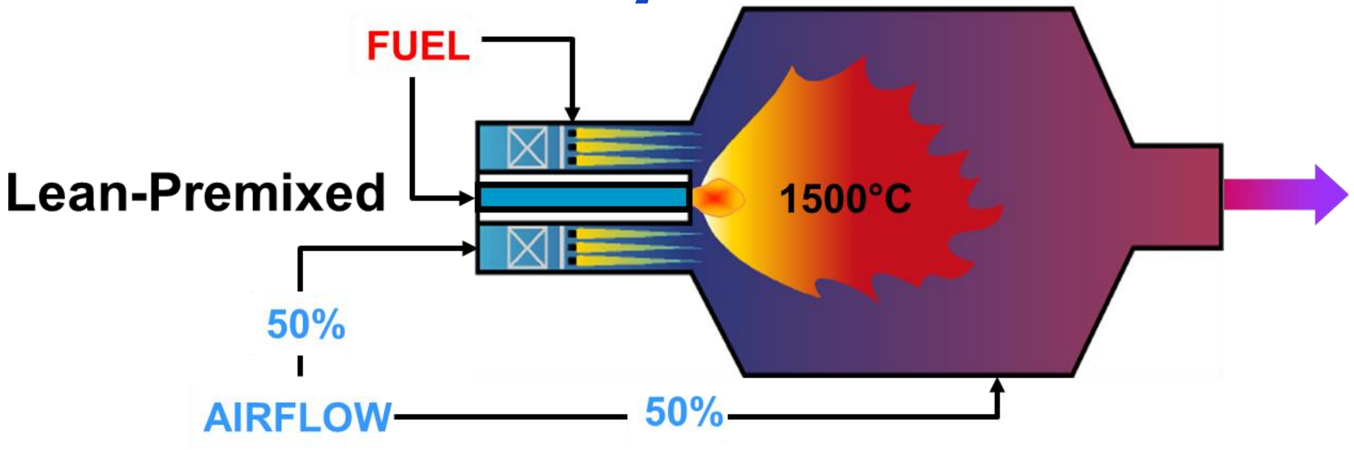


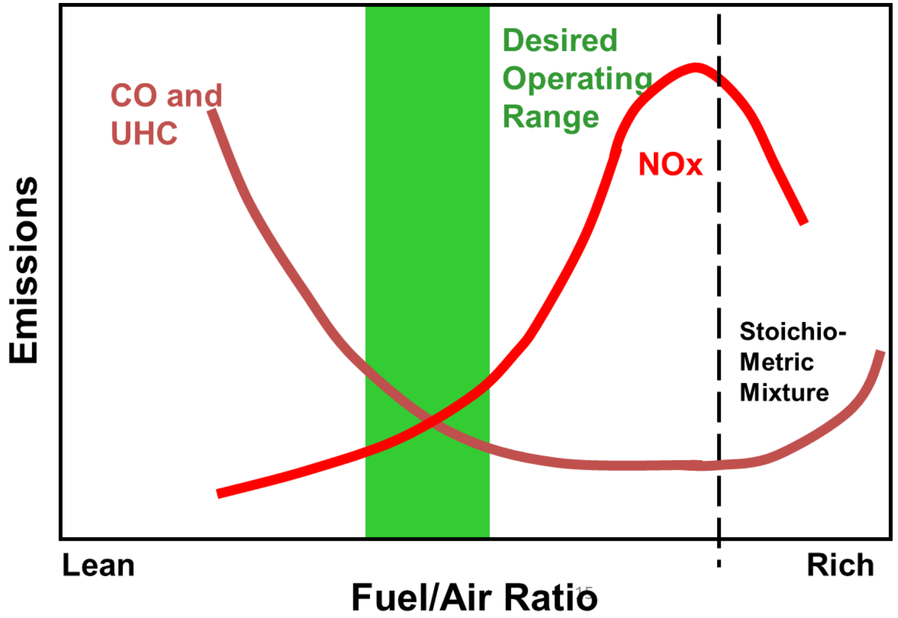


Cowell et. al, 2019

- Proven technology operating with H_2 concentrations up to 100%
- Control systems will mitigate the locally high flame temperature w/ H_2 (flame is shorter, more localized).
- NOx increase can be significant and require N_2 or steam injection.

Lean pre-mixed systems offer some benefits compared to conventional systems.



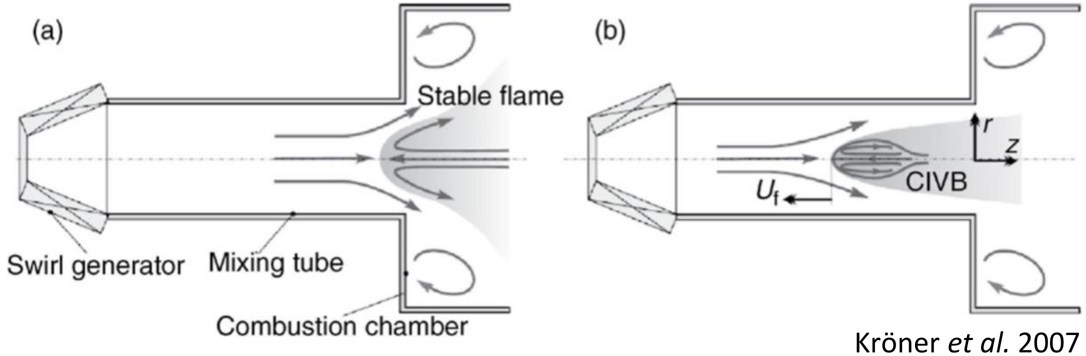


- Premixing air/fuel results in lower and more uniform flame temperature: lower NOx. (two orders of mag. less than diffusion systems[1])
- Additional NOx abatement systems/mechanisms not required.
- General consensus that existing systems could operate with 0-10% vol. with little to no modification (will vary between systems)

[1.] see https://www.hydrogen.energy.gov/pdfs/06-Goldmeer-Hydrogen%20Gas%20Turbines.pdf

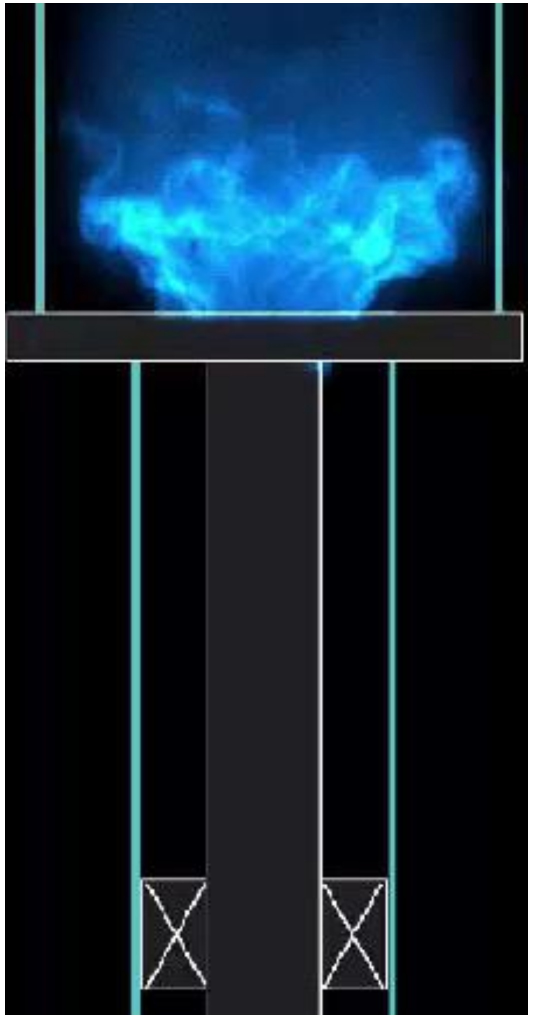
Flashback hazards amplified with H_2 combustion

- Flashback can occur at higher H2 concentrations
- Typically a max ϕ which will cause repeatable flashback
- Flashback is difficult to predict and simulate
- Autoignition can occur while premixing
- Benim & Syed identify four main flashback modes due to flame propagation:
  - Low frequency combustion instabilities
  - Flame propagation in core flow
  - Flame propagation within boundary layers (right)
  - Combustion-induced vortex breakdown (below)

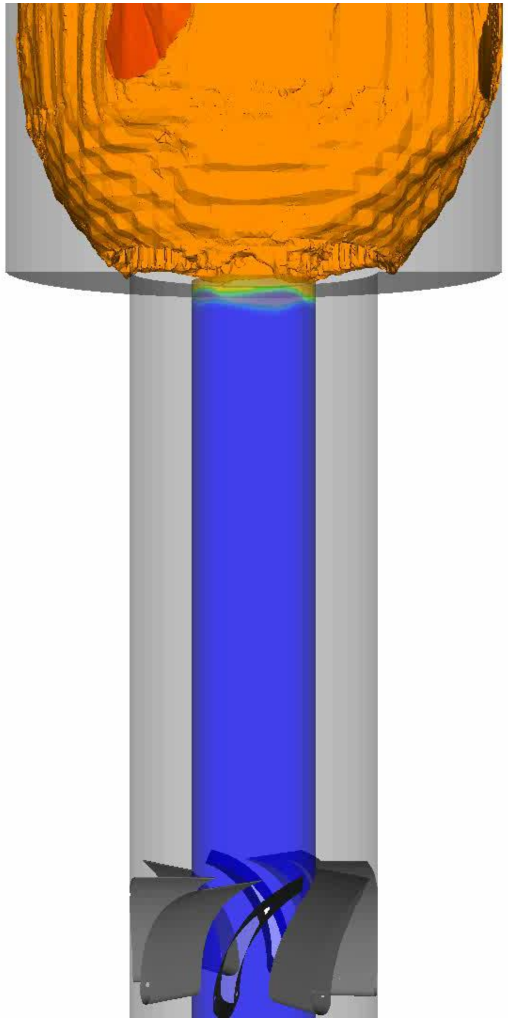


Kröner *et al.* 2007

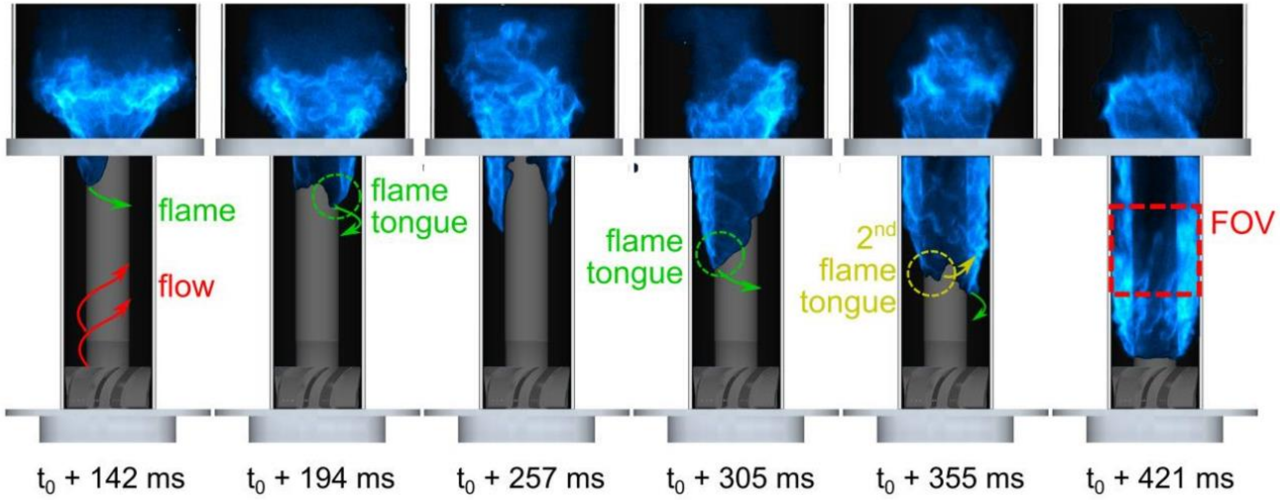
Ebi & Clemens, 2014



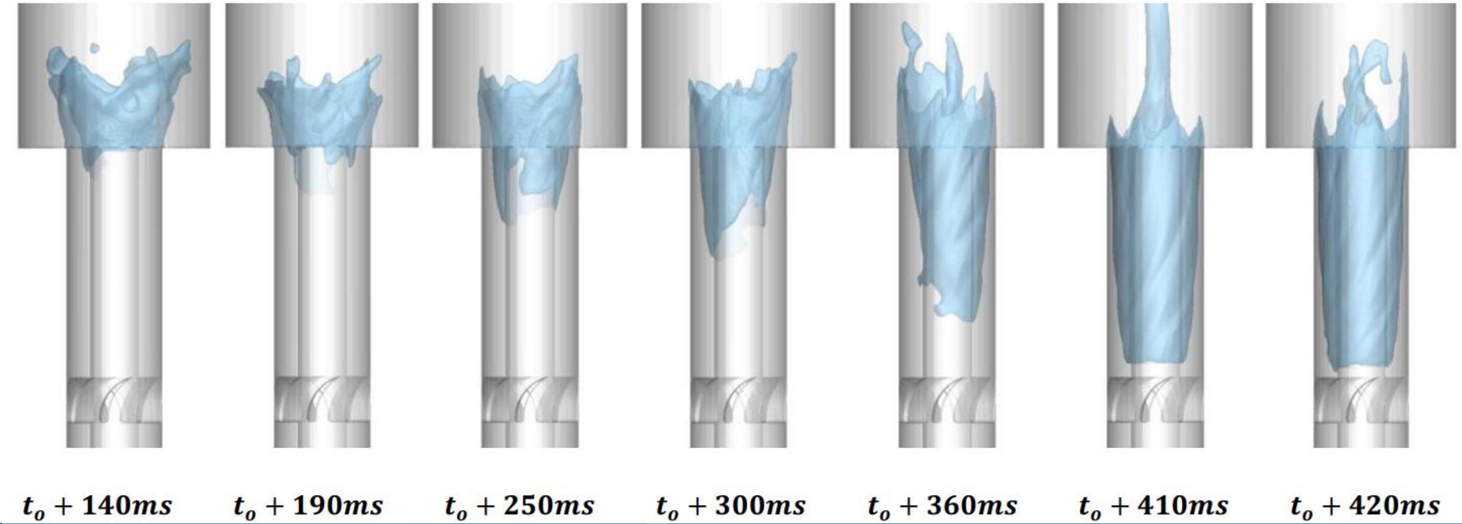
Convergent Sciences, Inc.



Modeling certain types of flashback is tractable

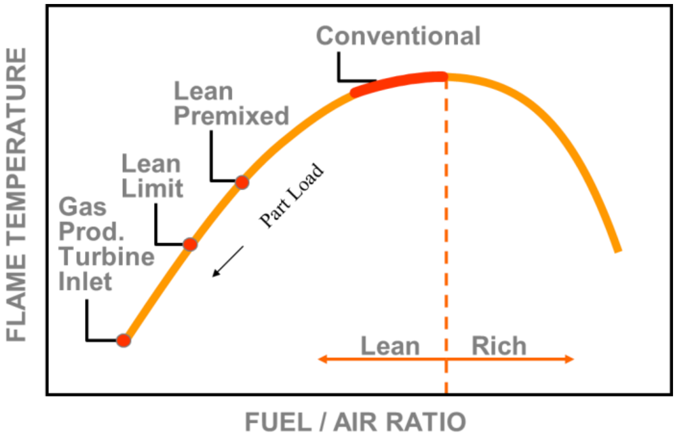


Experiments from
Ebi & Clemens, 2014

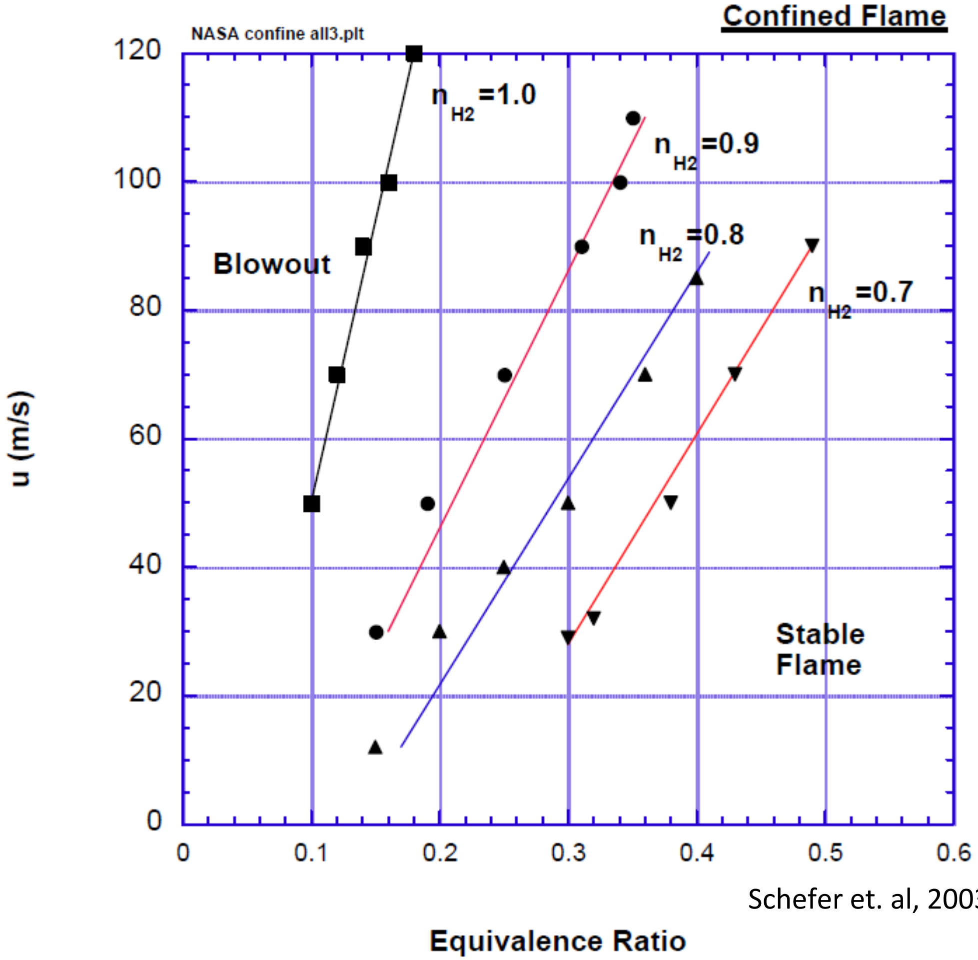


Simulations from
Convergent Science, Inc.
Kumar, 2022

H2 addition can *improve* stability and extend the lean blowout limit compared to NG operation.



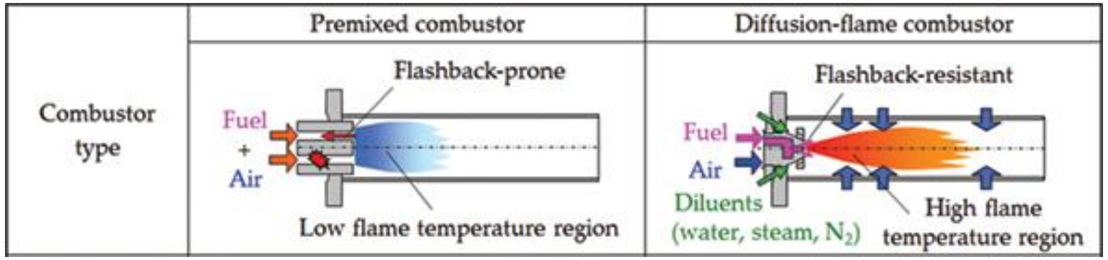
n_{H2}=0.8, u = 30 m/s, phi = 0.3 (Schefer et. al, 2003)

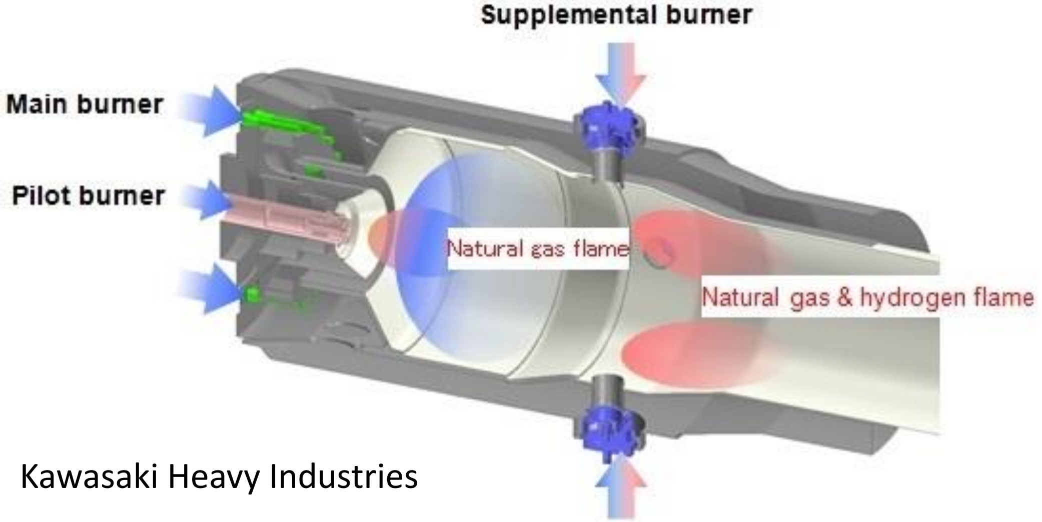


Schefer et. al, 2003

Emissions control approaches in gas turbines

- No carbon, so no carbon dioxide emissions (a main driver of adoption)
- SCR: Selective Catalytic Reduction approaches can be used to scrub NO_x
- Diffusion flames: 100% H_2 demonstrated
  - All mixing done in combustion chamber
  - More injectors, diluents, and smaller flames to manage temperature
- Premixing: 30% H_2 demonstrated
  - Premixing exacerbates autoignition and flashback problems
  - Dry Low NO_x (DLN) is proven for LNG





Kawasaki Heavy Industries

GT Package and Aux. Systems

The use of H2 fuels will impact other portions of the GT package.

- Material compatibility:
  - H_2 embrittlement
  - Seals and elastomeric components
- Fuel piping, valves, orifices, conditioning systems:
  - Sized & rated for H_2 usage and flow rates (~3X greater volume than NG)
  - Fuel flexibility? NG (or other) for startup-up?
  - Fuel analysis?
- Instrumentation:
  - Fire detection
  - Different hazardous classification
- Hot gas path components:
  - Combustion products contain more water vapor
  - Higher heat transfer
  - Increased risk of corrosion?
- Package ventilation:
  - H_2 molecule is light and accumulations must be considered
- Start sequences, failed starts, and purge cycles:
  - Increased flammability range

	H2% with Balance Pipeline NG					
H2 Blend (% by volume)	0%	5%	10%	20%	30%	100%
Combustion Parameters						
Laminar Flame Speed (cm/s)[1]	124	127	130	139	150	749
Autoignition Delay Time (msec)[2]	124	112	107	104	103	76
Wobbe Index (btu/scf)	1215	1199	1183	1150	1116	1039
Flame Temperature (°F)[3]	4206	4210	4215	4225	4238	4510
Package & Fuel System						
Flammability (% volumetric LEL)	4.88	4.83	4.79	4.71	4.63	4
Maximum Experimental Safe Gap (MESG)	1.10	1.06	1.02	.94	.86	.28
NEC/CSA & IEC Gas Groups	D & IIA	D & IIA	D & IIA	D & IIA	D & IIB	B & IIC

[1] *Calculated for Equivalence Ratio = 1.0 and Mixture Temperature and Pressure of 600°F and 1 atm.*
[2] *Calculated for Equivalence Ratio = 0.4 and Mixture Temperature and Pressure of 1200°F and 10 atm.*
[3] *Adiabatic Stoichiometric Flame Temperature Calculated for Titan™ 130 Full Load Conditions*

Cowell et. al, 2019

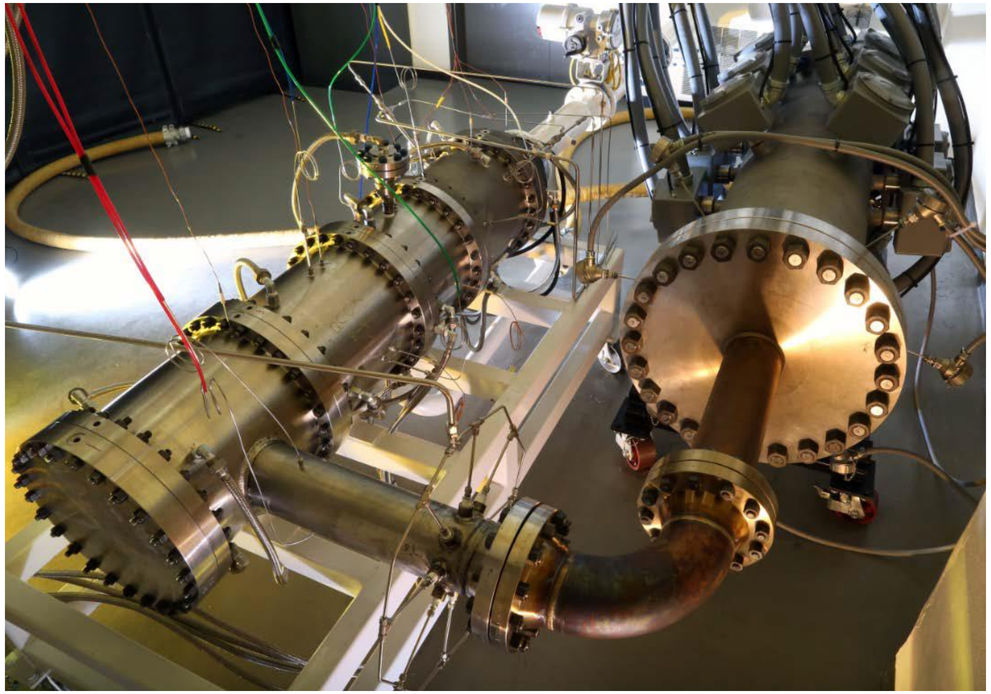
What is SwRI Doing?

SwRI operates a gas turbine (GT) combustion test facility to support the development of new combustion system designs.

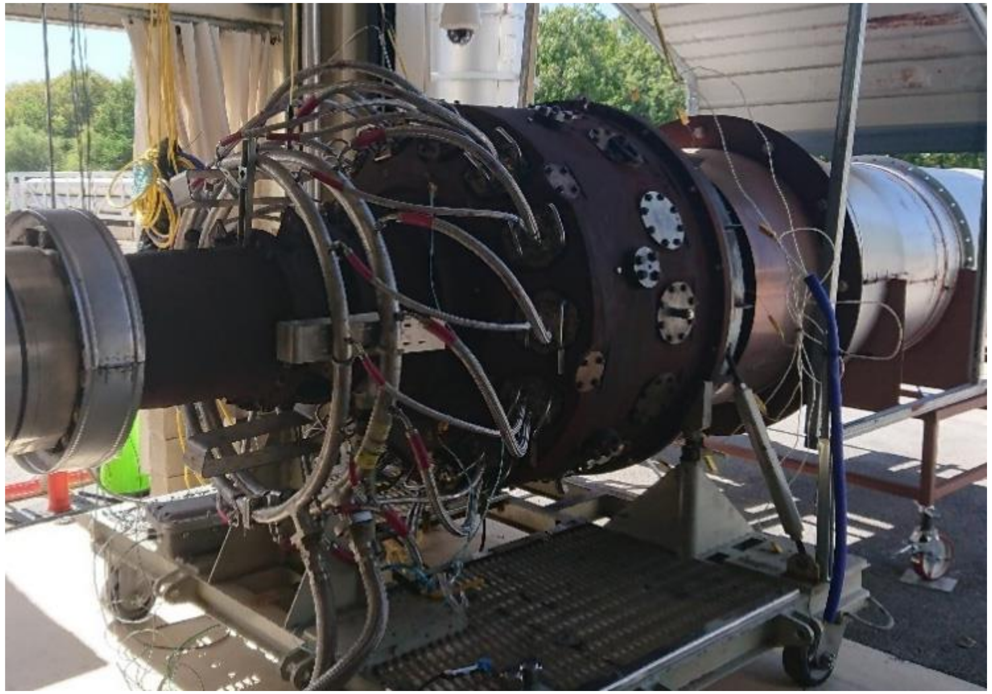
A variety of fuels are stored outside of the HEAT facility

Pre-heated air is supplied to the combustor to mimic typical compressor discharge temperatures

The air and fuel are supplied to combustor test rigs to examine a range of combustion parameters.



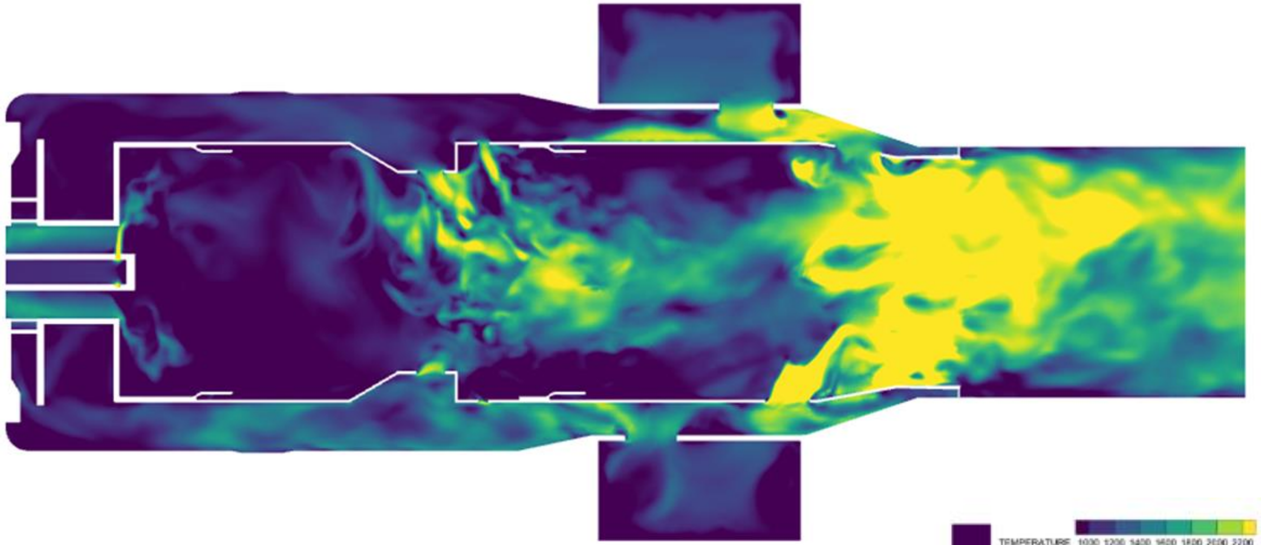
SwRI developed a novel combustor for Concentrating Solar Power applications – DE-EE0005805

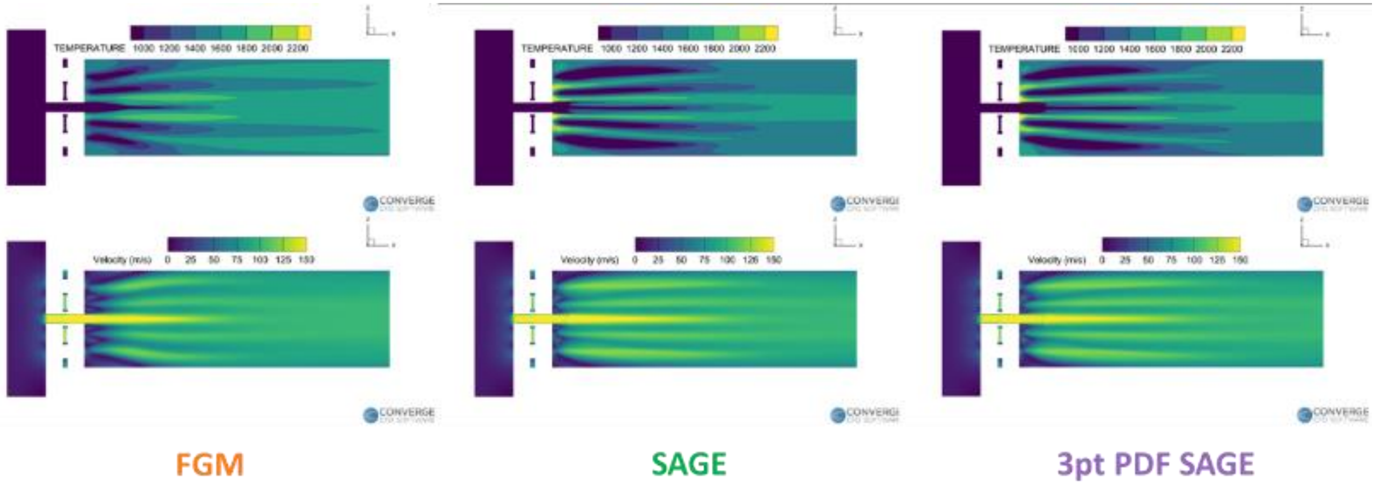


SwRI tested a Titan 130 SoLoNOx combustion system with CH_4/H_2 blended fuels – DE-EE0008415

- Advanced Fuels
  - H2, NH3, CH4, blends
  - O2
- Various measurements can be taken to observe:
  - Combustion dynamics/stability
  - Flame visualization
  - Emissions measurements

H_2-fueled combustor designs





Gas turbines will continue to play a critical role...

Original image credit: https://resources.sw.siemens.com/en-US/white-paper-3d-multiphysics-based-virtual-prototyping#disw-fulfillment-form, accessed

Thank you for your attention today.

Griffin Beck
Manager – R&D
Propulsion & Energy Machinery
Southwest Research Institute
griffin.beck@swri.org
(210) 522-2509

Brian Connolly, Ph.D
Research Engineer
Propulsion & Energy Machinery
Southwest Research Institute
brian.connolly@swri.org
(210) 522-3618

A PDF copy of the presentation slides will be emailed to all attendees after the conclusion of the Webinar.

For any questions, please contact Herminia Mares @ herminia.mares@swri.org