Carbon-free firing of state-of-the-art gas turbines: technology readiness, potential impact and research challenges

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Outline

- The context: *zero-emission thermal power cycles*
- Carbon-free firing of gas turbines: *technology readiness & potential impact*
- Research challenges: *stabilize flame, minimize fuel-dilution and emissions*

Acknowledgments:

CLIMIT

GASSNOVA

NCCS
NORWEGIAN CCS RESEARCH CENTRE
Industry-driven innovation for fast-track CCS deployment

FME

ANSALDO ENERGIA

SIEMENS
Ingenuity for life

equinor

Sandia National Laboratories

Air-breathing thermal power cycles: powering the world


Courtesy of MAN

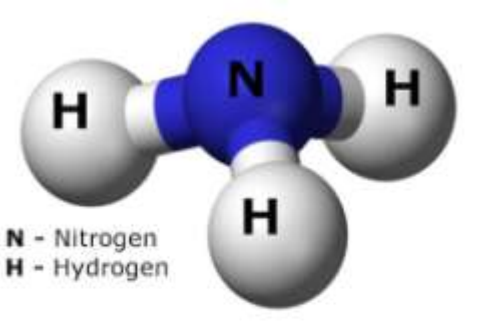
2-stroke, low-rpm ICEs:
- 10-80 MW
- Cycle efficiency ~ 55%
- HFO, Diesel and NG
- *MAN 'upgrades' to* NH_3

Gas + steam turbine (combined cycle):
- 50-800 MW
- Cycle efficiency ~ 63%
- 6100 TWh installed capacity (NG-fired)
- *Carbon-free firing of GTs 'within grasp'*

High-bypass turbofan engine:
- 100-600 kN thrust
- Cycle efficiency ~ 30-36%
- +30000 CFM56 sold
- *Enough biofuel?*

Thermal cycles are *not intrinsically dirty* but as clean as the *fuel* and *combustion technology* they utilize!

Why *hydrogen* (and *ammonia*)?



Hydrogen (H_2)

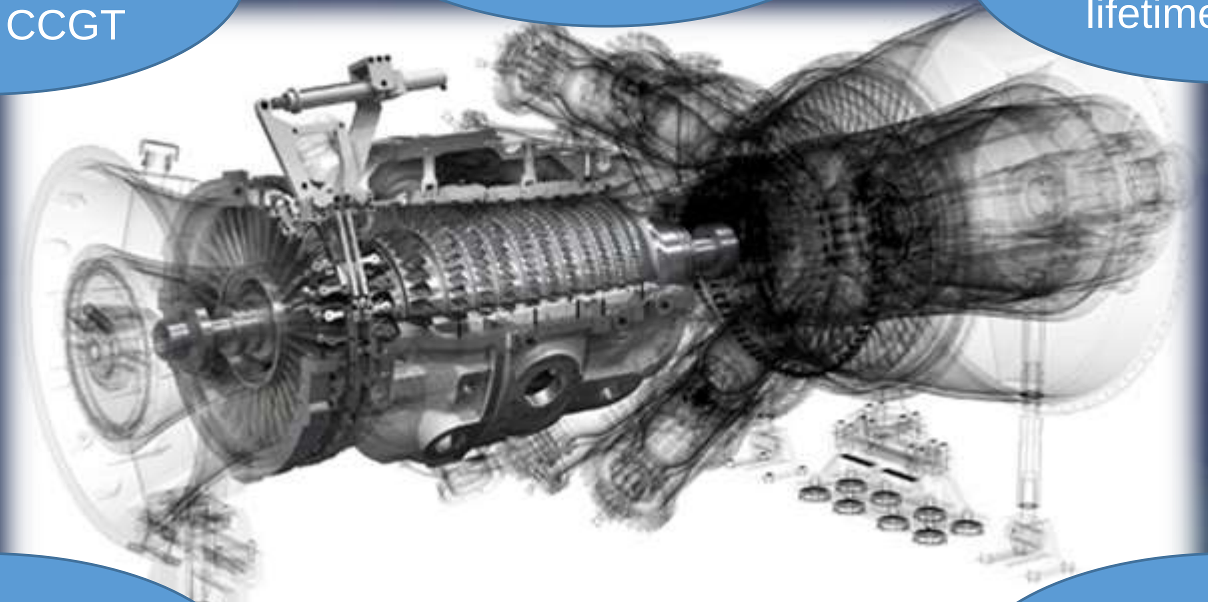
- H_2 to power completes *pre-combustion CCS* value chains
- Provides an optimal energy-carrier in *large-scale energy storage* schemes for integration of non-dispatchable & intermittent RES (power-to-gas-to-power)
- Effectively a bridge between "fossil" and "green" energy sources (blue and green H_2)

Ammonia (NH_3)

- Convenient H_2-carrier for remote transport and/or long-term storage in all of the above
- Represent a useful H_2-diluent (for stable combustion in gas turbines)

Both are *carbon-free* fuels: zero CO_2 emissions!

Why gas turbines?



SGT-750 / Courtesy of Siemens

- High cycle efficiency up to ~63% in CCGT
- Switch to H_2 (or NH_3) only requires burner modifications
- Well-established reliability and lifetime +25 yrs
- Relatively «low cost» at 200-1200 USD/kW_e (SCGT-CCGT)
- GTs handle well impurities & «minor» species in fuel (e.g. CO_2)
- Fast response to load variations up to ~50 MW_e/min
- High fuel flexibility from liquid HC and NG to H_2 and NH_3
- Unmatched specific power ~2-10 kW/kg

H_2-fired GTs: brief history and state of the art

FP6 ENCAPCO2 (2004-2009): preliminary investigations

FP7 DECARBit and BIGH2/Phase I&II (2008-2015): 50% by vol H_2 in NG is achieved in rig

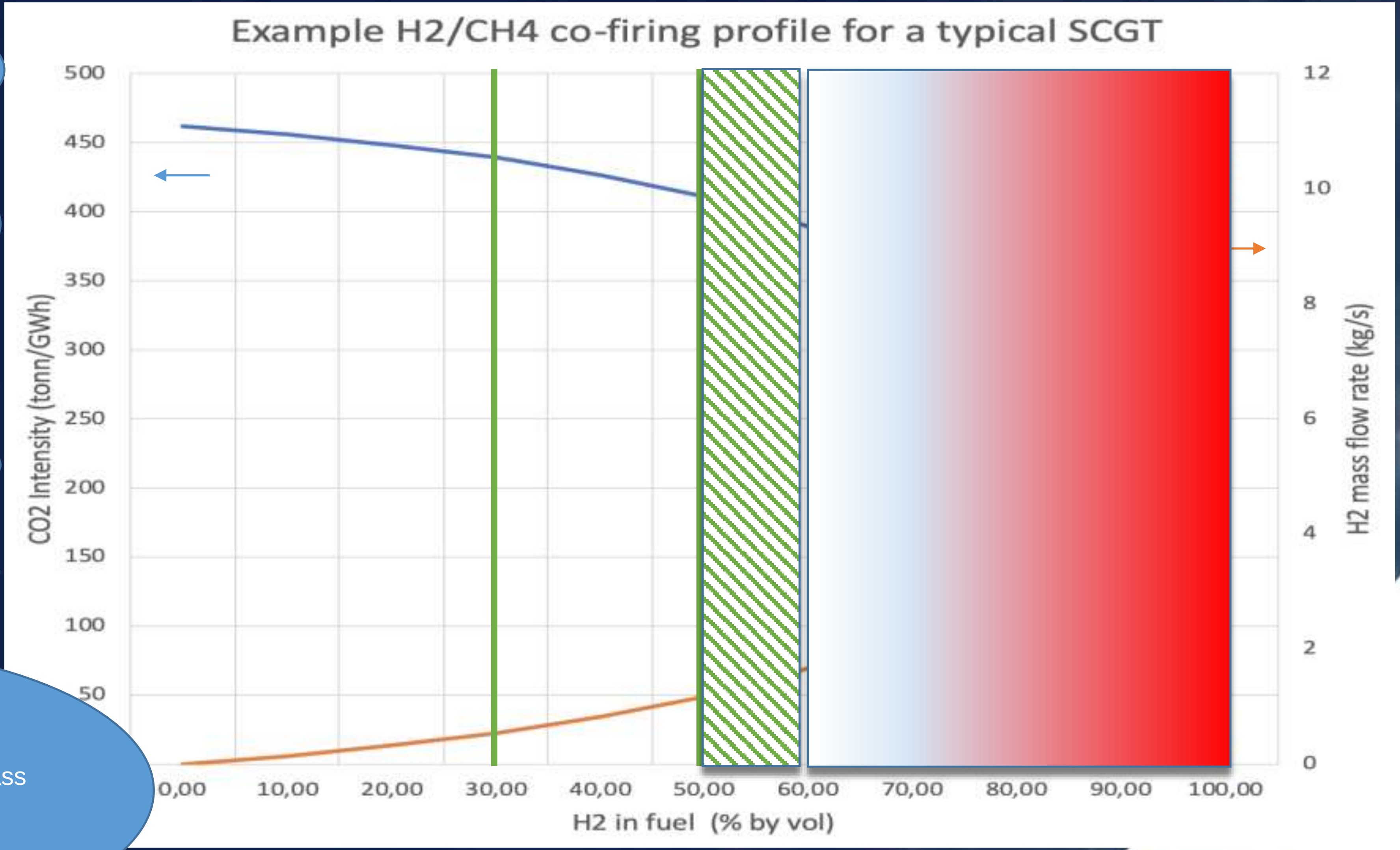
MHPS provides 30% H2 in H-class GT (2017)

AE provides 50% H_2 in H-class GT36 (2018)

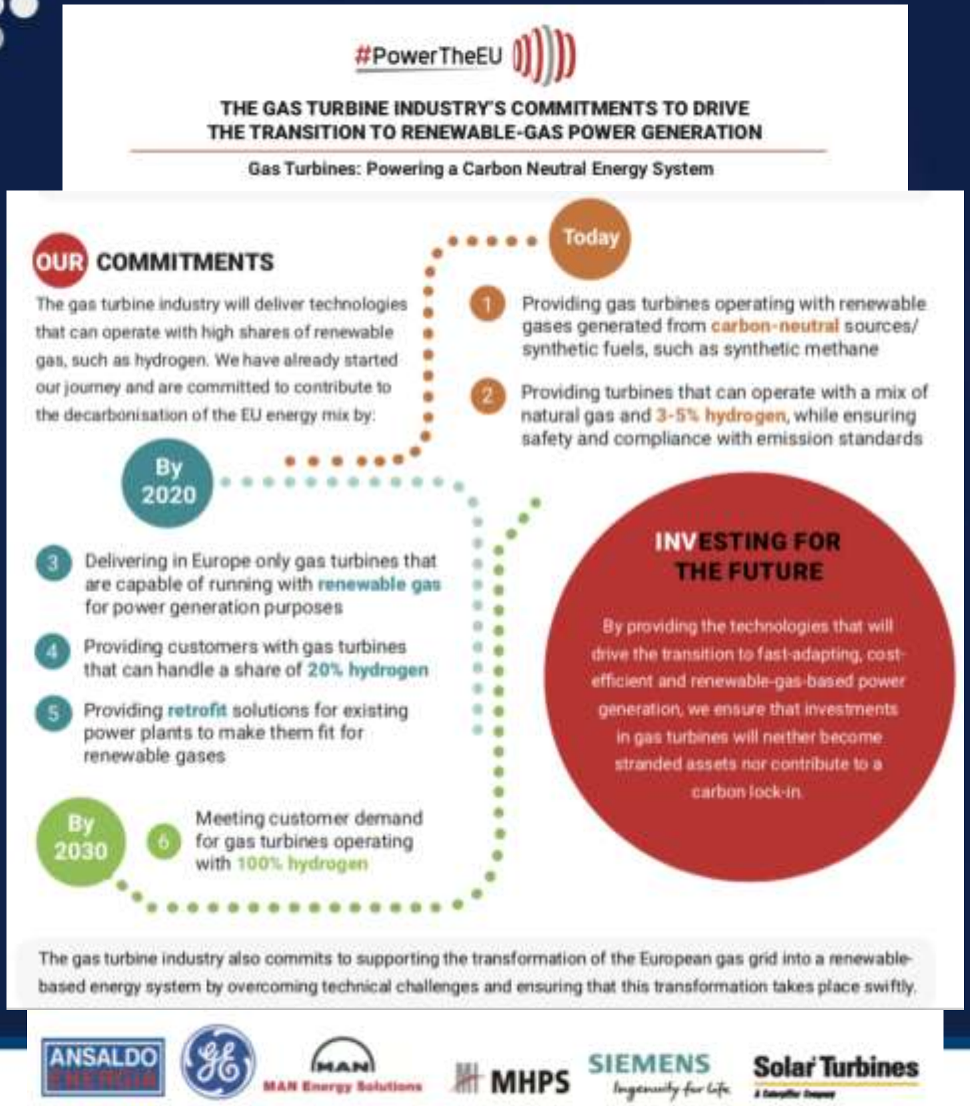
SIT provides 50-60% H_2 in GT600/700/800 (2018)

The race is on (2019)!

- AE achieves 70% H2 in rig @ H-class temperature (baseload GTs)
- SIT achieves 100% H2 in rig @ F-class temperature (industrial GTs)



GT OEMs commited to 100% H_2 firing by 2030



#PowerTheEU

THE GAS TURBINE INDUSTRY'S COMMITMENTS TO DRIVE THE TRANSITION TO RENEWABLE-GAS POWER GENERATION

Gas Turbines: Powering a Carbon Neutral Energy System

OUR COMMITMENTS

The gas turbine industry will deliver technologies that can operate with high shares of renewable gas, such as hydrogen. We have already started our journey and are committed to contribute to the decarbonisation of the EU energy mix by:

Today

① Providing gas turbines operating with renewable gases generated from **carbon-neutral** sources/ synthetic fuels, such as synthetic methane

② Providing turbines that can operate with a mix of natural gas and **3-5% hydrogen**, while ensuring safety and compliance with emission standards

By 2020

③ Delivering in Europe only gas turbines that are capable of running with **renewable gas** for power generation purposes

④ Providing customers with gas turbines that can handle a share of **20% hydrogen**

⑤ Providing **retrofit** solutions for existing power plants to make them fit for renewable gases

By 2030

⑥ Meeting customer demand for gas turbines operating with **100% hydrogen**

INVESTING FOR THE FUTURE

By providing the technologies that will drive the transition to fast-adapting, cost-efficient and renewable-gas-based power generation, we ensure that investments in gas turbines will neither become stranded assets nor contribute to a carbon lock-in.

The gas turbine industry also commits to supporting the transformation of the European gas grid into a renewable-based energy system by overcoming technical challenges and ensuring that this transformation takes place swiftly.

GT-industry's expertise and resources committed to achieve 100% H_2, however:

- ➢ High-pressure/full-size R&D of GT combustion system is extremely expensive and cash-flow is limiting factor
- ➢ Interest by committed customers is needed
- ➢ Public intervention is beneficial in the form of
  - A legal framework for non-conventional fuels
  - Set goals, do not pre-select technologies
  - Public co-funding of RD&D efforts

The challenge: the high reactivity of hydrogen

Key factors in design of gas turbine combustors include:

- the combustion velocity (flame speed)
- the fuel reactivity and flammability (time and composition needed for ignition)
- the flame temperature (controlling dilatation and acceleration of the working fluid)

Stoichiometric combustion properties at 1 bar and 300 K	**CH_4**	**H_2**	**NH_3**
Flame Speed	40 cm/s	300 cm/s	20 cm/s
Flame Temperature	~2200 K	~2400 K	~2050K
Flammability Limits (by volume %)	5-15	4-75	15-28
Ignition Energy (mJ)	0.28	0.011	680
Ignition Delay Time (ms) @ 1000K/17bar	45.6	6.2	N/A
LHV (MJ/Kg)	50	120	18

How to address hydrogen’s high reactivity

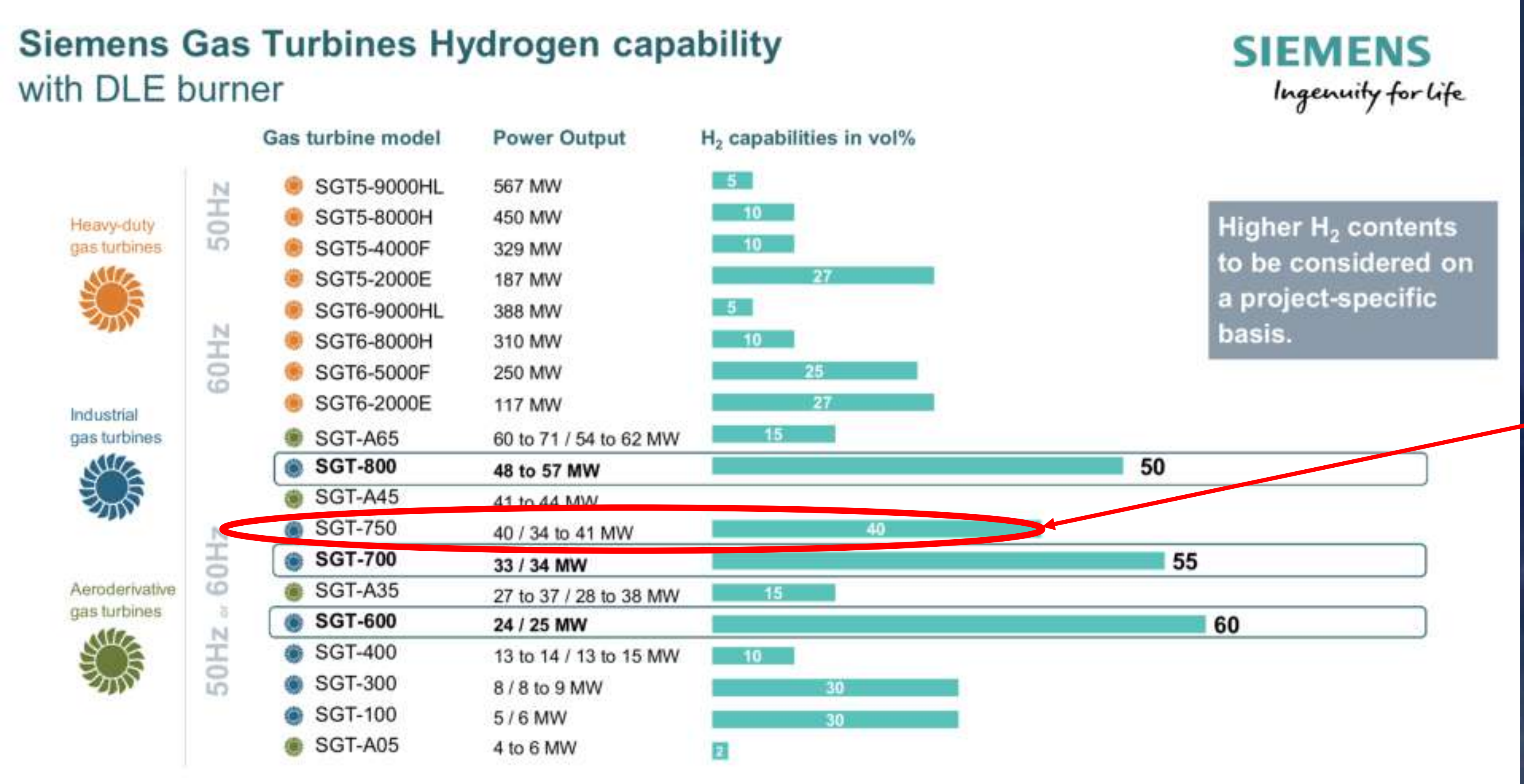
Two strategies at hand for clean, stable and efficient hydrogen combustion in GTs:

- *“handle H_2 reactivity” (e.g. combustion staging) → relies on autoigniton for flame stabilization*
- *“reduce H_2 reactivity” (e.g. fuel blending) → rely on inert gases or less reactive fuels*

SINTEF & NTNU work together with gas turbines OEMs at both approaches:

- *Auto-ignition H_2 flame stabilization in FME NCCS/Task 5 (+Reheat2H2 KPN) w/Ansaldo*
- *Hydrogen/nitrogen/ammonia-firing of a Siemens DLE burner (BIGH2/Phase III)*
- *New activity starting-up in LowEmission Petrosenter w/Siemens & Ansaldo*

Example: H_2 co-firing in DLE burner*



Siemens Gas Turbines Hydrogen capability with DLE burner

SIEMENS
Ingenuity for life

Heavy-duty gas turbines: 50Hz, 60Hz
Industrial gas turbines
Aeroderivative gas turbines: 50Hz or 60Hz

Gas turbine model	Power Output	H_2 capabilities in vol%
SGT5-9000HL	567 MW	5
SGT5-8000H	450 MW	10
SGT5-4000F	329 MW	10
SGT5-2000E	187 MW	27
SGT6-9000HL	388 MW	5
SGT6-8000H	310 MW	10
SGT6-5000F	250 MW	25
SGT6-2000E	117 MW	27
SGT-A65	60 to 71 / 54 to 62 MW	15
SGT-800	**48 to 57 MW**	**50**
SGT-A45	41 to 44 MW	
SGT-750	40 / 34 to 41 MW	40
SGT-700	**33 / 34 MW**	**55**
SGT-A35	27 to 37 / 28 to 38 MW	15
SGT-600	**24 / 25 MW**	**60**
SGT-400	13 to 14 / 13 to 15 MW	10
SGT-300	8 / 8 to 9 MW	30
SGT-100	5 / 6 MW	30
SGT-A05	4 to 6 MW	2

Higher H_2 contents to be considered on a project-specific basis.

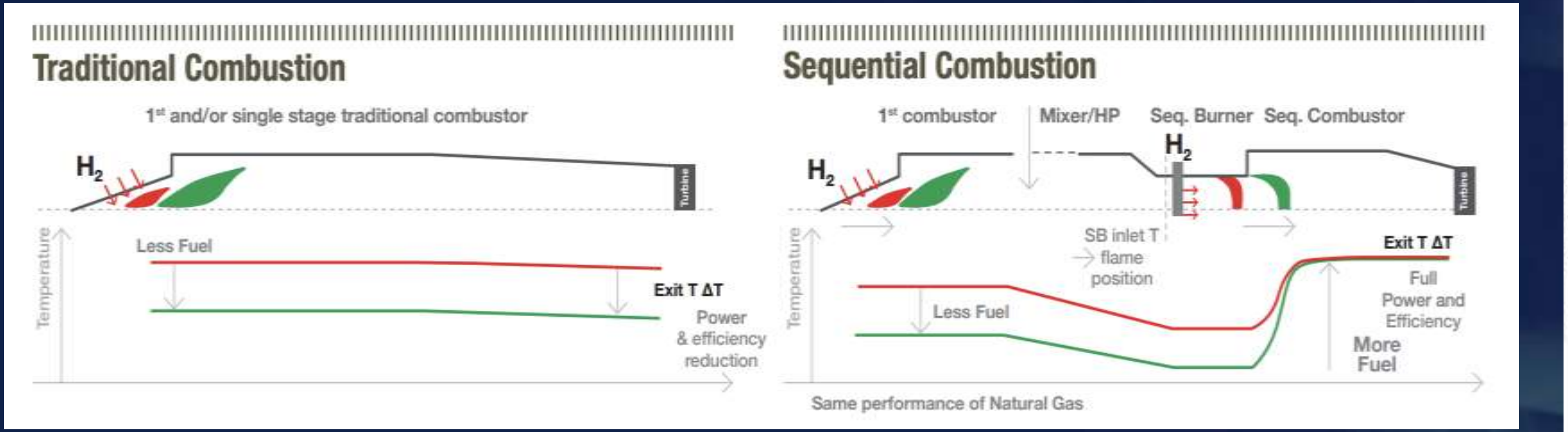
BIGH2
Phase III

SINTEF NTNU

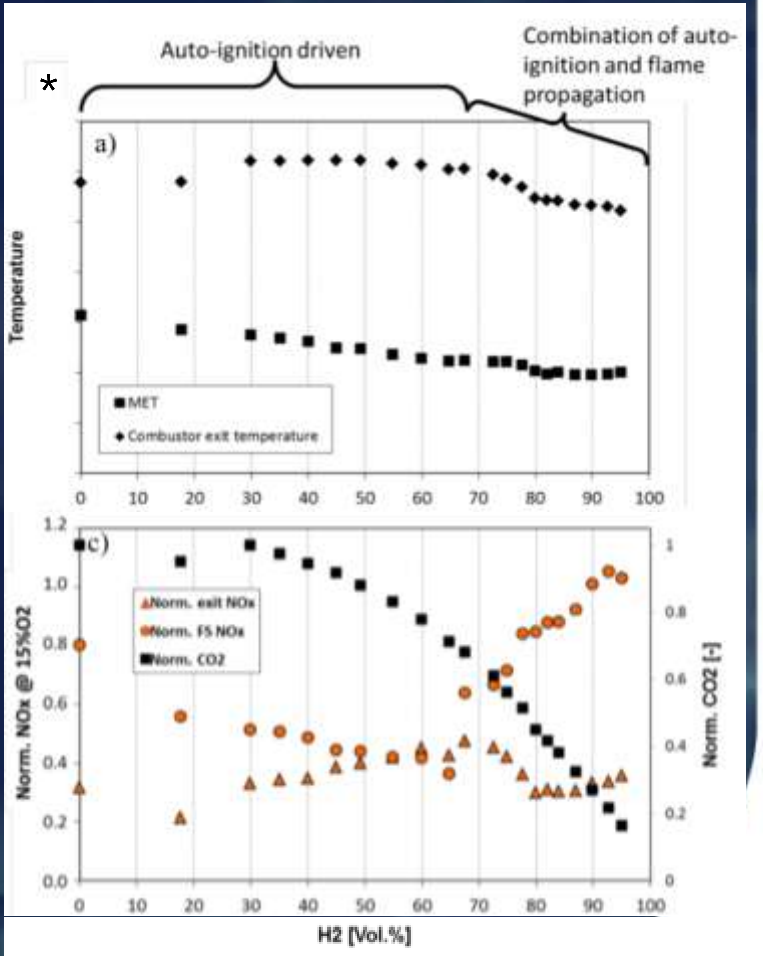
*Larfeldt et al. “Hydrogen co-firing in Siemens low NOx industrial gas turbines”, PowerGen 2018

Example: staged combustion

- *Ansaldo*’s reheat scheme: firing temperature of 1^{st} stage *controls ignition time* (t_{ign}) and ***flame stabilization*** in 2^{nd} stage!



Courtesy of Ansaldo Energia



Bottom line: large-scale power generation with hydrogen-rich fuels is feasible and R&D can help filling the remaining gap!

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*Bothien et al, “Sequential Combustion in Gas Turbines – The Key Technology for Burning High Hydrogen Contents with Low Emissions”, Asme Turbo Expo 2019, GT2019-90798

Technical challenges for H_2/H_2-rich fuels

Current GTs are highly “*tuned*” to burn NG-air mixtures and transitioning to H_2 rich fuels needs to maintain:

- low NO_x capabilities
- combustor stability and operating range
- avoid de-rating the engine
- improve dynamic loading (turn down/part load)

Requires different combustor design strategies for H_2 and H_2 rich fuels – large innovation potential!

Knowledge gaps

Scientific (independent of combustor geometry)

- ➢The effect of pressure & temperature of H_2/H_2-rich mixtures on:
  - ➢Flame speed, ignition delay times, chemical kinetics, turbulence-chemistry interaction

Technical (some geometry dependence)

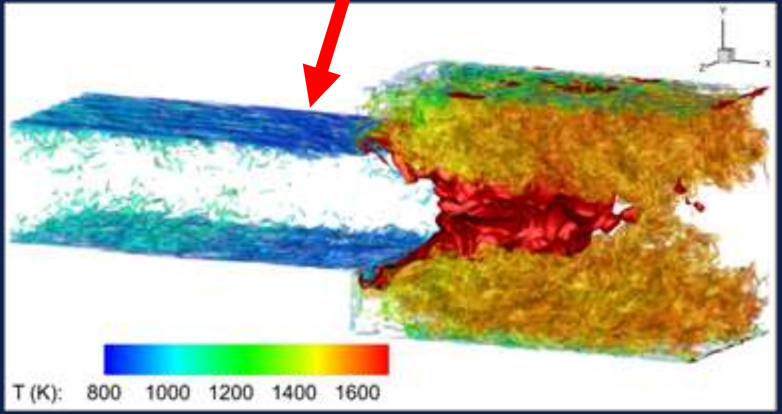
- ➢Ensure stabilisation of H_2/H_2-rich flames to prevent:
  - ➢Static instabilities: flashback and blow-off
  - ➢Dynamic instabilities: thermoacoustic oscillations

Research methodology

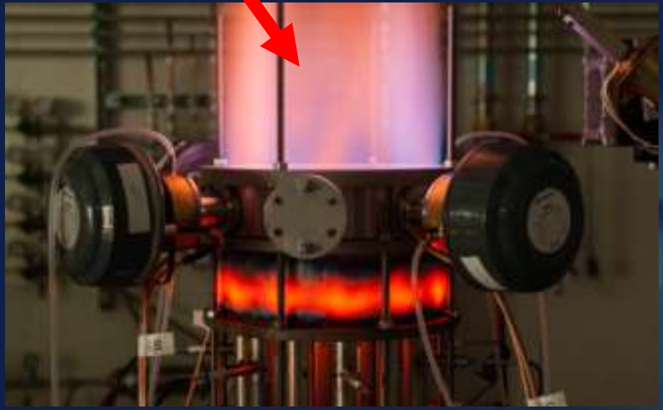
- To understand static and dynamic instabilities we must use simplified geometries enabling detailed measurements and computations

- To solve problems research activities over a range of TRLs is essential

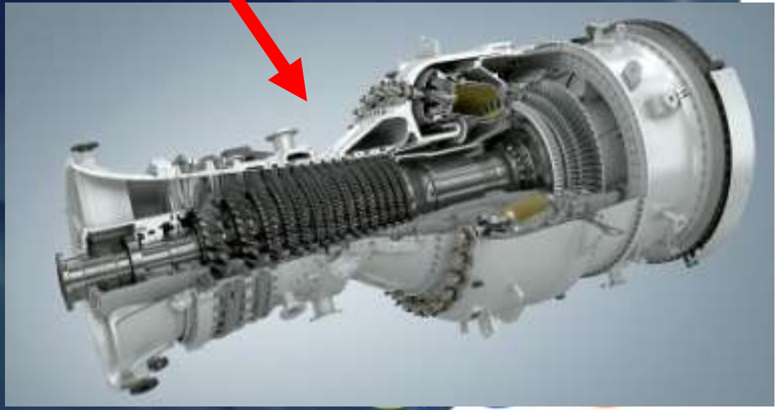
DNS of reheat flame in simplified geometry



Single sector and annular combustor

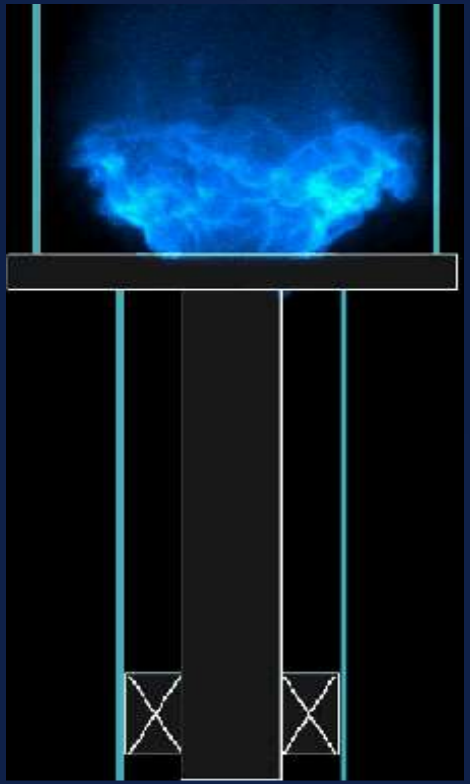


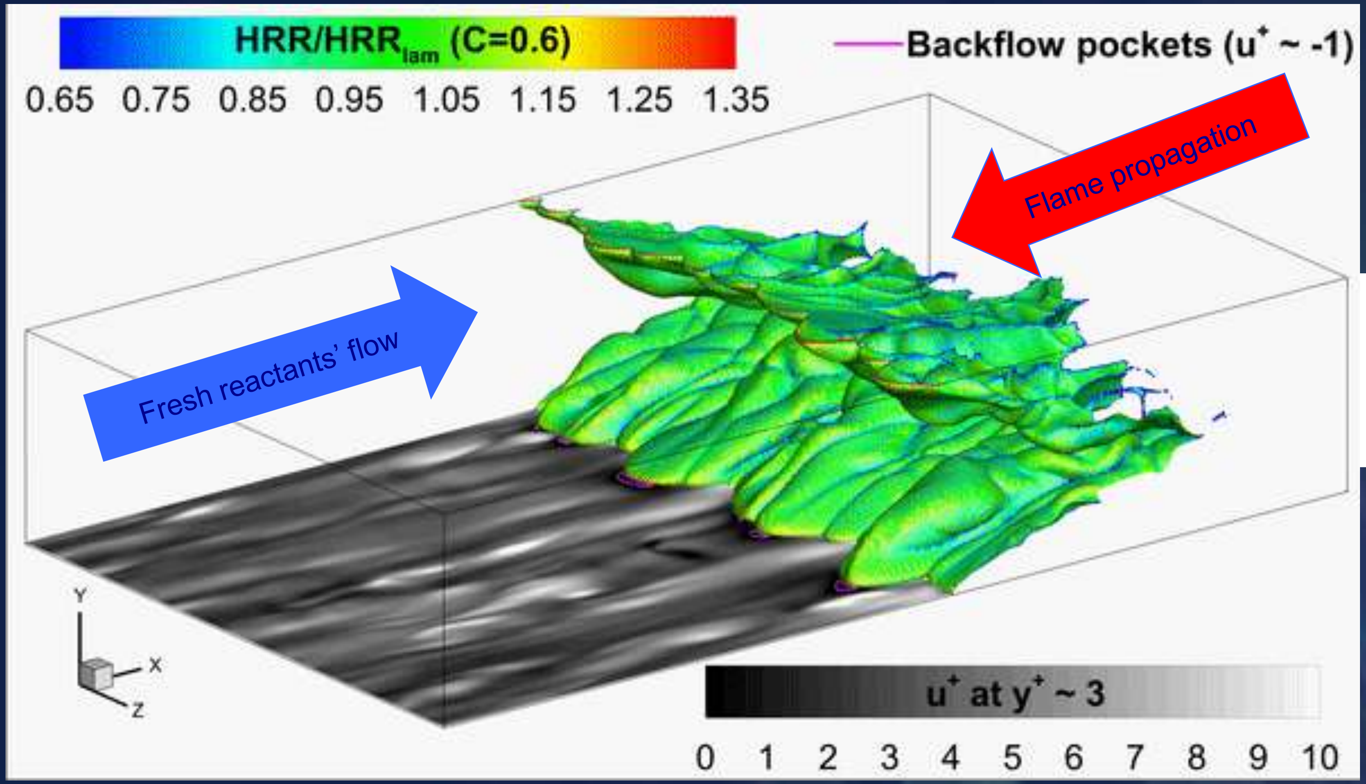
Siemens SGT600/700/800 - Annular combustor



Increasing TRL

Static flame stabilization: avoid flashback!

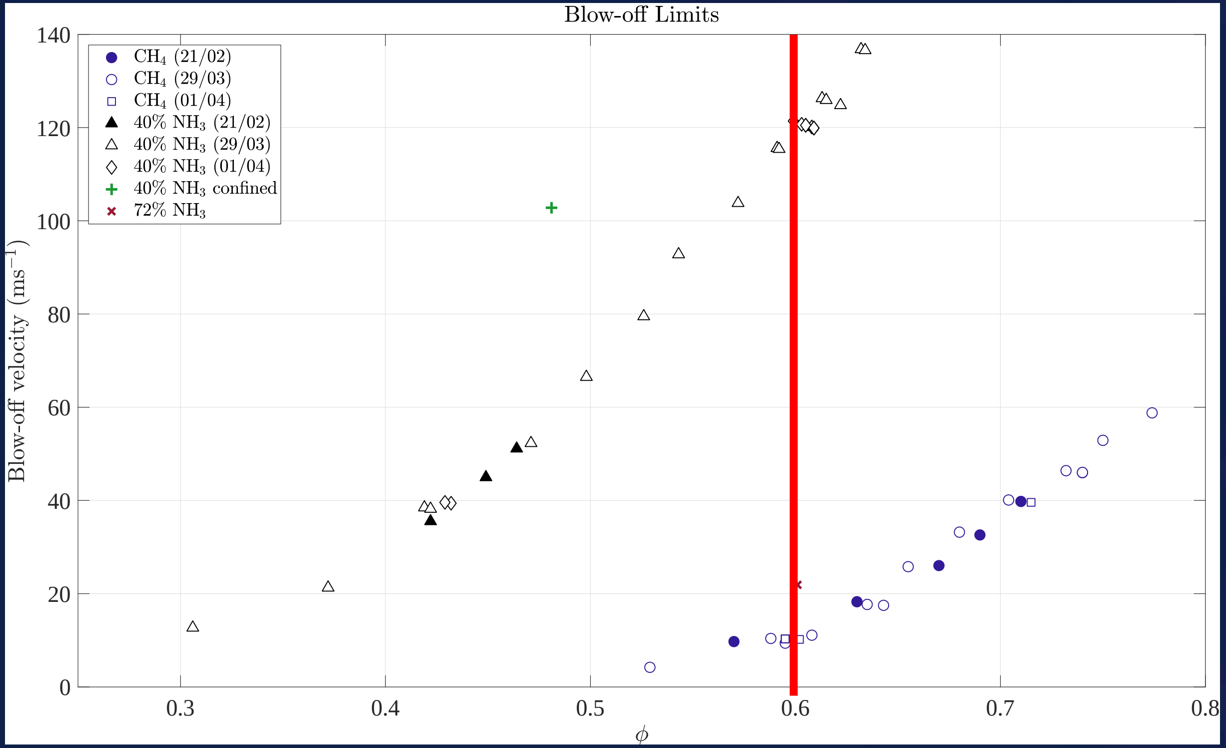




DNS of lean
H_2-air premixed
flame at φ=0.55

- Flashback occurs when the flame propagates much faster than the incoming flow velocity ($S_T >> U$)
- Always low-velocity regions in wakes and boundary layers

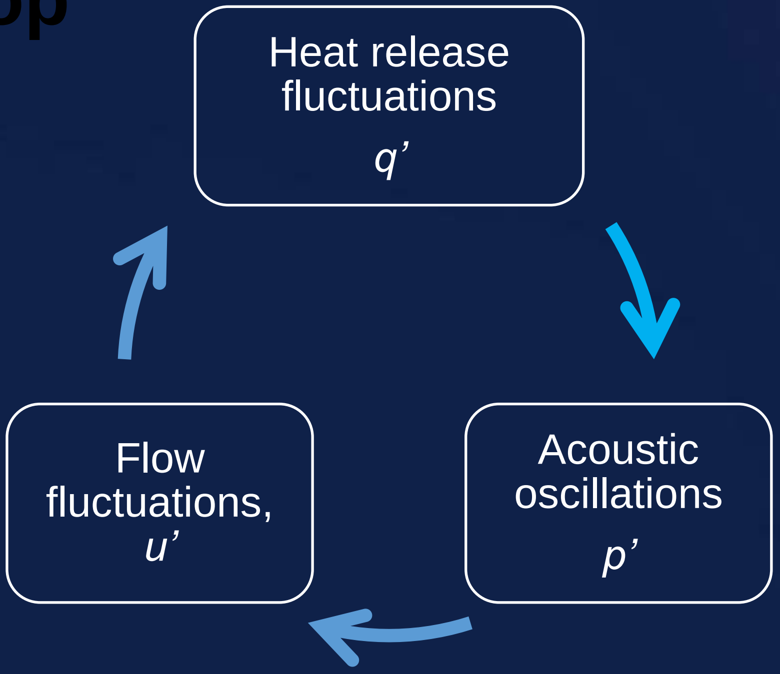
Static flame stabilization: blow-off limits!



- 40%NH3/45%H2/15%N2 blend matches T_{ad} and S_L for methane but exhibits order-of-magnitude deviation in blow-off limits

Dynamic instabilities: avoid thermoacoustics!

Thermoacoustic feedback loop



Heat release fluctuations

q'

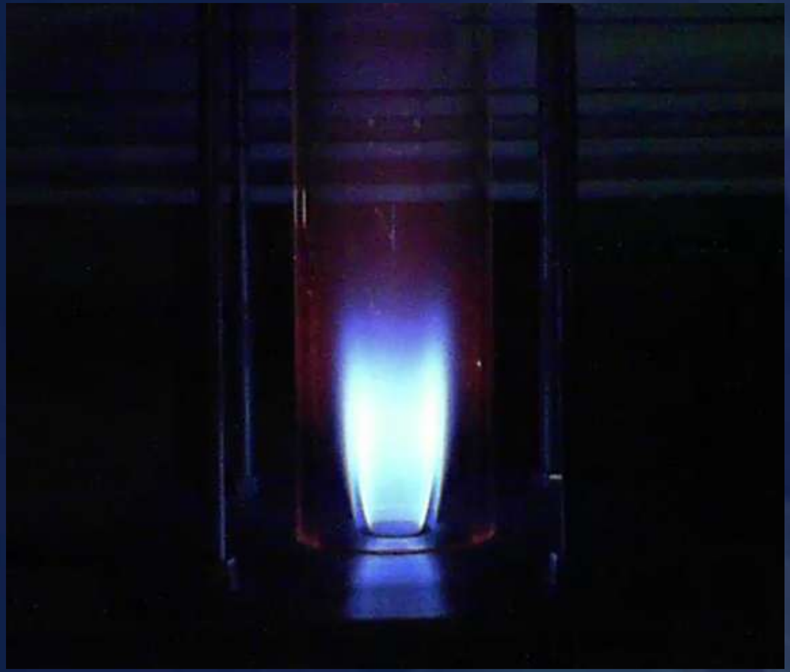
Acoustic oscillations

p'

Flow fluctuations,

u'

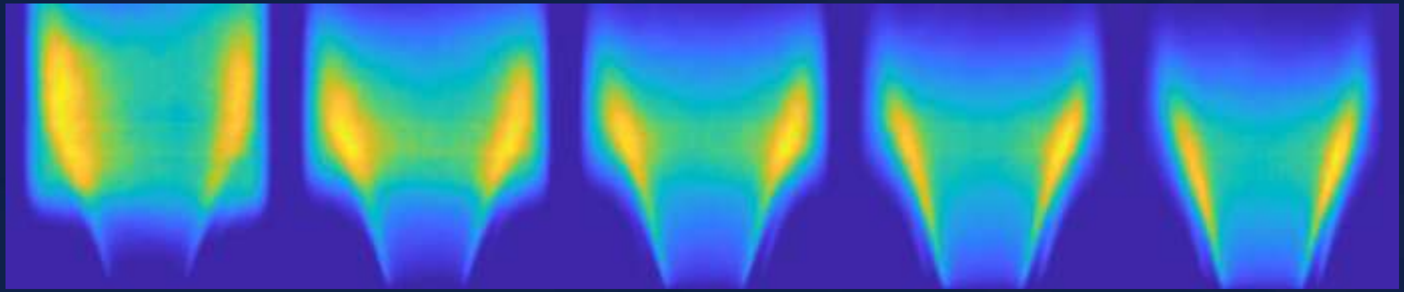
Stable – to violent – to very violent



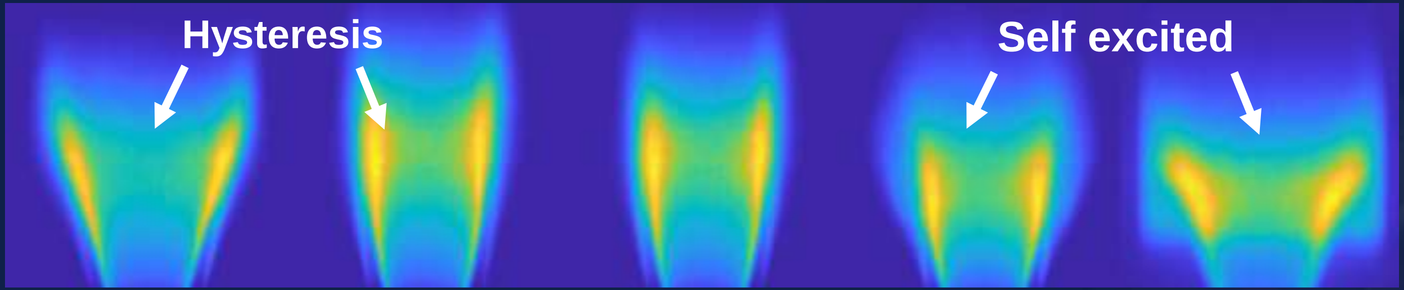
Addition of a small amount of H_2

Effect of increasing H_2 on flame shape

Mean H_2/CH_4 - air flame shapes for increasing H_2



P_{H2} :0% P_{H2} :5% P_{H2} :10% P_{H2} :15% P_{H2} :20%



P_{H2} :23% P_{H2} :23% P_{H2} :25% P_{H2} :27% P_{H2} :28%

Conditions:

- Power = 7kW
- Power fraction, P_{H2}: 0-28%
- Volume fraction: 0-50%
- Equivalence ratio = 0.7

Concluding remarks

- Combustion of H_2 fuels are a *technically viable route to large-scale decarbonisation* for the power generation sector with CCS
- Significant steps forward in co-firing H_2 with CH_4 have been already been made and GTs are commercially available
- There are still significant (and exciting!) scientific and technical challenges in combustion technology to get to zero carbon that need to be addressed