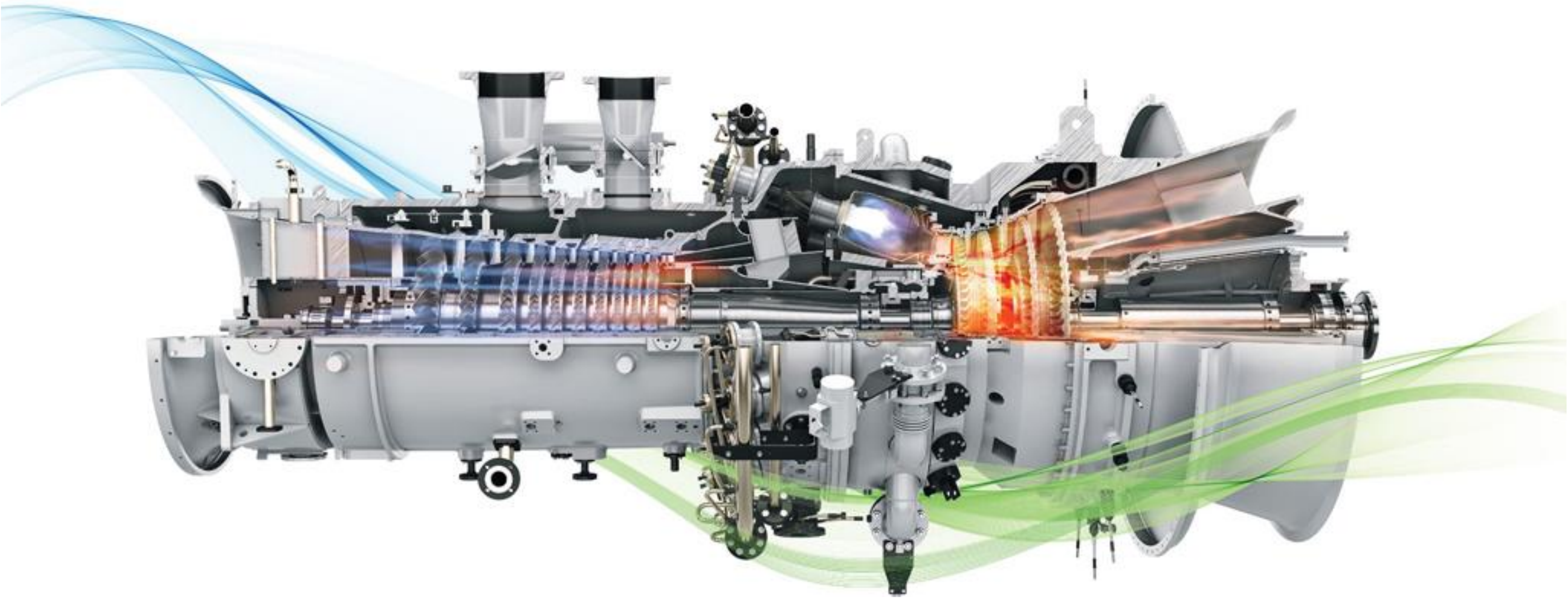


# Addressing the combustion challenges of hydrogen addition to natural gas

ETN Hydrogen Combustion Working group, **Felix Güthe**, Dr D Abbott

# Hydrogen combustion sub-group

## Motivation

- The following question was posed to the ETN Hydrogen Working Group:
  - Is there any fundamental reason why a well-optimised hydrogen flame should produce more NOx than a natural gas flame with the same flame temperature?
- This led to the follow up question:
  - What are the fundamental combustion differences between natural gas and hydrogen?
- A committee of specialists was formed to address these questions and their implications for gas turbine operation
- A paper outlining the findings is in the final stages of preparation

# $NO_x$ emissions with $H_2$ and $CH_4$

- Comparing varying fuels:
- The high reactivity of the $H_2$ often leads to higher $NO_x$ emissions
  - Is it more difficult to burn $H_2$ ? Thermal $NO_x$, Mixing, residence time, …
  - Do we have the right emission developing targets ?

$$[NO]_{15\% O_2} = \frac{(21\% - 15\%)}{(21\% - [O_2])} \cdot [NO]_{abs}$$

$$\mathrm{EMI\_NO_x} = \frac{[\mathrm{NO_x}] \cdot \mathrm{M(NO_2)}}{\mathrm{kg(fuel)}} = \frac{\mathrm{g(NO_2)}}{\mathrm{kg(fuel)}}$$

$$\mathrm{EMI\_J\_NO_x} = \frac{[\mathrm{NO_x}] \cdot \mathrm{M(NO_2)}}{\mathrm{MJ(fuel)}} = \frac{\mathrm{g(NO_2)}}{\mathrm{MJ(fuel)}}$$

- Energy released per $O_2$ [kJ / mol]: > 20% higher $H_2$ for $CH_4$
  - →For given power less $O_2$ consumed

# Impact of hydrogen on emissions corrections

Combustion of 1 mole of methane:

- $CH_4$ + M(air) → $CO_2$ + $2H_2O$ + M(air) - $2O_2$ +$XNO_X$

Combustion of R moles of hydrogen will have same thermal energy as 1 mole of methane if:

- R = LCV($CH_4$)/LCV($H_2$) = 3.3194
- $RH_2$ + M(air) → $RH_2O$ + M(air) - $RO_2/2$ +$XNO_X$

➢ Combustion product compositions (assuming X is small)

| | $CH_4$ | $H_2$ |
|---|---|---|
| **Moles of products (wet)** | M+1 | M+R/2 |
| **Moles $H_2O$ in product** | 2 | R |
| **Moles of products (dry)** | M-1 | M-R/2 |
| **Moles $O_2$ in products** | 0.2089M-2 | 0.2089M-R/2 |
| **Moles of NOx in Products** | X | X |
| **Energy released per O2** | 401.4 kJ / mol | 483.7kJ / mol |

➢ Gives ratio of corrections for hydrogen to methane:

$$\frac{C_{H2}}{C_{CH4}} = \frac{\left[1-\frac{2}{(M+1)}\right]}{\left[1-\frac{R}{(M+R/2)}\right]} \frac{\left[0.2089-\frac{(0.2089M-2)}{(M-1)}\right]}{\left[0.2089-\frac{(0.2089M-R/2)}{(M-R/2)}\right]} \left[\frac{(M+1)}{(M+R/2)}\right]$$

Ratio of wet to dry corrections

Ratio of oxygen corrections

Hydrogen correction for raw concentration

For DLN-GT ~7% ~31% and ~ -3% → 36%

➢ Simplifies to: $\frac{C_{H2}}{C_{CH4}} = \frac{4.5281}{R} = 1.364$

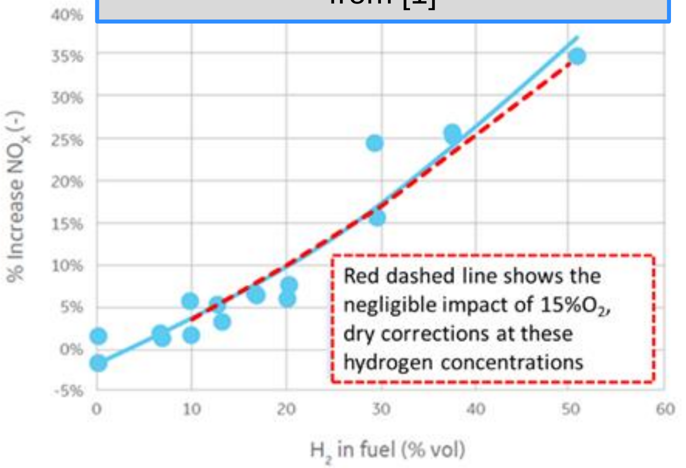
➢ NOx emissions corrected to 15%$O_2$, dry, results in emissions levels for hydrogen being 36.4% higher than for methane when the same number of moles of NOx are produced per unit of energy input

➢ Needs to be taken into account when assessing data and in allowable emissions levels

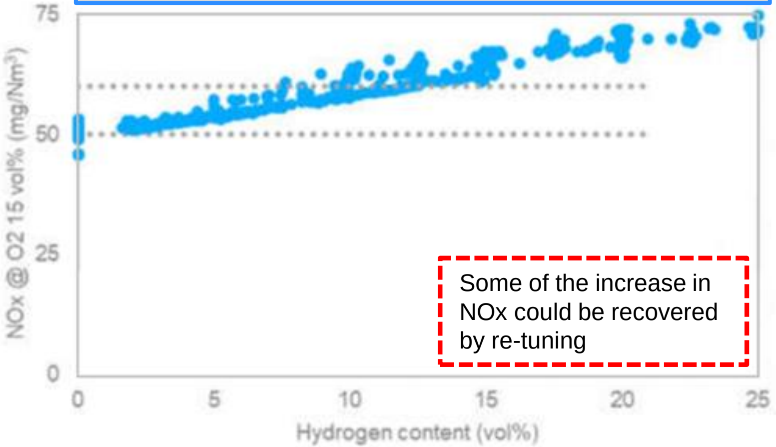
# Impact of hydrogen addition on NOx

## Measurements Practical GT Combustors

Rig tests on GE Combustors
from [1]



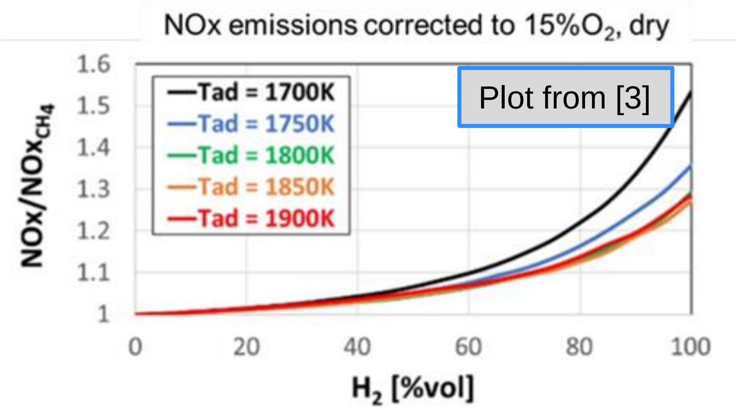

On-engine measurements Siemens SGT-600
from [2]

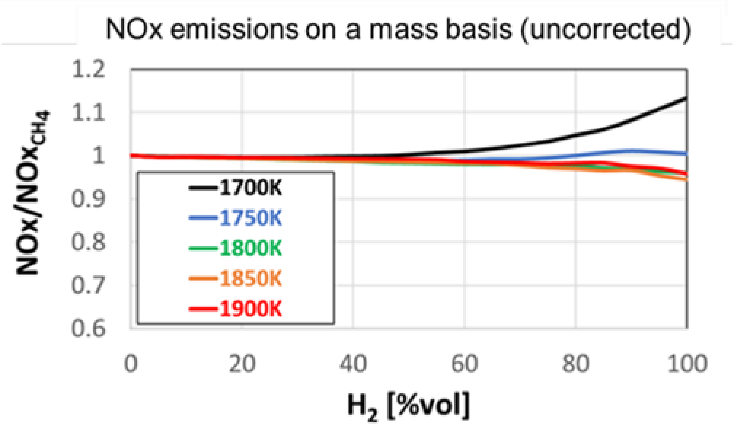



- Measurements on current gas turbine combustors indicate a significant increase in NOx as hydrogen is added to natural gas

# Impact of hydrogen addition on NOx

NOx Emissions at various flame temperatures in a 1D unstretched laminar premixed flame normalized by NOx of a pure methane case calculated using the Glarborg mechanism. (Residence time = 15ms, pressure = 20bara, reactant temperature = 450 °C)

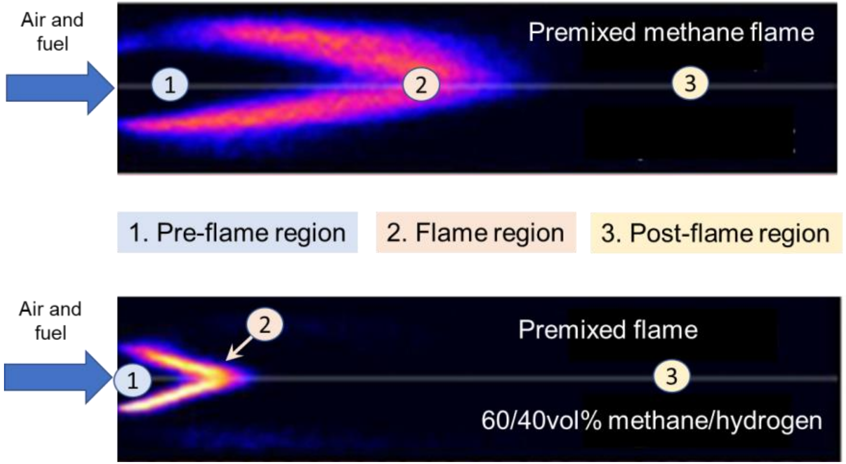



- Results quoted on a corrected basis appear to give a significant increase
- Results on a mass basis (uncorrected) show little or no increase depending on flame temperature
  - Temperatures above 1750K show a small decrease
  - Other studies (e.g. [4] also suggest a decrease)

# Why is NOx greater for a practical combustor?

- In a premixed flame, NOx depends on:
  - Chemical Kinetics
  - Flame location
  - Unmixedness of air fuel at flame front
  - Flame residence time
  - Post flame residence time




Flame images from [5]

- Adding hydrogen:
  - Affects fuel/air momentum and thus fuel placement and mixing
  - Higher reactivity increases flame speed, moves flame upstream, reducing mixing time and increasing unmixedness
  - Higher reactivity reduces flame residence time which could reduce NOx generation within the flame
  - Post flame residence time increases, negating benefit of lower flame residence time

# $NO_x$ emission target - summary

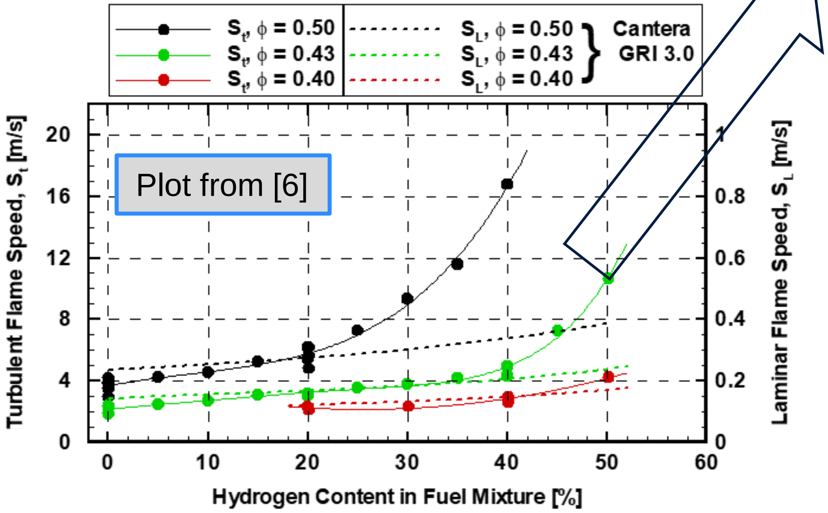
1. Yes. It is more difficult to operate $H_2$ in DLN Premix mode compared to $CH_4$
2. The $NO_x$ calibration account for up to 36% at pure $H_2$
3. Chemistry changes but does not cause a $NO_x$ increase
4. The flame physics (reactivity) is a challenge

# Reactivity, Flame Speed and Flashback

- Hydrogen increases reactivity
  - ➢ Increased flame speed
  - ➢ Change in flame position
  - ➢ Increased flashback risk
  - ➢ Change in thermoacoustic behaviour

In practical GT combustors flow is turbulent

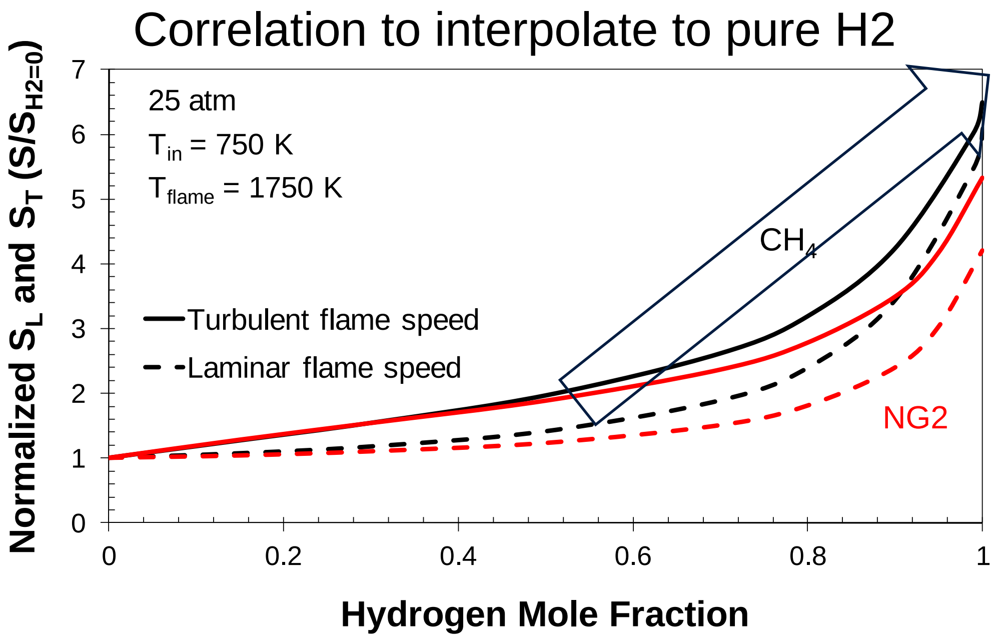
- Turbulent flame speed is related to laminar flame speed, but:
  - Measurements show greater impact of hydrogen on turbulent flame speed
  - This shows that kinetics is not the only impact
  - Other physical properties such as diffusivity also have an impact




Increased reactivity is a major concern when firing hydrogen or hydrogen containing fuels

# Turbulent Flame Speed correlation

## $H_2$ addition at constant inlet and flame temperatures




$S_T$ increases more at lower $H_2$ content than $S_L$

# Combustion technologies for hydrogen

- To cover the full range of hydrogen content from 0 to 100% likely to need
  - Redesign of combustion systems
  - Development of new combustion technologies
  - Development of automatic tuning systems taking into account hydrogen content
  - Use of exhaust cleaning systems (e.g. SCR) for lowest NOx

- A overview of some potential combustion technologies is given on the next two slides

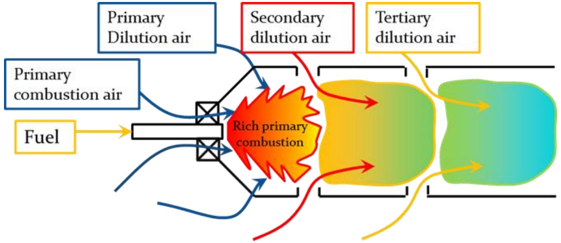
# Combustion technologies for hydrogen (1)

**Conventional or diffusion combustor**

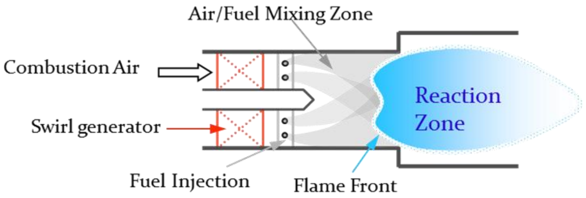
- Robust, stable and fuel flexible: capable of burning high hydrogen fuels
- High NOx unless diluent injection such as water or steam is used
- Main technology offered today for 100% hydrogen combustion.

**Lean premixed combustors**

- Dominant technology for natural gas combustion.
- Low NOx firing natural gas
- Issues with thermoacoustics
- Flashback risk with high reactivity fuels such as hydrogen
- Allowable hydrogen concentration depends on design details
- Unlikely that current systems can fire high hydrogen concentrations without re-design.




Diffusion




Lean Premixed

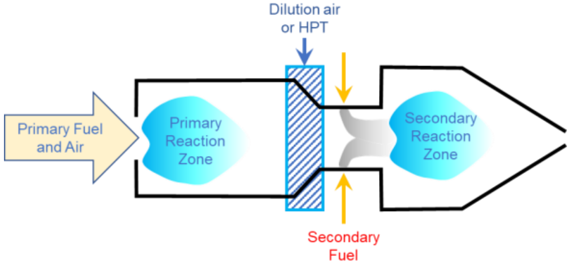
# Combustion technologies for hydrogen (2)

**Sequential combustion**

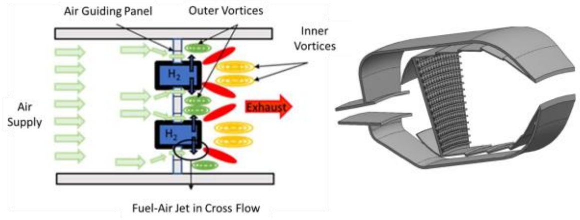
- Different fuel stages arranged axially
- Used to reduce initial flame temperature to reduce NOx improves fuel flexibility

**Micro-injection combustors**

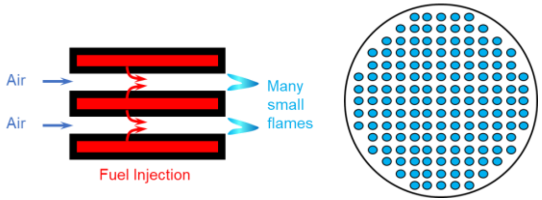
- Many small flames
- Low NOx due to the short residence
- Diffusion-based and premixed-based concepts are under development
- The term “micromix” sometimes used to refer to both concepts




Sequential




Micro-diffusion

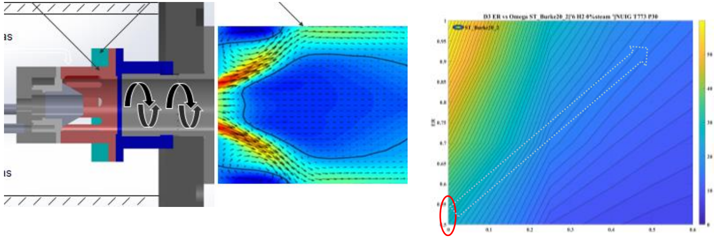



Micro-premix

# Combustion technologies for hydrogen (3)

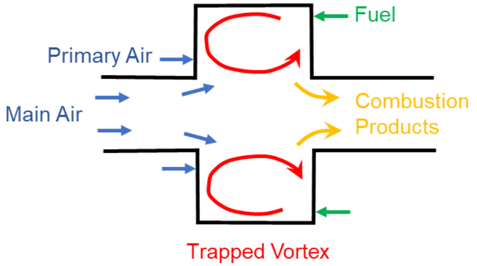
**MILD combustion or Flameless oxidation**

- Uses highly diluted oxygen depleted oxidiser instead of air
- Reactant temperature high, peak flame temperature relatively modest
- Leads to low NOx formation and reduced flashback risk
- Dilution and oxygen depletion achieved in a number of ways including exhaust gas recirculation and humid air cycles



**Trapped vortex combustors**

- Utilises a vortex typically trapped within a cavity
- Fuel is injected into the trapped vortex
- Efficient and rapid mixing of reactants and recirculated combustion products
- Combustion conditions typical of flameless oxidation




Trapped vortex

# Summary of Conclusions and Recommendations

- Emissions standards and legislation

Hydrogen is disadvantaged by NOx emissions in mg/m$^3$ or ppmv corrected to dry, 15% $O_2$:

  - Requirements should be on a mass production of NOx basis per unit of fuel energy used (e.g. mg/MJ) or allowance made if corrected values are retained
  - No kinetic reason why $H_2$ should produce more NOx than NG, but other processes need optimisation

- Key areas for R&D

High reactivity of hydrogen and its impact on combustion behaviour including flame position/flashback, thermoacoustics and NOx emissions will require research into:

  - Development and validation of tools and methods
  - Fundamental processes
  - Refinement of existing technologies and development of new concepts
  - Practical demonstrations and field trials
  - Supporting technologies: cooling, materials, safety, acoustic treatments, controls, flue gas treatments…

- Infrastructure development and RD&D

To be able to focus research on appropriate issues and to ensure hydrogen is available for large scale testing:

  - Clarity needed regarding future strategies on blending, storage and hydrogen production

# References


[1] Hydrogen for power generation: Experience, requirements, and implications for use in gas turbines, GE document GEA34850

[2] Laget et al, DEMONSTRATION OF NATURAL GAS AND HYDROGEN CO-COMBUSTION IN AN INDUSTRIAL GAS TURBINE, Proceedings of ASME Turbo Expo 2022, Turbomachinery Technical Conference and Exposition, GT2022, June 13-17, 2022, Rotterdam, The Netherlands, Paper: GT2022-80924

[3] Ciani et al, HYDROGEN BLENDING INTO ANSALDO ENERGIA AE94.3A GAS TURBINE: HIGH PRESSURE TESTS, FIELD EXPERIENCE AND MODELLING CONSIDERATIONS, Proceedings of ASME Turbo Expo 2021, Turbomachinery Technical Conference and Exposition, GT2021, June 7-11, 2021, Virtual, Online, Paper: GT2021-58650

[4] Breer et al NOx Production from Hydrogen-Methane Blends, Spring Technical Meeting, Eastern States Section of the Combustion Institute, March 6-9, 2022, Orlando, Florida.

[5] Muppala et al, COMPARATIVE STUDY OF DIFFERENT REACTION MODELS FOR TURBULENT METHANE/HYDROGEN/AIR COMBUSTION, Journal of Thermal Engineering, Volume 1, Issue 5, Pages 367 - 3801, February 2015

[6] Boschek et al, FUEL VARIABILITY EFFECTS ON TURBULENT, LEAN PREMIXED FLAMES AT HIGH PRESSURES, Proceedings of GT2007, ASME Turbo Expo 2007, Paper GT2007-27496

*Power generation gas turbine will play a role in the transition to a low carbon future, but combustion developments are needed to ensure reliable and efficient operation with acceptable emissions.*

# Thank you for your attention

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