High hydrogen gas turbine retrofit to enable a low carbon reliable electricity system

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March 2022

The hydrogen gas turbine gets a lot of attention, mainly a hype or what will its role be in the energy transition ????

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...ants 'will play ...rgy transition'

...H2 for elec... ...gy and Equinor tell R...

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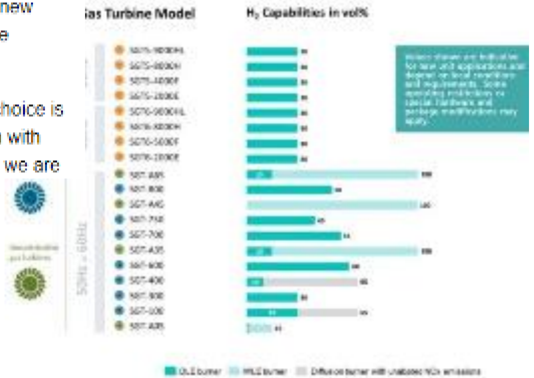
Man... countries' energy supp... resources to their electricity mix, and de... other fossil-fueled power plants. Yet, these a... options. Research and development (R&D) efforts are also ... the use of hydrogen and energy storage, and advance new technolog... as carbon capture and artificial intelligence, in an effort to reduce carbon emissions.

"I think there is a clear sign right now that the world has made the choice, and the choice is clearly the zero-CO_2 emission," Karim Amin, executive vice president of Generation with Siemens Energy, said as a guest on *The POWER Podcast*. "So, that's a given, and we are



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Future-proofing gas power

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Why Hydrogen in gas turbines ?

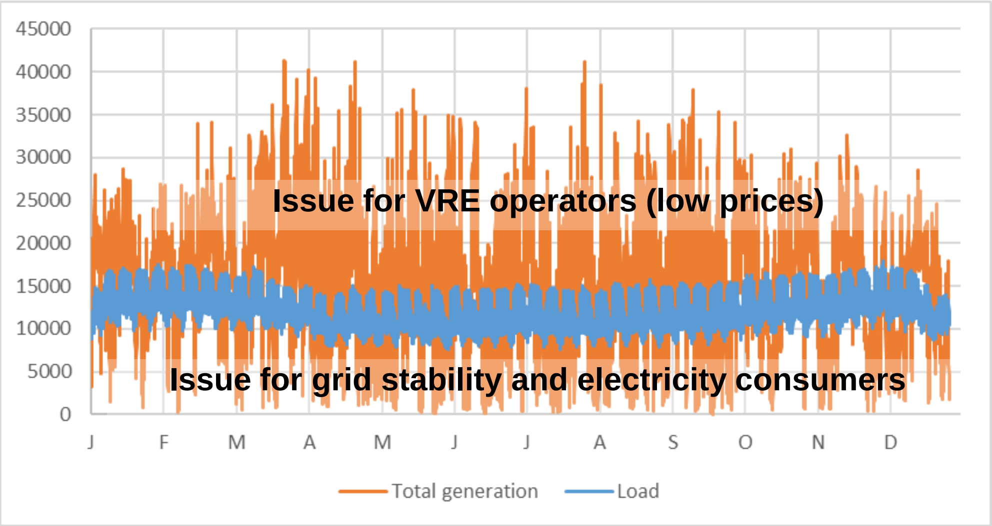
H_2

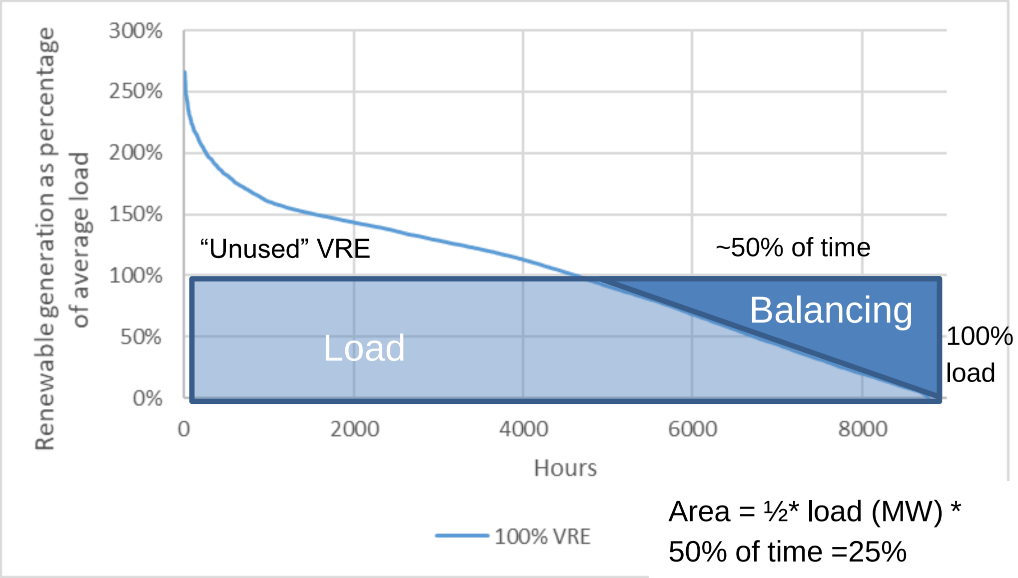
~~CO_2~~

Green hydrogen : no CO_2

Electricity supply
Assume a fossil free electricity system ….

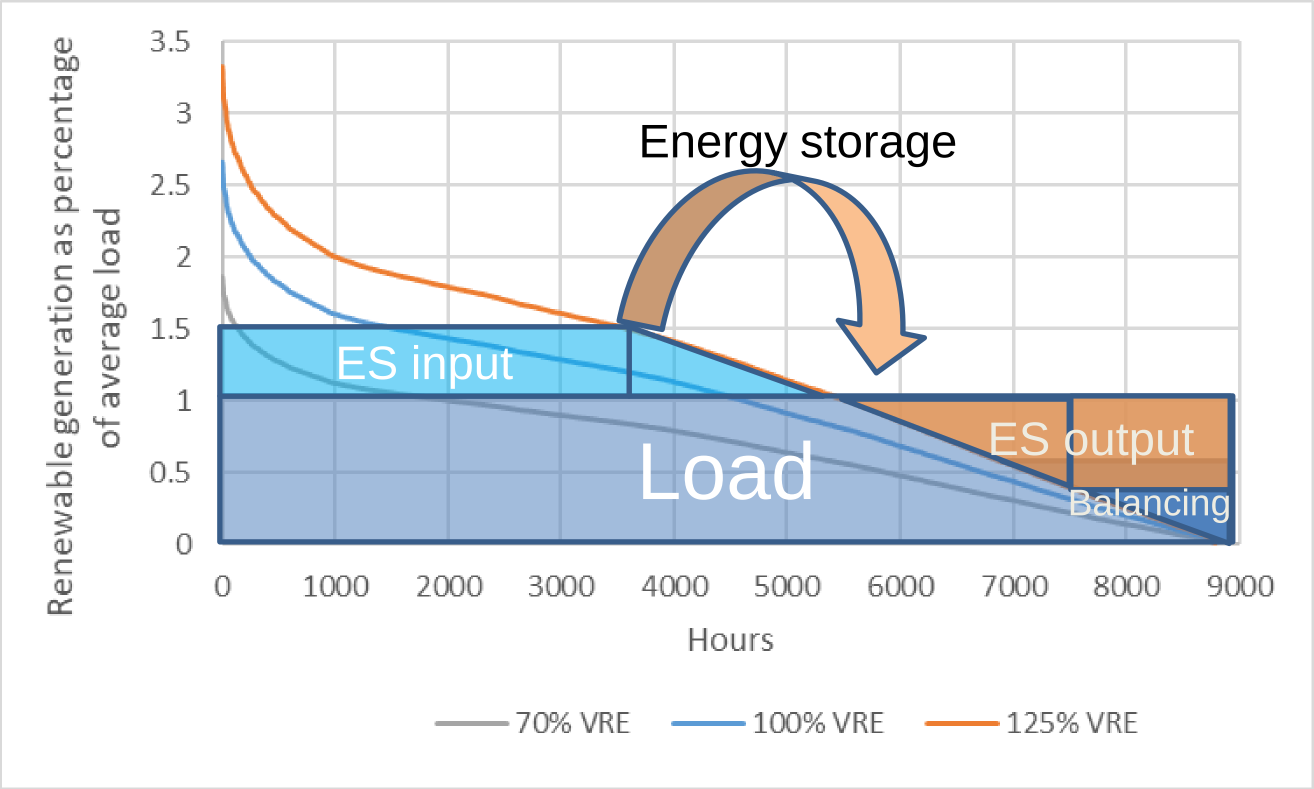
- Generation by Variable Renewable Energy (VRE): solar, wind on shore and wind off shore
- Balancing of supply and demand required: ~ 25% of (non flexible) load





Area = ½* load (MW) * 50% of time =25%

Utilization of excess Variable Renewable Energy for balancing



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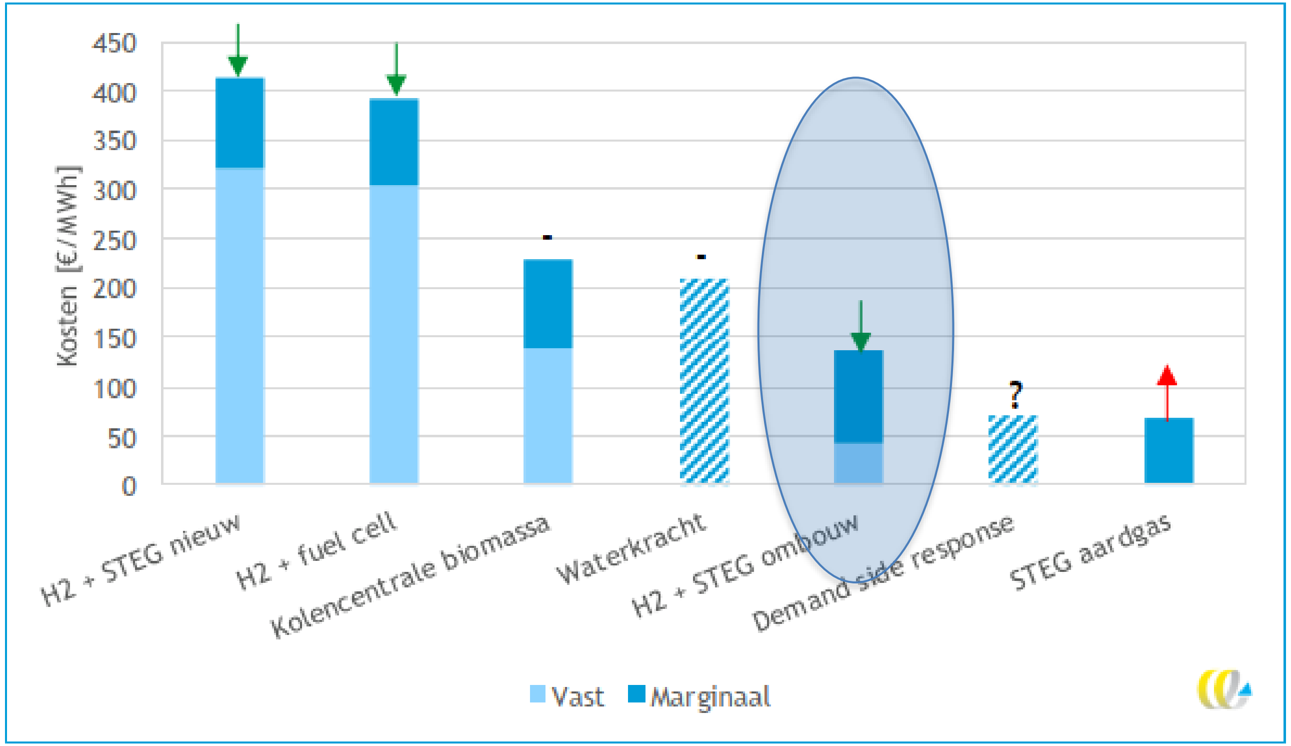
2020 CE Delft Study shows that H_2 in retrofit gas turbine power plant is attractive for balancing

Figuur 5 - Marginale en vaste kosten in 2030 van technieken om tekorten aan te vullen



CE Delft, Verkenning ontwikkeling CO2-vrije flexibele energietechnieken, Publicatienummer: 20.190402.041 , 2020

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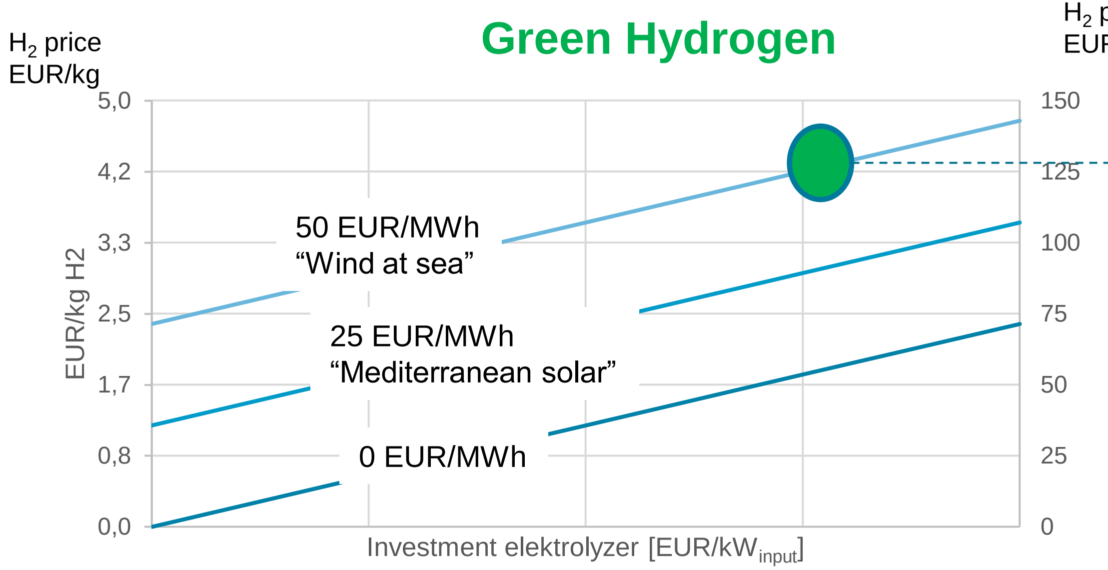
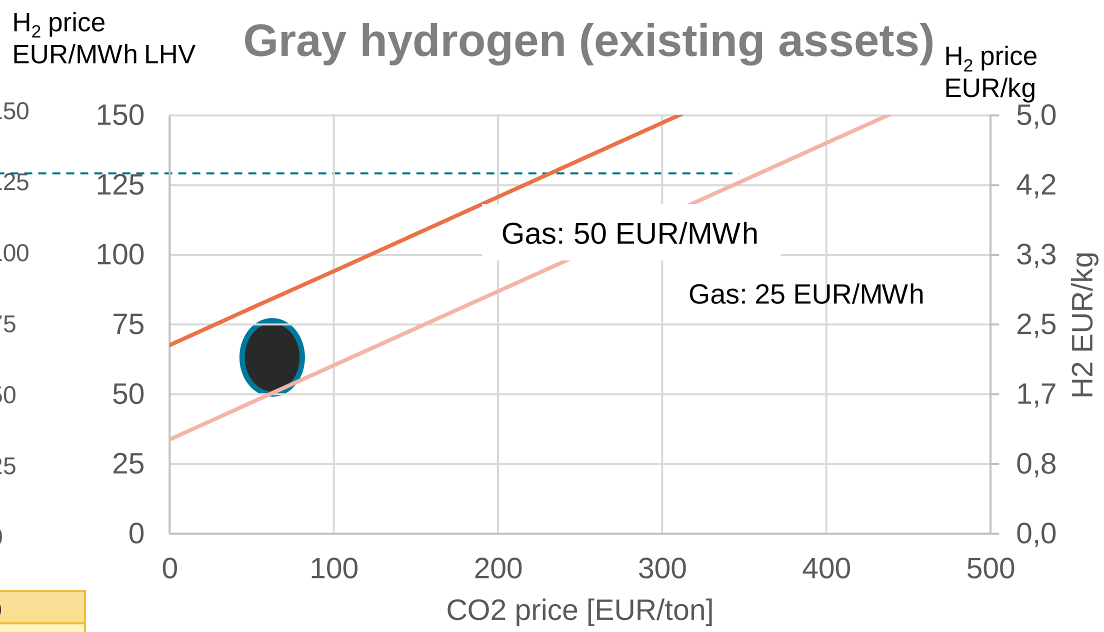
Hydrogen is however not cheap



@6000 hr/yr	0	750	1500	2250	3000
@4000 hr/yr	0	500	1000	**1500**	2000
@2000 hr/yr	0	250	500	750	1000

power 0 EUR/MWh power 25 EUR/MWh power: 50 EUR/MWh



Gas: 25 EUR/MWh Gas: 50 EUR/MWh]

Green H_2: investment, annual operational hours & costs of renewable power

Gray H_2: gas & CO_2

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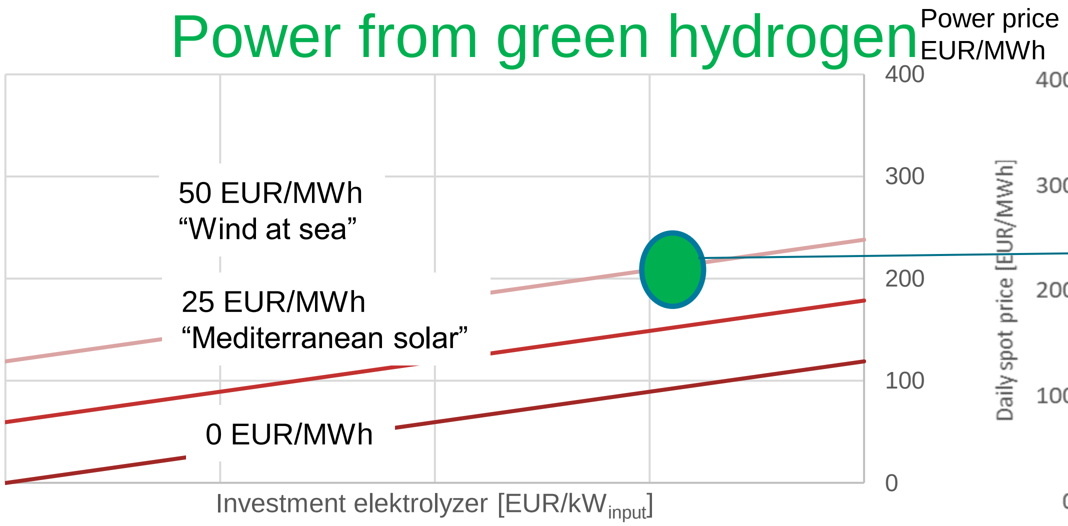
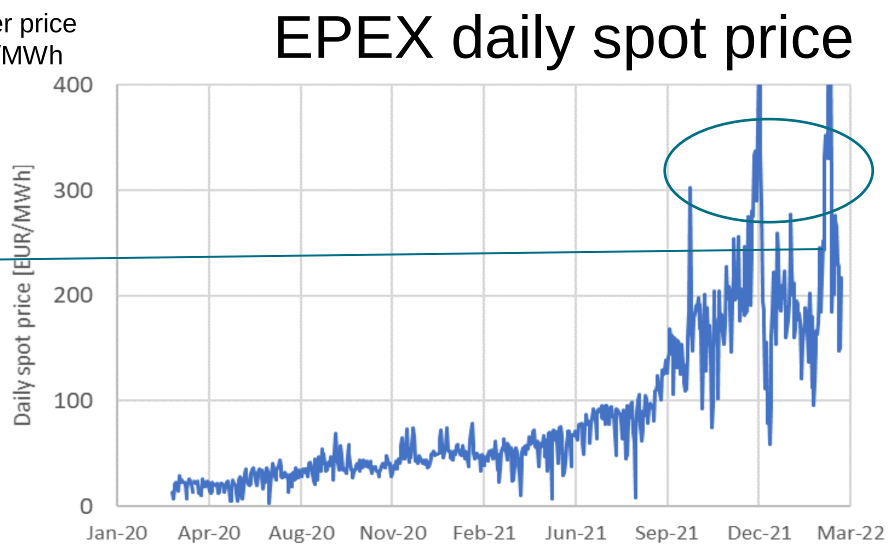
Simplified business cases: Green H_2: annual costs : 10% of CAPEX + average power costs (70% LHV efficiency)
Gray H_2: only commodity gas & CO_2 (81% LHV efficiency)
Both cases: transport & storage excluded

Power from hydrogen is even more expensive





@6000 hr/yr	0	750	1500	2250	3000
@4000 hr/yr	0	500	1000	1500	2000
@2000 hr/yr	0	250	500	750	1000

input power: 0 EUR/MWh — input power:25 EUR/MWh — input power 50 EUR/MWh

Current (extreme) price levels could match hydrogen based power

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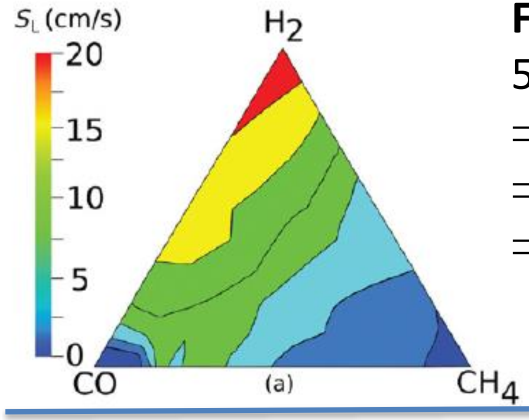
60% H_2 to power conversion

Challenges for hydrogen in gas turbines: flash back, emissions (NOx), dynamics and leakages

Flashback



Flame speed

5-10x natural gas

⇒ Burner flash back

⇒ Stability

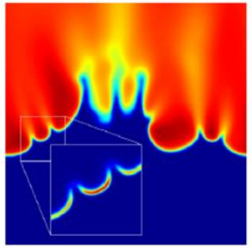
⇒ Dynamics

Lewis number << 1

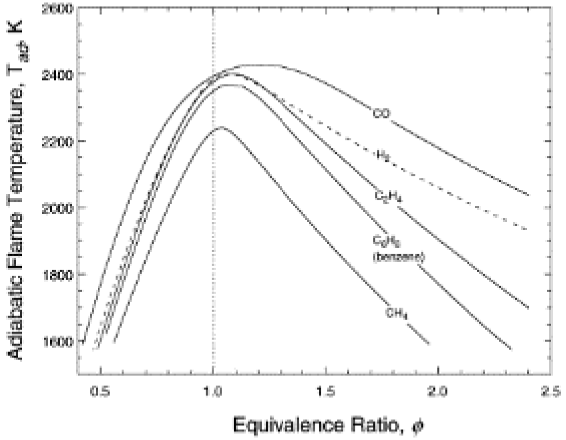
H_2 diffusivity >> thermal diffusivity

⇒ Increased flame speed at lean conditions

⇒ Stability, dynamics



NOx



Stoich. Flame temperature:

400K above natural gas

=> High NOx with non-premixed combustion

Diffusivity

3-4x higher than natural

⇒ Leakages valves and supply

⇒ Preferential diffusion

Substance	Symbol	Diffusivity (cm²/sec)
Flame gases (average effective value)	α	0.55
Oxygen	D_{O_2}	0.43
Methane	D_{CH_4}	0.47
Ethane	$D_{C_2H_6}$	0.30
Propane	$D_{C_3H_8}$	0.25
Butane	$D_{C_4H_{10}}$	0.22
Hexane	$D_{C_6H_{14}}$	0.18
Heptane	$D_{C_7H_{16}}$	0.17
Octane	$D_{C_8H_{18}}$	0.16
Decane	$D_{C_{10}H_{22}}$	0.15
C_nH_{2n+2} ($n \rightarrow \infty$)	$D_{M\rightarrow\infty}$	0
Hydrogen	D_{H_2}	1.86
Deuterium	D_{D_2}	1.32

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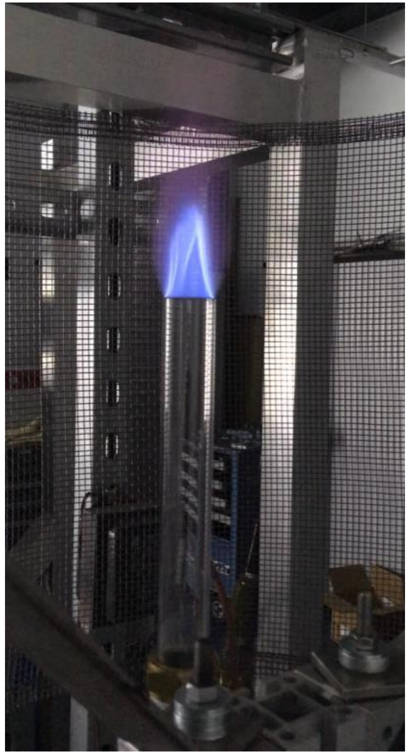
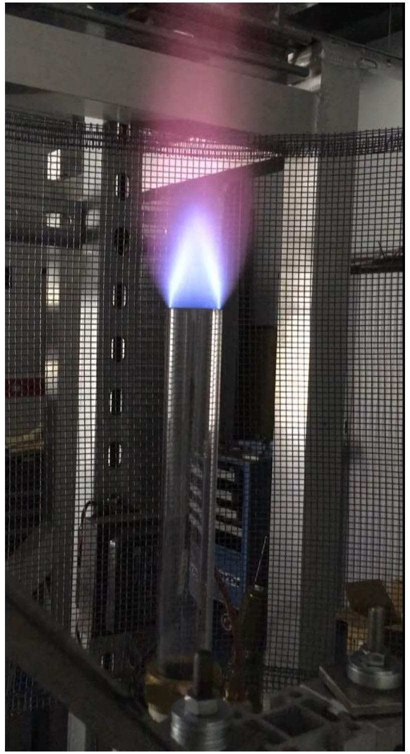
How does flashback look like?



Natural gas



Hydrogen

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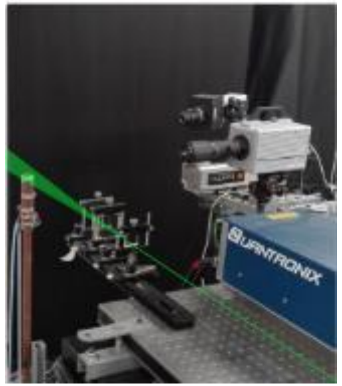
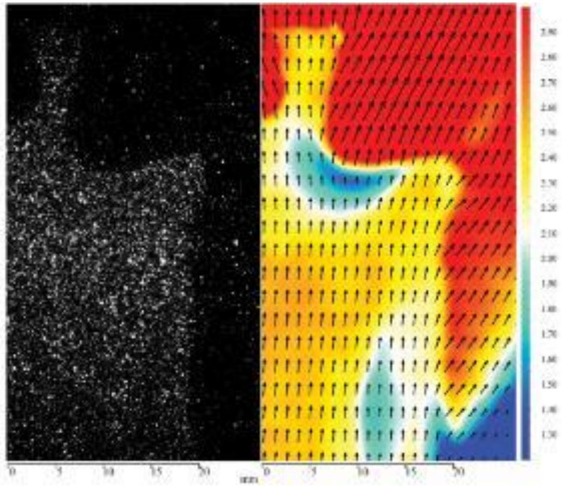
TU Delft H2 Combustion & Flashback research

Experimental

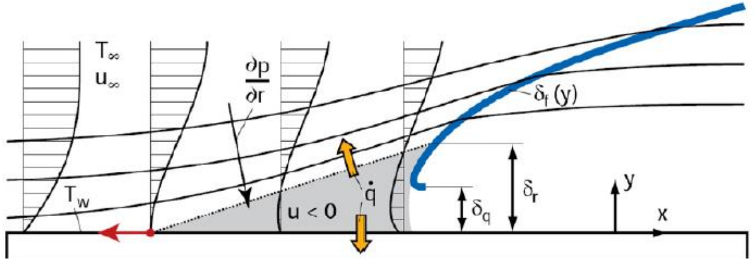




GT combustor set up

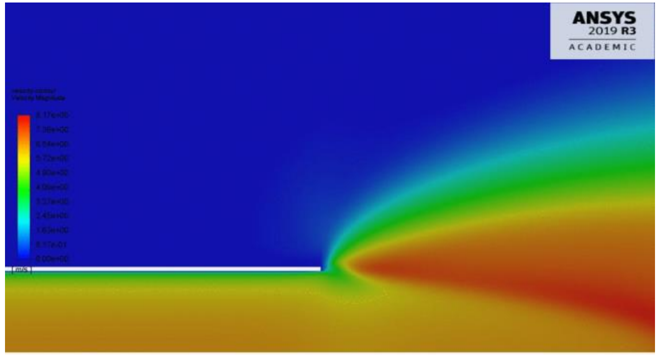
Advanced laser diagnostics

Theoretical/Modelling



$$C_p^{\frac{1}{4}(n-2)}\left(\delta\frac{dC_p}{dx}\right)^{\frac{1}{2}} = \left(\frac{3(0.41\beta)^4}{(n+1)n^2}\right)^{\frac{1}{4}}\left(1-\frac{3}{n+1}\right)^{\frac{1}{4}(n-2)}$$

Boundary layer flashback model



Transient CFD

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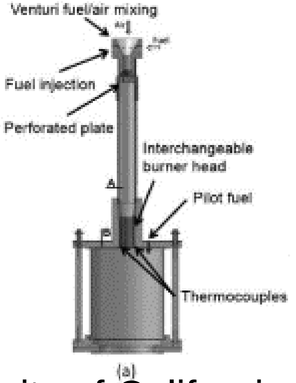
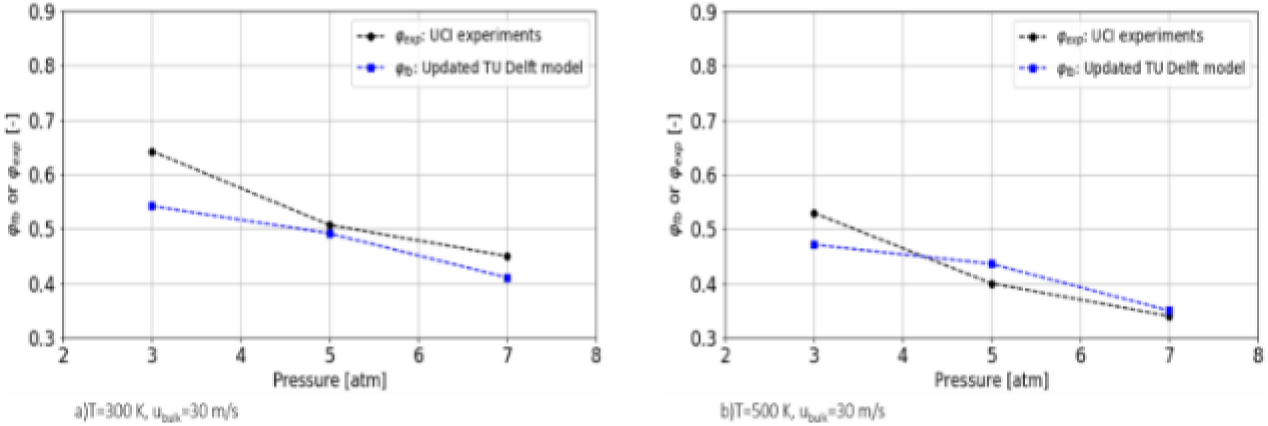
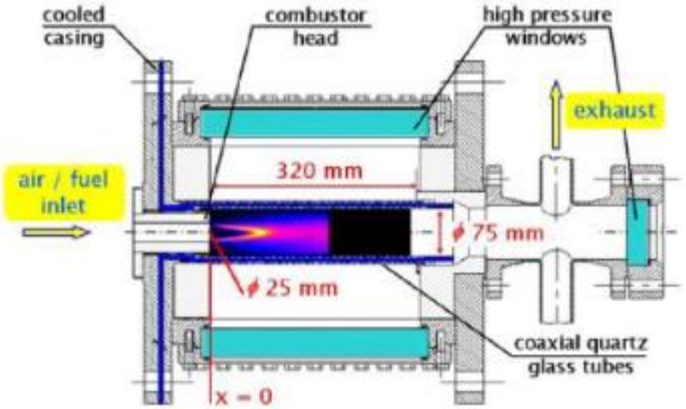
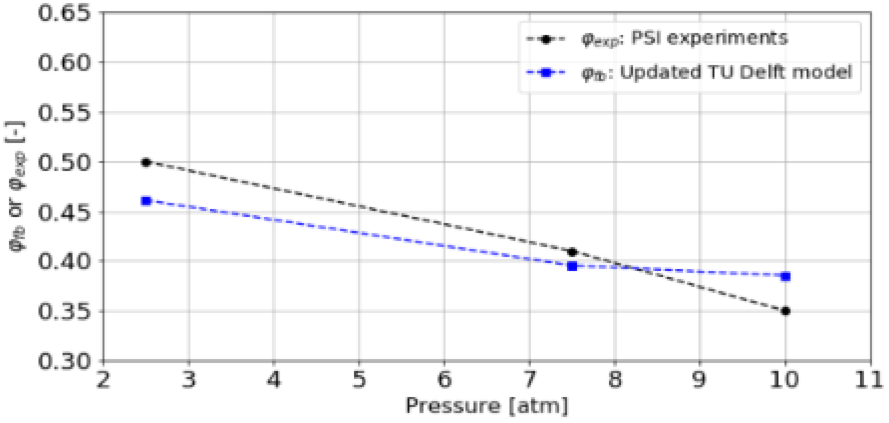
TU Delft BLF model performs well on gas turbine relevant geometries and configurations



University of California, Irvine
Kalantari et al. (2016)





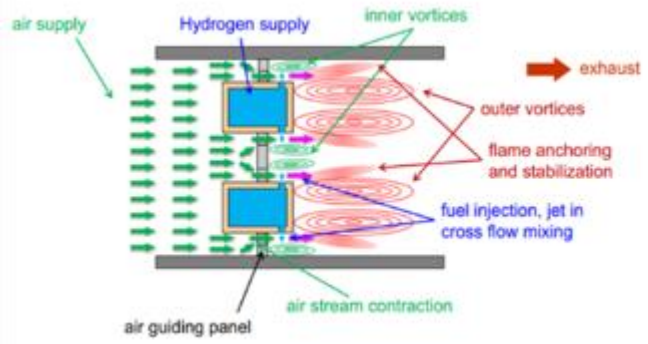


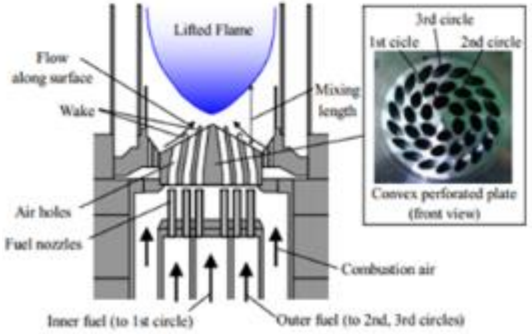
Paul Scheerer Institute
Lin, Daniele, Jahnson et al (2012)

Combustor designs under development for high hydrogen in gas turbines

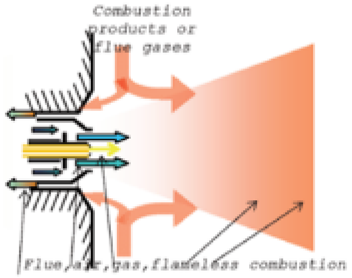
Non premixed combustion => high NOx

(reduction of NOx: flame temperature/residence time)

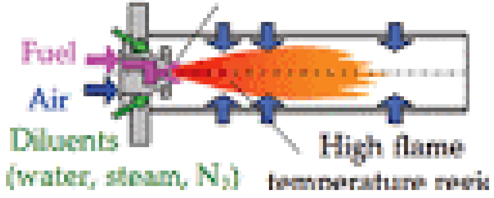




MicroMixing - Small diffusion flames



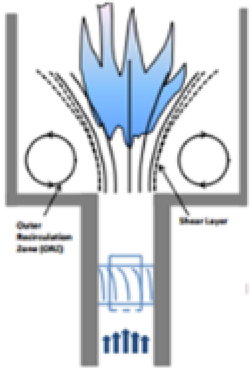
FLOX



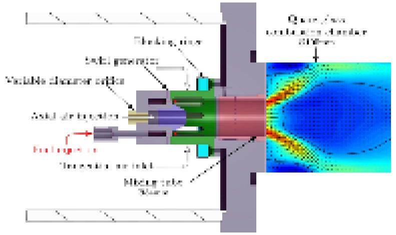
Steam injection

Premixed combustion => low NOx

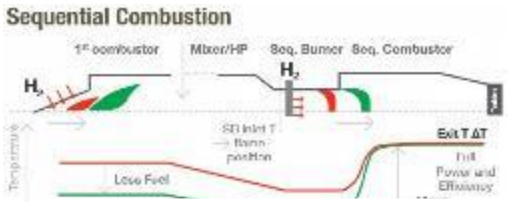
(flashback prevention)



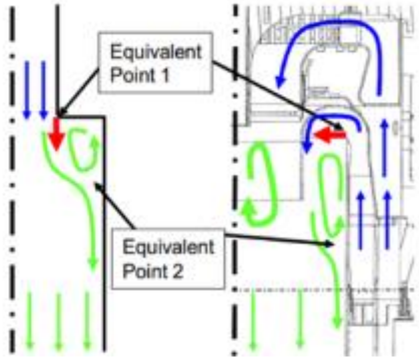
Low Swirl



High swirl + axial injection



Sequential combustion



Trapped vortex

Axial staged combustion

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Summary
TU Delft H_2 combustion research

Hydrogen in power plants

- Retrofit of existing power plants : zero carbon balancing
- Hydrogen combustion much more challenging than natural gas:
  - NOx, flame speed, diffusivity, ….
- 100% H_2 application in gas turbine not commercially available yet => demonstrations needed

TU Delft research

- TU Delft flash back model performs well for flash back prediction and is used in burner development
- Further research required on fundamentals, active instability control and applications
- TUDelft H2seminar:https://www.youtube.com/watch?v=3pfK1ZEeGEg

TU Delft

High hydrogen gas turbine retrofit to enable a low carbon reliable electricity system

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a Hanwha company

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Thomassen Energy

March 2022

Gas Turbine Services – Thomassen Energy / PSM

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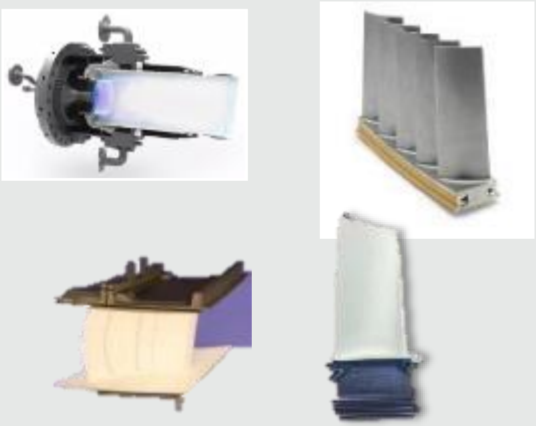
7F: 170 - 190 MW

501F: 175 - 200 MW

7E: 75 - 85 MW

Global M&D w/with Digital and Service Engineering

Upgraded Components



Repair

Field Service

9F: 230 - 245 MW

6B: 35 - 45 MW
Fr5: 20 - 28 MW

9E: 120 - 130 MW

Service with Innovation

Hanwha's Vision – Key Cornerstones

Thomassen Energy
a Hanwha company

"Transition to Low Carbon Economy"

Path to Carbon Neutrality

Growth of Renewables + *De*-Carbonization of Conventional Generation

Renewable Power Plants				H2 Infrastructure				Gas Power Plants		
Solar panel supply	Solar plant assets	ESS	Retail services	Production: Green	Production: Others	Storage	Distribu-tion	Gas plant assets	Retrofit/ H2 conversion	GT Services

Hanwha's current footprint → **Current & Future business expansion** ← **PSM/Thomassen Energy current footprint**

H2 Capabilities Under Development

Electrolysis	Ammonia	Storage	Equipment
Hanwha Chemical	Hanwha Corporation	Hanwha Solutions Advanced Materials	Hanwha Power Systems

"Renew, Revitalize, Repurpose and Reset" and *Decarbonize* the Installed Gas Turbine Fleet!

Filling The Renewable Gap

- The Gas Turbine Advantage

- Flexible fast load coverage
- Cleanest of the fossil fuels
- Ability to run on wide range of fuels,
  including green fuels such as **hydrogen**

- Excess renewable energy can be harvested, stored and released in gas turbines

- Existing gas turbine power plants available for retrofit with cost effective carbon free upgrades

- Ability to follow the transition to renewable World at a pace which is flexible and dependent on local & regional market drivers

H_2 =

Gas Turbines can meet the flexibility need … and go green

9E Hydrogen in Commercial Operation – Key Package Elements

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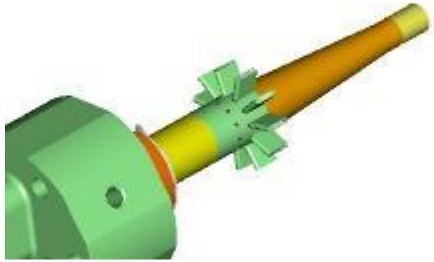
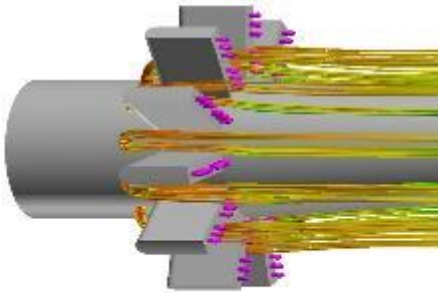
1. Fuel skid

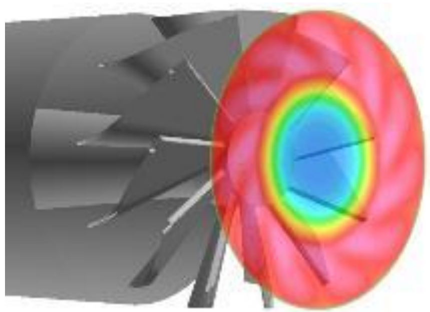
2. Control System / AutoTune

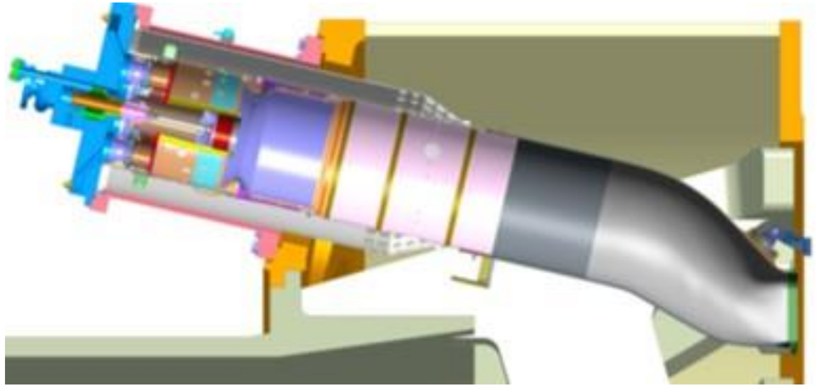
DOW Netherlands – 3 x 9E machines

3. Premix Combustion system (more than 100 natural gas E-class installations, 3 with H_2)









High hydrogen Secondary fuel nozzle upgrade

4 years stable and flexible sub-9ppm NOx Operation from 0% up to 35% Hydrogen

FlameSheet™ Commercial Machine Experience

Thomassen Energy
a Hanwha company

- **10** FlameSheet™ (7 FlameTOP) - enabled machines in operation, 6 years of experience
- Up to **20% additional load turndown** and **fuel flex** with **sub 9ppm NOx and CO**
- Hardware in excellent condition after 28,000 hours and 400 starts
- Up to **60% by vol H_2** F-class firing condition in test rig; up to 40% C2+'s*

FlameSheet™ Retrofit Enhances Operational and Fuel Flexibility

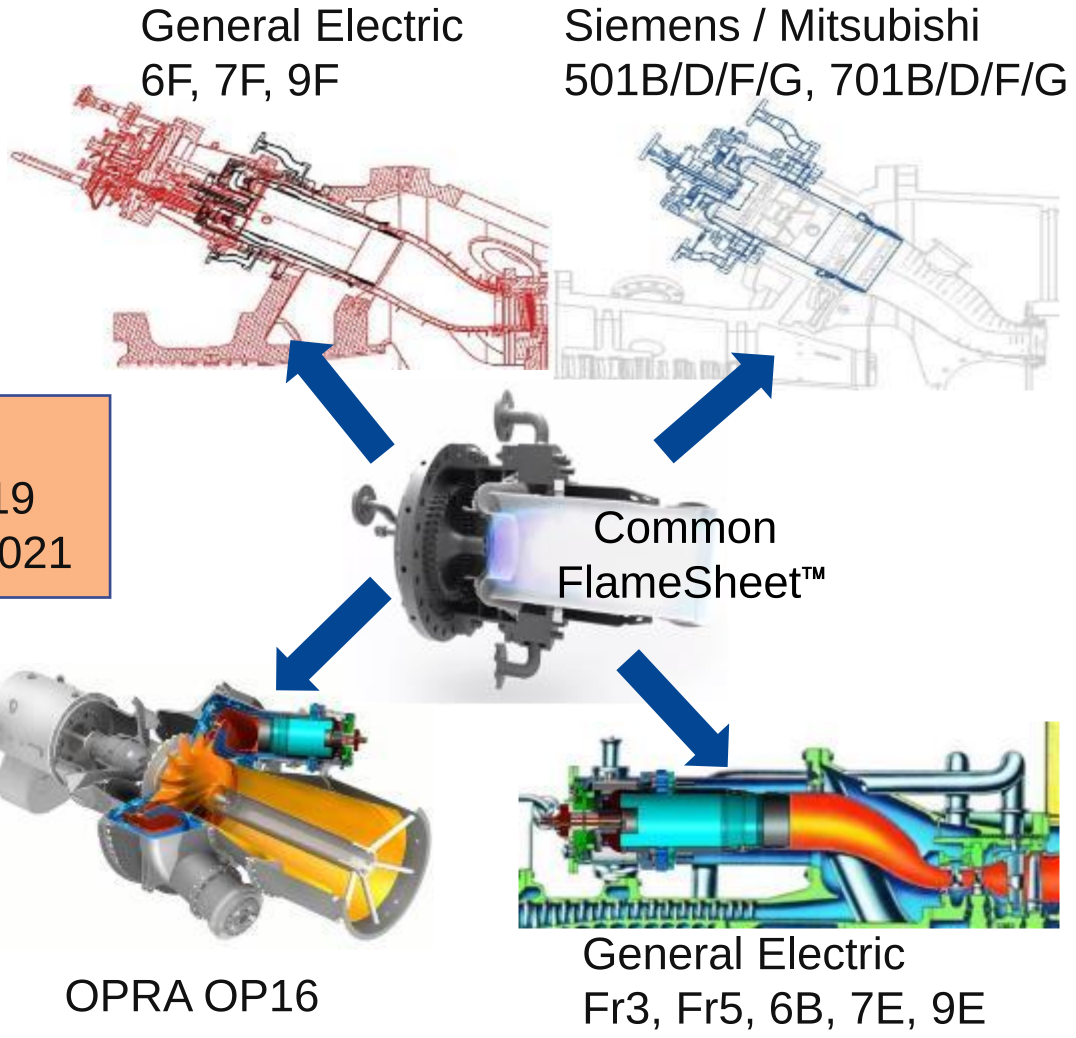
* Higher Hydrocarbon compositions

Thomassen Leading a Consortium for Hydrogen Retrofits

Objective:

- **Develop a low emission gas turbine combustor retrofit for fuel flexible operation from 100% Natural Gas to 100% Hydrogen and any mixture thereof**
- **Flexible fast load balancing capability**

Dutch subsidy awards won:
- Phase 1 awarded April 2019
- Phase 2 awarded March 2021



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NOBIAN A Nouryon company

PSM

ELEKTROCIEPŁOWNIA NOWA SARZYNA

EMMTEC

DOW

VATTENFALL

TU Delft

OPRA TURBINES

HYGEAR

DLR

TU/e Eindhoven University of Technology

1MW to 300MW with 0% to 100% Hydrogen with 1 Scalable Combustor Platform

High Hydrogen – High pressure rig testing

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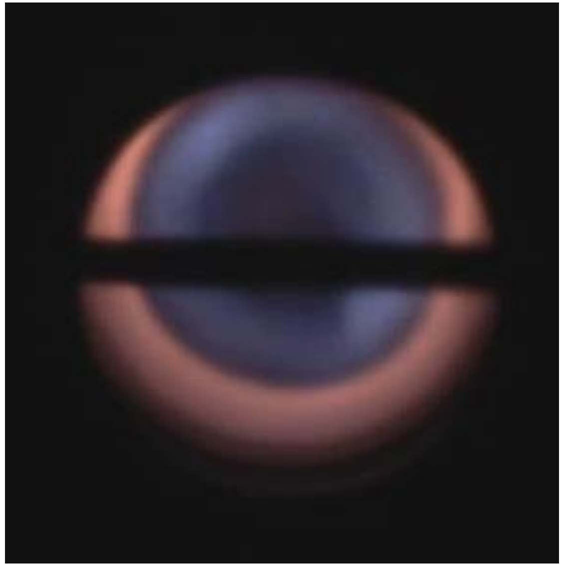
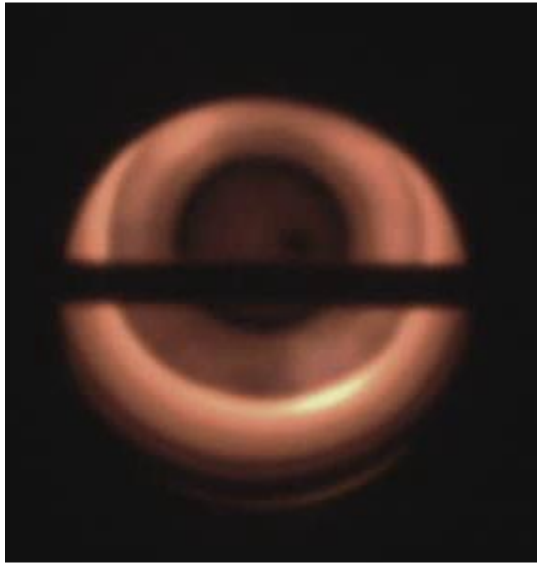


100% Natural Gas
OP16 Full Load
< 6 ppm NOx



100% Hydrogen
OP16 Full Load
< 10 ppm NOx

Operations from 100% natural gas to 100% hydrogen with dry low emissions

Carbon Free Value Chain Using Existing Gas Turbines

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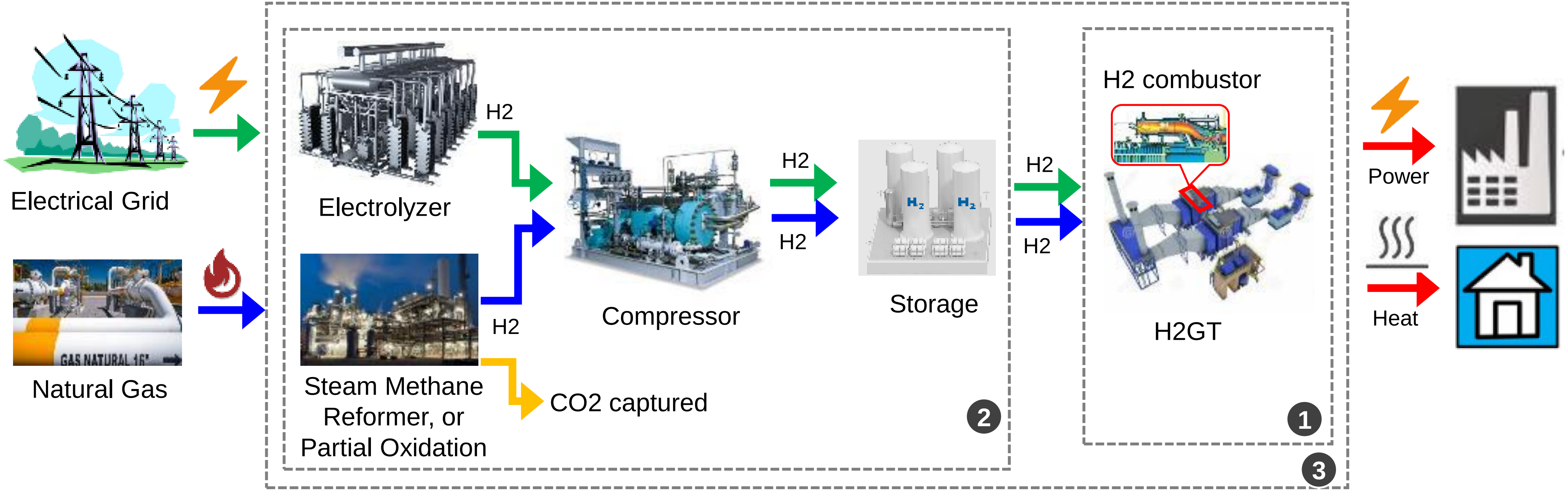
Hydrogen turbine, a reliable utility-scale power source, will play a crucial role in the decarbonization by utilizing hydrogen for gas turbine fuel



1. Co-development of H2GT retrofit projects
2. Co-development of H2 production/transport/storage projects
3. Co-investment on H2 production facility and hydrogen gas turbine

Solutions for the Energy Transition

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- The gas turbine advantage:
  - Rapid flexibility for power ***grid balancing***
  - Opportunity for ***clean energy storage*** with hydrogen

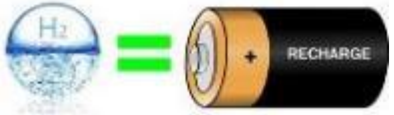
- Gas turbine retrofits for renewables maximize existing asset value, while supporting a demand far into the future

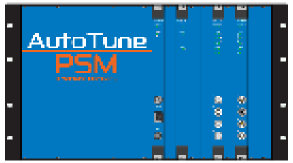
- 3+ years of commercial experience up to 35% H2

- 40%+ H2 – commercial operation in 2022

- First 0-100% hydrogen installations planned 2023/2024

- Partnership investment opportunities





High Hydrogen Combustion Retrofits for Carbon Free Power Generation and Energy Storage

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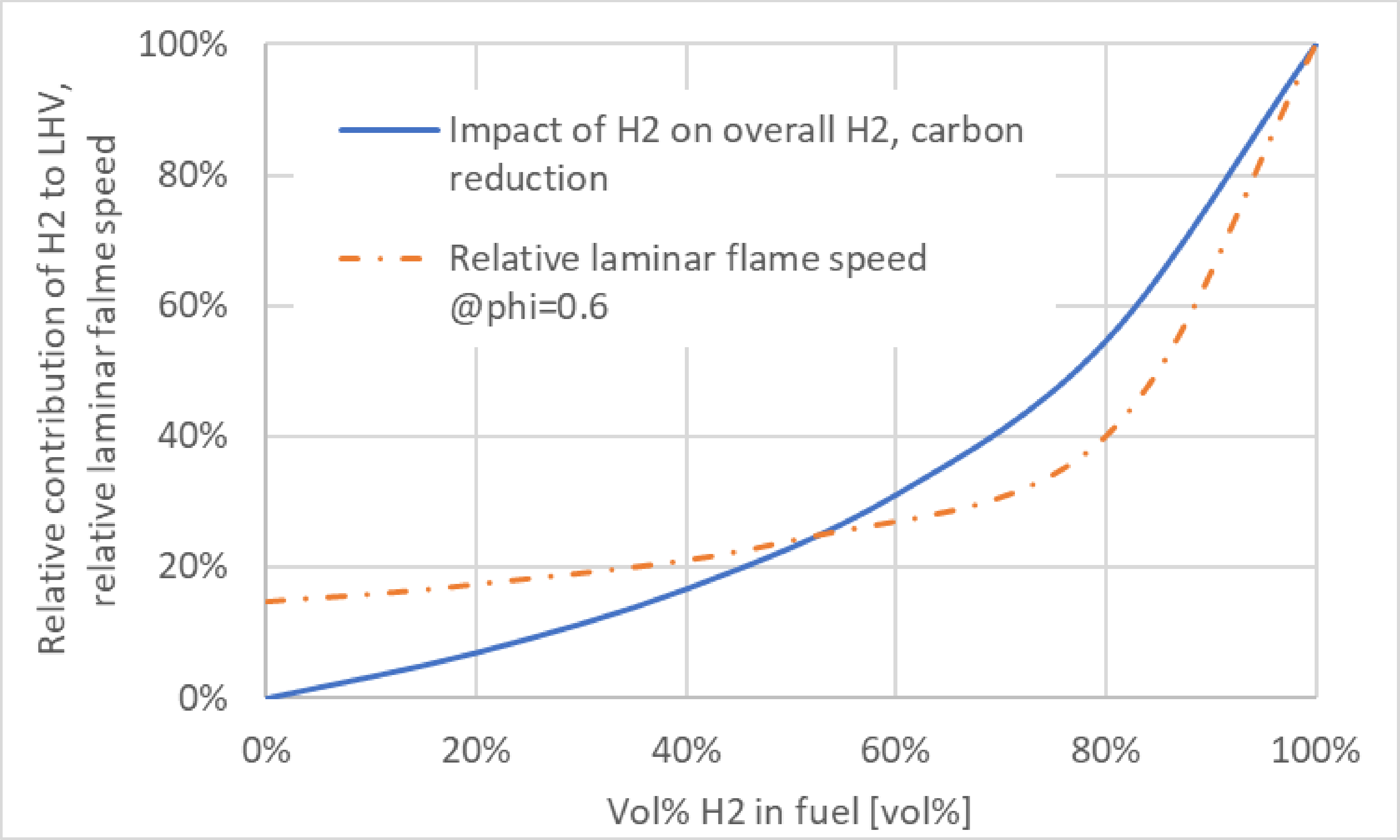
THANK YOU

DANK U WEL

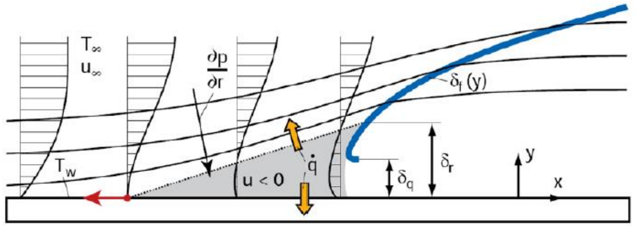
BACK UP

Main advantages & challenges for hydrogen at higher volume percentages



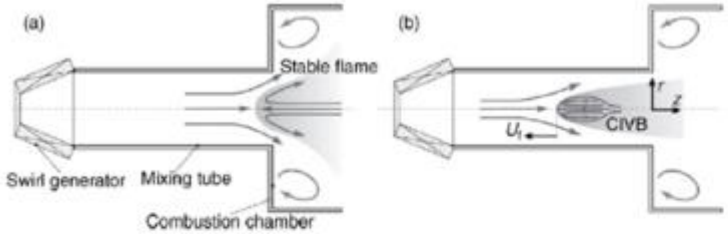
Flash back types for premixed H2 flames relevant for gas turbine applications

Confined



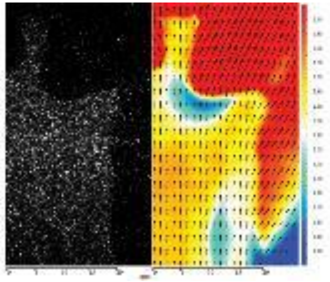
- Boundary layer instability by flame adverse pressure

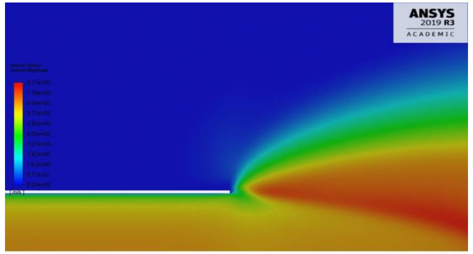
Swirl stabilized
(standard GT)



- Flow deceleration and movement of stagnation point recirculation zone by flame adverse pressure

Unconfined
('jet' flame)





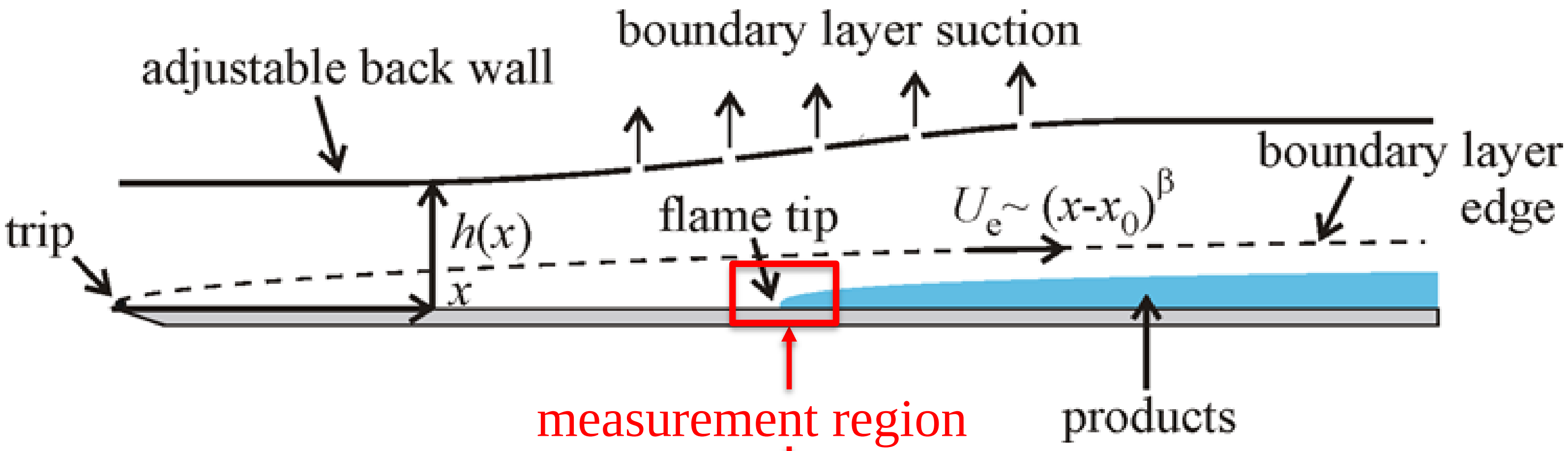
- Local (temporary) flame speed > local (temporary) velocity

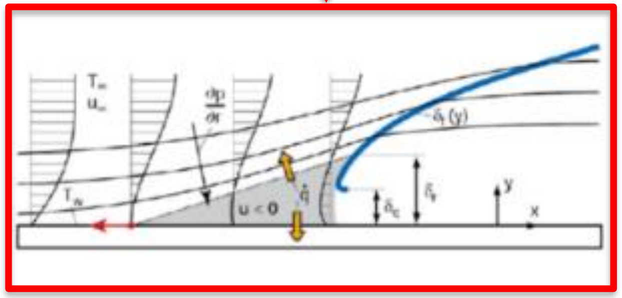
H_2:
- High flame speed
- Lewis number << 1: local enrichment => flame speed ⇧

Flame flashback in turbulent boundary layer on flat plate

Proposed new TTW proposal with TUe

Fully developed flow: e.g. long pipes or channels
Developing flow: e.g. boundary layer > complex, more relevant

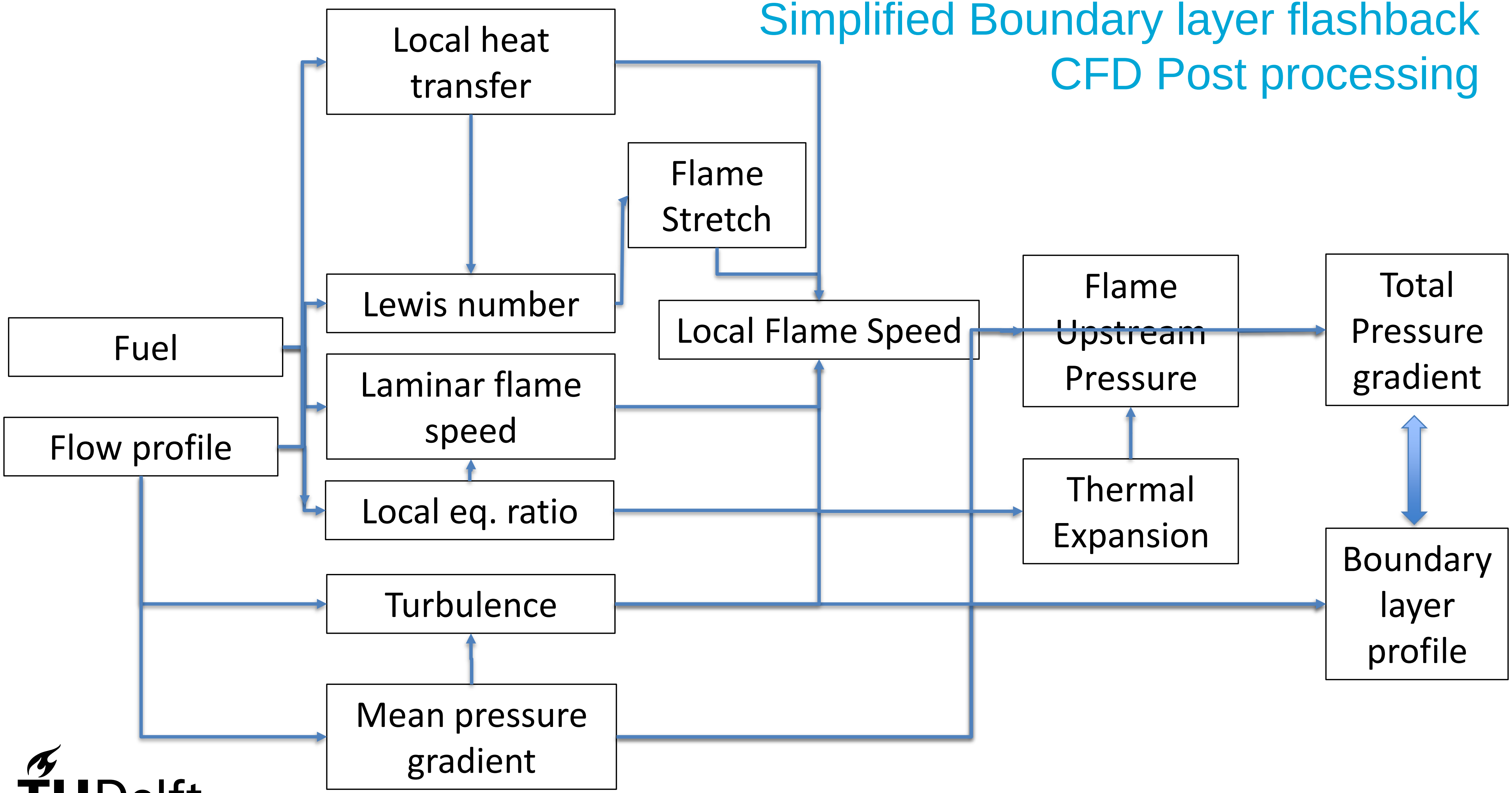




Detailed investigation of flame tip behaviour in near wall region

Optical measurement techniques:
PIV, LDA, CARS, PLIF

Simplified Boundary layer flashback CFD Post processing



TU Delft

Advertised maximum H_2 vol% for different gas turbine suppliers

		Frequency, Hz	Power Output, MW, Natural Gas, ISO Base Load	H2 Capability, Vol % DLE	WLE	Diffusion, unabated NOx
Heavy Duty	SGT5-9000HL	50	593	30	--	--
	SGT5-8000H	50	450	30	--	--
	SGT5-4000F	50	329	30	--	--
	SGT5-2000E	50	187	30	--	--
	SGT6-9000HL	60	405	30	--	--
	SGT6-8000H	60	310	30	--	--
	SGT-5000F	60	215 - 260	30	--	--
	SGT6-2000E	60	117	30	--	--
Industrial	SGT-800	50 or 60	48-57	60	--	--
	SGT-750	50 or 60	40/34 - 41	40	--	--
	SGT-700	50 or 60	33/34	66	--	--
	SGT-600	50 or 60	24/25	60	--	--
	SGT-400	50 or 60	10 - 14/11 - 15	10	--	65
	SGT-300	50 or 60	8/8	30	--	--
	SGT-100	50 or 60	5/6	30	--	65
Aero-derivative	SGT-A65	50 or 60	60 - 71/58 - 62	15	100	--
	SGT-A45	50 or 60	41 - 44	--	100	--
	SGT-A35	50 or 60	27 - 37/28 - 38	15	100	--
	SGT-A05	50 or 60	4/6	2	15	--

Siemens "Hydrogen Combustion in Siemens Gas Turbines: Sales Information v 3.0," July 2019

	Type	*Notes*	*TIT °C [°F] or Class*	*Max H_2 % (Vol)*
MHPS	Diffusion	N2 Dilution, Water/Steam Injection	1200~1400 [2192~2552]	100
	Pre-Mix (DLN)	Dry	1600 [2912]	30
	Multi-Cluster	Dry/Underdevelopment - Target 2024	1650 [3002]	100
GE	SN	Single Nozzle (Standard)	B,E Class	90-100
	MNQC	Multi-Nozzle Quiet Combustor w/ N2 or Steam	E,F Class	90-100
	DLN 1	Dry	B,E Class	33
	DLN 2.6+	Dry	F,HA Class	15
	DLN 2.6e	Micromixer	HA Class	50
Siemens	DLE	Dry	E Class	30
	DLE	Dry	F Class	30
	DLE	Dry	H Class	30
	DLE	Dry	HL Class	30
Ansaldo	Sequential	GT26	F Class	30
	Sequential	GT36	H Class	50
	ULE	Current Flamesheet™	F, G Class	40
	New ULE	Flamesheet™ -- Target 2023	Various	100

Emerson, B.E. et al., "Assessment of Current Capabilities and Near-Term Availability of Hydrogen-Fired Gas Turbines Considering a Low-Carbon Future", GT2020-15714

Some References TU Delft

Questions: s.a.klein@tudelft.nl

Link website: https://www.tudelft.nl/en/3me/about/departments/process-energy/people/gas-turbines/sikke-klein/

Some interesting MSc theses in the field of hydrogen

Boundary layer flashback prediction for low emissions full hydrogen gas turbine burners using flow simulation	Olafur Bjornsson	http://resolver.tudelft.nl/uuid:8272a27d-692d-4721-a24c-98ffd4c52511
HYDROGEN AND OXYGEN FIRED TURBINE CYCLE OPTIMIZATION	Bram Schouten	http://resolver.tudelft.nl/uuid:e0d209d5-1cba-4e4b-b2d8-4925b71502a5
Hydrogen flash back experiments	Filippo Faldella	http://resolver.tudelft.nl/uuid:ab0c472e-0dd1-4086-8eeb-18ef14ee226e
Modeling of hydrogen-elektrolysis-storage-utilization chain	Nick Kimman	http://resolver.tudelft.nl/uuid:46183251-f22a-42b5-a994-ed353d4338c0
Numerical modelling of flame flashback in premixed tube burners with turbulent flow and high hydrogen content	Max van Put	http://resolver.tudelft.nl/uuid:84b5e88d-72b8-4663-a597-84993aa347f7

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