Cardiff University
Prifysgol Caerdydd

CEAT
Centre of Excellence
on Ammonia Technologies

Ammonia for Power

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Cardiff University Press | Gwasg Prifysgol Caerdydd

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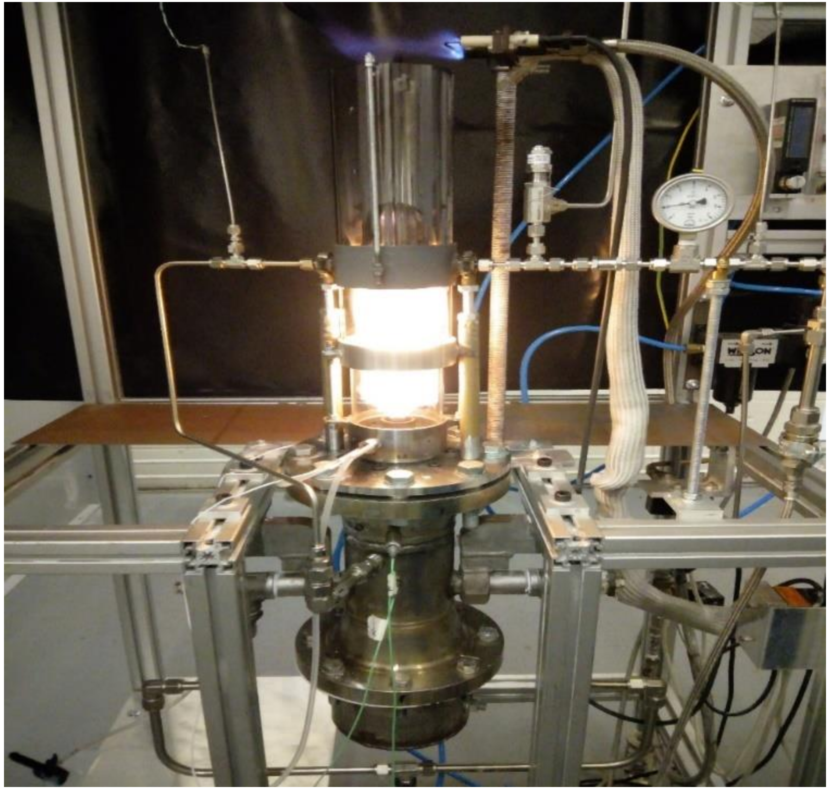
CAIPIRINH3A

MariNH3

GTRC
GAS TURBINE RESEARCH CENTRE

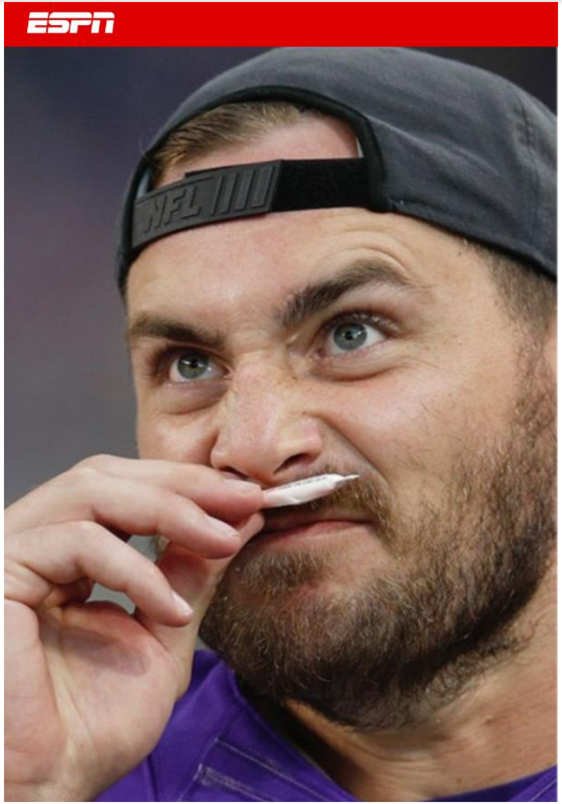
CONTENT

- INTRODUCTION
- CHALLENGES
- DEVELOPMENTS
  - FUNDAMENTALS
  - INTERNAL COMBUSTION ENGINES
  - BOILERS AND FURNACES
  - GAS TURBINES (AGT)
  - PROPULSION
  - PUBLIC PERCEPTION/ENVIRONM.
  - SAFETY
- COLLABORATION
- CONCLUSIONS

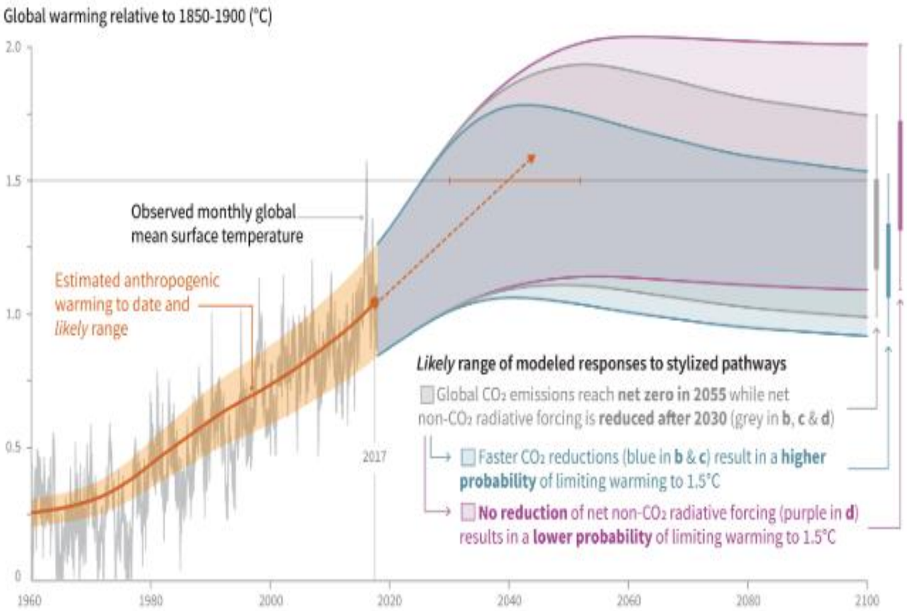


Introduction

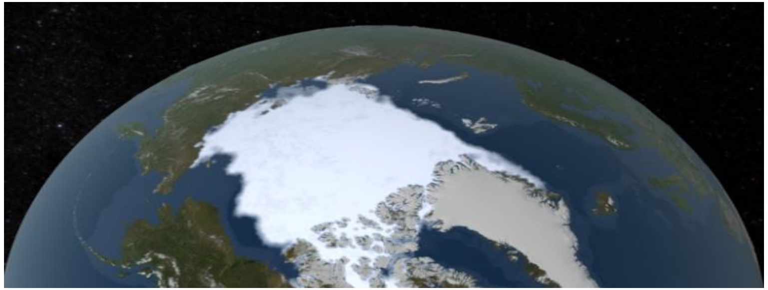
Professor at Cardiff School of Engineering. He has participated as PI/Co-I on 33 industrial projects with multi-nationals including PEMEX, Rolls-Royce, Siemens, Ricardo, Airbus and FloGas (>£38M). He has published +220 papers (h-index 44), most concerning ammonia power. Prof. Valera-Medina led Cardiff's contribution to the Innovate-UK 'Decoupled Green Energy' Project (2015-2018) led by Siemens and in partnership with STFC and the University of Oxford, which aims to demonstrate the use of green ammonia produced from wind energy. He is currently PI of various projects (incl. Endeavr Green Propulsion, SAFE-AGT, FLEXnCONFU, OceanREFuel, etc.) to demonstrate ammonia power in turbine engines, Internal Combustion Engines, boilers and furnaces. He has been part of various scientific boards, chairing sessions in international conferences and moderating large industrial panels on the topic of "Ammonia for Direct Use". He has supported two Royal Society Policy Briefings related to the use of ammonia as energy vector, and he is principal authors of two books concerning ammonia combustion. He chairs the topic of "Ammonia Firing" for the British Standards Institute, and he is Co-Director of the Institute of Net Zero Innovation, Director of the Centre of Excellence on Ammonia Technologies (CEAT), Cardiff University. He is a Fellow of the Learned Society of Wales and the Mexican Academy of Engineering.

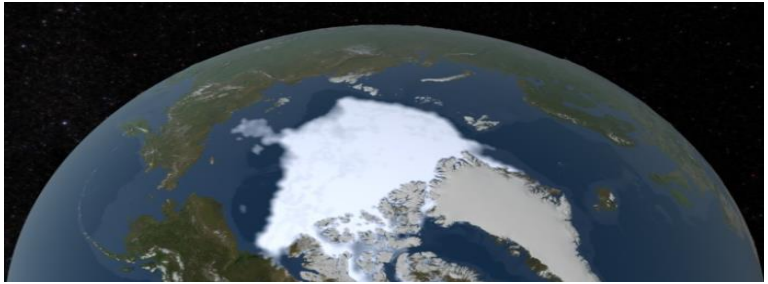


Introduction



Global Warming [IPCC, 2019. Summary Policy Makers]





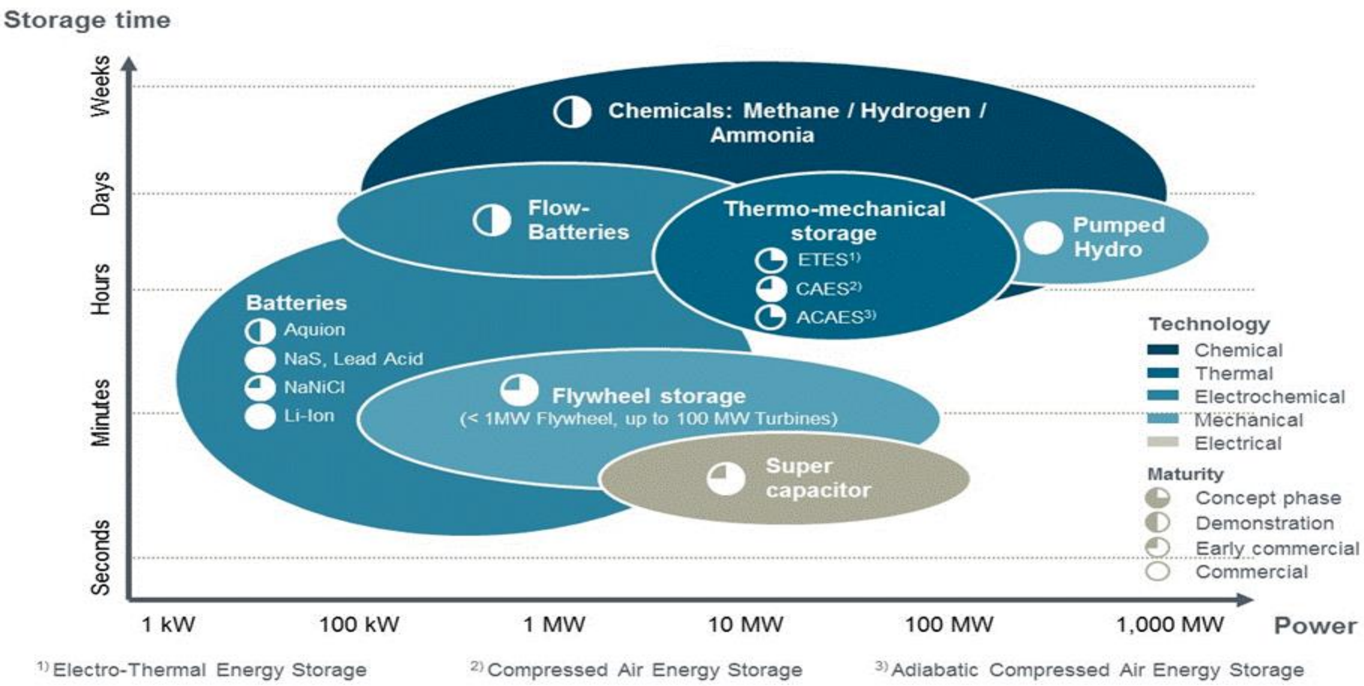
Effects of Climate Change [NASA, 2019]

Introduction

- Renewables are one of the best technologies to provide the needed energy whilst reducing greenhouse gases.
- The problem is their intermittency (i.e. UK – 1 Million People during ~48% Wind power).



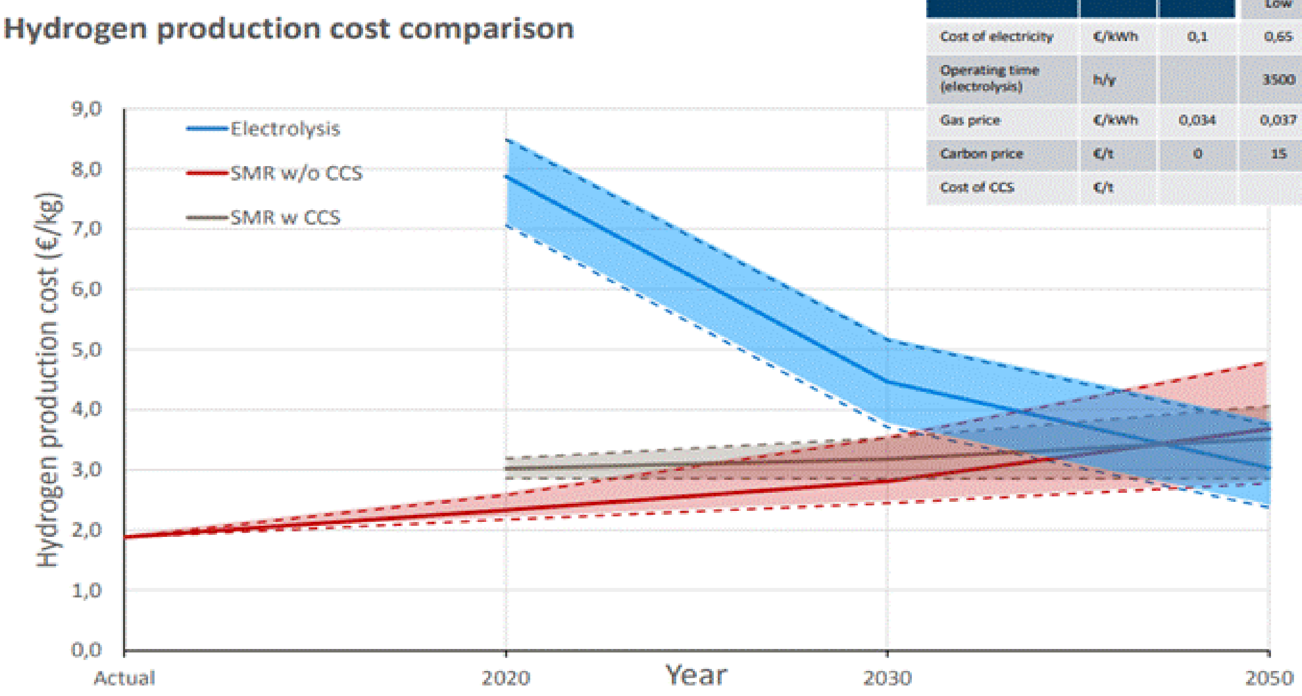
Introduction



Comparison between different storage technologies. Chemicals provide longest and largest arbitrage of storage. [Wilkinson I, 2017, 1st NH3 European Conference]

Introduction

Parameter	Unit	Actual	2020		2030		2050	
			Low	High	Low	High	Low	High
Cost of electricity	€/kWh	0,1	0,65	0,100	0,060	0,090	0,050	0,080
Operating time (electrolysis)	h/y		3500	3500	3750	4500	4000	6000
Gas price	€/kWh	0,034	0,037	0,044	0,041	0,054	0,044	0,068
Carbon price	€/t	0	15	25	30	80	50	150
Cost of CCS	€/t		100		80		60	



Hydrogen Cost Comparison [Dr. Nils A. Røkke, SINTEF, 9th Int. Gas. Turbine conference, 10-11 October 2018 Brussels Belgium]

Introduction

Exhibit 11: Distribution of global hydrogen resources and demand centers

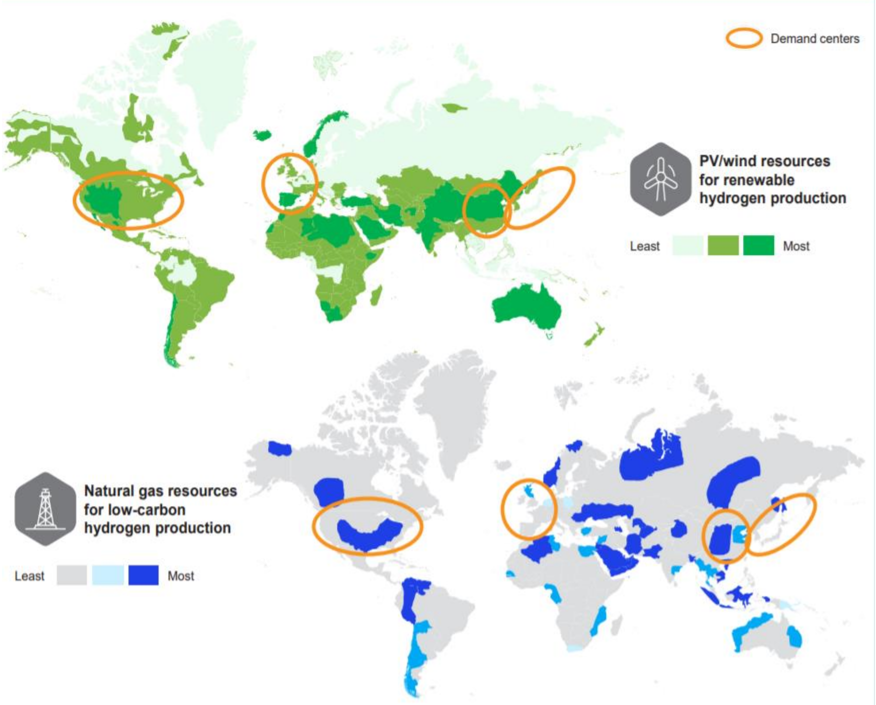
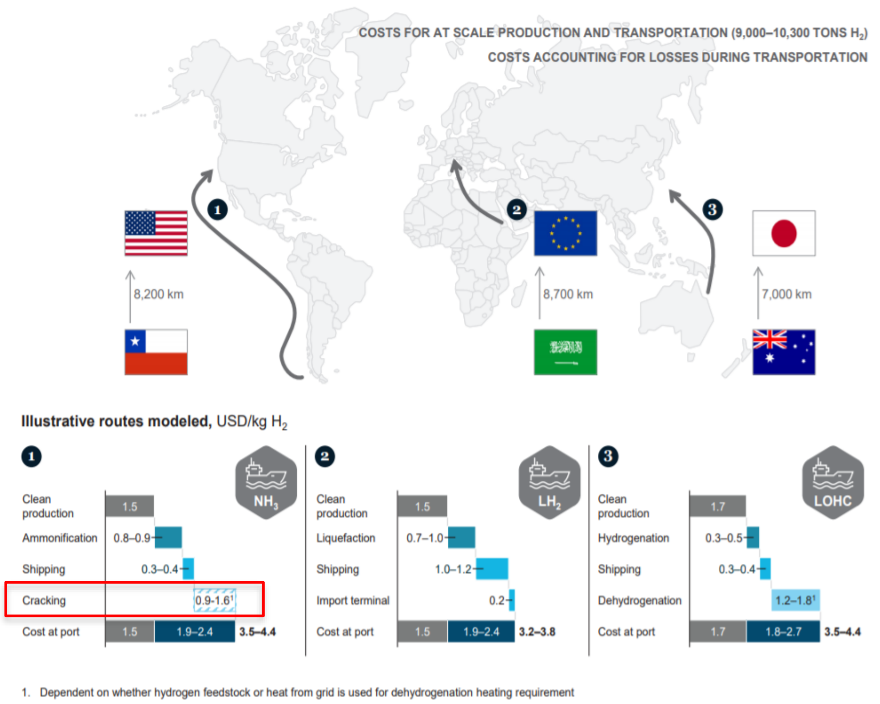
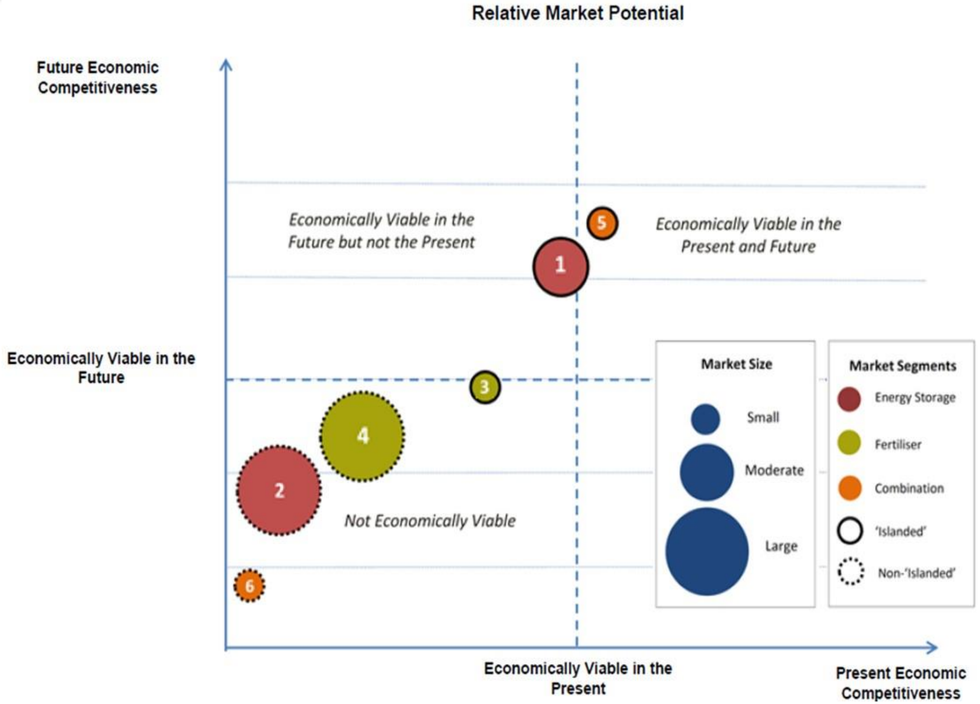


Exhibit 16: Landed costs of hydrogen at port for selected global transport routes

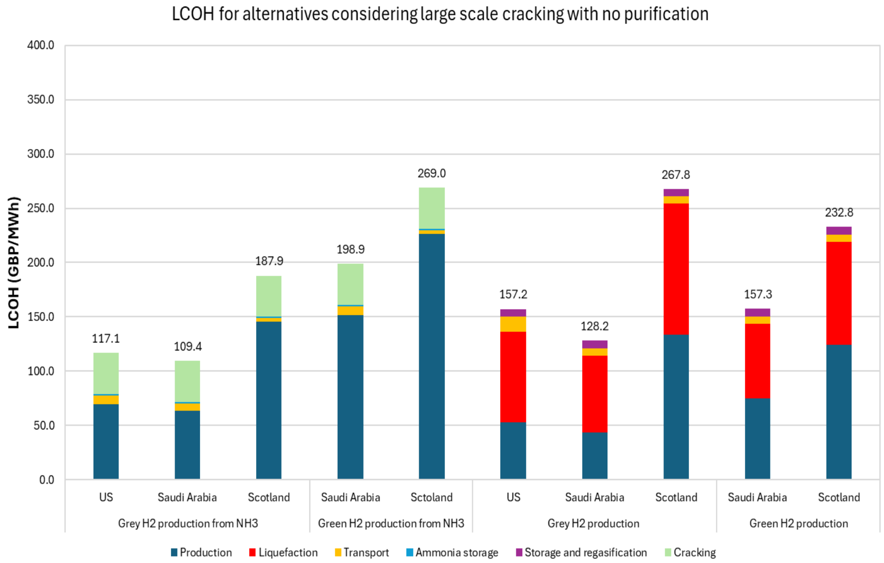


Hydrogen Distribution and comparison between vectors [Hydrogen Council 2021]

Introduction



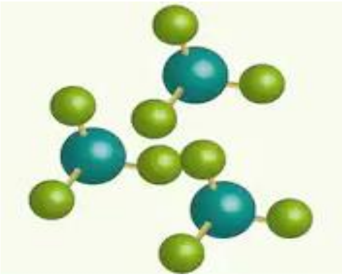
Ammonia Economy – Feasibility Study using novel techniques. [Banares R et al, 2015]

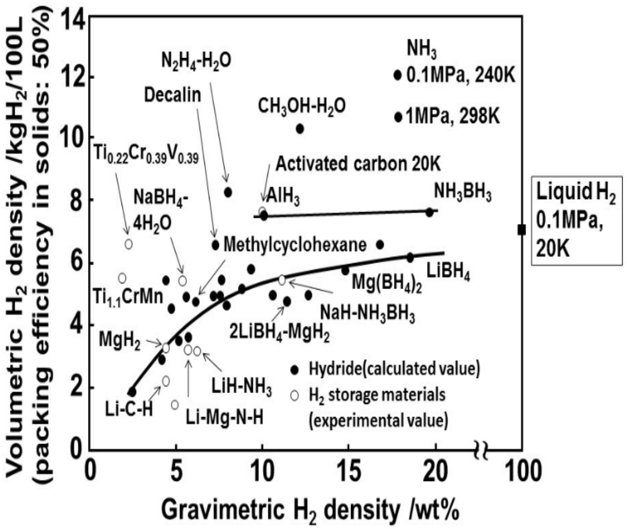


LCOH for delivery to CELSA (South Wales), GW-SHIFT, 2025

Introduction

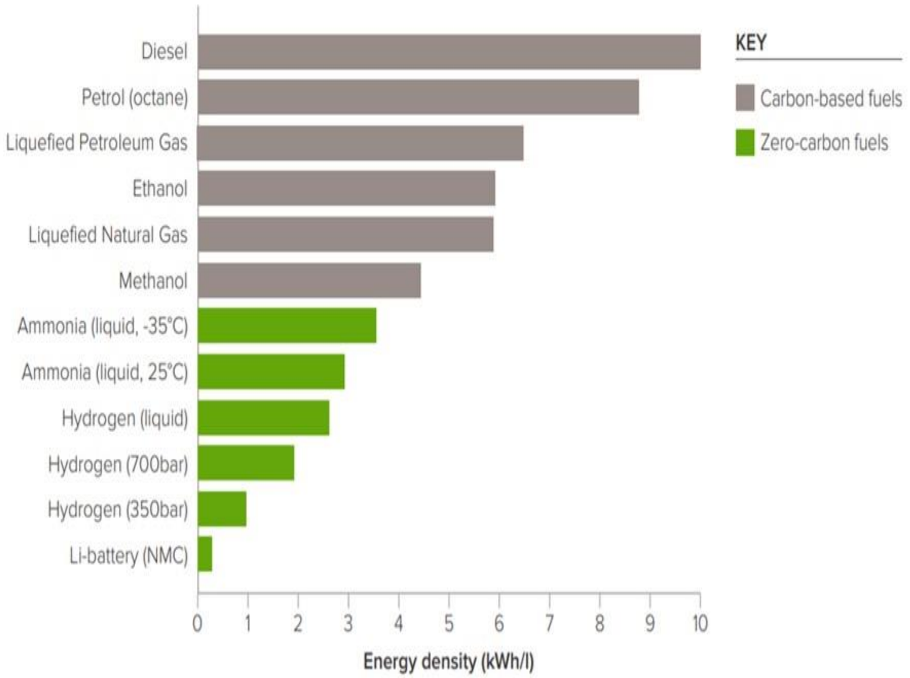
- Ammonia can
  - be obtained from renewable sources,
  - allow the rescue of stranded resources,
  - enables the use of waste streams,
  - allow storage of vast amounts of energy 30 times cheaper than H2,
  - be used to produce energy in Islands or isolated regions,
  - be used as a fuel, but also as a fertilizer,
  - High hydrogen content (higher than liquid H2),
  - have a great economical potential, with a market size up to 184 Billion Euros per year.

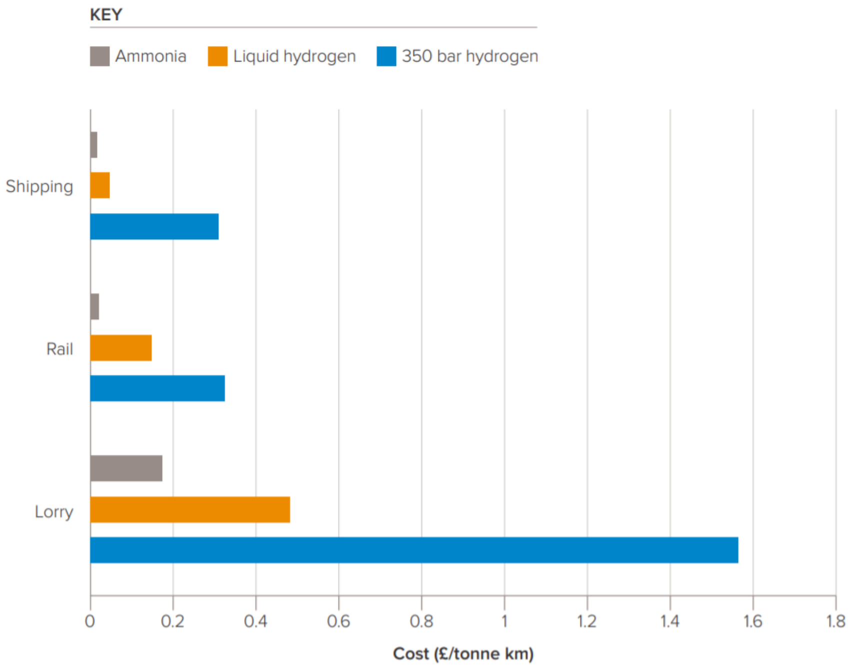




Hydrogen densities in hydrogen carriers. Courtesy of Prof. Yoshitsugu Kojima, Hiroshima University.

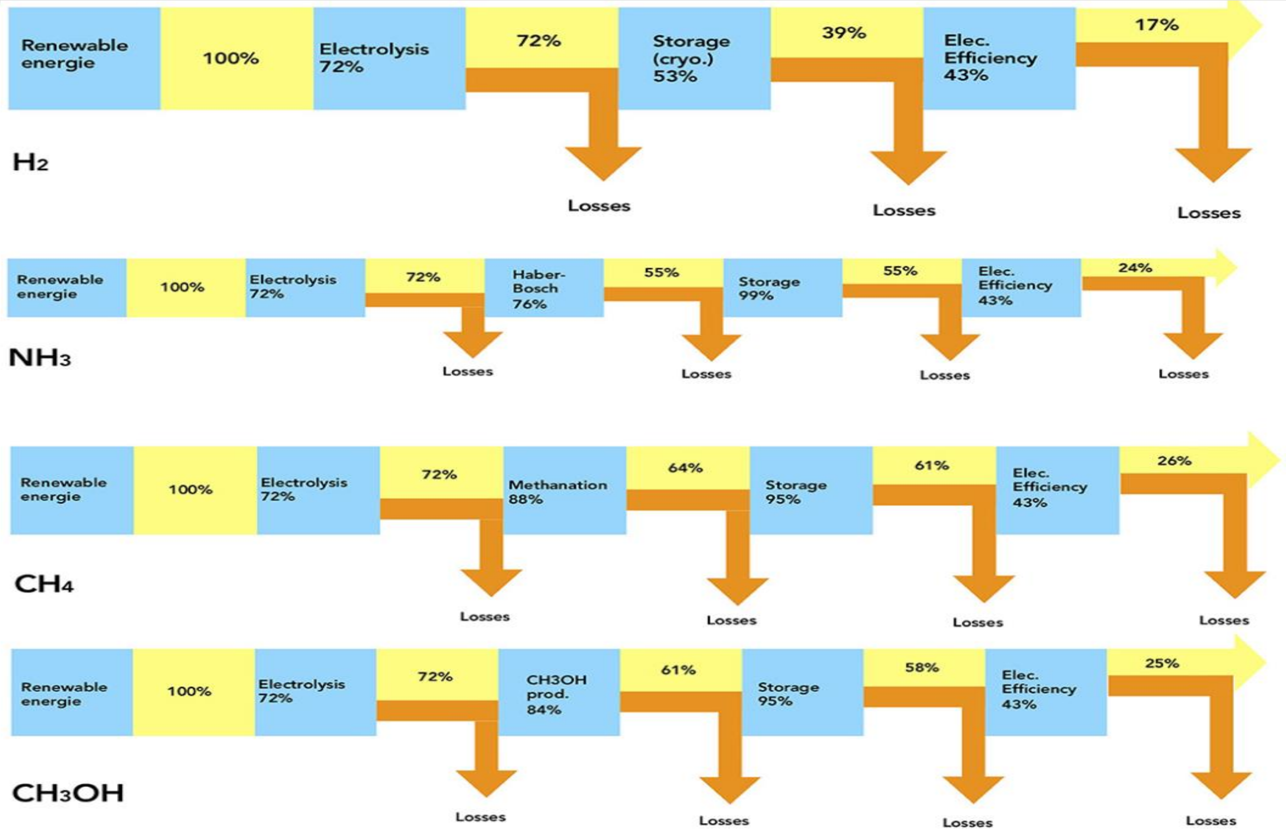
Introduction





Green Ammonia, Royal Society Policy Briefing [David et al. 2020]

Introduction

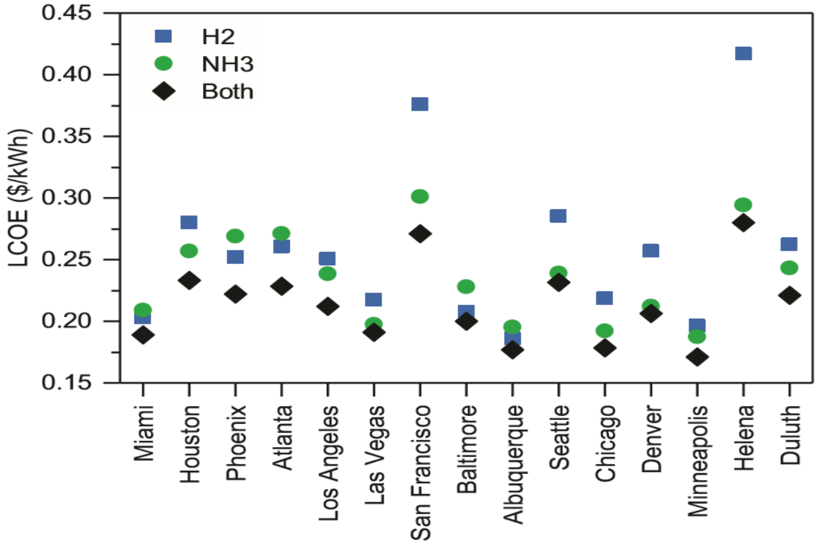


Comparison of ammonia with other chemicals in terms of efficiency for the production of electric power (from well to wheel).

[Dias et al. Energy and Economic Costs of Chemical Storage. Front. Mech. Eng. doi.org/10.3389/fmech.2020.00021]

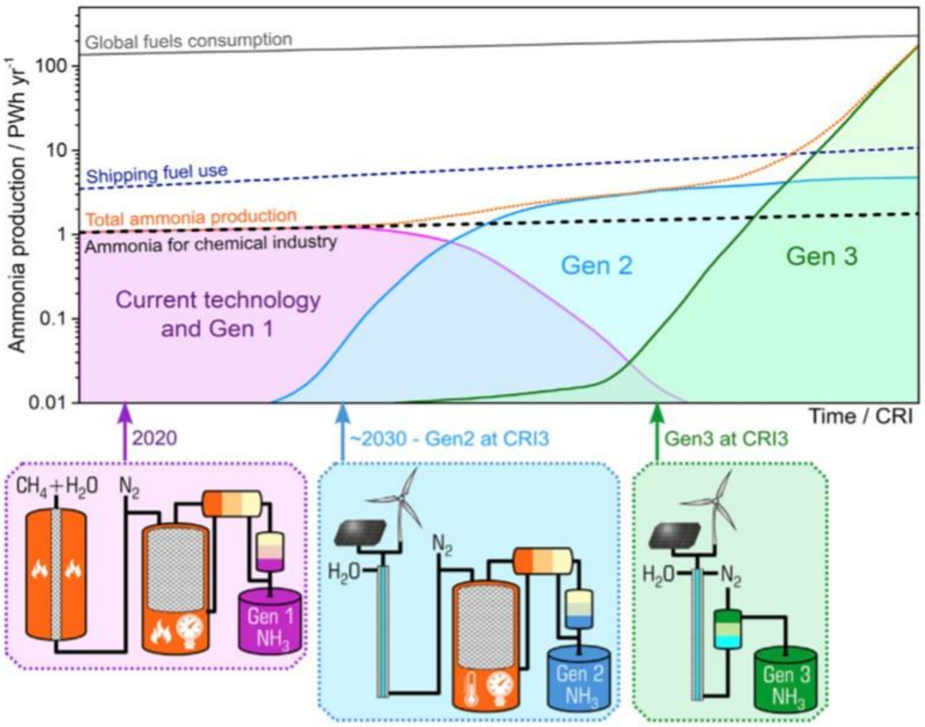
Introduction

- Ammonia is not intended to substitute Hydrogen, but to support the use of the latter;
- Recent studies show that ammonia can be combined with the use of hydrogen to optimise energy generation systems;
- Ammonia offers the flexibility to store hydrogen over long periods at relatively much lower costs;
- Ammonia can be used to store seasonal stranded energy (ie. Summer) for its later use (ie. Winter).
- Thus ammonia **COMPLEMENTS** the hydrogen transition.



Using hydrogen and ammonia for renewable energy storage: A geographically comprehensive techno-economic study [Palys MJ et al. 2020. Computers and Chemical Engineering]

Introduction



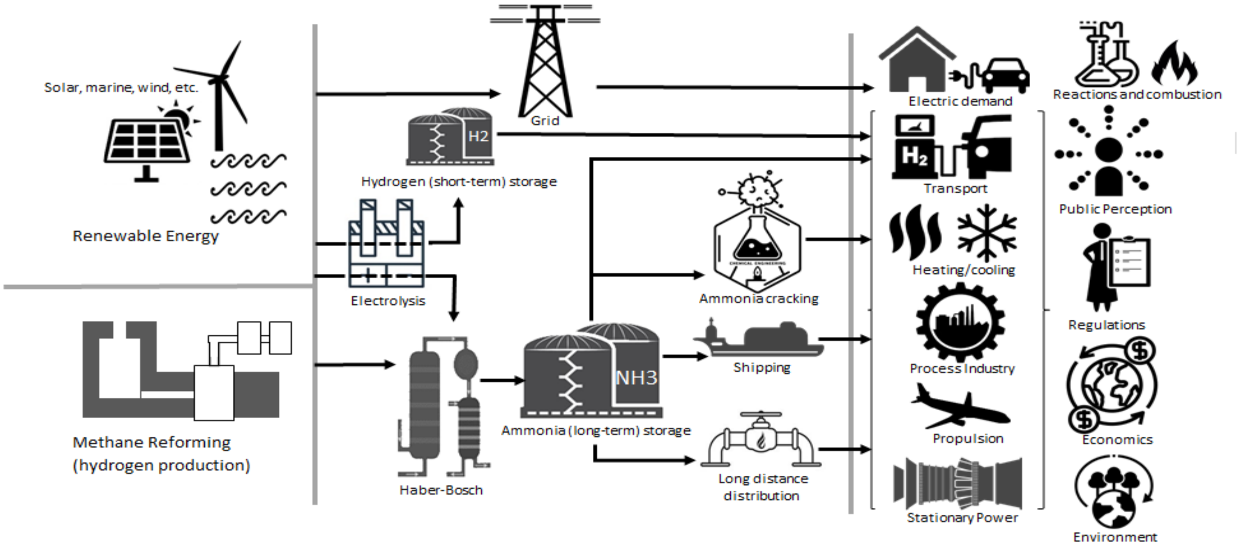
Generation developments needed for an "Ammonia Economy" [McFarlane et al. Joule, 2020]

- However, it has been conceived that for the progression of an "Ammonia-based Economy" there is a need for 3 Generation of technologies.
- Generation 3 does not require the split of water into hydrogen and oxygen.

Next Nobel Prize?

Introduction

- Although ammonia combustion is still seen as the lowest end of the use of ammonia for energy, cheaper distribution, higher hydrogen content and easier operation will change the position of NH3 in the energy arena.



Green Ammonia/Hydrogen Economy [Valera-Medina and Banares-Alcantara, 2020]

Introduction

Energy release technology	NH_3 pre-treatment required	Efficiency	Advantages	Challenges	Mitigations to challenges
Proton-exchange membrane (PEM) fuel cell	• NH_3 decomposition • Trace NH_3 removal	40-50%	• Established technology • High energy density (suitable for mobile applications)	• Cost/use of platinum • Sensitive to ppm NH_3	• Trend for decreasing platinum use • NH_3 removal membrane technology has seen step change
Alkaline fuel cell (AFC)	• NH_3 decomposition	50-60%	• Non-use of platinum- group metals • Highly tolerant of NH_3	• Low energy density • Few commercial suppliers • Requires CO_2 scrubbing	• Suitable for stationary applications • CO_2 scrubbing is facile
Solid oxide fuel cell (SOFC)	None	50-55%	• Established technology • Decomposes NH_3 in-situ • Non-use of platinum-group metals	• Full, at-scale commercialisation • Corrosion of steel fuel delivery pipework, SOFC system cost	• Suitable for stationary applications • Good for combined heat and power
Internal combustion engine (ICE)	Can be used directly but partial NH_3 decomposition might be used	25-40%	• Established technology with other fuels	• NH_3 has low flame speed, poor ignition characteristics • NO_x gases need to be limited • Low efficiency	• Partial cracking of NH_3 improves flame qualities • NH_3 can be used to remove NO_x gases • NH_3can be reduced by optimised combustion
Combined cycle gas turbine (CCGT)	Can be used directly but partial NH_3 decomposition might be used	55-60%	• Feasible technology with other fuels	• NH_3 has low flame speed, poor ignition characteristics • NO_x gases need to be limited • Materials impact still unknown	• Partial cracking of NH_3 improves flame qualities • NH_3 can be used to remove NO_x gases during combustion • NH_3 slip can be reduced by optimised combustion
Furnaces and Boilers	Can be used directly in combination with other conventional fuels	85-95%	• Established technology with other fuels	• NH_3 has low flame speed, poor ignition characteristics • NO_x gases need to be limited • Materials impact still unknown	• Partial cracking of NH_3 improves flame qualities • NH_3 can be used to remove NO_x gases during combustion • NH_3 slip can be reduced by optimised combustion

Challenges

However, the technology faces the following obstacles,

1.Ammonia Carbon-free synthesis (cost reduction, efficiency improvement)

2.Power generation at utility-scale from ammonia production (stable, low emissions)

3.Public acceptance through safe regulations and appropriate community engagement.

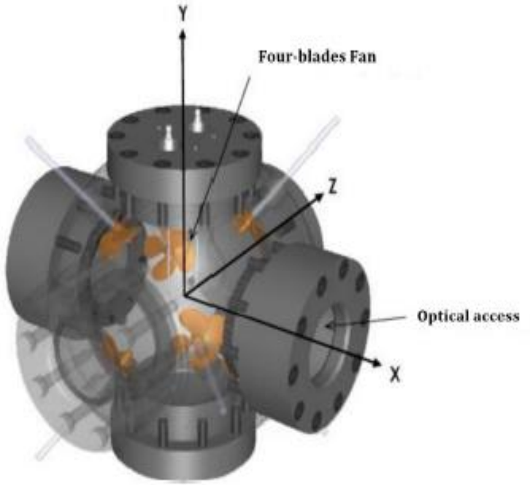
4.Economics – profitable scenarios (cannot be applied everywhere)

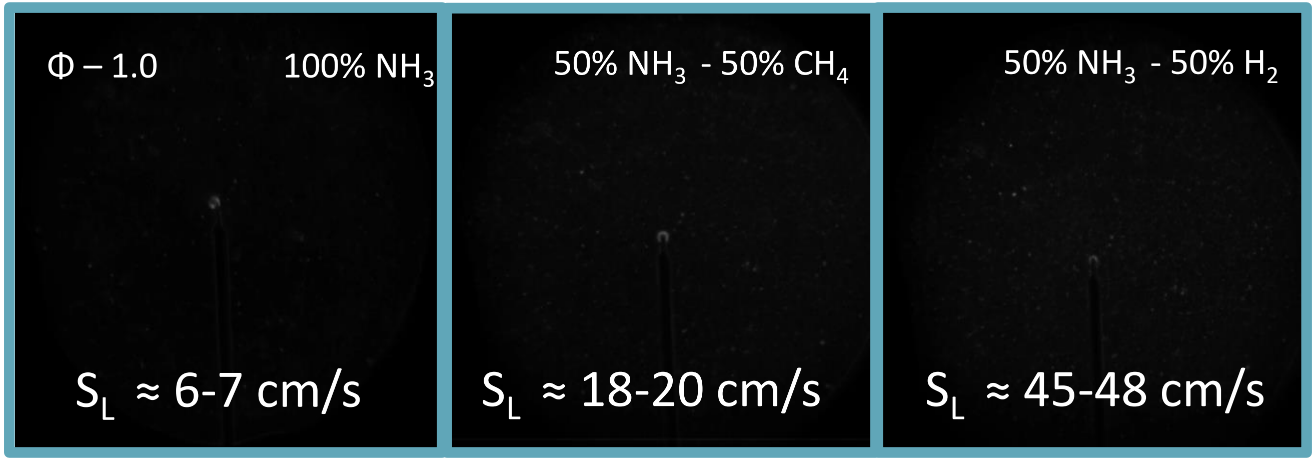
Developments - Fundamentals

	Ammonia	Hydrogen	Methane	Propane	Methanol	Ethanol	Gasoline	Diesel
Lower heating value [MJ/kg]	18.8	120.1	50	46.4	19.7	26.8	44.5	42.5
Maximum LBV [m/s]	0.07	2.91	0.37	0.43	0.50	0.47	0.47	0.52
Flammability [E.R.]	0.63–1.4	0.10-7.1	0.50-1.7	0.51-2.5	0.55-2.9	0.66-2.4	0.7-4	0.6-5.5 (vol%)
Auto-ignition [K]	924	844	810	723	743	638	503	498
Minimum ignition energy [mJ]	8	0.011	0.28	0.25	0.14	0.28	0.8	0.24
Density (g/L)	0.703	0.082	0.657	493	787	789	740	830

Premixed fuel-air mixture	Laminar Burning velocity at 298 K and 0.1 MPa [cm/s]		
	$\phi = 0.85$	$\phi = 1$	$\phi = 1.2$
NH_3-air	3	6.1	5.5
H_2-NH_3-air	11.8 (x_ H_2 = 0.25)	15.5 (x_ H_2 = 0.25)	14.1 (x_ H_2 = 0.25)
	21.3 (x_ H_2 = 0.40)	27.8 (x_ H_2 = 0.40)	26.7 (x_ H_2 = 0.40)
CH_4-NH_3-air	13.3 (x_ CH_4 = 0.40)	16.6 (x_ CH_4 = 0.40)	12.4 (x_ CH_4 = 0.40)
	22.5 (x_ CH_4 = 0.80)	27.7 (x_ CH_4 = 0.80)	22.8 (x_ CH_4 = 0.80)

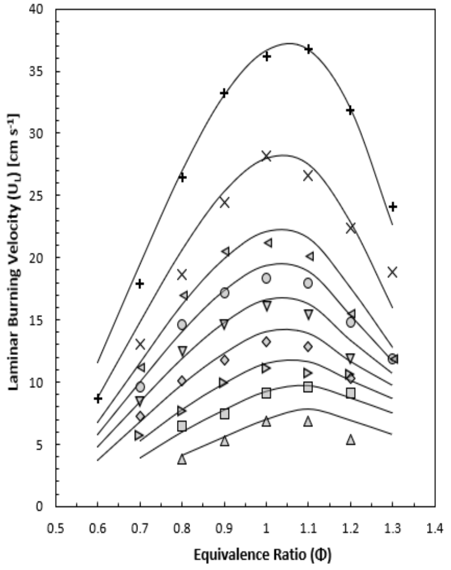
Developments - Fundamentals

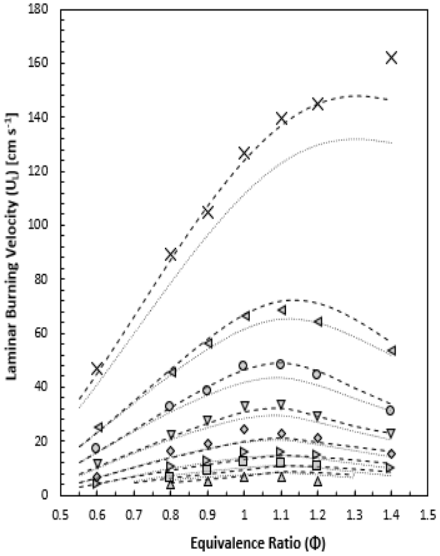




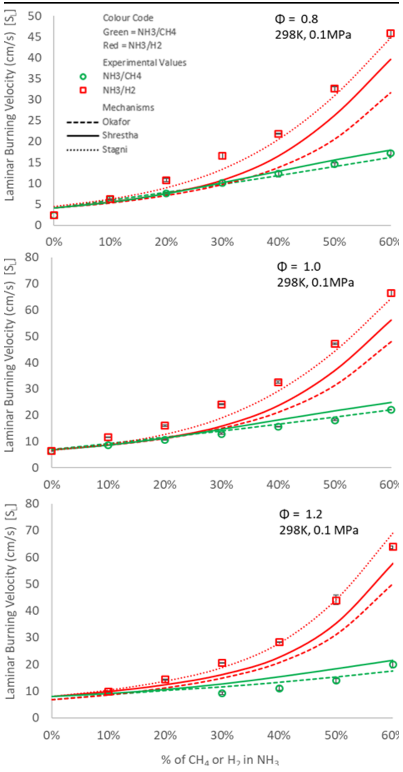
Change in Laminar burning velocity with the change in blending [U. Orleans]

Developments - Fundamentals





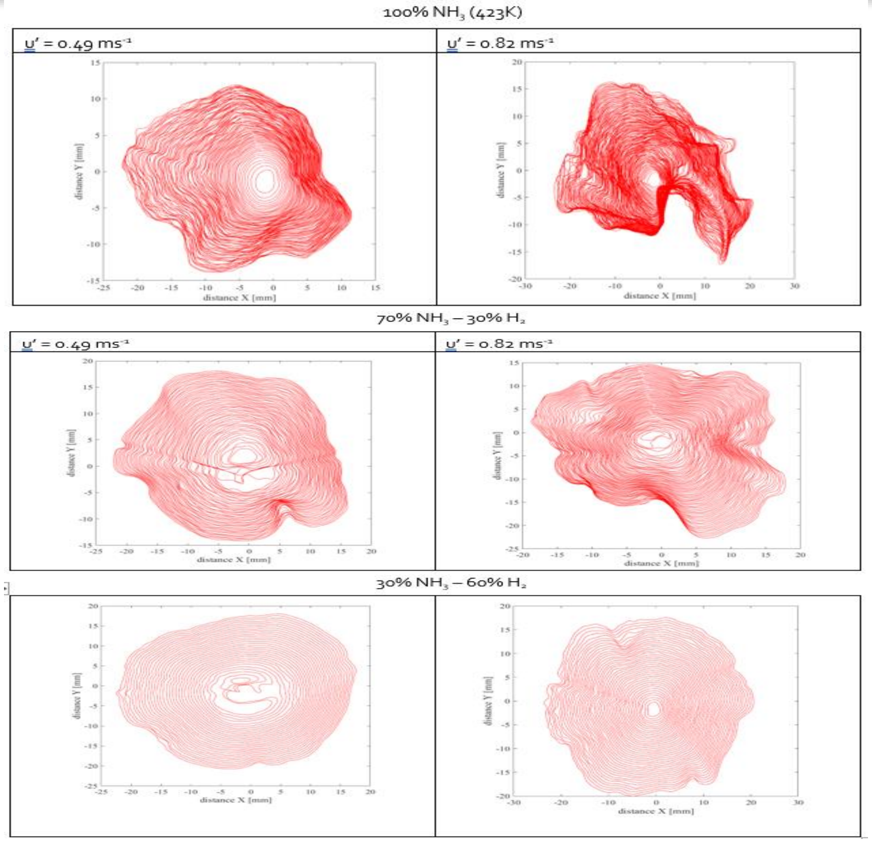
Laminar Burning Velocity [U. Orleans]

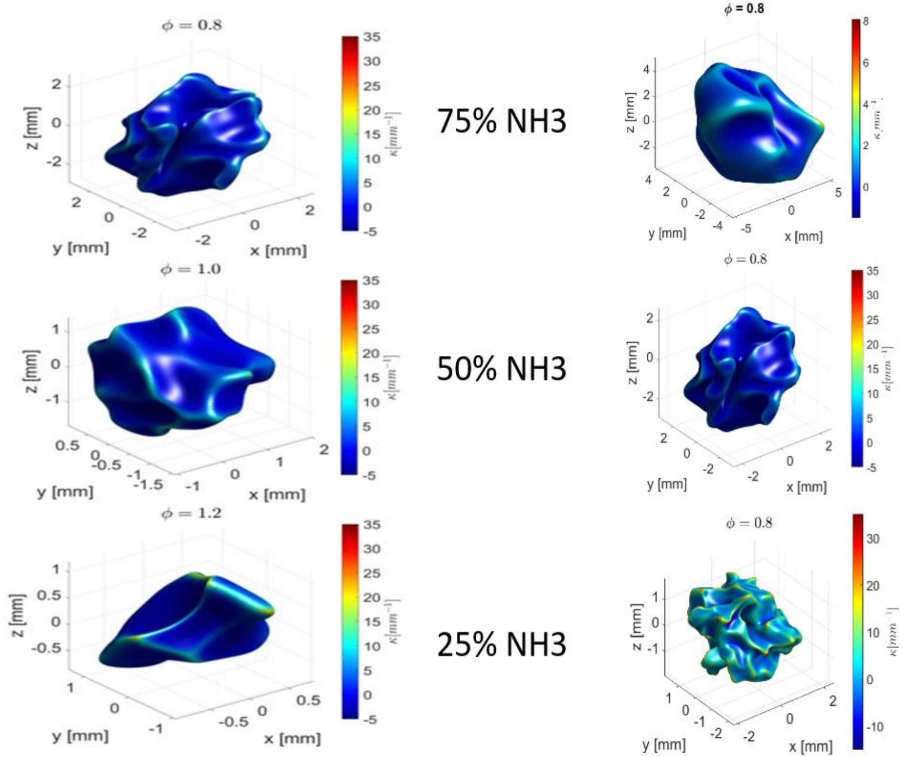


Results at various equivalence ratios show that below 20% doping (H2 or CH4) the LBV remains almost the same for the blends [Int Conf. Gas Turbines, 62-IGTC 21, U. Orleans]

Developments - Fundamentals

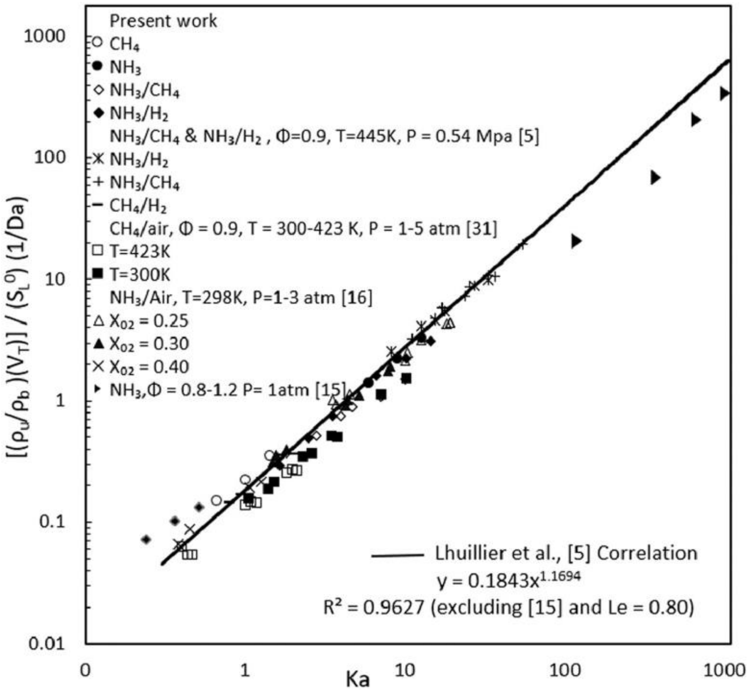
Recent findings for FLEXnCONFU [U. Orl]



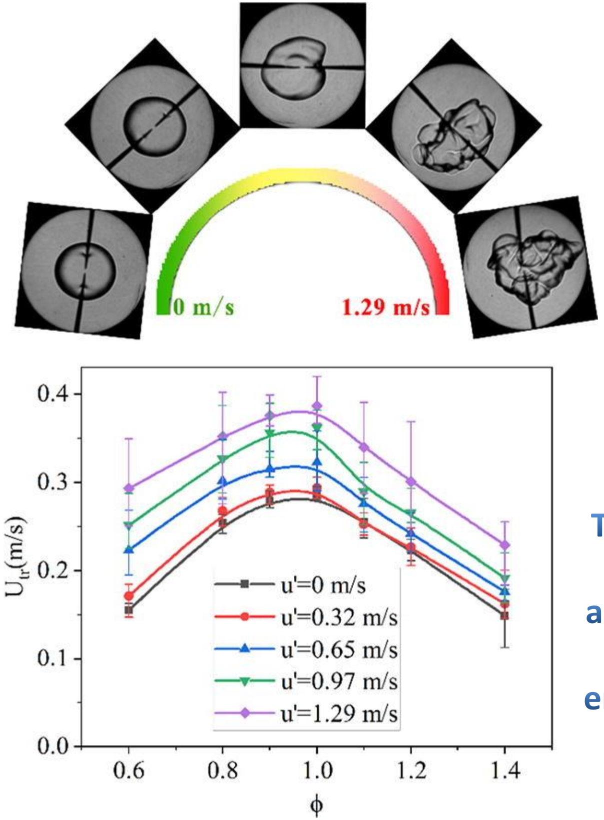


Recent findings for FLEXnCONFU [TUE].

Developments - Fundamentals

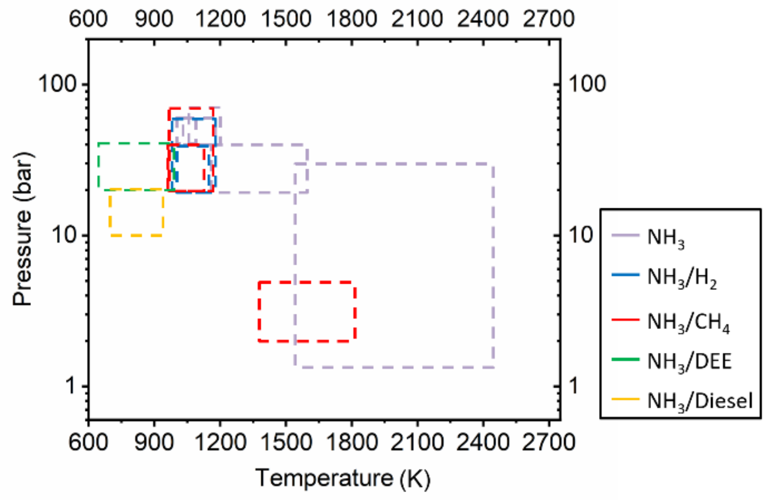


Correlation of Da-corrected ST/SL0 ratio against Ka [Zitouni et al, 2023]

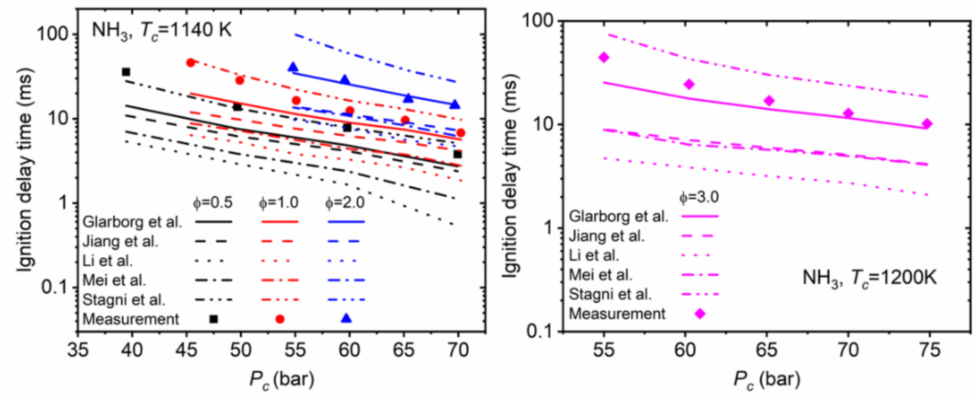


Turbulent burning velocity of ammonia/oxygen/nitrogen premixed flame in O2-enriched air condition [Xia et al, 2020]

Developments - Fundamentals

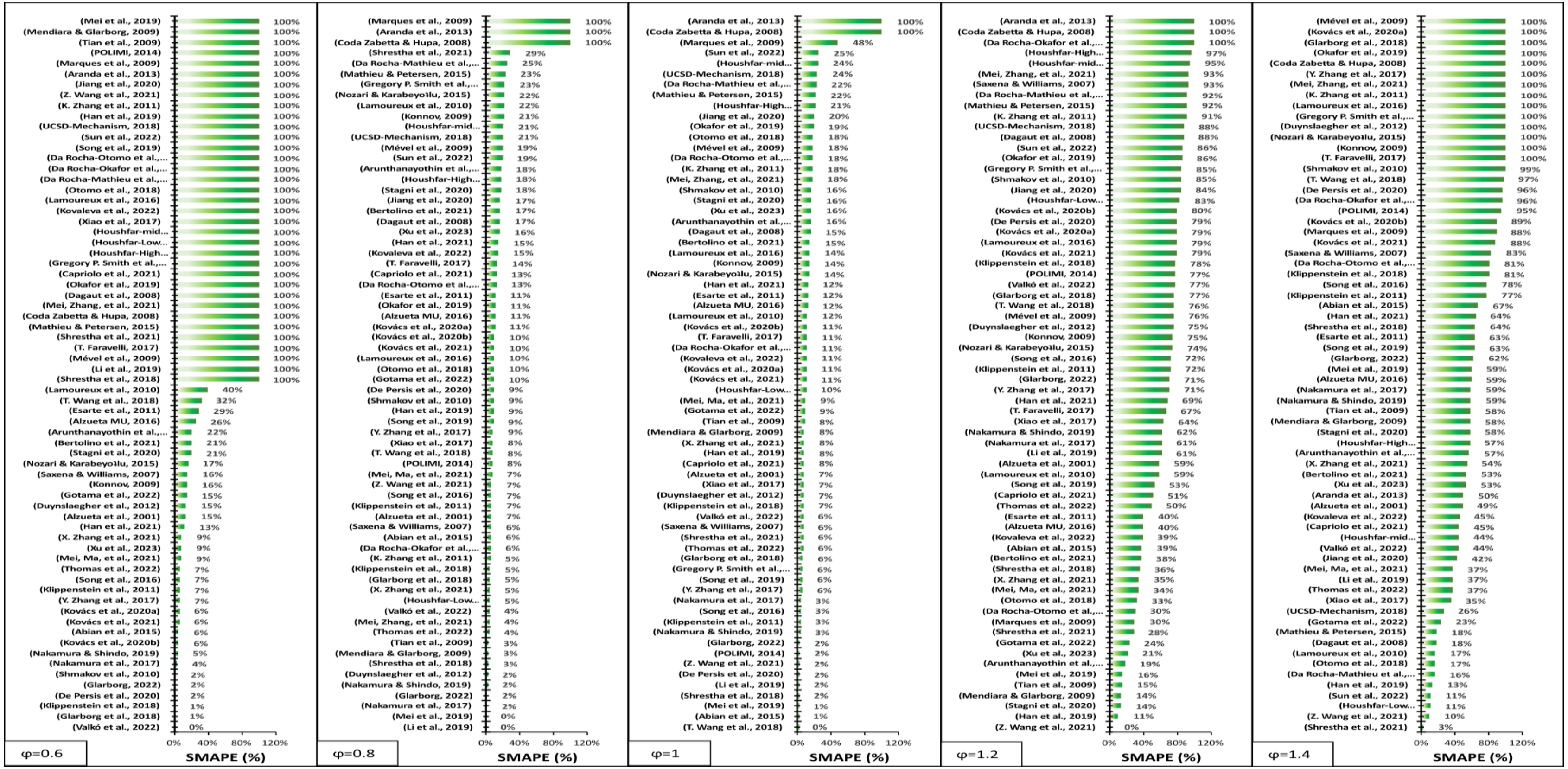


Summary of the conditions of ignition delay time measurements of mixtures containing ammonia from literatures [Valera-Medina et al. 2021]



Comparison between simulation results with different mechanisms and the measurements for ignition delay times of NH3/O2/N2/Ar mixtures (75% dilution for ϕ=0.5, 1.0 and 2.0 in the left, 80% dilution for ϕ=3.0 in the right [Valera-Medina et al. 2021]

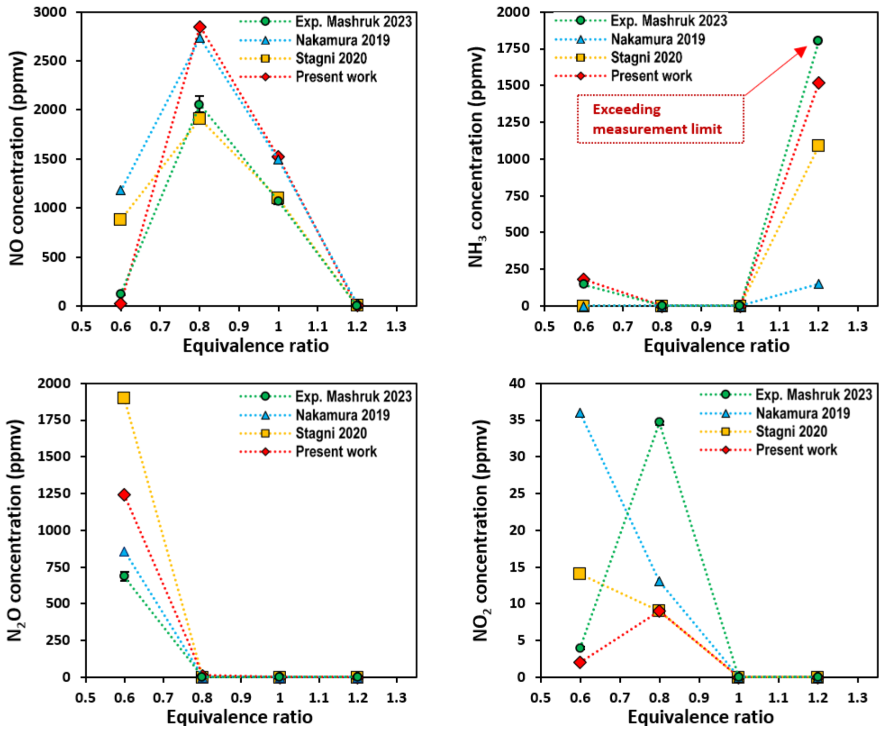
Developments - Fundamentals



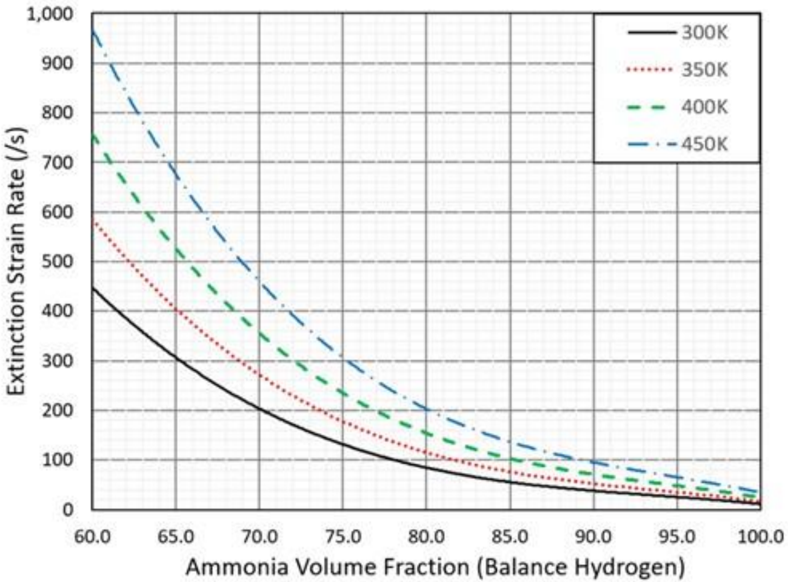
Developments - Fundamentals

Mechanism	N_{spec}	N_{reac}	$\sqrt{E_{LBV}}$	$\sqrt{E_{BSSF}}$	$\sqrt{E_{JSR}}$	$\sqrt{E_{Overall}}$
Zhu-2024	39	312	2.97	2.27	1.11	2.25
Han-2023	32	171	2.24	3.70	1.63	2.67
Present work	21	64	1.97	3.24	2.72	2.70
Jian-2024	32	233	3.23	3.79	1.80	3.06
Otomo-2018	32	213	3.67	3.65	2.03	3.21
Zhang-2021	34	224	2.45	4.59	2.78	3.41
Stagni-2023	31	203	3.46	4.69	1.75	3.51
Gotama-2022	32	165	3.28	4.59	2.91	3.67
Liu-2024	35	238	3.96	5.19	2.39	4.01
Glarborg-2022	34	227	6.42	4.45	2.55	4.74
Glarborg-2023	34	228	6.52	4.45	2.54	4.79
He-2023	34	221	7.37	4.45	2.46	5.17
Zhang-2024	34	224	8.46	4.50	1.14	5.57
Mei-2021	35	239	4.02	9.84	1.65	6.21
Wang-2022	32	140	2.53	10.13	2.64	6.22
Nakamura-2024	33	228	3.29	10.17	2.14	6.29
Meng-2023	39	269	10.14	4.62	3.11	6.68
Klippenstein-2018	33	108	10.28	4.73	3.03	6.76
Glarborg-2018	33	211	10.29	4.73	3.03	6.77
San Diego-2018	21	64	3.36	13.94	2.43	8.40
Mathieu-2015	33	160	4.32	14.11	2.12	8.61

Mechanism Comparison



Developments - Fundamentals



60% Ammonia in Hydrogen,
350K ER 1.0

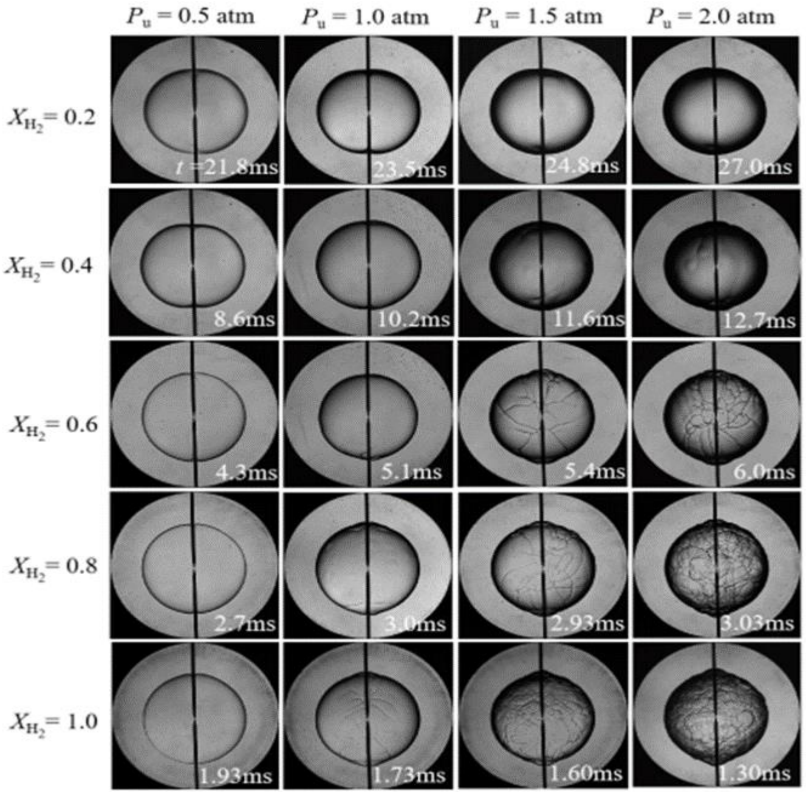
70% Ammonia in Hydrogen,
350K ER 1.0

Counterflow Burner to evaluate Extinction Strain Rate for model validation.

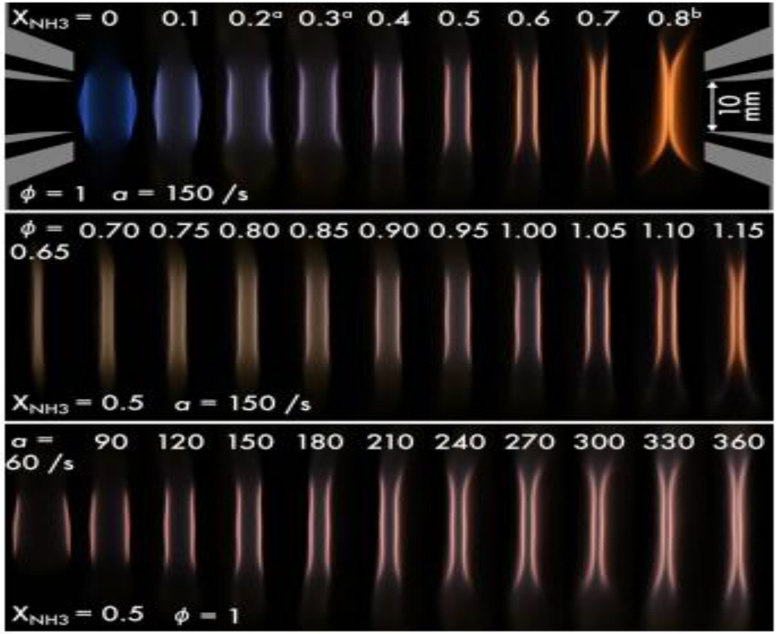
Developments - Fundamentals

- Thermo-diffusive and hydrodynamic instabilities are considerably increased as the percentage of hydrogen in increased. Also, low equivalence ratios tend to increase this behaviour.

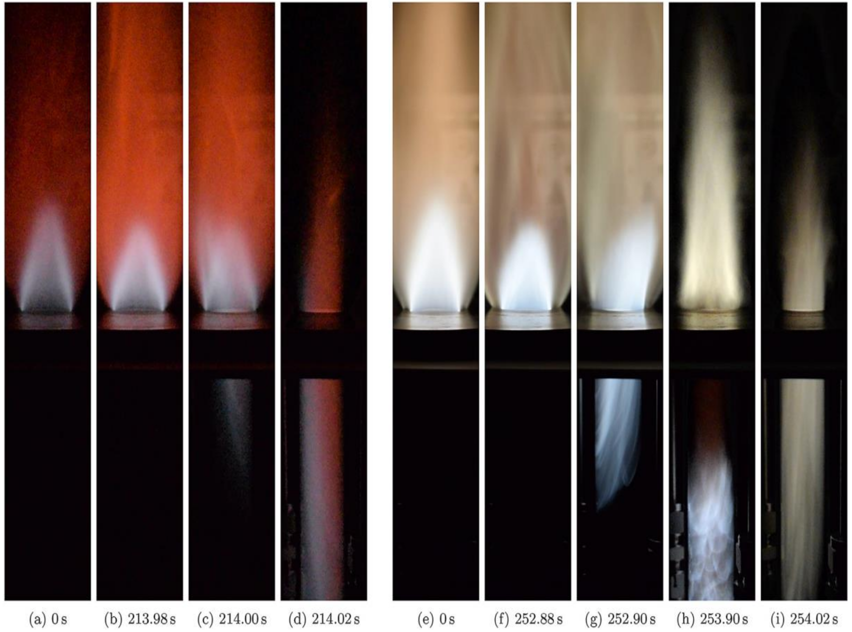
Schlieren images of spherically various ammonia/hydrogen in air flames at a radius of 25mm. Temperature of 298K, various pressures and equivalence ratio of 1.0 [Li H, Xiao H, Sun J. Combust Flame 2021]



Developments - Fundamentals

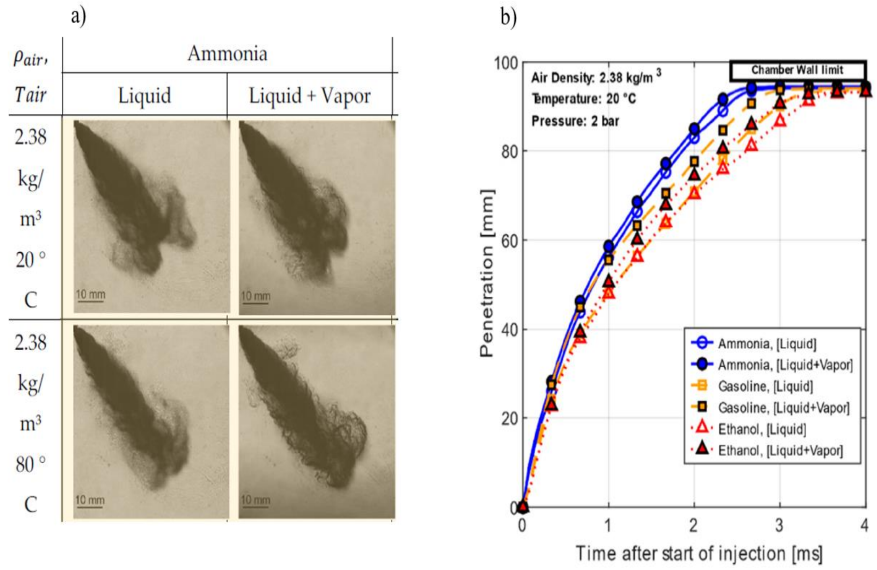


Time-averaged broadband images of the twin-flames for different ammonia fuel fraction (top row), equivalence ratios (middle row), and strain rates (bottom row) [Zhu X et al, 2021]

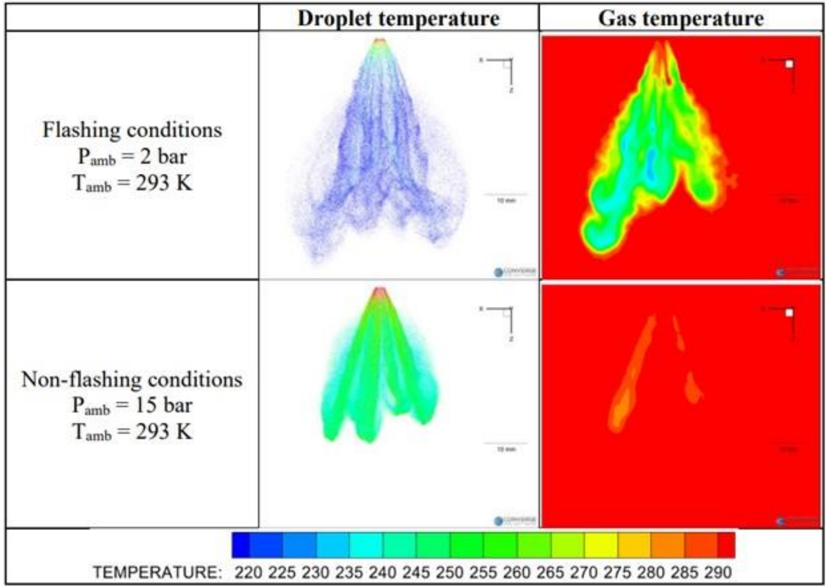


Sequence of images for pure hydrogen/air (a-d) and 80/20% (vol) hydrogen/ammonia at the BLF onset [Goldmann et al, 2021]

Developments - Fundamentals

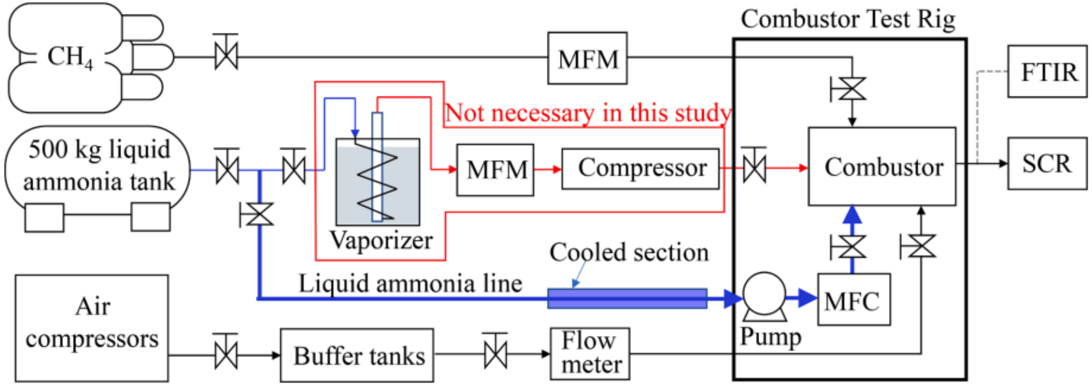


Comparison of spray shape for liquid and liquid/ vapor NH3 sprays b) Comparison of spray penetration for NH3 with more conventional fuels [Pele et al. 2021**]**

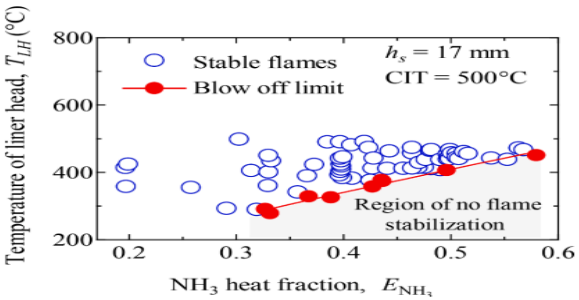


Comparison between droplet and gas temperature in flashing and non-flashing conditions. Strong impact and temperature change during vaporization [Zembi et al 2023**]**

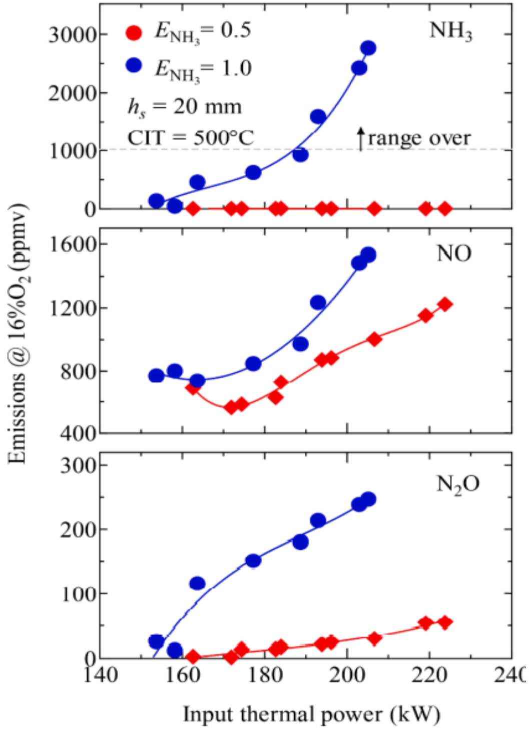
Developments - Fundamentals



Schematics of the layout of the experimental facility
[Okafor et al, 2021]

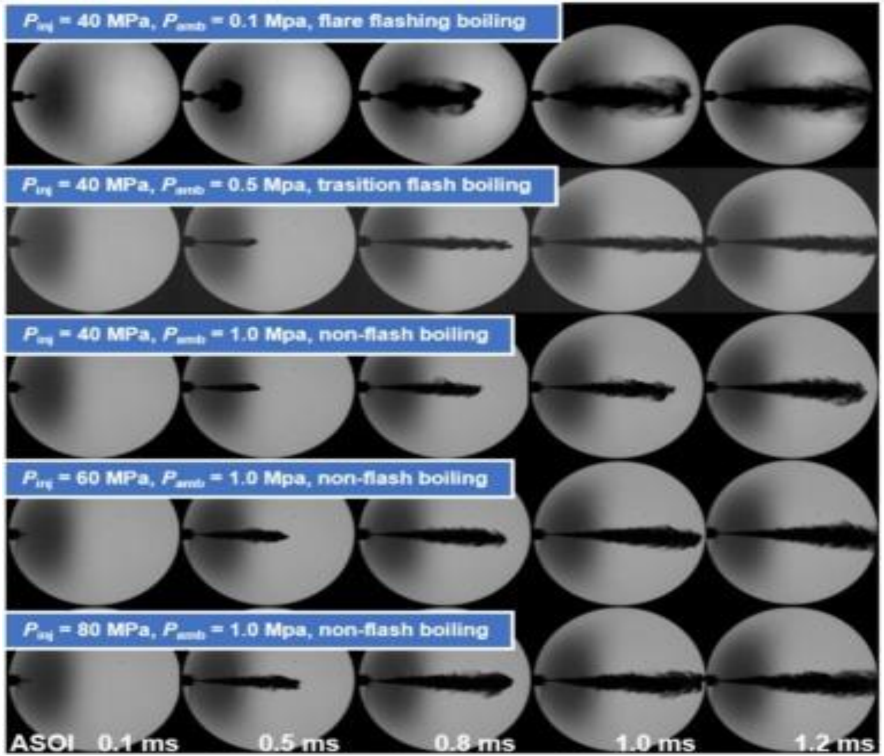


Stability maps [Okafor et al, 2021]

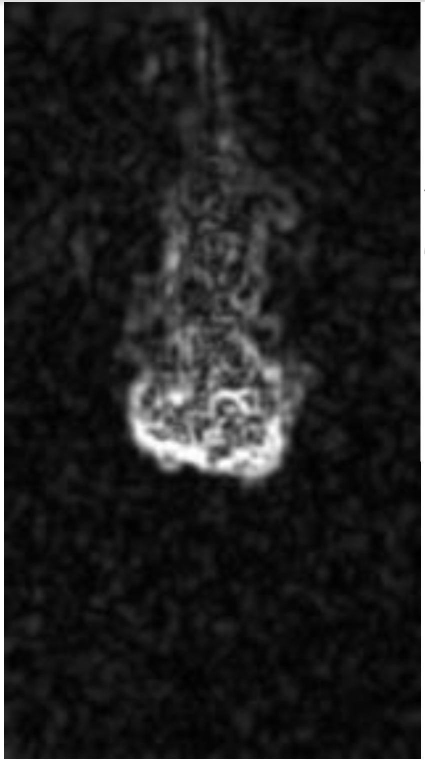


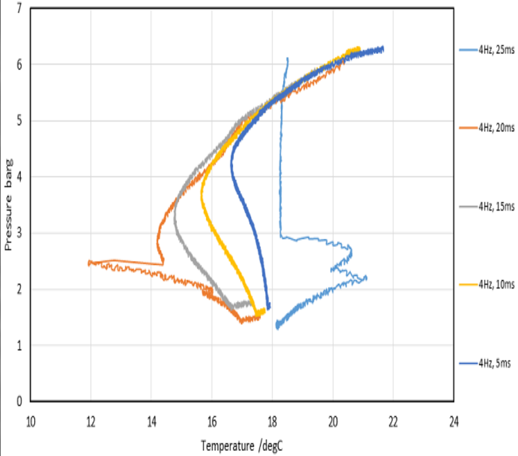
Comparison of the effects of ENH3 on emissions
[Okafor et al, 2021]

Developments - Fundamentals



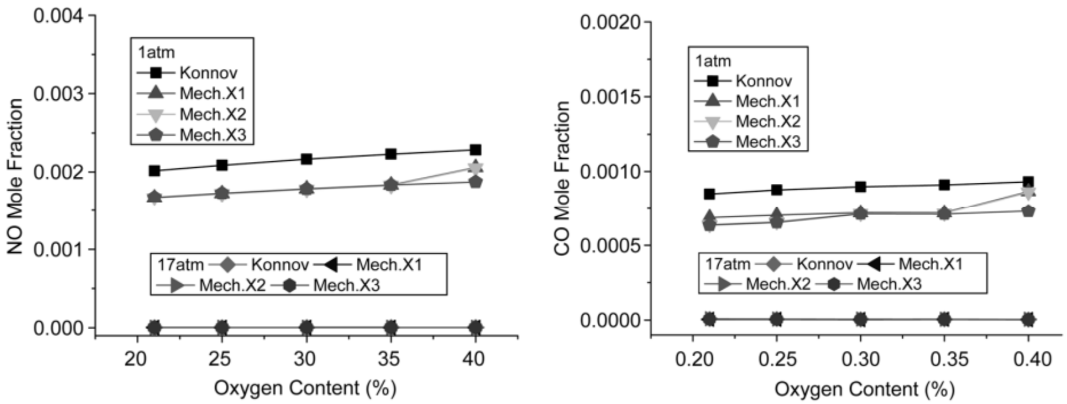
Spray morphology at different conditions[Okafor et al, 2021]



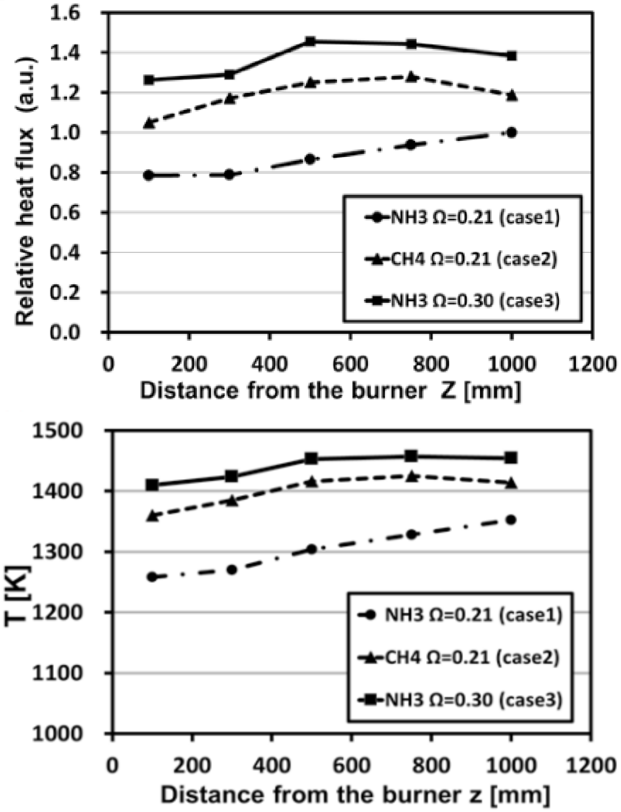


Injector Flow Rate Testing
Ammonia - Bosch EV-1/3A

Developments - Fundamentals

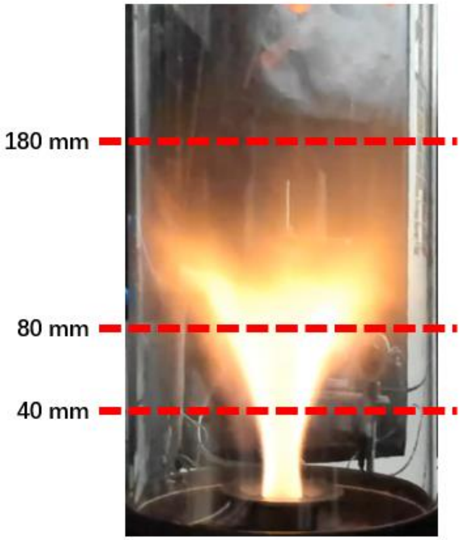


Emissions from oxygen enriched ammonia-methane co-firing [Xiao et al 2018]

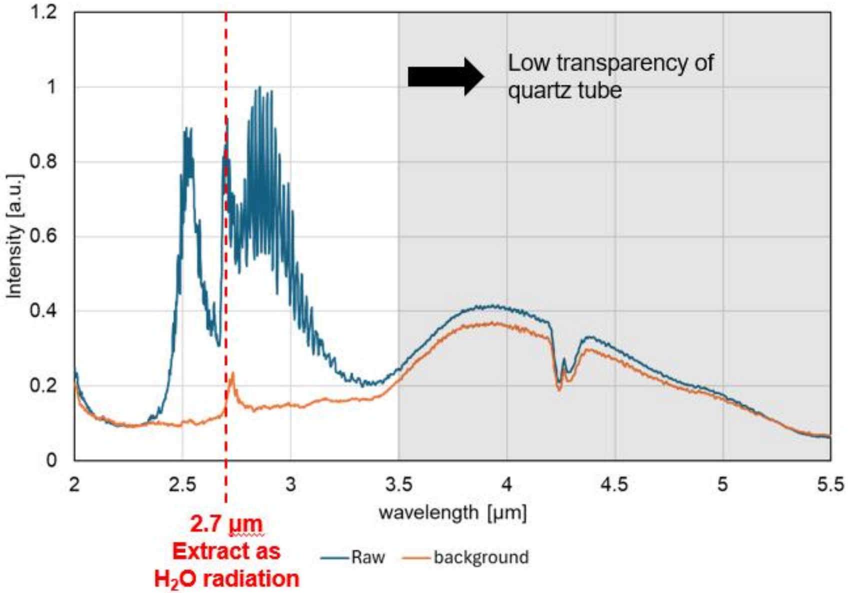


Relative heat flux (left) and temperature (right) measurements using ammonia, methane and oxygenated ammonia blends [Murai et al. 2017]

Developments - Fundamentals

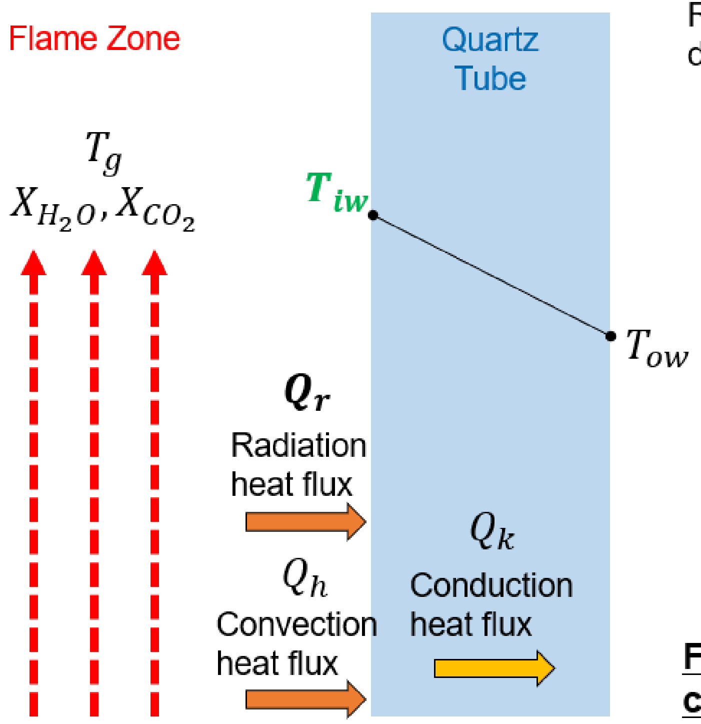


- Infrared spectroscopic measurements performed at three heights.
- Background from the hot quartz tube was taken immediately after the flame was extinguished.



Radiation measurements [Sato et al. 2025]

Developments - Fundamentals



Measured data: T_g, T_{ow}, X_{H_2O}, X_{CO_2}

[6] Hottel, H. C., and R. B. Egbert. 1941. Journal of Fluids Engineering 63 (4): 297–307.

Radiative heat flux was calculated using an approximate method developed by Hottel and Egbert[6].

$$Q_r = 0.5(1+\varepsilon_w)\sigma\left(\varepsilon_g {T_g}^4 - \alpha_g {T_{iw}}^4\right)A_{iw}$$

$$Q_h = h_w(T_g - T_{iw})A_{iw}$$

$$Q_k = \frac{2\pi L k}{\ln\frac{r_2}{r_1}}(T_{iw} - T_{ow})$$

$$Q_r + Q_h = Q_k$$

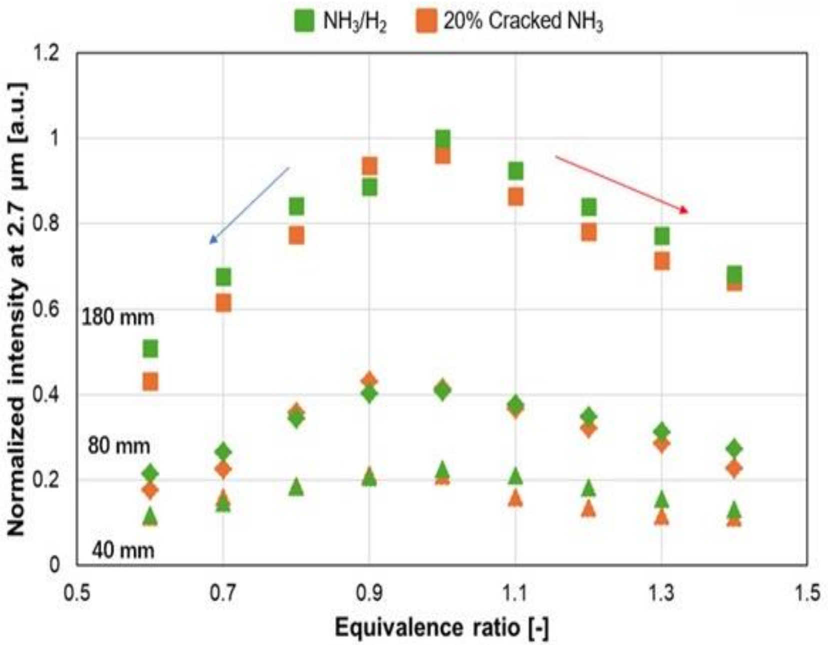
h_w: Heat transfer coefficient for inside wall
h_c: heat transfer coefficient for thermocouple
L: Quartz tube thickness
k: Thermal conductivity of quartz tube
r_1 r_2: Inner and outer radius of quartz tube

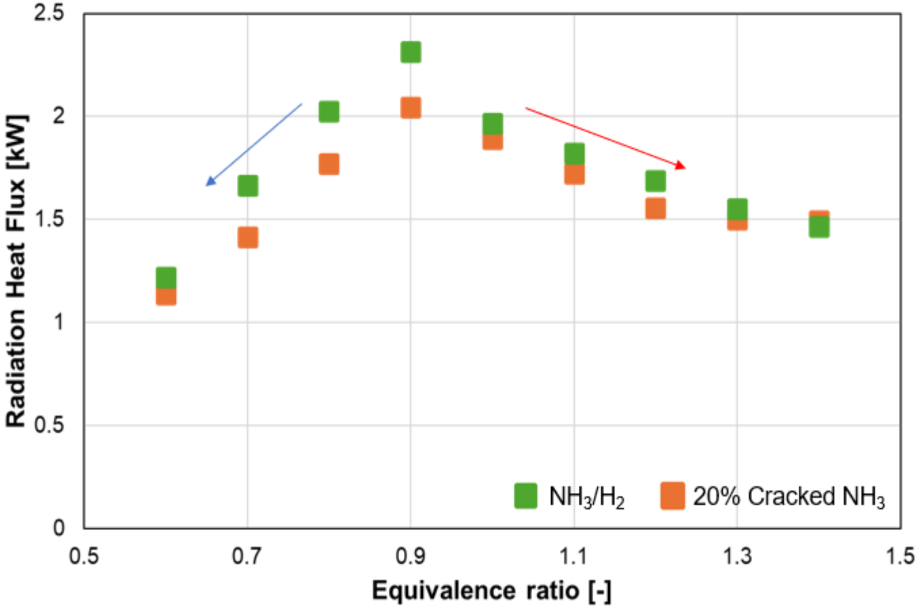
T_{iw} was able to calculate by heat flux balance.

From this calculation, the radiation heat flux (Q_r) will be compared with various conditions in next slide.

Numerical methodology [Sato et al. 2025]

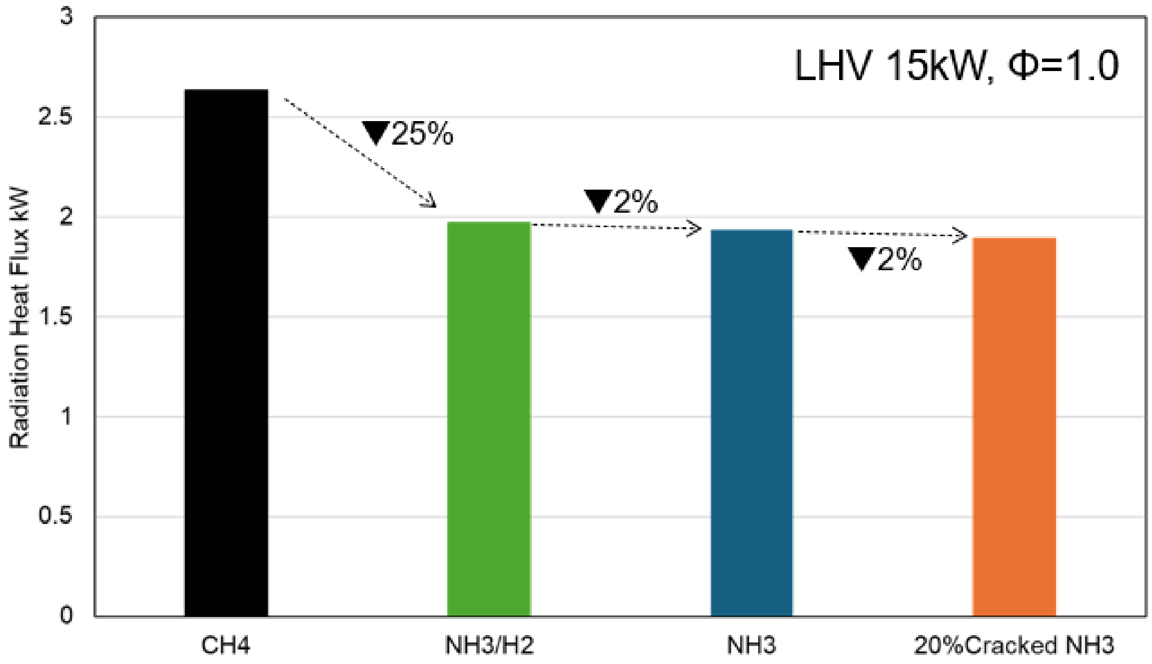
Developments - Fundamentals





Experimental and numerical results. Trends follow same pattern [Sato et al. 2025]

Developments - Fundamentals



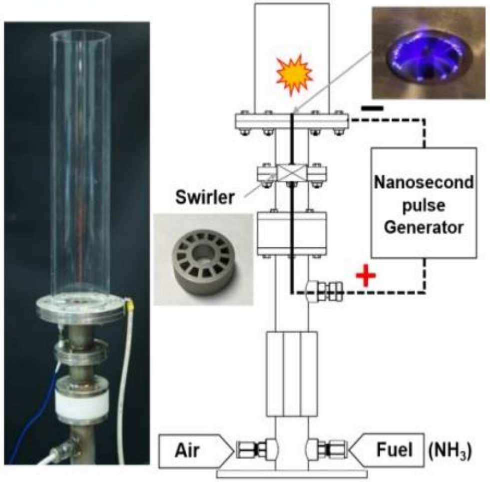
Experimental comparison between fuels.

Not ideal due to a loss in radiation by ammonia/hydrogen compared to methane (consequence of carbon species missed in the process).

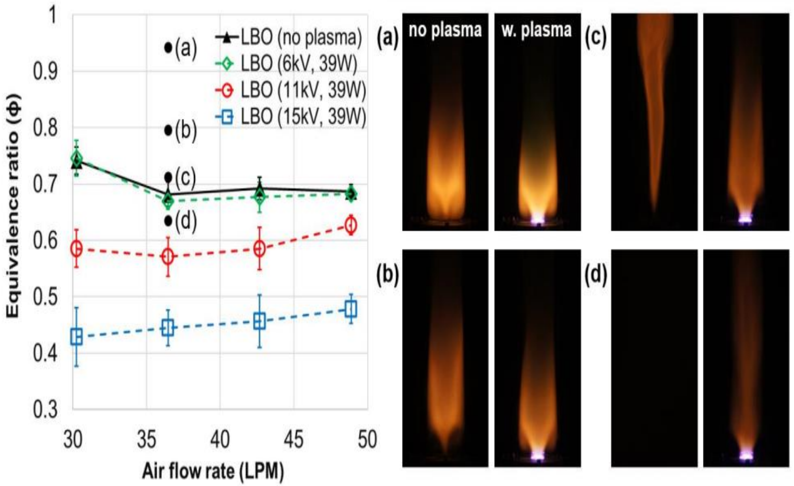
Problem that can be partially resolved by improving the thermodynamic cycles.

[Sato et al. 2025]

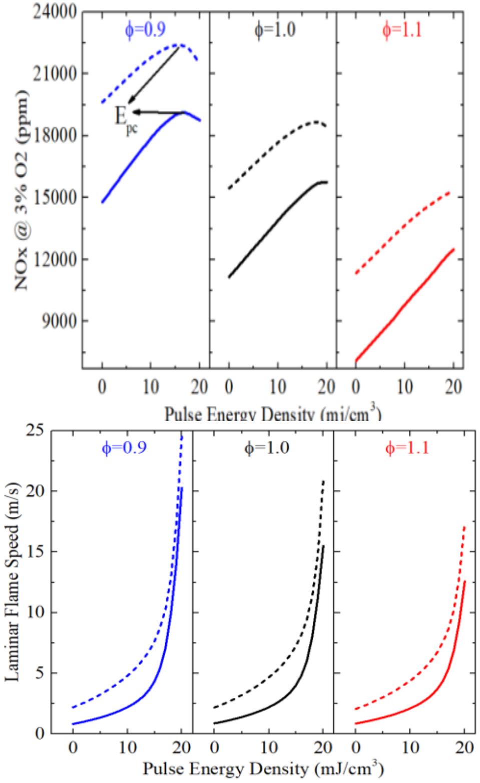
Developments - Fundamentals



Schematic of the experimental setup [Choe and Sun, AIAA, 2021]

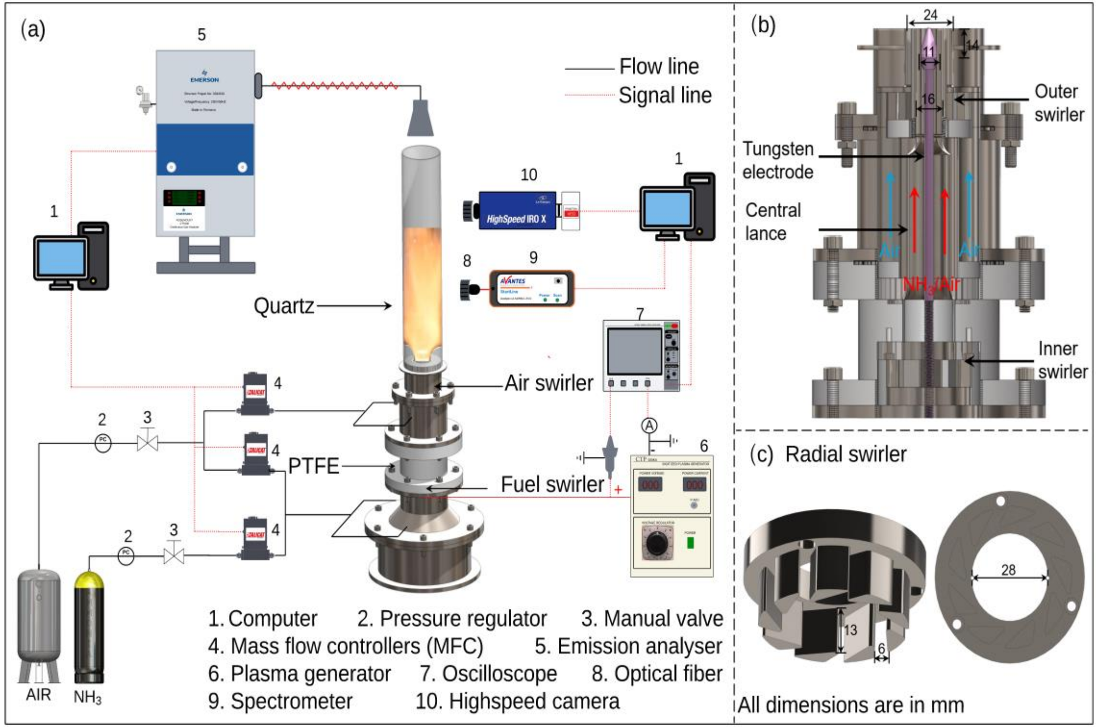


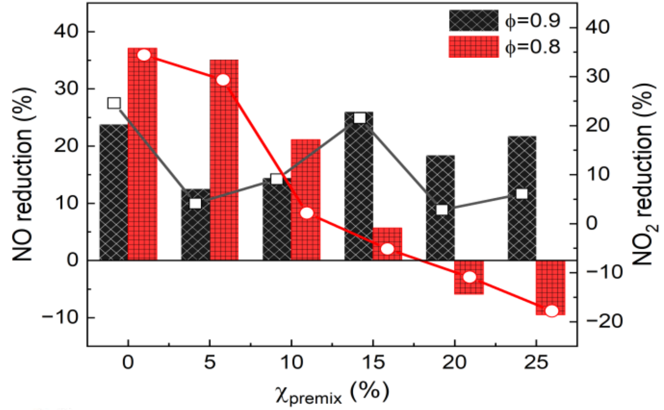
Flame stability map, and photographs of flames without and with plasma (V=11 kV, f=7 kHz, 39W)[Choe and Sun, AIAA, 2021]

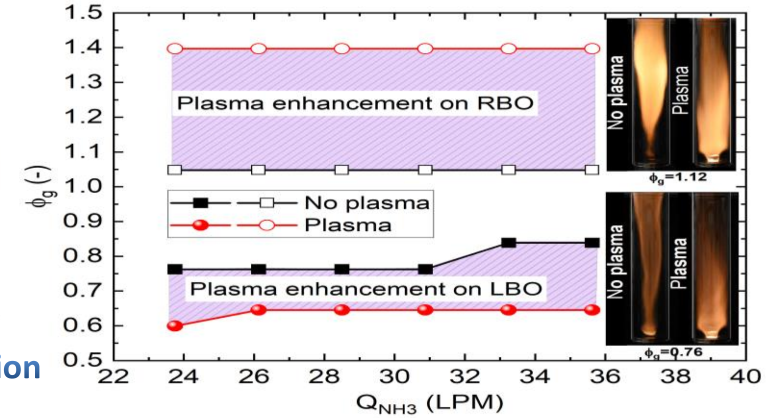


Change in NOx emissions and laminar flame speed with N2 (solid) and He (dashed) dilution

Developments - Fundamentals





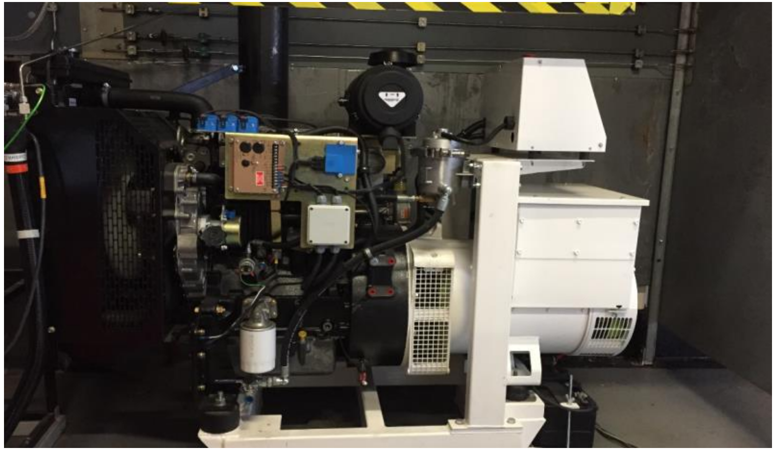


Plasma system used for ammonia/hydrogen/methane enhanced combustion

Developments - ICEs

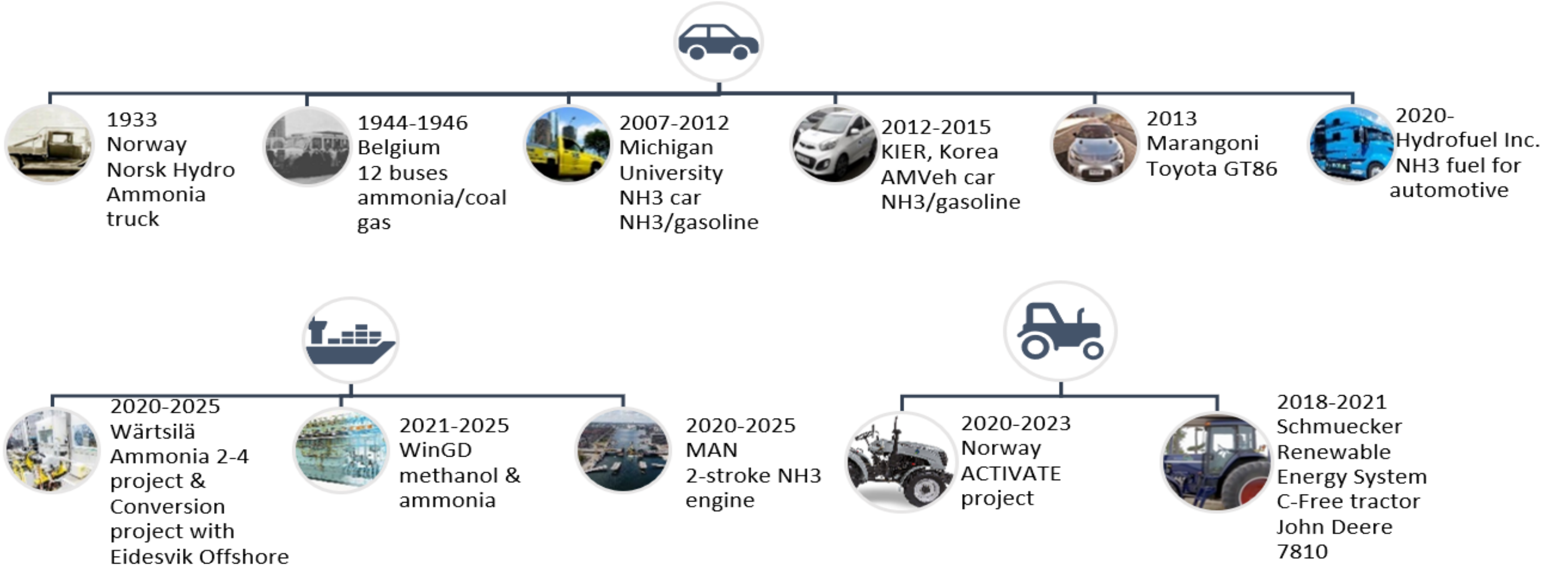
Internal combustion engine running on H2/NH3

- Ammonia Demonstrator at RAL, Oxford. Cardiff developed the ammonia engine and container for the production of power and its transmission back to the grid.



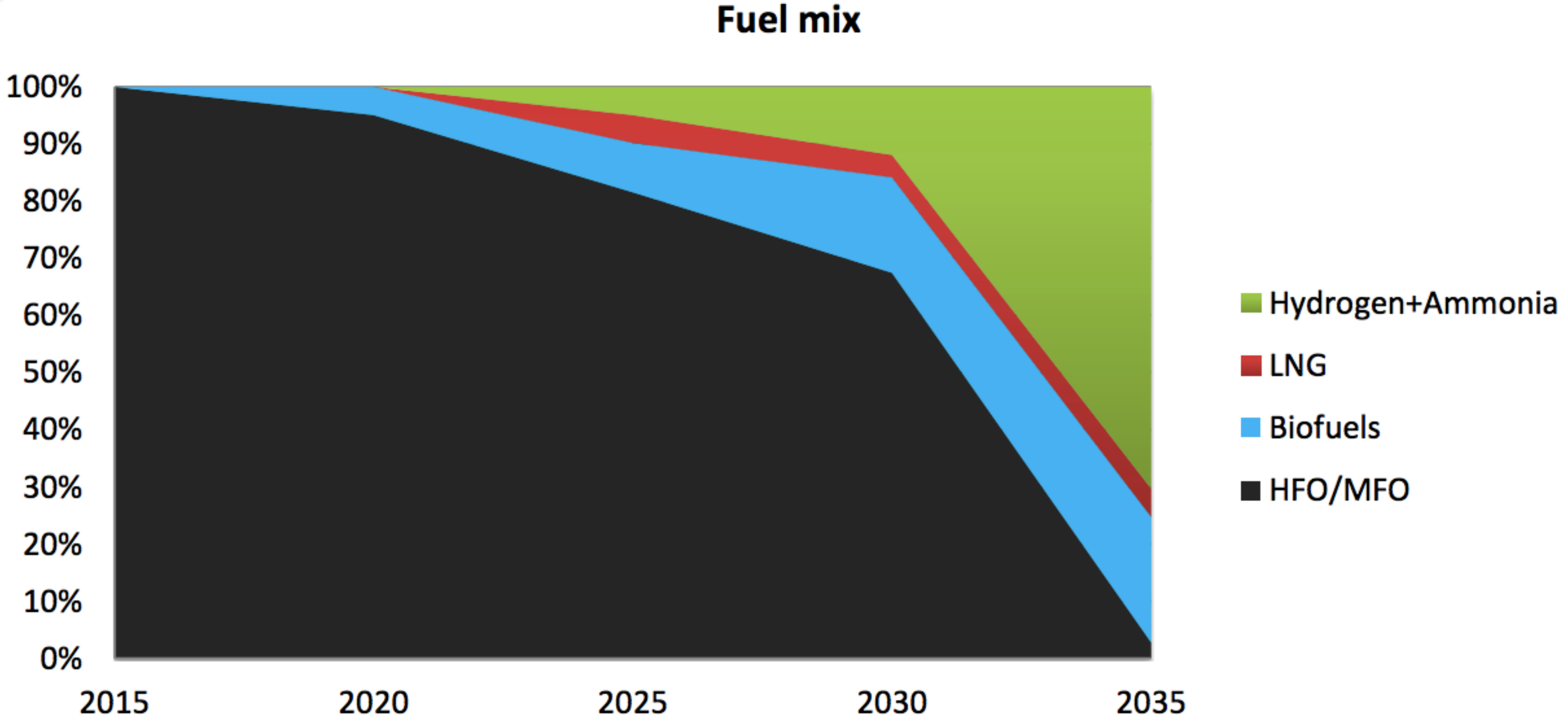
Emissions (CO2 and NOx) using ICE-H2/NH3

Developments - ICEs



Vast research in terms of Ammonia for fuelling applications in Internal Combustion Engines. Various blends (gasoline, diesel, DME, etc.) have been attempted.

Developments - ICEs



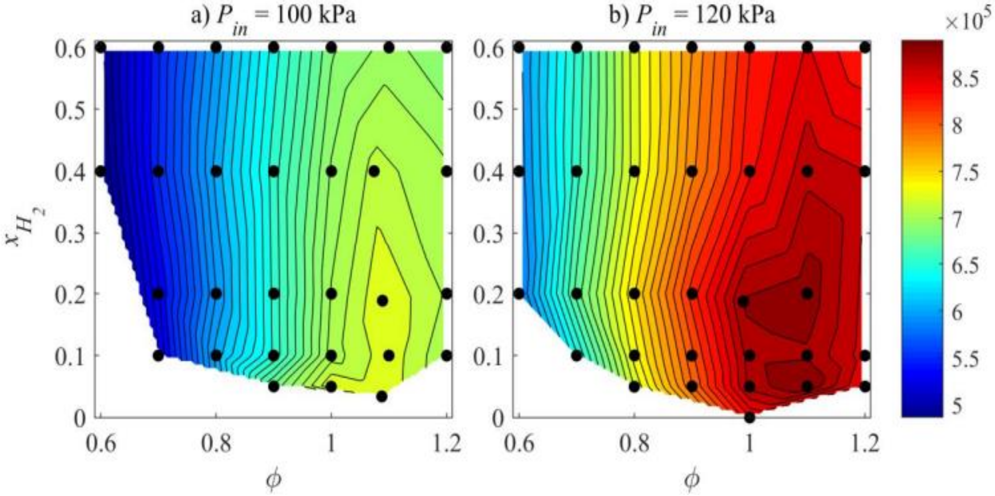
Decarbonising the marine sector, OECD, 2018.

Developments - ICEs

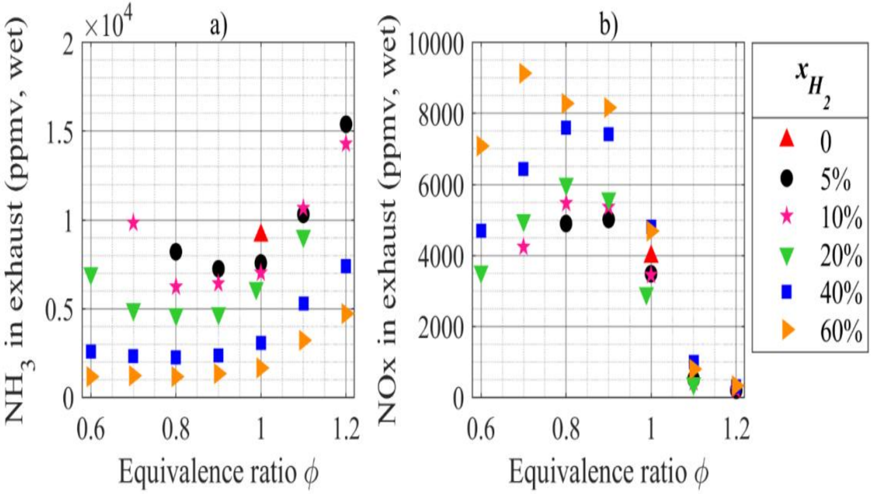
		BLEND					
		SI ENGINE				CI ENGINE	
		H2	NH3/CH4 (NG)	NH3/ syngas	Gasoline	DME	Diesel
EMISSIONS	NH3	For increasing ER: Stable until ER ~1.0 Increase when ER>1.0 Decrease with increasing H_2 content	Increase	Increase	Increase	Increase	Increase
	NOx	For increasing ER: NOx increases until ER ~07.-0.8 NOx decrease for richer mixture	Increase	Slight increase	Increase	Increase	Usually decrease
	H2	For increasing ER: Stable until ER~1.0, Increase for ER>1.0	N/A	N/A	N/A	Increase	N/A
	HC	-	Present	Decrease	Decrease (increase if with ethanol)	Increase	Usually decrease
	CO	-	Decrease	Decrease	Decrease (increase if with ethanol)	Increase	Usually decrease
	CO2	-	Decrease	Decrease	Decrease	Increase	Usually decrease

- **Combinations with various fuels denote the these fuels on the production of emissions such as Nox, unburned fuel traces (NH3, H2, UHC) and carbon species (CO, CO2).**
- **NOx are still major issues when using ammonia in Internal Combustion Engines**

Developments - ICEs

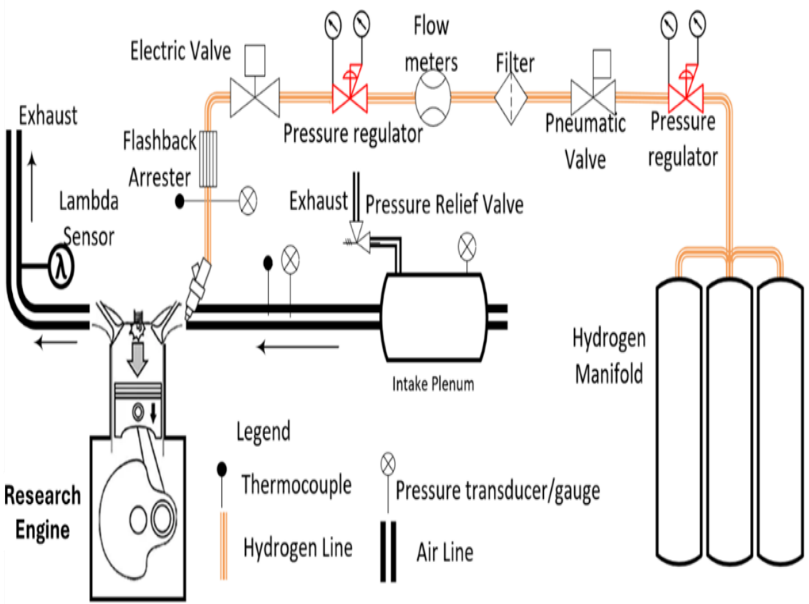


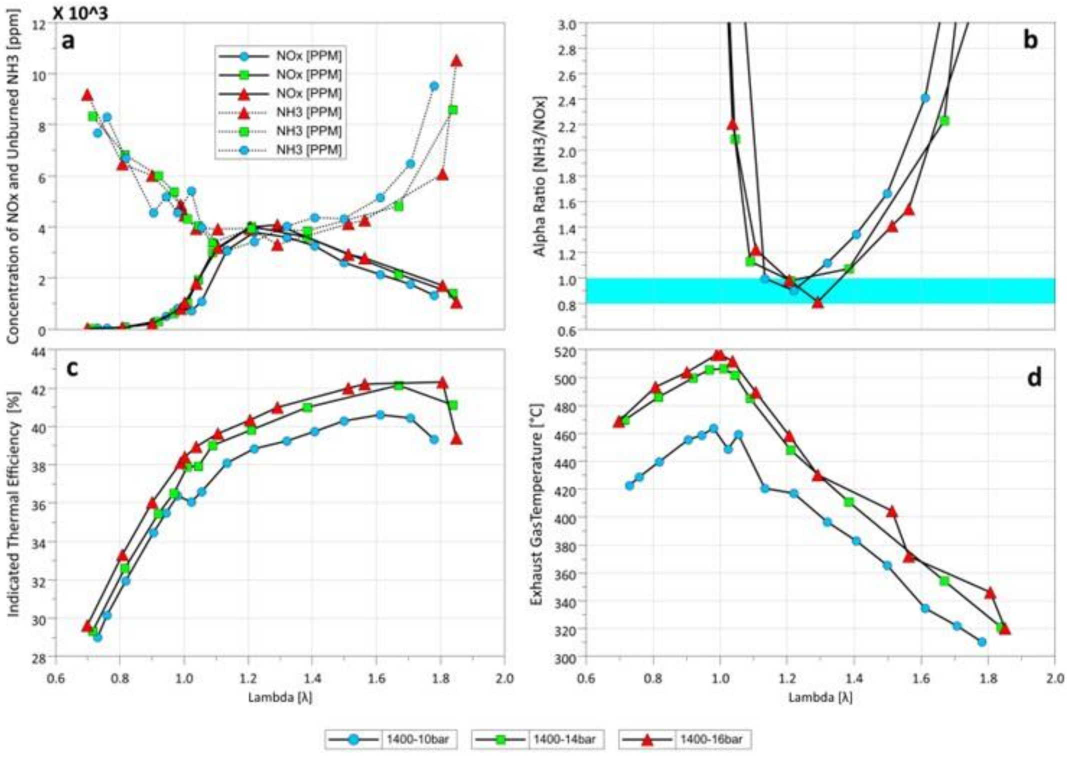
Indicated mean effective pressure measured for various mixture compositions. Circles: experimental conditions. Colour contours (see online version): IMEPn in Pa, from low values (top-left, blue) to high values (bottom-right, red) [Lhuillier et al. 2019]**.**



Pollutant emissions in exhaust at Pin = 120 kPa
[Lhuillier et al. 2019]

Developments - ICEs

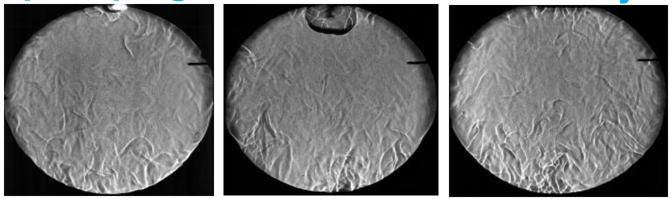


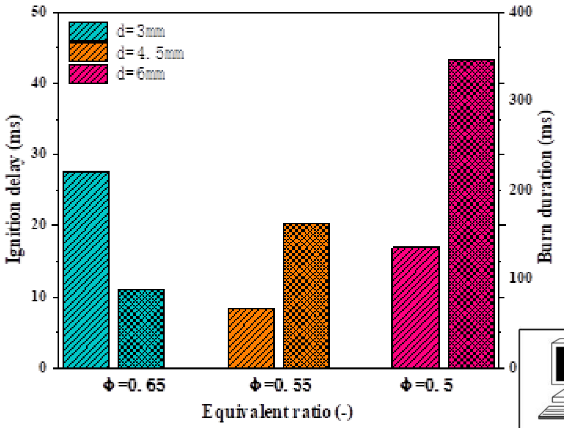


By controlling the Lambda value and mixing rate of unburned ammonia and NOx, a theoretical ratio of 1 should be able to mitigate emissions whilst providing high efficiency [Murugan et al., 2025**]**

Developments - ICEs

Normal spark plug	High energy spark plug	Ignition chamber jet



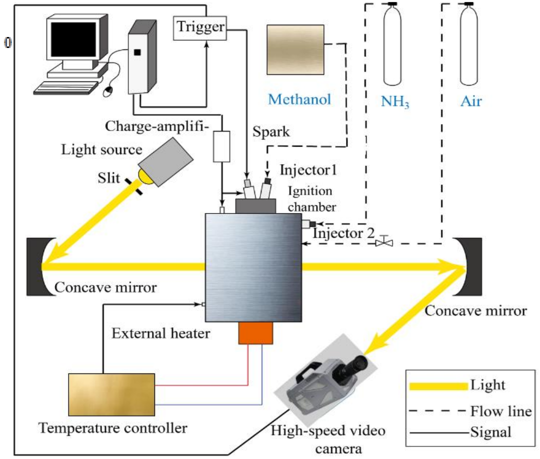


Ignition chamber jet vs Normal spark plug

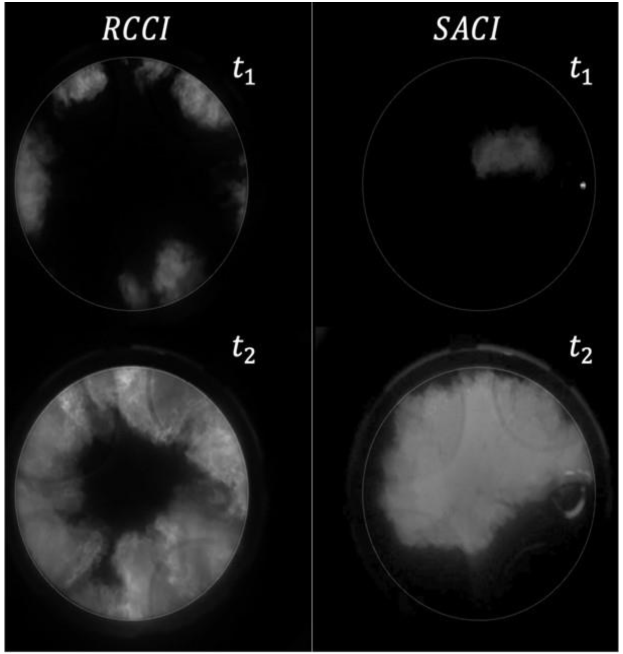
Combustion duration ↓72%

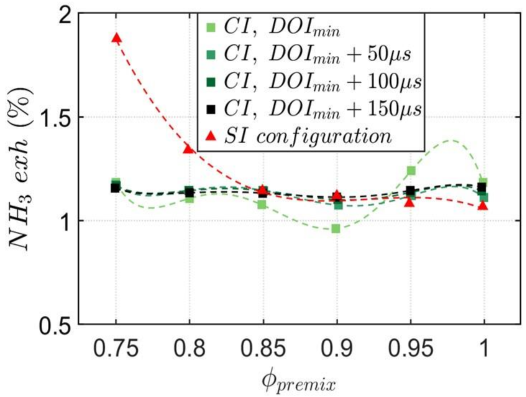
Combustion Efficiency ↑8%

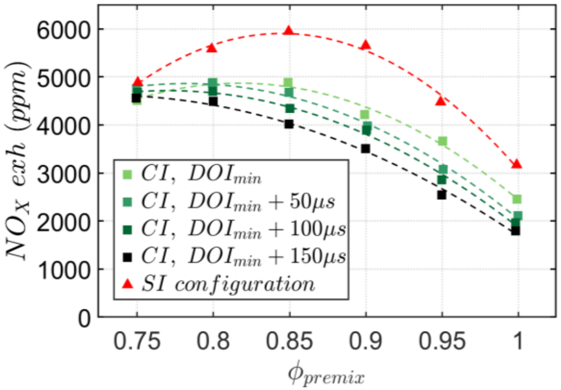
Impact of injection method, jet nozzle diameter and rig set up using ammonia-methanol
[Courtesy of Dalian Tech Univ, 2023]

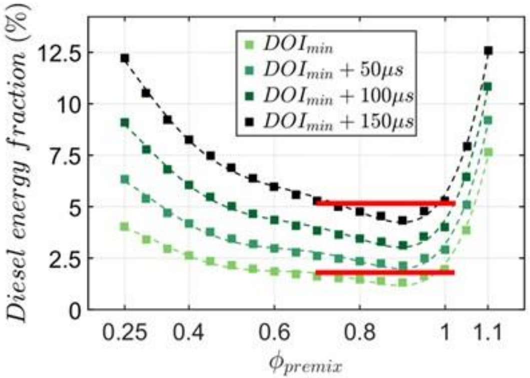


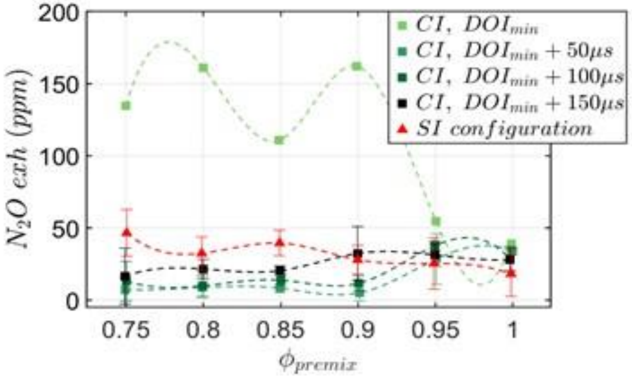
Developments - ICEs



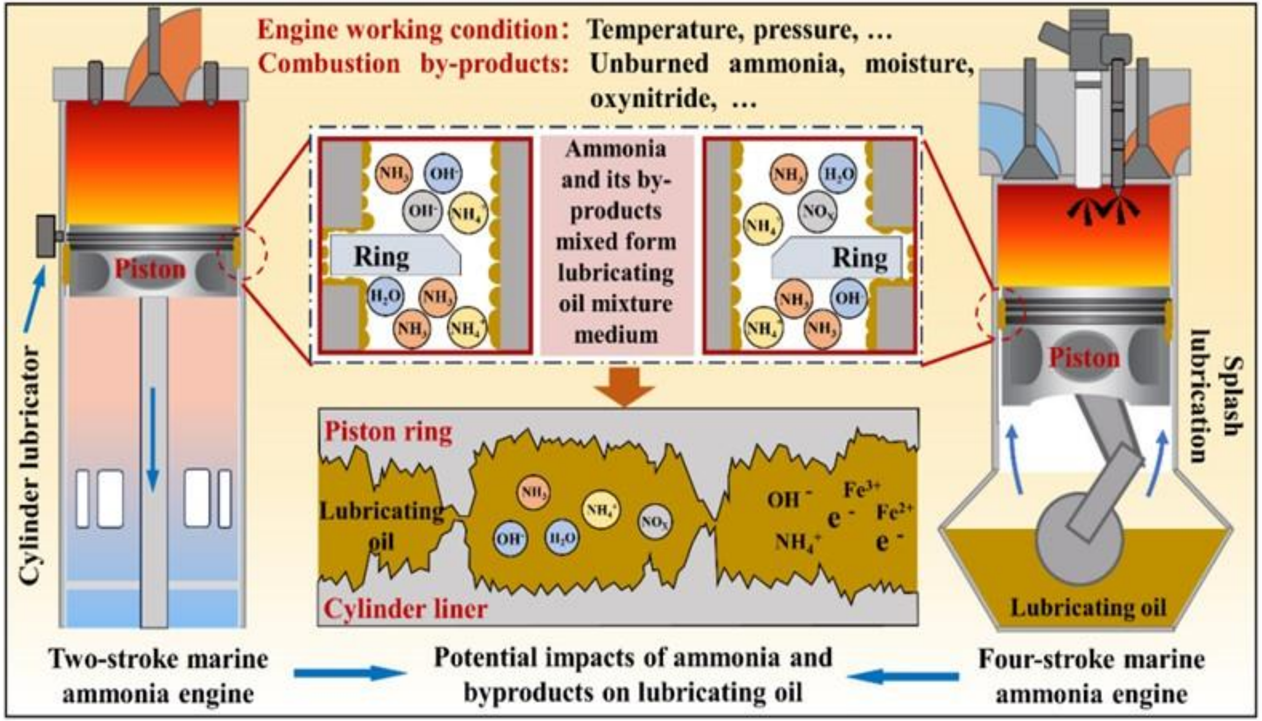








SI vs RCCI Engines using NH3 [U. Orleans]



Ammonia addition leads to,

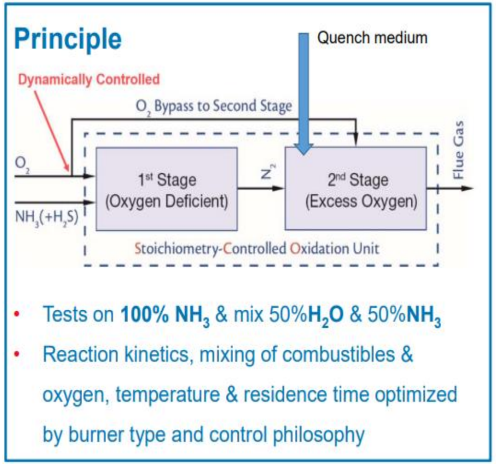
- More opacity
- Change in viscosity
- Lower temperature stability
- Recombination of species which lead to additional reactions in the lubricant
- Calcium and magnesium precipitates
- Greater wearing

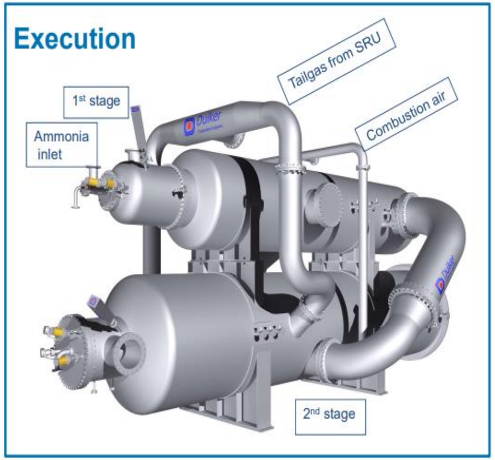
Mechanistic insights into evolution of lubricating oil in marine ammonia engines: from molecular interactions to macroscopic performance [Rao et al. 2025]

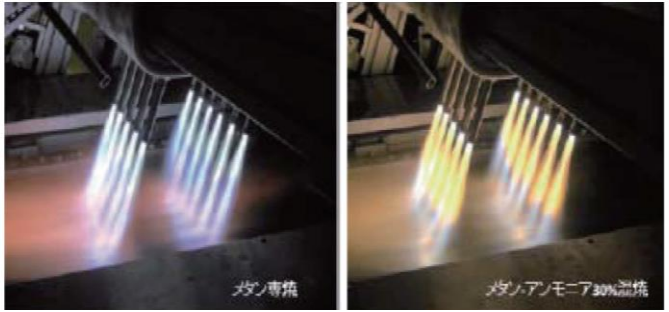
CONCLUSIONS (day 1)

- Ammonia can be used to decarbonise cooling, heat, power and propulsion generation.
- Ammonia blends can be used efficiently, although care needs to be taken to keep stable flame profiles and low NOx.
- The use of novel systems is currently attracting vast scientific attention as a way to mitigate emissions and improve ammonia reactivity (Holy Grails of Ammonia Combustion)
- The marine sector will open the use of ammonia fuelling commercially by the end of the decade. However, many technicalities still need to be resolved.

Developments – Boilers/Furn.



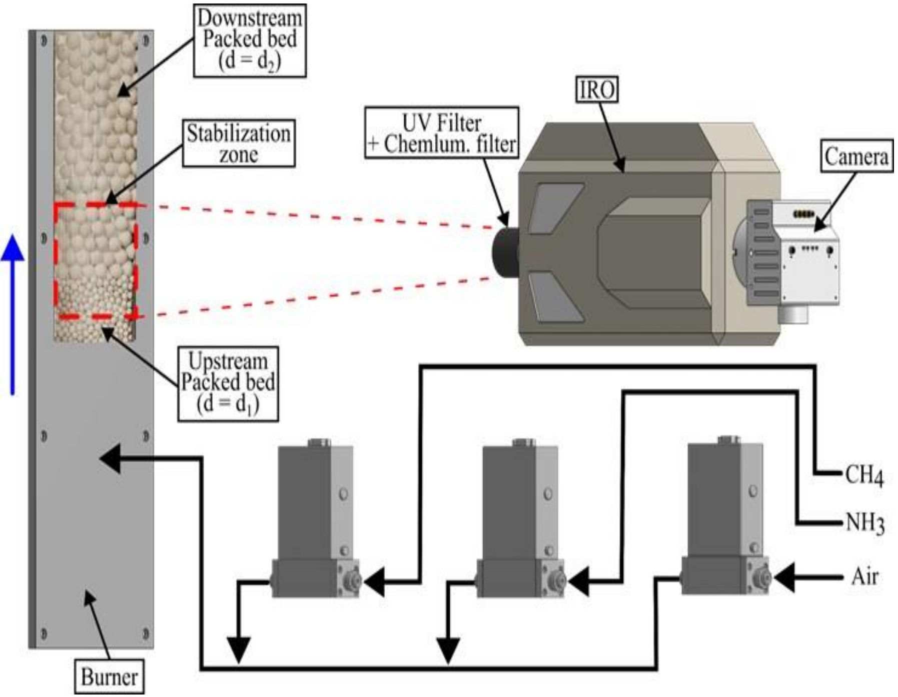


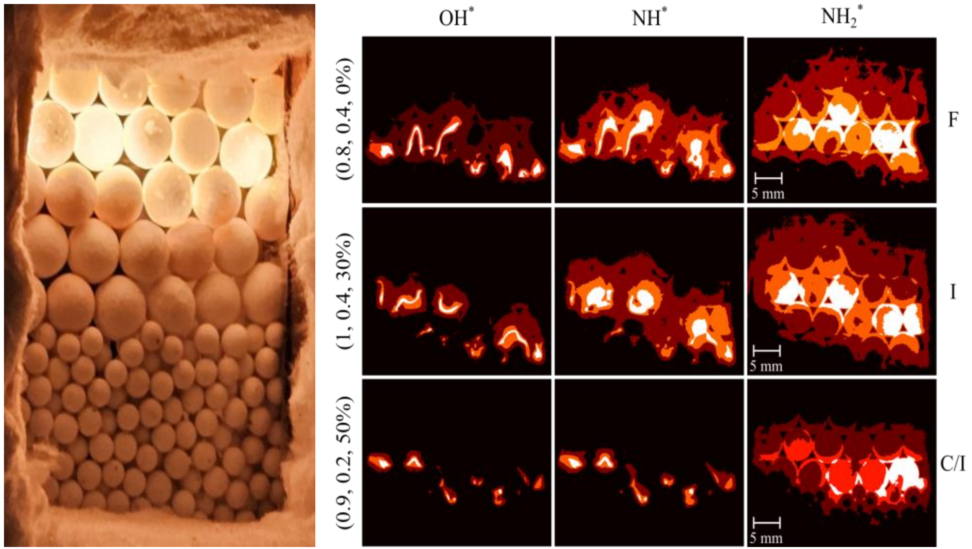


Stoichiometric Controlled Oxidation (SCO) technology developed by Duiker [with permission from Duiker Combustion Engineers**]**

Other programs for steel plates, ceramic kilns, replacing natural gas by ammonia.

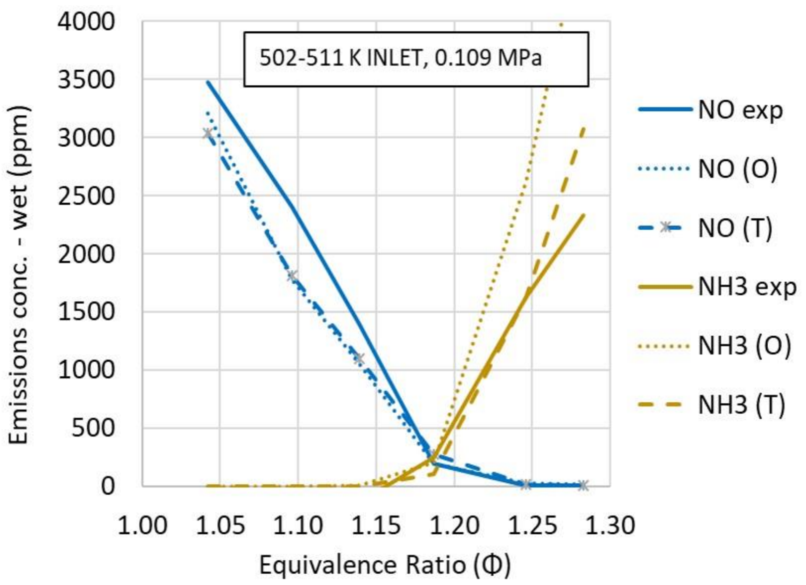
Developments – Boilers/Furn.



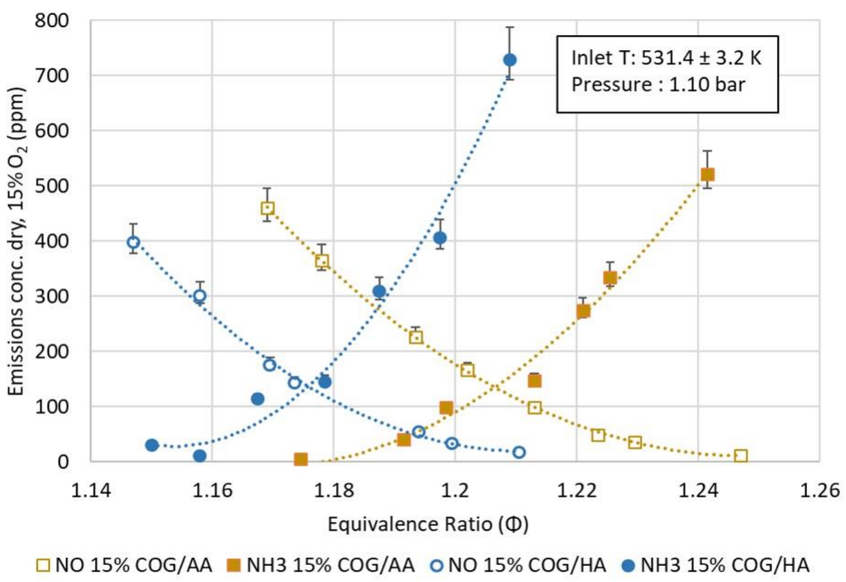


Porous media employed to burn ammonia/methane at low power (2kW). As expected, pellet density had an impact on the final emissions/combustion efficiency.

Developments – Boilers/Furn.

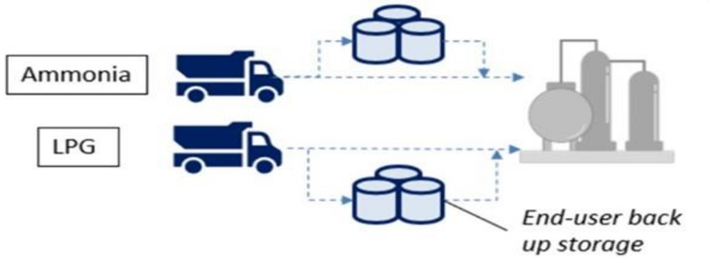


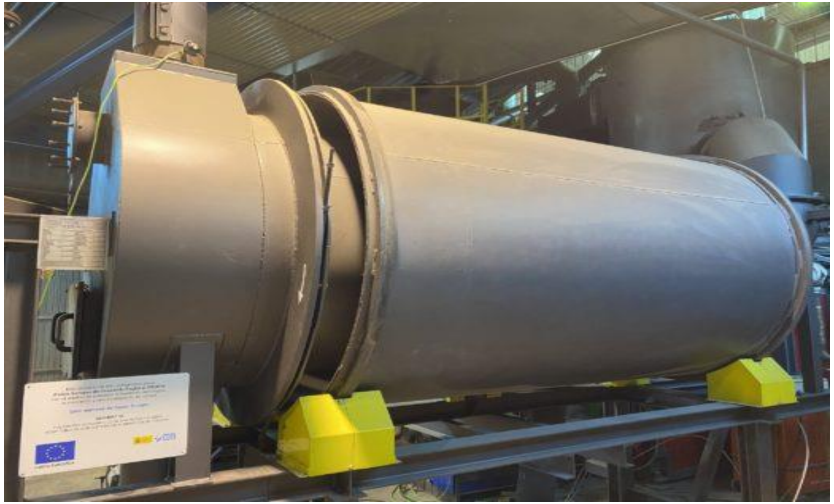
Correlation between experimental and numerical models [Tian and Okafor] using COG (20%) and Ammonia [Hewlett S, 2022]



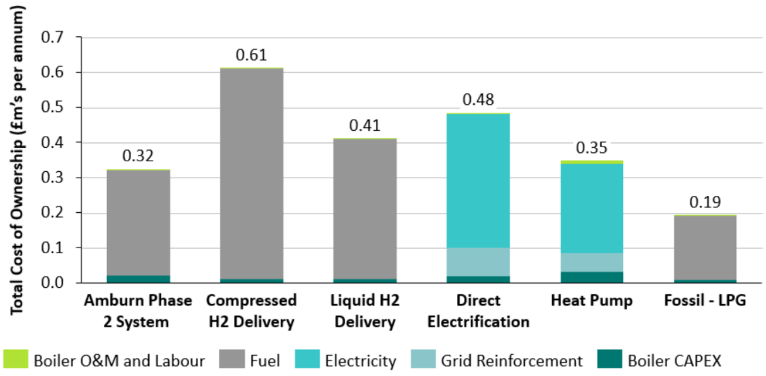
Shift in the reaction by using Humidified (60% water) ammonia blends [Hewlett S, 2022]

Developments – Boilers/Furn.



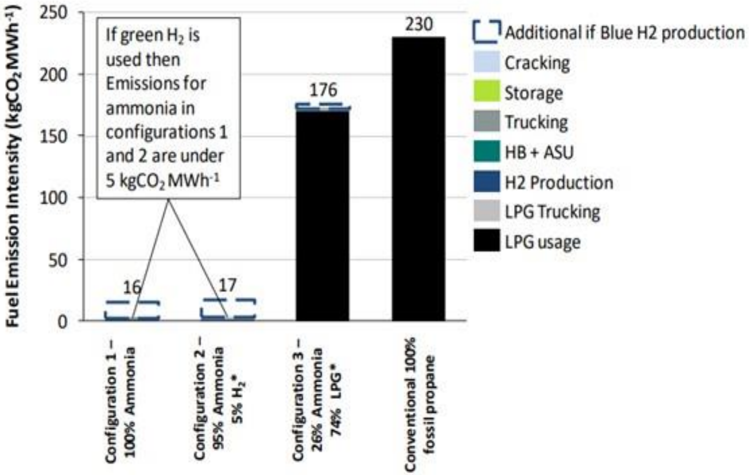


Pure and Residual ammonia can be used for extra power



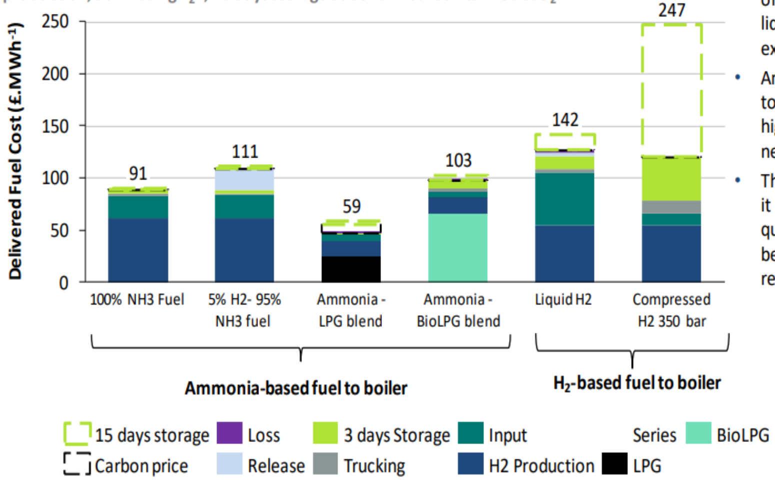
- Works in collaboration with TATA steel and the South Wales Industry have led to the recognition of several streams, product of waste gases, from which ammonia can be recovered for additional power generation via engines, gas turbines or furnaces.
- Current work is taking place with FloGas for new burners running up to **2MW**.

Developments – Boilers/Furn.



Scenario 1: Delivered cost of fuel to an industrial end users comparing low-carbon ammonia and H_2 fuels with increased end user storage at boiler site, 15 days (£.MWh^{-1}, Lower Heating Value)

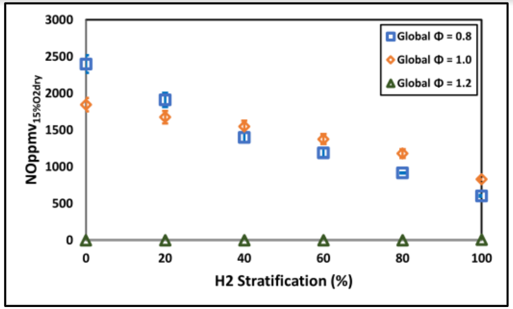
12 MW distillery, 200 km distribution distance, large scale 200MW NH_3 synthesis, Blue H_2 production, at £1.80.kgH_2^{-1}, 15 days storage at boiler – Carbon tax £50 tCO_2^{-1}

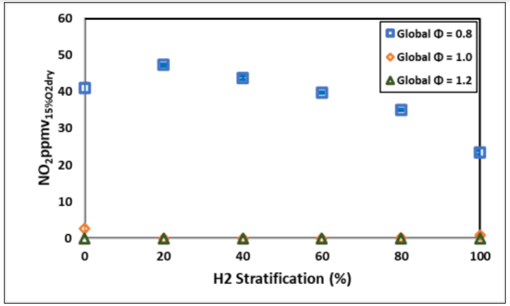


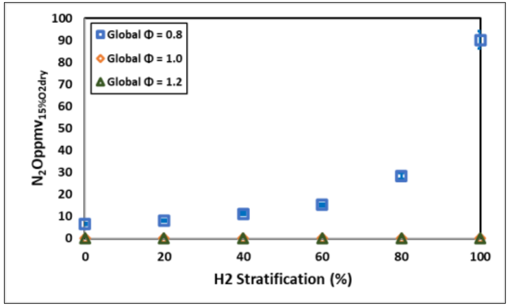
- Existing off-gas grid boiler sites have between 10 and 15 days of storage.
- If this higher storage is needed Ammonia offers a comparative cost improvement over liquid and compressed hydrogen which are expensive to store.
- Ammonia can be stored at similar conditions to LPG whilst compressed hydrogen needs high pressures (350 bar), or liquid hydrogen needs extremely low temperatures (-253℃).
- Though this gives an advantage to ammonia, it may be that for new technologies lower quantities of storage are used due to storage being more expensive and possible regulatory/safety constraints.

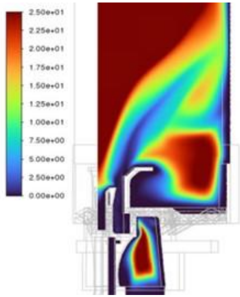
Emissions and Delivery Fuel Cost of various options (report 2023, 145 pages)

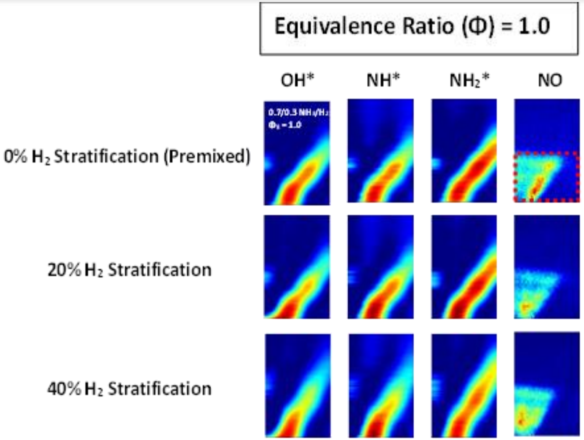
Developments – Boilers/Furn.







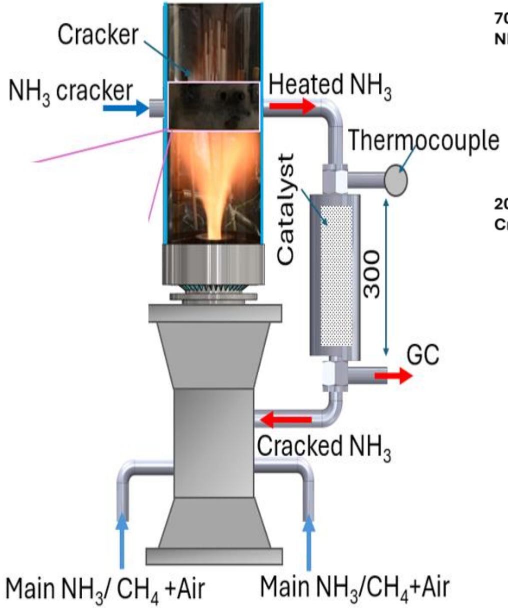


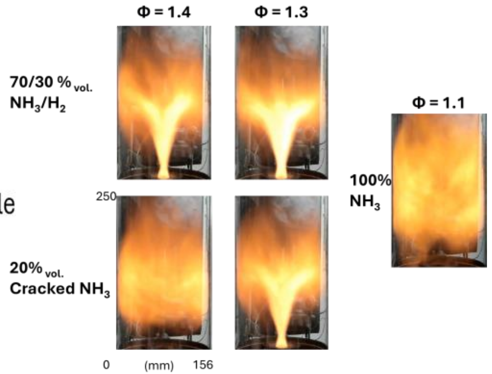


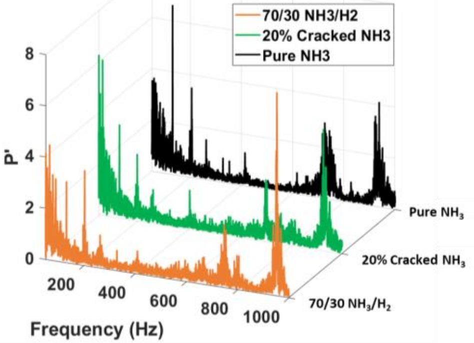
Stratification brings down NO whilst complex CFD models validate the stable nature of the flame.

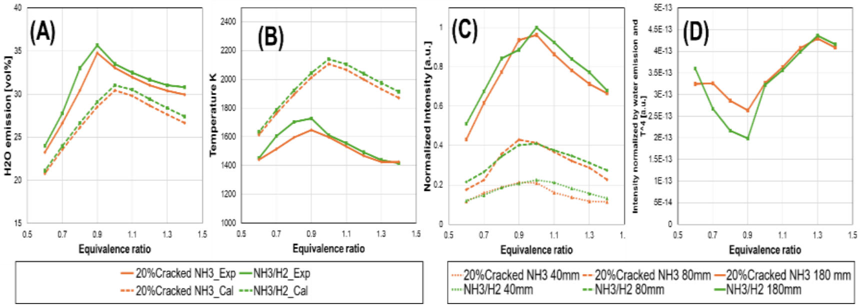
Stratification appears as a good potential for NOx mitigation whilst enabling good flame stability (Mashruk et al 2023 JAE).

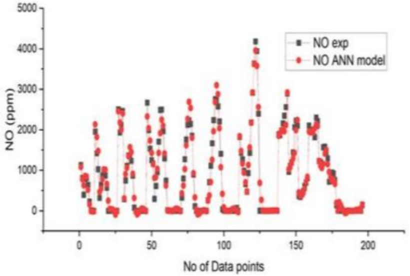
Developments – Boilers/Furn.

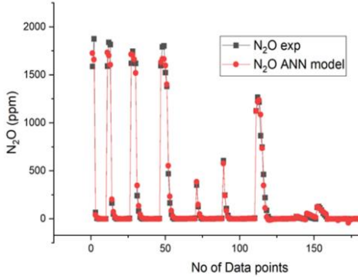






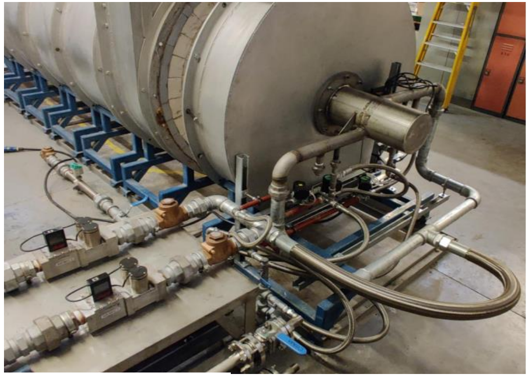




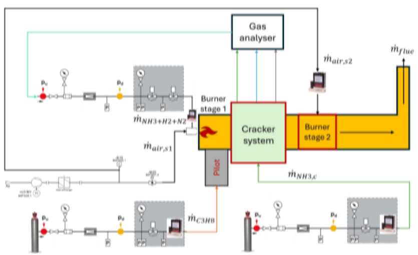


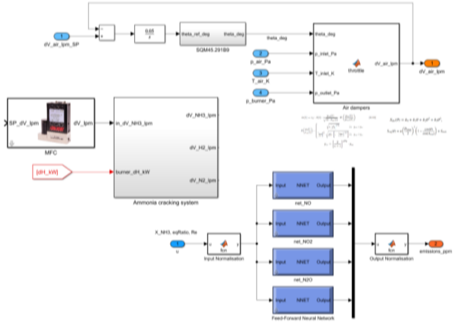
Fundamental work on cracking, thermoacoustics, radiation, neural networks and chemical kinetics (presented at the 3rd Symp Ammonia Energy)

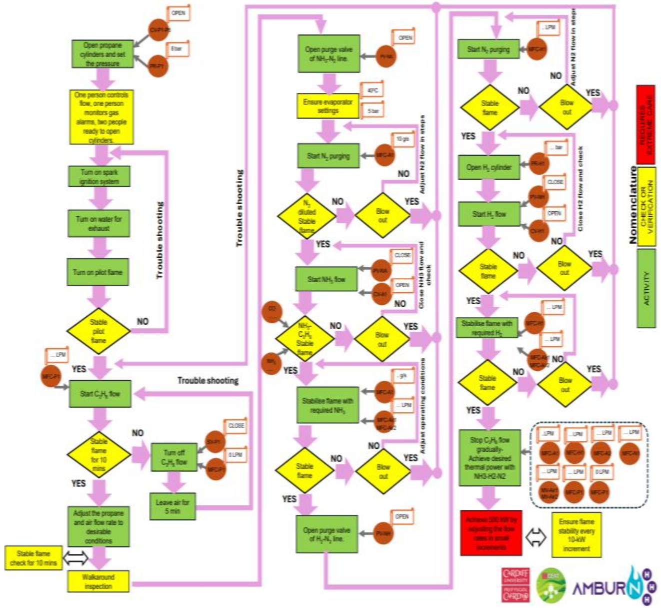
Developments – Boilers/Furn.



Automatic ammonia-hydrogen (NH_3/ H_2) combustion system



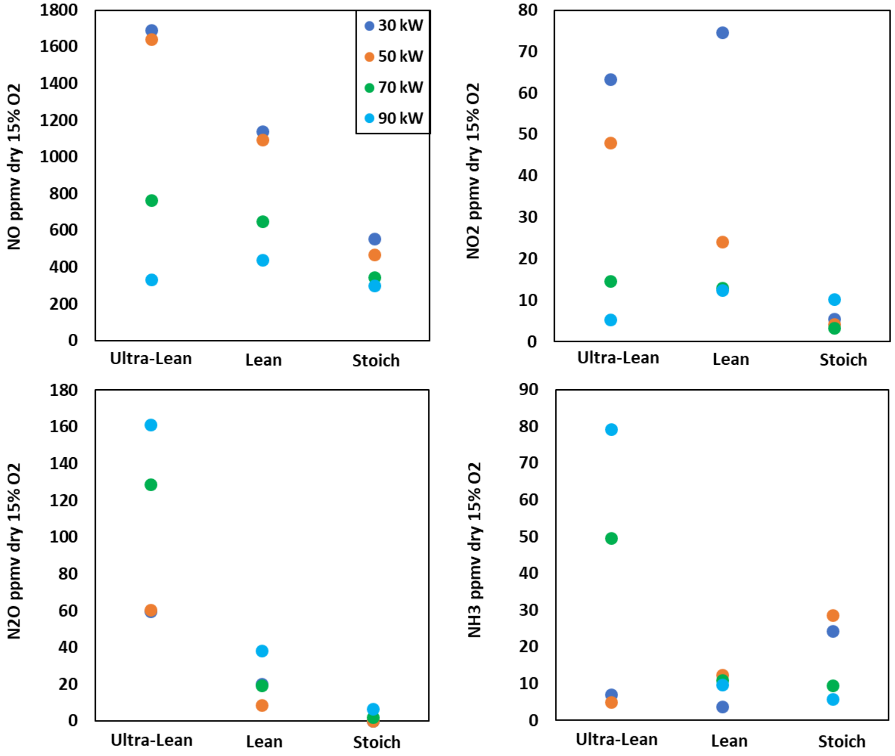




Commissioning, Control Design using AI, Bespoke Protocols, HAZID/HAZOP, Dispersion analyses

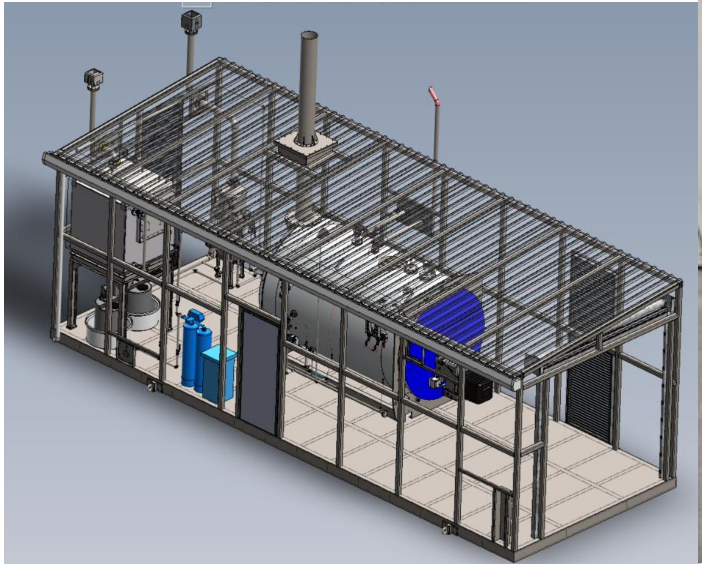
Developments – Boilers/Furn.

300 kW flame using 70-30% NH3-H2

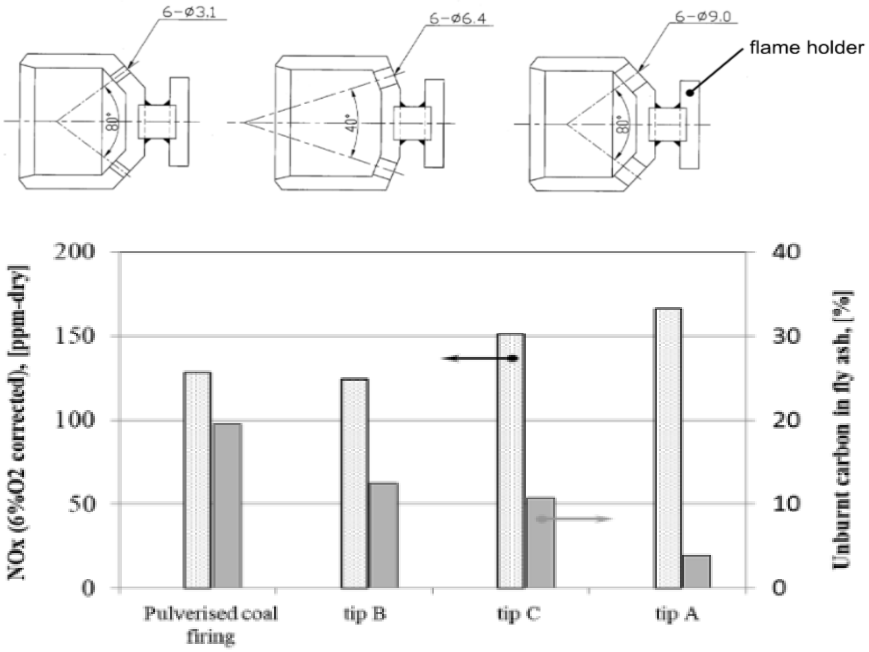


Developments – Boilers/Furn.

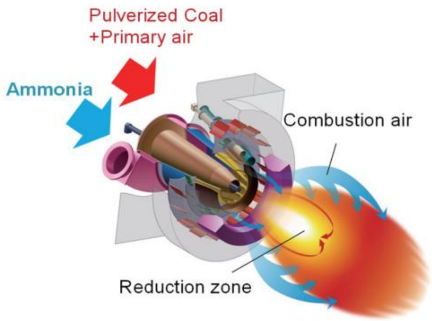
The unit will be used for demonstration in a Poultry farm. Further developments are expected for the deployment of ammonia to isolated regions.



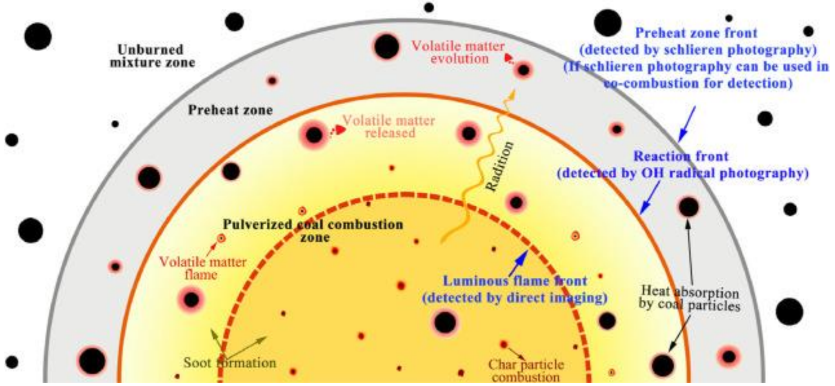
Developments – Boilers/Furn.



Various ammonia tips (A, B, C from left to right) and emission results at 35% ammonia co-firing content (vol) [Tamura et al 2020]



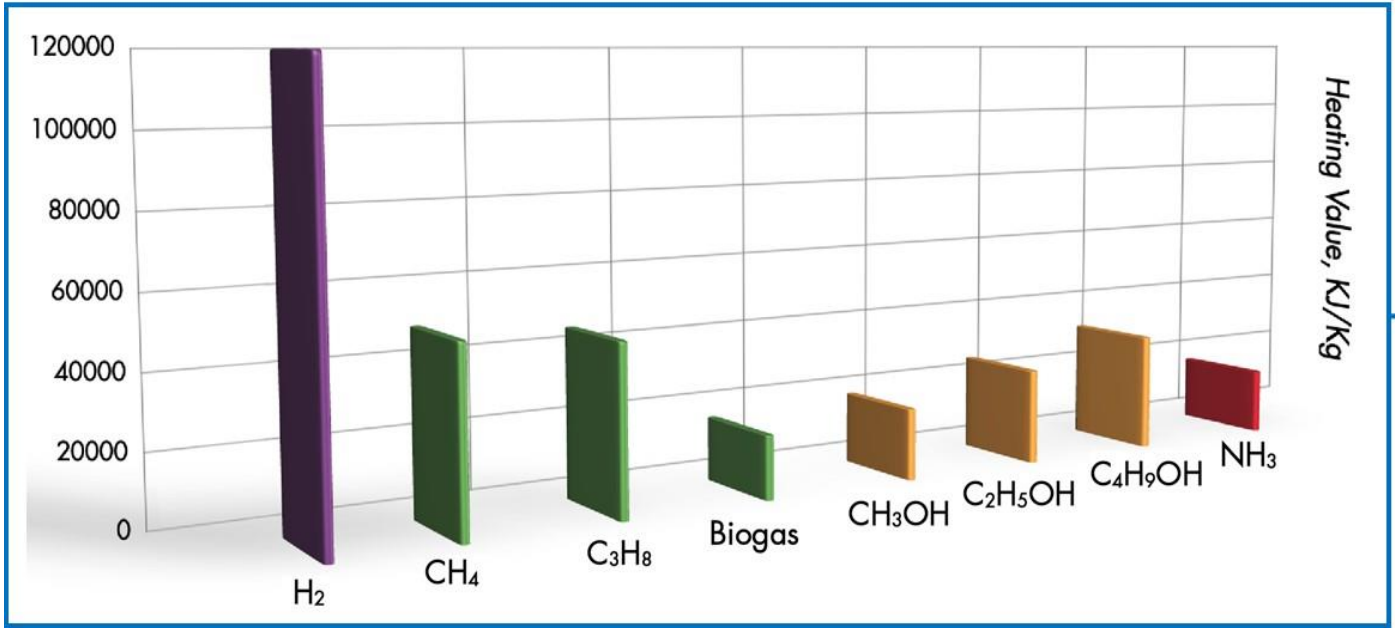
IHI Burner [Ito et al 2019]

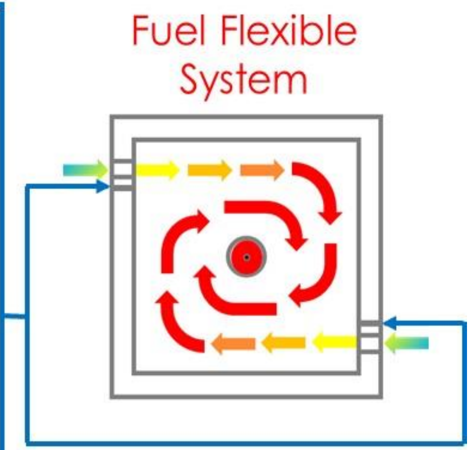


One dimensional assumption of co-combustion flames [Xia et al 2020]

Developments – Boilers/Furn.

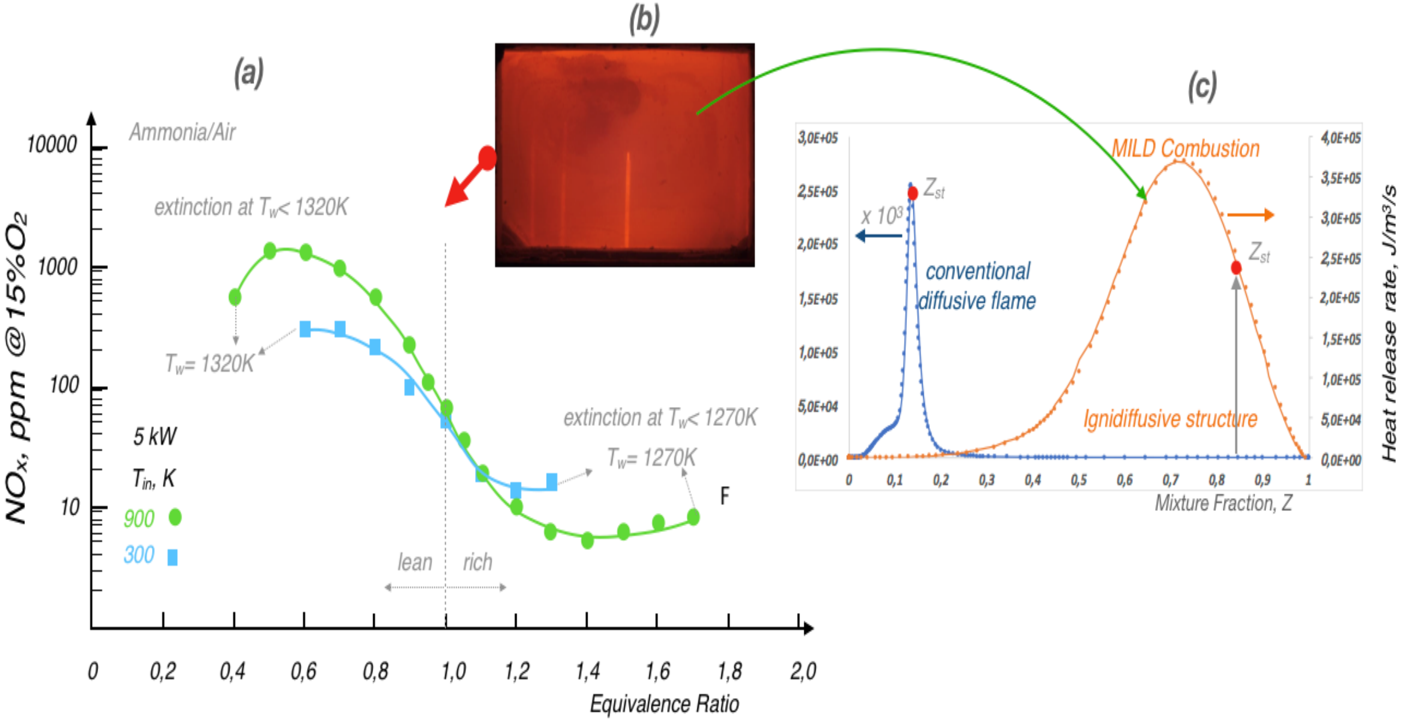
MILD combustion enables multi-fuel operation





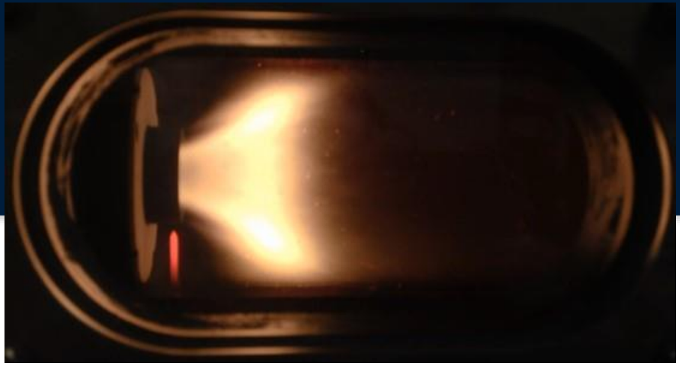
MILD Combustion using a variety of fuels.

Developments – Boilers/Furn.

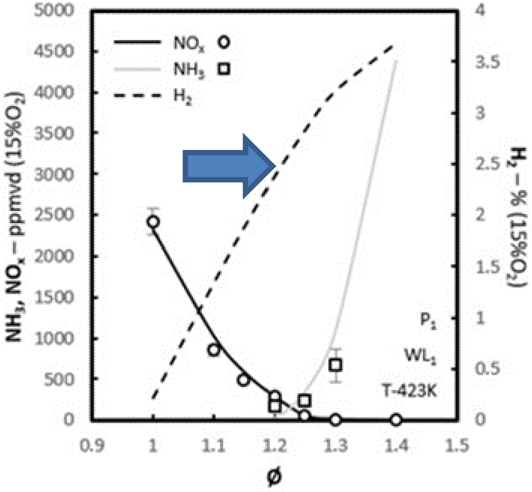


Emissions from the use of MILD Combustion employing ammonia/air [Valera-Medina et al. 2020]

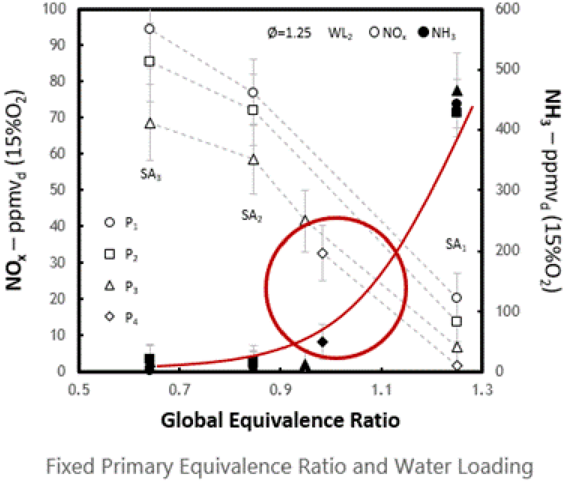
Developments – Gas Turbines



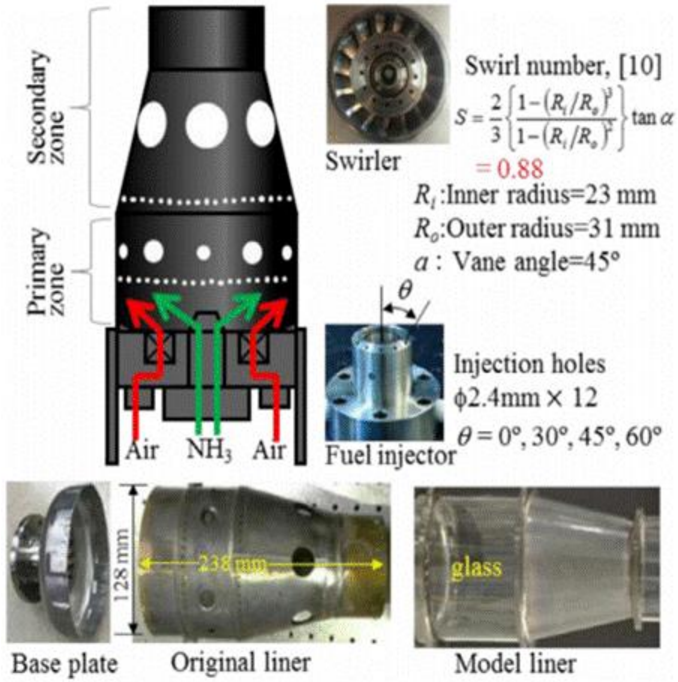
$70\%_{vol}$ NH3 $30\%_{vol}$ H2. Cardiff University.



Clear reduction of NOx at high E.R. and high concentration of hydrogen

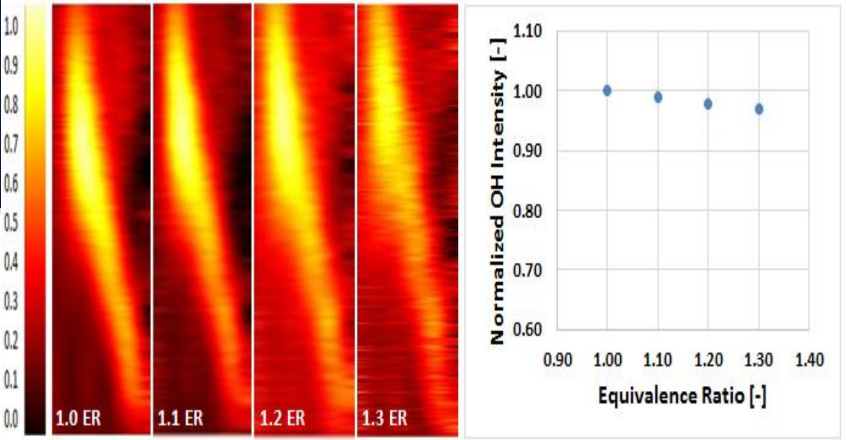


Secondary Air (SA) addition with steam injection. Cardiff University [Pugh et al, 2018]

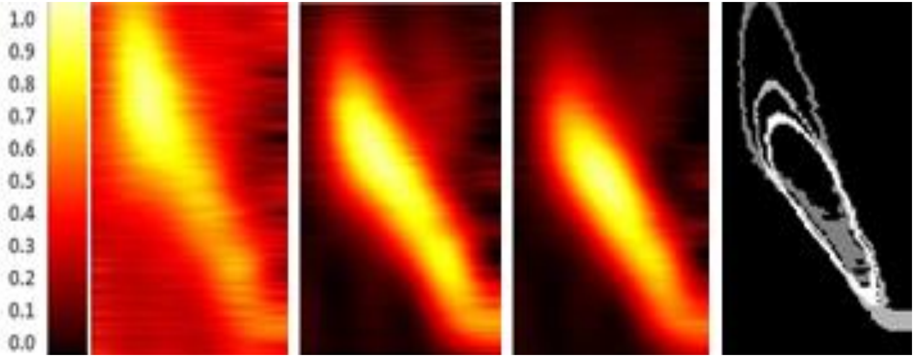


The MGT high-swirl combustor [Okafor et al, 2018]

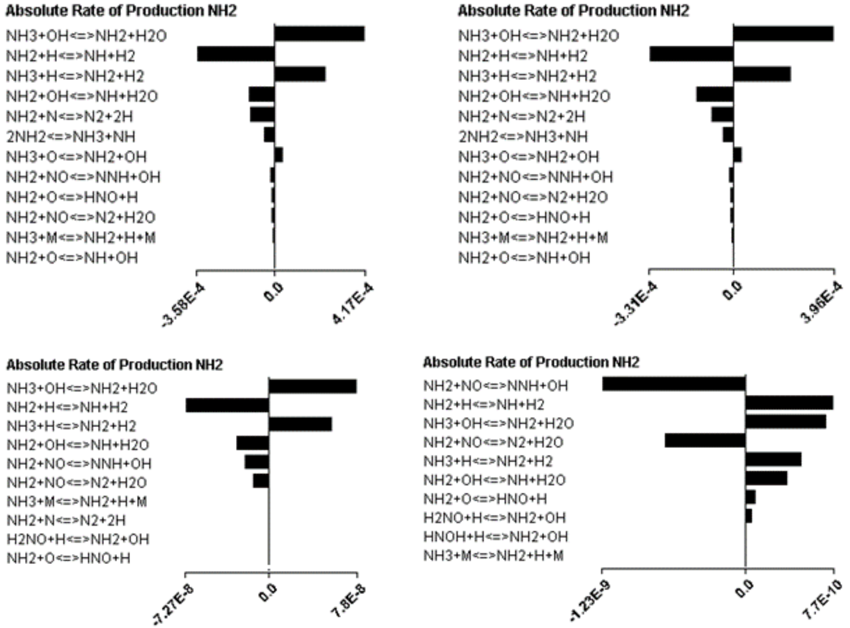
Developments – Gas Turbines



OH profiles and Normalized values, room temperature [Valera-Medina et al. 2018]

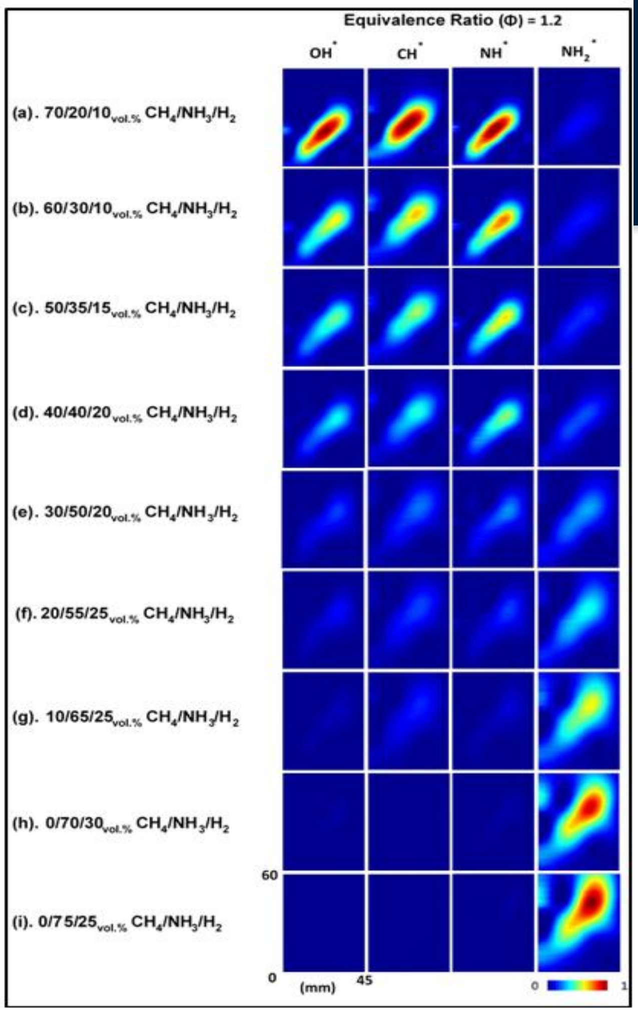


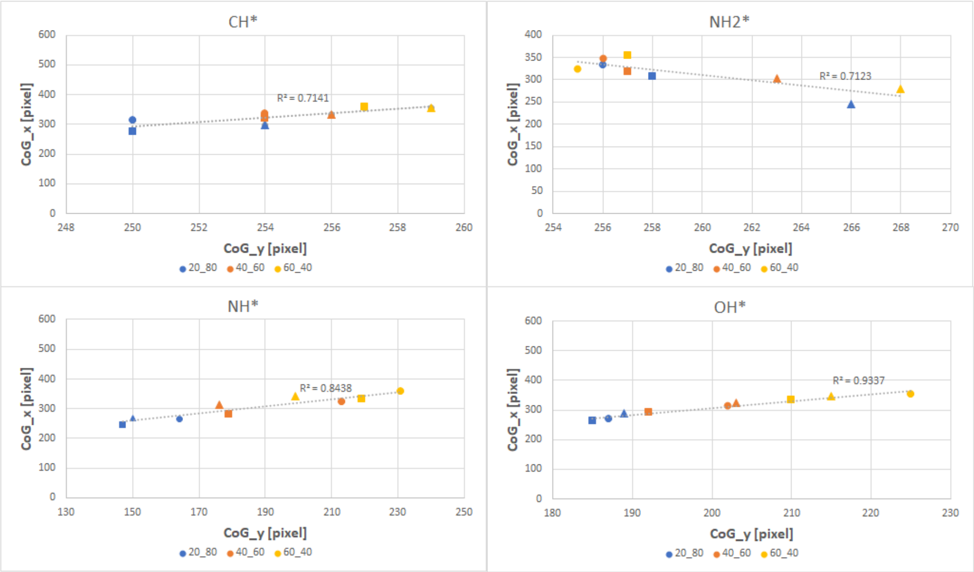
OH profiles and Normalized values. A) 288K; B) 400K; C) 500K; D) Comparison



NH2 rate of production at 1) the flame zone and 2) post-combustion zone; left) 288K, right) 500K.

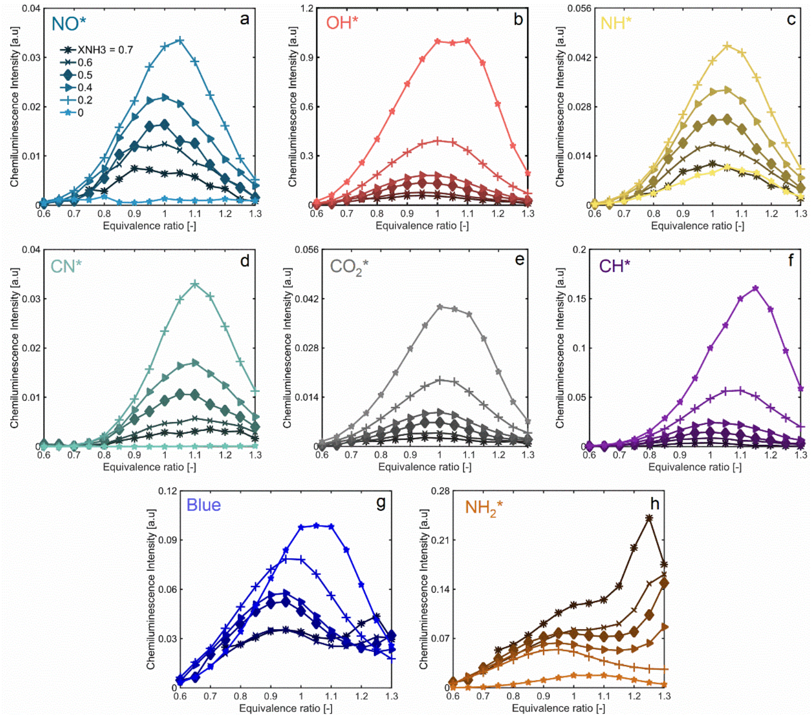
Developments – Gas Turbines

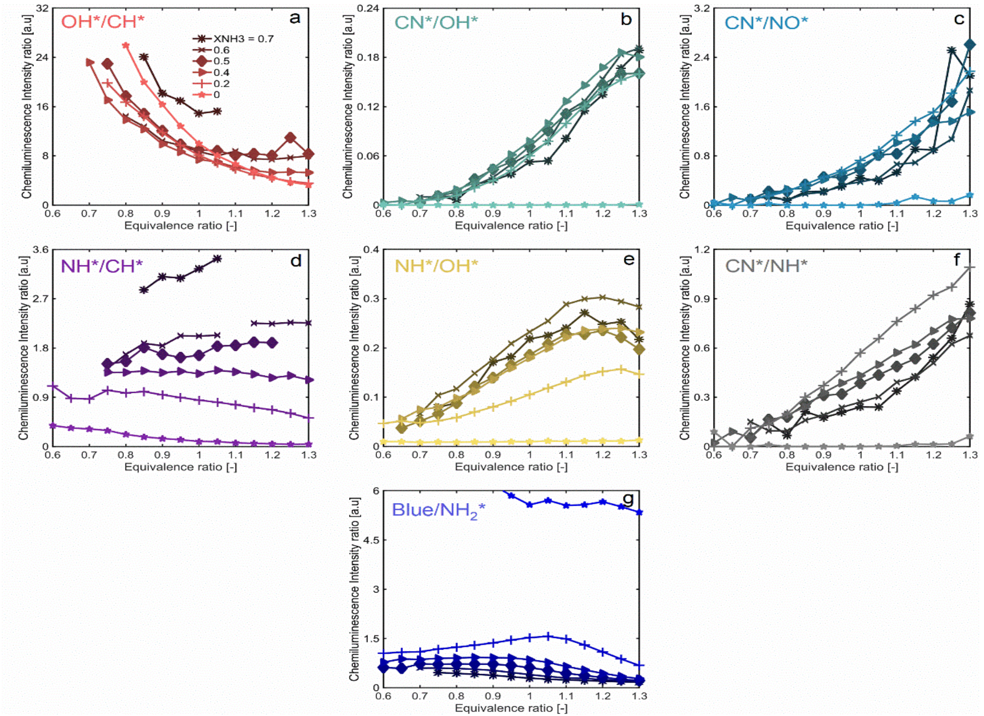




Chemiluminescence profiles using various ternary blends. Ammonia increase augments NH2 whilst decreasing the intensity of other radicals.

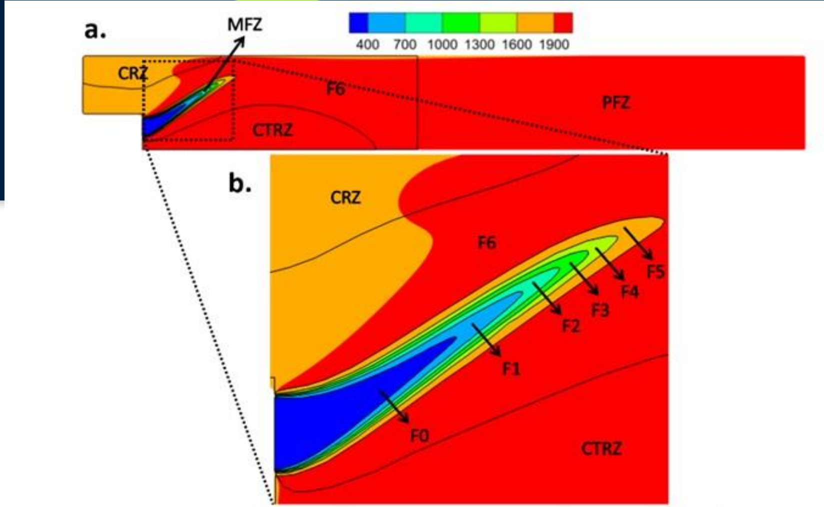
Developments – Gas Turbines

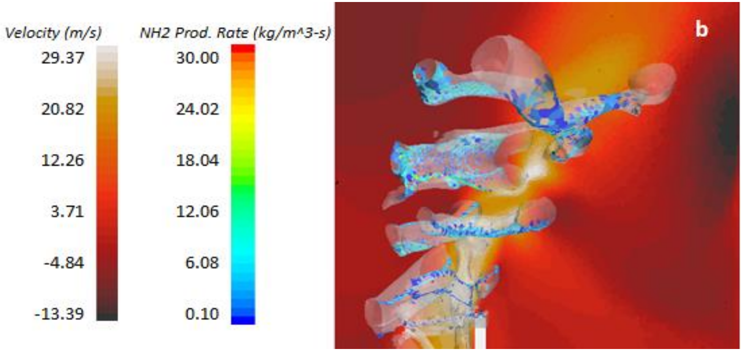


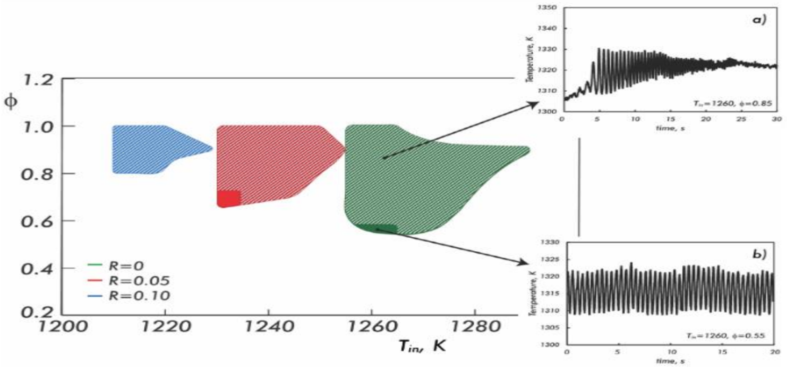


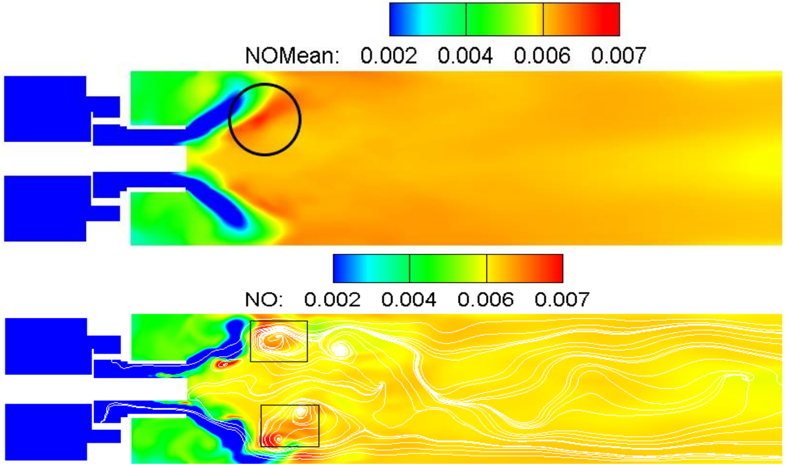
Spectral signals of various radicals and their correlation between each other [Mashruk S et al. 2022].

Developments – Gas Turbines



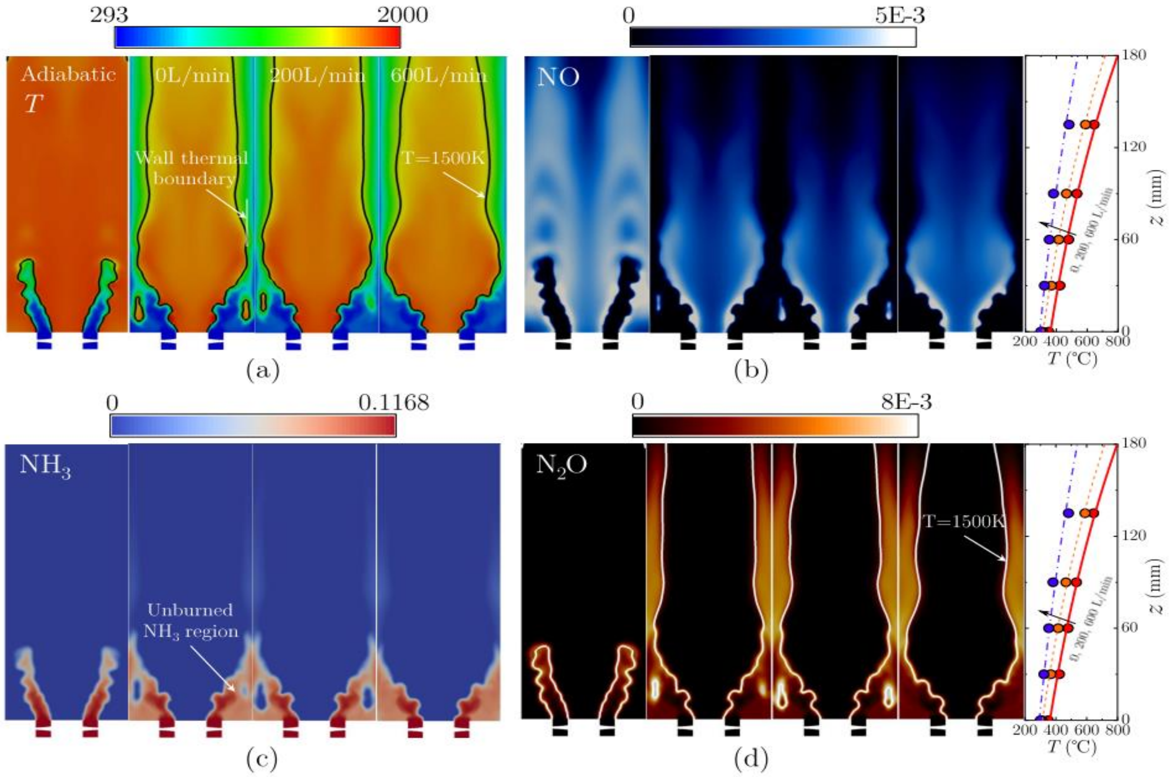






Detailed mechanisms, complex CRN and CFD modelling using RANS and LE (in collaboration with Italy, Mexico, India and China).

Developments – Gas Turbines

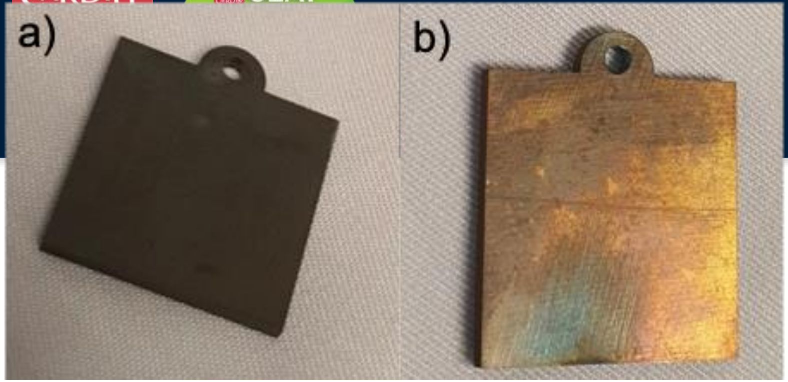


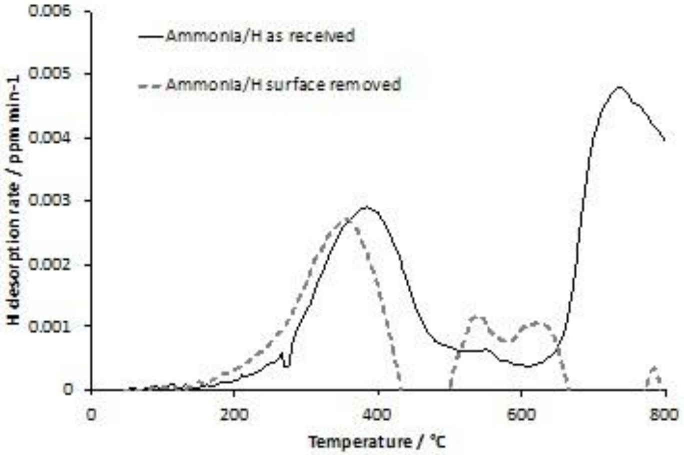
Impacts on emissions formation and flame characteristics using different cooling rates for ammonia-based combustion systems.

Although NO decreases, N2O can considerably increase.

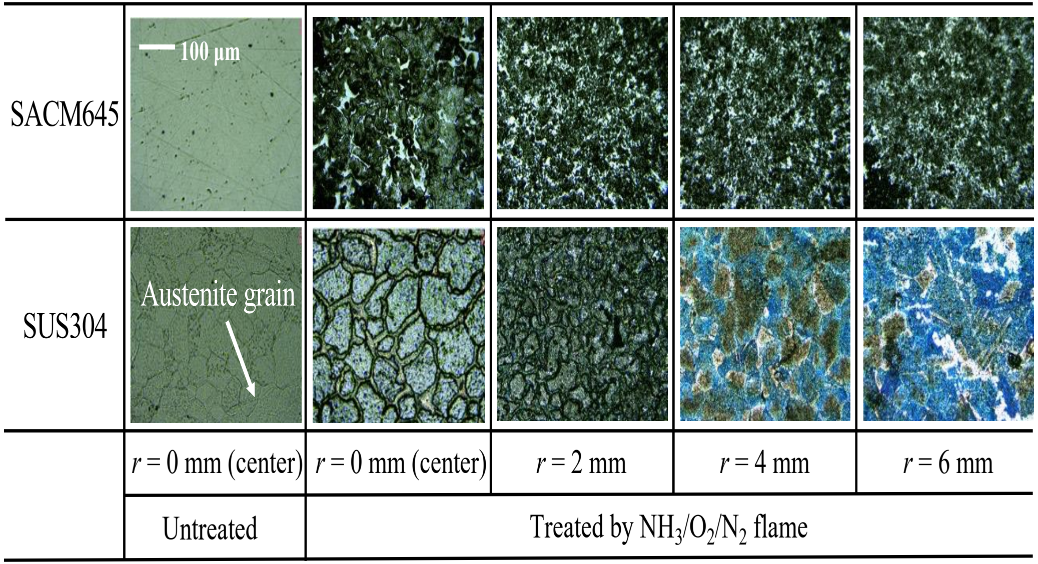
Zhang et al. Combustion and Flame (2023).

Developments – Gas Turbines



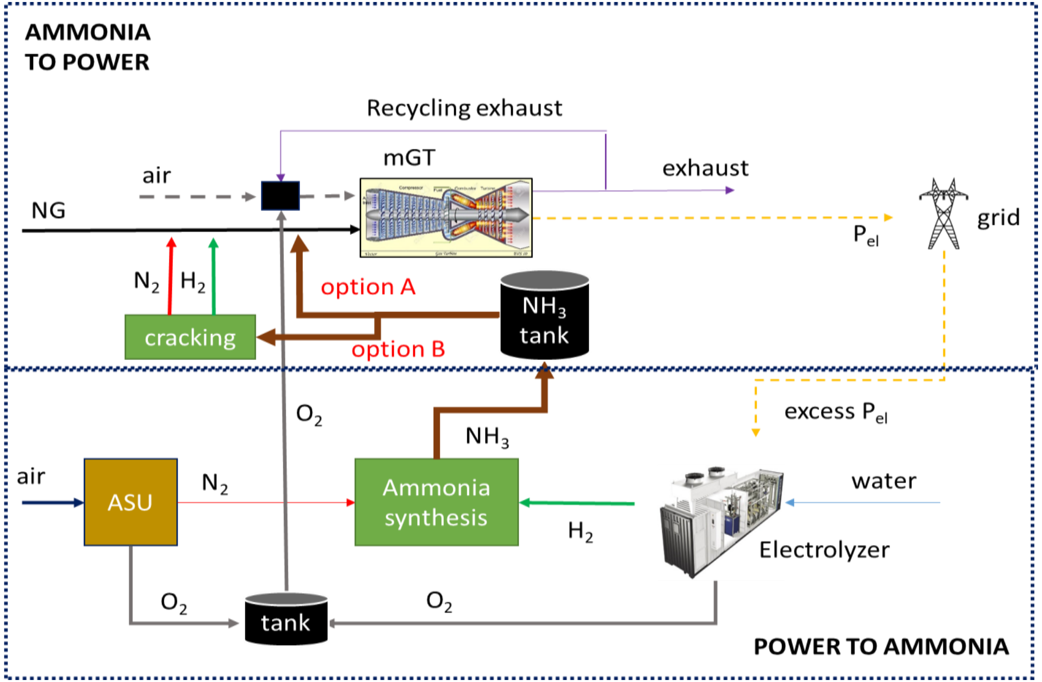


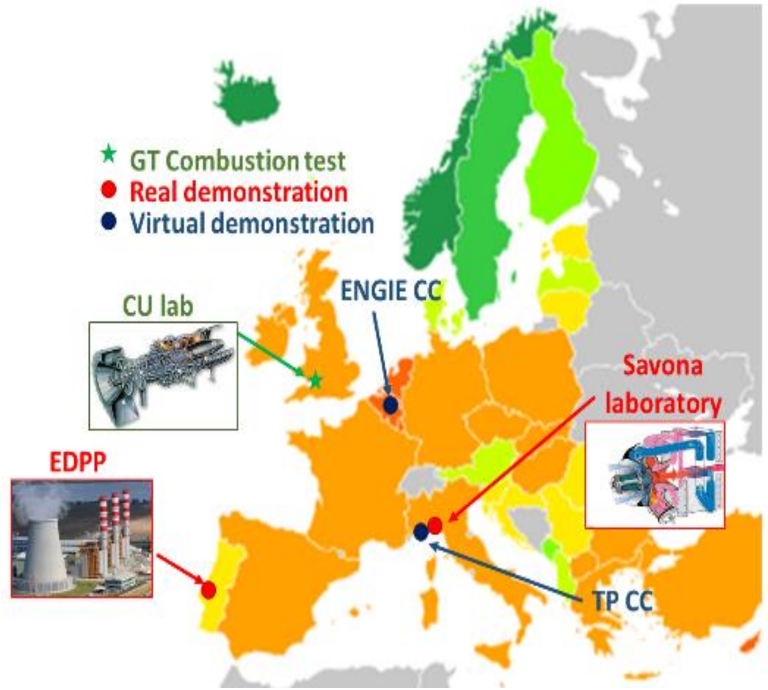
Samples exposed to ammonia/hydrogen and methane, respectively. Also, the peak at ~400oC denotes hydrogen permeation [Kovaleva M et al. 2022]**.**



Optical micrographs of the SACM645 and SUS304 test plate surfaces after being exposed to the NH3/O2/N2 flame at 550 ºC for 5hr [Wang et al. 2023].

Developments – Gas Turbines

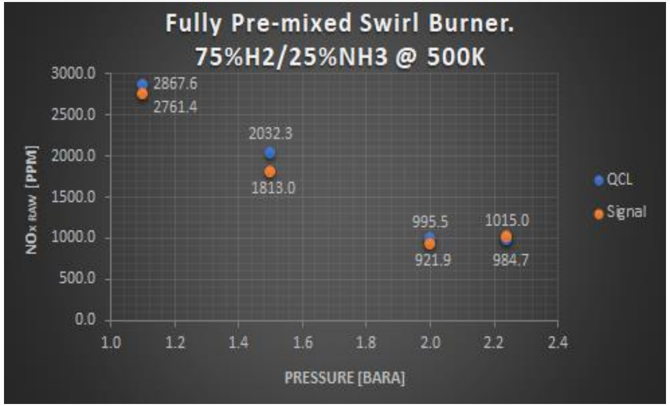


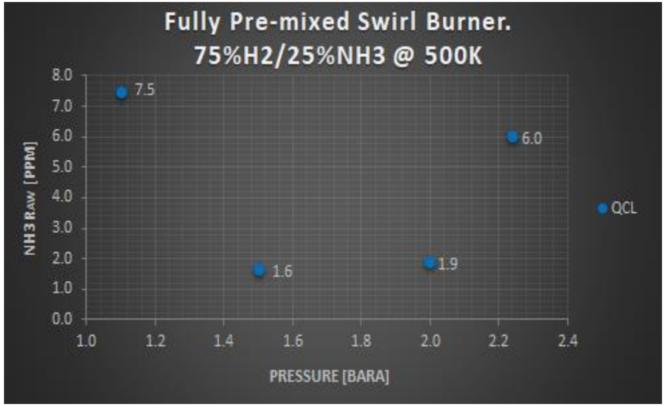


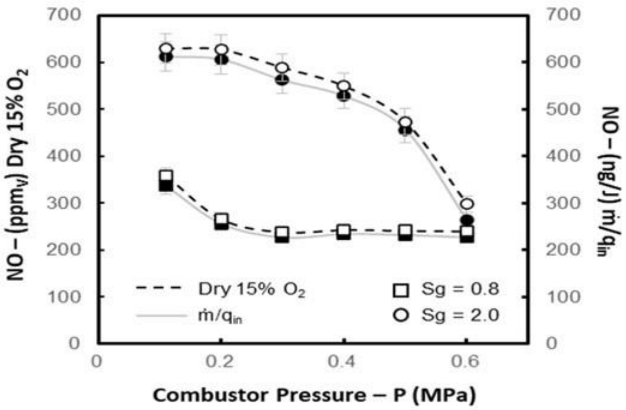
FLEXnCONFU – First large GT ammonia/hydrogen/NG demonstrator

This Project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement N. 884157

Developments – Gas Turbines



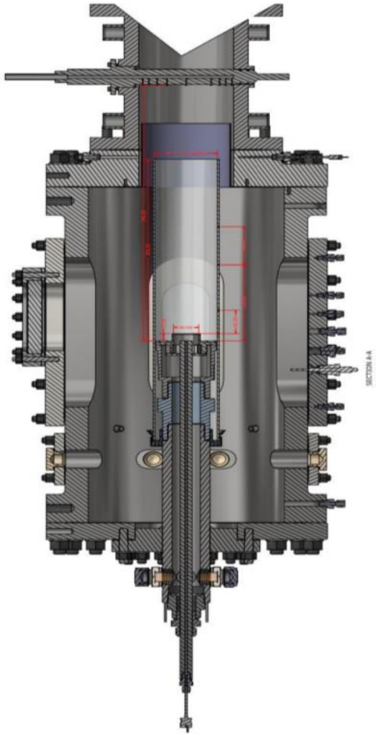




Notes: Equivalence ratio maintained ~0.29 and ~0.56

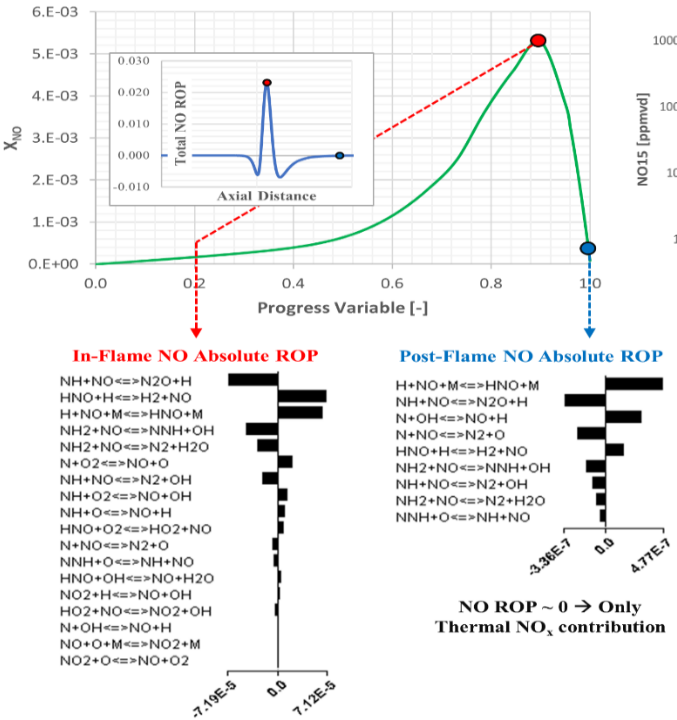
Power scaled with pressure @12.5kW/1.1bar

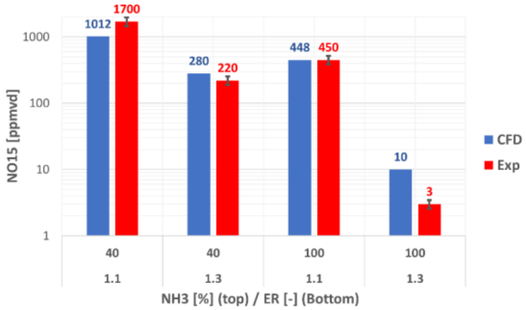
Relative %heat loss from the flame reduces as power/pressure increases. This can be seen by increasing exhaust temperatures.

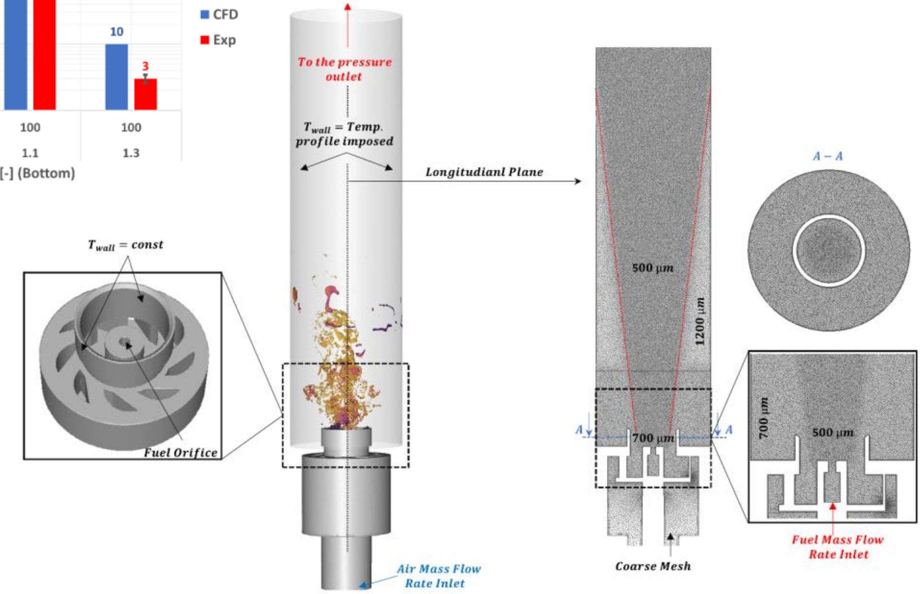


This Project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement N. 884157

Developments – Gas Turbines

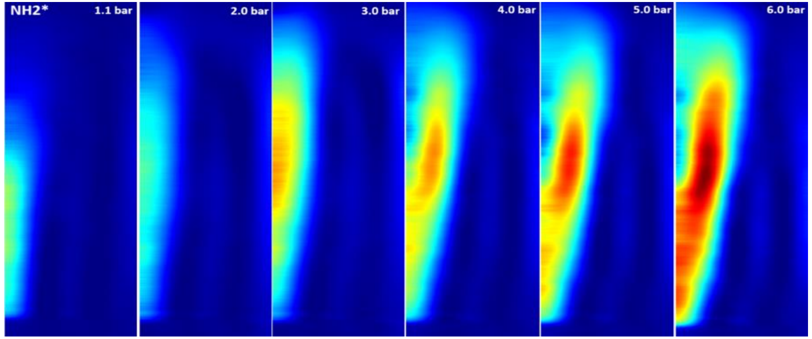


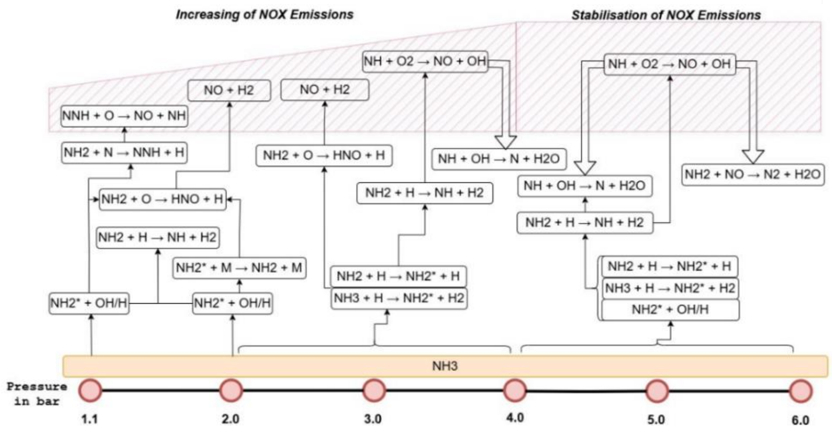


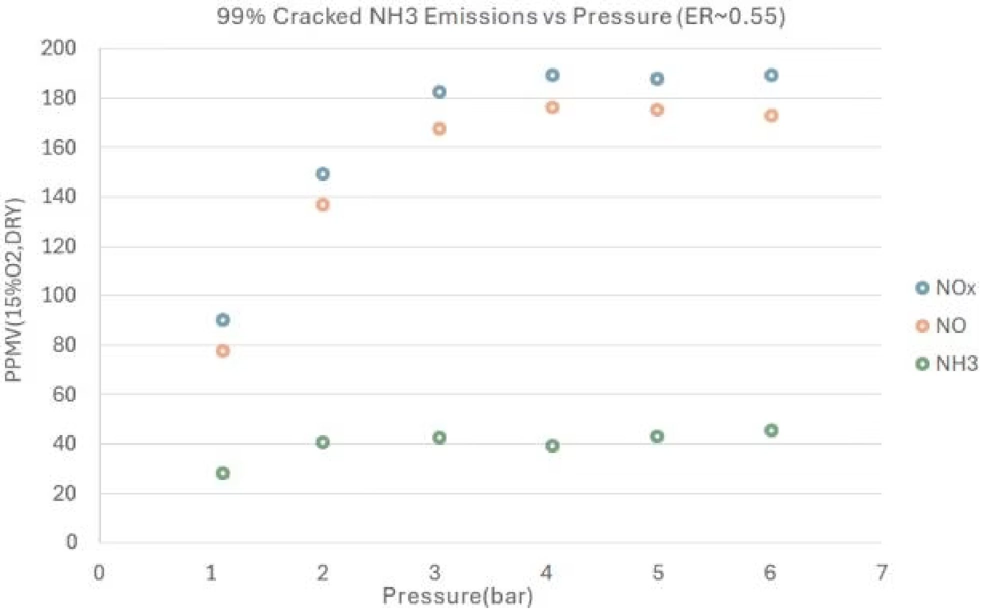


Baker Hughes - Ammonia/Hydrogen CFD modelling

Developments – Gas Turbines

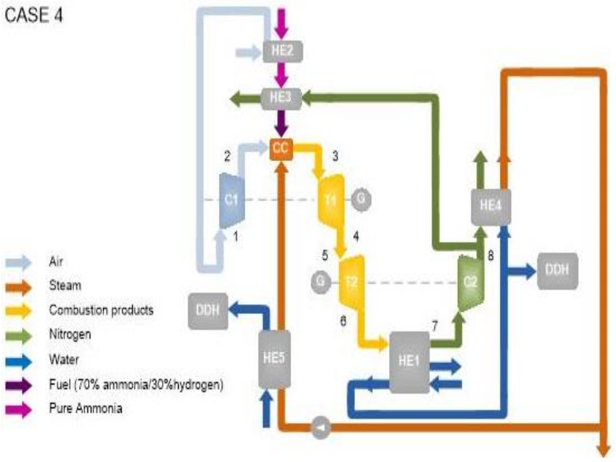






Highly cracked ammonia (99%) for its use in GT under various pressures. NH2* considerably increases, whilst the NO chemistry shifts.

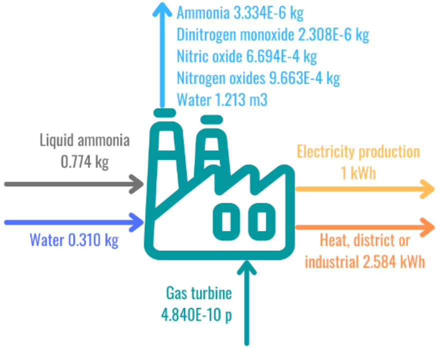
Developments – Gas Turbines

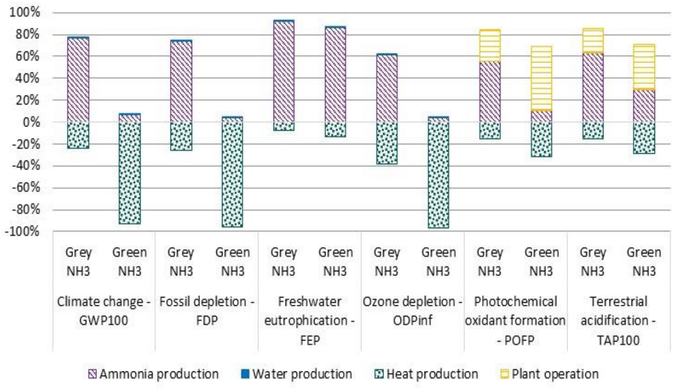


Modified Brayton Cycle
Inlet temperature 1260K
Outlet temperature 827K
Supplied heat 10.45MWth
Power 3.56MWe
Plant efficiency 34%

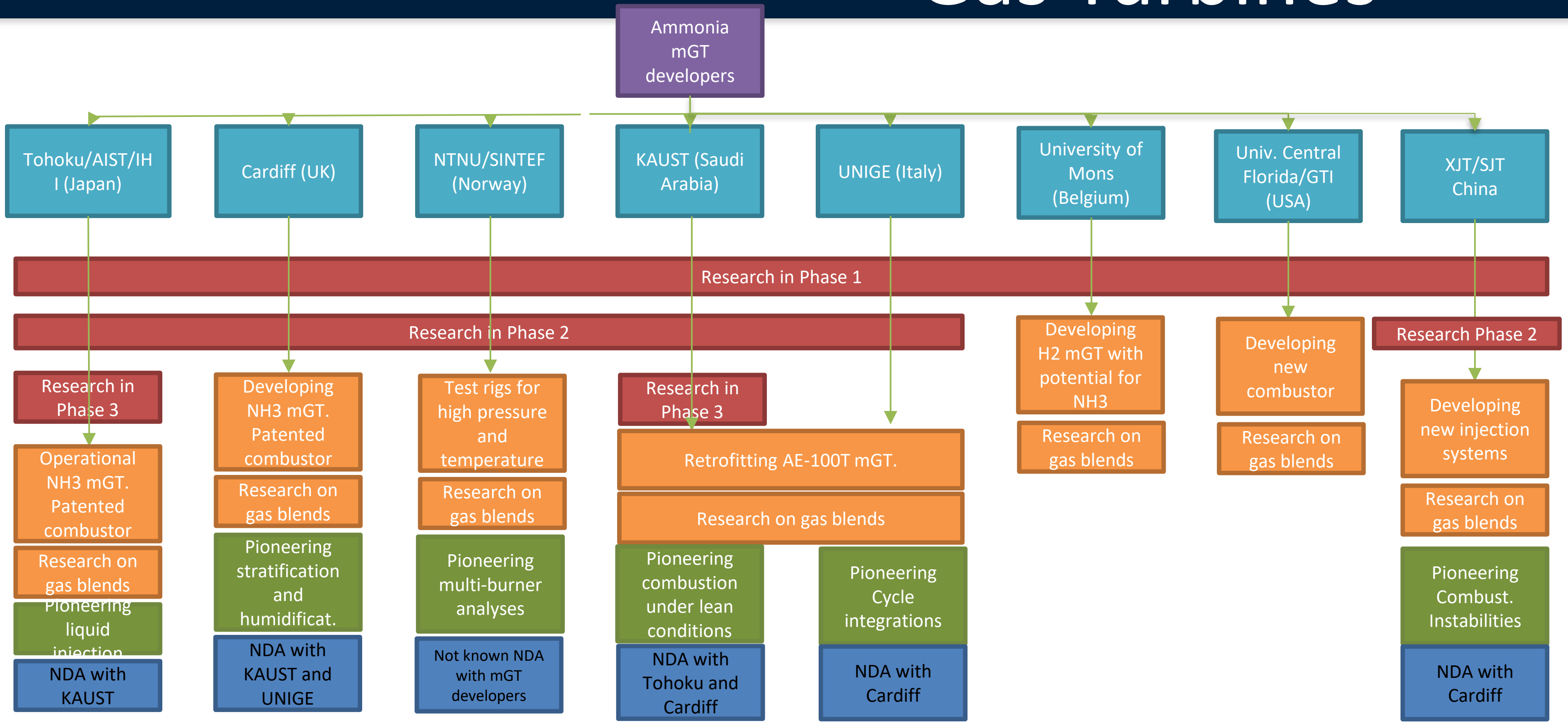
Trigeneration Cycle
Cooling+Power+Heating
Initial calculations: 62.5% (compared to ~80%)

Similarly, LCA shows the superior environmental advantages of green NH3



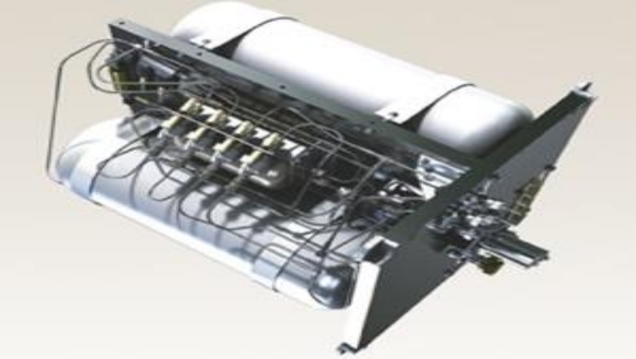


Developments – Gas Turbines



Developments – Propulsion

- The X-15 Rocket (powered with ammonia and LOX) performed 199 missions (2 space missions) with speeds up to 6.7 MACH and 108 km altitude (record for airplanes)
- Energomash (Russia) has been developing a propulsion system fuelled by acetylene and ammonia (atsetam).
- Micro-thrusters (Ammonia Propulsion Systems, APS) are under development, specially in Russia, using ammonia. The systems are intended for satellite and UAV applications. Solar Thermal Propulsion is also based on the use of ammonia (UK, US, China).



Developments – Propulsion

Jet-A1 - 6hr range, 78.5m3 tank. 60,7837kg. 2,676,828MJ

LBM - 4hr 05min range, 78.5m3 tank. 33,127kg. 1,821,985MJ

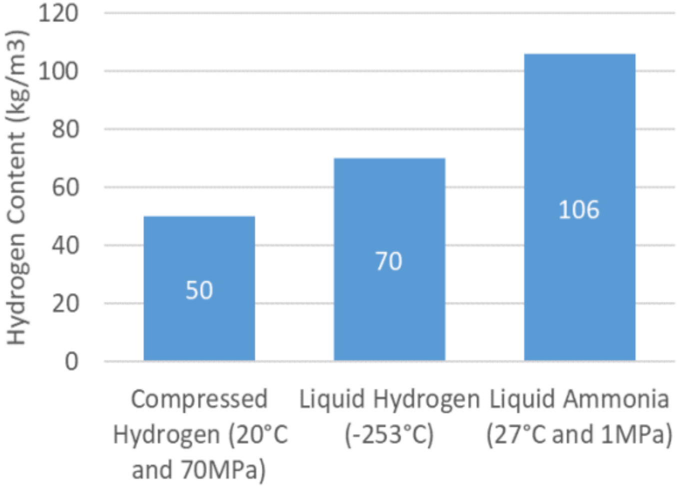
68%

LNH3 - 2hr20min range, 78.5m3 tank. 47,100kg. 1,059,750MJ

39%

LH2 - 1hr45min range, 78.5m3 tank. 5,557kg. 787,426MJ

29%



Developments – Propulsion

Parameters	Jet A-1 (AS)	nC_8H_{18}	CH_3OH	CH_4	H_2	NH_3
κ (-)	1.3117	1.3116	1.3095	1.3121	1.3144	1.3130
R $(\mathrm{J\,kg^{-1}\,K^{-1}})$	289.14	289.58	292.31	292.09	299.84	301.07
$\frac{\kappa-1}{\kappa}$ (-)	0.2376	0.2376	0.2363	0.2379	0.2392	0.2384
$\sqrt{\frac{\kappa}{R}}$ $\left(\mathrm{kg^{1/2}\,K^{1/2}\,J^{-1/2}}\right)$	0.0674	0.0673	0.0669	0.0670	0.0662	0.0660
$\sqrt{\kappa R}$ $\left(\mathrm{J^{1/2}\,kg^{-1/2}\,K^{-1/2}}\right)$	19.47	19.49	19.56	19.58	19.85	19.88
$\dot{m}_4$ $(\mathrm{kg\,s^{-1}})$	19.79	19.77	19.67	19.69	19.45	19.40
n_{LPT} $(\mathrm{min^{-1}})$	4028	4031	4047	4049	4106	4112
T_{t5} (K)	638.8	638.9	641.2	638.4	636.1	637.6
P_T (MW)	13.51	13.52	13.59	13.58	13.74	13.77
η_P (-)	91.29	91.29	91.26	91.29	91.29	91.27

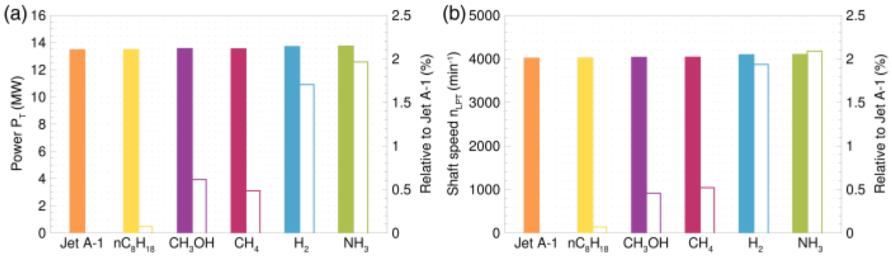
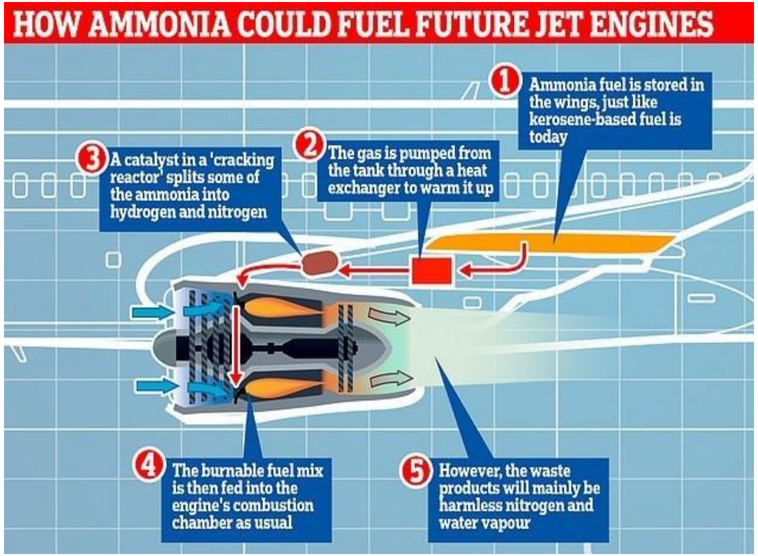


Table 8. Evaluation matrix for the selected electrofuels in this study (excellent: 5, good: 4, satisfactory: 3, challenging: 2, problematic: 1).

Property	Jet A-1	nC_8H_{18}	CH_3OH	CH_4	H_2	NH_3	NH_3/H_2
CO_2 emission	1	4	4	4	5	5	5
Electro-synthesis	-	3	3	4	5	5	5
Specific energy	4	4	2	4	5	2	2
Energy density	5	5	2	3	1	2	2
Storage	5	5	4	2	1	3	3
Toxicity	3	3	2	4	5	1	1
Combustion properties	5	5	4	5	5	2	5
NO_x & soot emissions	2	2	4	4	4	3	4
Drop-in capability (combustion)	5	4	2	2	2	2	4
Turbine power output	4	4	4	4	5	5	5
Drop-in potential (turbine)	5	5	4	3	2	2	3
Structural considerations	4	4	3	3	2	2	3

A Study on Electrofuels in Aviation. Comparison between different potential fuels [Goldmann et al. 2018]

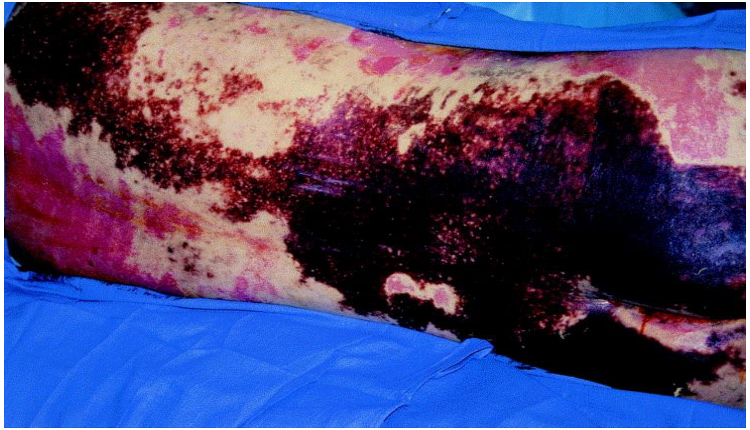
"Dock-to-Dock" is an InnovateUK project that evaluates the potential of H2 and NH3 for cargo distribution. Simultaneously, Reaction Engines has recently announced their intentions of using NH3 as fuel.



- The project "Dock-to-Dock" (InnovateUK) intends to determine the techno-economic challenges and needs to use H2 and NH3 as fuel for cargo distribution between Cardiff and Bristol, aiming at a larger analysis for the entire UK.
- Similarly, Reaction Engines has announced their intentions to start working on ammonia as a hydrogen vector. A PhD between RE and Cardiff will commence in October 2021 on this matter.

Developments – H&S/Envirn.

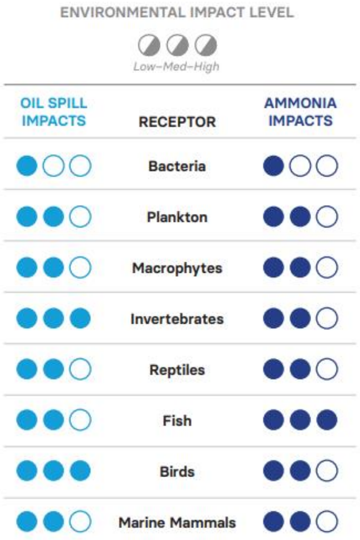
Ammonia gas cloud in Seward, Illinois. Cause: ruptured hose

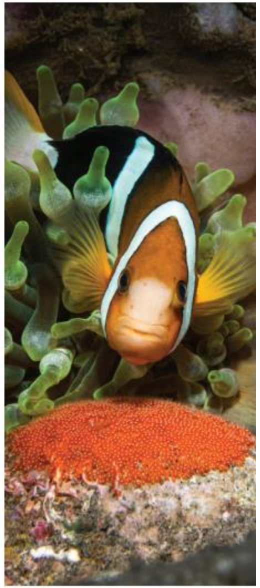


Exposure of skin to anhydrous ammonia [Amshel et al 2000].

Explosions and cylinder damage

Developments – H&S/Envirn.



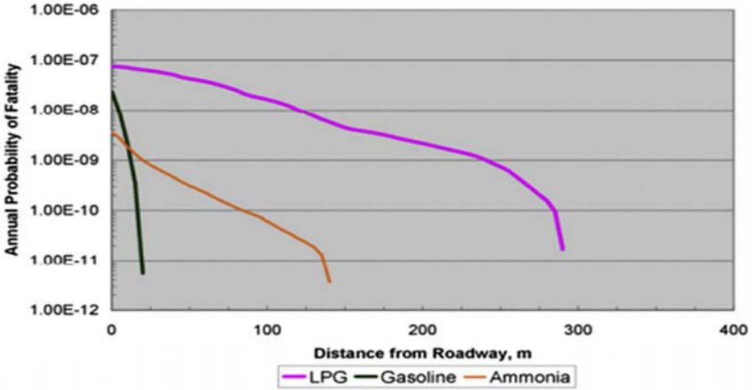


Environmental Defence Fund, 2022. [Online]. Available in: https://cdn.ricardo.com/ee/media/assets/ammonia-at-sea-report-summary.pdf

TABLE 10.6
Reported Accidents With Transporting Anhydrous Ammonia and Ammonia Solutions, United States, 1971–2019 (Reports Only for Anhydrous Ammonia).

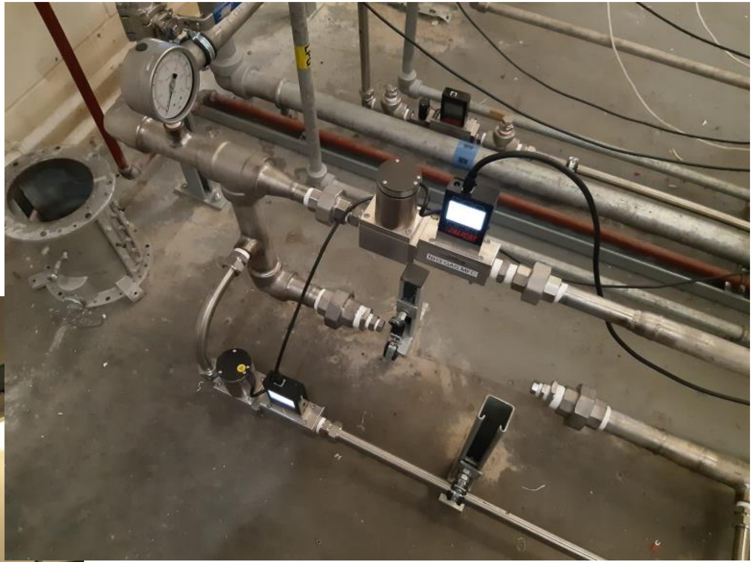
	Total reported	Total fatalities	Total hospitalized injuries	Total nonhospitalized injuries
Highways	3209 (797)	25 (23)	36 (29)	744 (602)
Rail	2460 (2301)	11 (11)	23 (21)	321 (290)
Water	21 (14)	0 (0)	0 (0)	4 (4)

Appl Energy 2017. https://doi.org/10.1016/j.apenergy.2016.10.088.

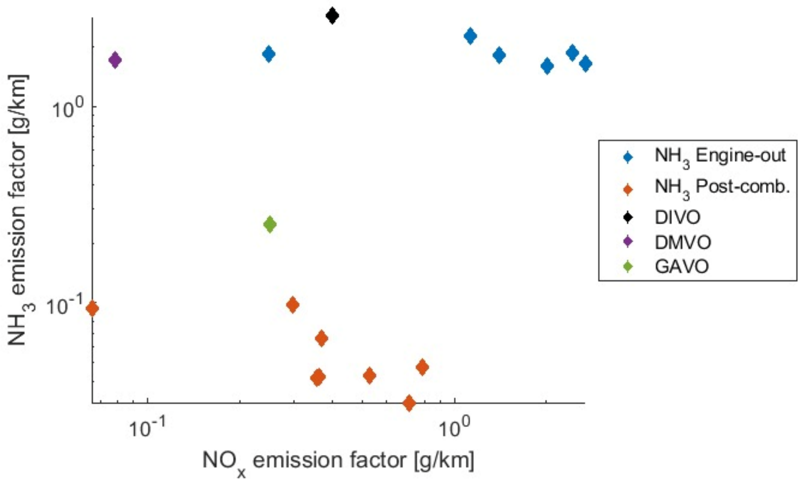


Quest Consultants Inc. Comparative Quantitative Risk Analysis of Motor Gasoline, LPG and Anhydrous Ammonia as an Automotive Fuel. Iowa, USA: 2009. Courtesy of Quest.)

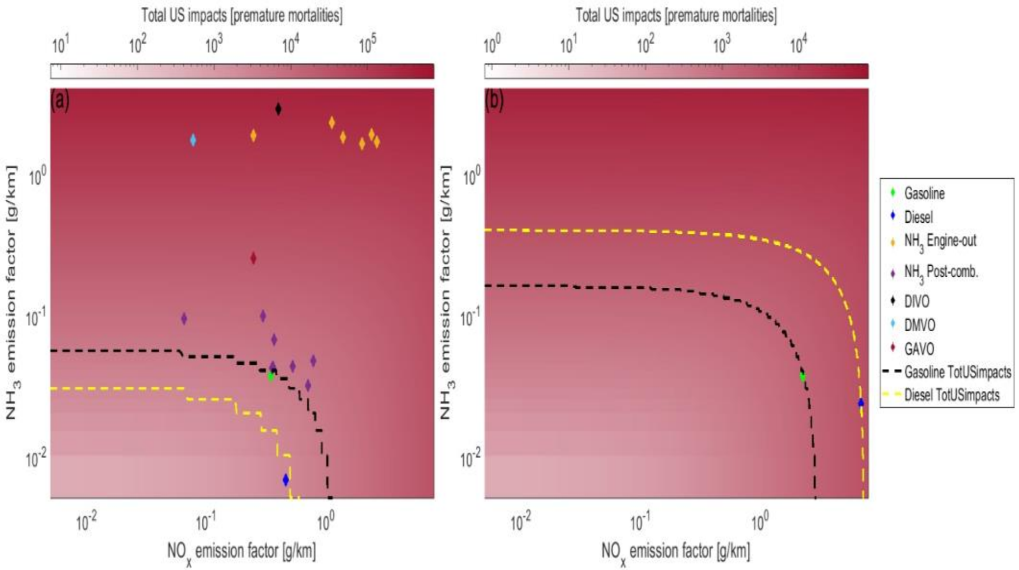
Developments – H&S/Envirn.



Developments – H&S/Envirn.

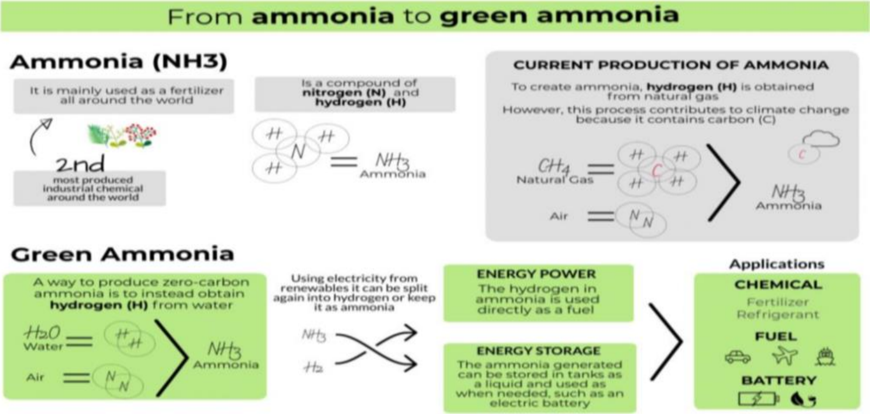


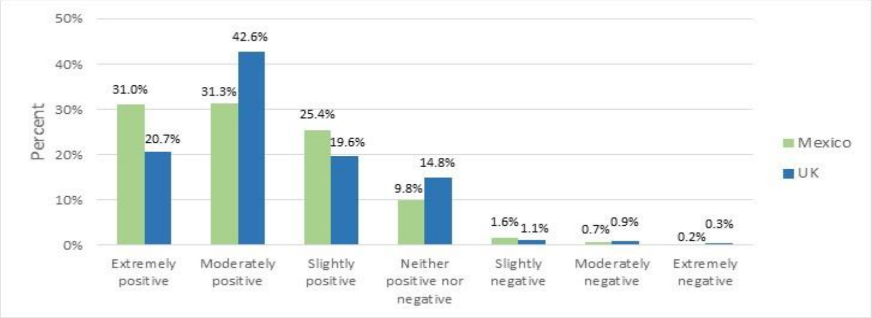
Configurations: NH3 Engine-out: neat ammonia with varying engine parameters; NH3 After-treatment engines with SCR; DIVO: ammonia-diesel; DMVO: ammonia-DME; GAVO: ammonia-gasoline



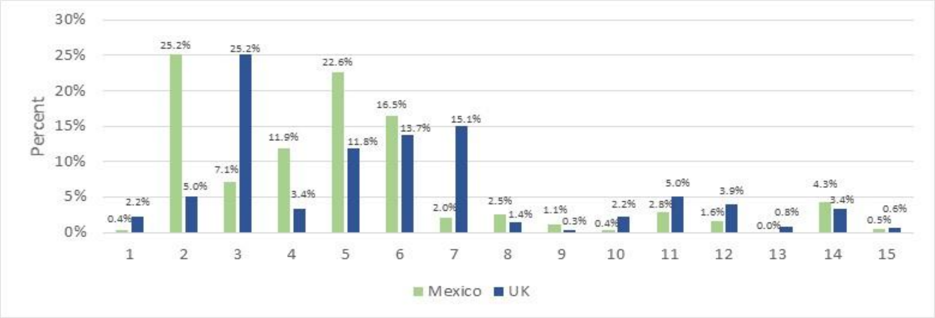
Average 2011 emission factors Gasoline and Diesel passenger cars and trucks

Developments – H&S/Envirn.

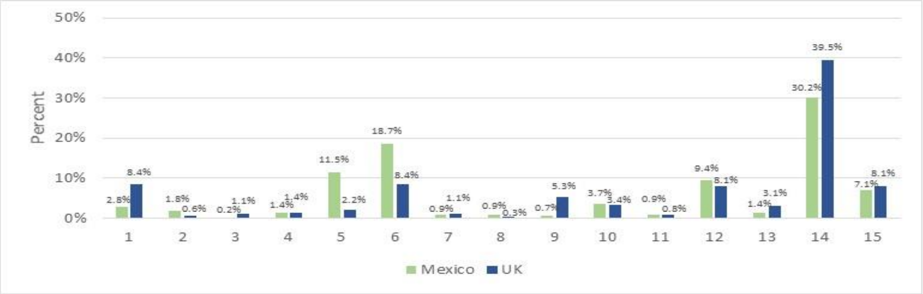




Percent of responses for opinion of green ammonia technology (920 individuals – 357 UK, 563 Mexico).



Percentages for most common answers by country of first associations of ammonia. (1) Nothing/Don't know (2) Poison/toxic (3) Smell (4) Safety (5) Chemical (6) Cleaning products (7) Urine/manure (8) Pollutant (9) Death/killing (10) Fuel (11) Fertilizer/refrigerant (12) Other products (13) Negative (14) Substance (15) Confusion with other chemicals.



Percentages for most common answers by country of perception of green ammonia. (1) Nothing/Don't know (2) Poison/toxic (3) Smell (4) Safety (5) Solution/alternative (6) Novel concept (7) Cost (8) Pollutant (9) Complex/confusing (10) Need more information (11) Water (12) Positive for the environment (13) Negative (14) Generic positive (15) Sceptical.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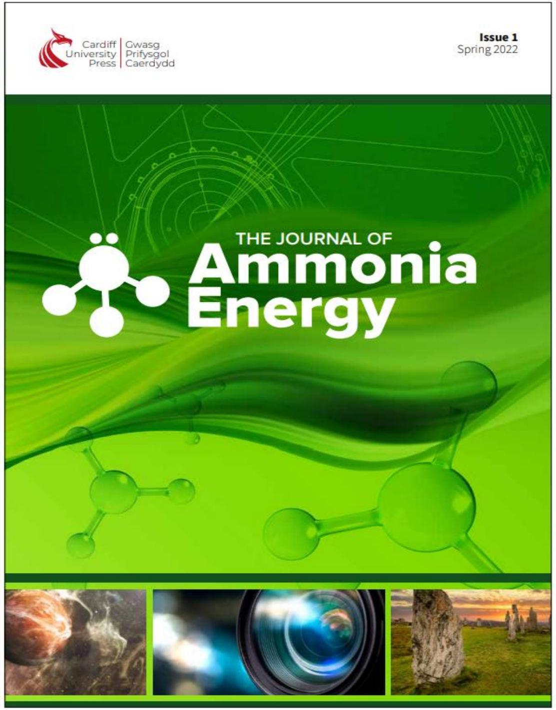
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Issue 1
Spring 2022
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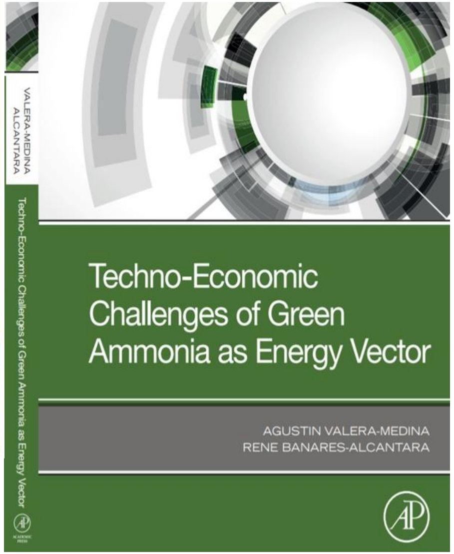
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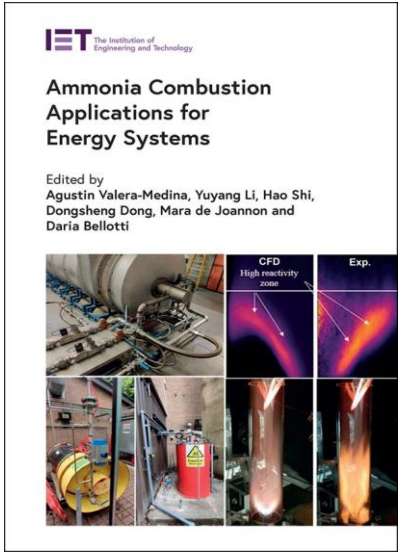
IET The Institution of Engineering and Technology
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CONCLUSIONS

- Ammonia in rural areas seems an option for boilers, whilst furnaces can deliver energy to remote industrial sites with limited gas network access.
- Gas Turbines will operate on ammonia – many companies already evaluate their potential purely or blended.
- Aerospace might see an onset on the use of ammonia if a large manufacturer (like Boing) demonstrates its versatility.
- Safet and Public engagement are critical for the sustainable progression of the subject. Hydrogen blending needs to be properly addressed.
- There are still many points in the combustion of ammonia that require further research, with a lot of input from Public Perception – a fascinating area to explore!
- However, for the "Hydrogen through Ammonia" economy to happen, lower costs and higher efficiencies of conversion from renewables are needed.

THANKS FOR YOUR ATTENTION

FURTHER INFORMATION:
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