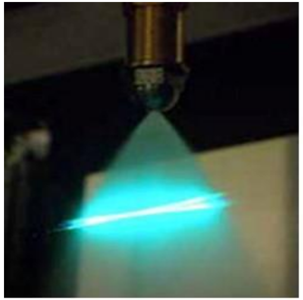
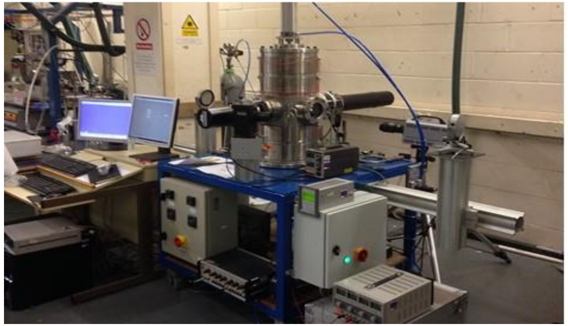
Use of ammonia blends for zero carbon power

Prof. Agustin Valera-Medina





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- CHALLENGES
- CENTRE OF EXCELLENCE ON AMMONIA TECHNOLOGIES (CEAT)
- DEVELOPMENTS
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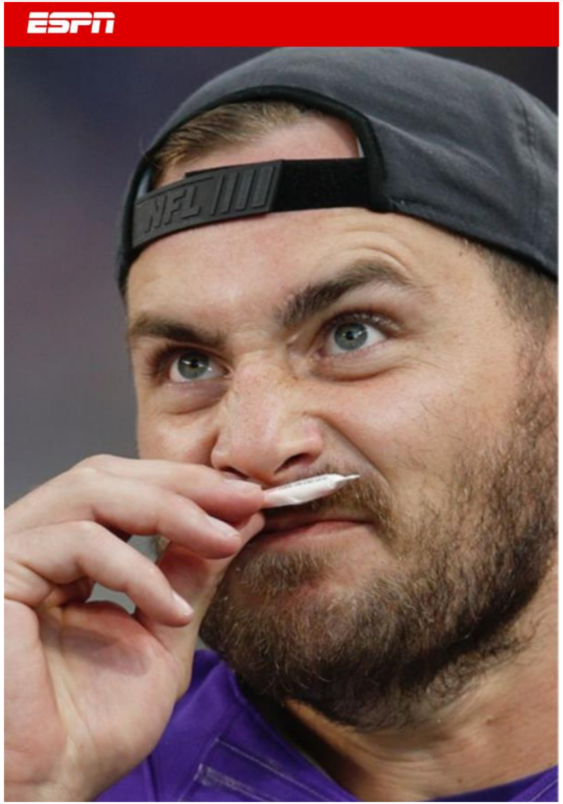
Introduction

- Professor at Cardiff School of Engineering. He has participated as PI/Co-I on 31 industrial projects with multi-nationals including PEMEX, Rolls-Royce, Siemens, Ricardo, Airbus and FloGas (>£35M). He has published 225 papers (h-index 39), 94 of these specifically 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 (Endeavr Green Propulsion, SAFE-AGT (EP/T009314/1), FLEXnCONFU (884157), OceanREFuel, etc.) to demonstrate ammonia power in turbine engines, Internal Combustion Engines 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 the book "Techno-economic challenges of ammonia as energy vector". He is Co-Director of the Institute of Net Zero Innovation, Cardiff University and Director of the Centre of Excellence on Ammonia Technologies (CEAT). He is a Fellow of the Learned Society of Wales.



Introduction

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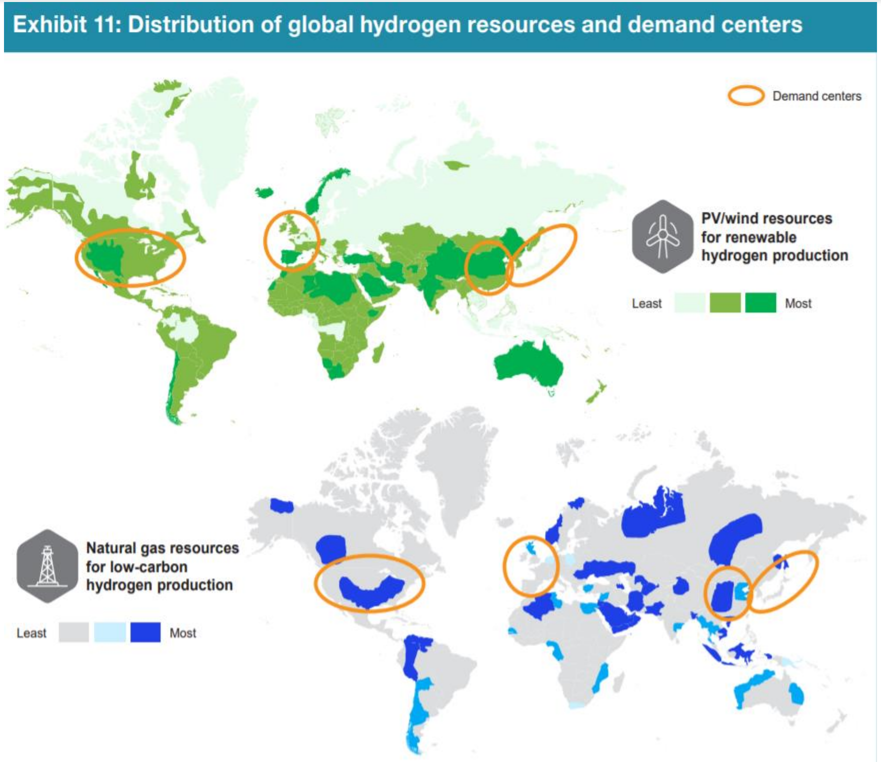

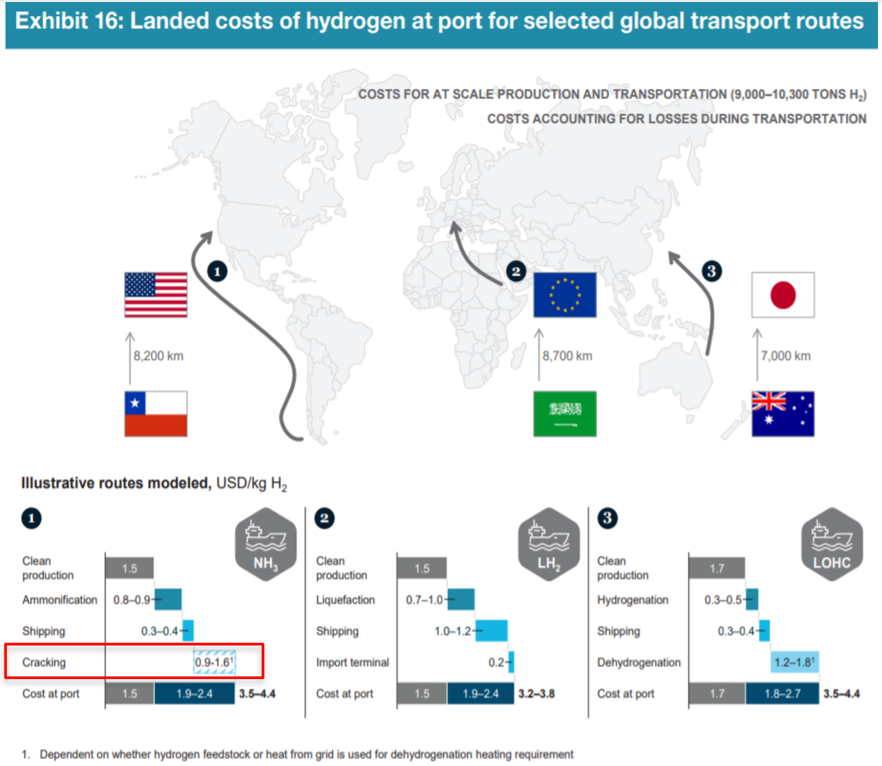

Hydrogen Distribution and comparison between vectors [Hydrogen Council 2021]

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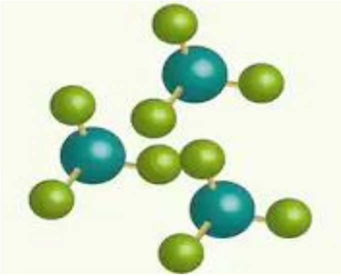
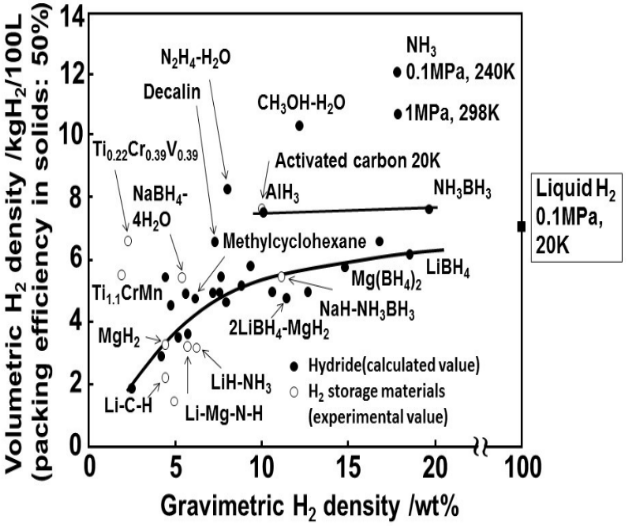
Introduction

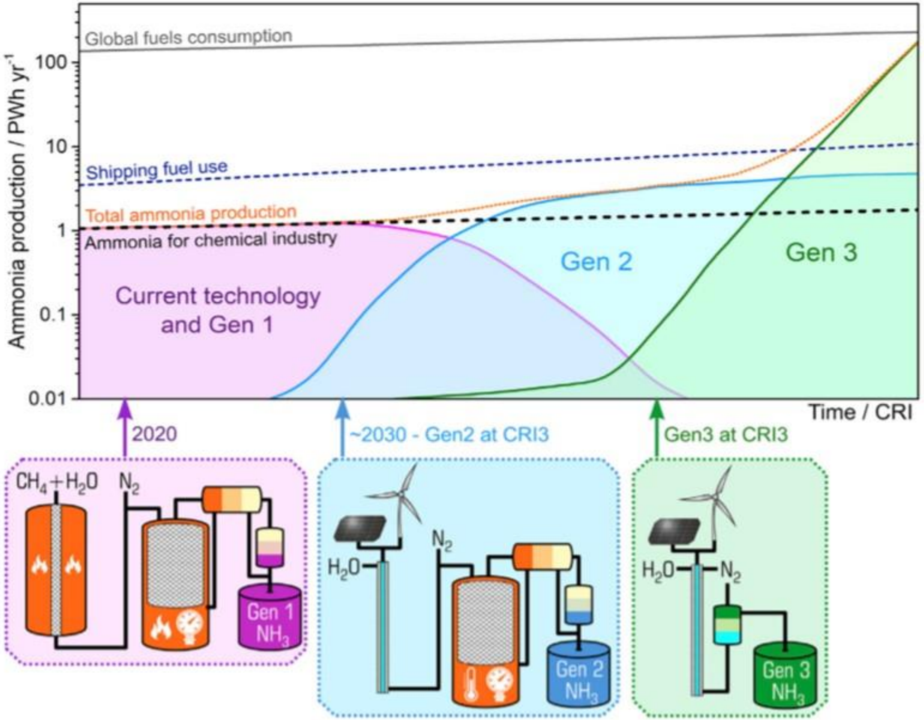
- Ammonia can
  - be obtained from renewable sources,
  - allow the rescue of stranded resources,
  - enables the use of waste streams,
  - allow storage of vast amounts of energy 30 times cheaper than H2,
  - be used to produce energy in Islands or isolated regions,
  - be used as a fuel, but also as 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



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.

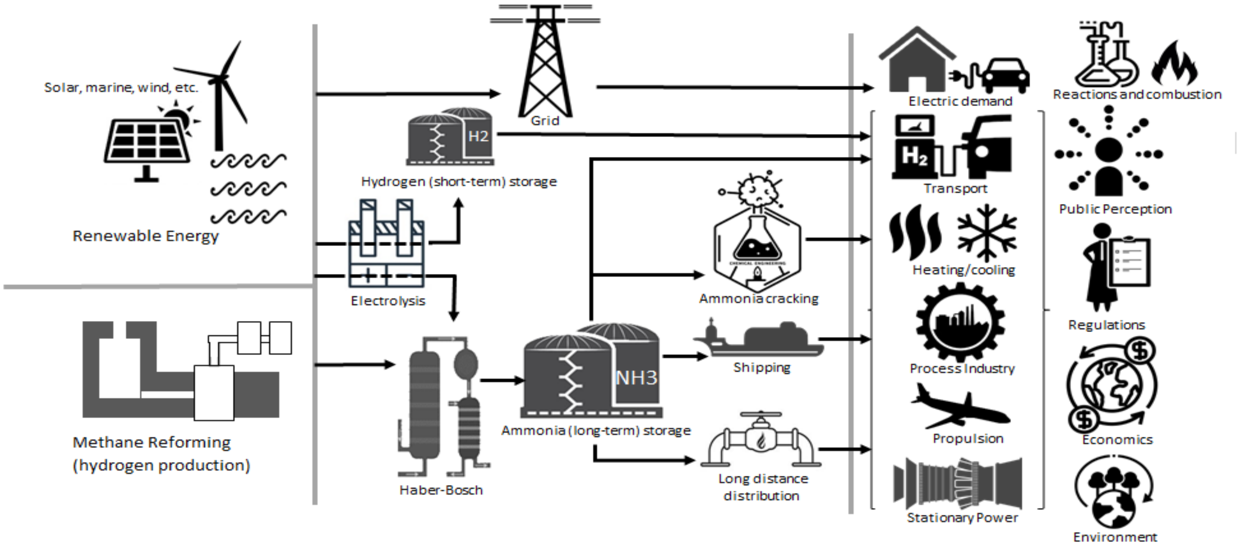
Next Nobel Prize?

Introduction

- A new potential method for the production of ammonia is taking place for research and development, aiming at large scale demonstration in the next 5 years.
- Pink ammonia via Thorium reactors is currently being developed across Europe, US, Japan and China.
- The technology promises to reduce the cost of ammonia to half of its current price.
- https://www.youtube.com/watch?v=HUue5-QjT_o

Introduction

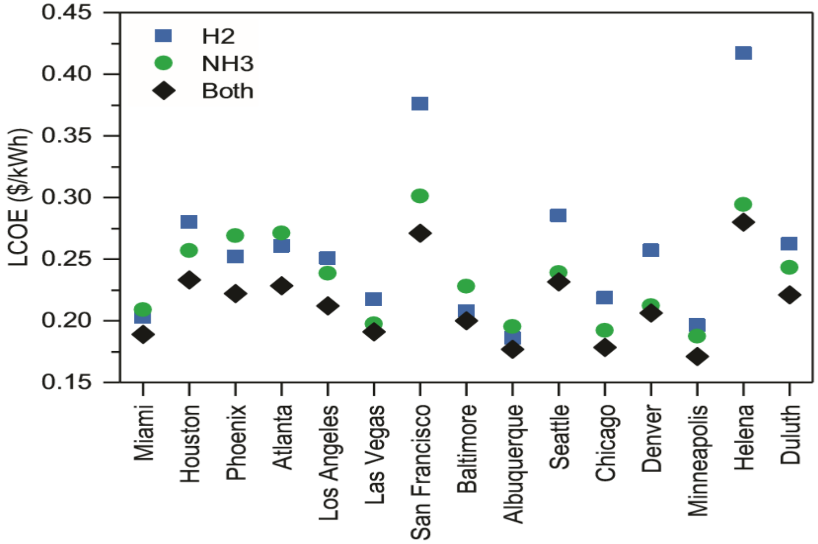
- Although ammonia combustion is still seen as the lowest end of the use of ammonia for energy, cheaper distribution, higher hydrogen content and easier operation will change the position of NH3 in the energy arena.



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

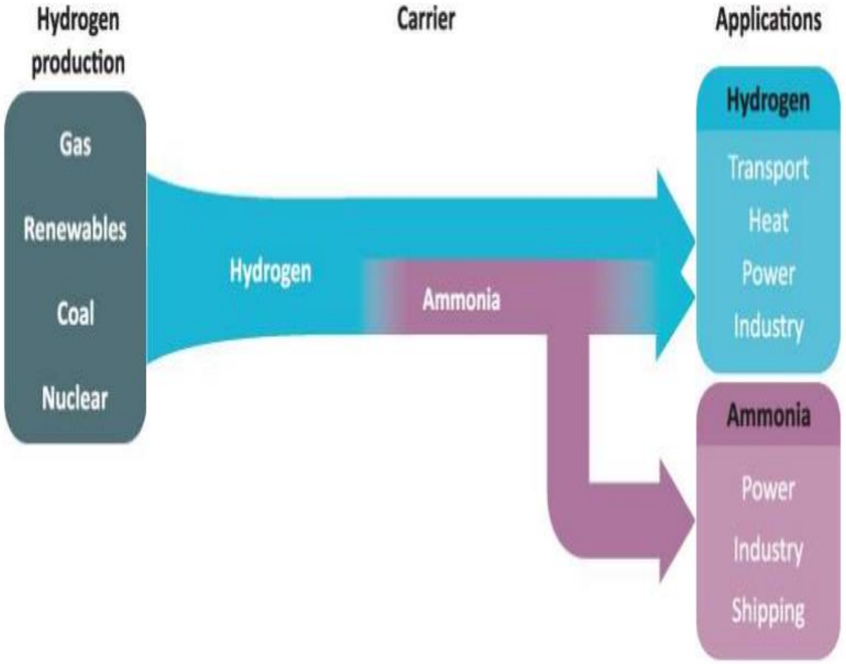
Introduction

- 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



Hydrogen: Accelerating and Expanding Deployment, IEA [Birol F, 2018]

International program working on ammonia

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)

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Current outcomes

- 1st International Demonstrator on Green Ammonia Energy
- Director of the Green Ammonia Working Group (UK)
- 2 Royal Society Policy Briefings
- Publication of 92 (+5 under 2nd review) papers, two books and 3 book chapters
- Editors in Chief of the new Journal on Ammonia Energy
- Lead of the 1st Symposium on Ammonia Energy
- Chair of the Combustion Section of the Ammonia Energy Association

Current funding profile

- Current projects (for Cardiff) are **£12.3m**

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CEAT

Vision

- Establish a physical facility for the Net Zero Innovation Institute with labs for CEAT/LCB/etc.
- CEAT, under the umbrella of NZII, will
    - Develop bespoke ammonia technologies for
        - Heat (boilers, furnaces)
        - Power (gas turbines, ICEs)
        - Transport (aerospace, terrestrial, heavy load)
        - Social sciences and Geopolitics
        - Biotechnology and physics
- Demonstrate NZ technologies at commercial scale at Aberthaw Green Park

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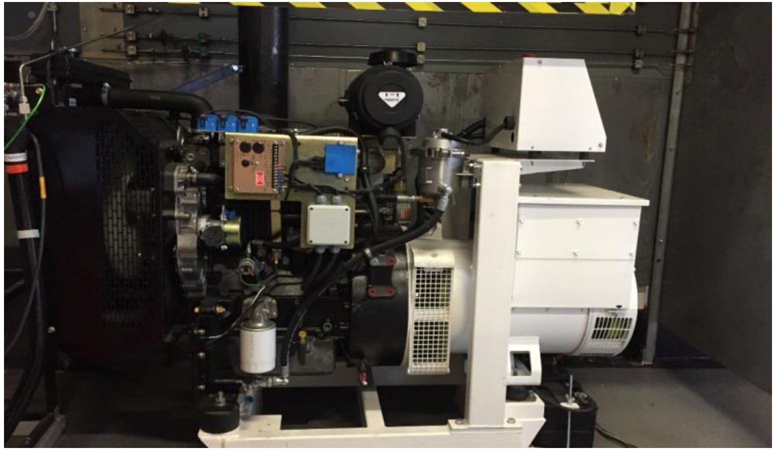
Developments - ICEs

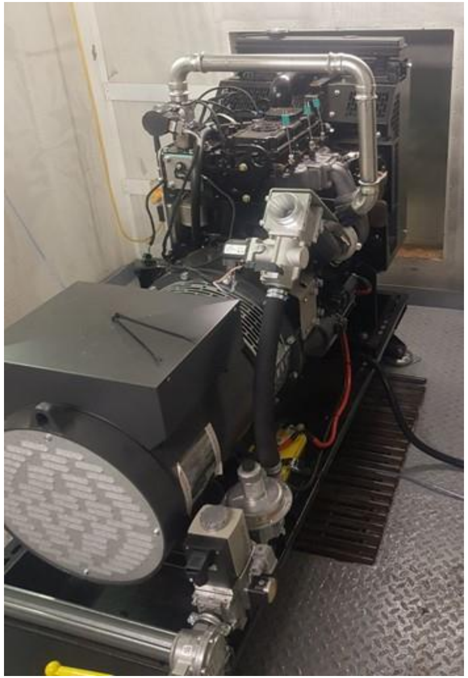
Internal combustion engine running on H2/NH3

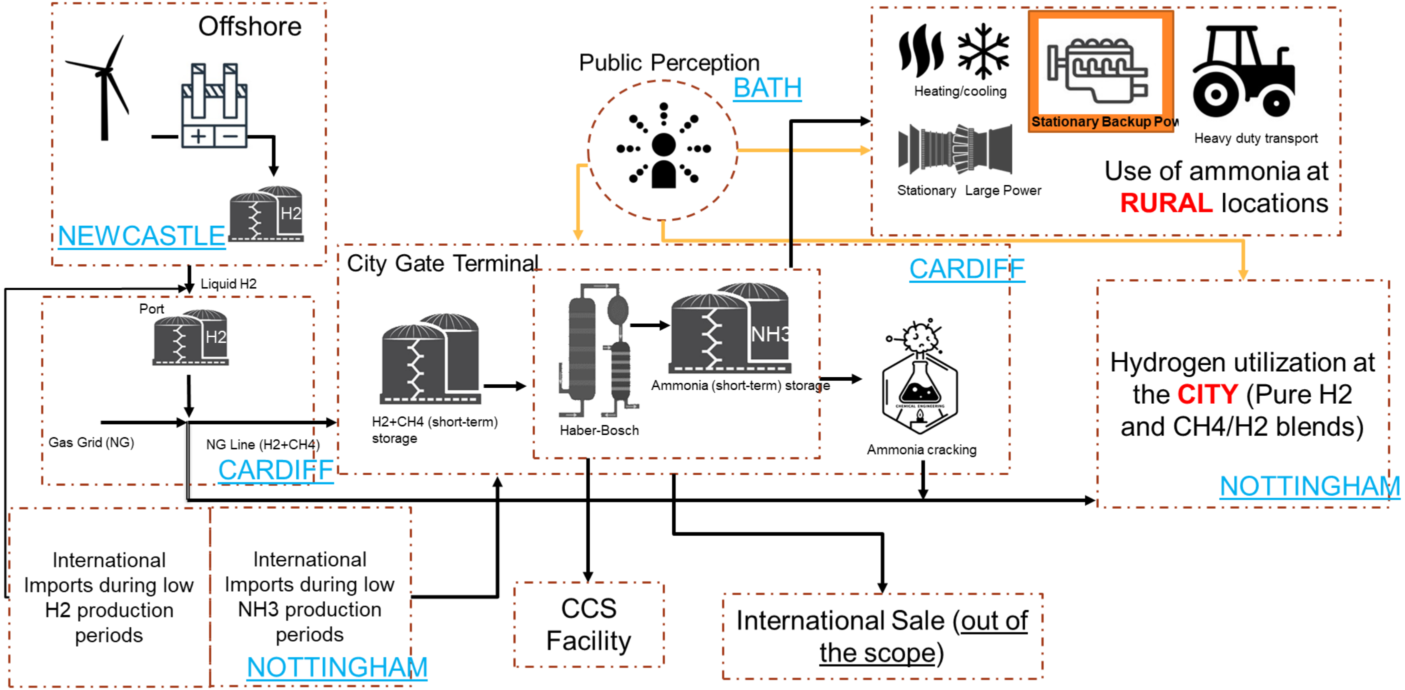
- Ammonia Demonstrator at RAL, Oxford. Cardiff developed the ammonia engine and container for the production of power and its transmission back to the grid.



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

Developments - ICEs





OceanREFuel Program to develop ammonia-based capabilities in the UK.

PRESS RELEASE

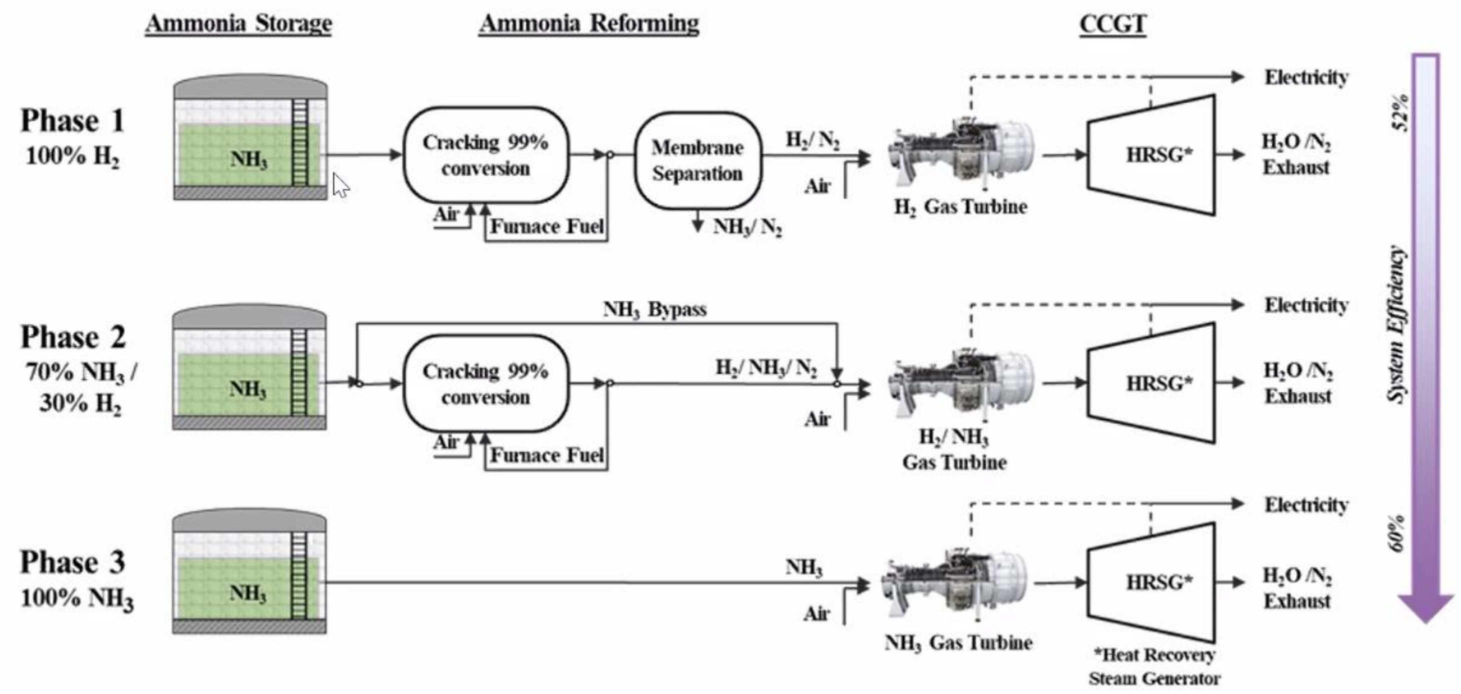
GE and IHI Sign Agreement to Develop Ammonia Fuels Roadmap across Asia

June 22, 2021

First Ammonia Gas Turbine Engine, MHI (H25), 40 MW Power [https://power.mhi.com/news/20210301.html]

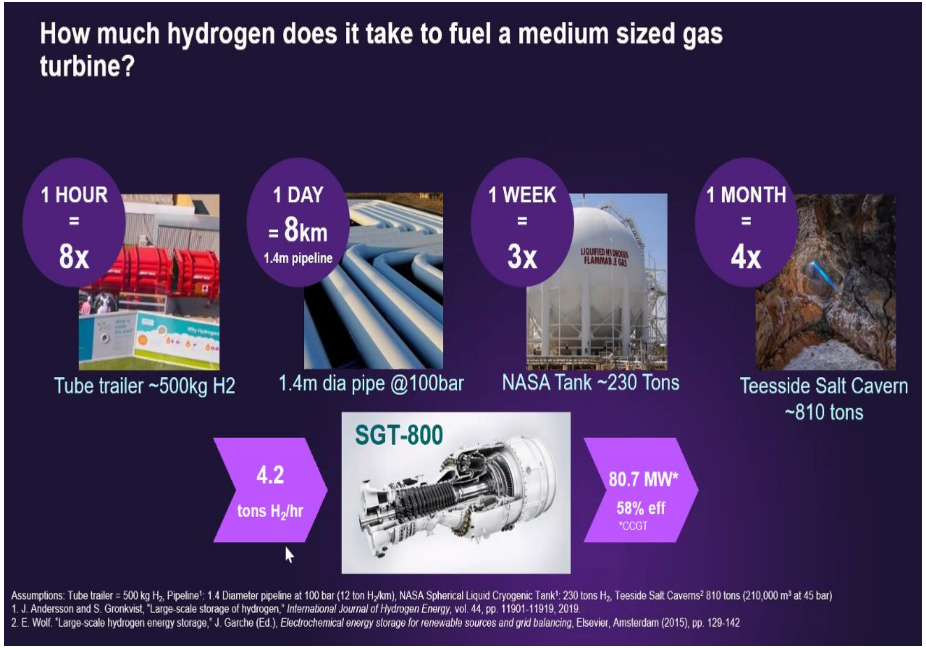
IHI Ammonia Gas Turbine- 100% NH3 [https://www.ihi.co.jp/en/all_news/2022/resources_energy_environment/1197938_3488.html]

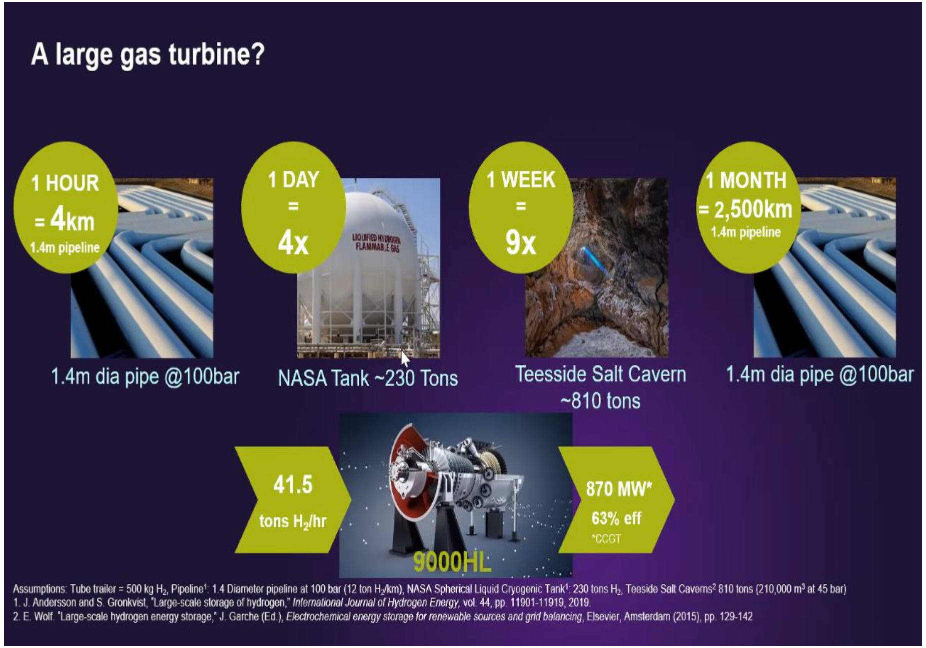
Developments – Gas Turbines



Efficiency of conversion of energy from ammonia in gas turbines [Cesaro Z, et al. Applied Energy, 2020]

Developments – Gas Turbines





Hydrogen requirements for two different sized gas turbines [Cesar Z, UK-India Ammonia meeting, 2020]

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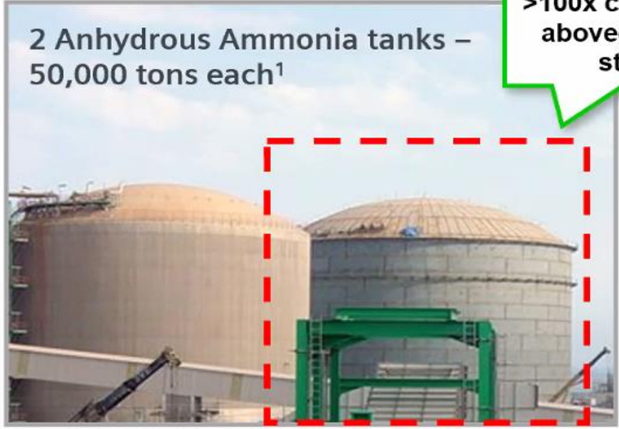
Developments – Gas Turbines

Bulk hydrogen stored as ammonia

2 Anhydrous Ammonia tanks – 50,000 tons each[1]



>100x cheaper than aboveground H2 storage

=

Salt caverns

11x

80 MW CCGT

3 months

870 MW CCGT

1 week

1x 50,000t NH_3
= 8,880t H_2

50,000t NH_3
=8,880t H_2

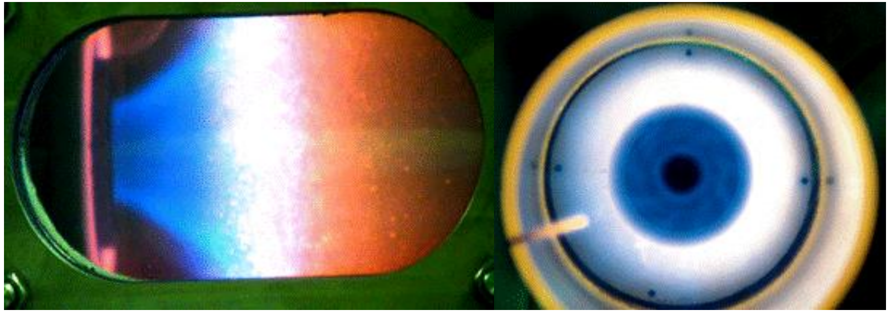
1. https://www.mcdermott.com/What-We-Do/Project-Profiles/QAFCO-Ammonia-Storage-Tanks - tanks are approximately 50 meters in diameter and 40.5 meters high, single-wall refrigerated, concrete containment walls.

Hydrogen requirements for two different sized gas turbines [Cesar Z, UK-India Ammonia meeting, 2020]

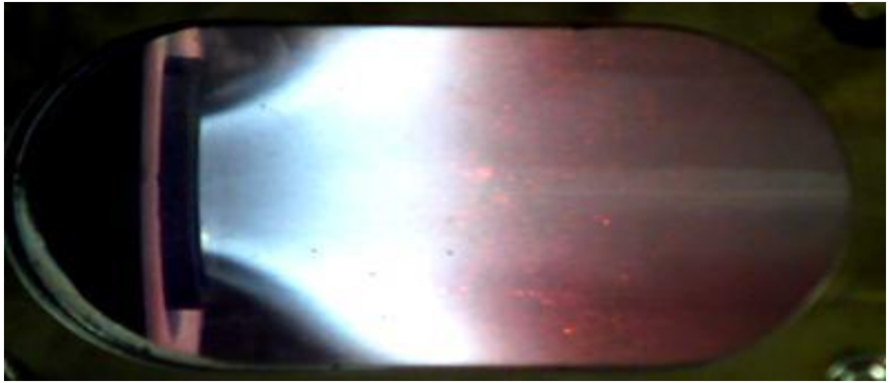
Developments – Gas Turbines

The Whitegate gas-fired power plant in southwest Ireland, where Centrica wants to develop ammonia-fired facilities.

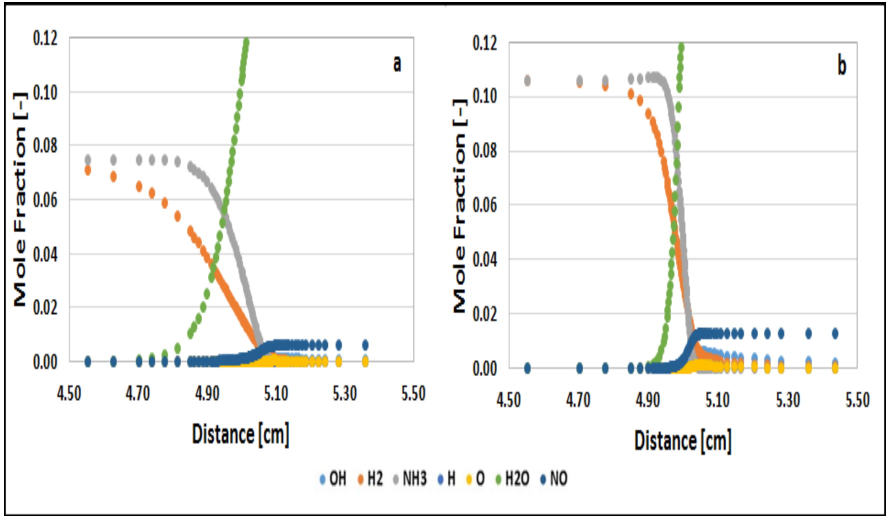
Developments – Micro Gas Turbines



66%$_{vol}$ NH3 - 33%$_{vol}$ CH4

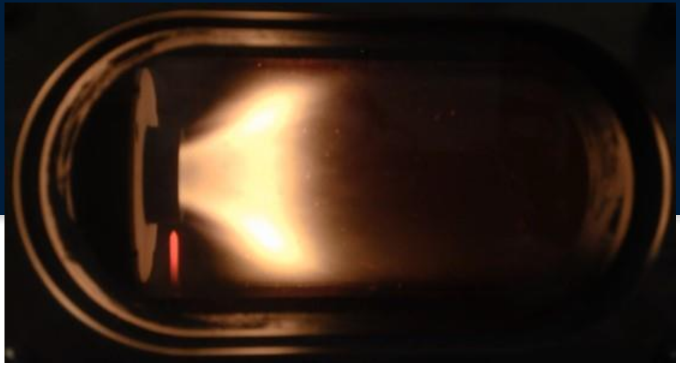


50%$_{vol}$ NH3 - 50%$_{vol}$ H2

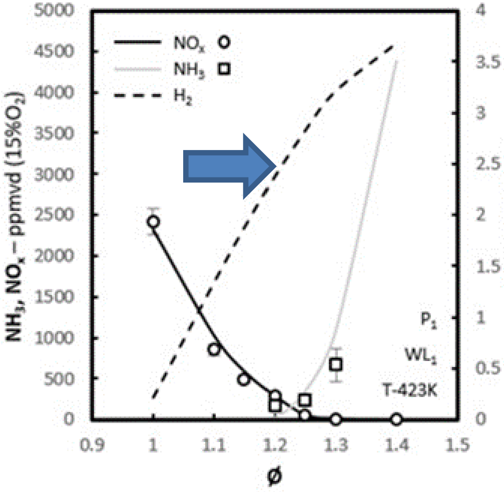


1-D Model for 50:50 ammonia/hydrogen reaction at a) Ø=0.52; b) Ø=0.80.

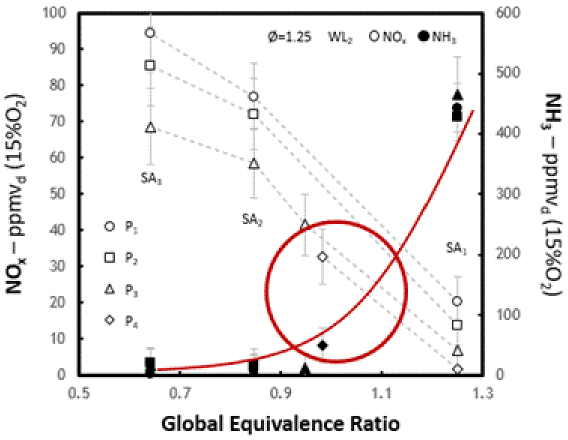
Developments – Micro Gas Turbines



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

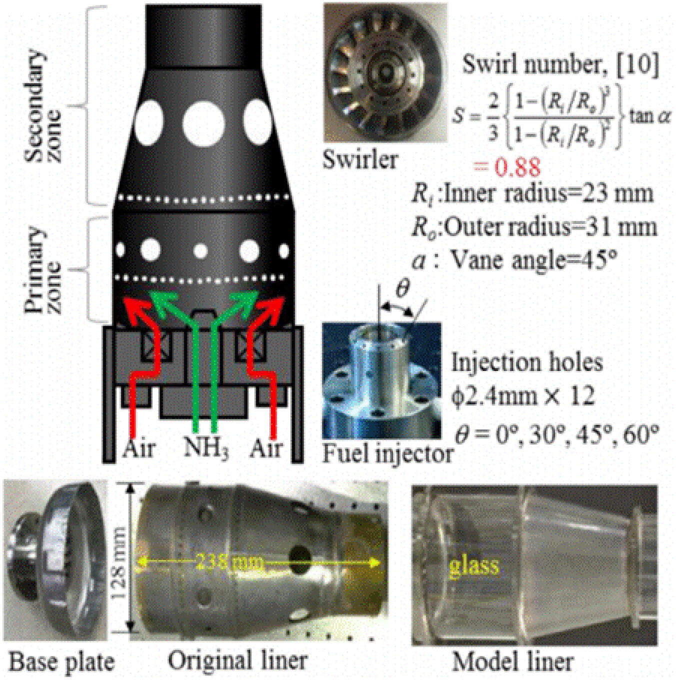


Clear reduction of NOx at high E.R. and high concentration of hydrogen



Fixed Primary Equivalence Ratio and Water Loading

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



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

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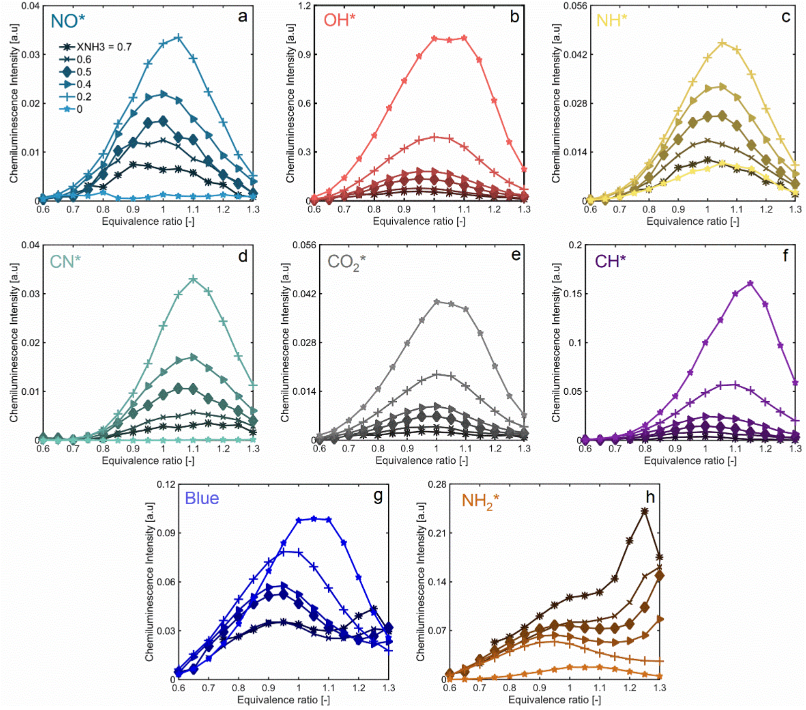
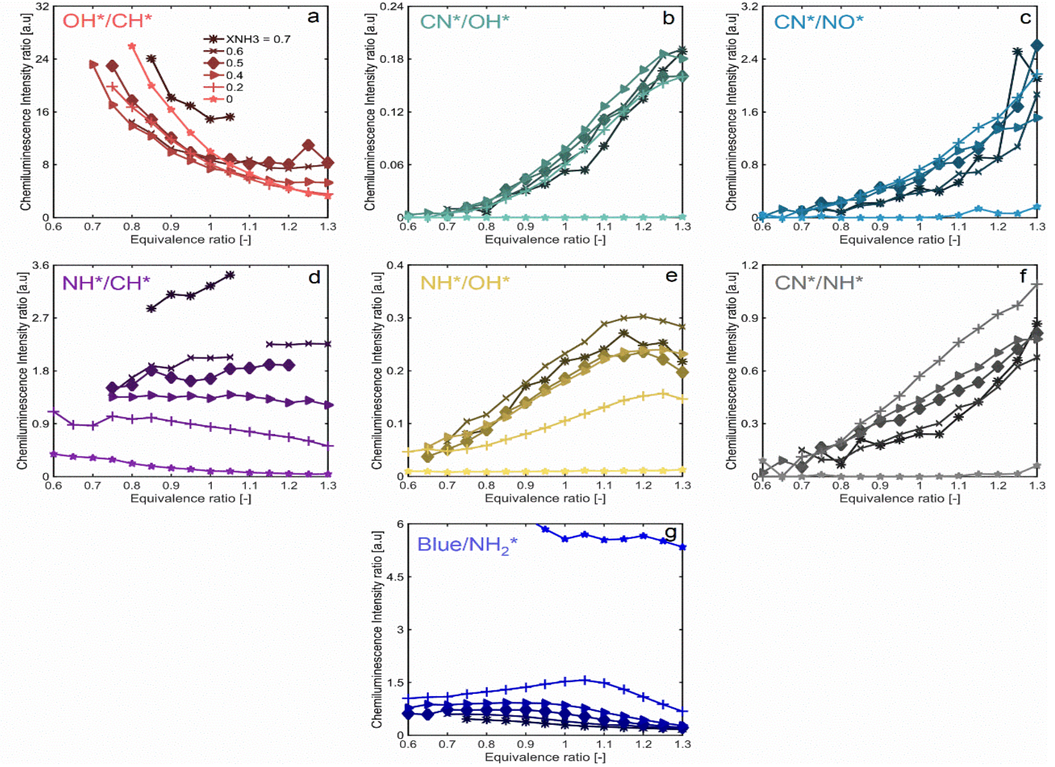
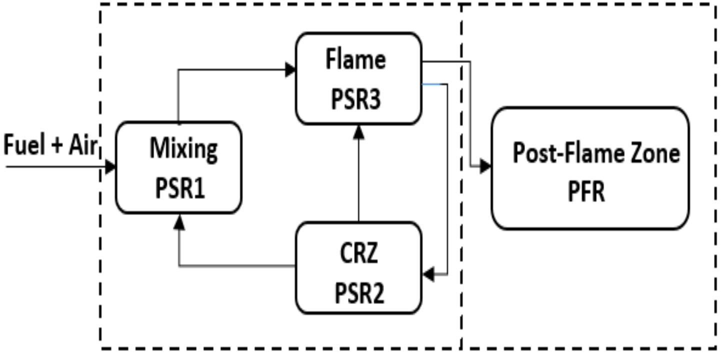
Developments – Micro Gas Turbines

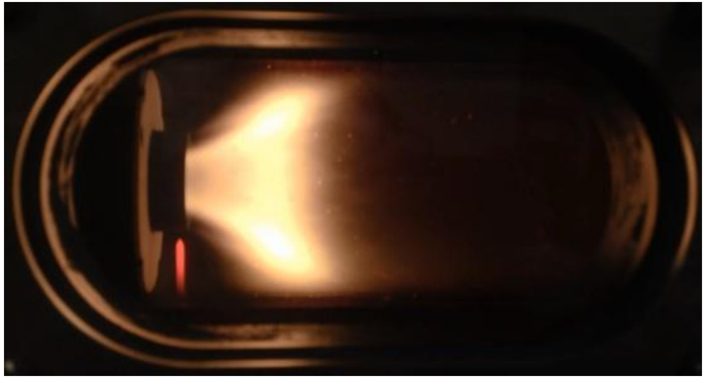




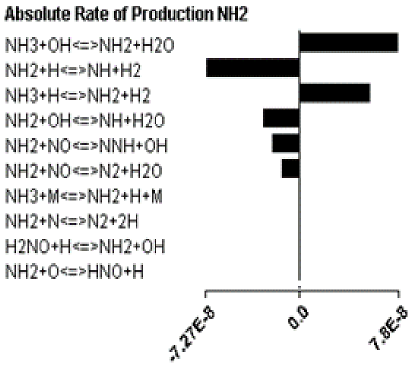
Spectral signals of various radicals and their correlation between each other [Mashruk S et al. 2022].

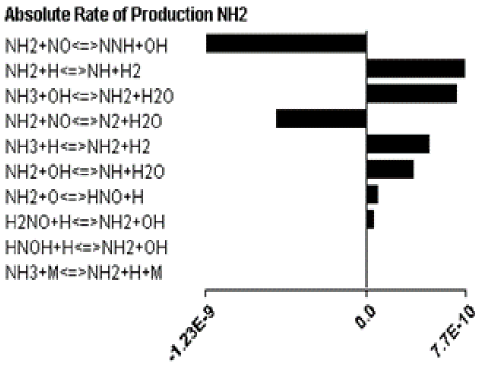
Developments – Micro Gas Turbines





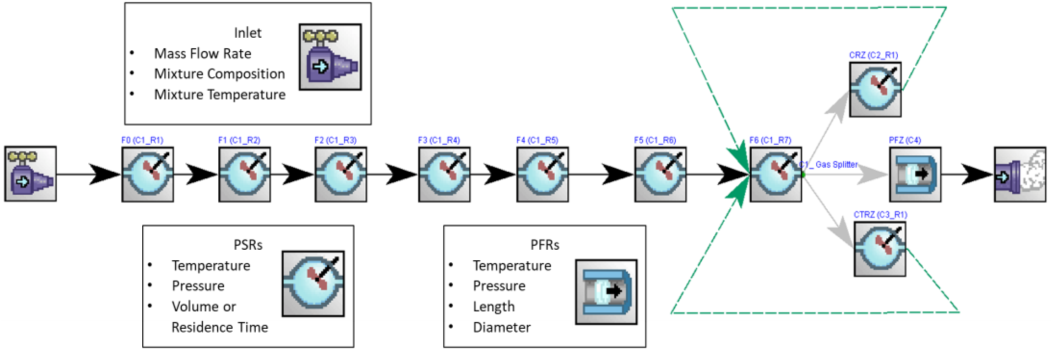
Reactions	*A*	*n*	*Ea*	*Ref.*
$N+NO=N_2+O$	2.10E+13	0	0	[26]
NO+H+M=HNO+M	1.50E+15	-0.4	0	[27]
$HNO+H=NO+H_2$	4.40E+11	0.7	650	[27]
N2O+H=NH+NO	6.70E+22	-2.16	37155	[28]
$N2O+H=N_2+OH$	5.00E+13	0.00E+00	1.52E+04	[29]

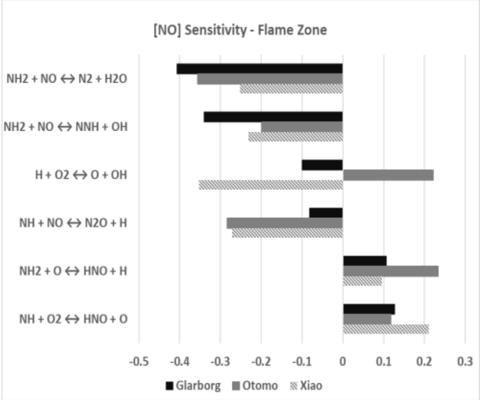


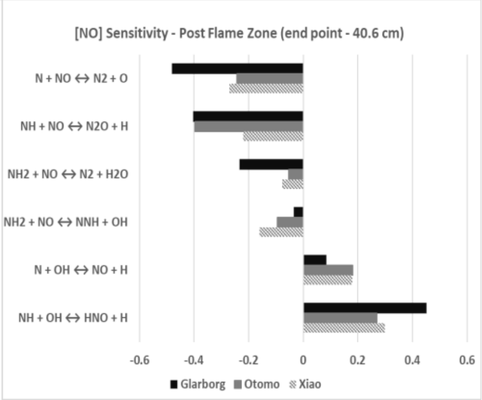


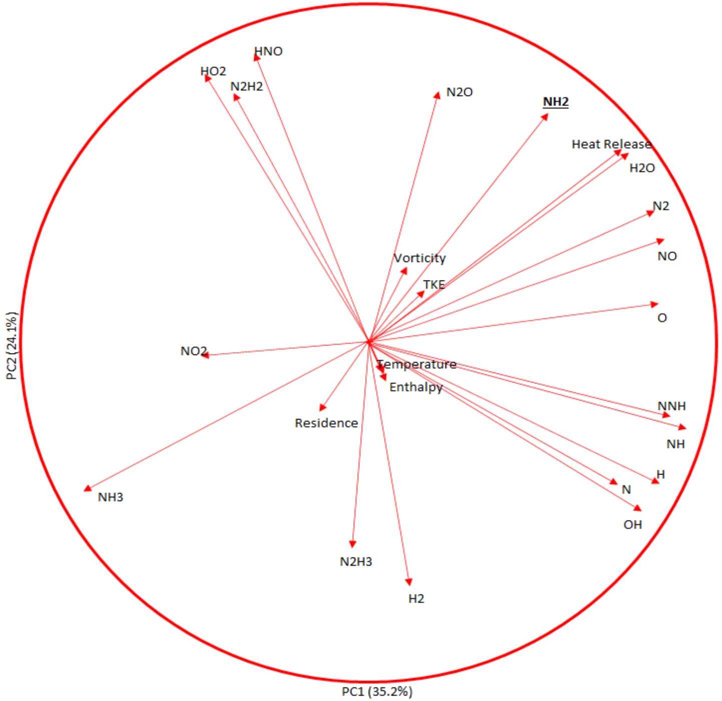
Correlation between experiments and numerical modelling adequate but not perfect.

Developments – Micro Gas Turbines



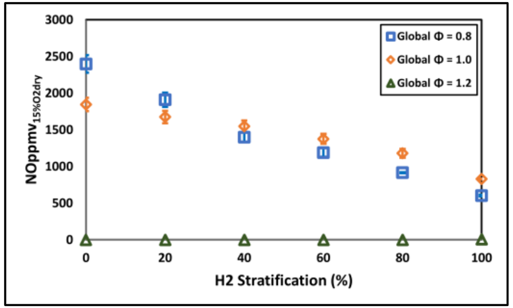


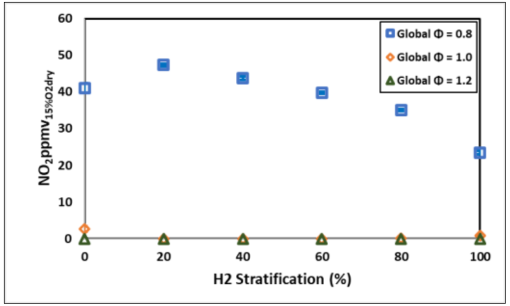


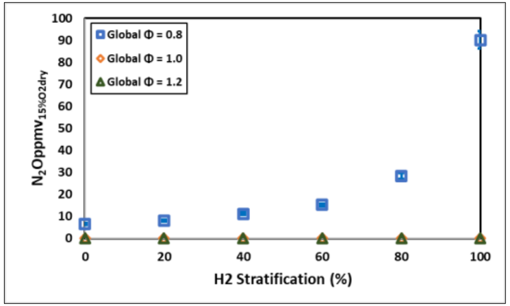


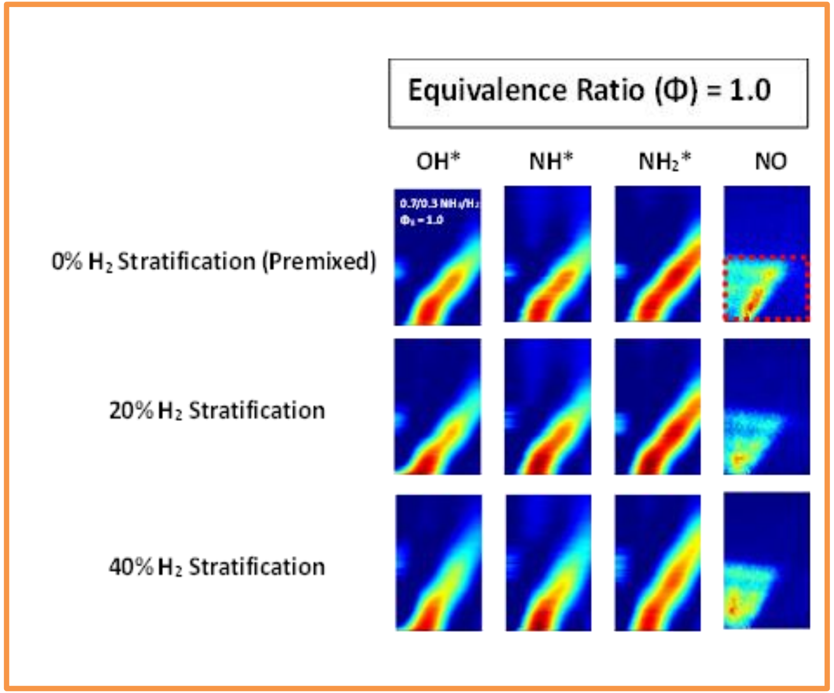
Bipolar multivariable analysis for NH2, with correlations between radicals and species.

Developments – Micro Gas Turbines



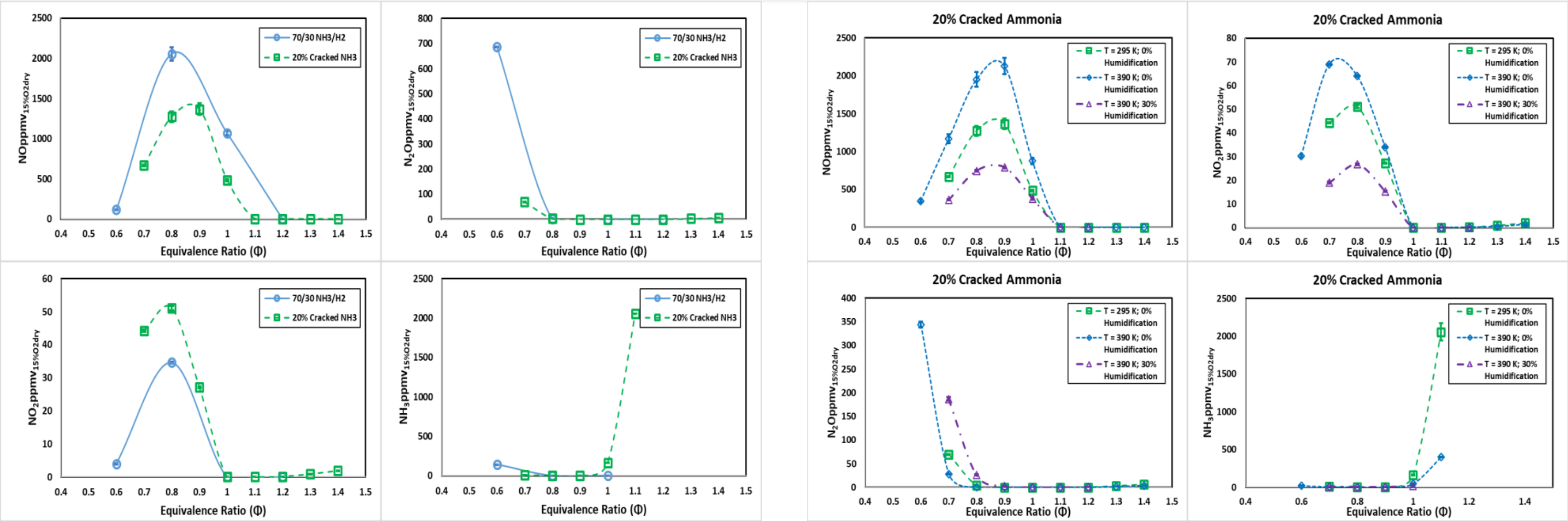






Stratification appears as a good potential for NOx mitigation whilst enabling good flame stability.

Developments – Micro Gas Turbines



Ammonia/Hydrogen vs Cracked Ammonia (20%) under atmospheric and higher temperature inlet conditions, with/without humidification.

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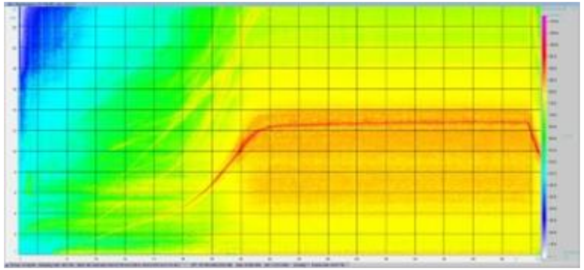
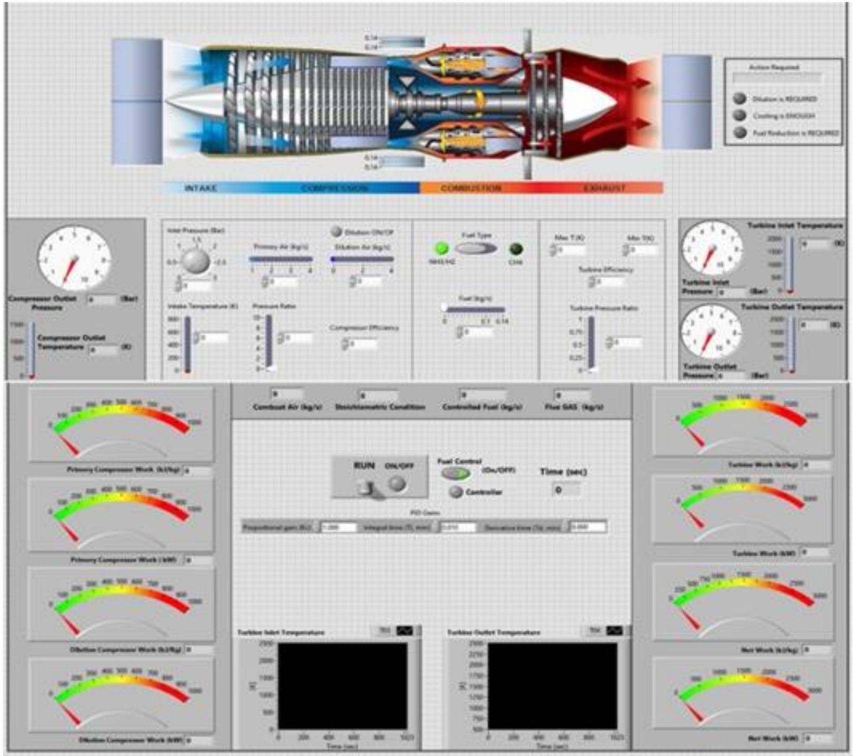
Developments – Micro Gas Turbines

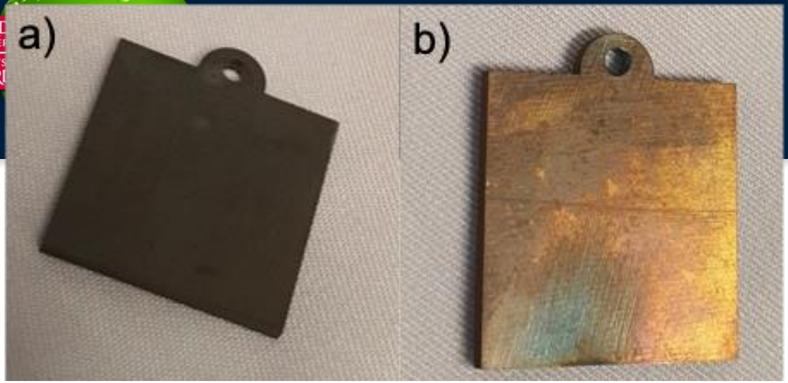


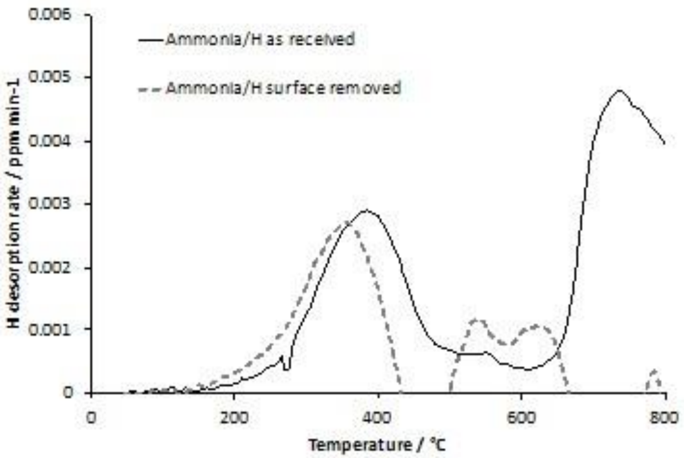


HELICOPTER AIR START UNIT (HASU)

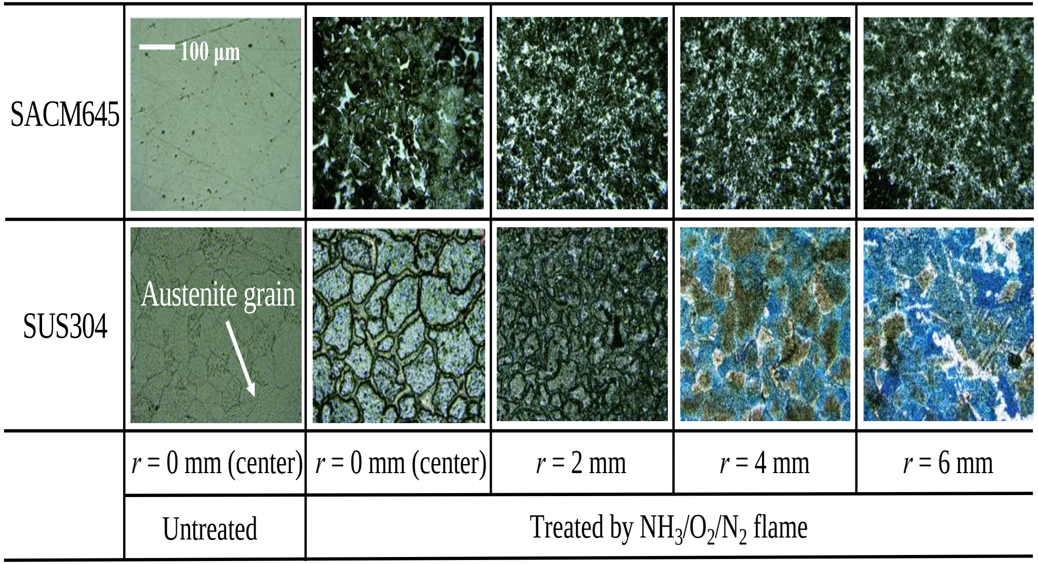
- Combustor will be replaced by new combustor
- Acoustic signature of the unit has been obtained
- A bespoke controlling systems is under development to enable stratified/humidified combustion

Developments – Micro 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].

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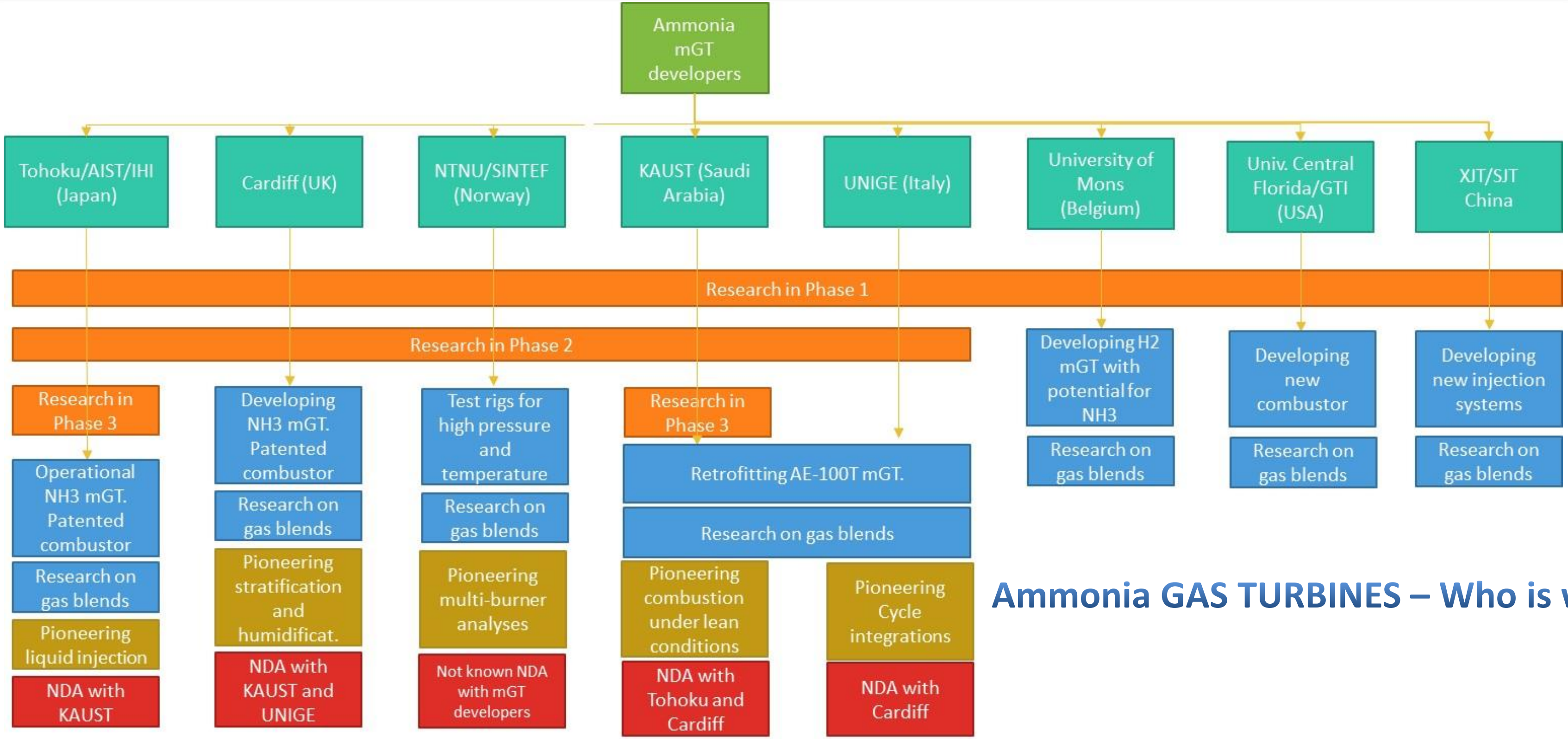
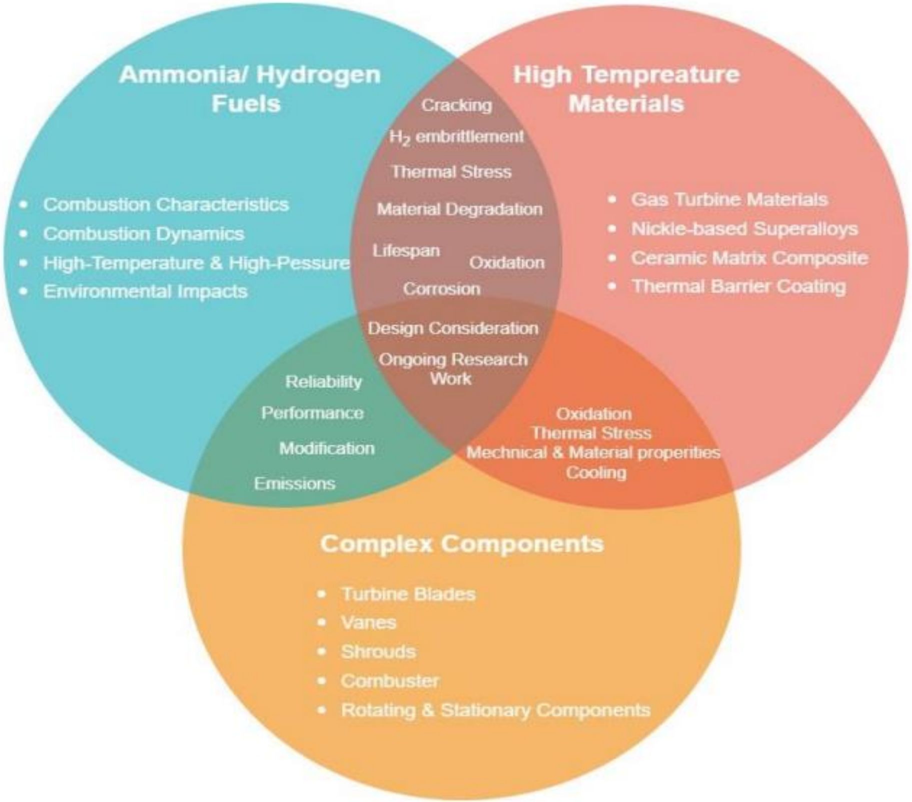
Developments – Micro Gas Turbines



Ammonia GAS TURBINES – Who is who

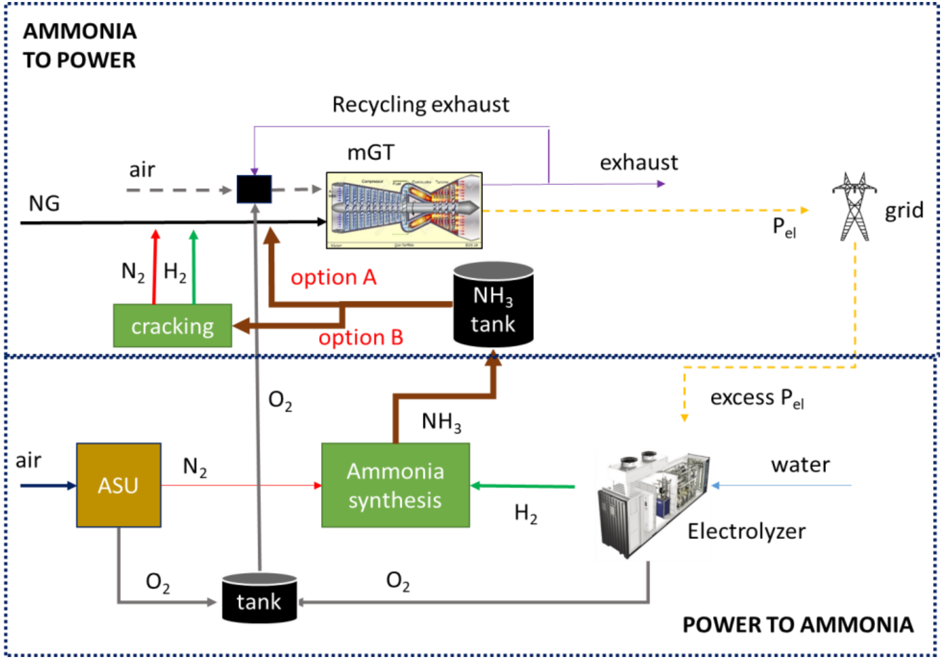
Developments – Gas Turbines

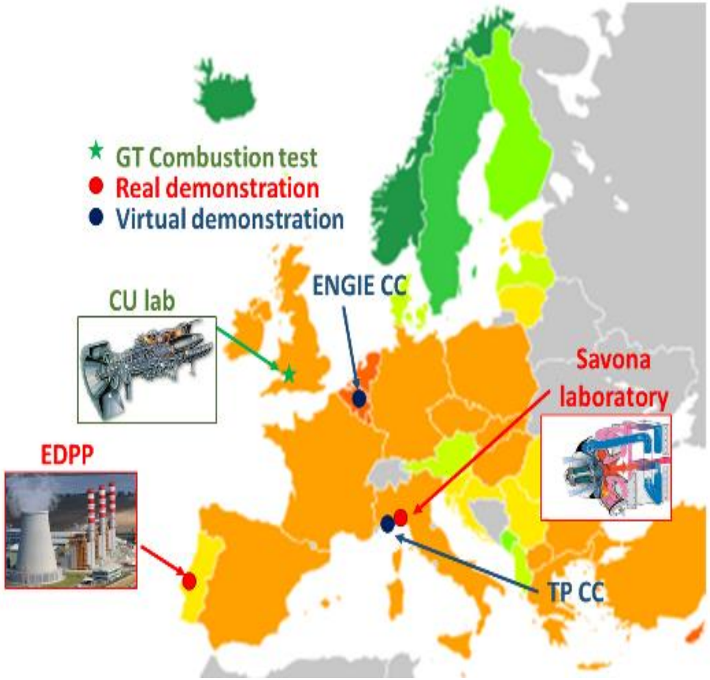


Complex Interactions with Gas Turbine materials

- Hydrogen Embrittlement
- Ammonia Nitration
- Acids
- Basic atmospheres
- Third Body reactions
- Heat Losses
- Radiation

Developments – Gas Turbines

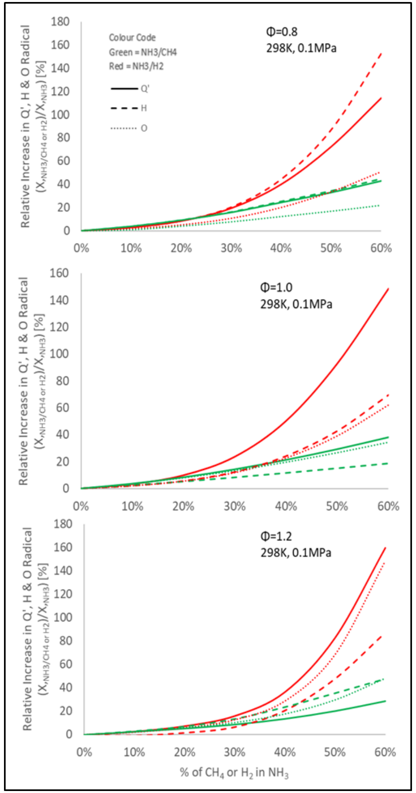


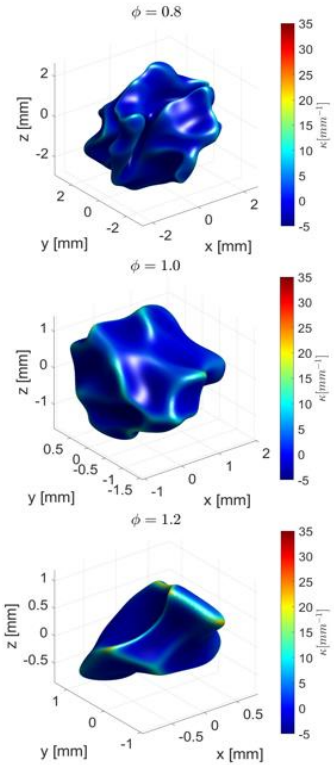


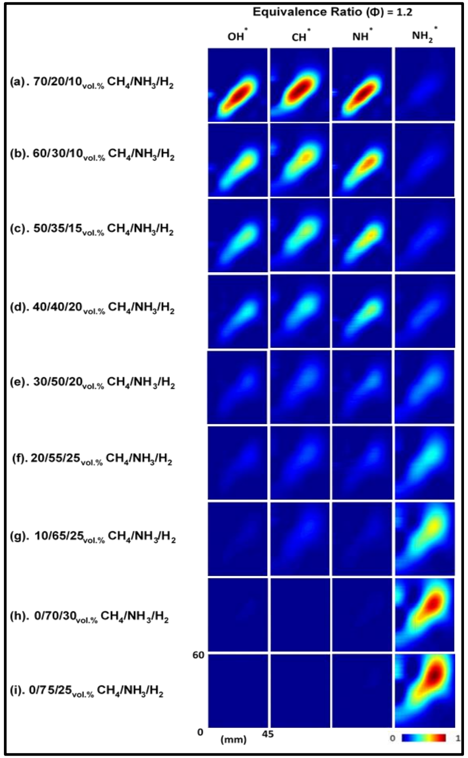
FLEXnCONFU – First large GT ammonia/hydrogen/NG demonstrator

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

Developments – Gas Turbines







Initial Results

- High NOx at low Equivalence Ratios
- Rich conditions boost the production of NH2*
- Hydrodynamic and Thermodiffusive instabilities have a high impact on flame morphology
- Up to 20% NG/H2 replacement can be feasible without major retrofitting.

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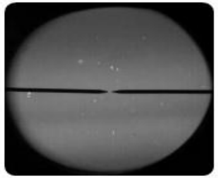
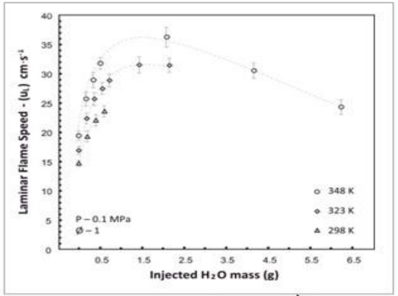
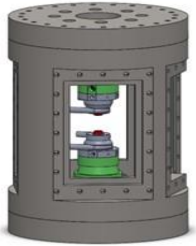
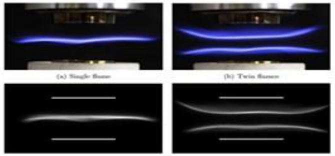
Developments – Gas Turbines

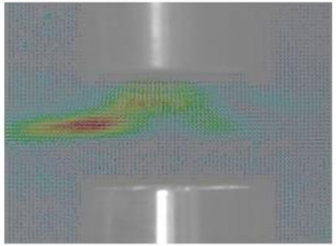
LAMINAR HT FLAMES → TURBULENT HT/HP FLAMES → GENERIC HP/HT TURBULENT/SWIRL FLAMES → OPERATIONAL POWER-GEN DEMONSTRATORS

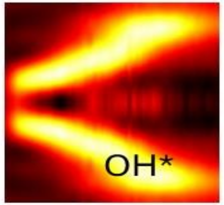


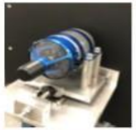


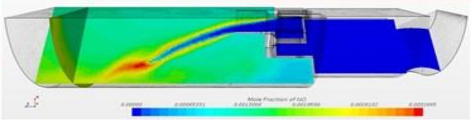




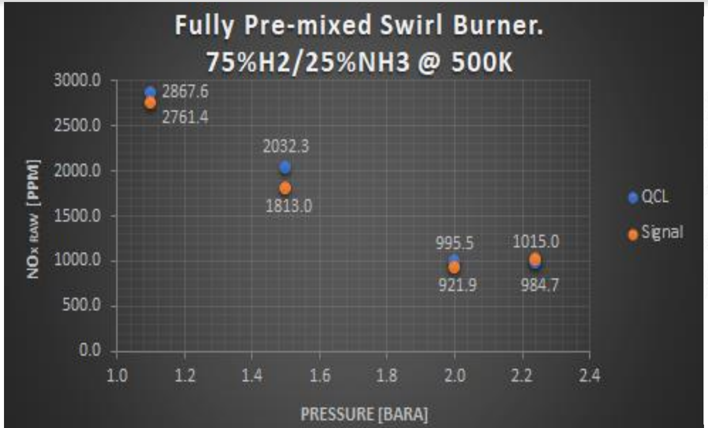


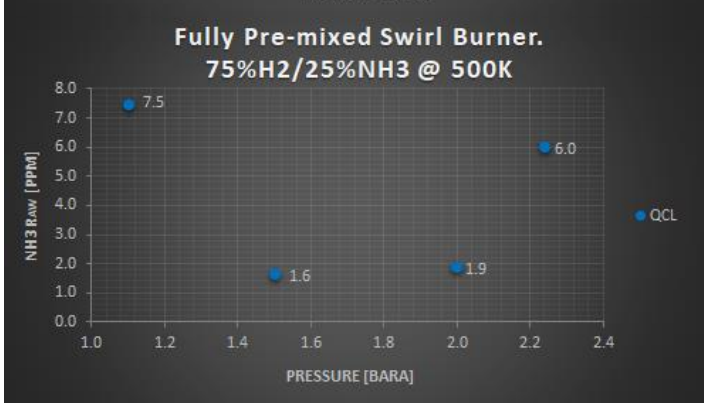


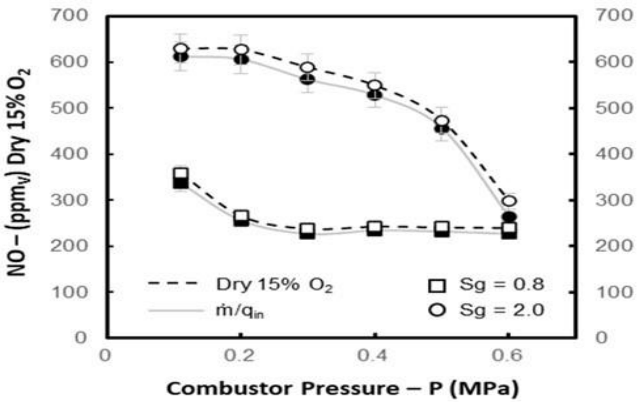


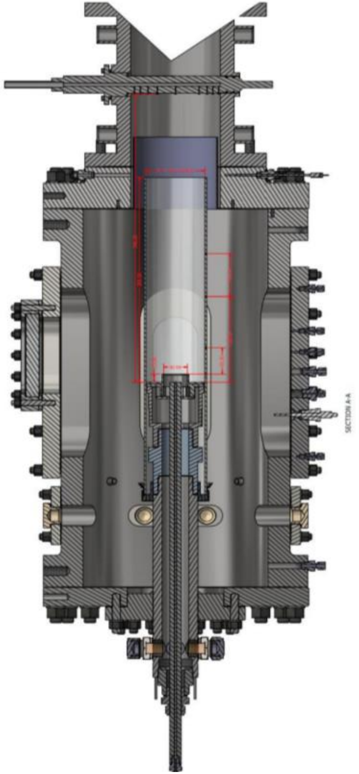


Developments – Gas Turbines









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.

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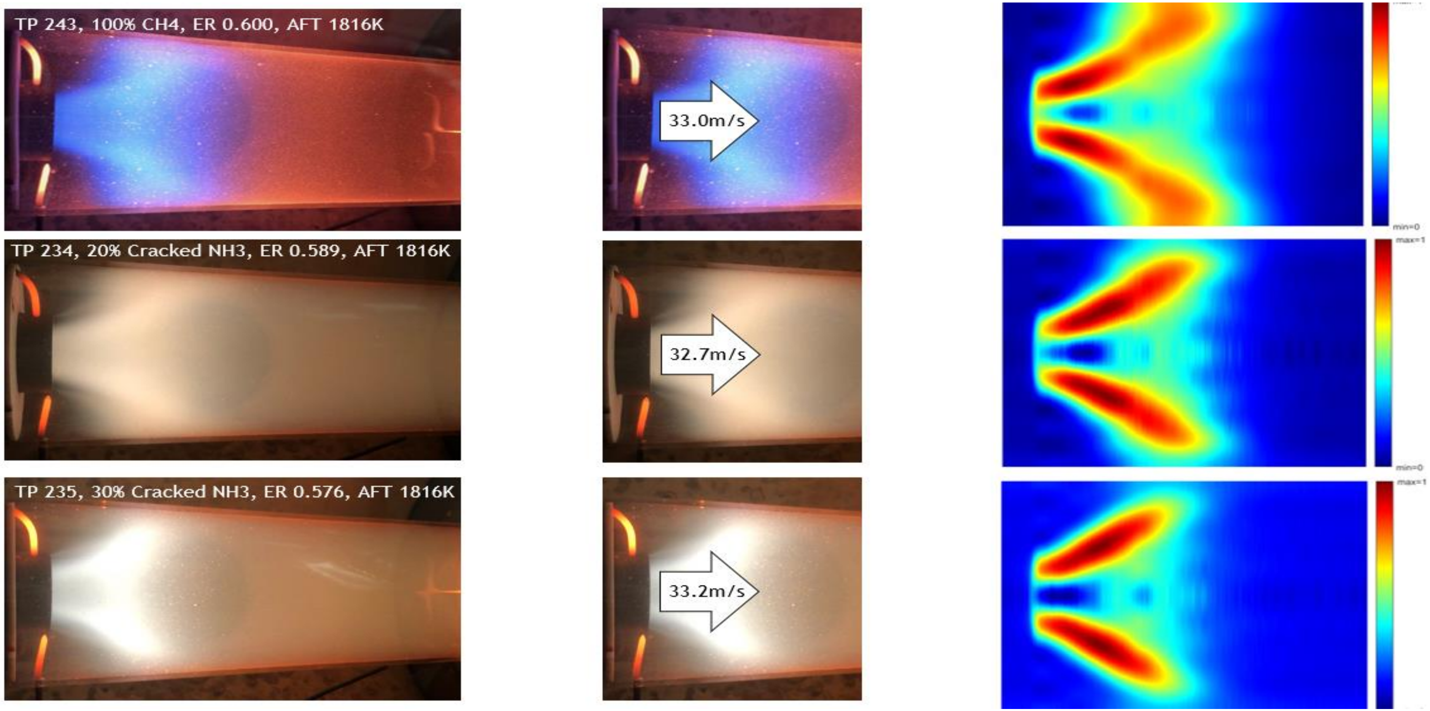
Developments – Gas Turbines



Photographs and OH*Chemi. 50kW,1.1bara, 538K

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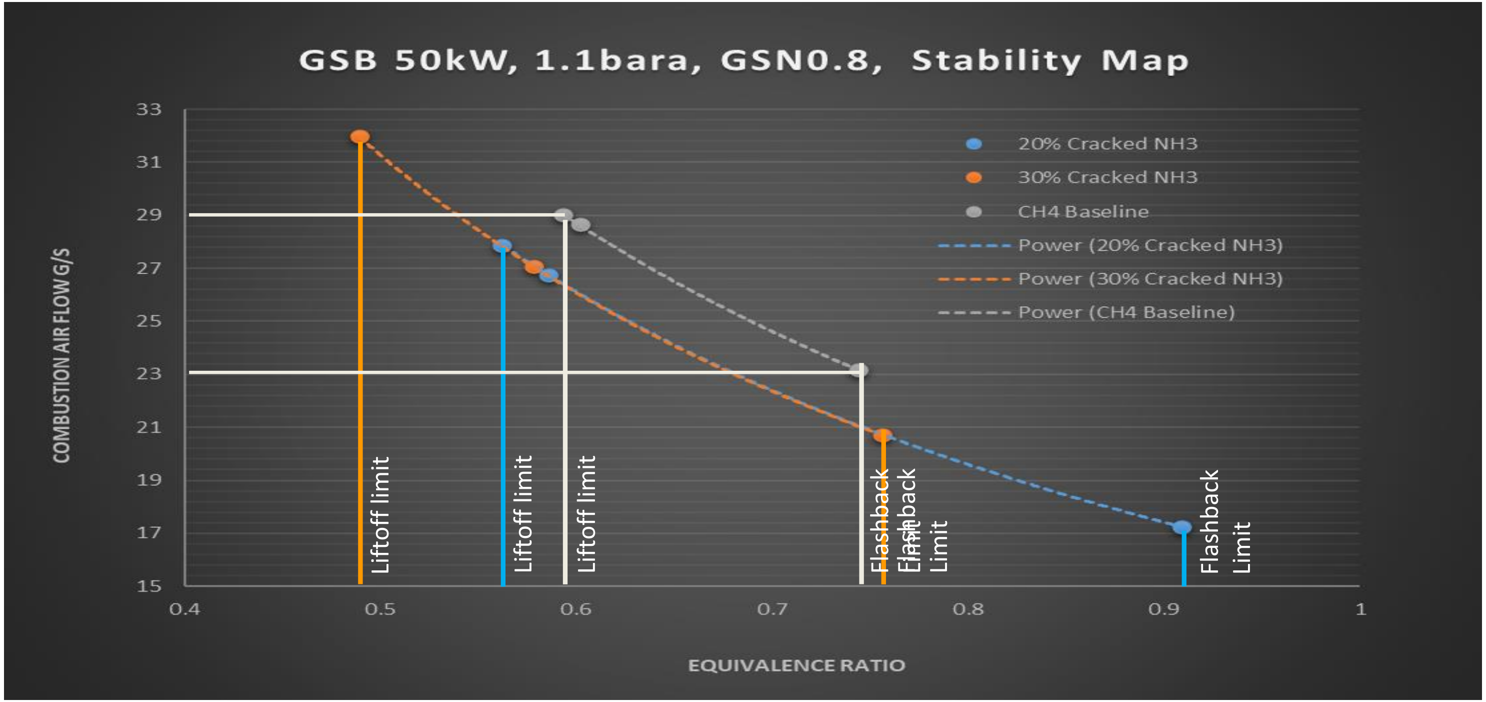
Developments – Gas Turbines



Operability limits using cracked ammonia compared to methane.

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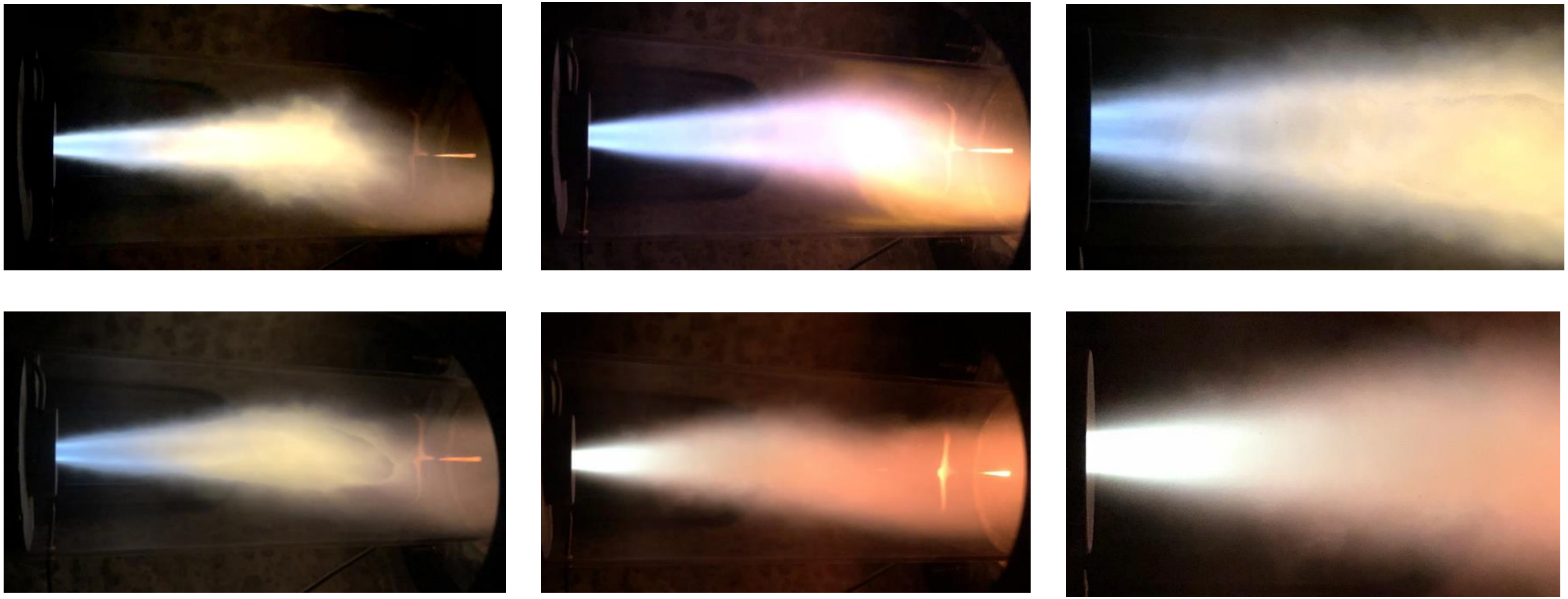
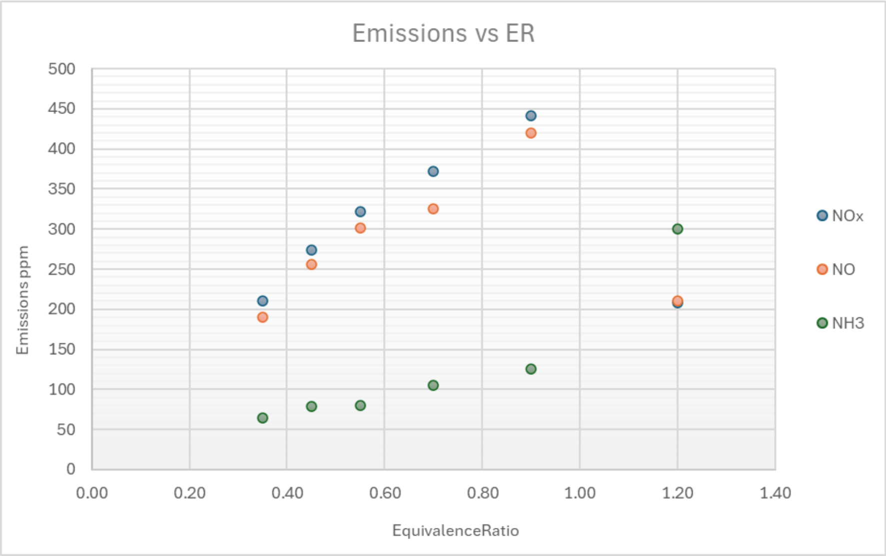
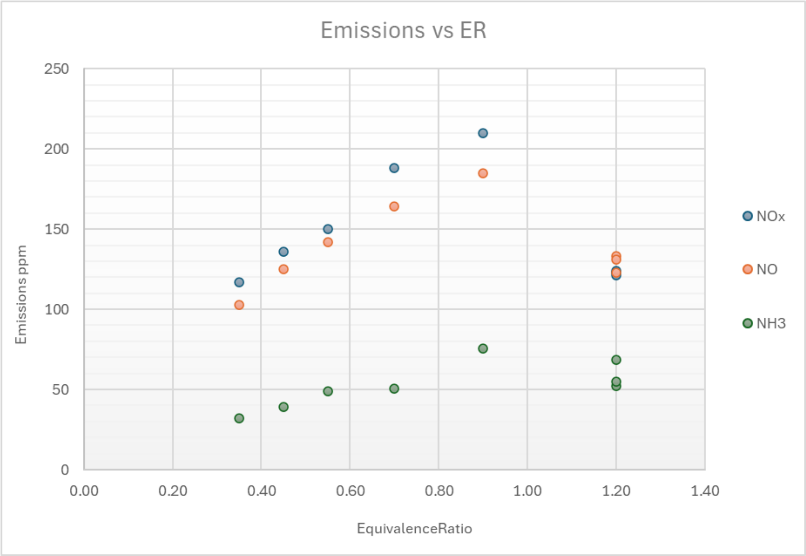
Developments – Gas Turbines



Photographs. 50kW,1.1bara, 538K. Heavily cracked conditions.

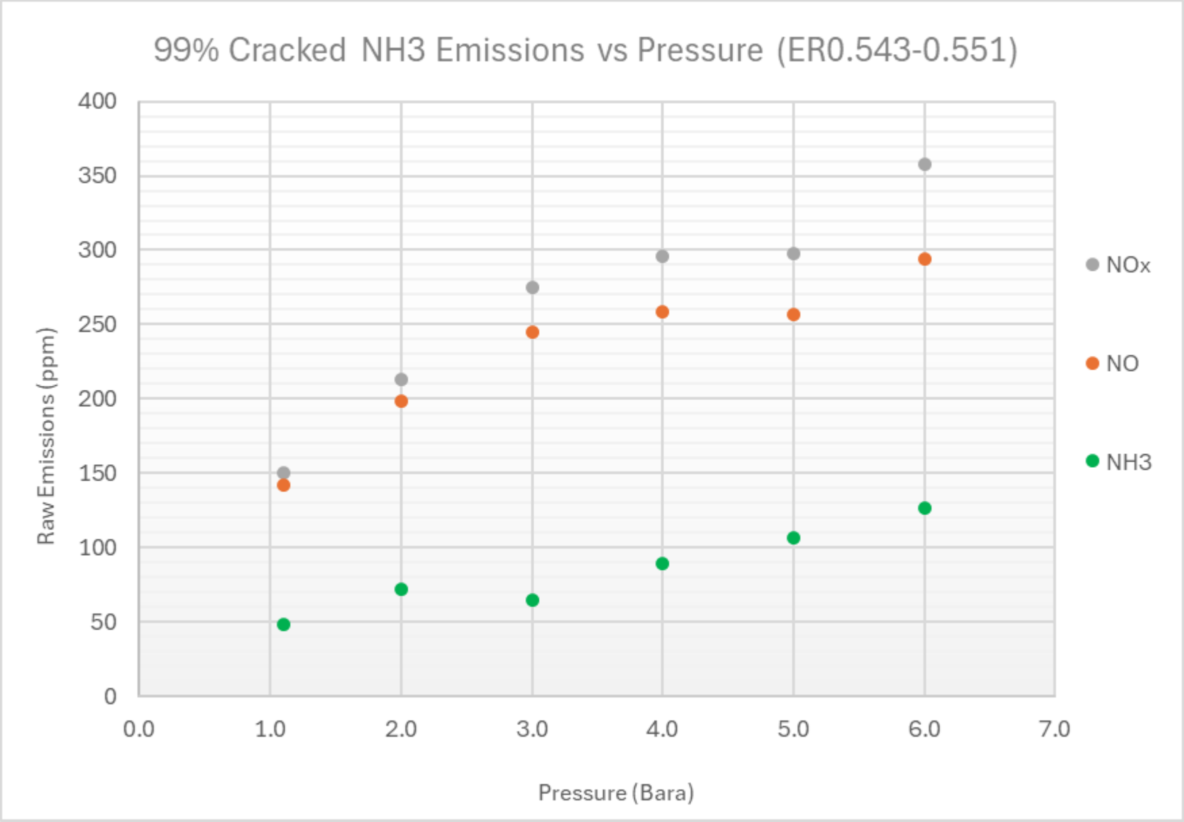
Developments – Gas Turbines





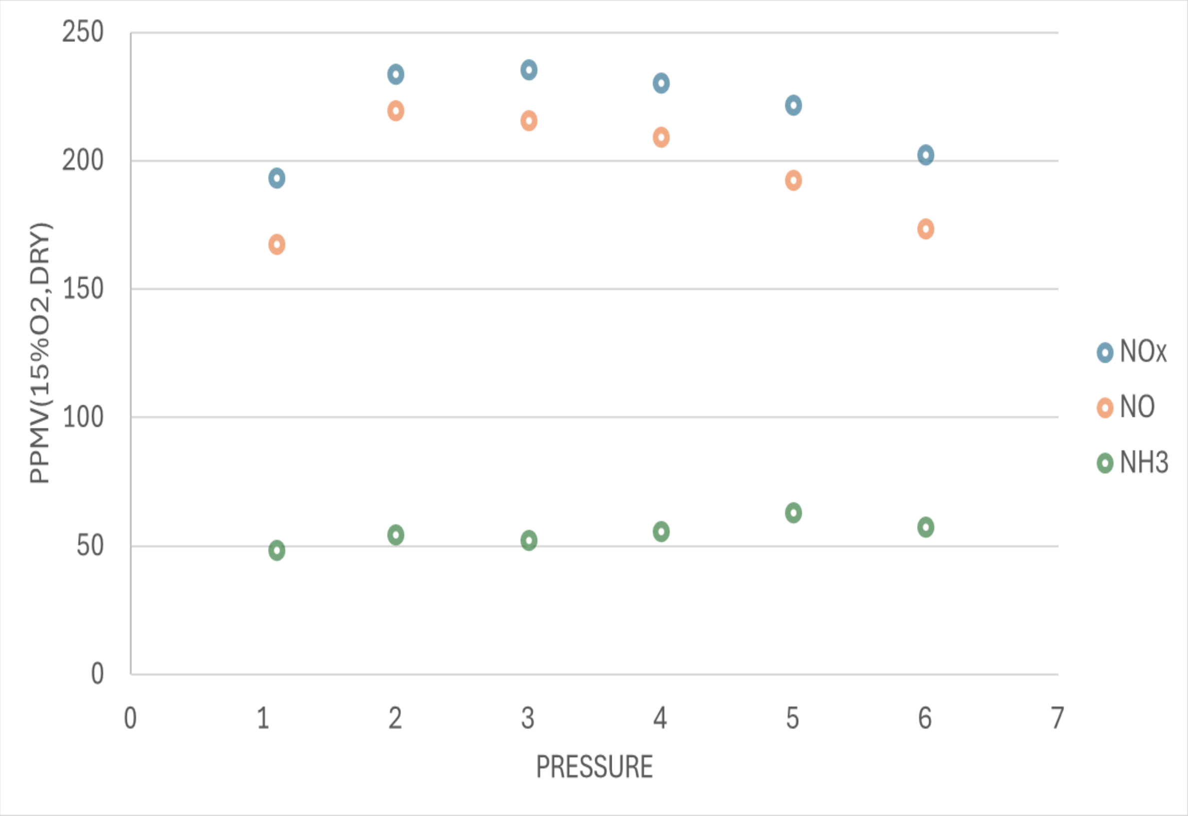
Emissions. 50kW,1.1bara, 538K. 92 and 99% cracked conditions.

Developments – Gas Turbines



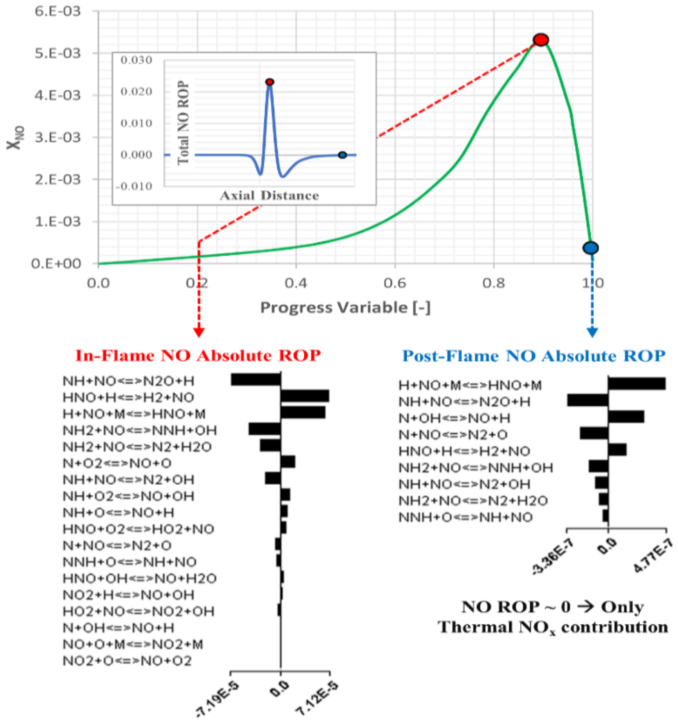
Emissions. Up to 75kW,1.1-6 bara, 538K. 99% cracked conditions.

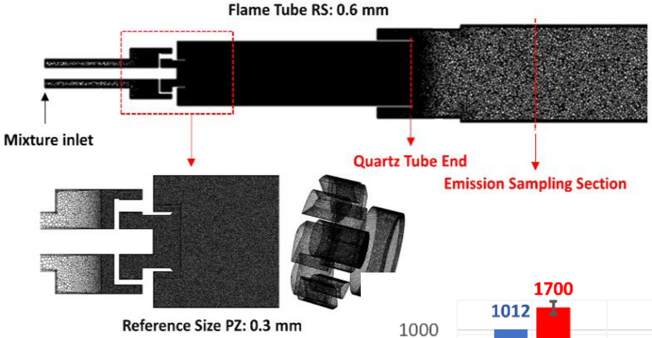
Developments – Gas Turbines

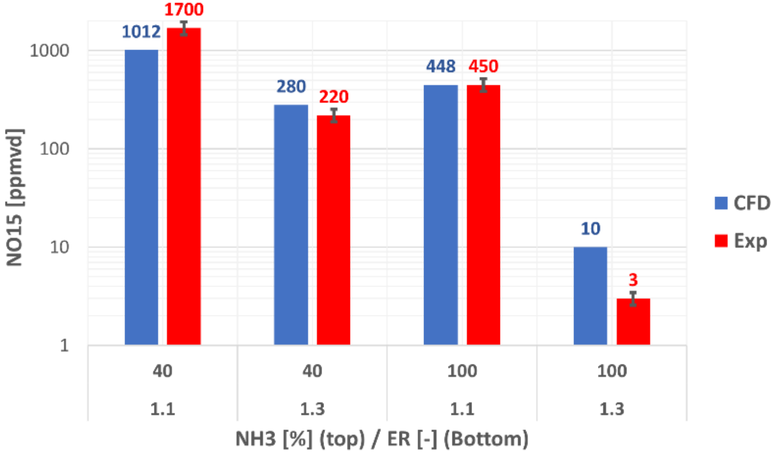


Emissions. Up to 75kW,1.1-6 bara, 538K. 92% cracked conditions. Corrected to 15%O2.

Developments – Gas Turbines







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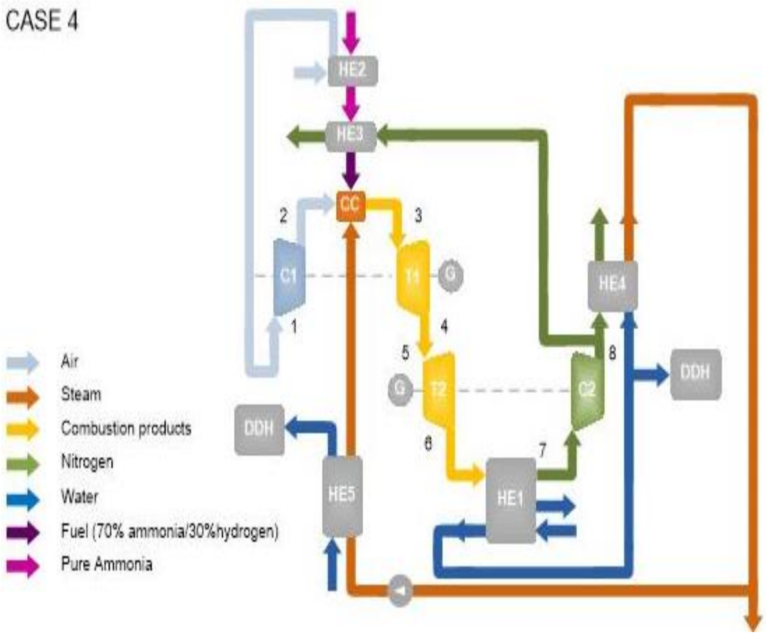
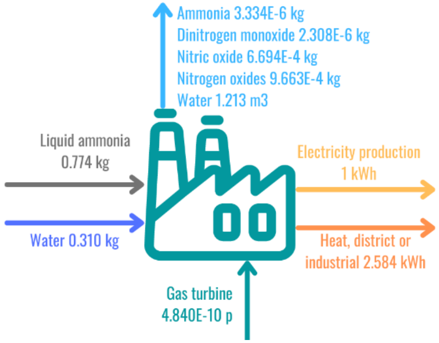
Developments – Gas Turbines

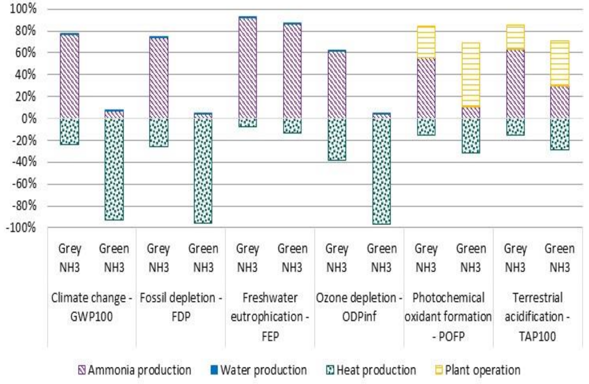


Modified Brayton Cycle
Inlet temperature 1260K
Outlet temperature 827K
Supplied heat 10.45MWth
Power 3.56MWe
Plant efficiency 34%

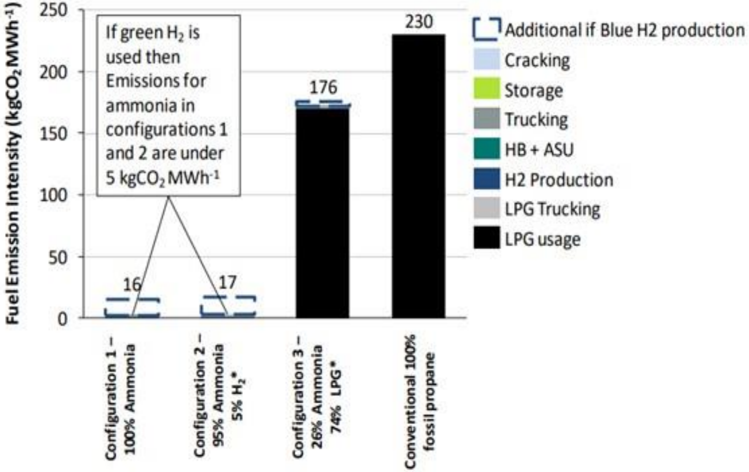
Trigeneration Cycle
Cooling+Power+Heating
Initial calculations: 62.5%
(compared to ~80%)

Similarly, LCA shows the superior environmental advantages of green NH3



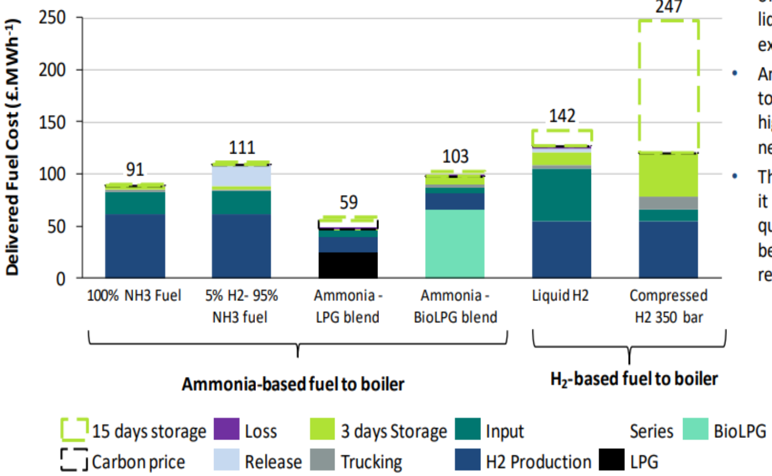


Developments – Boilers/Furn.



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°C).
- 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)

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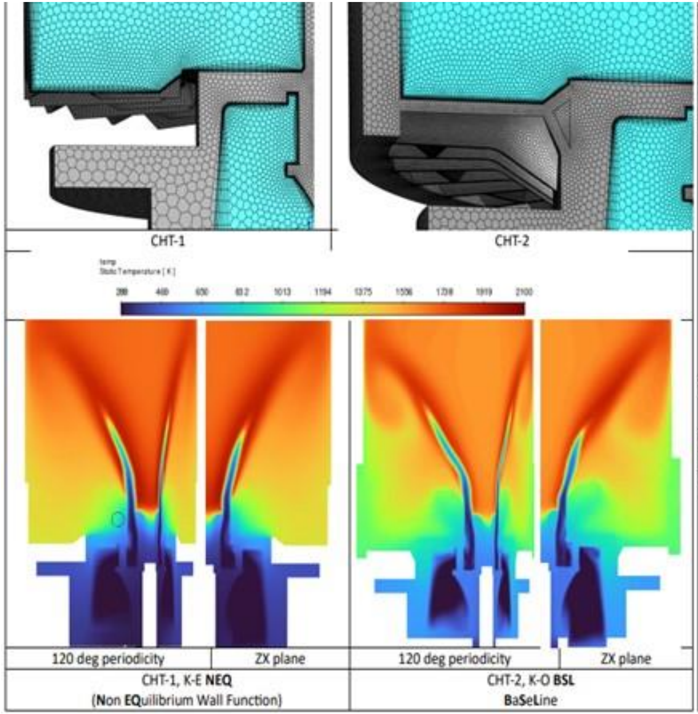
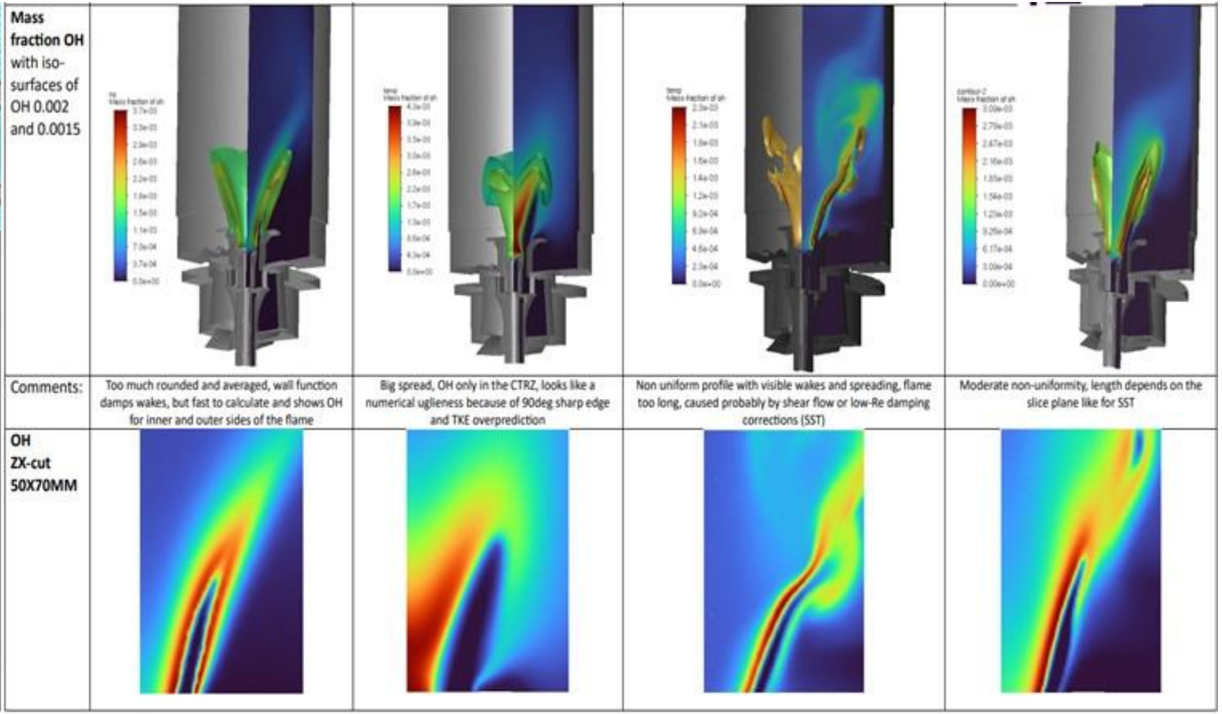
Developments – Boilers/Furn.





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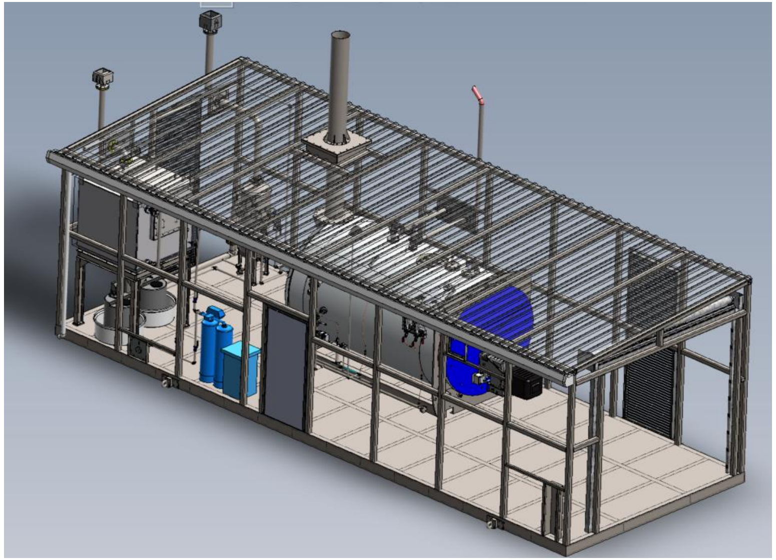
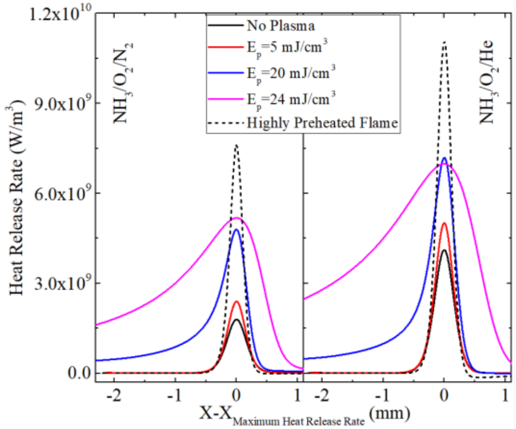
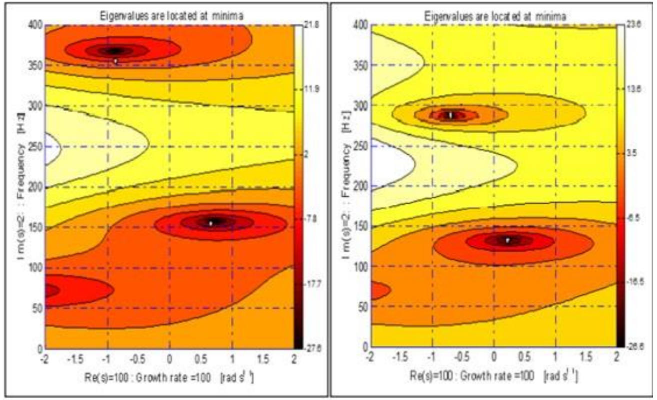
Developments – Boilers/Furn.

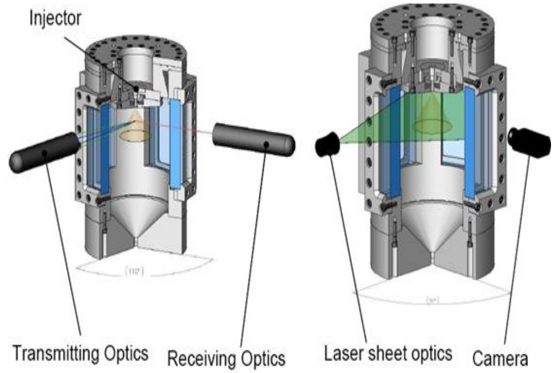
- The unit will be used for demonstration in a Poultry farm. Further developments are expected for the deployment of ammonia to isolated regions.

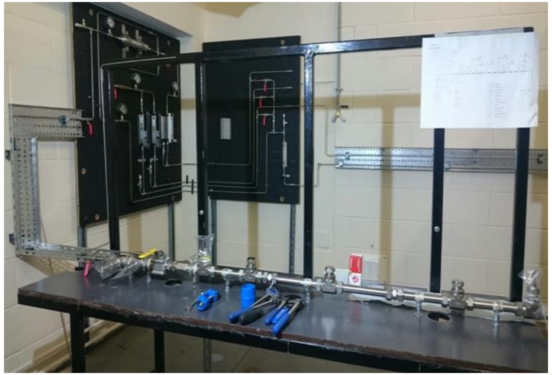


Developments – Other areas









Experimental Additions

Plasmas Combustion (Nox reduction)

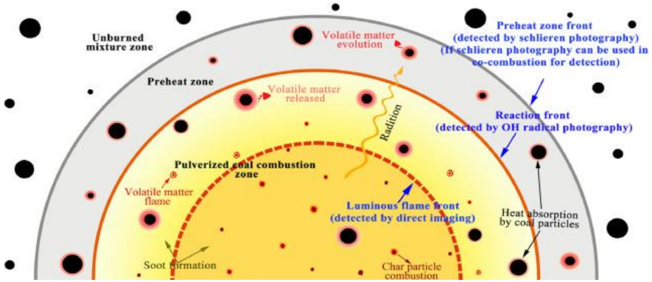
Thermoacoustics (flames stability)

Multi-phase injection (fuel replacement)

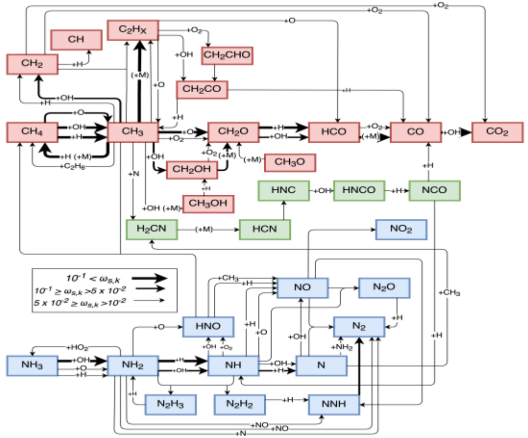
Direct ammonia injection (liquid spray)

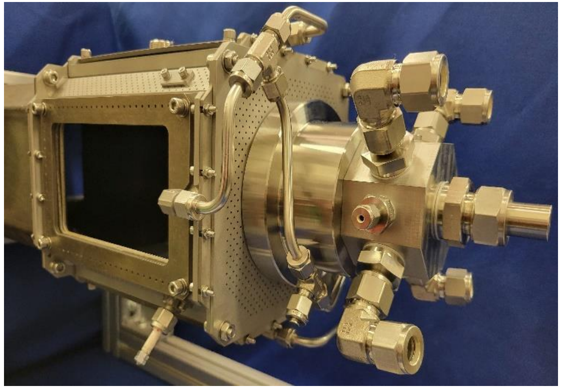
Pulse detonation (explosions)

Developments – Other areas



Assumption of co-combustion flame structures [Xia et al. 2021]





Experimental Additions

Jet Injection (in collaboration with Nottingham)

Materials Analyses

Multi-phase Injection

Coal-ammonia co-firing

Additional molecules (ie. cyanide) in reaction pathways

Radiation studies

Health and Safety

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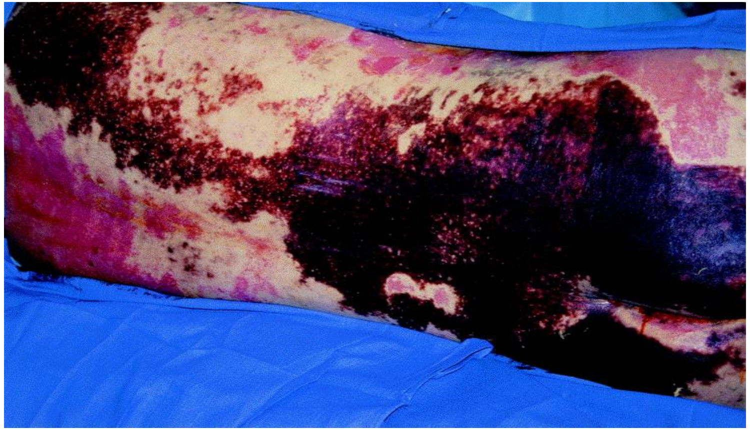
Developments – H&S/Envirn.

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



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

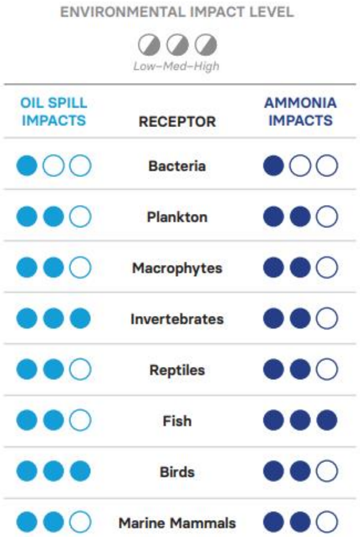
Explosions and cylinder damage

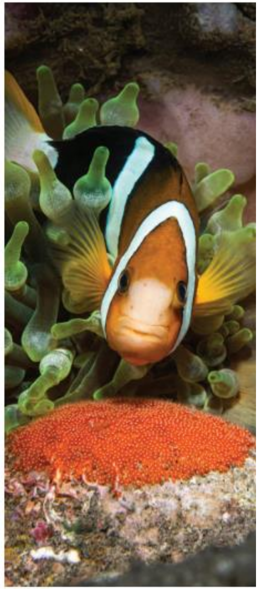
Developments – H&S/Envirn.

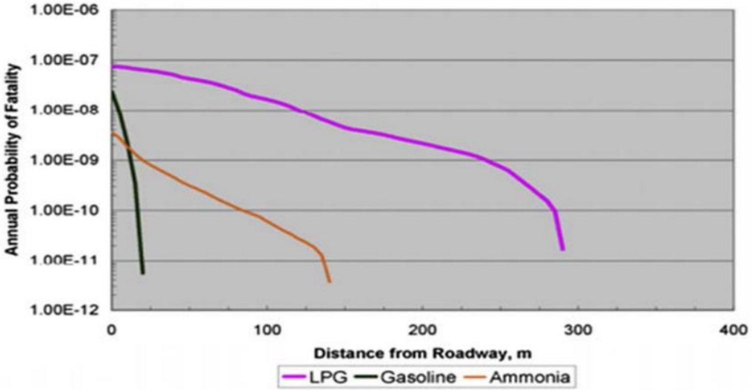
TABLE 10.6
Reported Accidents With Transporting Anhydrous Ammonia and Ammonia Solutions, United States, 1971–2019 (Reports Only for Anhydrous Ammonia).

	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.



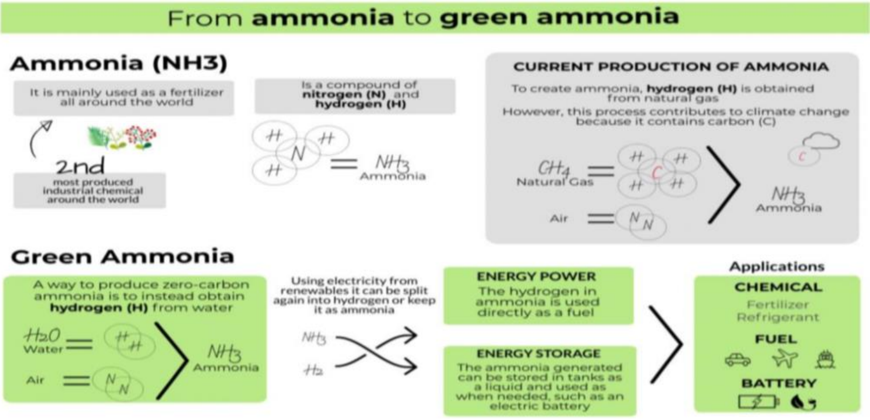


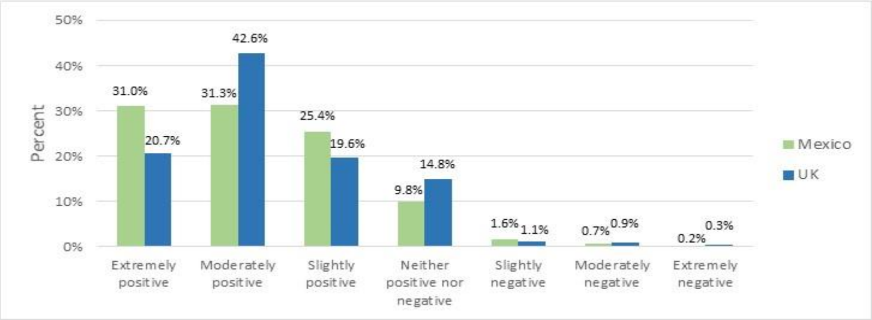


Environmental Defence Fund, 2022. [Online]. Available in: https://cdn.ricardo.com/ee/media/assets/ammonia-at-sea-report-summary.pdf

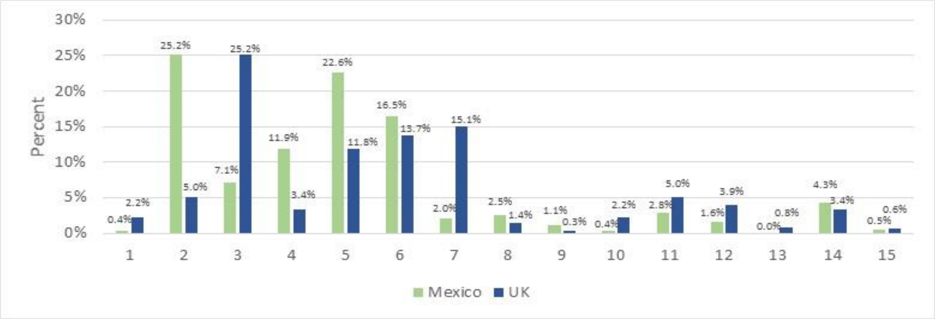
Quest Consultants Inc. Comparative Quantitative Risk Analysis of Motor Gasoline, LPG and Anhydrous Ammonia as an Automotive Fuel. Iowa, USA: 2009. Courtesy of Quest.)

Developments – H&S/Envirn.

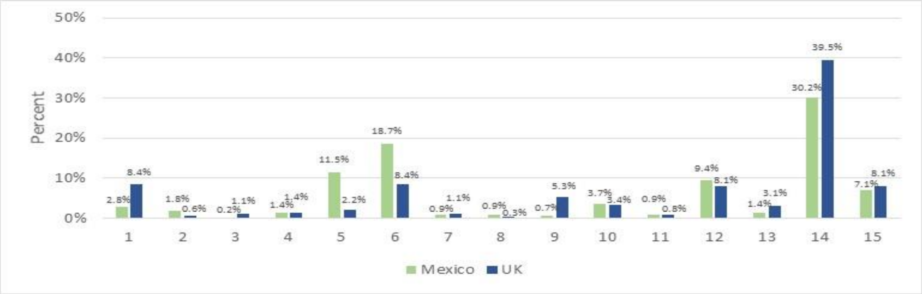




Percent of responses for opinion of green ammonia technology (920 individuals – 357 UK, 563 Mexico).



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.

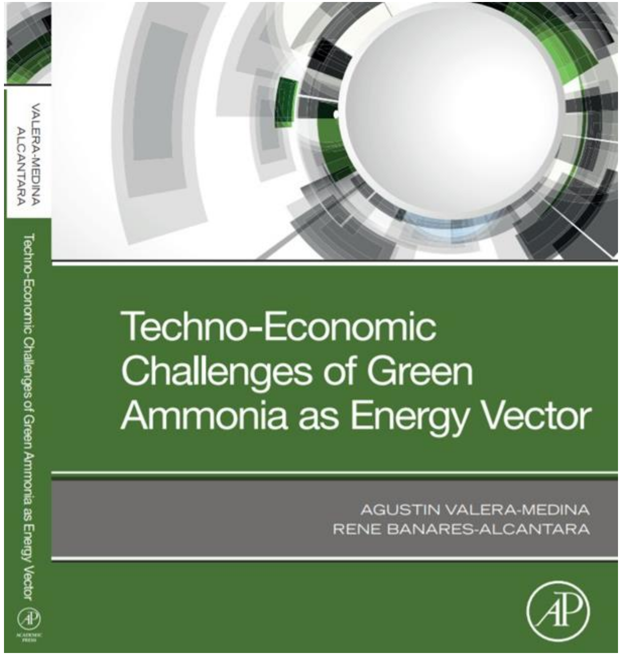


Percentages for most common answers by country of perception of green ammonia. (1) Nothing/Don't know (2) Poison/toxic (3) Smell (4) Safety (5) Solution/alternative (6) Novel concept (7) Cost (8) Pollutant (9) Complex/confusing (10) Need more information (11) Water (12) Positive for the environment (13)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

Conclusions

- Ammonia blends can be used efficiently, with low NOx, and production of species that can be used for combined processes.
- However, ammonia will be only useful for some niche applications.
- Reaction mechanisms need to be accurate and include a variety of complex processes still requiring vast research.
- There are still many points in the combustion of ammonia that require further research, with a lot of input from Public Perception.


NH3
3rd SYMPOSIUM on 氨能
AMMONIA ENERGY
2024/SEP/3-5 SHANGHAI·CHINA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ALCANTARA
Techno-Economic Challenges of Green Ammonia as Energy Vector
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Challenges of Green
Ammonia as Energy Vector
AGUSTIN VALERA-MEDINA
RENE BANARES-ALCANTARA
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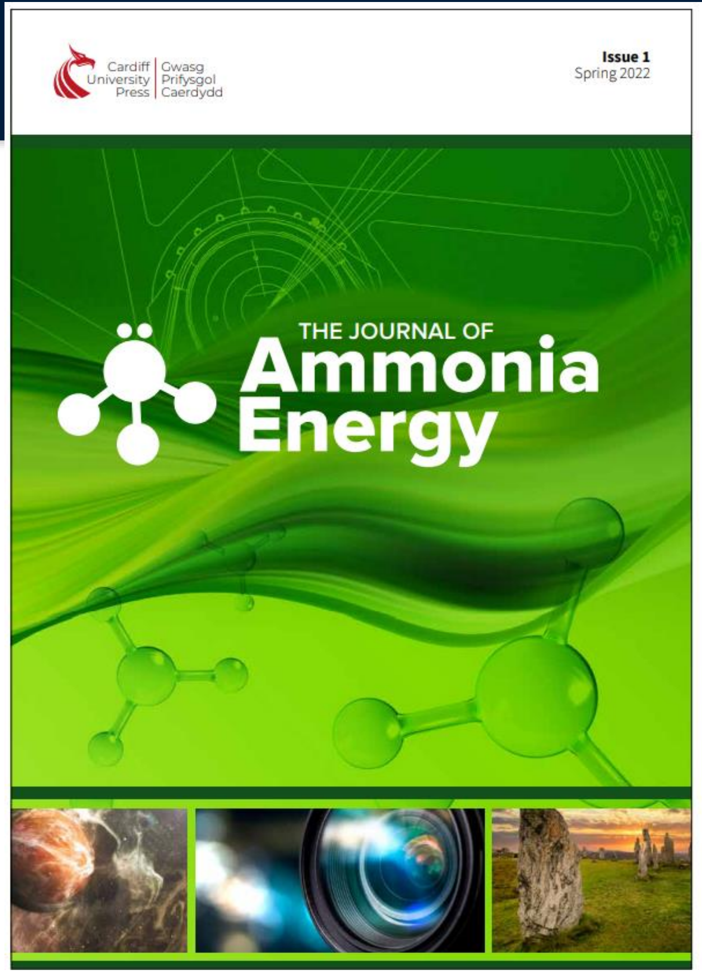
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