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CEM for ammonia- and hydrogen-fired power generation

CEM 2023, Barcelona

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Variable renewable power sources must be integrated with molecular energy storage (Power to X) and subsequent power generation (X to Power) to balance power supply and demand. Green or blue hydrogen- and ammonia-fired thermal power generation will have specific CEM challenges.

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Power and energy transition

Hanwha achieves almost 60% hydrogen blending on a natural gas turbine for power generation.

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- Hanwha Impact (division of Hanwha Energy)
  - Daesan, South Korea
  - 80MWe turbine
  - 59.5% hydrogen with natural gas
  - 22% CO_2 emissions reduction
  - 30% NO_x emissions reduction
- South Korea has a 44% CO_2 emissions reduction target by 2030
  - Nuclear power generation is threatening gas fired systems
  - Hydrogen blending is seen as a route to extend the life of gas fired turbines

https://www.hydrogeninsight.com/power/-world-record-south-korean-firm-blends-nearly-60-hydrogen-in-its-80mw-gas-turbine/2-1-1472878

Hydrogen blending in natural gas is possible, but CO2 emissions reduction lags the H2 blend composition. Pure hydrogen must be the goal. NOx emissions reduction can be achieved with steam injection.

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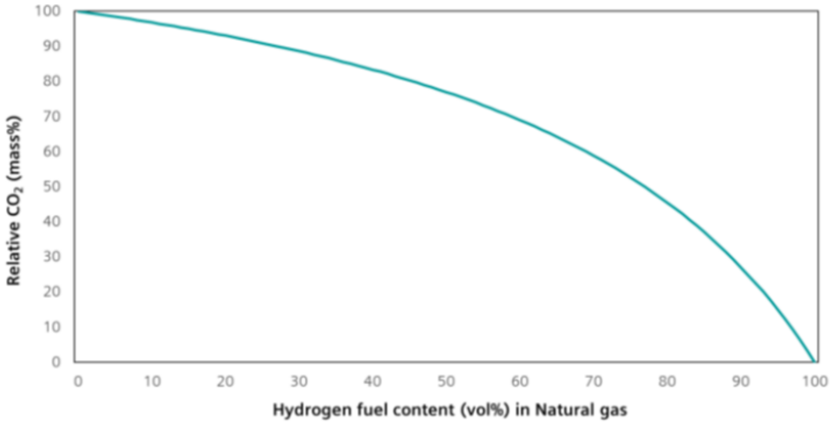
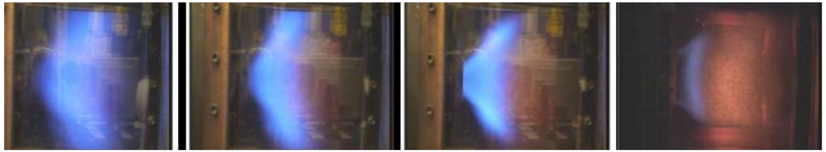


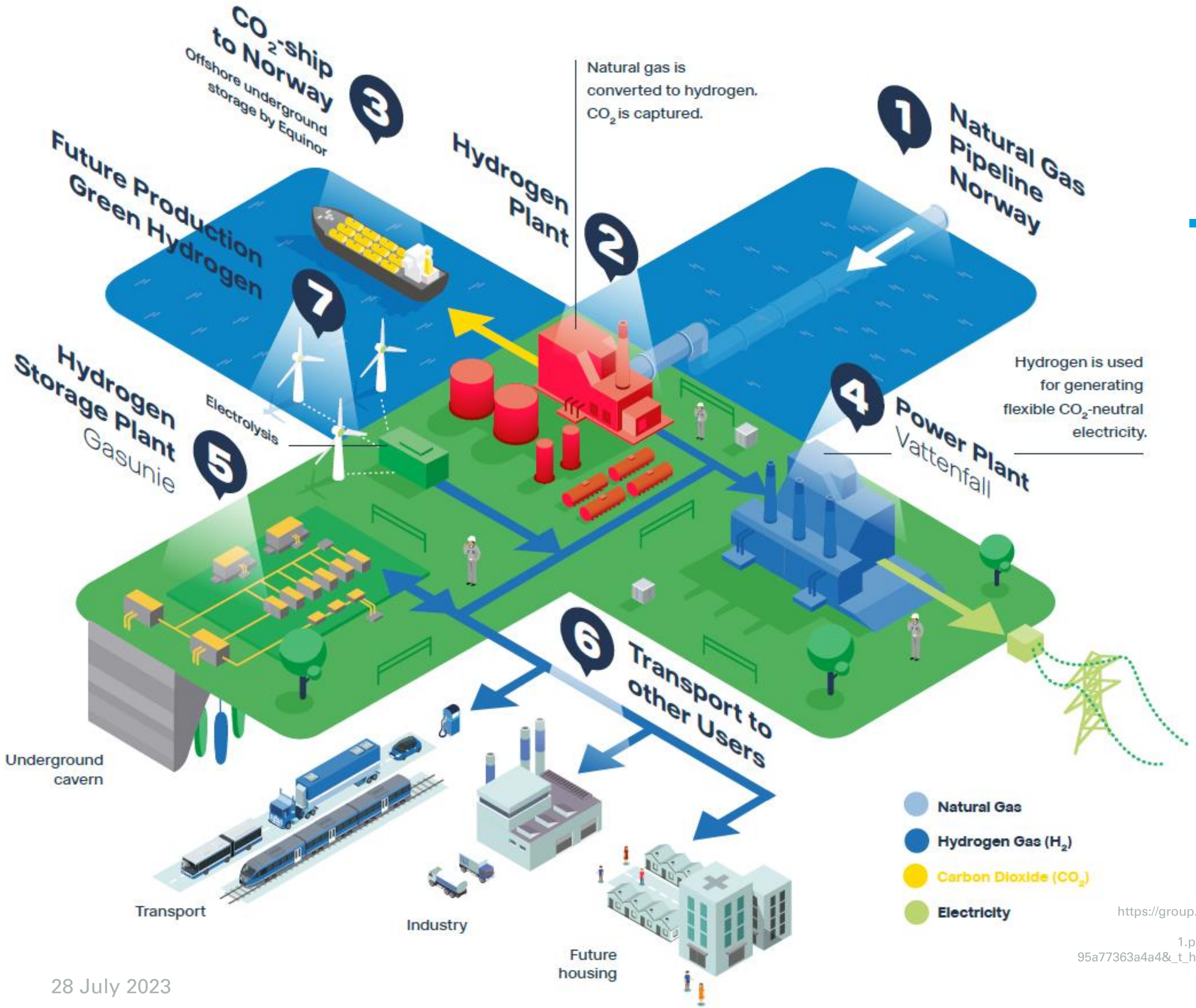


- A pure hydrogen flame is shorter than a methane (natural gas) flame meaning combustion happens closer to the injection zone
  - Burners must be re-designed to avoid the risk of combustion in the gas mixing chamber
  - Process control software must be re-configured to manage the flame dynamics
- The pure hydrogen flame speed and flame temperature are both higher than a methane flame meaning that NOx generation can be higher
  - Dilution with nitrogen or steam can mitigate NOx production
  - The use of steam injection is preferred and can increase power generation capacity

H2M

Hydrogen to Magnum

- Blue hydrogen production
- CCS in Utsira formation
- Long-duration Hydrogen storage in UHS salt caverns
- Hydrogen to power at RWE Magnum power plant in Eemshaven, NL (previously Vattenfall
- 1.4 GW on 3x 440MW Mitsubishi Power M701F power blocks, 100% hydrogen ready in 2025



https://group.vattenfall.com/nl/en/SysSiteAssets/vattenfall-nl-site-assets/wat-we-doen/onze-energiebronnen/waterstof/vattenfall-h2m-infographic-a-1.pdf?_t_tags=language%3Anl%2Csiteid%3A7fbc093b-3d2b-4207-8ee7-95a77363a4a4&_t_hit.id=Corporate_Web_Cms_ContentTypes_Media_PdfFile/_70931777-4936-418a-bda8-c3997af5e177&_t_hit.pos=6

International shipping of hydrogen, hydrogen carriers and hydrogen derivatives

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	Compressed hydrogen gas	Liquid Hydrogen	Liquid Ammonia	Liquid Methanol	LOHC – Liquid Organic Hydrogen Carrier (MCH used as an example)	LNG, Liquefied Natural Gas
Temperature for transportation and storage	Ambient	-253 °C	-33.3 °C	Liquid at ambient temperature	Hydrogenation: 150-200 °C; Transported at ambient temperature; Dehydrogenation: 250-320 °C	–162 °C
Pressure for transportation and storage	250 bar	Close to atmospheric pressure	Close to atmospheric pressure	Close to atmospheric pressure	Hydrogenation: above 20 bar; Transported at atmospheric pressure; Dehydrogenation: below 5 bar	Close to atmospheric pressure
Density	0.017 kg/L	0.071 kg/L	0.68 kg/L	0.79 kg/L	0.77 kg/L	0.46 kg/L
Toxicity	non toxic	non toxic	TWA 25 ppm	TWA 200 ppm	TWA 400 ppm	TWA 1,000 ppm
Flammability (% in air)	4-74 %	4-74 %	14.8-33.5 %	6.0-36.5 %	1.2-6.7 %	4 -15 %
Volumetric Lower Heating Value (LHV)(MJ/L)	2.43	8,52	12.7	15.7	5.76-8.5	22.2
Gravimetric LHV (MJ/kg)	120	120	18.6	19.9	7.48-11	48.6
Infrastructure readiness for large scale deployment in mid-term H/M/L	L	L	H	H	M	H
Commercialisation status and pilot projects	Global Energy Ventures, adapting CNG technology for compressed hydrogen shipping	HySTRA-Hydrogen Energy Supply-chain Technology Research Association – Australia to Japan LH2 shipping	Many commercial liquid ammonia production, distribution and storage assets worldwide with 120 ports locations able to handle ammonia	Methanol is a widely traded commodity with tankers up to 50,000 tonnes	The HySTOC (Hydrogen Supply and Transportation using Liquid Organic Hydrogen Carriers) project in Finland	Many commercial LNG production, distribution, storage and regasification assets worldwide

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- Green or blue hydrogen can be converted to ammonia to make international transportation of clean energy vectors more cost effective.
- Ammonia is 83% nitrogen by mass.
- N_2O emissions have a GWP circa 300 worse than CO_2.
- Ammonia combustion in air for thermal power generation will require N_2O. continuous emissions monitoring, in addition to traditional NOx measurement.

Ammonia in efficient power generation cycles can yield a net electrical power generation efficiency of 55% or more. Almost as good as natural gas fired IGCC at 58%.

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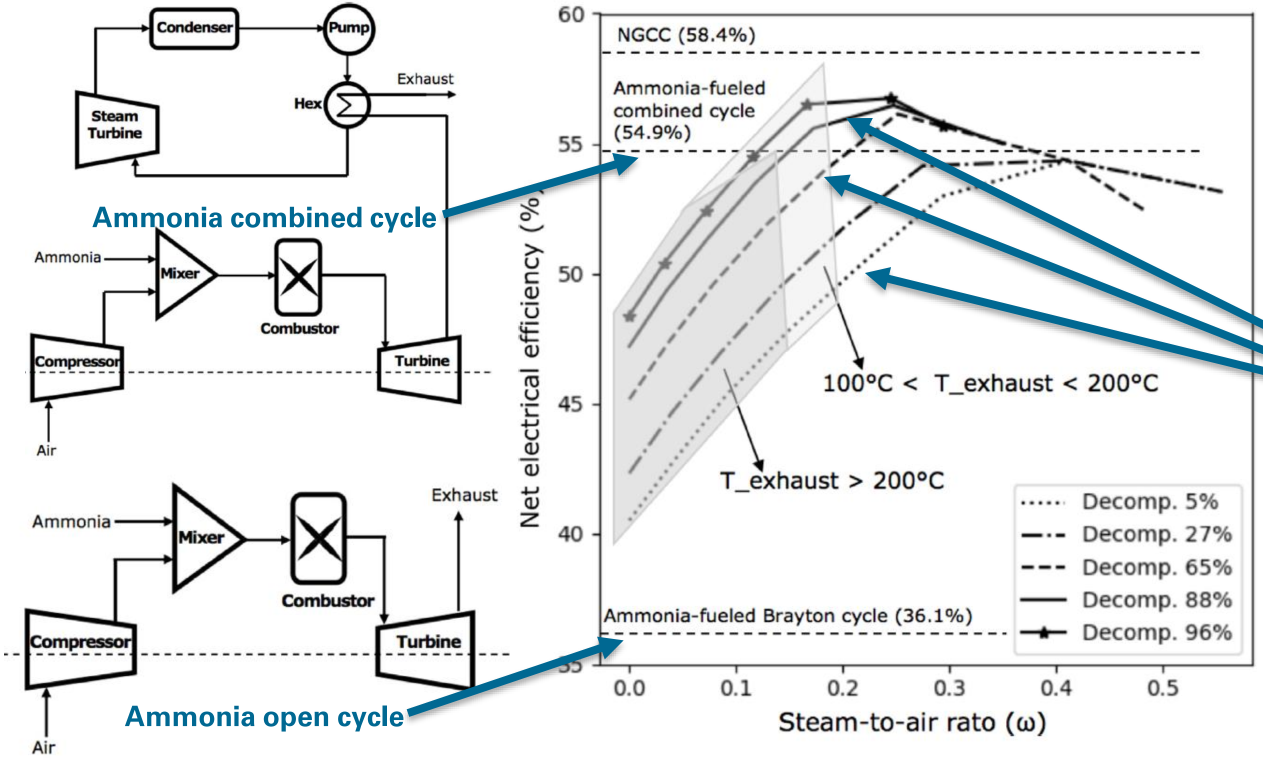

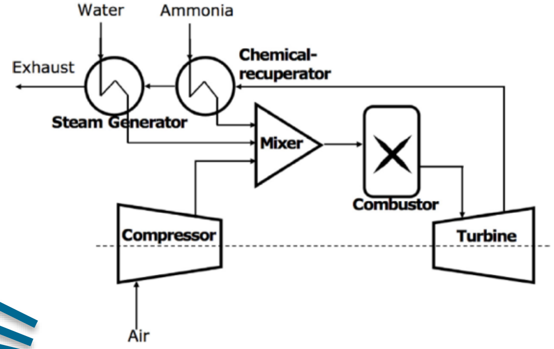

- **Ammonia CGHT Cycle: Chemical-recuperated and humidified gas turbine Cycle.**
- **Turbine exhaust is used to crack ammonia through thermal decomposition.**

Waste heat recovery optimization in ammonia-based gas turbine applications, Shen et al 2023

Ammonia-fired gas turbines are in development for power generation. Ammonia combustion pathways are complex and can result in N_2O emissions. N_2O is an extremely potent GHG.

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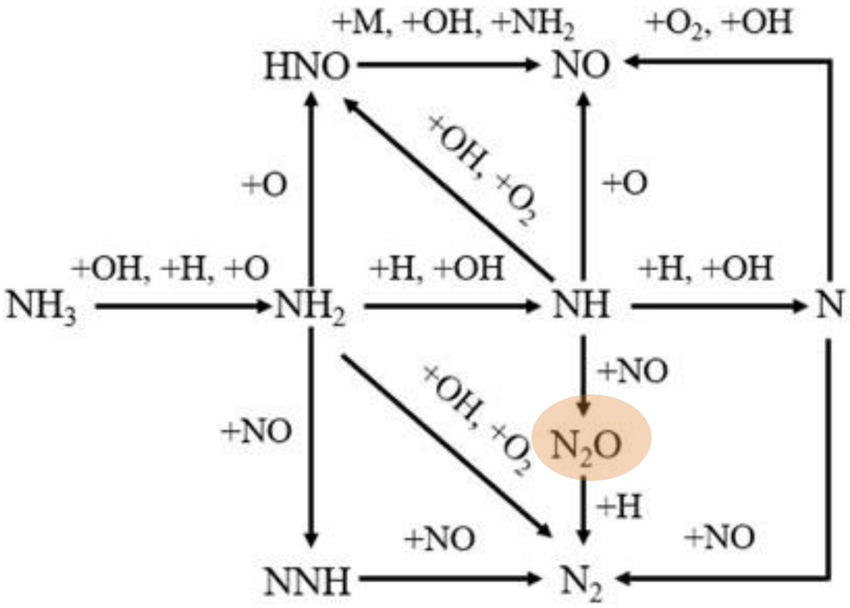
Mitsubishi Power H-25 Series gas turbine, 40MW class



https://power.mhi.com/news/20210301.html
https://www.frontiersin.org/articles/10.3389/fenrg.2021.760356/full

Partial cracking of ammonia to hydrogen can increase the flame speed to reduce N_2O emissions.

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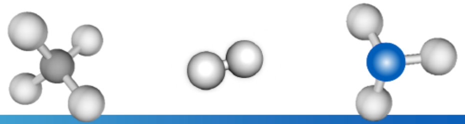
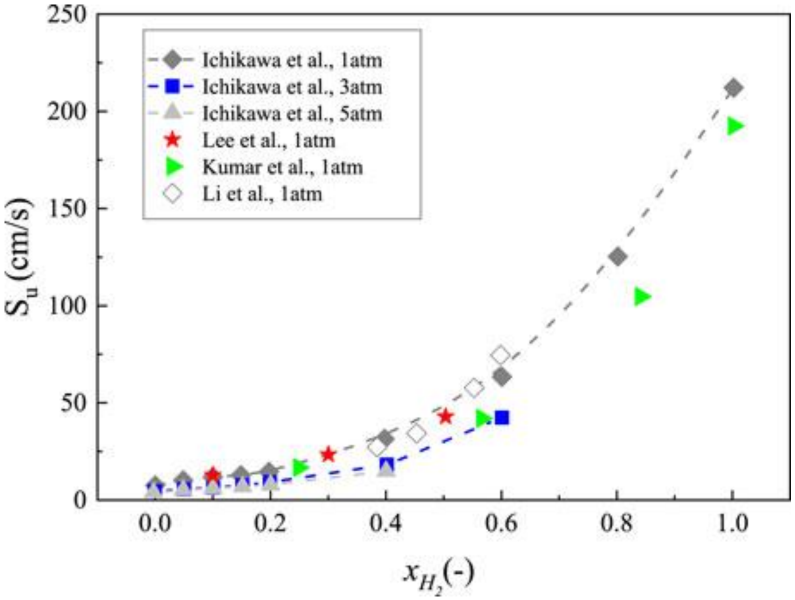


Characteristics		Methane	Hydrogen	Ammonia
Formula		CH_4	H_2	NH_3
Molecular weight	grams/mol	16	2	17
Boiling temperature	°F (°C)	-258.7 (-161.5)	-423.2 (-252.9)	-28 (-33.3)
Lower flammability limit (LFL)	%	4.4	4	15
Flame speed	cm/sec	~30-40	~200-300	~6-7
Adiabatic flame temperature	°F (°C)	~3565 (~1963)	~4000 (~2204)	~3270 (~1799)
Lower Heating value	MJ/Nm^3 (BTU/scf)	35.8 (911.6)	10.8 (274.7)	14.1 (360)



https://www.frontiersin.org/articles/10.3389/fenrg.2021.760356/full

In addition to cracking of ammonia to yield circa 20% to 30% hydrogen, N_2O generation can be controlled by using a stoichiometric or slightly oxygen-rich gas mix to the burner.

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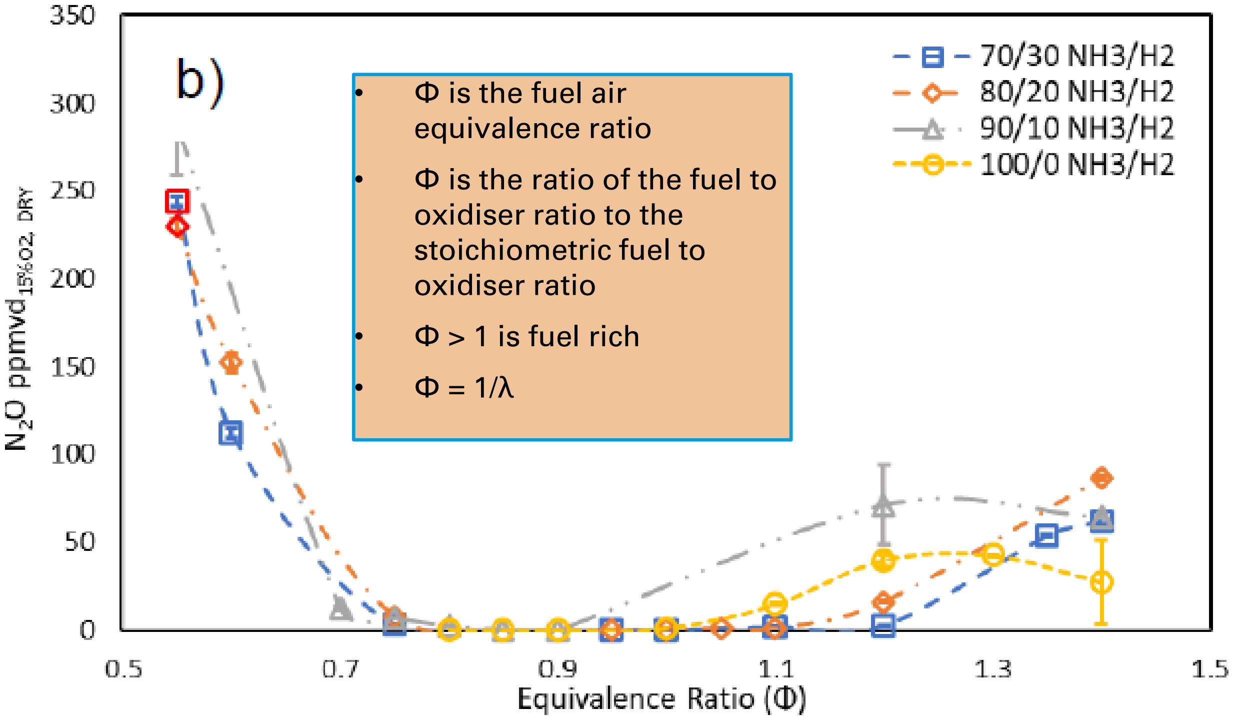

- Φ is the fuel air equivalence ratio
- Φ is the ratio of the fuel to oxidiser ratio to the stoichiometric fuel to oxidiser ratio
- Φ > 1 is fuel rich
- Φ = 1/λ

A Rosemount CT5100 QCL gas analyser was used for this 2021 paper

Nitrogen Oxides as a By-product of Ammonia/Hydrogen Combustion Regimes

Syed Mashruk[a,*], Marina Kovaleva[a], Cheng Tung Chong[b], Akihiro Hayakawa[c], Ekenechukwu C. Okafor[d], Agustin Valera-Medina[a]

https://www.emerson.com/en-us/catalog/rosemount-ct5100-continuous-gas-analyzer

AIST in Japan has run a pilot project to co-fire ammonia with liquid fuels or natural gas on a micro gas turbine.

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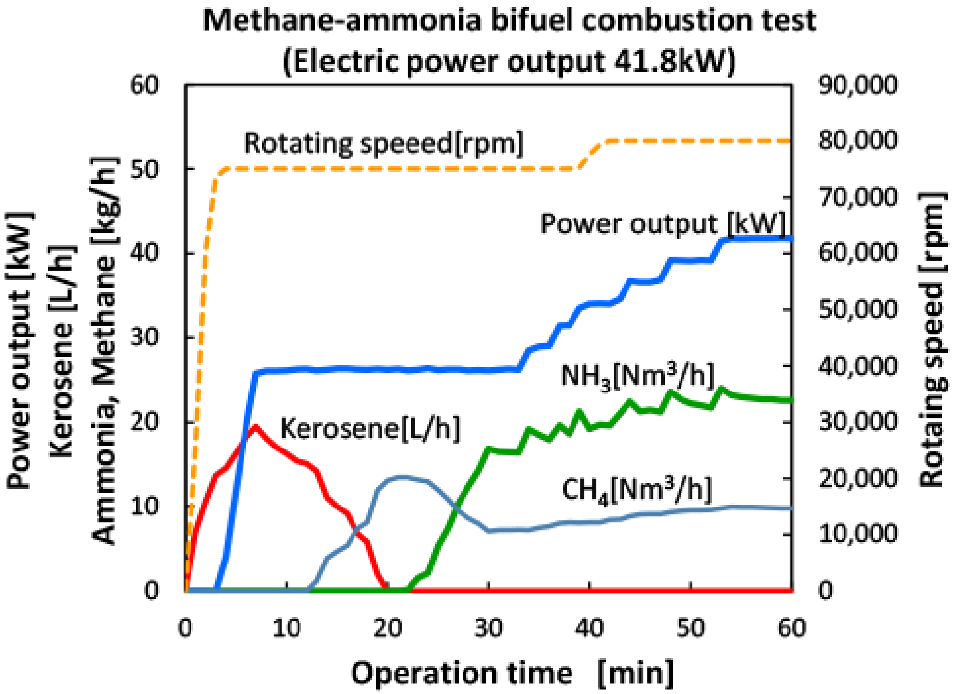

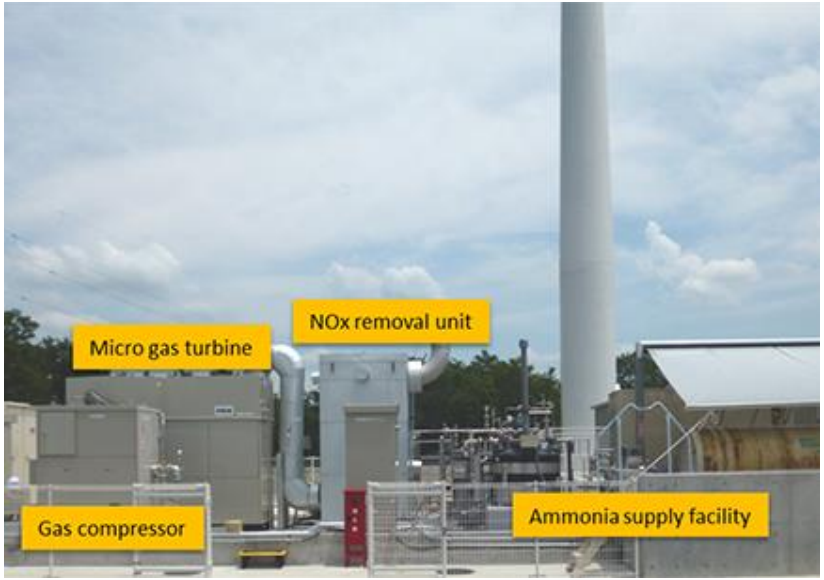

https://www.aist.go.jp/aist_e/list/latest_research/2016/20160412/en20160412.html

Ammonia co-firing on coal-fired power plant in Japan planned for 2024. N_2O emissions monitoring will also be required.

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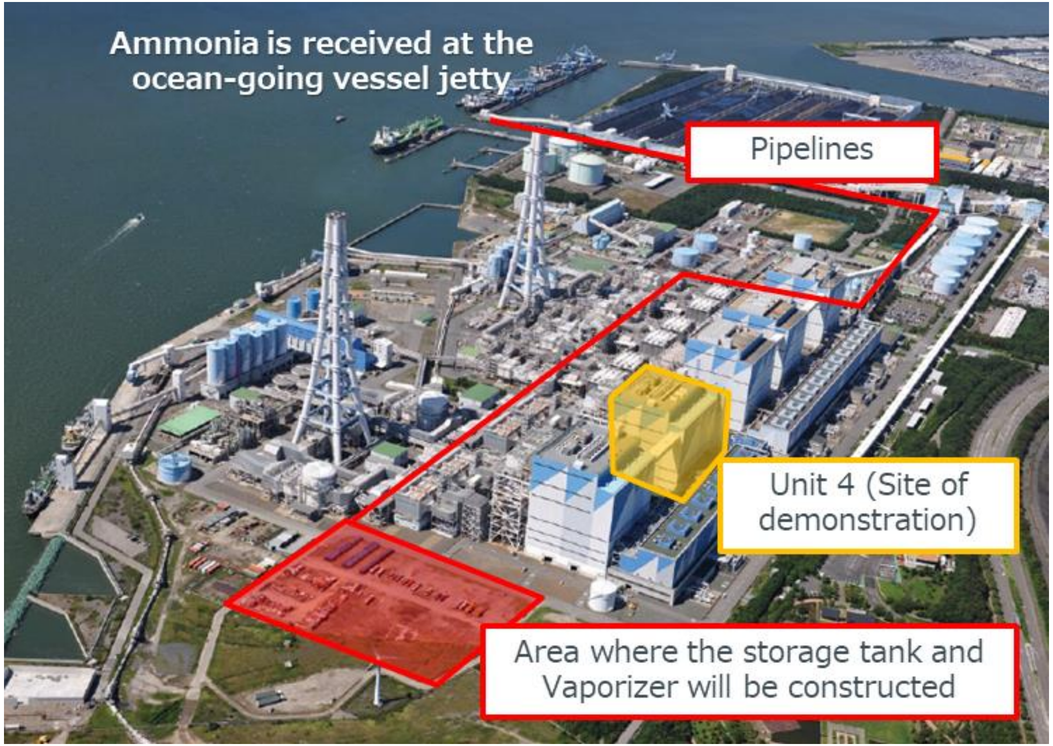
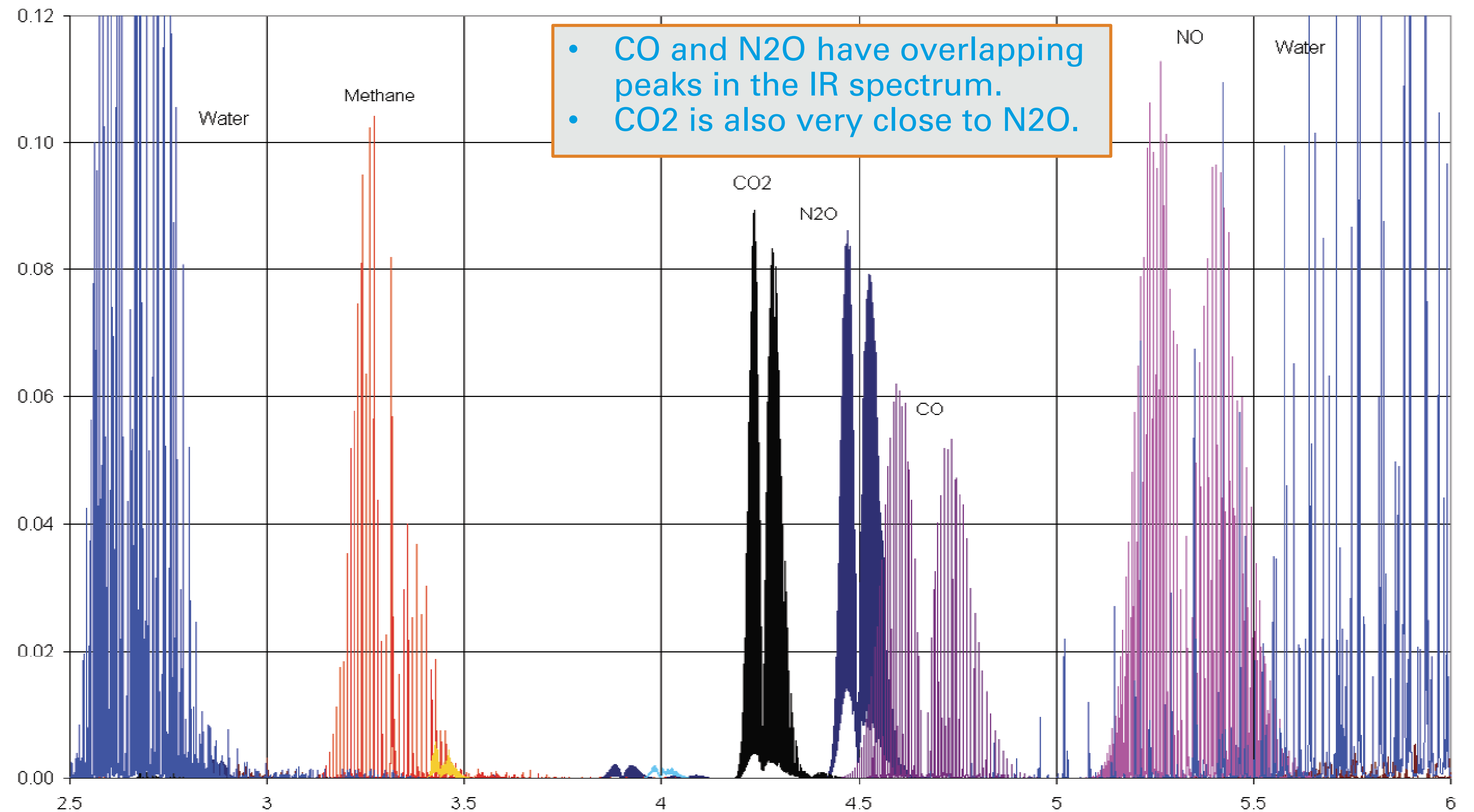


Buyer	JERA
Supply period	Long-term contract from FY 2027 into the 2040s
Quantity	Up to 500,000 tons per year
Delivery mode	FOB
Other	• As a rule, CO_2 is either not generated during ammonia production or is captured and stored. • JERA has the opportunity to participate in production projects

- JERA's Coal-fired Hekinan power station (4.1GWe)
- Demonstration project on unit 4 (1GWe)
- First commercial demonstration of 20% ammonia co-firing

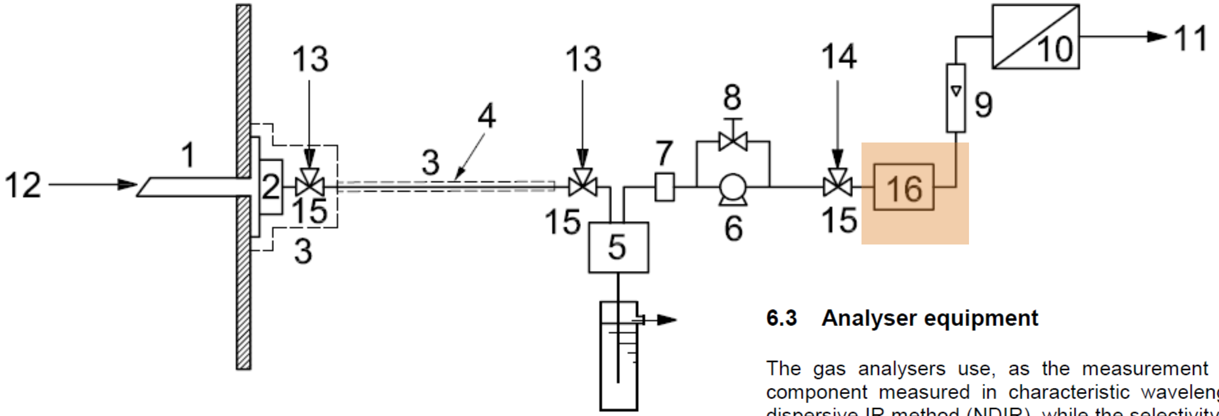
https://www.jera.co.jp/english/information/20210524_677

https://www.reuters.com/business/energy/hooked-coal-power-japan-aims-ammonia-fix-2021-10-29/



- CO and N2O have overlapping peaks in the IR spectrum.
- CO2 is also very close to N2O.

https://edinburghsensors.com/non-dispersive-infrared-sensing-technology/



- CO must be converted to CO2 to enable accurate N2O measurement.
- CO2 interference can be compensated with an additional channel in the analyser.

Key

1 gas sampling probe
2 primary filter
3 heating (for use as necessary)
4 sampling line (heated as necessary)
5 sample cooler with condensate separator
6 sample pump
7 secondary filter
8 needle valve
9 flow meter
10 N_2O analyser
11 output
12 inlet for zero and span gas (preferably in front of the nozzle) to check the complete system
13 inlet for zero and span gas to check the conditioning system and N_2O analyser
14 inlet for zero and span gas to check the converter and N_2O analyser
15 valve
16 converter for CO oxidation

6.3 Analyser equipment

The gas analysers use, as the measurement principle, the absorption of infrared radiation (IR) by the component measured in characteristic wavelength ranges. The analysers operate according to the non-dispersive IR method (NDIR), while the selectivity of measurement is achieved by the radiation detector which is filled with the component to be measured. A schematic diagram of a typical analyser is given in Figure A.1.

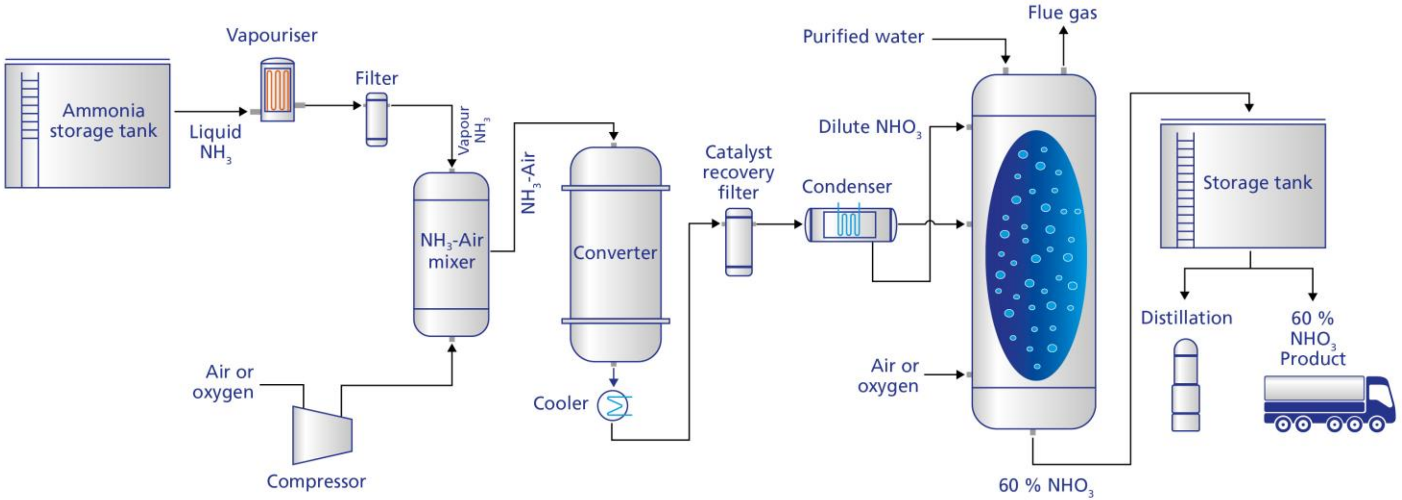
Special attention should be given to CO and CO_2 interference, since for detection of N_2O the absorption at around 4,5 µm is usually used, while CO has its absorption at 4,5 µm to 4,7 µm and CO_2 has its absorption at 4,3 µm. The CO interference can be excluded by using the converter (see 6.2.8). The CO_2 sensitivity requires determination with CO_2 test gases. During real operation, CO_2 requires simultaneous measurement to yield data for real-time correction of the N_2O readings. In many instruments, this CO_2 interference correction is done automatically through a CO_2 channel.

Since it can interfere with the measurement and lead to condensation in the analyser, water vapour present in the sampled gas is condensed in a gas cooler before the gas enters the analyser. Note that the presence of water droplets can affect the analysis of N_2O, since the solubility of N_2O in water is 1,2 g/l (at 20 °C, 101,3 kPa).

INTERNATIONAL STANDARD **ISO 21258**

Stationary source emissions — Determination of the mass concentration of dinitrogen monoxide (N_2O) — Reference method: Non-dispersive infrared method

Ostwald Process for Nitric Acid Production



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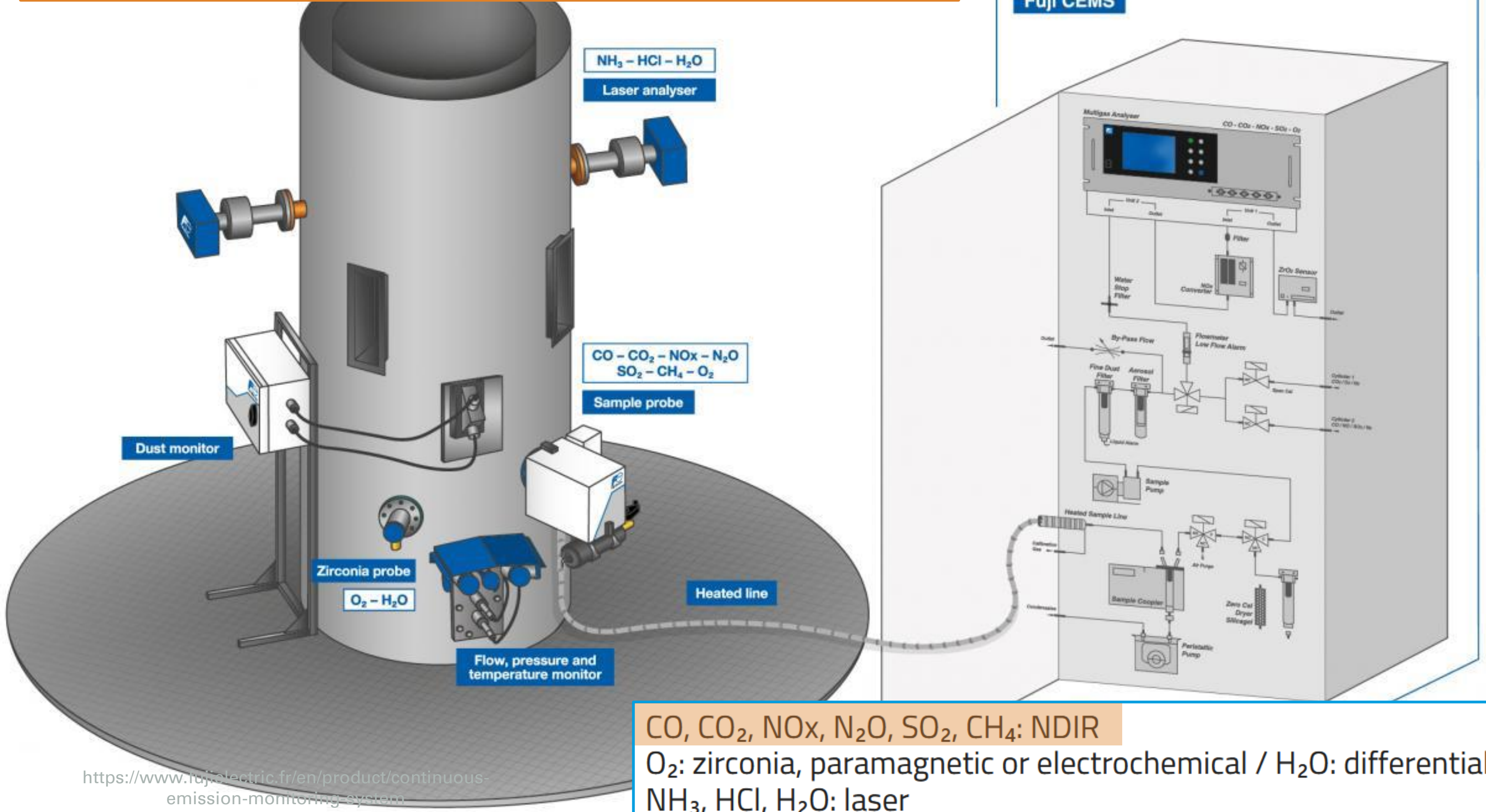
- As a GHG, N_2O emissions are covered in Annex I of the EU ETS Directive.
- Relevant industries are production of nitric acid, adipic acid, glyoxal and glyoxylic acid.
- N_2O emissions monitoring technologies from these sectors can be leveraged for ammonia fired power generation.

Example commercial system from Fuji Electric using NDIR.



https://www.fujielectric.fr/en/product/continuous-emission-monitoring-system

CO, CO_2, NOx, N_2O, SO_2, CH_4: NDIR
O_2: zirconia, paramagnetic or electrochemical / H_2O: differential ZrO_2
NH_3, HCl, H_2O: laser

Example commercial systems from MRU using NDIR.

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https://mru-instruments.com/product/swg-200-in-situ-continuous-emission-monitor/

Example commercial system from MKS using FTIR.

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Gas Comp.	Cert. Range	Supp. Range 1	Supp. Range 2
CH_4	0 - 15	0 - 50	0 - 500
CO	0 - 75	0 - 300	0 - 1500
HCl	0 - 15	0 - 90	0 - 200
HF	0 - 3	0 - 10	—
N_2O	0 - 50	0 - 100	0 - 500
NH_3	0 - 10	0 - 75	—
NO	0 - 200	0 - 400	0 - 1500
NO_2	0 - 50	0 - 100	0 - 1000
SO_2	0 - 75	0 - 300	0 - 2000

Table 1 — Gas Components and Ranges in mg/m³ Addressed by the TÜV & MCERTS certified MGS300 system. For availability of additional gases and ranges, please contact MKS for more information.

Partial cracking of ammonia can also be used in rail, maritime and aviation combustion engines. N_2O and NOx emissions reduction is a major development challenge and monitoring will be required during system testing and engine development.

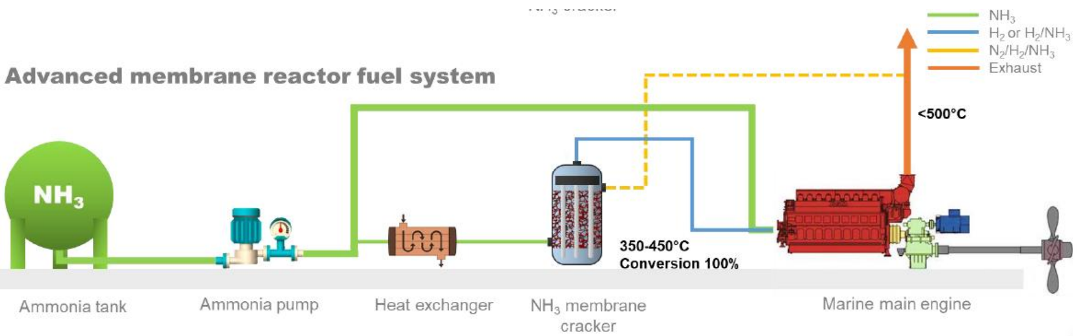
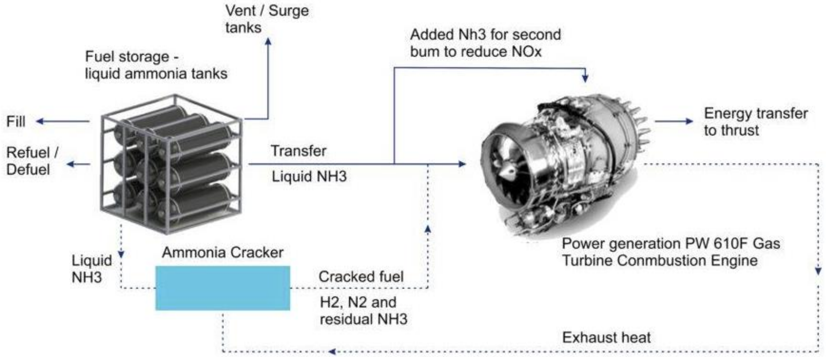


Image courtesy of Ammonigy



https://www.ammoniaenergy.org/wp-content/uploads/2020/12/Camel-Makhloufi.pdf sbh4

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Introduction to Stephen B. Harrison

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Stephen B. Harrison is the founder and managing director at sbh4 GmbH in Germany. His work focuses on decarbonisation and greenhouse gas emissions reduction. Hydrogen and CCTUS are fundamental pillars of his consulting practice, and he supports many industrial clients with their decarbonisation programmes.

Operating companies, gas analyser OEMs, private equity firms, investment fund managers and start-ups are also regular clients. Stephen has accumulated extensive M&A and investment due diligence experience in the clean-tech sector.

Stephen served as the international hydrogen and CCTUS expert for multiple World Bank, IFC and ADB projects in Namibia, Pakistan, Palau and Viet Nam. His background is in industrial and specialty gases, including 27 years at BOC Gases, The BOC Group and Linde Gas. For 14 years, he was a global business leader in these FTSE100 and DAX30 companies.

As a member of the H2 View and **gas**world editorial advisory boards, Stephen advises the direction for these leading international publications.

Stephen has served as a member of the scientific committee for CEM 2023. He also served on the Technical Committee for the Green Hydrogen Summit in Oman in December 2022 and the Advisory Board of the International Power Summit in Munich in September 2022.