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Real World Solutions for Clean Ammonia Production

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European Clean Ammonia Summit

Köln, 22nd April 2026, 16:10 to 16:55

Real World Solutions for Clean Ammonia Production

1. Grey to blue conversions: revamping existing ammonia production units
2. Practical improvements in CO2 capture technology for blue ammonia
3. Grey to green conversions and on-purpose green ammonia
4. End-to-end value chain solutions for CO_2 transportation

Hi, I'm Steve.
I help industrial CO2 emitters to decarbonise cost-effectively.
And I support solution providers to bring their technologies to market.

Stephen B. Harrison
Managing Director
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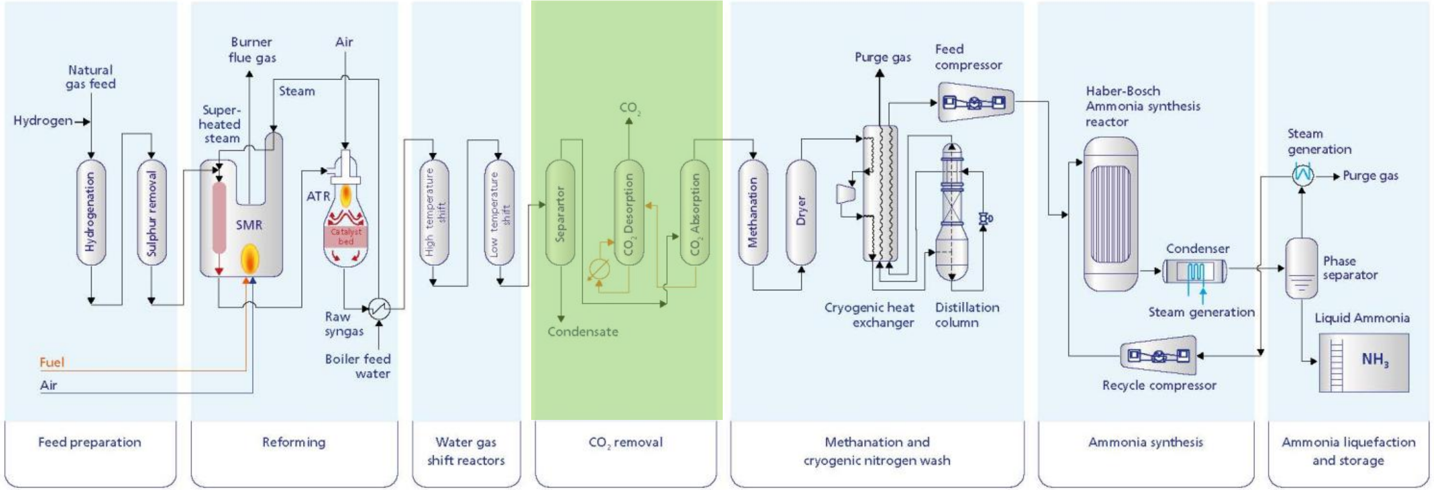
1. Grey to blue conversions – revamping existing ammonia production units

Air-fed Ammonia Production Process



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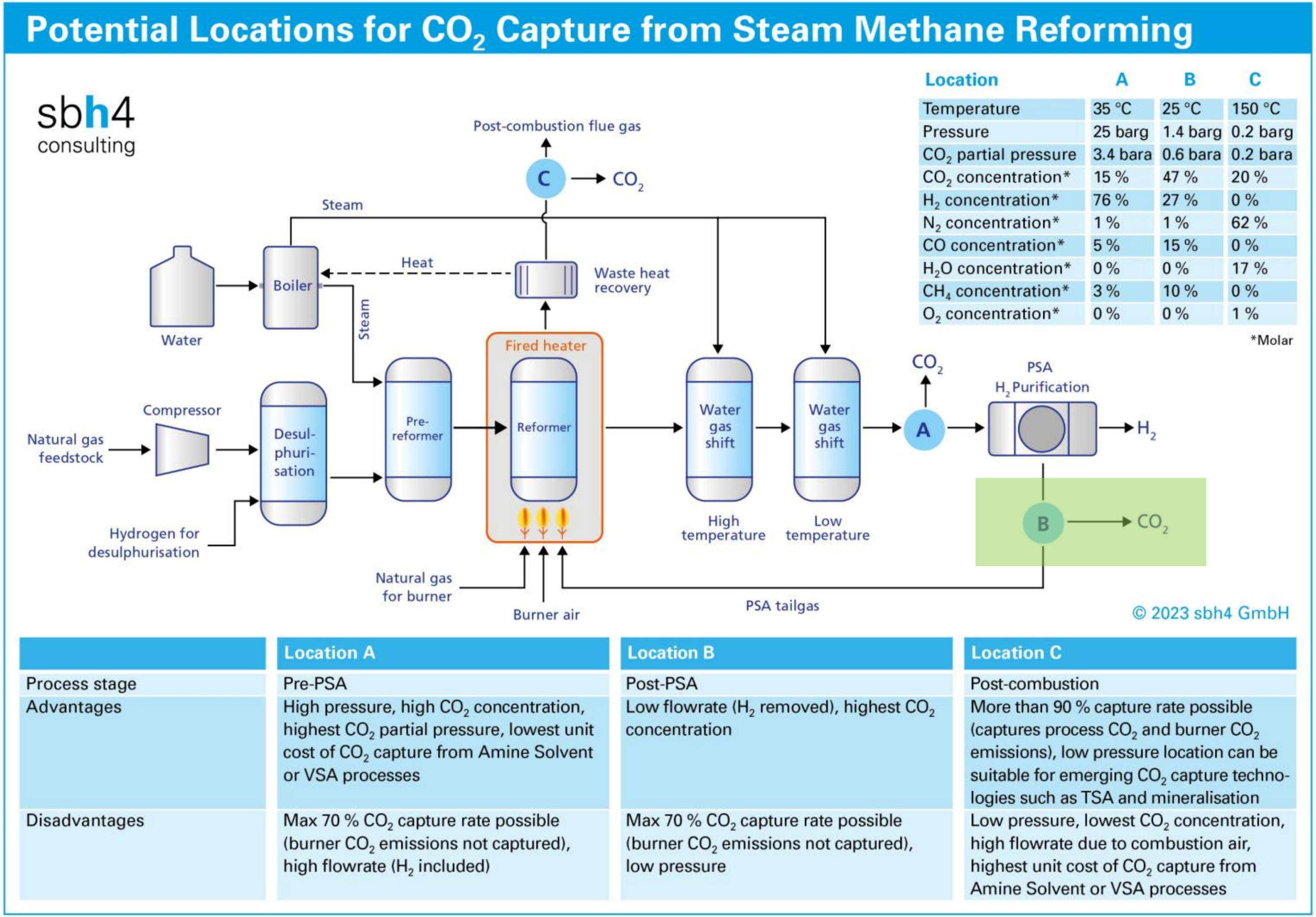
Grey ammonia – nitrogen from air feed to ATR (secondary reformer)

- The reforming stages for grey ammonia can either be air- or oxygen-fed
- Use of an SMR is with the subsequent use of an ATR is common
- If the ATR is oxygen-fed, pure nitrogen must be added in the ammonia synthesis loop
- Pure oxygen is introduced to the ATR to make hydrogen
- CO2 emissions from reforming are removed to protect the ammonia synthesis catalyst
- Most of the CO2 is vented to atmosphere
- Some captured CO2 is used to make urea or used for food and beverage applications
- Alternatively, CO2 can be sequestered



Potential Locations for CO_2 Capture from Steam Methane Reforming

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Location	A	B	C
Temperature	35 °C	25 °C	150 °C
Pressure	25 barg	1.4 barg	0.2 barg
CO_2 partial pressure	3.4 bara	0.6 bara	0.2 bara
CO_2 concentration*	15 %	47 %	20 %
H_2 concentration*	76 %	27 %	0 %
N_2 concentration*	1 %	1 %	62 %
CO concentration*	5 %	15 %	0 %
H_2O concentration*	0 %	0 %	17 %
CH_4 concentration*	3 %	10 %	0 %
O_2 concentration*	0 %	0 %	1 %

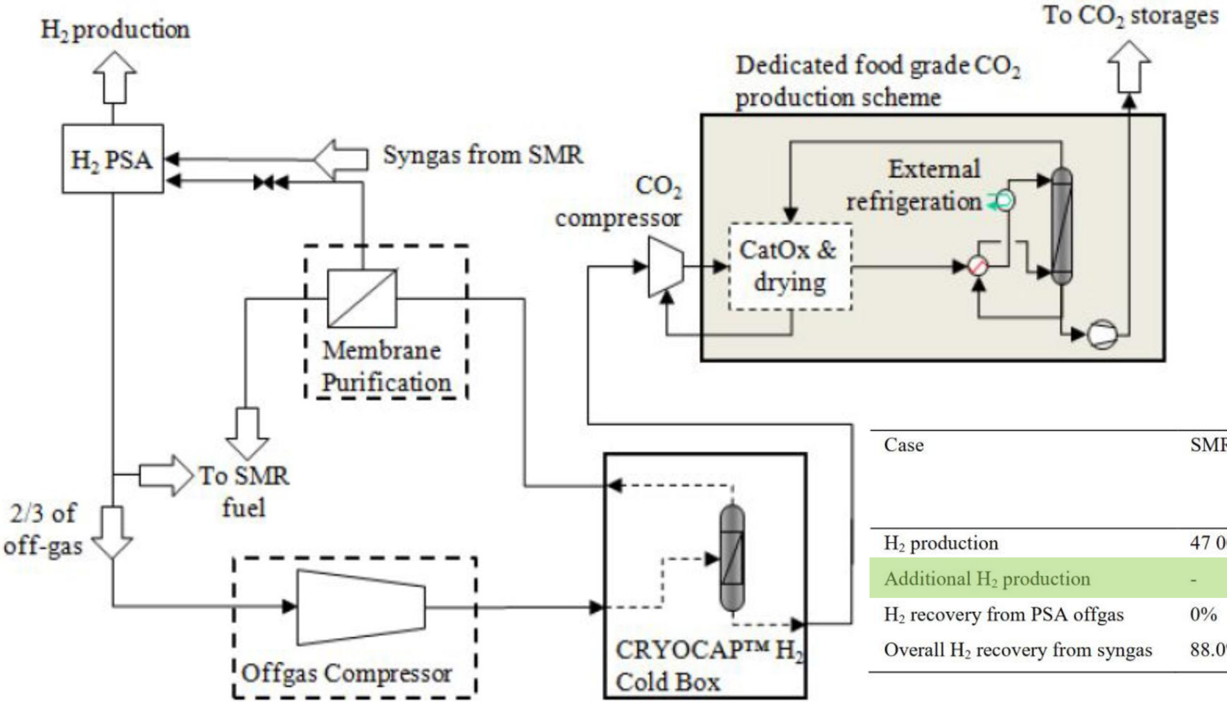
*Molar

	Location A	Location B	Location C
Process stage	Pre-PSA	Post-PSA	Post-combustion
Advantages	High pressure, high CO_2 concentration, highest CO_2 partial pressure, lowest unit cost of CO_2 capture from Amine Solvent or VSA processes	Low flowrate (H_2 removed), highest CO_2 concentration	More than 90 % capture rate possible (captures process CO_2 and burner CO_2 emissions), low pressure location can be suitable for emerging CO_2 capture technologies such as TSA and mineralisation
Disadvantages	Max 70 % CO_2 capture rate possible (burner CO_2 emissions not captured), high flowrate (H_2 included)	Max 70 % CO_2 capture rate possible (burner CO_2 emissions not captured), low pressure	Low pressure, lowest CO_2 concentration, high flowrate due to combustion air, highest unit cost of CO_2 capture from Amine Solvent or VSA processes

Hydrogen + nitrogen for ammonia production with increased hydrogen yield from SMR

- The PSA vent (Location B) is rich in hydrogen at circa 27%.
- This hydrogen typically get burned with natural gas to provide the high temperature heat for the reforming reaction.
- Hydrogen recovery and CO2 removal from location B are both possible.
- The increased hydrogen yield can offset the costs of hydrogen and CO2 recovery.

Cryocap™ H2 can **increase the H2 yield of an SMR by 12%** whilst capturing CO2 from the PSA vent gas (location B). This schematic shows the Cryocap™ H2 process integrated with a CO2 liquefier.



Case	SMR only	SMR + CRYOCAP™ H_2 *Partial CO_2 capture (Port-Jérôme unit)*	SMR + CRYOCAP™ H_2 *Full CO_2 capture*
H_2 production	47 000 Nm^3/hr	50 155 Nm^3/hr	52 480 Nm^3/hr
Additional H_2 production	-	+7%	+12%
H_2 recovery from PSA offgas	0%	87%	87%
Overall H_2 recovery from syngas	88.0%	93.9%	98.3%

https://netl.doe.gov/sites/default/files/netl-file/24CM/24CM_PSCC_6_Sarkar.pdf

Amine and HPC solvents are not totally selective to CO2 and will absorb some hydrogen (amine circa 2%, HPC circa 0.5%). This **hydrogen may need to be flashed out of the solvent** to protect downstream steel piping and equipment from hydrogen embrittlement.

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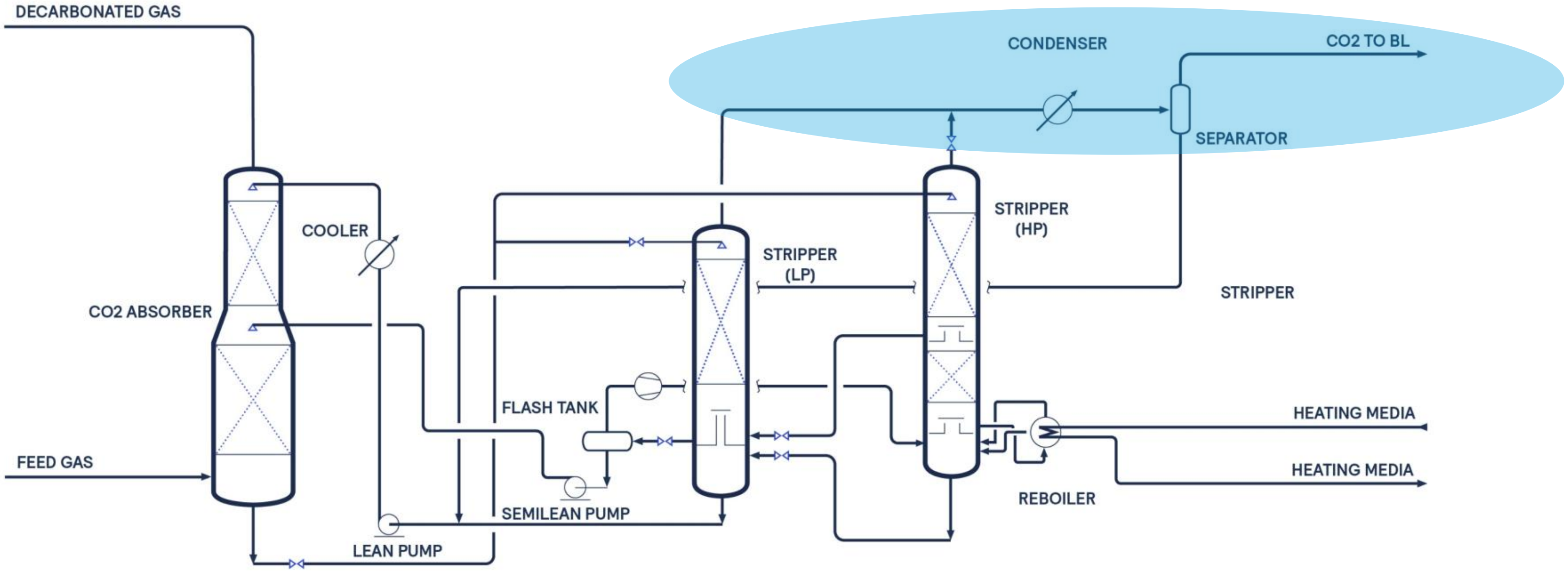

Graphic courtesy of Giammarco Technologies

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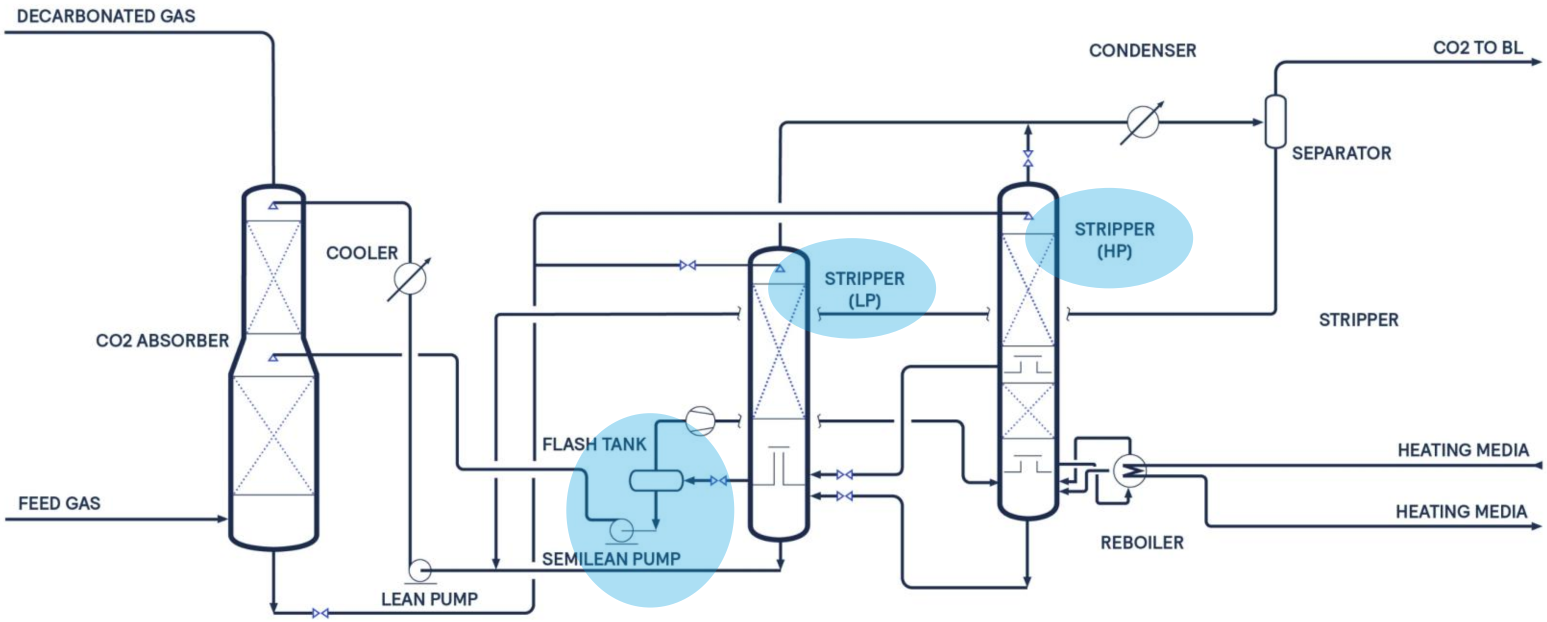
2. Practical improvements in CO2 capture technology

Giammarco Technologies NovaFlash®: high-efficiency Hot Potassium Carbonate CO2 capture for high-pressure streams. **A flash between the high-pressure and low-pressure stripper columns, and an additional flash tank reduce the energy input requirement.**

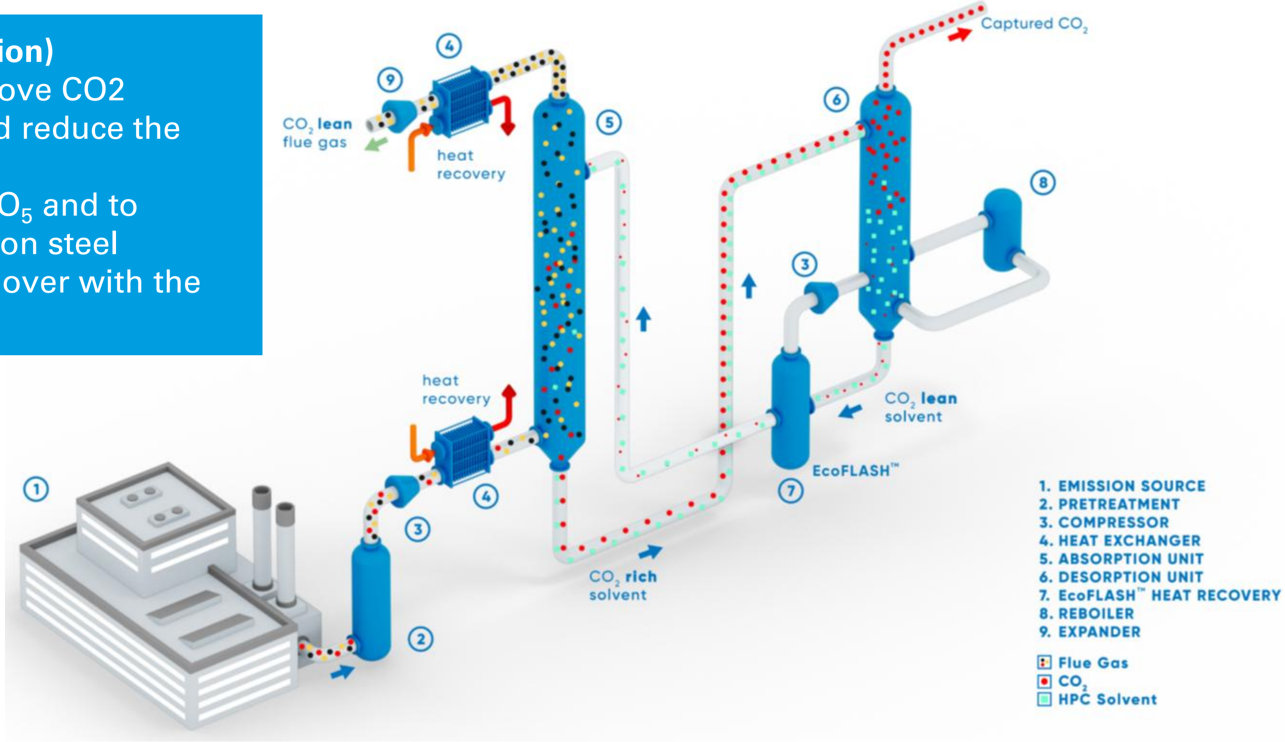


Graphic courtesy of Giammarco Technologies

Andritz integrates the CATACARB® process additives to optimise CO2 capture. HPC **regeneration temperature is reduced to as low as 90°C (compared to 110 °C for ‘normal’ HPC)** meaning the potential to use of waste heat is increased, thereby reducing energy input.

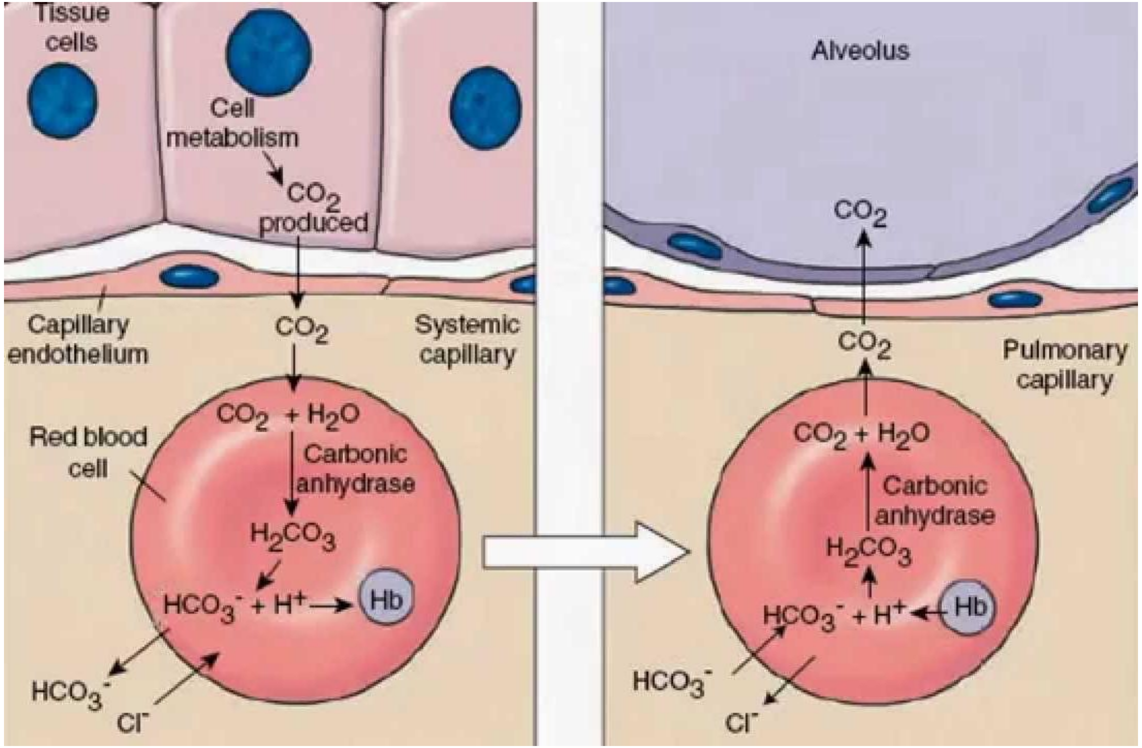
CATACARB (proprietary formulation)

- Activators such as DEA to improve CO2 absorption reaction kinetics and reduce the size of the equipment
- Corrosion inhibitors such as V_2O_5 and to enable the use of low-cost carbon steel
- Antifoams to reduce HPC carry over with the clean flue gas or captured CO2



https://www.andritz.com/environmental-solutions-en/clean-air-technologies/technologies-clean-air-technologies/decarbonization-clean-air-technologies/hot-potassium-carbonate

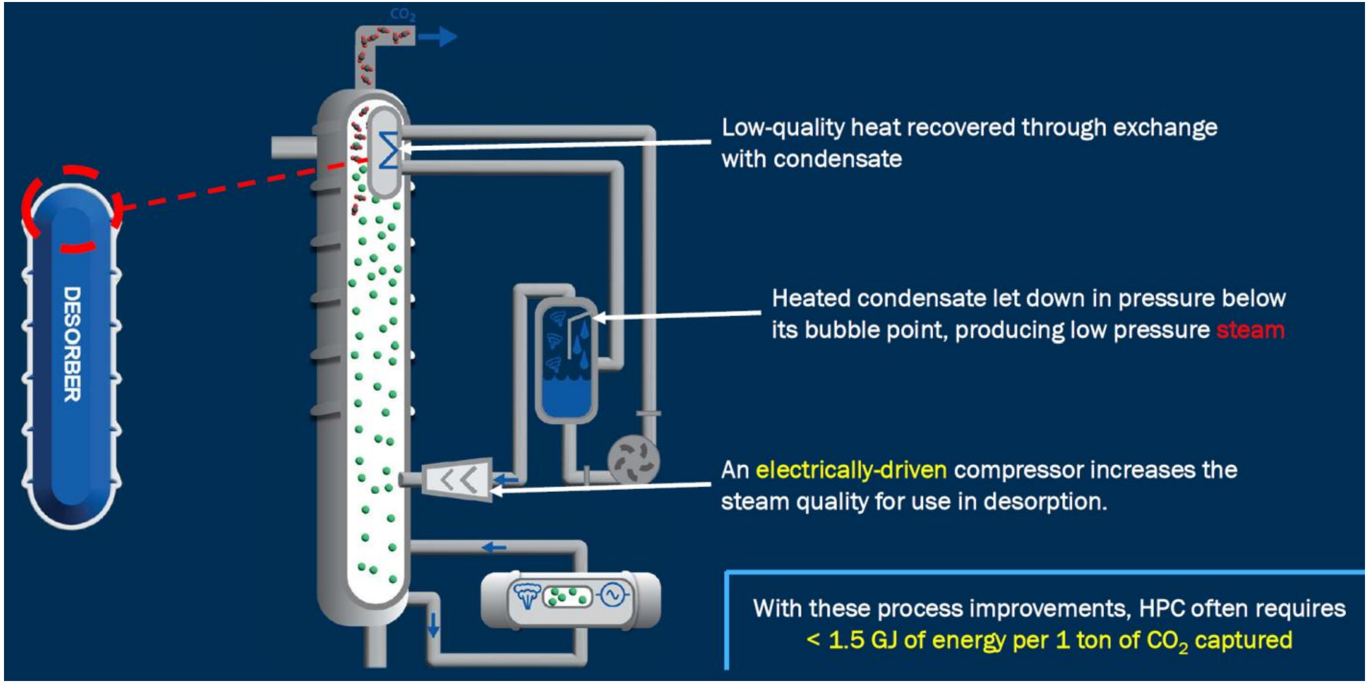
Saipem uses Carbonic Anhydrase (CA) enzyme additive to enhance HPC performance in their Bluenzyme™ process. CA enables respiration in our lungs and can be produced industrially by Novonesis (Novozymes) or others. **HPC regeneration temperature is reduced to as low as 80°C.**



https://www.saipem.com/sites/default/files/2023-08/background_4%201.png

https://www.mrgscience.com/d6-transport-of-respiratory-gases-hl.html

Partial electrification using mechanical vapour recompression (MVR) reduces the temperature for regeneration and enables better use of waste heat. The energy input to the HPC process can be reduced to less than 1.5 GJ / tonne of CO2 captured (compared to circa 2 to 2.5 GJ / tonne for conventional HPC).



Low-quality heat recovered through exchange with condensate

Heated condensate let down in pressure below its bubble point, producing low pressure steam

An electrically-driven compressor increases the steam quality for use in desorption.

With these process improvements, HPC often requires < 1.5 GJ of energy per 1 ton of CO_2 captured

https://content-cdn.sessionboard.com/content/Zeebs6yjQSaqee7OTfyA_POWERGEN%20-%20CATACARB.pdf

Full electrification: CapsolEoP™ claims 0.7 to 1.5 GJ Electrical power required per tonne of CO2 captured. The compressor / expander (compander) recovers pressure energy from the flue gas. High pressure operation means that **no additional heat** is required for HPC regeneration, which is achieved using a flash.

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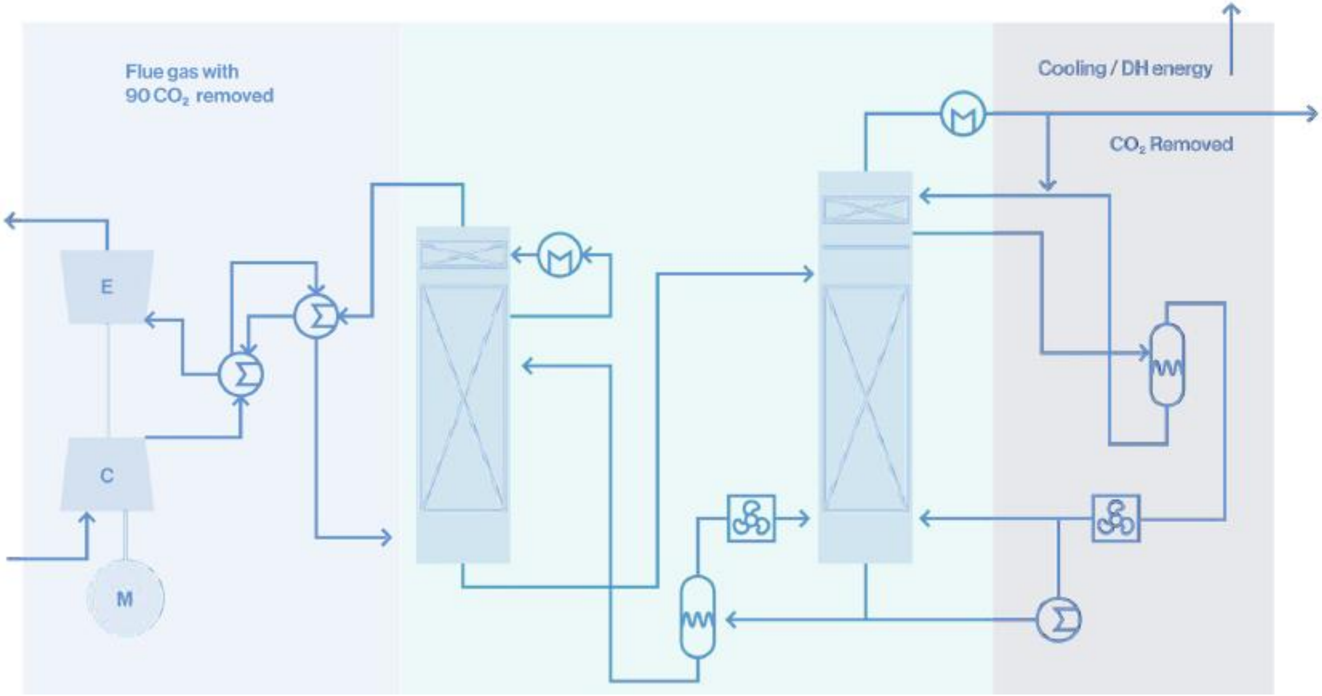

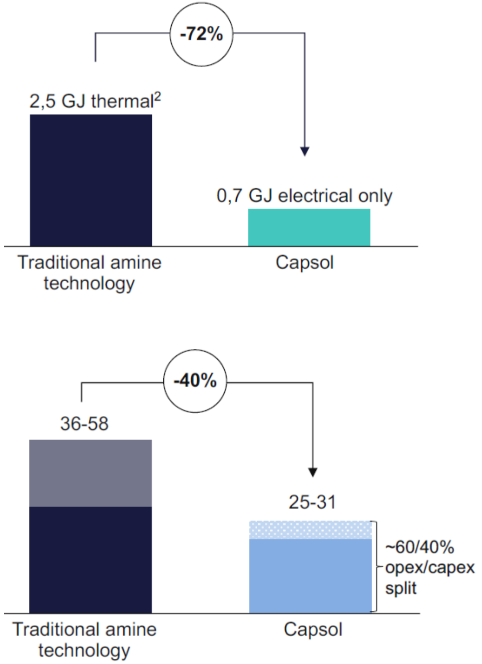

https://co2capsolcom.sharepoint.com/:b:/g/ESt0wmer3t9Alfd-_x84H-EBMmBb4cKMAHB_tBF0eAzz2A?e=ZJVS1w

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3. End-to-end value chain solutions for CO2 transportation

Overland, CO2 pipelines are the most efficient mode of CO2 transportation. For offshore routes, it is likely that there is a crossover at longer distances favouring shipping over pipelines.

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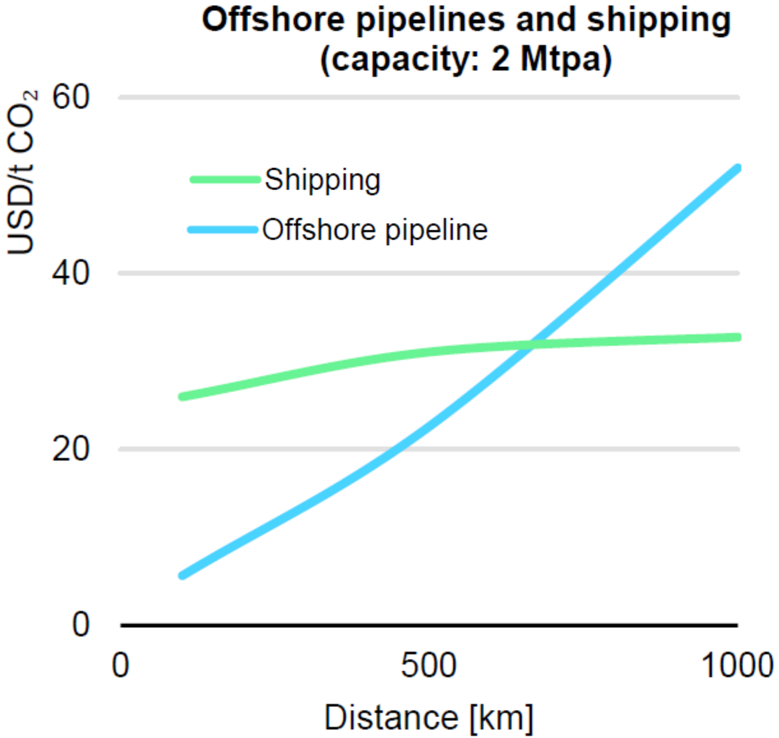
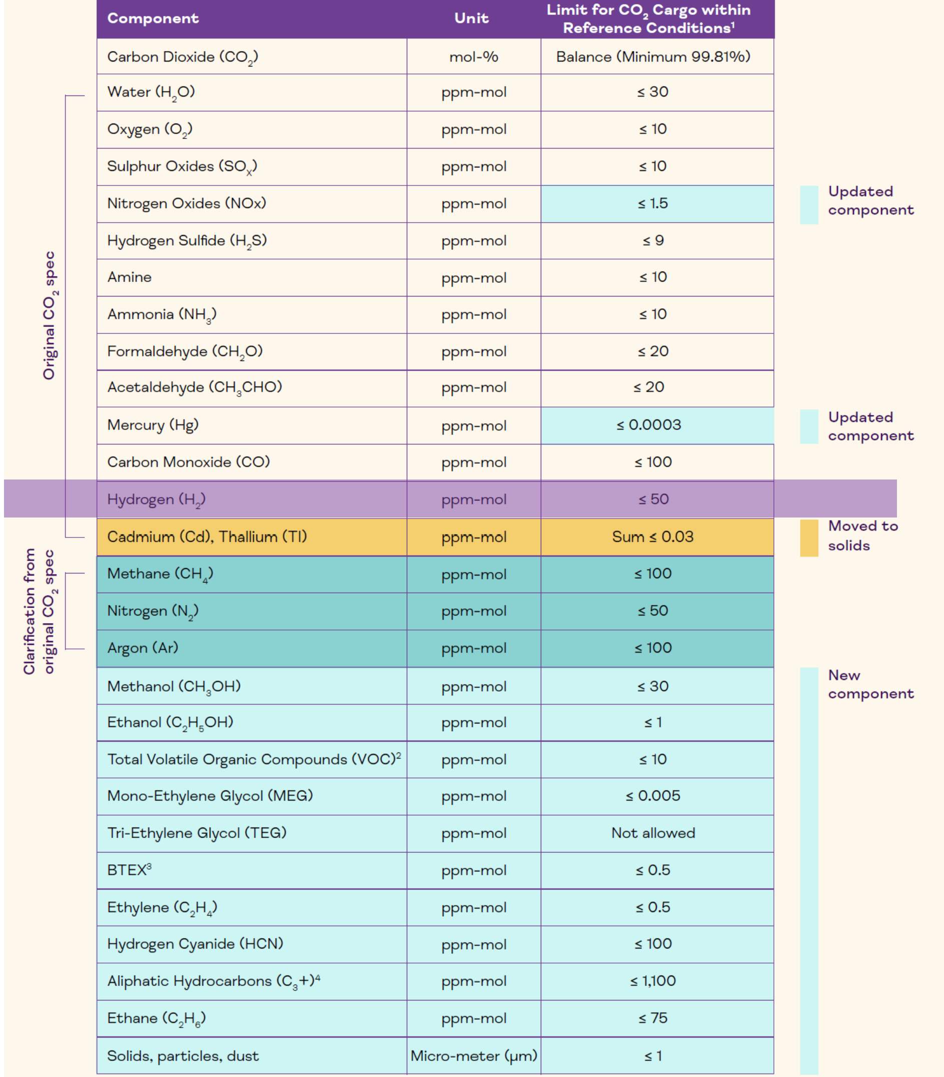


https://iea.blob.core.windows.net/assets/d0cb5c89-3bd4-4efd-8ef5-57dc327a02d6/CCUSPoliciesandBusinessModels.pdf

Northern Lights liquid CO2 specification leans towards CO2 liquefaction and cryogenic distillation for purification. **For ammonia, the hydrogen spec is highly relevant.**



	Component	Unit	Limit for CO_2 Cargo within Reference Conditions[1]	
	Carbon Dioxide (CO_2)	mol-%	Balance (Minimum 99.81%)	
Original CO_2 spec	Water (H_2O)	ppm-mol	≤ 30	
	Oxygen (O_2)	ppm-mol	≤ 10	
	Sulphur Oxides (SO_x)	ppm-mol	≤ 10	
	Nitrogen Oxides (NOx)	ppm-mol	≤ 1.5	Updated component
	Hydrogen Sulfide (H_2S)	ppm-mol	≤ 9	
	Amine	ppm-mol	≤ 10	
	Ammonia (NH_3)	ppm-mol	≤ 10	
	Formaldehyde (CH_2O)	ppm-mol	≤ 20	
	Acetaldehyde (CH_3CHO)	ppm-mol	≤ 20	
	Mercury (Hg)	ppm-mol	≤ 0.0003	Updated component
	Carbon Monoxide (CO)	ppm-mol	≤ 100	
	Hydrogen (H_2)	ppm-mol	≤ 50	
	Cadmium (Cd), Thallium (Tl)	ppm-mol	Sum ≤ 0.03	Moved to solids
Clarification from original CO_2 spec	Methane (CH_4)	ppm-mol	≤ 100	
	Nitrogen (N_2)	ppm-mol	≤ 50	
	Argon (Ar)	ppm-mol	≤ 100	
	Methanol (CH_3OH)	ppm-mol	≤ 30	New component
	Ethanol (C_2H_5OH)	ppm-mol	≤ 1	
	Total Volatile Organic Compounds (VOC)[2]	ppm-mol	≤ 10	
	Mono-Ethylene Glycol (MEG)	ppm-mol	≤ 0.005	
	Tri-Ethylene Glycol (TEG)	ppm-mol	Not allowed	
	BTEX[3]	ppm-mol	≤ 0.5	
	Ethylene (C_2H_4)	ppm-mol	≤ 0.5	
	Hydrogen Cyanide (HCN)	ppm-mol	≤ 100	
	Aliphatic Hydrocarbons (C_3+)[4]	ppm-mol	≤ 1,100	
	Ethane (C_2H_6)	ppm-mol	≤ 75	
	Solids, particles, dust	Micro-meter (μm)	≤ 1	

https://norlights.com/wp-content/uploads/2024/06/NorthernLights-GS-co2-spec2024.pdf

4. Grey to green ammonia conversions, and on-purpose green ammonia

AM Green (Greenko ZeroC) Kakinada, India: grey to green hydrogen conversion on existing ammonia plant. Integration of 1.3GW of hydrogen electrolysis into an existing ammonia plant to serve export markets. Uniper has signed a large offtake agreement.

https://power-to-x.de/en/am-green-ammonia-production-in-india-with-1-million-ton-capacity/

Envision, Chifeng, Inner Mongolia China: 500MW of electrolysis capacity from 1,500MW of integrated wind and solar renewable capacity for green ammonia. Exporting low-cost renewable power as ammonia.

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https://ammoniaenergy.org/articles/envision-chinese-renewable-ammonia-exports-to-hit-the-market-this-year/

Atome, Itaipu dam, Paraná River, Paraguay: green CAN from 250MW of pressurised alkaline electrolysis on the 14GW hydro dam. Green hydrogen is the first block in a complex value chain to CAN for export.

Adding value to hydrogen with ammonia and its derivatives

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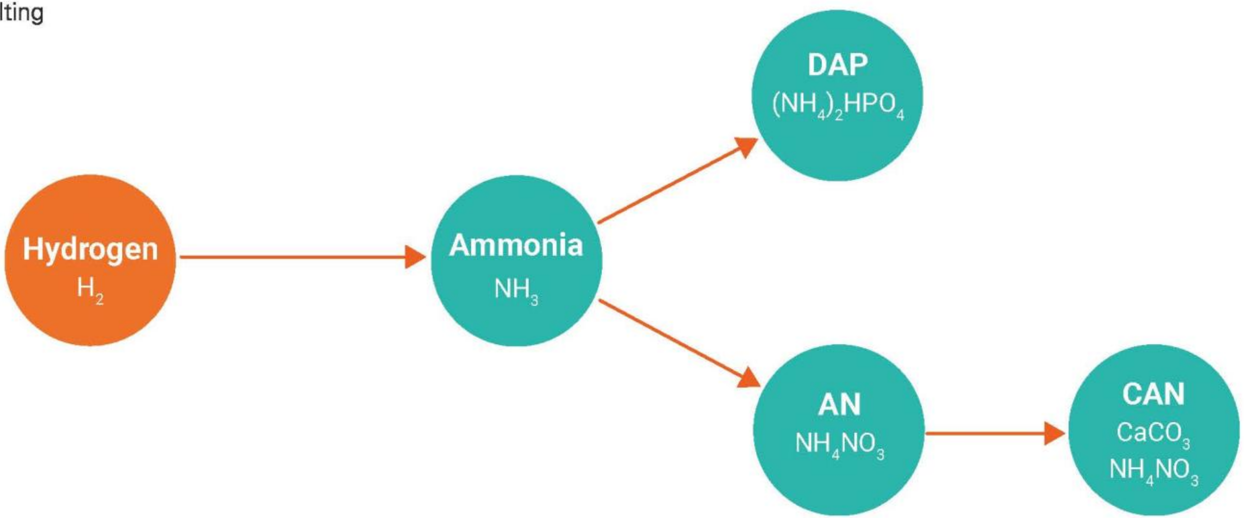

Product	H_2 % in product	Grey H_2 value/ton	H_2% of value	Blue H_2 value/ton	H_2% of value	Green H_2 value/ton	H_2% of value	Green H_2 value/ton	H_2% of value
Hydrogen	100%	**$1,500**	100%	**$2,000**	100%	**$3,000**	100%	**$5,000**	100%
Ammonia	17.8%	$600	44.5%	$689	51.7%	$867	62%	$1,223	73%
AN	5.0%	$340	22.1%	$365	27.4%	$415	36%	$515	49%
CAN	3.5%	$300	17.5%	$318	22.0%	$353	30%	$423	41%
DAP	6.9%	$600	17.3%	$635	21.7%	$704	29%	$842	41%

Adding value helps dilute the "green premium"

- These value-added ammonia derivatives dilute the increased cost of green or blue hydrogen versus the grey hydrogen baseline

The cost of the hydrogen input is less significant for higher value products. Higher value products have a lower percentage "green premium".

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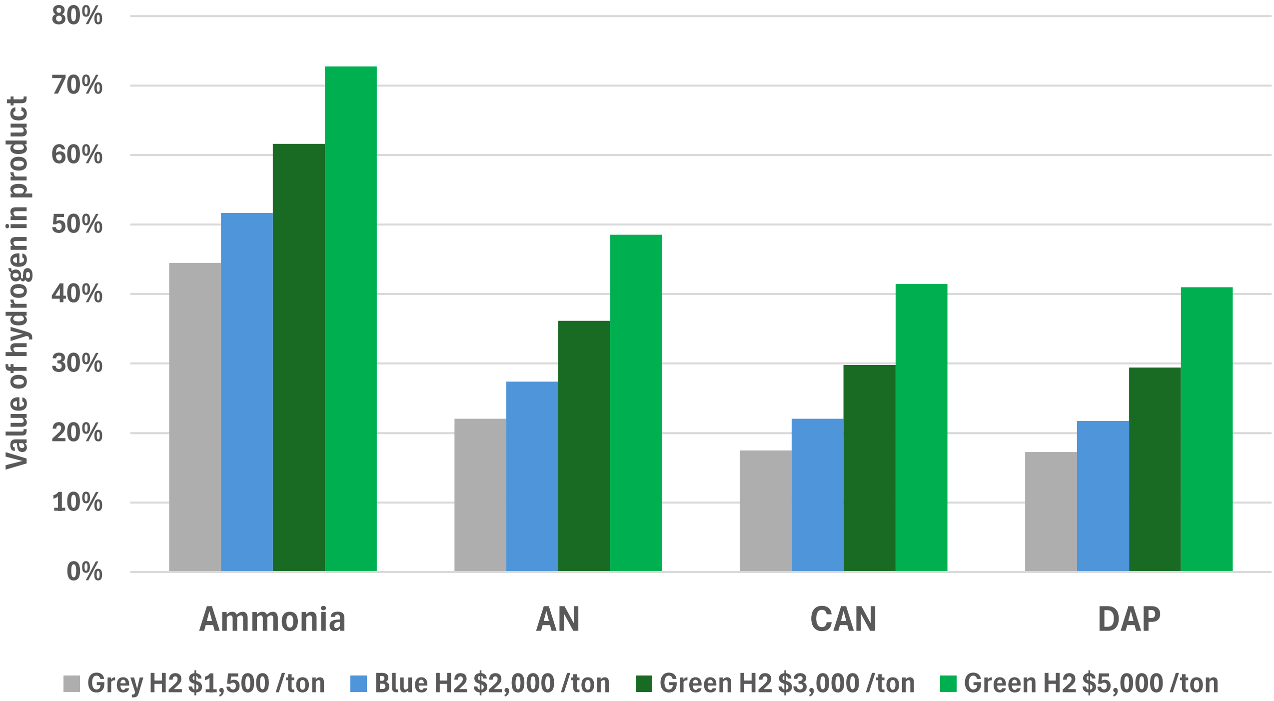

- When making ammonia or ammonia derivatives from any given grade of hydrogen, the cost of the hydrogen ($/kg) is constant.
- Green and blue hydrogen are more expensive than grey.
- Making high value ammonia derivatives makes the blue and green hydrogen price premiums less relevant in the total product price because the percentage of hydrogen in the final product is reduced.

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Introduction to Stephen B. Harrison and sbh4 consulting

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Stephen B. Harrison is the founder and managing director at sbh4 GmbH in Germany. His work focuses on decarbonisation and GHG emissions reduction. E-fuels, hydrogen, ammonia and CCTUS are fundamental pillars of his consulting practice.

Stephen has extensive M&A and investment due diligence advisory experience in the energy and clean-tech sectors. Private Equity firms, investment fund managers and green-tech start-ups are regular clients. He also supports operating companies in their mission to decarbonise their scope 1, 2 and 3 GHG emissions.

In 2023, Stephen evaluated seven CCTUS, hydrogen and e-fuels submissions to the European Commission's Third Innovation Fund. The fund allocated €2 billion to large-scale decarbonisation projects in Europe. In 2024 he supported the European Commission with venture capital investment due diligence and assessed eight Horizon grant applications. Again in 2025, Stephen is assessing seven Innovation Fund applications related to e- and bio-methanol production.

Stephen has served as the international expert and team leader for three ADB projects related to CCTUS and renewable hydrogen deployment in Pakistan, Palau and Viet Nam. He has also supported the IFC and world bank on e-fuels and green hydrogen strategy development projects in Namibia and Pakistan.

With a background in industrial and specialty gases, including 27 years at BOC Gases, The BOC Group and Linde Gas, Stephen has intimate knowledge of e-fuels, hydrogen, ammonia and carbon dioxide from commercial, technical and operational perspectives. 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 the leading hydrogen-focused international publications. Through H2 VIEW, World Hydrogen Leaders and Sustainable Aviation Futures, he has led Masterclasses covering many hydrogen, SAF and hydrogen derivatives themes in virtual and live sessions.

Stephen was session chair for the e-fuels and hydrogen propulsion track at the Bremen Hydrogen Technology Exhibition in September 2023 and chaired the same stream at that conference in Hamburg in 2024. He was also conference chair for the CO2 utilisation Summit in Hamburg in 2023 and the same event in Berlin in 2024.