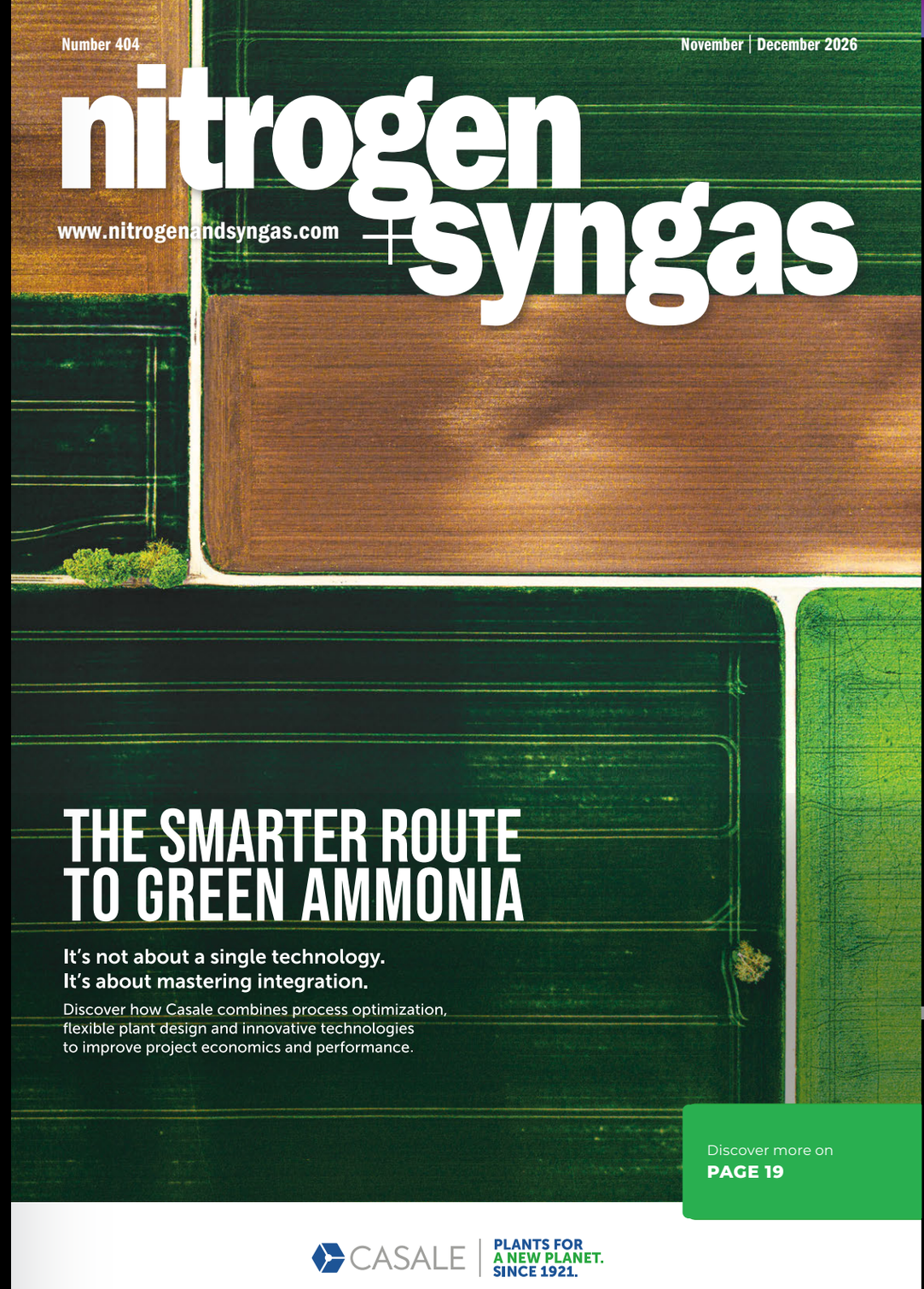
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NITROGEN+SYNGAS
ISSUE 404
NOVEMBER-DECEMBER 2026

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A word in urea



> "... the AI that now squats on my shoulder as I type hates the way I write, which is perhaps my cue to stop."

This marks my final editorial and indeed final issue of *Nitrogen+Syngas* magazine. After 31 years and 189 issues, the time has come to put away the keyboard and retire from a magazine that has occupied much of my life. I joined what was then CRU's British Sulphur Publishing division in 1995, and have seen the magazine through two changes of ownership, and two changes of title, from plain *Nitrogen* first to *Nitrogen&Methanol*, and then *Nitrogen+Syngas*.

The remit of the magazine has not changed much during that time – we aim to keep readers in touch with technological and commercial changes within this sector of the chemical process industry, dependent as it is on that simple and yet incredibly versatile combination of hydrogen and carbon monoxide that we describe as 'synthesis gas', or just syngas.

As the interview with me – which our new Editor-in-Chief Natalie Noor-Drugan indulged me with in this issue – describes, during that time, it is changes in feedstocks that seem to have been the continuing obsession of the industry. Initially, in the 1990s, as natural gas production was gradually privatised, and as expanding pipeline and LNG transport turned it into a global commodity, the era of cheap, 'stranded' gas ended, and there was a brief resurgence of coal and other gasification-based feedstocks, before fracking once again changed the economics of gas production. Now it is climate change and decarbonisation which are changing the industry, but always it is about how you make that crucial hydrogen first step. Methanol, too, has grown over those decades from a chemical intermediate and solvent into an industry almost as large as ammonia, spanning, fuels, petrochemicals and potentially even a shipping fuel of the future.

The constant change in the industry makes it one that it is never dull to cover, and it has been my privilege to have been able to keep up with it over all of these years. But an industry is never just ideas and engineering, it is also a collection of people. Impossible as it is to try and pick out names from an entire career, I would like to pay here a special tribute here to my colleagues and partners in BCInsight Ltd, Lisa Connock, Tina Firman and Mark Evans, with whom I bought the magazines in 2007, and alongside whom ran them for 17 years before the magazines' return to the CRU fold in 2024. Although Tina and Mark have preceded me to well-earned retirement, Lisa – who has been with the magazines even longer than I – continues to provide her expert coverage of the technical side of the magazine. Marlene Vaz, who was for many years our subscriptions agent and latterly commercial manager must also be mentioned, and our various designers, Dani, John, Craig and Darren, and especially Tim Stephens, the latter now on his second stint with CRU, and who gave the magazine its distinctive look.

Meanwhile, the return to CRU has brought additional resources that a small publishing company could not, allowing us to finally take the magazines online, as well as regaining access to their expert team of analysts. There is now a larger sales and marketing team, led by Michelle Bingham. And, as of this issue, it has also brought an expansion of the editorial team, with our new Editor-in-Chief Natalie, herself a veteran of *Fertilizer Week* magazine, our new Editor Beatrice Bedeschi, and Editorial Executive Sofia D'Olivo, bringing between them a wide range of backgrounds across the fertilizer, chemical, mining, and oil and gas fields.

Finally, and most of all, I would like to thank you, the reader, for putting up with my long and convoluted sentences for so long – the AI that now squats on my shoulder as I type hates the way I write, which is perhaps my cue to stop. ■

Thank you,



Richard Hands, Editor

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Price Trends

Ammonia prices firmed across most markets during October, with the sharpest gains west of Suez. In northwest Europe, CFR values climbed to $710-730/t from the low-to-mid $600s/t in early October, and held there as Dutch TTF gas prices broke above €100/MWh ($33.30/MMBtu) on 28 October. CRU estimates that around one third of European ammonia production is now curtailed, leaving buyers reliant on imports. A run of Algerian sales lifted FOB values from $610-625/t in mid-October to $670/t, and Sorfert's latest sale of 30,000 t at $665/t FOB leaves Algeria and Egypt largely sold out to year-end, with Libyan plants offline for at least another two months.

In the US, the November Tampa contract settled at $640/t CFR, up $95/t from October and well above market expectations of a $30-80/t increase. Gulf Coast Ammonia remained down for a turnaround at the end of October, while strong domestic demand continues to limit export availability.

East of Suez, tight supply lifted Southeast Asian values to $480-520/t FOB, with Indonesian exports falling to under 120,000 t in October from 210,871 t in September. Chinese exports recovered to 102,300 t, but remained well below the March-August average of 148,000 t a month. In India, offers were heard near $580/t CFR, but buyers were unwilling to pay above $550/t CFR, leaving the market at a standstill.

Urea prices bounced in mid-October but were subdued by month-end, with attention focused on India. IPL's mid-month tender secured only 410,000 t against the 1.7 Mt sought, as Chinese producers resisted supplying at the lowest offer levels. NFL is now expected to issue a fresh enquiry, potentially for 2.5 Mt, although comfortable stocks of around 8.1 Mt have delayed its return.

In China, September exports reached a record 2.45 Mt, including 1.59 Mt to India. Producer inventories have since risen to around 1.8 Mt, with end-October offers at $345-360/t FOB for prills and $425-435/t FOB for granular.

In the Middle East, granular indications edged up to $450-460/t FOB without fresh business. Around 326,000 t remained west of the Strait of Hormuz, although four vessels carrying 174,000 t exited the Gulf during October. In Iran, offers rose to $355/t FOB, but no sales were confirmed. In Egypt, granular prices climbed $55/t from 12 October to $535/t FOB, supported by European demand, while Algeria's Sorfert targeted $550/t FOB and above without sales.

In the US, NOLA November barges traded at $432-438/st FOB, with autumn demand limited by the harvest, though some buyers are positioning for spring amid fears of Middle East escalation. In Brazil, prices held at $470-490/t CFR, with buying slow after the 25 October presidential run-off as a weaker real raised import costs.

European markets were mixed. In the Baltic, prills were assessed at $370-395/t FOB, as Russian rail congestion threatened deliveries and a drone attack affecting TogliattiAzot led one supplier to nearly suspend sales. Black Sea granular was $480-490/t FOB, with freight deterring buyers. French prices rose to €560-565/t FCA, but buying remained 10-15% below normal. ■

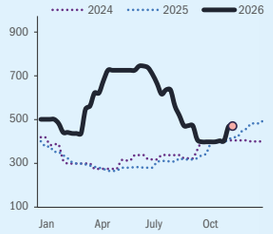
Table 1: **Price indications**

Cash equivalent	mid-Oct	mid-Sep	mid-Aug	mid-Jun
Ammonia Bulk ($/t)				
FOB Caribbean	505	515	595	735
FOB Middle East	400-435	400-425	455-525	750-780
FOB Southeast Asia	450-480	400-420	450-500	730-750
CFR NW Europe duty paid spot/contract	680-705	680-685	700-760	860-910
Urea Bulk ($/t)				
FOB Baltic Sea (prilled)	310-395	375-390	325-370	365-390
FOB Middle East (granular, all netbacks)	415-450	438-480	347-410	308-425
FOB NOLA barge (granular, $/st)	437-455	458-478	380-400	340-405
FOB China (prilled)	335-350	360-380	348-365	480-500
DAP Bulk ($/st)				
FOB NOLA barge	803	808	795	785
UAN Bulk (€/t)				
FCA Rouen, 30%N	445-455	435-440	420-430	430-435

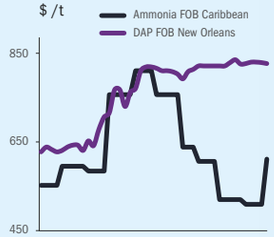
All prices are spot unless otherwise stated. Source: CRU Fertilizer Week.

END OF MONTH SPOT PRICES

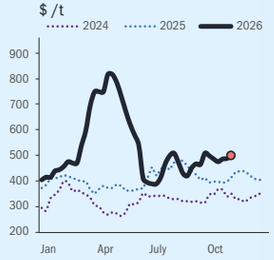
Ammonia FOB Middle East Spot
$ /t



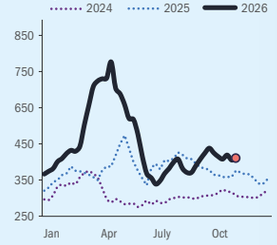
Ammonia & DAP prices
$ /t



Urea Granular FOB Black Sea Spot
$ /t

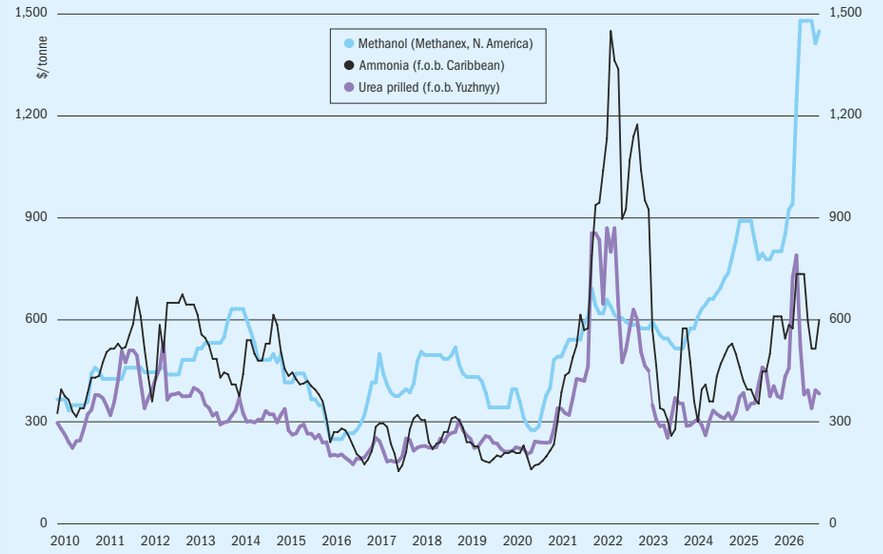


Urea Granular FOB US NOLA Spot
$ /t



Market Outlook

Historical price trends $/tonne



Source: CRU

AMMONIA

- West of Suez, high gas costs and committed North African supply should keep northwest European CFR prices firm. With Dutch TTF gas around €100/MWh, around one third of European ammonia production is curtailed, and further cuts could follow if gas prices hold. CRU does not expect TTF to fall below $30/MMBtu until February.
- East of Suez, December demand from East Asia is set to support further gains, although Indian resistance to prices above $550/t CFR may slow the pace.
- Once gas costs subside, CRU expects ammonia prices to follow suit. Beyond 2026, new merchant capacity will see supply-driven pressure return outside Europe, though wide regional price disparities are likely to persist. North African supply offers little relief, with Algeria and Egypt largely sold out to year-end and Libyan plants offline for at least another two months.

UREA

- All eyes are on India, with prices unlikely to see any major correction before NFL's next tender closes. Indian import requirements are expected to remain supported, while Chinese suppliers continue to target around $350/t FOB for prills.
- Of around 9 Mt of Chinese export quota allocated for 2026, some is likely to go unused or flow into 2027 Q1, while US autumn demand remains limited by the harvest.
- Seasonal demand in Europe and the US, together with elevated winter gas costs, is expected to keep prices high through 2027 Q1. New capacity in Iran and Nigeria, followed by Russia in 2027 Q1, and a gradual resumption of Gulf flows should then place downward pressure on prices through 2027-28, though geopolitics remains a significant upside risk. Brazilian buying also remains slow as import costs rise.

METHANOL

- The methanol market remains tight. Methanex estimates that Middle East supply, normally 15-20 Mt/y or 30-35% of traded methanol, is reaching the market at only 5-10% of normal levels, with October attacks on shipping adding further risk.
- Demand destruction of 10-15 Mt/y has balanced the market, including the first-ever shutdown of all coastal MTO capacity in China. Methanex's North American reference price holds at $1,450/t for November and its Asian posted price at $700/t, with spot prices at $500-550/t in the Atlantic, $550-650/t in Asia ex-China and around $500/t in China.
- Methanex expects tightness through winter, as coal restrictions may constrain Chinese output, but warns of significant uncertainty over how long current pricing will last. Its New Zealand plants will be idled from 2027 Q1, while Chilean output is expected at around 1.4 Mt in 2027. ■

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SAUDI ARABIA

SABIC AN approves $3.5 bn nitrogen expansion



PHOTO: SABIC AGRI-NUTRIENTS

Signing ceremony awarding the seventh SABIC Agri-Nutrients project to Samsung E&A Co., Ltd.

SABIC Agri-Nutrients has taken the final investment decision on its SAN-7 project at Al Jubail, adding 1.2 Mt/y of ammonia and 2.6 Mt/y of urea capacity. Samsung E&A has been awarded the about $3.5 billion engineering, procurement and construction contract. Construction is expected to begin in 2026 Q4, with commercial operations targeted for 2030 Q4.

The complex will include two urea plants using technologies from Stamicarbon and thyssenkrupp Uhde Fertilizer Technology. Nextchem, through Stamicarbon, will supply an NX STAMI Urea package under a €125 million contract covering licensing, process design and proprietary equipment. The ammonia plant will use KBR technology and natural gas feedstock. A carbon-capture unit will use Shell Global Solutions technology. SAN-7 will increase SABIC AN's urea capacity by 54%, from 4.8 Mt/y to 7.4 Mt/y.

However, the project will enter an increasingly competitive supply pipeline, according to CRU senior analyst Pranshi Goyal. "We have been seeing a lot of announcements in low-cost regions recently, because of which the supply pipeline looks very crowded, especially beyond 2030," she said. Goyal pointed to QatarEnergy's planned capacity expansion and the challenge of securing sufficient demand for new output. She described SABIC AN's decision as a surprise given the crowded pipeline and continuing regional uncertainty. ■

ARGENTINA

Profertil taps Saipem for urea plant study

Profertil has appointed Saipem, working with Techint Engineering & Construction, to provide technical evaluation and design services for a proposed expansion of its fertilizer complex in Bahía Blanca.

Announced on 29 September, the project involves a new ammonia-urea plant with urea capacity of 4,450 t/d. It will combine Topsoe ammonia technology, Saipem urea technology and thyssenkrupp Uhde granulation technology.

The 11-month contract covers technical services, licensors' design packages and a structured proposal for subsequent development phases. Profertil's existing complex at Ingeniero White has nominal granulated urea capacity of about 1.44 Mt/y.

The proposal is separate from Pampa Energía's planned Bahía Blanca fertilizer complex, which would add 2.1 Mt/y of urea capacity.

EUROPE

Gas costs put Europe's NH_3 units at risk

High natural gas costs are forcing European fertilizer producers to curtail ammonia output, raising the risk that temporary shutdowns become permanent closures and increase dependence on imports, according to CRU.

Fertiberia halted ammonia and urea production at Palos de la Frontera in Spain, citing gas prices. AGF Nitrogen said on 2 September that it was considering curtailments across its 3.6 Mt/y ammonia portfolio. OCI also reported reduced operating rates where ammonia production economics did not support full output.

CRU estimated European production costs in the high $900s/t, excluding EU emissions trading costs, at the end of September – more than $300/t above northwest European ammonia import prices. "If high gas prices persist through the winter, the risk shifts from temporary curtailments to permanent closures, particularly at older, standalone ammonia plants," CRU Nitrogen Analyst Rachel Gould said.

The 2022 energy crisis provides a precedent. Several producers subsequently closed ammonia capacity while retaining downstream operations supplied with imported ammonia. "In most cases the downstream units were kept running on imported ammonia, so the result was not lost nitrogen output but a structural shift towards imports," Gould said. Integrated sites with downstream nitrate or industrial customers are more likely to retain those operations and purchase ammonia rather than close entirely.

Carbon costs also influence reinvestment decisions. The phase-down of EU ETS free allocation raises domestic production costs, while the Carbon Border Adjustment Mechanism (CBAM) offers partial protection by adding carbon costs to imports. A recovery in LNG supply or improved access through Hormuz would weaken the case for closures.

AUSTRIA

KBR wins AGF Nitrogen NH_3 revamps

KBR has been awarded contracts to revamp ammonia plants operated by AGF Nitrogen subsidiaries LAT Nitrogen in Linz, Austria, and SKW Piesteritz in Lutherstadt Wittenberg, Germany. The upgrades are intended to reduce natural gas consumption, improve energy efficiency and lower CO_2 emissions.

KBR's scope includes technology licensing, engineering services, process equipment and catalyst supply. At SKW Piesteritz's 1,900 t/d plant, the work also includes back-end modifications and a new ammonia converter for the synthesis loop, building on engineering awarded in March 2026. KBR will modernise the steam reforming sections at both plants. Its Linz scope also includes proprietary engineering design.

BELGIUM

NH_3-powered bulk carrier sets sail

CMB.TECH's Mineral Europa has begun its maiden voyage to Australia. The Antwerp-based maritime group describes the 210,000 dwt ship as the world's first ammonia-powered dry bulk carrier. The vessel is the first of 21 ammonia-powered ships scheduled to join the company's fleet by 2029. The programme comprises 18 dry bulk vessels, one container ship and two chemical tankers.

The claimed first relates specifically to dry bulk shipping. Ammonia has already been used aboard other vessel types, including NYK's Sakigake tugboat and Fortescue's dual-fuel Green Pioneer demonstration vessel. CMB.TECH is also investing in ammonia storage and bunker barges to support fuel deliveries to ocean-going ships, sourcing ammonia through its own production and third-party suppliers.

CANADA

Uhde wins CF Courtright DEF study

thyssenkrupp Uhde has won a front-end engineering design study for a proposed urea liquor upgrade plant at CF Industries' Courtright complex in Ontario. The project could add more than 400,000 st/year, about 363,000 t/y, of diesel exhaust fluid capacity. It would use CO_2 streams at Courtright that are currently underused.

Uhde announced the award on 29 October. CF first disclosed the agreement in its second-quarter results on 5 August and expects to make a final investment decision in 2027. Diesel exhaust fluid is used to reduce nitrogen oxide emissions from diesel engines.

CZECH REPUBLIC

Casale starts up Ostrava nitric acid unit

Casale has completed start-up of a 450 t/d weak nitric acid plant for BorsodChem MCHZ in Ostrava. First production was achieved on 30 September, with the acid supplying BorsodChem's downstream aniline production chain.

Casale Project, the group's Czech subsidiary, executed the project under a turnkey engineering, procurement and construction contract awarded in 2024. The plant uses Casale's DualPURE dual-pressure nitric acid technology.

In its 1 October announcement, Casale said about 1,000 t of nitric acid had been produced and used in downstream facilities. Production was increasing through stabilisation and ramp-up ahead of full-capacity operation and a subsequent performance test. Steam export had also begun. The project received support from the European Union Modernisation Fund.

INDIA

AM Green wins €585m NH_3 deal

AM Green has secured a 10-year agreement worth at least €585 million with Hintco, the trading arm of H2Global, to supply renewable ammonia from its Kakinada project for delivery to Germany from 2029. Announced on 30 September, AM Green was selected as the sole winner of the Asian lot in H2Global's auction.

The ammonia will be produced at Phase 2 of the Kakinada development in Andhra Pradesh, where AM Green is converting an existing natural gas-based ammonia and urea complex into a renewable ammonia facility. Production will use alkaline electrolysis supplied by round-the-clock renewable electricity backed by pumped-hydro storage. The agreement covers ammonia meeting EU Renewable Fuels of Non-Biological Origin requirements.

Shipments will leave through Kakinada Seaports, adjacent to the plant. Hintco may purchase additional quoted volumes using proceeds from European resales. AM Green's initial 1 Mt/y Kakinada plant is under construction.

JAPAN

INPEX begins blue NH_3 output

INPEX has begun ammonia production at its demonstration project in Kashiwazaki, Niigata, and started supplying Mitsubishi Gas Chemical. The project uses natural gas from INPEX's Minami-Nagaoka field. CO_2 generated during production is captured and reinjected into a depleted reservoir in the field's Hirai area.

Ammonia synthesis uses Tsubame BHB's proprietary electride catalyst, allowing operation at lower temperatures and pressures than conventional Haber-Bosch synthesis. The technology is intended to support compact facilities and decentralised production near customers. INPEX describes the project as Japan's first integrated low-carbon hydrogen and ammonia value chain from production to utilisation.

Production and capture facilities receive NEDO support, while geological storage evaluation is being undertaken through joint research with JOGMEC.

JAPAN

JERA secures NH_3 for bunkering

JERA and AM Green signed a binding heads of agreement on 27 October for about 70,000 t/y of green ammonia over five years, with provision to extend the supply term. The ammonia will come from AM Green's Kakinada facility in India and support a planned marine-fuel supply chain in Japan's Chubu region.

JERA, K Line, NYK and four shipbuilders announced the wider initiative on the same day. JERA will procure ammonia and build ship-loading facilities at its receiving terminal beside Hekinan thermal power station in Aichi Prefecture. Kyokuyo Shipyard will build a dedicated ammonia bunkering vessel for completion in 2030. NYK or a wholly owned subsidiary will own and operate it. K Line and NYK will establish an equally owned fuel-sales joint venture, supplying vessels through ship-to-ship bunkering, mainly at Nagoya and Mikawa.

The shipping companies will each operate two ammonia-fuelled car carriers, also due in 2030. Their dual-fuel engines and ammonia tanks are intended to enable trans-Pacific voyages using ammonia alone. Customers will include Toyota Motor Corporation.

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Ethiopian prime minister Abiy Ahmed and Aliko Dangote, president and chief executive of Dangote Industries Limited (centre, in grey), are briefed at the Gode fertilizer project site in May 2026.

PHOTO: ETHIOPIAN GOVERNMENT COMMUNICATION SERVICE.

ETHIOPIA

TR wins Dangote reformer order

Técnicas Reunidas (TR) will supply two hydrogen reformers for Dangote Group's ammonia and urea complex at Gode in Ethiopia's Somali region. The reformers will have combined hydrogen capacity exceeding 200,000 normal cubic metres/hour and will use Topsoe technology. Announced on 28 October, the contract covers design, procurement, manufacture and free-on-board supply, with delivery within 18 months. The contract value was not disclosed.

The complex will use Ethiopian natural gas and have capacity for 3 Mt/y of urea. Its main technology licences include two 2,500 t/d Topsoe ammonia plants and Saipem urea technology. Dangote holds 60% of the project and Ethiopian Investment Holdings 40%. Construction began in October 2025.

In May 2026, Dangote raised planned investment from an initial estimate of up to $2.5 billion to more than $4 billion, adding NPK capacity and infrastructure. The development forms part of the group's wider fertilizer expansion programme in Ethiopia and Nigeria.

CHINA

Indorama secures Anyang loan

Anyang Indorama Gases, a subsidiary of Indorama Corporation, has signed a RMB 2.4 billion ($360 million) long-term loan with a consortium of five banks to finance expansion of its fertilizer plant in Anyang. The project is expected to double urea capacity to around 2 Mt/y by 2029.

The brownfield expansion follows Indorama's acquisition of the Anyang Nitrogen Fertilizer business from investment firm PAG earlier in 2026. The lending consortium comprises OCBC Bank, Bank of China, Bank of Communications, Bangkok Bank (China) and China CITIC Bank.

ZAMBIA

UCF launches $1.6bn expansion

United Capital Fertilizer, a subsidiary of China's Wonderful Group, has launched a $1.6 billion expansion of its fertilizer manufacturing facilities in Chilanga. According to UCF, the Phase II development will add capacity for 540,000 t/y of ammonia, 520,000 t/y of urea, 400,000 t/y of ammonium nitrate and 50,000 t/y of food-grade carbon dioxide. The additional output is intended to support agricultural fertilizer production and supply products and raw materials for other industrial applications.

Completion is targeted for 2030. The development would broaden the site's nitrogen product range while substantially increasing its ammonia and downstream fertilizer manufacturing capacity.

TRINIDAD & TOBAGO

Nutrien closes Trinidad nitrogen units

Nutrien has announced the indefinite closure of its Trinidad Nitrogen operations at Point Lisas, citing continuing natural gas constraints and uncertainty over future supplies.

The decision follows a controlled shutdown on 23 October 2025, prompted by port access restrictions and unreliable and uneconomic gas supplies.

The complex comprises four ammonia plants with combined capacity of 1.79 Mt/y and a 660,000 t/y urea train. Before the 2025 shutdown, production was around 1 Mt/y of ammonia and 600,000 t/y of urea.

Nutrien said an extensive review of alternatives concluded that indefinite closure offered the best route to improving free cash flow and returns on invested capital.

The company does not expect the decision to affect its 2026 nitrogen sales-volume guidance, which already assumed no Trinidad production.

It said customer demand could be met through its North American nitrogen assets, supported by reliability improvements and low-cost debottlenecking projects. The announcement therefore extends the loss of Trinidad supply rather than removing additional output from the company's existing 2026 production forecast.

NETHERLANDS

Yara starts Sluiskil CCS

Yara International began industrial-scale carbon capture and storage operations at its Sluiskil ammonia and fertilizer complex on 7 September. The facility will capture and liquefy up to 800,000 t/y of CO_2 for shipment to Norway and permanent offshore storage through project partner Northern Lights. Liquefied CO_2 will be transported to Øygarden on Norway's west coast, transferred to onshore tanks and then sent through a 120 km pipeline for injection into a saline aquifer about 2,600 metres below the seabed.

Yara took the final investment decision in 2023. Investment is estimated at €200 million, with plans to capture and liquefy 12 Mt of CO_2 over 15 years. The Sluiskil system captures CO_2 from ammonia production using MDEA absorption technology. Liquefaction capacity is up to 125 t/h, with seven on-site tanks providing 15,000 t of temporary storage.

Northern Lights' ships, each with CO_2 capacity of 7,200 t, will transport the liquid on a twice-weekly schedule. Yara intends to use CCS to supply lower-carbon fertilizers, marine fuels and ammonia for industrial and energy applications. The company says its Climate Choice fertilizers produced at Sluiskil using CCS will have a carbon footprint 40% below conventional fertilizers, and that the project demonstrates a cross-border chain connecting industrial capture, liquefaction, marine transport and permanent geological storage.

NORWAY

Casale to supply Glomfjord NH_3 plant

Casale has signed a contract with Neptun Glomfjord Green Ammonia for engineering and supply of a 100 t/d modular green ammonia plant at Glomfjord Industrial Park. Announced on 23 September, the agreement uses Casale's SMART-N technology under an engineering, procurement and fabrication model. The facility will serve local demand, with third parties processing ammonia into nitric acid, ammonium nitrate solutions and downstream fertilizers.

The plant is designed to operate between 10% and 100% of nominal capacity. Initial synthesis operation is expected at about 50% load as hydrogen production is introduced in stages. The contract value and commissioning date were not disclosed. ■

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Syngas News

MEXICO

Pacifico Mexinol signs electrolyser EPC contract

Transition Industries has signed a definitive engineering, procurement and construction (EPC) agreement with Siemens Energy and Techint Engineering & Construction (Techint E&C) for the electrolyser plant at its Pacifico Mexinol project in Sinaloa, Mexico. The agreement is subject to customary conditions precedent, including completion of project financing. Construction is expected to begin in early 2027.

"Moving from front-end engineering to a signed EPC agreement is a significant milestone for Pacifico Mexinol," said Rommel Gallo, chief executive of Transition Industries.

The plant, of about 210 MW, will use Siemens Energy's Elyzer P-300 electrolyser technology. Siemens Energy said it would be the company's largest electrolyser installation in the Americas. The contract builds on the front-end engineering design (FEED) contract announced in August 2025.

The electrolysers will produce renewable hydrogen for methanol that qualifies as a renewable fuel of non-biological origin (RFNBO). The methanol complex is planned at 6,130 t/d and is due to start up in 2030. It will produce about 175,000 t/y of RFNBO methanol and 175,000 t/y of recycled carbon fuel (RCF) methanol. Most of the output, about 1.8 Mt/y, will be ultra-low-carbon methanol made from natural gas with carbon capture. Transition Industries says the complex will be the world's largest standalone ultra-low-carbon chemical plant.

Houston-based Transition Industries is the parent company of Pacifico Mexinol. Techint E&C, headquartered in Buenos Aires, Argentina, is working on the project through its alliance with Siemens Energy. ■

SPAIN

Priority status for eM-Numancia

The government of Castilla y León has granted priority industrial project status to eM-Numancia, a €320 million green methanol project in Soria. The plant will combine renewable hydrogen from water electrolysis with syngas from the gasification of forest biomass, mainly pine wood, and will include CO_2 capture and recovery. Initial capacity is set at 100,000 t/y, with potential expansion to 200,000 t/y depending on electricity supply.

INDIA

Work starts on Kandla methanol plant

Construction has begun on what is claimed to be India's first port-based green methanol plant, at the Deendayal Port Authority in Kandla, Gujarat. The $240 million project is a joint venture between the Deendayal Port Authority and Assam Petro-Chemicals Ltd (APCL), which are contributing capital in a 76:24 ratio.

The plant will have total capacity of 150 t/d and will use renewable power, water and biogenic CO_2. It will be built in two phases: a 50 t/d first phase costing $125 million, scheduled for January 2027, and a further 100 t/d costing $115 million, scheduled for March 2027. The methanol will fuel ships on the Asia–Europe trade corridor, with Kandla planned as a green-fuel hub on the Singapore–Rotterdam route.

NORWAY

H2SITE wins ammonia-to-power funding

Spanish hydrogen technology developer H2SITE has secured €3.4 million ($3.8 million) in funding for its HydraNord Power project in Norway, which will convert ammonia into high-purity hydrogen on board ships. The system will produce up to 1 t/d of hydrogen to supply maritime fuel cells with 700 kW of net electrical power.

H2SITE's membrane reactor combines ammonia cracking and hydrogen separation in a single process, producing fuel-cell-grade hydrogen while protecting the fuel cells from ammonia contamination. Modules can be deployed in parallel for larger installations, on new or existing vessels.

The system will be installed and tested at Energy House in Stord under conditions representative of commercial maritime operation. Development and integration will take place during 2027, with commissioning planned for early 2028.

GERMANY

C1 wins grant for Leuna plant

Berlin-based technology developer C1 Green Chemicals has secured a €13.3 million ($14.8 million) EU Innovation Fund grant to build a green methanol demonstration plant at Leuna Chemical Park. The 20 t/d METHANOL.ONE plant will convert biomethane into green methanol, with production scheduled to begin in 2029. The project was one of 16 selected from 79 applications under the Innovation Fund's Pilots category.

C1 uses homogeneous catalysis rather than the heterogeneous catalysis conventionally used in methanol production. The company says its process achieves higher conversion efficiency at significantly lower pressures and temperatures, with greater feedstock flexibility.

The plant follows C1's Leuna100 pilot, which recently completed more than 120 days of continuous operation without a catalyst refresh. METHANOL.ONE is intended to take the process into continuous commercial operation and provide a reference for future licensing customers. C1 says it has memoranda of understanding for plants with combined capacity exceeding 3,000 t/d. It expects the plant to avoid around 318,000 tonnes of CO_2-equivalent emissions over its first ten years.

CANADA

Québec e-methanol joint venture formed

Canadian ethanol producer Greenfield Global and Danish renewable energy company European Energy have formed a joint venture to build a 48,000 t/y e-methanol plant next to Greenfield's ethanol facility near Montréal.

The joint venture builds on a memorandum of understanding signed in 2025. Preliminary engineering studies are complete, construction of the grid connection is under way and the partners will now begin talks with offtakers.

The plant will combine hydroelectricity with biogenic CO_2 from fermentation at Greenfield's fuel ethanol distillery. The companies said Québec offers some of the lowest-cost, lowest-carbon-intensity

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Senior executives from European Energy and Greenfield Global shaking hands on the new deal.

PHOTO: EUROPEAN ENERGY

hydroelectricity in North America, and that the site has export routes to Europe as well as access to domestic markets. The e-methanol is intended to meet the EU's RFNBO requirements and is aimed at maritime fuel and renewable polymer markets.

Greenfield will provide the site, infrastructure and CO_2. European Energy will contribute its Power-to-X experience as majority owner and operator of the 42,000 t/y Kassø e-methanol plant in Denmark, which it describes as the world's first large-scale commercial e-methanol facility.

European Energy chief executive Knud Erik Andersen said the partners saw an opportunity to establish "a strong platform for future growth across North America".

JAPAN

Mizushima starts steel-gas methanol trial

JFE Steel, Mitsubishi Gas Chemical and Mitsubishi Chemical have begun a demonstration project that converts steelmaking by-product gas into methanol and then into propylene. The supply chain started operating in September 2026 at the Mizushima industrial complex in Kurashiki, Okayama Prefecture, the companies announced on 22 October.

JFE Steel supplies by-product gas from its steelmaking processes to Mitsubishi Gas Chemical, which produces methanol at a newly built demonstration plant on its Mizushima site. The plant forms part of Mitsubishi Gas Chemical's Carbopath carbon-recycling platform. Mitsubishi Chemical then converts the methanol into propylene at an existing demonstration facility, using JGC's DTP process.

The partners will evaluate the economic viability of the chain and identify the challenges to commercialisation. Production capacities, the length of the demonstration and a commercialisation timetable were not disclosed.

NETHERLANDS

Perpetual Next selects Air Liquide technology

Perpetual Next has signed an agreement with Air Liquide for syngas-to-methanol technology for its planned 220,000 t/y DeltaNor biomethanol plant in Delfzijl, its first biomethanol facility. The agreement includes an option to use the technology at other Perpetual Next sites. The company's process integrates torrefaction, gasification, syngas cleaning and upgrading with methanol synthesis to convert low-grade organic waste, including waste wood, into biomethanol. Further projects are planned in Moerdijk, Poland and Estonia.

Separately, Perpetual Next has signed a memorandum of understanding with Lhyfe to assess the supply of up to 12,000 t/y of renewable hydrogen to DeltaNor from Lhyfe's planned 120 MW DelfzHyl facility in the same industrial cluster. Any supply arrangement remains subject to further technical and commercial evaluation.

Adding renewable hydrogen to biomass-derived syngas could increase methanol yields by converting more of the biogenic carbon into methanol. The companies are targeting maritime and chemical markets.

SPAIN

Moeve starts building Onuba hydrogen project

Spanish energy company Moeve, formerly Cepsa, has started construction of the 300 MW Onuba renewable hydrogen project in Palos de la Frontera, Huelva. Onuba represents more than €1 billion ($1.18 billion) of investment, including associated infrastructure and a dedicated solar plant. It is designed to produce about 45,000 t/y of renewable hydrogen and avoid around 250,000 t/y of CO_2 emissions. The plant could later be expanded by a further 105 MW.

The project is being developed at Moeve's La Rábida Energy Park, next to Fertiberia's Huelva facilities. The two companies plan to use the hydrogen in their industrial operations and have identified green ammonia, AdBlue and crop-nutrition products as potential outputs.

Onuba is the first phase of a planned 1 GW Huelva hub, part of Moeve's wider 2 GW Andalusian Green Hydrogen Valley, which also includes San Roque in Cádiz. Moeve holds 51% of Onuba. Hy24 and COFIDES together hold 29%, and Enagás Renovable and Alter Enersun the remaining 20%. The project has received €304 million from Spain's Recovery, Transformation and Resilience Plan.

SWEDEN

Topsoe wins NorthStarH2 FEED contract

Topsoe has signed a contract with Uniper to carry out front-end engineering design (FEED) for the NorthStarH2 green methanol project in Östersund, northern Sweden. The plant will use Topsoe's ModuLite e-methanol technology, including gas compression. ModuLite has a prefabricated modular design intended to speed up construction and commissioning. Topsoe says its dynamic synthesis loop allows reliable operation as renewable power supply fluctuates.

NorthStarH2 will combine renewable hydrogen with biogenic CO_2 captured from biomass combustion to produce around 115,000 t/y of methanol for shipping and chemicals. A final investment decision is expected in 2028.

"With the contracts with Topsoe and the other key suppliers in place, we can now develop the plant design in much greater detail and define how NorthStarH2 will be built," said Broghan Helgeson, NorthStarH2 project manager at Uniper. ■

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People

Norwegian green hydrogen developer Gen2 Energy has appointed **Camilla Nilsson** as Chief Executive Officer, effective from 1 September 2026. She succeeds **Lena Halvari**, who will continue as Chief Operating Officer. Nilsson joined the company as Chief Financial Officer in June as part of a planned leadership transition and will continue to cover the finance role alongside her new responsibilities. She has more than 20 years of international leadership experience across the energy, cleantech and industrial sectors. Before joining Gen2 Energy, she served as CEO of thermal energy storage company Kyoto Group. Her earlier career included positions at Yara International and Norsk Hydro, with responsibilities spanning international business development, investments and operational management.

Announcing the appointment, Bård Mikkelsen, Chair of Gen2 Energy's Board, said: "Camilla brings the strategic, commercial and financial experience we were looking for. With Lena continuing as COO, we combine continuity and deep company knowledge with additional experience in scaling and financing energy and technology businesses."

Engro Corporation has appointed **Junaid Iqbal** as President and Chief Executive Officer-designate, with the leadership transition planned for April 2027. He will succeed **Ahsan Zafar Syed** following completion of the incumbent's current term, subject to Board approval after the election of the Board of Directors in April 2027. Iqbal currently serves as Advisor to the CEO of Engro Holdings. The coming months will be used for a structured handover, during which he will work closely with Engro's businesses and operations and contribute to strategic priorities under Syed's mentorship. Engro has also announced that Syed will become Counsel to the Chairman of Engro Holdings after completing his term.

The Mosaic Company has announced that **Walt Precourt** will become Executive Vice President – Operations, effective from 1 December 2026. He will succeed **Karen Swager**, who will remain with the company as a senior advisor until her retirement in the second quarter of 2027. Precourt currently serves as Senior Vice President and Chief Administrative Officer. Since joining Mosaic in 2009, he has led its phosphate and potash businesses, as well as its environmental, health and safety and strategy activities. He has been a member of the company's Executive Leadership Team since 2014. In his new role, he will lead global operations and the environmental, health and safety function, remaining based at Mosaic's executive office in Tampa, Florida.

Swager's career at Mosaic and its predecessor companies spans more than three decades. She has served as General Manager of several operating facilities, led the potash business and the company's supply chain, and held the position of Executive Vice President – Operations since 2023.

The Methanol Institute has unveiled a new identity as MI – The Global Methanol Alliance, reflecting its expanded membership and the growing range of industries participating in the methanol value chain. Announced on 1 September 2026, the change is accompanied by a new website bringing together industry data, market insights and resources covering methanol applications, safety, policy and regulation. The association connects companies across the methanol value chain and has offices in Washington DC, Brussels, Beijing, Delhi and Singapore.

Commenting on the change, **Ben Iosefa**, Chair of MI's Board of Directors, said: "The methanol industry has changed, and we have changed with it. Over the past six years, we have seen methanol move into new markets and our membership expand across sectors and the value chain."

Alexander Döll, CEO of MI, added: "Our new identity is about making that clearer. The Global Methanol Alliance reflects who we are today: a place where the industry comes together, connects across markets and sectors, and works collectively on the issues that will shape methanol's next phase of growth." ■

Calendar 2026/7

NOVEMBER

26-28
FAI Annual Seminar 2026, NEW DELHI, India
Contact: Secretary, The Fertiliser Association of India
Tel: +91-11- 46005204
Email: secy@faidelhi.org

JANUARY 2027

17-20
Fertilizer Latino Americano, RIO DE JANEIRO, Brazil
Contact: CRU Events
Tel: +44 (0) 20 7903 2444
Email: conferences@crugroup.com

FEBRUARY

2-4
33rd AFA Int'l Annual Fertilizer Conference & Exhibition, CAIRO, Egypt
Contact: Arab Fertilizer Association
Tel: +202-23054464 – 67 Ext: 126
Email: events@arabfertilizer.org

25-26
IMPCA Methanol Mini-Conference America, PORT OF SPAIN, Trinidad and Tobago
Contact: International Methanol Producers and Consumers Association
Email: meetings@impca.eu

MARCH

9-10
StocExpo Tank storage and future fuels 2027, ROTTERDAM, Netherlands
Web: https://www.stocexpo.com/en/visit/conference/

10-11
Gasification 2027, HELSINKI, Finland
Contact: ACI
Tel: +44 (0)20 7981 9800
Email: luca@acieu.net

16-18
Nitrogen+Syngas Expoconference 2027, ROME, Italy
Contact: CRU Events
Tel: +44 (0) 20 7903 2444
Email: conferences@crugroup.com

APRIL

6-8
Nitrogen+Syngas USA Expoconference 2027, TULSA, Oklahoma, US
Contact: CRU Events
Tel: +44 (0) 20 7903 2444
Email: conferences@crugroup.com

MAY

24-26
IFA Annual Conference 2027, LONDON, United Kingdom
Contact: IFA Conference Service
Tel: +33 1 53 93 05 00
Email: ifa@fertilizer.org

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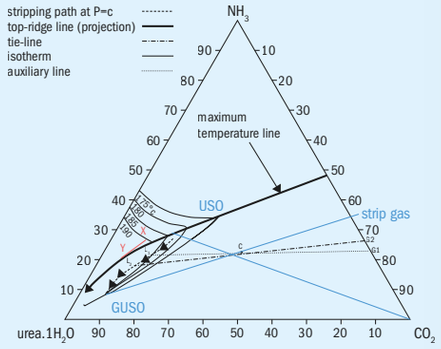
Plant Manager+

Problem No. 80 Stripper flooding

In 1967, Stamicarbon revolutionised the urea process with the invention of the high-pressure (HP) CO_2 stripper by Petrus J.C. Kaasenbrood. The HP CO_2 stripper brought three main benefits:

- **carbamate could be recycled at synthesis pressure, eliminating the need to add extra water to the recycle stream;**
- **a medium-pressure recirculation section was no longer required;**
- **condensing the stripping gases in the high-pressure carbamate condenser made it possible to produce low-pressure steam for downstream sections. This reduced a urea plant's steam consumption by about half.**

Snamprogetti (Saipem) later introduced the NH_3 stripper. The figure to the right shows the phase diagram for mixtures of ammonia, carbon dioxide, urea and water. It includes a maximum temperature line and illustrates how liquid composition changes through the stripper.
In a CO_2 stripper, the liquid composition moves from the inlet (USO) to the outlet (GUSO), away from the maximum temperature line. This means that a CO_2 stripper operates at relatively low temperatures. Lower stripping efficiency results in a higher outlet temperature.
In an NH_3 stripper, the liquid composition moves from the inlet (X) to the outlet (Y), towards the maximum temperature line. Here, lower stripping efficiency results in a lower outlet temperature.
These differences are important to keep in mind when discussing the effects of stripper flooding on stripping efficiency.
This article covers only part of a much broader discussion. Stripper efficiency is a particularly interesting topic as many more factors can reduce it. ■



Ahmed, an engineer at Alexfert in Egypt, opens the discussion: Has anyone experienced flooding on the tube side of a stripper during start-up or while increasing plant load? What could cause it, and what signs indicate that it is happening?

Nour of El Delta, Egypt, replies: Flooding in a stripper is mainly caused by maldistribution of the solution or blockage of the liquid distribution holes in the ferrules.

Abbas of PIC, Kuwait, adds: Another possible cause is PTFE rings that are not properly fixed in place on the tube ends. Flooding may be indicated by lower stripper steam consumption and a lower stripper liquid outlet temperature. When 25-22-2 material is used, this can lead to higher corrosion rates in the stripper tubes.

Ahmed clarifies his question: Have you experienced flooding when increasing plant load without increasing steam to the stripper shell side in line with the load increase? In other words, what happens if the plant load is raised without supplying the required additional steam?

Nasir Hussain of Pak Arab Fertilizer, Pakistan, responds:
Flooding may be caused by:

- A malfunctioning stripper level controller.
- Low steam flow to the shell side of the stripper.
- Excessive opening of the stripper inlet valve.

Possible indications include:

- High temperatures in the E-1 (stripper) off-gases.
- Blockage in the downstream lines from the carbamate separator.

Mark Brouwer of UreaKnowHow.com, the Netherlands, explains: HP stripper flooding occurs when the liquid film in the tubes can no longer be sustained. This can result from high liquid loads, but the gas load in the tubes also plays a role.

When flooding occurs, the liquid film along the tube walls breaks up and stripping efficiency falls. This leads to a high ammonia content in the HP stripper liquid outlet. A rapid rise in the liquid outlet bottom temperature is another indication.

Flooding can increase corrosion rates in 25-22-2 tubes. High liquid loads may also occur locally: if liquid distribution is poor, some tubes may flood while others do not.

Increasing plant load without increasing steam supply will reduce stripping efficiency. If the load becomes high enough to break up the falling film, it can also cause flooding.

Ahsan Sarfraz of Fatima Fertilizer Ltd, Pakistan, offers a different interpretation: I would distinguish flooding from overloading or weeping, which I believe many of the replies are describing. Flooding is the carryover of an excessive amount of liquid with the stripper off-gases.

In Stamicarbon or TOYO ACES plants, one possible cause is unequal gas distribution from the CO_2 sparger pipe. Gas then flows at higher velocity through some holes, giving the tubes above them a higher gas velocity than tubes elsewhere. Other areas may have low gas flow or velocity, causing weeping. The stripper's operation can then become disturbed, with flooding and weeping occurring at the same time.

Possible indications of flooding may include higher off-gas temperatures and:

- an unusual rise in reactor level at the same plant load;
- greater opening of the reactor level controller, which further overloads the stripper and can subsequently trigger a cycle of further disturbance.

We experienced this problem at our plant. The stripper bottom outlet temperature gradually increased by 10°C, the recovery section became overloaded, and frequent flooding occurred in the HP absorber. Online flushing of the CO_2 sparger using the HP flushing pump provided temporary relief. A later investigation found that the liquid-distribution holes were larger than specified and that several were plugged.

Abbas returns to the effect of increasing load without increasing steam: If plant load is increased without the required increase in shell-side steam, stripping efficiency will fall. This can overload the downstream recirculation and evaporation sections and increase pressure.

We have not experienced stripper flooding solely because load was increased without a corresponding increase in shell-side steam. However, the situation could lead to flooding if the reactor level becomes unstable or the reactor ratio is poor. The level controller may then open further, overloading the stripper and triggering a cycle of disturbance.

Ahmed asks about the stripper steam drum: If the steam line to the HP stripper carries two-phase flow (steam and condensate) this will cause a pressure drop across the line.
Could that pressure drop push the condensate level in the stripper shell to a higher level?

Fahed Waseem of FFBL, Pakistan, shares his experience with STAC plants:
Flooding can occur when the liquid-gas flow balance varies, for example, when more liquid enters from the reactor while CO_2 flow is lower.

With a higher liquid feed, liquid may enter from the tops of the ferrules, disrupting the falling film. The stripper bottom level may also rise to the tubes, and low steam pressure can contribute.

When flooding occurs, operators may observe:

- lower stripper steam demand;
- a sharp rise in stripper bottom outlet temperature;
- a rising stripper bottom level and increased downstream-section pressure as stripping is reduced;
- a decrease in the first reactor's level due to a lower flow of stripper off-gases.

The recommended action is to close the stripper inlet liquid valve immediately and protect the downstream LP recirculation section from higher operating pressure.

Ahmed asks Mark to explain the role of gas load in the tubes.

Mark replies: If the gas load (CO_2 and dissociated carbamate) is high, flooding will occur sooner.

Safyan Manzoor of FFC, Pakistan, lists these indicators and possible causes:

- low temperature at the stripper bottom;
- low steam consumption on the stripper shell side;
- overloading downstream;
- a high level or a high opening of the stripper bottom outlet valve;
- film disturbance is the main cause. It may result from damaged ferrules, a very high stripper bottom level – associated with a low opening of the outlet valve – or a sudden increase in the opening of the reactor outlet valve.

Mark notes that the indicators described by Nasir and Safyan apply to an NH_3 stripper: The consequences of flooding in a CO_2 stripper are partly different. The major difference is the effect on the bottom temperature: flooding in a CO_2 stripper leads to a sudden increase in bottom temperature.

Mark adds a further consideration on behalf of a urea engineer: Another factor is operating at a highly stretched rate, where both vapour and liquid loads per tube are high. In the Stamicarbon design, there is a maximum recommended liquid load. A plant limited by its stripper may experience frequent flooding-related "excursions"; resolving them may require a significant rate reduction, which can upset the plant.

At the plant I was involved with, the problem was addressed by installing the Stamicarbon MP Add-On section. This provided:

- no stripper flooding at a plant load more than 10% higher;
- lower HPCC load and, consequently, higher LP steam pressure, which can become limiting at very high loads;
- the ability to increase production by more than 10% at a constant HP CO_2 compressor limit, because the MP section requires CO_2 at 20 bar, which can be supplied by lower-cost oil-flooded screw compressors.
- the ability to use spent cooling water (third pass) in the MPCC, without increasing cooling-water requirements.

Ahmed asks whether an inaccurate stripper level reading could reduce stripping efficiency: If the stripper level indication is incorrect, for example, the actual level is higher than normal but the DCS indicates a lower level, could this cause a high liquid outlet temperature and low stripping efficiency?

Mark replies: A high stripper level becomes problematic when it reaches the tubes, as this creates a risk of active corrosion in 25-22-2 tubes.

Even when the level rises above the CO_2 distributor, stripping efficiency can fall and bottom temperature can increase because of CO_2 maldistribution.

Biuret formation and hydrolysis can also occur. ■

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Financing large scale fertilizer plants

Rendering of the 1.4 million t/y Blue Point One ammonia plant under construction in Louisiana, USA.

Large scale ammonia and downstream projects face a variety of challenges relating to financing structures, bankability factors and risks, especially for low-carbon 'blue' and 'green' developments.

Costs for a modern large scale ammonia-urea plant typically start at around $1 billion, and can be double or triple that for world-scale export-oriented units. Capital costs must cover the reformer or reformers, and ammonia conversion sections which are designed to operate at the high temperatures and pressures needed for the Haber-Bosch process. Plants are often designed for large scales to take advantage of economies of scale, particularly in the ammonia conversion section, but this presents issues with raising the required costs. Lenders and investors must assess whether the project can be built on time and on budget, whether it can secure a sufficient quantity of reliable and affordable feedstock and other utilities, and generate sufficient cash flow to repay debt despite volatile fertilizer and input prices. Low-carbon projects face these same questions, while adding further dependencies: carbon capture and storage (CCS) infrastructure for some gas-based projects; or renewable electricity and electrolysers for renewable-hydrogen projects; and evidence that the resulting product meets a specified emissions standard.

Financing structure

A large plant may be financed with a combination of sponsor equity, commercial bank loans, export credit agency support, development finance institution (DFI) lending, government support and, in some cases, bond or other capital-market finance. Commercial arrangements such as long-term product offtake or prepayment may also contribute to the financing plan.

Sponsor equity is generally exposed to project losses before senior debt. It helps fund development and construction and demonstrates that sponsors have capital at risk. Lenders will consider sponsors' financial strength, experience and ability to provide further support if the project encounters delays or cost overruns.

Senior debt may come from commercial banks, multilateral development banks or other lenders. For a project-financed plant, repayment is expected to come mainly from the project's own cash flow, rather than from the sponsor's general balance sheet. A lender's assessment therefore centres on the project's contracts, cash-flow resilience, legal structure, assets and ability to complete and operate. Offtake or prepayment arrangements can support revenue visibility or provide funding, but may constrain sales flexibility and pricing.

Export credit agencies may provide loans or guarantees linked to equipment and services supplied from their countries. DFIs may lend directly, mobilise other lenders, provide guarantees or help address risks that make a project difficult to finance commercially. Government support can take different forms, including infrastructure contributions, grants, tax measures or guarantees; availability and eligibility depend on the jurisdiction and project.[1]

Bond or capital-market debt is possible for larger or established sponsors, often after construction or once the project has a stronger operating record. The precise mix depends on the sponsors, host country, project maturity, risk allocation and market conditions. Financing can be project-level, relying mainly on the plant's cash flows and assets, or corporate-level, supported by the sponsors' balance sheets.

Finance case

A project's finance case can rely on several elements:

Feedstock and energy: natural gas is the principal feedstock for most conventional ammonia plants and generally forms most (70-80%) of their operating cost. Gas price, availability, transport and contract terms can make or break the project economics. A low-cost gas assumption cannot be treated as secure revenue support unless it is backed by a credible supply arrangement. Conversely, a plant with substantial exposure to volatile or expensive gas may have less predictable operating margins and debt-service capacity.

Product markets: urea sales depend on global and regional supply-demand conditions, export access, logistics, and the project's cost position. Lenders assess where ammonia and urea will be sold, how much output is contracted, the reliability of buyers and the degree of exposure to market prices. A long-term offtake agreement can make revenues more visible, but it does not automatically remove market risk. Its value depends on the buyer's creditworthiness, contract duration, pricing mechanism, delivery terms and protections if either party cannot perform.

Scale and integration: integrated ammonia and urea (or other downstream product) production can capture conversion value and share infrastructure, but it also increases the project's capital requirement and execution complexity.

Location and infrastructure: access to ports, pipelines, power, water, storage and transport links affect both costs and lender confidence. A site that appears attractive on paper may be challenging to finance if critical infrastructure is unavailable, uncontracted or dependent on another project that is not yet complete. In an export-oriented project, product logistics and access to buyers are part of the financing case, not merely operational details.

Technology and performance: proven process design, guaranteed plant capacity, energy consumption, emissions performance and availability are central to technical due diligence.

Policy and carbon exposure: carbon costs, emissions rules, incentives and trade measures may affect competitiveness, particularly in markets with tightening climate policies.

Construction, technology and operational risks

Before committing funds, lenders commonly seek evidence that the project can be built on an agreed schedule and within a credible budget. They examine the engineering, procurement and construction (EPC) arrangement, including the allocation of cost, schedule and performance risk. They also consider whether the contract includes meaningful tests, remedies for underperformance, delay provisions and clear limits on exclusions.

Contract terms do not eliminate all risk. Cost overruns may arise from scope changes, inflation, labour or equipment constraints, site conditions, infrastructure dependencies or delays in permits. Lenders may therefore consider whether sponsors have sufficient funds and contingency arrangements to cover costs that are not borne by contractors.

Technology and operating plans are another part of due diligence. Relevant factors include whether the process design has a track record at the proposed scale, whether equipment suppliers can meet performance commitments, and whether the project has an experienced operator. The business plan also needs to account for commissioning, ramp-up, maintenance, spare parts and the possibility that the plant will not immediately achieve its design output.

Country and legal risks can influence both debt availability and financing costs. Investors and lenders may examine permitting, land and water rights, currency convertibility, the ability to repatriate funds, export rules and political risk. Insurance, guarantees or Development Finance Institution (DFI) participation may help address some risks, but do not necessarily cover every form of delay, loss or regulatory change.

Contract strategy

The construction contract is a central part of a project's risk-allocation framework. It affects who is responsible for design coordination, procurement, construction management, schedule, cost overruns and performance at completion. Those responsibilities matter to lenders because delays or underperformance can postpone revenue, increase funding needs and weaken debt-service capacity.[2]

Under an engineering, procurement and construction (EPC) contract, a contractor is typically responsible for delivering a defined scope, often on a turnkey basis. A fixed or capped price, completion date, performance guarantees and delay remedies can provide a clearer basis for budgeting and financing. This can be attractive to lenders, particularly where the contractor has the technical capability and financial strength to stand behind its obligations.

But EPC does not transfer every project risk. The protection depends on the contract's scope, exclusions, change-order provisions, liquidated damages, performance tests and liability limits. Lenders and sponsors also need to consider whether the contractor can meet its obligations if the project encounters serious difficulties. A fixed-price offer may include a risk premium, and it may not eliminate risks arising from sponsor decisions, permitting, infrastructure dependencies or changes to project requirements.

Under an engineering, procurement and construction management (EPCM) arrangement, the EPCM contractor generally provides engineering and project-management services, while the owner contracts directly with equipment suppliers and construction contractors. This can offer greater transparency and flexibility, which may be useful where the design is evolving or where the sponsor wants to procure specialist technologies separately. However, the owner generally retains more responsibility for delivery, including cost and schedule exposure, coordination between contractors and management of interfaces.

For lenders, the question is therefore not simply whether the project uses EPC or EPCM. They will assess whether responsibility for each major risk is clearly allocated and whether the party carrying that risk has the capacity to manage it. An EPCM project may need to demonstrate experienced sponsor and project-management teams, a realistic contingency, robust procurement controls, clear interface arrangements, and a credible plan for addressing delays or cost overruns.

These considerations are particularly relevant to renewable-hydrogen and green-ammonia projects, which may combine renewable generation, grid connections, electrolysers, hydrogen systems, ammonia synthesis and supporting infrastructure. Some components may be sufficiently established and well-defined to support an EPC package; others may require more flexibility, specialist supplier contracts or staged development. The project may therefore use a mixed contracting strategy rather than one model across the entire facility.

The same principle applies to conventional ammonia–urea plants. Whether the project uses a single EPC contract or several packages, lenders will examine the completeness of the scope, the integration between plant units and infrastructure, the strength of performance guarantees, and the project company's ability to manage any risks that are not transferred to contractors.

Low-carbon projects

A low-carbon ammonia project must still demonstrate that it can be built, supplied and operated. It then has to make a further case: that its emissions profile is defined and verifiable, that the infrastructure required for its chosen production route is dependable, and that any expected premium or public support is sufficiently reliable to include in the financing plan.[3,4]

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There are two broad routes to lower carbon production. The first is natural-gas-based ammonia with CCS, often described as blue ammonia. The second is renewable-hydrogen ammonia, often described as green ammonia. They have different capital, operating and infrastructure requirements, so they should not be treated as a single financing category.

Blue ammonia

A gas-based ammonia project with CCS retains the core dependence on natural gas. It adds equipment to capture carbon dioxide and requires a route to transport and store the captured CO_2, unless the project has another permitted and credible use for it. From a lender's perspective, CCS introduces a chain of related questions: can the capture system meet its contractual performance requirements? Is the CO_2 transport network available when the plant starts operating? Is storage capacity sufficient, permitted and technically suitable? Who bears the costs and liabilities associated with transport, storage, monitoring and long-term performance?

The project's emissions claims also depend on what is captured and what remains. A capture rate figure alone may not describe the plant's full emissions performance. The relevant accounting boundary, measurement approach and treatment of emissions from feedstock and energy use need to be clear. These details can affect eligibility for incentives, certification and any premium associated with low-carbon product sales.

This route can therefore introduce important infrastructure and contractual dependencies outside of the plant. If the capture equipment, pipeline or storage site is delayed, unavailable or underperforms, the project may face lower output, additional cost or reduced eligibility for policy support. A financing plan may need to address these risks through construction guarantees, operating agreements, carbon storage contracts, insurance or sponsor support. The exact mix will depend on the project and jurisdiction.

Green ammonia

Green ammonia uses electricity from renewable sources to produce hydrogen through electrolysis. That hydrogen is then used to make ammonia. The financing case depends heavily on the price, availability and reliability of electricity, as well as the cost and performance of electrolysers.

A project using intermittent renewable power may not operate at the same utilisation as a plant with continuous feedstock and energy supply. The sponsors must decide how to manage the variability: for example, by contracting power from multiple sources, connecting to a grid, using storage, or accepting variable production. Each choice affects capital needs, operating costs and output predictability.

Lenders will also scrutinise the electricity supply agreement, the project's access to grid capacity, the expected performance and replacement requirements of electrolysers, and the plan for matching electricity sourcing to the project's emissions claims. A plant may have a technically feasible design but still present a challenging financing case if it cannot secure dependable power at a cost consistent with the revenue assumptions.

Renewable-hydrogen projects may also need to address a first-of-a-kind or scale-up risk premium. The more project components depend on relatively new or rapidly scaling supply chains, the more important clear performance guarantees, contingency funding and well-defined completion tests may become. These factors do not make a project unfinanceable; they affect the evidence and contractual protections lenders may require.

Offtake and policy support

For low-carbon ammonia, the revenue case may depend in part on buyers' willingness to pay for verified emissions attributes, on public policy support, or on a combination of both. These sources of value need to be distinguished from ordinary product-market revenue.

A long-term offtake contract can improve revenue visibility, but the details matter. Lenders may look at the buyer's credit quality, the contracted volume and duration, price adjustments, delivery obligations and the treatment of certification changes. If the offtaker pays a premium for lower emissions, the contract should explain how that premium is calculated and what happens if the product no longer qualifies under a relevant standard.

Policy support can include grants, tax credits, carbon-pricing mechanisms or other instruments. Such support may strengthen a project's economics, but lenders will want to understand its legal status, duration, eligibility rules, conditions and exposure to policy changes. An announcement of a policy or an anticipated future market premium is not the same as a committed, contractable cash flow.

Comparing the financing cases

The most useful comparison is not simply "conventional versus low-carbon," but how each project's particular supply, construction and revenue risks are allocated. A conventional plant's financing case is often strongly exposed to gas prices and availability, market revenues and execution risk. Its core production process may be familiar to lenders, but project scale, location, infrastructure and sponsor capability remain decisive.

A CCS-enabled plant retains gas-price risk and adds capture performance, CO_2 transport, storage and emissions-accounting dependencies. A renewable-hydrogen plant is less directly exposed to natural gas but depends on power costs and supply, electrolyser performance, grid or generation infrastructure, and its ability to operate at a commercially viable utilisation rate.

For all three cases, financing analysis should test the assumptions under adverse conditions. Examples include higher feedstock or electricity costs, lower product prices, construction delays, weaker-than-planned plant performance, reduced capture performance, lower utilisation or changes in policy support. The objective is not to predict one outcome, but to establish how much cash-flow resilience the project has and who bears losses if assumptions are not met. ■

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India: supply chain resilience and risk mitigation



PHOTO: AM GREEN AMMONIA

AM Green's production site at Kakinada (formerly Nagarjuna Fertilizers Ltd).

Dr MP Sukumaran Nair, former secretary to the chief minister of Kerala chairman of the Kerala Public Sector Restructuring and Audit Board, looks at India's response to the fertilizer supply chain disruptions of the past few years,

Fertilizers remain central to agricultural productivity and food security in India. Balanced use of nitrogen, phosphorus, and potash nutrients supports higher crop yields, sustains soil health, and underpins the country's ability to feed a population of 1.45 billion, while contributing to global food supplies. India's fertilizer sector, however, operates within a highly import-dependent framework that has been tested repeatedly by global shocks since 2020. The result has been a necessary policy shift from a low-cost, just-in-time model toward a more diversified, risk-resilient structure.

Import dependence

India's reliance on external sources is structural. For urea, that external dependence reaches 68-70% when natural gas, raw materials, and intermediates are considered. For diammonium phosphate (DAP), dependence stands at approximately 98%, covering rock phosphate, phosphoric acid, and finished products. India's external potash dependence is total – 100% – because India has no significant domestic primary sources. Until 2020, global availability of these commodities was generally adequate and prices remained manageable. However, that equilibrium broke down under successive disruptions.

Recent disruptions

The period 2020–2022 marked the first major wave of disruption. The Covid-19 pandemic disrupted logistics and production. The Russia–Ukraine war, trade sanctions, and export restrictions followed. European supplies from Russia were affected; potash and phosphate flows from Russia and Belarus to India were interrupted, and the closure of Ukraine's Yuzhnyy port on the Black Sea compounded constraints.

Subsequent Middle Eastern conflicts have added further pressure. The Israel–Hamas war, Houthi attacks in the Red Sea, and wider US–Israeli–Iranian tensions raised risks around transit through the Strait of Hormuz. Damage or threats to energy assets across Qatar, Saudi Arabia, Bahrain, Kuwait, Iran, Abu Dhabi, and Oman affected refineries, pipelines, and gas infrastructure. Shipping constraints in the Strait of Hormuz tightened vessel availability, while higher energy and input costs filtered through the fertilizer value chain. Freight and insurance rates rose, and the industry faced renewed volatility.

These events exposed India's structural vulnerabilities: a heavy dependence on volatile trade corridors (Strait of Hormuz, Black Sea), raw-material protectionism via export bans and licensing caps on urea, sulphur and DAP, continued tethering of fertilizer production to natural gas and coal prices, and logistical limits arising from slower growth in the commercial vessel fleet, combined with stricter maritime emissions rules. The global decarbonisation agenda itself faced temporary setbacks amid the turmoil.

Strategic resilience measures

Governments and agricultural enterprises have responded with multi-layered risk-mitigation strategies aimed at securing yields and safeguarding food security. Supply sourcing diversification has been a priority. India has used diplomatic channels and foreign missions to secure long-term bilateral agreements with alternative suppliers. Overseas joint-venture plants, long-term supply contracts, asset acquisitions abroad, and sourcing from less conventional origins have all diluted the impact of sudden export freezes or localized infrastructure failures.

Collective procurement and enhanced bargaining allowed fragmented buyers to pool orders for ammonia, sulphur, and other inputs. This improved price transparency and strengthened negotiating leverage against concentrated global suppliers.

The transition to environmentally friendly nutrient technologies also seeks in part to reduce exposure to fossil fuel price shocks. Companies such as Yara International are advancing green hydrogen and green ammonia infrastructure. Localised green ammonia plants can buffer against international natural gas price volatility. India's own green hydrogen and ammonia initiatives, including projects under the Strategic Interventions for Green Hydrogen Transition (SIGHT) program, form part of this longer-term decoupling effort. Technology maturity, renewable power availability, and project viability remain critical determinants of scale.

Demand management and nutrient efficiency programmes have helped farmers cope with higher input prices. Precision agriculture tools, smart irrigation, balanced fertilization programs, and greater use of bio- and organic products maximise nutrient-use efficiency. These measures protect farm margins while moderating overall demand growth. Sourcing from Southeast Asian origins has also been explored as a complementary route.

> **"Imports have remained necessary to bridge the gap between domestic production (around 30 million t/a from 33 plants) and demand (around 40 million t/a)."**

Improving availability

India has also advanced a portfolio of domestic and overseas projects across the three major nutrients:

Nitrogen: Hindustan Urvarak & Rasayan Limited (HURL) is developing a 1.27 million t/a brownfield ammonia-urea plant at Namrup through a joint venture. Rashtriya Chemicals and Fertilizers (RCF), National Fertilizers Ltd (NFL), and Indian Potash Ltd (IPL) have signed a joint-venture agreement with Russia's Uralchem for a 1.8–2 million t/a urea plant in Samara, expected around 2027–2028. ACME Group has a green ammonia purchase agreement with the Solar Energy Corporation of India (SECI) for 370,000 t/a under the SIGHT program, involving substantial investment over a decade. Parallel efforts to expand compressed biogas (CBG) plants create potential bio-based methane feedstock for hydrogen and ammonia production, aligning with decarbonisation goals.

Phosphates: Domestic rock phosphate production remains concentrated in Rajasthan and Madhya Pradesh, with the Jhamarkotra mine accounting for the bulk of output. Even so, India continues to import 60-90% of its phosphate raw material needs because many deposits are low grade or chemically complex and require intensive beneficiation. Recovery of phosphate from sewage sludge via struvite precipitation, wet-acid extraction, or thermochemical treatment of ash offers an alternative circular-economy route. Overseas agreements include Paradeep Phosphates Ltd's long-term rock-phosphate arrangements with Morocco's OCP Group, IFFCO's joint ventures in Jordan and Senegal (including equity in ICS Senegal), and Coromandel International's majority stake in Senegal's Baobab Mining and Chemicals Corporation. Israel's ICL Group opened a specialty water-soluble fertilizer plant in Maharashtra in March 2026.

Potash: The Nagaur–Ganganagar Evaporite Basin project in Rajasthan (extending into Punjab) is exploring indigenous sub-surface reserves under the Geological Survey of India and state entities. Gujarat State Fertilizers & Chemicals (GSFC) holds a strategic stake in Karnalyte Resources' Wynyard solution mining project in Saskatchewan, Canada, with planned production of 675,000 t/a of granular potash (expandable in phases). Recovery of potash derived from molasses (PDM) from sugar and ethanol distillery spent wash provides an organic potassium source with a minimum 14.5% potash content, reducing reliance on imported muriate of potash (MoP).

Urea self-sufficiency

Historical policy shaped the current urea production landscape. The 1978 Retention Pricing Scheme, following the Marathe Committee recommendations, offered an assured 12% return on net worth and encouraged public, private, and cooperative investments. Discovery of Bombay High gas and the HBJ pipeline supported rapid growth, enabling urea self-sufficiency by around 2000. Thereafter, domestic investment stagnated while demand continued to rise, and imports climbed. From 2010 onward, revival of closed units became a priority. Five brownfield plants - Ramagundam, Gorakhpur, Sindri, Barauni, and Talcher - were rebuilt for a combined additional 6.35 million t/a of gas-based urea capacity. Additional capacity at Brahmaputra Valley Fertilizer Corporation Ltd (BVFCL) Namrup (1.27 million t/a) brings the total potential addition from these efforts to roughly 8.5 million t/a once fully operational. Even so, imports have remained necessary to bridge the gap between domestic production (around 30 million t/a from 33 plants) and demand (around 40 million t/a).

Geopolitical pressures have reinforced the case for a further push. The New Investment Policy for Urea (NIPU) 2026 aims to catalyse the construction of eight or nine new gas-based standard capacity plants of 1.27 million t/a each, adding approximately 10 million t/a of annual capacity. Relative to the earlier NIP 2012 (which expired in 2019), key changes include the separation of fixed and variable costs for greater subsidy transparency, an assured return on equity ranging from a minimum of 12% to a maximum of 16%, conversion of fixed costs to Indian rupees after four years to mitigate foreign exchange risk, and applicability limited to new projects (excluding retrofits and revamps). The policy is expected to improve financial viability and generate significant savings per plant. It applies equally to public, private, and cooperative investors.

Complementing urea capacity expansion, the government continues to encourage domestic production of ammonium sulphate, ammonium nitrate, mono-ammonium phosphate, DAP, calcium ammonium nitrate, urea ammonium nitrate, coated urea, nano-urea, and nano-DAP.

Outlook

India's fertilizer strategy now combines aggressive diversification of supply sources, overseas asset creation, domestic capacity revival and expansion, nutrient use efficiency, and gradual adoption of greener production routes. These measures do not eliminate exposure to geopolitical or energy-market shocks, but they reduce single-point vulnerabilities and improve the country's ability to maintain agricultural productivity and food security under stress. Sustained implementation of the new urea investment framework, successful commissioning of announced projects, and continued progress on phosphate and potash security will determine how resilient the system becomes in the decade ahead. ■

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An ammonia-fuelled vessel

PHOTO: CMB. TECH

Low emissions bunker fuels gain traction

Prospects for low emissions bunkering fuels are looking mixed despite regulatory mandates pushing for a switch away from traditional, fossil-based fuels. Alternative fuels such as ammonia and methanol are increasingly gaining traction as longer-term options to decarbonise fleets. Written by **Beatrice Bedeschi**, Editor, BCInsight.

While most of production is currently derived from fossil fuels, ammonia and methanol can also be produced from renewable energy or decarbonised using carbon capture technology. However, in the near term the shipping industry is turning to LNG, biomethane and energy efficiency measures in a push to reduce emissions, amid challenges including availability of alternative fuels, infrastructure development and costs.

Methanol

The prospects for methanol in shipping "are strong…[Methanol] has gone from being the most talked-about alternative fuel to the one actually being bunkered, in real volumes, at real ports, week in and week out," Felicia Mester, managing director for Europe and IMO at MI - the Global Methanol Alliance told Nitrogen+Syngas. Renewable methanol capacity is projected to grow from 1 Mt today to 1.5 Mt by the end of this year, and to around 4 Mt by 2030, with China and Europe accounting for more than 80% of the project pipeline. In August, the city of Shanghai set a global record by completing the world's largest single green methanol bunkering operation of 8,000 t at Yangshan Port.

There are now more than 150 methanol-capable vessels already operating at sea worldwide, with another 290 on order. The fleet is also broadening beyond container ships, with the first methanol-fueled VLCC having been ordered alongside methanol-fueled bulk carriers.

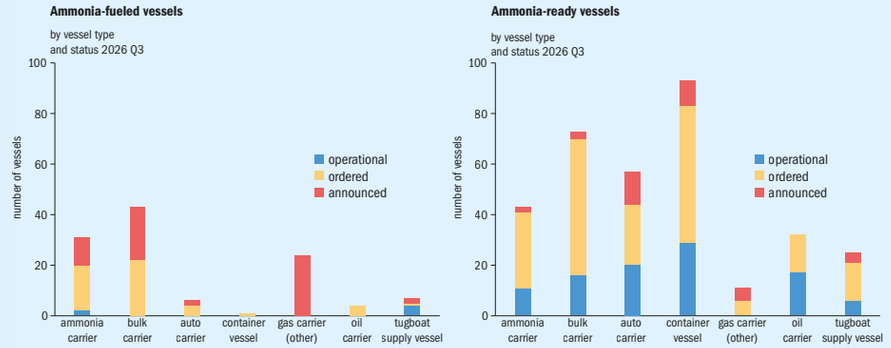
"Methanol presents practical advantages against other fuels (…) It is a liquid at ambient temperature and pressure, it is already handled as a commodity chemical at ports worldwide," she continued. "The engine technology is mature, and existing ships can be converted to run on methanol. For an owner, a dual-fuel methanol ship is the lowest-regret investment available" as "it runs on conventional fuel today, on bio- and e-methanol as volumes build, and it protects asset value under any regulatory outcome," she added.

Ammonia

Demand for ammonia as a maritime fuel, on the other hand, is expected to reach 2.3 Mt/y by 2030 from virtually zero today, while costs for ammonia could fall to $1,000–1,900 /tonne of Marine Gasoil (MGO) Equivalent by 2050. This means the fuel is approaching parity with marine gasoil (MGO) thanks to the implementation of carbon pricing regimes, according to DNV.

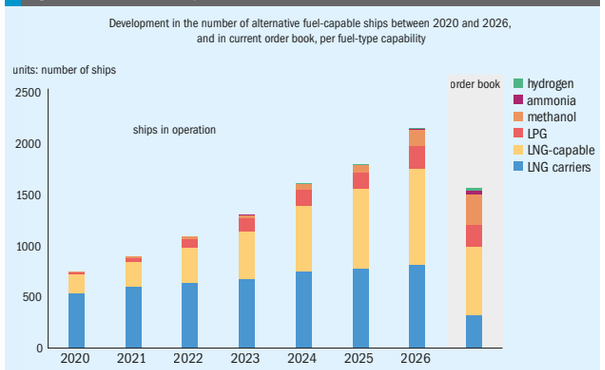
The first ammonia carriers with ammonia-capable engines hit the water in 2026, with two vessels operational as of September 2026 and additional vessels expected to hit the water in 2026, 2027, and 2028, according to the Ammonia Energy Association. Sufficient low-emission ammonia fuel is expected to be available, with supply at around 3.6 Mt by the end of 2028.

Fig. 1: **Shipping gears up for ammonia**



Source: Ammonia Energy Association

Fig. 2: **Alternative fuels gather steam**



Source: DNV

Regulatory drivers

Regulatory developments at both global and regional level represent a major driver behind the shift to alternative maritime fuels. In 2025, the International Maritime Organization's (IMO) reached an agreement on the Net-Zero Framework (NZF), which stipulates that all oceangoing ships over 5 000 gross tonnage – estimated to be responsible for 85% of global shipping emissions – must gradually reduce fuel-related GHG emissions in order to reach a net zero target by 2050.

To achieve that, IMO also set interim targets of 20-30% reduction by 2030 and 70-80% by 2040 against 2008 levels, and a 5-10% zero and near-zero GHG fuels share target of the total energy used by international shipping by 2030. Under the framework, shipping emissions are calculated on a well-to-wake basis, covering the entire fuel life cycle, from production and delivery to use on board ships. The agreement also established a pricing mechanism that awards compliant ships and imposes fees on those that exceed the limits.

Adoption of the new rules however was postponed amid pressure from some countries, including the US, with a formal vote expected at an upcoming IMO meeting in December 2026. "The IMO is continuing its work on a global mid-term measure to scale the use of zero- or near-zero-emission (ZNZ) fuels," Mester said, using "the combination of a progressively tightening GHG fuel intensity standard with an emissions pricing mechanism." She added that "the reward provision is a major opportunity for methanol."

Other regulations already in force, including the Fuel EU Maritime, EU ETS and UK ETS schemes are also contributing to a tightening in emissions requirements for ships. However, the regulations "currently do nothing for renewable and low-carbon fuels" she warned.

The EU Commission's first-year FuelEU data show the fleet surpassed the 2025 target on a fuel mix that is 98.3% fossil, with fossil LNG accounting for 11.3% of the energy used, seven times the share

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of all biofuels at 1.6% "and e-fuels are effectively zero." Alternative fuel-capable gross tonnage surged from 0.4% to 5.2% of the global fleet between 2020-2026, with LNG and methanol dominating the segment, according to DNV's latest Maritime Forecast to 2050 report.

The report shows that in August 2026, 813 LNG carriers and 929 other ships could use LNG as a fuel, while there were 42 methanol tankers and 112 other ships capable of using methanol as a fuel. Looking at vessels on order, 991 are set to be LNG-capable, 371 battery/hybrid, 294 methanol-ready, 42 ammonia-capable, DNV data shows. While installed capacity is currently not fully used, the development of a bunkering infrastructure for alternative fuels is gradually progressing, with low-GHG fuel bunkering activity concentrated at ports along major trade routes in Europe and East Asia.

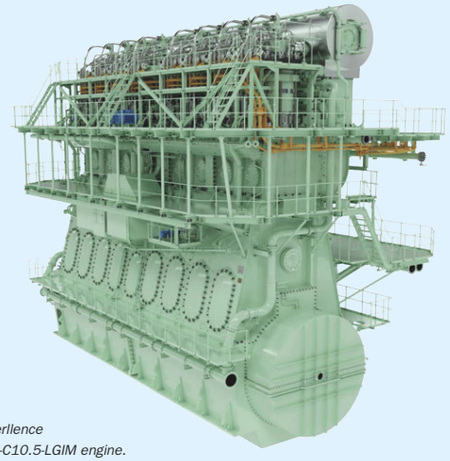


IMAGE: EVERLLENCE

The Everllence G95ME-C10.5-LGIM engine.

Demand-side push

Shipping giant Maersk threw its weight behind methanol in recent years, both by retrofitting ships to run on both conventional fuel and methanol, and by expanding its fleet with a number of new dual-fuel vessels. Each ship will require 35 000-40 000 tons of methanol annually, or a total of 500 000 t/y of low carbon methanol. The company says that by 2030 it is aiming to run 25% of its 700+ vessel fleet on renewable methanol, which will take its annual requirement to 6 Mt/y.

In 2025, Laura Mærsk, Maersk's first dual-fuel methanol vessel, received the first e-methanol delivery from the newly inaugurated Kassø facility in Aabenraa, Denmark. Developed by European Energy in collaboration with Mitsui, the Kassø facility was the first of its kind globally to produce e-methanol at commercial scale, Maersk said. The company has also signed deals to secure fuel supply, including a 10-year supply deal with Goldwind for 500,000 t/year of methanol from a new facility in China.

Other demand-side initiatives supporting uptake of low-GHG fuels include the Zero Emission Maritime Buyers Alliance (ZEMBA), which acts as a demand aggregator and aims to accelerate commercial zero-emission shipping by enabling economies of scale. It currently has over 45 members, including Amazon, IKEA, and Nike.

In December 2025, Hapag-Lloyd secured e-methanol supplies for dual-fuel containerships on trans-oceanic routes, while North Sea Container Line (NCL) secured e-ammonia supplies for its Yara Eyde, the world's first ammonia-capable containership as part of ZEMBA's second tender. Hapag-Lloyd is targeting deployment of e-methanol on a trans-oceanic lane on large methanol dual-fuel containerships from 2027 and is expecting to achieve 90% emission reductions on a lifecycle basis.

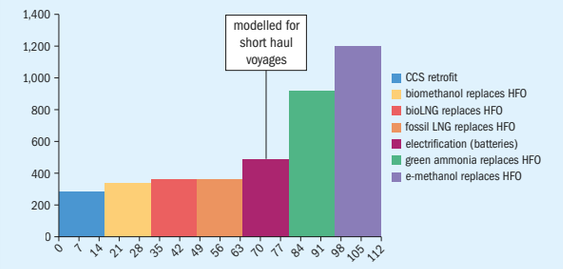
Another major shipping player, France's CMA-CGM announced in early October it had added the 13 000 TEU CMA CGM Gold to its fleet of dual fuel vessels running on methanol as well as conventional fuel. The company is undertaking a wider $20 billion fleet renewal programme and expects to operate around 200 container ships capable of using low-carbon energies by 2031. The company inaugurated its first dual-fuel methanol vessel, the CMA CGM Iron in July 2026, when it completed the first bunkering of bioethanol bunkering of a deep-sea container at the Port of Santos in Brazil. The vessel is equipped with the world's first tri-fuel engine, the Everllence G95ME-C10.5-LGIM capable of burning bioethanol, green methanol, and conventional marine gas oil. The bioethanol – which can be used as a fuel methanol-ready vessels – was supplied by Copersucar, a Brazilian sugar and bioethanol producer, positioning the country as a potential leading exporter and supplier of bioethanol for shipping and the Port of Santos as a key green bunkering fuel hub. The company's methanol fleet also includes the CMA CGM Osmium, CMA CGM SIlver and CMA CGM Copper vessels.

Meanwhile, Belgian shipowner CMB.TECH said in October that its 210 000 dwt bulk carrier Mineral Europa had begun its maiden voyage to Australia. The company said this is the world's first ammonia-powered dry bulk carrier which can burn either ammonia or conventional marine fuel. The vessel is the first of 21 ammonia-fueled ships CMB.TECH expects to take delivery of by 2029, comprising 18 dry bulk carriers, one container ship and two chemical tankers. CMB.TECH signed an offtake agreement in December 2025 for green ammonia from CEEC Hydrogen Energy's Songyuan project in Jilin province, China, where first-phase output is expected at around 158 000 t/y, CRU reported. It also agreed to take a minority stake in Chinese ammonia logistics company Jiangsu Andefu Energy Technology, which is developing storage and ship-to-ship bunkering capacity. The company is also investing in ammonia storage and bunker barges to supply ocean-going vessels with the fuel.

Cost challenges

While these developments show a growing interest among the shipping industry for low emissions fuels, experts note that there are still unresolved challenges.

Fig. 3: **The price of cleaner shipping**



DATA: CRU Energy Transition and Decarbonisation Service, International Maritime Organization (IMO). Note (1): the carbon price requirements are shown on a tank-to-wake basis. note (2): all scenarios are based on long-haul voyages using a 20,000 DWT bulk carrier except the 'electrification (batteries)' scenario that has been modelled based on a - day voyage using 10,00 DWT bulk carrier. Note (3): potential CO_2 savings are shown as equally distributed across options for illustrative purposes only; the chart does not assess the likely prevalence or uptake of individual pathways.

Source: CRU

Ports need to adapt to supplying the new fuels requiring significant investments in infrastructure and staff training. In addition, security concerns particularly around ammonia usage on ships due to potential toxicity remain. Alternative fuels also require more storage capacity than bunker fuels, rendering them less cost-effective than fossil-based fuels.

At a geopolitical level, the Middle East crisis has driven an increase in conventional bunker fuel prices and shipping rates, which would in theory support the case for switching to alternative fuels. Global average bunker fuel prices have soared to above $800/t in October, nearly doubling from pre-war levels in early 2026, thus narrowing the gap with lower emission fuels prices.

Nonetheless, the price premium of low emission fuels remains significant and other alternatives, such as CCS retrofits, biomethanol and bio-LNG remain more cost-competitive for players in the near term, analysis by CRU suggested. CRU has developed a shipping abatement cost curve that captures the carbon price required to incentivise fuel and technology switching across the existing dry bulk fleet. The tool indicates that the highest-cost pathways are the ones most exposed to clean hydrogen prices, with green ammonia and e-methanol sitting at the top end of the ranking given they are both heavily dependent on access to scalable, low-cost green hydrogen.

Neither the Middle East disruption or higher freight rates are expected "to move ammonia or e-methanol from the top of the cost curve...If the conflict raises oil prices, the gap narrows somewhat, but not enough to change the overall ranking, especially in the near-term as low carbon fuels, particularly hydrogen, remain quite expensive," CRU sustainability analyst Halima Abu Ali told Nitrogen+Syngas. Green ammonia prices in Europe are estimated at ~ $1500/t in 2026, with e-methanol standing at around ~$2000/t.

Alternative, greener bunkering fuels such as ammonia, hydrogen and methanol "are not competitive for now," agreed Jeroen Dierickx, a Belgium-based energy and fuel expert. "To increase their competitiveness "economies of scale are required" and "stable regulations with penalty systems" to create an incentive to purchase more expensive alternative fuels, he told Nitrogen+Syngas.

"The cost gap" remains a key hurdle faced by alternative fuels like methanol, Mester agreed. "Renewable methanol is more expensive than fossil fuels…Not a single shipowner will invest in new ships if it doesn't make financial sense. The industry is already investing billions in vessels, production facilities, and bunkering infrastructure, but without clear global rules that reward lower lifecycle emissions, it's difficult to build the long-term demand needed to justify further investment."

Supply infrastructure presents another challenge.

"Supply today is concentrated in a handful of hubs, and a global fleet needs a global network," she said, although this is "being solved port by port."

Singapore has issued methanol bunkering licenses from January 2026. Methanol bunkering is already available at Antwerp, Bremen, Busan, Dalian, Hong Kong, Ningbo-Zhoushan, Shanghai, Shenzhen, Rotterdam, Tianjin and Wuhan. European terminals are also adding methanol storage and bunkering, and purpose-built bunker vessels are being designed for regional ports.

"Methanol's advantage here is that it is already a globally traded liquid chemical handled at ports around the world, so we are adapting existing infrastructure rather than inventing it," Mester said.

But regulatory uncertainty remains an obstacle. "A fuel production project goes from regulatory signal to first production in three to six years" as it navigates design, engineering and permitting, financing and off-take contracting and construction, she noted.

"Under current market conditions, production capacity could reach 6–12 Mt by 2031, while the wider project pipeline represents a potential capacity of around 50 Mt. Turning that announced potential into actual production requires a stronger demand signal, long-term offtake agreements, and investment across the supply chain. The industry needs a clear, predictable IMO framework that gives producers, shipowners and investors the confidence to commit capital at scale," she said.

She concluded that "further delays risk slowing investment and leaving shipping with a patchwork of regional regulations, adding cost and complexity to an industry that operates globally". ■

Sources

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2026 AIChE Ammonia Safety Symposium

Venkat Pattabathula, a member of the AIChE Ammonia Safety Committee, reports on the American Institute of Chemical Engineers' Safety in Ammonia Plants and Related Facilities Symposium held in Montreal, Quebec, Canada, on 30 August – 3 September 2026.

Montreal, site of this year's symposium.

From August 30th to September 3rd 2026, about 330 engineers from more than 30 countries and 100 companies attended the AIChE's 70th Annual Ammonia Safety Symposium at the Le Centre Sheraton Montreal, Quebec, Canada.

The Ammonia Safety Committee is dedicated to improving the safety of plants that manufacture ammonia and related chemicals, such as urea, nitric acid, ammonium nitrate, and methanol. The conference's objective is to improve the safety performance of the ammonia industry. This is achieved by sharing information on incidents, safety practices, and technology improvements in presentations and open discussions.

Attendees who participated in the symposium included plant managers, production managers, safety managers, process/reliability engineers, and everyone responsible for the safety and performance of ammonia plants or handling facilities. Worldwide experts discuss the latest advances in the safe production and use of ammonia, as well as case studies and lessons learned at these symposiums.

Keynote address

The keynote presentation, delivered by Rob Fisher, was titled: "Operational excellence and process safety: integrating human and organisational performance". He argued that process safety is not solely about equipment integrity, containment systems and engineering controls. Rather, sustainable safety and operational excellence depend on understanding how people interact with systems, how organisations shape behaviour, and how workers adapt to real-world operating conditions. Fisher emphasised that workers are often the best source of solutions because they experience the gap between "work as imagined" and "work as done." He advocated shifting from a compliance-focused mindset to one that actively enables success by making the right actions easier, the wrong actions harder, and learning continuously from both successes and failures.

A central theme of the presentation was applying human and organisational performance principles: error is normal, blame fixes nothing, systems influence behaviour, response matters, and learning is essential. Fisher stressed that most incidents are driven by systemic factors rather than isolated human mistakes, and therefore organisations should focus on understanding error traps, improving procedures, strengthening leadership behaviours, and creating resilient systems. He encouraged leaders to ask better questions using the 'TEDS' approach (tell, explain, describe, show) instead of immediately asking "why," which often triggers blame rather than learning. The presentation concluded that operational excellence cannot exist without safety, and that true lessons are only learned when they result in lasting changes to organizational behaviours, processes, and culture.

His key takeaway for the ammonia industry was a challenge for organisations to move beyond traditional incident investigation and compliance programs toward a holistic approach that integrates leadership, workforce engagement, error-reduction tools, organisational learning, procedure quality, and resilience. By recognising worker adaptability, managing human error scientifically, and focusing on systemic improvements, companies can achieve safer, more stable, and more reliable operations.

Safety papers

Some of the key safety-related papers that were presented during the Symposium were as follows:

Ammonia converter weld failure

During a planned 2023 turnaround at Proman Trinidad and Tobago, extensive cracking was discovered in two circumferential closure welds of an ammonia converter that had been operating since 2009. Advanced ultrasonic inspection identified more than 160 crack indications, many deep and originating from the vessel's internal surface. Detailed metallurgical examinations showed intergranular cracking, brittle fracture features, and elevated weld hardness. Although the equipment operated within accepted Nelson curve limits, investigators determined that the damage mechanism was hydrogen embrittlement rather than high-temperature hydrogen attack.

The root cause was linked to shutdown practices that cooled the converter with cold synthesis gas while it remained pressurised with hydrogen for an extended period. This combination of low metal temperature and high hydrogen partial pressure created ideal conditions for hydrogen embrittlement. The damaged welds were extensively repaired, and the plant implemented significant improvements, including revised shutdown procedures, minimum pressurisation temperature limits, enhanced post-weld heat treatment requirements, advanced inspection techniques, and updated risk-based inspection programs. The case highlighted how transient operating conditions during startup and shutdown can be more damaging than normal operating conditions.

Partial collapse of reformer dome

In June 2025, OCI Nitrogen's Ammonia 2 plant experienced a trip that was traced to the partial collapse of the secondary reformer dome. Operators first observed abnormal process conditions, including increased pressure drop and elevated temperatures, before inspection revealed a collapsed section of the refractory dome and significant catalyst bed disturbance. The dome had originally been designed to distribute gas flow and support the catalyst bed, but modifications made during a 2018 turnaround introduced several deviations from the original design, including mixed refractory materials, partial support repairs, and the omission of refractory cement between dome bricks.

The investigation found that the primary failure mechanism was degradation of phosphate-bonded repair mortar used in the dome support structure. Exposure to a high-temperature, hydrogen-rich reducing atmosphere progressively weakened the support system, eventually causing loss of structural integrity and dome collapse. Contributing factors included the use of mixed refractory materials, an inadequate engineering review, and incomplete management-of-change practices. The 72-day outage resulted in replacement of the dome, support structure, refractory lining, and catalyst, while reinforcing the importance of preserving original design intent, conducting rigorous engineering evaluations, and maintaining robust quality assurance for major refractory repairs.

Feed effluent exchanger failure

In June 2024, a fire occurred at Nutrien's Augusta ammonia plant following the failure of a diaphragm in the E-6155B synthesis feed-effluent exchanger. The diaphragm consisted of a 2¼Cr-1Mo steel component with an Inconel 82 layer, and examination revealed cracking and separation at the interface between the two materials. Additional inspection found similar indications on spare diaphragms, suggesting that fabrication-related defects may have existed prior to installation.

The investigation concluded that long-term thermal stresses generated by differential expansion between the dissimilar materials contributed to the failure. The rigid bolted-channel exchanger design further increased stresses at the diaphragm interface. During repairs, the failed component was replaced with a diaphragm fabricated entirely from Inconel 625, eliminating the problematic dissimilar-metal interface and improving resistance to thermal fatigue. The incident emphasises the importance of material compatibility, inspection of spare components, and careful consideration of long-term thermal effects when designing and maintaining high-temperature ammonia synthesis loop equipment.

Emergency revamp of an ammonia synloop

This paper describes how the Nutrien Trinidad No.3 ammonia plant successfully recovered from a critical failure of the synthesis converter waste heat boiler (E-738), an essential piece of equipment in the synthesis loop. Inspection revealed extensive cracking in the channel head and partition plate welds, and metallurgical analysis concluded that the primary damage mechanism was reheat cracking associated with highly restrained welds, elevated hardness, weld defects, and susceptibility



PHOTO: ISTOCKPHOTO.COM/ MIRCEAX

The 2026 AIChE Ammonia Safety Committee. SEATED: Mark Schroeder (Koch), Venkat Pattabathula (SVP Chemical Plant Services), Kristina Balch (Dyno Nobel), Mohamad Noueiri (Yara), Seshu Dharmavaram (Air Products), Samuel Okulaja (Nutrien), Taylor Archer (Clariant), Marc Gilberston (East Dubuque Nitrogen Fertiliser). BACK: Ameet Kakoti (KBR), Federico Zardi (Casale SA), Klaus Noelker (thyssenkrupp Uhde), Ashutosh Shukla (FFI), Lari Bjerg Knudsen (Topsoe), John Brightling (Honeywell Technologies), Eugene Britton (CF Industries). Not in the picture: Ahmed Esmael Rahimi (Qatar Fertiliser Company).

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to temper embrittlement. Under normal circumstances, replacement of such equipment would have resulted in many months of lost production. However, an earlier revamp completed by Casale in 2015 had installed a boiler feedwater preheater (E-1038) with sufficient design flexibility and overcapacity to potentially assume some of the functions of the failed boiler.

Working jointly, Nutrien and Casale developed an emergency synloop reconfiguration that bypassed the failed E-738 and used E-1038 as a temporary waste heat boiler. Additional piping modifications, control adjustments, and steam system changes were implemented within approximately four weeks, allowing the plant to restart safely and operate at about 93% of design capacity while awaiting a permanent replacement. Although energy consumption increased modestly, the approach avoided a prolonged shutdown and major commercial losses. The case demonstrates the value of designing plants with operational flexibility, maintaining strong partnerships between operators and technology providers, and incorporating future contingency capabilities during revamp projects.

Flow-accelerated corrosion

This paper reviews three separate cases of flow-accelerated corrosion (FAC) encountered in urea plant steam and condensate systems operated by Yara International ASA. FAC occurs when protective magnetite layers on carbon steel dissolve under certain flow, temperature, and water-chemistry conditions, leading to rapid wall thinning. The cases involved a pool condenser at Yara Sluiskil, a carbamate condenser system at Yara Ferrara, and a high-pressure carbamate condenser condensate line at Yara Babrala. Investigations showed that low condensate pH, turbulent flow conditions, and contaminants in recycled condensates contributed to localised corrosion and metal loss in several vessels, steam drums, and piping systems.

The study highlights that effective FAC management requires both mechanical and chemical mitigation strategies. In some cases, maintaining condensate pH above 9.5 through ammonia dosing significantly reduced corrosion rates, while in others, hardware solutions such as duplex stainless-steel sleeves and stainless-steel impingement plates were implemented to eliminate vulnerable areas. Advanced thermochemical modelling helped explain differences between ambient pH measurements and actual operating-temperature chemistry, leading to more effective treatment programs, including monoethanolamine (MEA) dosing. The authors concluded that successful FAC prevention depends on proper water chemistry control, suitable materials selection, robust risk-based inspection programs, and disciplined management-of-change procedures.

Failure analysis on waste heat boilers

This paper presented the investigation and repair of two parallel synthesis loop waste heat boilers, H306A and H306B, at the OCI Nitrogen ammonia plant in Geleen, Netherlands. H306B developed an internal leak that gradually worsened during 2024. Inspection during a 2025 turnaround revealed extensive cracking in approximately 70% of the inlet-side tubes, hydrogen blistering within the tube sheet region, and through-wall failures behind the tube sheet. Metallurgical analysis showed that the damage was primarily caused by hydrogen embrittlement and hydrogen blistering, which were linked to high weld hardness, inadequate preheating during fabrication in 2014, material inclusions, and a protruding tube design that increased exposure to hot synthesis gas. Because of the widespread damage, the repair strategy involved shortening the entire tube bundle and redesigning the tube-to-tube sheet joints, resulting in a 61-day outage.

Following the H306B findings, a detailed assessment was performed on the sister boiler H306A. Although its original flush tube-sheet design showed no tube cracking after more than 50 years of service, inspectors found significant cracking in the knuckle transition area and tube sheet ligaments. Investigations concluded that these cracks were associated with hydrogen embrittlement, nitriding, thermal stresses, and structural constraint effects. The defects were removed by controlled grinding and evaluated through a comprehensive API 579 Fitness-for-Service assessment, which confirmed the equipment could continue operation without weld repairs. The paper emphasised the continuing threat of hydrogen-related degradation mechanisms in ammonia synthesis services and recommended improved material quality control, proper welding practices, sufficient preheat temperatures, flush tube designs, and enhanced inspection programs to improve long-term reliability.

Process condensate stripper failure

During the 2025 turnaround at Yara Trinidad's Tringen II ammonia plant, inspectors discovered an unexpected integrity issue in the T3406 process condensate stripper. While the vessel had a known history of localised corrosion caused by acidic condensate contaminants, previous mitigation measures had successfully stabilized that damage. However, detailed inspections revealed widespread cracking in tray support welds throughout the lower section of the stripper. Subsequent metallurgical examinations, hardness testing, and replica analyses confirmed the presence of carbonate stress corrosion cracking (CSCC), a degradation mechanism that had not previously been identified in this service. The cracking occurred primarily in the heat-affected zones adjacent to welds and exhibited the characteristic branching "spider-web" morphology associated with CSCC.

The root cause investigation linked the cracking to elevated carbonate concentrations resulting from a process gas leak in the Benfield system that increased carbonate carryover into the stripper. Contributing factors included operating pH conditions in the CSCC susceptibility range, high weld hardness, and the absence of post-weld heat treatment. Repairing the damage required removal of all 26 trays, extensive weld inspections, crack excavation, and rewelding using controlled deposition techniques to minimise residual stresses. The repair scope expanded the planned work duration from 10 days to 52 days, but the vessel was successfully returned to service. The incident highlighted the importance of considering previously unrecognised damage mechanisms, strengthening inspection programs, and improving monitoring of process chemistry throughout ammonia plant condensate systems.

Incomplete reformer fuel combustion

This paper describes an incident that occurred in January 2025 at an Air Liquide hydrogen and carbon monoxide production facility when incomplete combustion developed inside a steam methane reformer (SMR) during normal operation. Operators were attempting to reduce methane slip by increasing reformer firing, but abnormal conditions gradually developed, including rising carbon monoxide levels in the flue gas, declining oxygen concentrations, and falling reformer temperatures. Visual inspection through reformer peepholes revealed excess fuel combustion occurring in the lower section of the furnace, prompting operators to initiate an emergency shutdown. The rapid response prevented personnel injuries and major equipment damage, although syngas production was interrupted.

The investigation determined that the primary cause was an inaccurate flue-gas oxygen analyser reading, likely influenced by calibration and sampling-system issues exacerbated by unusually cold weather. Additional contributing factors included control logic that automatically increased fuel flow when temperatures dropped, thereby worsening an already fuel-rich condition, as well as the absence of compensation for variations in fuel heating value. To prevent recurrence, the facility upgraded instrumentation, incorporated carbon monoxide monitoring as an early warning indicator, added automatic fuel-rich protection overrides, and began implementing fuel BTU compensation in the combustion control system. The case demonstrates how instrumentation reliability and robust automated safeguards are critical to maintaining safe furnace operation and preventing incomplete combustion events.

Runaway catalyst reduction

During a 2024 turnaround at the LSB Industries Cherokee ammonia plant, a runaway reaction occurred while reducing a newly installed low-temperature shift (LTS) catalyst. The reduction process utilised hydrogen-rich gas and methane carrier gas, requiring careful control to avoid excessive temperatures. Several difficulties arose during the operation, including unreliable gas chromatograph measurements, inconsistent flow indications, pressure-control challenges, and limited operator experience with catalyst reductions. After switching to a larger hydrogen supply valve to increase hydrogen concentration, temperatures in the top portion of the catalyst bed rose rapidly and ultimately reached approximately 1085°F (585°C) – well above normal operating limits. Operators immediately isolated hydrogen and initiated a nitrogen purge, limiting the temperature excursion to the upper section of the catalyst bed.

Following cooldown and technical assessment, engineers determined that only a small portion of the catalyst had been damaged and that the vessel remained mechanically fit for service. The catalyst reduction was completed using a revised and more conservative approach that relied on continuous monitoring of catalyst-bed exotherms, reduced operating pressure, and tighter control of hydrogen addition. The investigation identified several contributing factors, including outdated procedures, inadequate preservation of lessons learned from previous reductions, unreliable instrumentation, and knowledge loss due to personnel turnover. Corrective actions included locking out the larger hydrogen valve, updating reduction procedures, improving knowledge management systems, and installing dedicated flow measurement and pressure-control equipment. The incident underscored the importance of reliable instrumentation, robust documentation, effective training, and disciplined execution during infrequent but high-risk catalyst activation operations.

Final day

On the fourth and final day of the symposium, a round table session was held, which provided open exchange and discussion through brief presentations from panellists, followed by a question-and-answer session on topics of interest such as industry incidents and near misses, and improvement of safety.

Next year's symposium will be held in Seattle, Washington State, USA, from 12-16 September, 2027. ■



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Nitrogen affordability: a mixed global picture

Stronger crop prices and lower urea prices eased the pressure on nitrogen fertilizer buyers after the sharp squeeze in the first half of 2026. But the relief was uneven, with regional supply conditions and differences between products shaping the recovery in buying.

Written by Natalie Noor-Drugan, Editor-in-Chief, BCInsight.

Nitrogen fertilizer markets experienced sharp changes during the first nine months of 2026. Urea prices rose steeply before retreating as buyers pulled back and alternative supplies became available. Stronger crop values subsequently helped ease the pressure on growers, although the extent of that relief varied between regions and products, according to CRU's market assessments through September.

The supply shock followed the outbreak of the war involving the United States, Israel and Iran on 28 February 2026. Fighting disrupted fertilizer production in the Arabian Gulf and shipping through the Strait of Hormuz. Plant shutdowns, reduced operating rates and interrupted vessel movements restricted exports, pushing urea prices to levels last seen in 2022.

"Disruption in the gulf was the primary driver of the urea price surge in first half of the year," says CRU Senior Analyst, Urea Market Service, Pranshi Goyal. She notes that the Arabian Gulf normally accounts for around 30% of world urea trade.

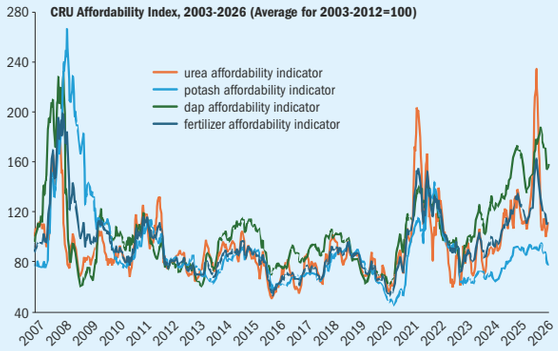
Goyal attributes the subsequent price retreat to a combination of changing sentiment around a temporary US-Iran peace deal, seasonally slow demand towards the end of the second quarter, resistance to high prices and China's announcement that it would reopen urea exports after restricting them during January-April.

Suppliers elsewhere also helped replace some of the missing Gulf volumes. Renewed purchasing and higher European production costs subsequently supported another price increase during the third quarter, underlining the volatility of the recovery.

For growers, affordability depended not simply on the price of nitrogen fertilizer, but on its cost relative to the value of their crops. The availability of fertilizer during the main buying and application periods also influenced purchasing decisions. These factors produced markedly different outcomes in Europe, Brazil, the United States and Asia.

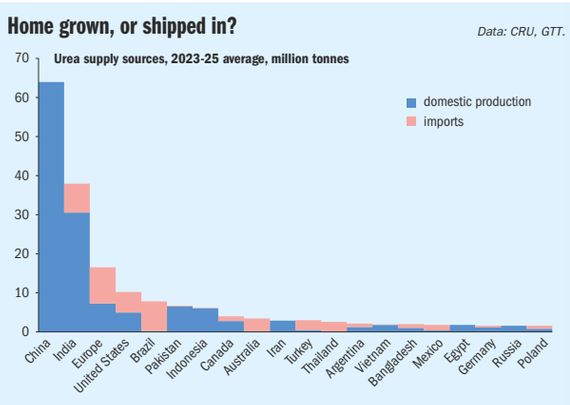
Urea takes the hardest hit

Data: CRU, IGC.



Home grown, or shipped in?

Data: CRU, GTT.



Europe: relief varied by nitrogen product

Europe showed that improved urea affordability did not mean other nitrogen fertilizers had become more affordable.

Stronger crop prices improved regional purchasing economics during late summer, according to CRU. Urea benefited most because its price declined at the same time. Ammonium nitrate (AN) also became more affordable despite a price increase, as higher crop values more than compensated for the additional fertilizer cost.

Calcium ammonium nitrate (CAN) and urea ammonium nitrate (UAN) moved in the opposite direction. Their price increases outweighed the benefit from stronger crop prices, leaving both less affordable month on month. The relief experienced by growers therefore depended on which nitrogen product they were purchasing.

Buying also remained sensitive to price. CRU reported that a surge in European purchasing during July quickly subsided as prices increased. Underlying nitrogen requirements had not necessarily disappeared, but buyers were reluctant to commit at the higher values.

Northwest European ammonium sulphate (AS) prices also rose, supported by stronger crop prices and higher urea values, according to CRU. The European Union's Carbon Border Adjustment Mechanism (CBAM) also added to the cost of imported AS.

Goyal identifies rising crop prices as the main driver of the broader improvement in nitrogen affordability, alongside urea's retreat to pre-conflict price levels. However, Chinese export availability helped differentiate AS from urea. "AS prices have been a bit more supported due to lesser exports from China," she says.

Higher crop prices therefore brought growers some relief, but also helped support higher fertilizer prices.

The ammonia market was different. European producers still had ample supplies entering September, so there was little need for additional imports. Slow buying of nitrate fertilizers also held back demand for ammonia.

Rising gas costs added another source of pressure. CRU reported that TTF gas prices had surged since mid-July, exceeding EUR 80/MWh in September—a level last seen in December 2022. The increase eroded European nitrogen producers' margins, with LAT Nitrogen, Fertiberia and OCI curtailing production during September. CRU also found that, from August, AN production using imported ammonia had become more economic than production based on ammonia manufactured on-site.

Brazil: better economics after delayed purchasing

In Brazil, a simple way to measure affordability is to ask how many bags of corn a grower needs to sell to buy a tonne of urea.

That relationship improved during late summer. CRU reported that stronger corn prices and easing fertilizer values brought Brazil's urea-to-corn barter ratio to its most favourable level since late 2025. Its analysis showed that affordability had returned to historically normal levels after an earlier squeeze more severe than that experienced in 2022.

The earlier difficulties had already affected buying. Brazil imported 2.8 Mt of urea during January–August, the lowest volume for that period since 2016. CRU attributed the slowdown to poor affordability and reduced availability from Iran, previously an important supplier.

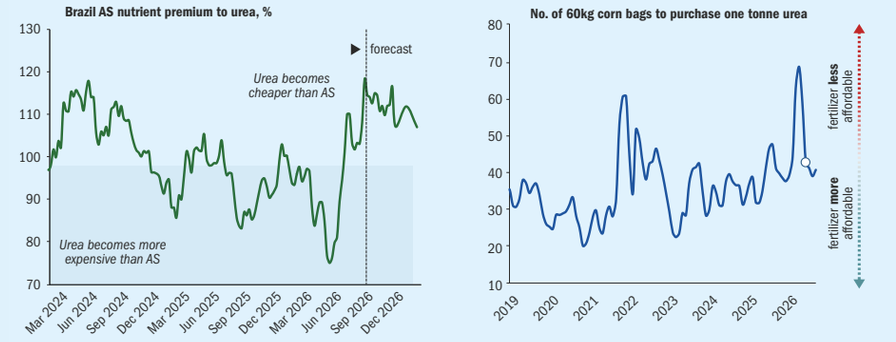
CRU also reported delayed nitrogen purchasing and inventories at their lowest level in four years. Buying had begun to pick up as the seasonal window opened, but this reflected the need to secure supplies as well as more favourable prices.

The choice of nitrogen product mattered too. AS had gained share in Brazil's nitrogen imports during 2025 and into mid-2026, supported by Chinese supplies, before Chinese export controls slowed the trade.

Ammonium sulphate prices rose in early August amid concerns about Chinese export restrictions, before falling back as urea became cheaper. Brazilian buyers therefore had to consider not only how much fertilizer cost compared with their crops, but also which product offered better value for nitrogen.

More nitrogen for your corn in Brazil

DATA: CRU, CME, Agrolink



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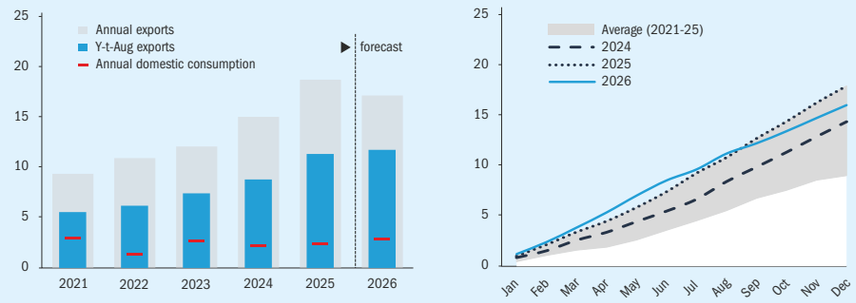
Green Ammonia And The New Operating Reality

NITROGEN+SYNGAS
ISSUE 404
NOVEMBER-DECEMBER 2026

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China's AS export engine slows



Data: CRU, GTT.

United States: stronger corn prices lessened the squeeze

The US Midwest showed that affordability can improve even when fertilizer costs rise.

CRU reported that the Iowa fertilizer basket increased by $11/short ton during August to $532/short ton. However, the weekly average corn futures price rose by $0.36/bushel to $5.24/bushel. The increase in corn prices more than offset the higher fertilizer cost, improving the relationship between the fertilizer basket and corn values to its best level since February 2025.

CRU Senior Analyst, Fertilizer Demand, Anthony Rizzo, says nitrogen affordability was a significant concern in the spring, when corn prices moved within a much tighter range than urea. By the beginning of July, however, affordability had returned to around the level seen for much of the year.

Subsequent urea price increases were also accompanied by higher corn prices, particularly following the late-summer gains.

"While urea prices remain historically elevated, so do corn prices, which offers some relief as long as corn prices continue to outrun or match rising nitrogen costs," he says.

This did not mean fertilizer was cheap, or that buying had fully recovered. US urea demand was still described as thin in CRU's assessment, while ammonium sulphate prices were firming with stronger grain values. The US experience showed that better crop prices can ease the pressure on growers without lowering their fertilizer bills.

India and other Asian markets: availability mattered

India's procurement showed why strong imports should not be treated as a direct measure of farm demand.

Global Trade Tracker data in CRU's September Urea Market Outlook showed January–July urea imports more than double their year-earlier level. African and Russian supplies helped support purchases when access to Middle Eastern and Chinese material was constrained.

Domestic sales, however, weakened. CRU reported July year-to-date urea sales down 5%, linking the slowdown to delayed and irregular monsoon rainfall. Strong imports, relatively stable production and slower sales contributed to rising stocks.

CRU estimated stocks above 7 Mt at the beginning of September, roughly twice the year-earlier level. Substantial buying was therefore taking place alongside subdued immediate demand.

Other Asian markets were less successful in replacing missing supplies. January–July imports into Southeast Asia were down 49% y/y, while other South Asian markets excluding India recorded a 29% decline. CRU linked these shortfalls to disrupted Gulf supply and greater price sensitivity.

Australia also faced supply concerns, but arrangements with Southeast Asian suppliers and new trade deals involving Nigeria helped address the urea shortfall.

These contrasts show why availability belongs alongside price in the affordability discussion. A more favourable international price offered little practical relief if buyers could not obtain fertilizer when it was needed.

China: plentiful urea eased price pressure

China's abundant urea supplies contrasted with shortages elsewhere. Export restrictions helped shield domestic buyers from rising international prices during the spring 2026 application season, while a substantial surplus remained after exports reopened in May.

China's ammonium sulphate market was much more export-oriented, with domestic consumption small compared with overseas shipments, according to CRU data. Changes in Chinese supply and export policy therefore mattered mainly to buyers abroad, including Brazil.

Affordability is more than price

The easing of urea prices brought welcome relief after the severe squeeze in the first half of 2026. But the regional picture showed that better affordability did not automatically bring buyers back. Stronger crop prices helped growers in Brazil and the US, while European buyers saw different outcomes across nitrogen products and some Asian markets struggled to secure replacement supplies.

For growers, the real test was whether they could buy the nitrogen they needed, when they needed it, at a cost justified by the value of their crops. Lower prices were only part of that equation. The experience of 2026 showed that affordability and access to supply cannot be separated when assessing growers' ability to meet their nitrogen needs. ■



PHOTO: CRU

Richard Hands: "It's always been about what you make your ammonia and methanol from"

Interview by Natalie Noor-Drugan, Editor-in-Chief, BCInsight

From a childhood fascination with aircraft to more than three decades editing Nitrogen, **Richard Hands** has followed his curiosity through some unexpected turns. As he prepares to retire, he looks back on British Sulphur's colourful origins, life inside CRU, the challenges of becoming a publisher, and the feedstock shifts, methanol booms and much-hyped technologies that have shaped the industry along the way.

Richard Hands on stage at one of CRU's industry conferences.

What interested you growing up?

I grew up in Walsall, in England's West Midlands. It was an old industrial town, particularly known for leatherworking.

I loved aircraft. My father had done his National Service in the Royal Air Force, and I was always making model planes. Space was another fascination. I remember sitting on his knee watching a moon landing on a tiny black-and-white television with cupboard doors you could close over it.

I thought I might become a pilot, until I discovered you needed good eyesight.

Was chemistry your first choice at university?

Not really. I wanted to study history, but my science teacher persuaded me that, because I was good at science, I should do science.

I studied chemistry at the University of York, in England. I enjoyed my time there, although perhaps not all of that enjoyment was academic.

After graduating, I joined the UK Ministry of Defence in 1987. I expected to work in analytical chemistry, but found myself researching coatings and camouflage — particularly radar camouflage, or what we'd now call stealth materials.

It wasn't what I'd signed up for, but it turned out to be interesting.

How did you find your way into publishing?

As the Cold War ended, funding for our department began to disappear. They were looking for voluntary redundancies, and I thought it was probably time to move on.

I'd always enjoyed writing and wrote fiction as a hobby. A colleague spotted an advertisement in one of the journals circulating around the laboratory and said: "You should apply for that. You could do that."

That took me to the Polymer Paint Colour Journal as a technical editor. After a few years, I started looking for an editor's position and joined British Sulphur as editor of Nitrogen in 1995. CRU had bought British Sulphur in 1986, so the magazines were by then part of a wider organisation that also ran industry conferences and provided market analysis and consultancy.

What do you remember about the offices and the people?

We were in an old Victorian building in Mount Pleasant, London, looking out at the great grey concrete bulk of the Mount Pleasant postal sorting office. Inside, the editors had tiny rooms with enormously high ceilings. You could almost touch both walls from the middle. If you've seen the film Brazil, you get something of the atmosphere.

The technology seems extraordinary now. There was one shared modem for sending work to the designer, so you carried your material down the corridor on a floppy disk.

My office was on the other side of a fire door from the other editors, so I was a bit out on a limb and missed most of the conversations. But there were memorable characters. John French, the publisher and a driving force behind the original

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PHOTO: CRU

At CRU's offices in 1995: seated, Lisa Connock (left) and Tina Firman; standing, Mark Evans, editor of Fertilizer International (left), and Richard Hands, editor of Nitrogen



PHOTO: CRU

The BCInsight publishing team after the 2007 management buyout from CRU, with Richard Hands (centre, in sunglasses) and Mark Evans (in red shirt) to his right

Sulphur conference, and Mark Evans, the editor of *Fertilizer International*, were larger-than-life people.

How did the magazines connect with CRU's conferences and consultancy work?

The magazines and conferences were closely linked. Our technical colleagues worked on the conference programmes, and the commercial team sold both magazine advertising and exhibition space.

The conferences began with Sulphur in Calgary in 1981. When that was a roaring success, CRU did the same in our other fields, nitrogen in particular, as well as fertilizers. The conferences' remit came largely from the magazines' editorial, so they covered the same kind of ground.

For an editor, they were invaluable. You could see your contacts in one place and talk to them. Before the internet, that was how you found out about a lot of what was happening.

We got to know the consultants too, people like Bernard Brentnall on the nitrogen side. Whatever formal boundaries existed, people still went to the pub at lunchtime and talked. That helped with ideas and understanding the industries.

When you joined Nitrogen in 1995, what were the big issues?

With nitrogen, it's almost always feedstock. When I joined, the gas industry was being privatised in the United States and the UK, and eventually in Europe. At first that made gas very cheap. Then it made gas very expensive, and suddenly everyone was looking at coal.

Then the Americans discovered fracking and gas became incredibly cheap again. Now, with growing concern about climate change, it's biomass, electrolysis and carbon capture.

But the question has always been the same: what are you making your ammonia and methanol from? That's always been the big issue for the industry.

The magazine became Nitrogen & Methanol, then Nitrogen + Syngas. What drove those changes?

The front half of an ammonia plant is essentially the same as the front half of a methanol plant, and people gradually looked at co-producing the two.

Methanol had a big surge in the 1990s because of MTBE, methyl tert-butyl ether, a fuel oxygenate that makes petrol burn more cleanly. The Americans took to it in a huge way, and everyone was asking: can we convert part of our ammonia plant to make methanol?

We teamed up with Jim (James R) Crocco, who had run his own consultancy before selling it to Chemical Market Associates (CMAI), and who ran the World Methanol Conference. He wrote a regular methanol column for us, we distributed the magazine at his conference, and we started bringing methanol papers into the nitrogen conference. Covering methanol alongside ammonia and its derivatives became a logical development, and so we became Nitrogen & Methanol.

Then there was the idea of syngas hubs. For economies of scale, you'd have a big front end generating lots of synthesis gas, and use it for all kinds of things: hydrogen for refineries, ammonia, methanol, gas-to-liquids. So we became Nitrogen + Syngas. The hub idea is not as prevalent now, but covering syngas still makes sense. Ammonia, methanol and hydrogen are all made from it.

Which development changed your understanding of the industry most?

It came on the methanol side. Kvaerner Process Technology, which later became Davy Process Technology and is now part of Johnson Matthey, developed really large-scale methanol plants, and so did Lurgi – now part of Air Liquide – at about the same time.

I remember sitting at a methanol conference in the 1990s and hearing one of Kvaerner's technical gurus say these plants would produce methanol so cheaply that you'd be able to use it as a fuel. I thought: "Yeah, right." Typical journalist cynic. But he was absolutely right. These 5,000 tonne-a-day plants, and bigger ones, transformed the methanol industry.

And China?

China is the other big story of the first couple of decades of this century. It started building those plants in earnest and finding new uses for the methanol: blending it into gasoline, making dimethyl ether to blend into LPG, and then turning methanol into plastics through methanol-to-olefins.

Methanol demand has roughly tripled over that time and grown much faster than ammonia. It isn't as big as ammonia yet, but it's getting close. If methanol takes off as a shipping fuel, that could be another step up and could even push it past ammonia.

Where does hydrogen fit in?

At the moment, hydrogen is mainly used in refineries to break large hydrocarbon molecules into smaller ones. There's been a lot of talk about a hydrogen economy, but the trouble is that you can't liquefy hydrogen without enormous pressure or cooling, and even then its density is so low that it's an inefficient fuel. Your fuel tank ends up being mostly insulation with a small amount of hydrogen inside.

Pretty much any fuel you can name is more efficient, and hydrogen is hard to transport and hard to store. I just think it's too difficult to use on that kind of scale. I'm probably completely wrong, and by the 2050s everything will be running on hydrogen. But at the moment I can't see it.



PHOTO: CRU

Lisa Connock, BCInsight's managing editor, presents Richard Hands with a plaque at CRU's Sulphur+Sulphuric Acid Expo conference 2026, marking 31 years of service to the magazines.

Which developments do you think will really reshape the industry?

Lower-carbon production is clearly the big one. The costs of electrolysis and renewable power have come down a great deal. I think green ammonia will eventually be cost-competitive with ammonia made from natural gas, and then everyone will switch over. At the moment it's still too expensive and needs subsidies or mandates. So I expect carbon capture and storage first, then electrolysis.

And ammonia as a fuel?

That's where I'm a sceptic. Ammonia is just too unpleasant a substance. If you get a methanol leak, you have a flammable puddle, but it dissolves in water and you can mop it up. If you get an ammonia leak, people die.

I can't imagine filling your car with ammonia at the pump, and I find it hard to imagine fuelling a ship with it either. Picture a truck driving over the fuelling line and suddenly there's ammonia everywhere. These things happen. Burning ammonia for power also seems an odd way of doing things when you could be turning it into fertilizer.

I'll believe it when I see it.

Which much-heralded technologies never made it?

Following an industry for so long, you also see the technologies that fall by the wayside, and methanol has had plenty of false starts. There was the idea of methanol as a "carbon fertilizer", which the Israelis were very keen on. Methanol was going to be the cooking fuel for the developing world, with little canisters and methanol stoves replacing LPG. That never happened.

Then everyone was going to be driving a fuel-cell car. Your laptop would have a fuel cell rather than a battery, and you'd plug in a little methanol cartridge, like an ink cartridge for a pen. That never happened either, because batteries got better.

What led to the management buyout in 2007?

CRU decided to divest its publishing business, and we bought the company. That was also when I took over Sulphur magazine from Chris Cunningham, alongside editing Nitrogen.

My workload effectively tripled: two magazines plus the administration of a company. We didn't initially have an accountant, so I did the accounts as well. That was two difficult years until we finally bit the bullet and paid a professional. There were a lot of evenings and weekends.

But it was exciting too. The four of us could sit down, discuss something and decide to do it, and it would just happen. You didn't have to take it through several layers of management.

You returned to studying history while working. What drew you back?

It was what I'd originally wanted to do. My wife, Željka, needed to do further study because her qualifications from the former Yugoslavia weren't fully recognised in the UK. I said I'd keep her company by doing an Open University degree.

I enjoyed it enough to begin an MA in medieval studies. Unfortunately, I got halfway through and then we bought the business, and I couldn't keep up with both. I've often thought about going back to it, although I suspect academia is a very different environment now.

What I realised is that I enjoy researching and writing things. That's the connection between history and editing magazines.

In 2024, CRU bought the magazines back after 17 years of independent ownership. How did you feel about that?

I thought it was the right move. We'd bought the publishing business from CRU in 2007, while the conferences stayed with CRU. Bringing the magazines back into the same organisation felt logical. They fitted naturally alongside the conferences and the analytical business.

As a small publisher, there were things we wanted to do, particularly online, that we didn't have the resources or spare manpower for. Returning to CRU brought those resources.

The company is very different from the one I joined in 1995. It's much more business-like, with clearer structures and goals. Publishing itself has changed enormously too. The working culture of the 1980s and 1990s, liquid lunches and all, was a very different world.

What are your fondest memories, and what has kept you interested for so long?

The industries are always changing, and that keeps it interesting. I've been editing Nitrogen for more than 30 years, which I think may be the longest run of any editor on any title in the field. I don't know whether that's a source of pride or terrible shame, but I look back on it with fondness.

Then there are the people and places. Casale held its customer conferences in its hometown of Lugano, in Switzerland, and you'd sit in a hotel with the lake in front of you and the mountains beyond. It was an astonishing place. Dr Umberto Zardi, then president of Casale, God rest him, was a great patron of the magazine and always very generous. At one conference, everybody was given an iPad.

What are you looking forward to in retirement?

I'll tell you what I won't miss: deadlines. It can be a bit of a treadmill. Travel has become more of a chore too, with the security queues and sitting around drinking overpriced coffee.

Iceland is on my list, but I'd also like to see more of the UK and visit friends in Scotland, the North East and Cornwall. And I get a third off train travel now that I'm over 60.

To readers, colleagues and industry friends: thank you for making it such an interesting journey. One of the nice things about being around an industry for so long is that you see the long-term trajectories. And in ten years' time, people can look back at this and see just how wrong I was. ■

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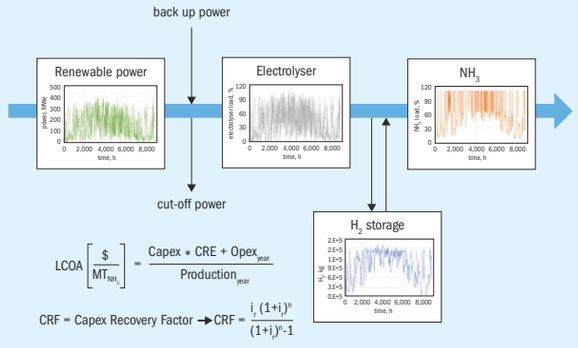
The smarter route to green ammonia

Green ammonia plants often need to integrate intermittent renewable power, hydrogen production and ammonia synthesis without compromising reliability or project economics. In this article, **Davide Carrara**, Ammonia Technology Manager at Casale, explores innovative technologies and design solutions that enhance plant flexibility and operability, supported by dynamic simulation studies and practical industrial experience.

The transition from conventional to green ammonia involves far more than adopting renewable energy. It calls for a new approach to plant design and process integration – one that can address renewable intermittency, market uncertainty and sustainability targets while maintaining economic competitiveness. Alongside proven technologies and efficient resource use, innovation is becoming an important differentiator for project success.

Innovative solutions challenge traditional design assumptions and create opportunities to improve energy efficiency, reduce investment costs, enhance operability and better align production with project-specific requirements.

Fig. 1: **Block diagram of green ammonia complex and optimisation**



Source: Casale

Design and control of a green ammonia plant

Careful design and control of a renewable-powered plant are essential to avoid unnecessary capital expenditure and support stable, reliable operation of its equipment.

Tools such as levelised-cost optimisers and dynamic-operation simulators are increasingly important to the feasibility and reliability of green ammonia projects. In particular:

- A process optimiser, such as the one developed by Casale, can assess the power-input profile and identify a design that minimises the levelised cost of ammonia (LCOA).
- Dynamic analysis under fluctuating operating conditions is needed to assess equipment reliability.

Optimising the process scheme and design

The levelised cost of hydrogen (LCOH) is the main contributor to LCOA: more than 90% of both operating expenditure (opex) and capital expenditure (capex) is tied to hydrogen production. Making effective use of the hydrogen produced is therefore a key determinant of project viability. For a given power profile, a process optimiser can identify how to use available power to achieve the lowest LCOA (Fig. 1).

The dynamic analysis includes:

- Renewable power profile
- Grid power availability and cost
- Electrolyser sizing
- Hydrogen storage sizing, control philosophy and integration with the plant
- The ammonia plant and its independent control system
- Nitrogen generation and the optimal nitrogen profile in response to hydrogen availability

All plant sections operate as an integrated system. Their designs are closely interconnected and collectively influence project economics.

A conventional, relatively inflexible ammonia plant, with a 70–110% operating range, supplied with renewable hydrogen could have a high LCOA, largely because of the hydrogen storage capacity required to buffer fluctuations in power and hydrogen supply.

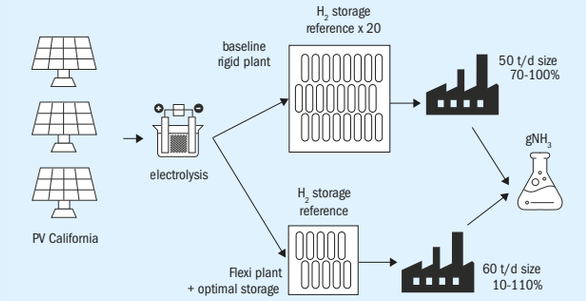
By contrast, a plant that can respond quickly to fluctuations by adjusting production to the hydrogen flow available can offer substantial economic benefits. Casale's ammonia plant is designed to operate from 10% to 110% of nominal capacity, with load ramps of up to 3% per minute in either direction.

The flexible synthesis loop, combined with the Casale optimiser, can significantly reduce the required hydrogen storage capacity, by more than a factor of 20 (see Fig. 2).

For a reference case based on solar power, the LCOA calculated for the Casale flexible loop was up to 35% lower than for the rigid-loop approach (Fig. 3).

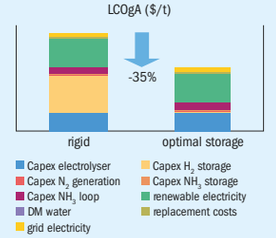
Maximising project viability requires robust process optimisation tools combined with a highly flexible ammonia synthesis scheme.

Fig. 2: **Schematic comparison of a rigid loop and Casale's flexible loop for a US solar photovoltaic system**



Source: Casale

Fig. 3: **LCOA comparison for rigid and flexible approaches in a solar photovoltaic system**



Source: Casale

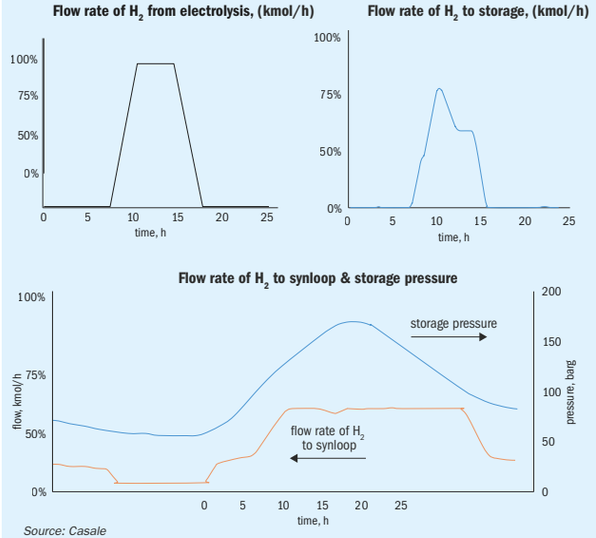
Dynamic capacity control

In addition to the optimiser, Casale developed tools to assess system dynamics and predict how the plant responds to changes in power and reagent supply.

Casale's flexible plant, designed to operate under a fluctuating power profile, is based on four principles:

- Use the available power supply to keep the synthesis loop operating at minimum load.
- Enable the plant to accommodate intermittent hydrogen production.
- Design and operate hydrogen storage so that it does not become completely full or empty.
- Control the synthesis loop by managing reactor and loop load, as well as the hydrogen-to-nitrogen ratio, to avoid depressurisation, over-pressurisation or loss of reaction.

Fig. 4: **Dynamic analysis of hydrogen generation and distribution to the synthesis loop and hydrogen storage**



Source: Casale

Extensive dynamic simulations have been conducted using a real power profile as an input. The model includes the electrolysers, hydrogen storage and ammonia plant, with the plant sized and a full control strategy implemented (Fig. 4).

The refined model supports the development of effective control strategies for ammonia synthesis operating parameters. Pressure control is particularly important: in all Casale schemes, loop pressure is maintained to avoid fatigue cycles caused by pressure fluctuations. The strategies delivering the best performance have been patented by Casale.

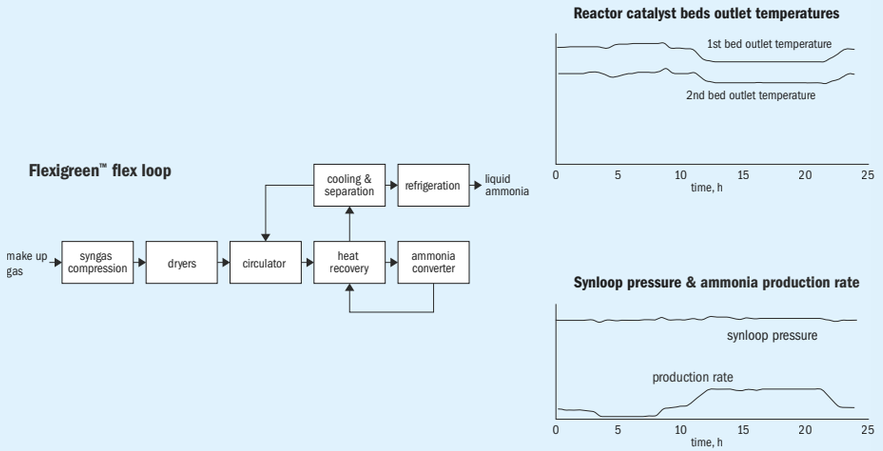
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Fig. 5: **Dynamic analysis of the ammonia converter**



Source: Casale

Dynamic analysis of the ammonia converter

The synthesis converter is central to ammonia production, and its reliability is essential to avoiding costly losses caused by reaction extinction, equipment failure or lengthy repairs.

The effects of a 100%–10%–100% capacity cycle can be assessed by examining changes in operating temperature and pressure between nameplate capacity and minimum turndown.

To address variable-load operation, Casale conducted extensive computational fluid dynamics (CFD) studies of converter performance at reduced loads. The studies covered process, fluid-dynamic and mechanical behaviour under highly dynamic conditions.

Although operating pressure is controlled and maintained, temperature within the ammonia converter is affected by several phenomena:

- The exothermic reaction raises temperature along the catalyst bed
- As chemical equilibrium is reached, the reaction and associated heat production stop
- Reaction heat preheats the converter feed
- The inlet temperature of each bed is controlled to optimise performance.

Because these factors are incorporated into Casale's proprietary kinetic model, the model can represent converter behaviour accurately, including at minimum turndown (Fig. 5).

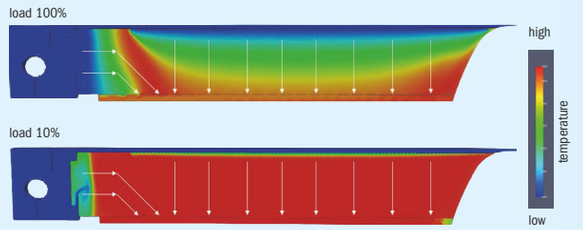
CFD simulation is then used to further validate the thermal and kinetic predictions and generate a temperature-field map for the subsequent mechanical assessment (Fig. 6).

At reduced plant loads, ammonia synthesis rapidly approaches thermodynamic equilibrium. CFD analyses found no flow maldistribution within the catalyst bed. However, the outlet collector temperature varies as operating conditions move progressively closer to the equilibrium temperature.

In green plants operating cyclically, temperature changes associated with load variation may cause fatigue. Cyclic stress fluctuations can initiate and propagate cracks, potentially leading to component failure at stresses well below the material's yield strength.

In an ammonia converter, stress fluctuations arise from the pressure and temperature changes caused by load variations, which in turn reflect fluctuations in plant feedstock. To account for these effects, Casale has developed an assessment methodology that builds on established static-load evaluation practices and adds analysis steps for this operating scenario (Fig. 7).

Fig. 6: **CFD temperature profile of an adiabatic catalyst bed at different loads**



Source: Casale

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Low-load test campaign

As a further validation step, an operating test at reduced load was carried out in an ammonia synthesis loop equipped with a Casale converter. The facility had not originally been designed to accommodate the large capacity fluctuations typical of green ammonia applications automatically, so plant operators made all process adjustments manually.

The test produced several key outcomes:

- Continuous operation at 10% of design capacity for 27 consecutive hours.
- A stable, self-sustaining reaction in the Casale converter, without an external heat source, even at this low throughput.
- Effective control of key process parameters, including synthesis loop pressure.
- Validation of the kinetic model and CFD predictions.

The successful test demonstrated the converter's performance during low-load operation and supported the modelling approach under highly flexible operating conditions. The results indicate that the converter can maintain stable performance amid significant load fluctuations, as may occur when green ammonia production is integrated with intermittent renewable power.

Innovative solutions

Green ammonia projects operate in diverse settings. Differences in design basis, geography, regulatory requirements and resource availability can significantly affect project economics, competitiveness and viability.

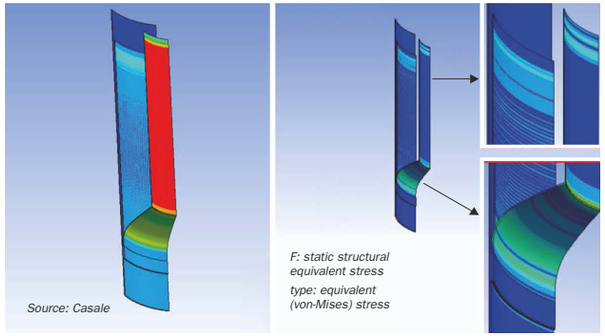
No single solution is likely to suit every project. A range of options allows developers to select an approach that best fits their requirements. The following sections describe several new technologies emerging as viable alternatives to conventional process schemes.

Coupling SOEC electrolysers with ammonia synthesis

Ammonia synthesis is exothermic. The resulting heat is typically recovered to preheat boiler feed water (BFW) and produce steam, making heat recovery an important part of process efficiency.

In conventional ammonia plants, steam is widely used in the process or to drive major equipment through turbines. Green ammonia plants may have fewer direct uses for steam, so excess steam is often consumed within the synthesis loop, for example, in a power turbine-generator.

Fig. 7: **Mechanical stress calculation and mitigation strategies**

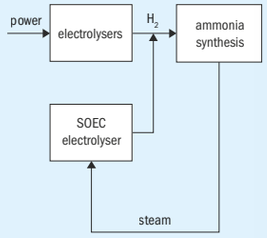


High-efficiency solid oxide electrolysis cells (SOECs) offer a different configuration: they use substantial quantities of high-temperature steam and can recover thermal energy from ammonia synthesis.

Because steam from the synthesis loop cannot meet the complex's full hydrogen requirement, a hybrid electrolysis system is typically needed. SOECs can supply part of the hydrogen feed, with alkaline or proton-exchange membrane (PEM) electrolysers providing the balance. This configuration retains flexibility and allows the plant to start up with conventional electrolysers before SOECs come online as steam becomes available.

The integrated system combines conventional electrolysis, flexible ammonia synthesis and SOEC efficiency (Fig. 8). Drawing on its ammonia synthesis and process integration experience, Casale can optimise the interaction between the synthesis loop and SOEC electrolysers to increase energy recovery, improve overall plant efficiency and strengthen project economics.

Fig. 8: **Hybrid electrolysis integration with ammonia synthesis**



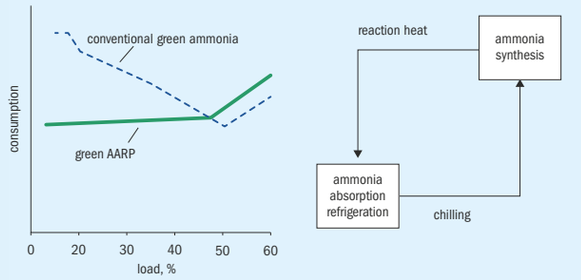
Ammonia condensation with absorption units (AARP)

Ammonia is traditionally condensed using mechanical refrigeration based on evaporating ammonia. Although efficient at full load, refrigeration compressors and steam turbines can become less effective at reduced loads. In green ammonia plants with variable production rates, this can reduce efficiency and power recovery while increasing net power consumption.

Absorption refrigeration systems have historically been used in ammonia plants to recover low-grade heat and provide refrigeration for ammonia condensation. The technology is attracting renewed interest because of its turndown capability, operational flexibility, simplicity, reliability and lower capex. In a green ammonia configuration, heat released by ammonia synthesis can drive regeneration of the ammonia-water solution, providing refrigeration with limited electrical power requirements.

This integrated scheme may be suitable for projects with variable operating profiles and moderate capacity factors.

Fig. 9: **Process-specific consumption by load: AARP scheme (green line) and conventional green ammonia (dotted line)**



Absorption refrigeration can maintain ammonia condensation over a wider operating range while using synthesis heat that might otherwise be converted to electricity with limited efficiency. This can improve flexibility and performance and reduce specific energy consumption under off-design conditions (Fig. 9).

The technology may also reduce investment costs compared with conventional ammonia compression refrigeration. A simpler process configuration, including the removal of large refrigeration compressors, could reduce installed costs for the synthesis section by more than 20%, while improving operational flexibility. Combined with improved part-load efficiency, these savings could support lower overall LCOA.

Improved reactor and catalyst

Heat recovery from ammonia synthesis is important to unit efficiency, particularly for large plants operating at high capacity factors, such as grid-connected, world-scale facilities.

For projects targeting high capacity and efficiency, reactor technology can increase conversion while supporting heat recovery (Fig. 10).

In conventional reactors, ammonia conversion and heat recovery can involve a trade-off. Higher conversion reduces loop circulation but can also reduce the heat available for recovery. Casale's Optimale™ reactor, the latest addition to its reactor portfolio, is a high-efficiency design intended to separate these two outcomes, allowing each to be optimised independently.

- Higher ammonia conversion can reduce power requirements for syngas and ammonia compressors, lowering opex.
- Lower circulation can reduce the required size of piping and equipment, lowering capex.
- Greater heat recovery can improve overall plant efficiency, lowering opex.

Together, these effects can contribute to a lower LCOA (Fig. 11).

Conclusions

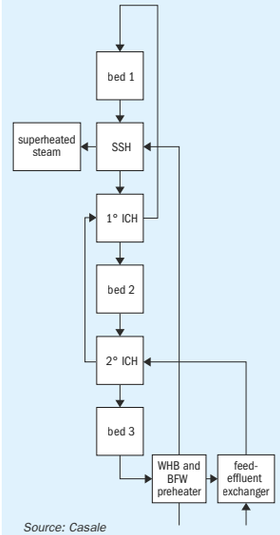
Green ammonia projects require an integrated design approach that considers process optimisation, dynamic operability, equipment reliability and technology selection. The analyses and operating experience presented in this article indicate that a flexible ammonia synthesis loop, supported by optimisation and dynamic simulation tools, can respond to intermittent hydrogen availability while maintaining stable pressure, reaction continuity and reliable equipment operation.

Project competitiveness may also benefit from complementary innovative technology options. Integrating SOEC electrolysis with synthesis loop heat recovery, using absorption-based ammonia condensation and applying the Optimale™ reactor concept are potential routes to reduce energy use, capital expenditure and overall LCOA. The most suitable combination will depend on each project's power profile, capacity factor, resource availability and economic objectives. ■

Fig. 10: **Casale Optimale™ reactor for ammonia conversion and heat recovery**



Fig. 11: **Heat recovery after the first bed to optimise reaction kinetics and heat recovery**



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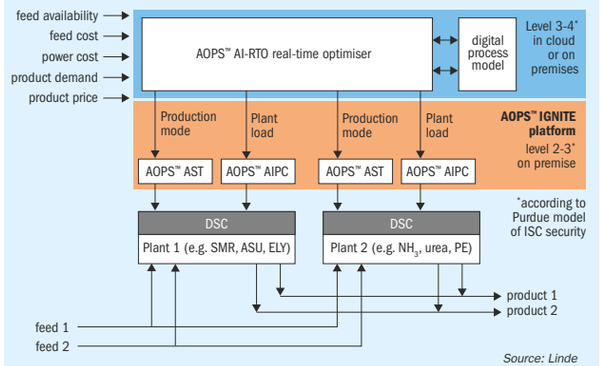
Advanced optimisation and control for emerging ammonia plants

Next-generation ammonia facilities combine conventional process units with large electrolysers supplying renewable hydrogen. This broadens the operating envelope and requires plants to respond to rapidly changing power prices, grid signals and feedstock availability. **Michael Kiesel** of Linde outlines an AI-powered automation approach that combines artificial intelligence plant control, an AI-enabled real-time optimiser, and procedural automation. Together these technologies coordinate the plant as an integrated operating system.

Emerging ammonia facilities must operate safely and profitably despite volatile power and feedstock conditions. They may experience frequent, less predictable changes in load during both daytime and overnight operation. Addressing this variability requires an advanced automation platform that integrates all operating units across the ammonia complex.

This article describes an integrated automation approach based on proven Linde software solutions, with a focus on the future application of AI-RTO for site-level economic optimisation and AIPC for robust closed-loop control. The approach can be applied to ammonia configurations incorporating electrolysers, air separation units (ASUs), steam methane reformers (SMRs), ammonia synthesis loops and storage. Its scope includes both process units and critical utilities, while allowing additional units to be incorporated as the complex evolves.

Fig. 1: **Typical Linde software architecture for operating, optimising and monitoring site production**



Source: Linde

Operational challenges and variability

The need for advanced operating solutions arises from several key challenges:

- **Complex integration and coordination**: ASUs, SMRs, electrolysers, ammonia loops and storage systems have different process dynamics, operating constraints and response times.
- **Volatile production profiles**: Plants may need to ramp repeatedly between deep turndown (e.g. 20% of ammonia-loop capacity) and full load in response to market conditions or grid requirements.
- **Intermittent renewable energy supply**: Variability in power availability must be managed without compromising safety, reliability or plant economics.

Linde advanced operations solutions overview

Linde Advanced Operations Solutions (LAOS) provides software, services and consulting designed to support autonomous operations at scale. Its portfolio includes AIPC for closed-loop control, AI-RTO, AST, digital twins and predictive diagnostics for both Linde and third-party plants.

These proprietary software tools have been proven over decades and are installed across more than 1,200 Linde and third-party plants. Many Linde plants are now operated centrally through remote operations centres (ROCs), enabling multi-site operations with demonstrated efficiency, maintenance and reliability benefits. Linde ROCs serve as process-know-how centres, supported by advanced automation, control and performance-monitoring capabilities.

AI-powered automation architecture

At the site-supervisory layer, AI-RTO determines the optimum production mode and load allocation based on demand, energy prices and operating constraints. It is supported by a Digital Process Model, which can also enable real-time performance monitoring by comparing actual plant behaviour with modelled performance (see Fig. 1).

At plant level, AIPC executes load changes and steady-state optimisation through self-learning models. Procedural automation, including AST, coordinates start-ups, shutdowns and operating-mode transitions. The overall architecture aligns with the Purdue model and can be deployed either on-premises or in the cloud.

The Digital Process Model supports real-time evaluation by comparing operating data against historical performance, guaranteed values and defined operating limits. This provides a structured basis for identifying deviations and maintaining accurate operational insight.

Use cases, results and outlook

Network optimisation: load distribution across multiple ASUs

Several years ago, a Linde plant site in the Netherlands requested a site-wide production-optimisation solution. The site (see Fig. 2) comprised multiple ASUs producing gaseous and liquid nitrogen (N_2) and oxygen (O_2) for several consumers, including a steel manufacturer with fluctuating demand.

In response, Linde developed and enhanced a customised real-time optimiser (RTO), integrated with its proprietary advanced process control software.

For this complex multi-plant network, the combination of the RTO and improved automatic load change (ALC) functionality reduced venting by up to 80% and delivered energy savings of approximately 2.5%. The implementation also reduced the workload for site and ROC operators.

In 2025, Linde began the next stage of RTO development by extending the existing platform with AI capabilities, introducing the AI-RTO solution (Fig.3).

Traditional digital process models, whether developed by Linde or third parties, typically perform one updated calculation every 10 seconds. A future surrogate-model implementation is expected to enable AI-RTO model training using more than 100 calculations in the same timeframe. This could substantially improve responsiveness during load changes and support near-continuous optimisation across ammonia, electrolyser, SMR and ASU applications.

Closed-loop AIPC on ASUs and other process plants

In recent years, Linde's proprietary AIPC closed-loop control has progressed from concept to proven industrial use cases. Since 2021, Linde has developed and installed AI-based closed-loop control systems on smaller ASUs, where conventional model predictive control (MPC) was either economically unattractive or required excessive effort for model training.

Development milestones

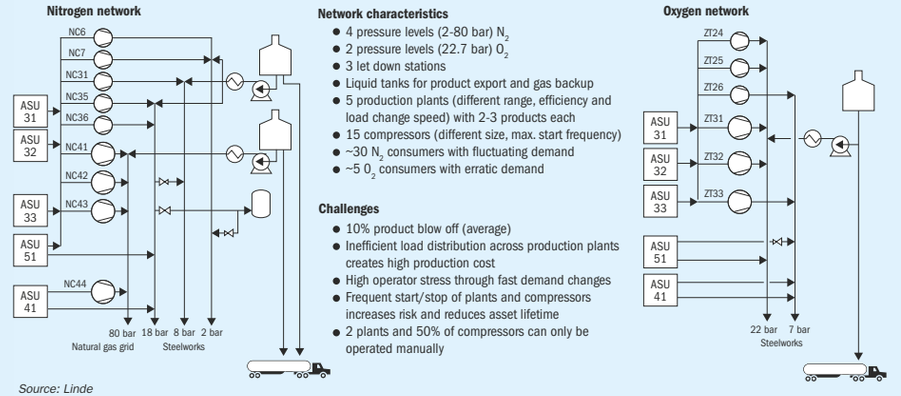
Pre-2021

- Conceptualisation and feasibility studies for AI-based closed-loop control.
- Identification of limitations associated with conventional MPC in smaller ASUs.

2021

- Start of AI-based closed-loop-control development.
- First site installations on smaller ASUs where MPC implementation was not economically viable or required significant training effort.

Fig. 2: **Operating conditions and architecture of the Linde ASU site in the Netherlands**



Source: Linde

AI PROCESS CONTROL

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2022–2023
- Validation and optimisation of initial installations.
- Demonstration of operational improvements and cost-efficiency benefits.
- Expansion to additional ASU sites.

2024 (Fig. 4)
- Integration with Linde's advanced process control platform.
- Enhancement of algorithms for dynamic load management and predictive optimisation.
- Successful completion of installations across eight Linde ASUs or plants.
- Faster load changes and improved yields without step-testing or disruption to normal operations.
- Short implementation timelines and rapid re-training when operating conditions change.

2025
- Next-stage development of AI-RTO, incorporating AI functionality into real-time optimisation.
- Start of the first third-party AIPC implementation for a process unit at a steam-cracker plant in Spain.

2026 and beyond
- Extension of software capabilities to a broader range of process-plant applications, including ammonia, electrolysers, SMRs and ASUs.
- Deployment of surrogate models capable of supporting more than 100 calculations per 10 seconds.
- Continuous optimisation across diverse process-plant types.
- Full-scale deployment across global operations.

Conclusions

AI-powered AIPC and AI-RTO can help ammonia plants manage operational volatility by coordinating process units, optimising economics and reducing the need for manual intervention. A phased, safety-gated implementation pathway enables operating teams to capture early benefits while progressing towards more autonomous operation.

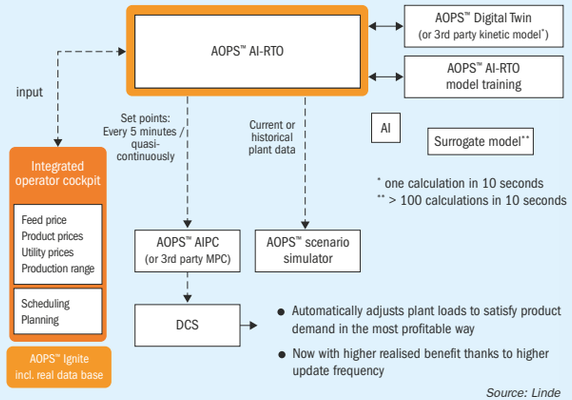
The advanced process control platform is modular. Models, operating guardrails and optimisation objectives can be reconfigured as feedstock availability, electrolyser capacity, market conditions or emissions limits change. New units can be added through templated workflows, helping the site remain stable, efficient and adaptable throughout its operating life.

AI-RTO and AIPC therefore provide a practical route towards autonomous, economically optimised ammonia production under volatile power and feedstock conditions. By respecting equipment constraints and embedding procedural automation, the approach maintains safe operation while shortening response times to market and grid signals.

For emerging ammonia plants, anticipated benefits include:
- higher on-stream time;
- lower specific energy consumption;
- reduced emissions;
- improved responsiveness to changing operating conditions; and
- fewer manual interventions.

Immediate next steps comprise confirming scope and data readiness, aligning performance indicators and operating guardrails, and selecting a suitable pilot unit. Model development, factory acceptance testing and a staged cutover (initially using shadow-mode operation) can then reduce implementation risk while supporting organisational learning and change management. ■

Fig. 3: **Future AI-RTO architecture incorporating a surrogate model**



Source: Linde

Fig. 4: **AIPC closed-loop-control status and benefits achieved across Linde ASUs in 2024**

Results from 3 years operation of complex process plants compared to classical APC		
Boosted control performance	**Fast implementation without disturbing operations**	**Automatic adaptation to changing operating scenarios**
2-3% increase in product yield	No disturbance of operations: No step tests, no test cases	No disturbance of operations: No step tests, no test cases Retraining of AI model within few hours
1-2% reduction in energy consumption		
35% faster load change	60-80% faster implementation	60-80% reduced effort to maintain solution
3-12 month payback		

Source: Linde

IMAGE: GENERATED BY CHATGPT / OPENAI



Green ammonia retains the familiar chemistry of the Haber–Bosch process, but renewable-powered hydrogen production introduces a far more variable operating environment. Safe, reliable plants will require operational readiness to be embedded from design through early operation, with people, procedures and controls prepared for dynamic conditions – not just steady state.

There is a phrase frequently heard in discussions of green ammonia:

"The synthesis loop is the same."

Technically, that is true. The Haber–Bosch process does not distinguish between grey, blue or green hydrogen. The final molecule is unchanged. But this observation can obscure a critical operational reality: while ammonia chemistry remains familiar, the operating environment around the plant is changing substantially.

Ammonia has always been unforgiving. It rewards operational discipline and punishes negligence. Green ammonia does not alter that fundamental principle; in many respects, it makes it more important.

The integration of variable renewable generation, electrolysers, hydrogen storage and advanced controls shifts the ammonia facility from an operation designed principally for stability towards one that must safely accommodate more frequent and potentially faster transitions.

For green ammonia projects, operational readiness must therefore be designed into the plant from the outset – not added during commissioning.

From steady-state operation to dynamic behaviour

Historically, ammonia plants have been designed around a straightforward operating objective: start safely, reach the required production rate, establish steady-state conditions and maintain them for as long as possible.

In reality, no ammonia plant is perfectly steady. Operators routinely manage disturbances, equipment trips, turndowns, shutdowns, start-ups and changing process conditions. Nevertheless, conventional operating philosophy has generally focused on minimising transients and restoring stable operation as quickly as possible.

Green ammonia introduces a different challenge.

Renewable electricity is variable by nature. Solar generation changes throughout the day; wind output can fluctuate rapidly. Electrolyser loading responds to available power, changing the rate of hydrogen production. This variability can affect hydrogen supply to the synthesis loop, including compressor suction conditions and the operating response required from compression, anti-surge protection and process controls.

The degree to which those fluctuations reach the ammonia plant depends on the overall project architecture. Renewable oversizing, grid connectivity, battery systems, hydrogen storage capacity, control philosophy and other buffering measures will all influence plant behaviour.

Yet the broader conclusion remains: the integrated facility becomes a more dynamic system.

This means that a minimum turndown figure is no longer sufficient to describe operational capability. Project teams must also understand:
- How quickly can the plant ramp?
- How frequently can it cycle?
- What occurs during transitions between operating points?
- How do the synthesis compressor, refrigeration system, synthesis loop and control system interact?
- What is the cumulative effect of repeated cycling on equipment, catalyst performance and plant availability?

A turndown number alone does not define dynamic operability.

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Understanding the transient

During a ramp-up or turndown, process conditions do not change independently. Temperatures move, pressures change, flows redistribute, compressor operating points shift, control valves respond and catalyst bed temperatures evolve. Equipment expands and contracts. Each response influences the others.

Consider a rapid reduction in hydrogen availability. The key questions are not limited to whether the ammonia plant can continue operating. They include:

- What does the master control system do first?
- What does the synthesis compressor experience?
- How does loop pressure respond?
- What happens to catalyst-bed temperature profiles?
- How is refrigeration balance affected?
- What are the safe operating limits?
- When should hydrogen storage compensate for the reduction?
- At what point should ammonia production be ramped down?
- What happens if a second equipment trip occurs while the plant is already in transition?
- Does the operator clearly understand the event and the required response?

These questions illustrate why green ammonia should not be treated simply as a conventional ammonia plant supplied with a different hydrogen source.

> **“... green ammonia should not be treated simply as a conventional ammonia plant supplied with a different hydrogen source.”**

The plant must be designed, commissioned, staffed and operated for transients as well as steady states. The human system must develop alongside the technology.

The sector is investing heavily in technical flexibility. Electrolyser suppliers are extending operating ranges. Ammonia technology licensors are developing more flexible synthesis loop designs. Dynamic simulation and advanced process-control strategies are improving. Hydrogen storage is being optimised to buffer renewable variability.

All of this is necessary. But an equally important system must receive the same attention: the human system.

An operator training simulator (OTS) should reflect the true operating philosophy of a dynamic facility. It should not focus solely on conventional start-up, shutdown and process-upset scenarios. Operators also need practical exposure to renewable-power transitions, hydrogen supply fluctuations, storage-system responses, rapid ramping and the interaction of these events with the ammonia synthesis plant.

Critical questions include:

- Do operating procedures adequately cover ramping?
- Does the alarm philosophy remain effective when multiple process variables are changing rapidly?
- Have operators experienced interactions between electrolysers, hydrogen storage and ammonia synthesis before encountering them in a live plant?

Technology can create flexibility. People must ultimately operate that flexibility safely.

Operational readiness begins in design

Operations should not be treated as a team that arrives once construction is nearly complete. Experienced ammonia operations personnel should be involved from early design and remain engaged through engineering, construction, pre-commissioning, commissioning, start-up and early operation.

An experienced operator views the plant through a different lens.

A designer may see a valve correctly represented on a piping and instrumentation diagram. An operator asks whether that valve can be accessed, isolated and safely operated during an emergency.

A project team may see an instrument installed according to specification. An operator asks whether its indication will be credible and useful during start-up, shutdown or rapidly changing process conditions.

A construction team may declare mechanical completion. An operator asks whether the system is genuinely ready to receive process chemicals and gas.

Neither perspective replaces the other. Both are essential.

Bringing these disciplines together early improves safety, operability and the quality of final plant readiness.

Walk the line

A successful commissioning programme cannot be managed solely through dashboards, completion percentages and meeting rooms. Personnel must walk the plant and follow the piping and instrumentation diagrams in the field. They should inspect valves, instruments, vents, drains, supports, access routes, isolation points, flow directions and temporary arrangements. They should ask questions and raise concerns immediately when something does not look right.

One of the most valuable lessons from project and commissioning experience is simple: a small deviation identified and corrected early can prevent a major problem later. A difficult-to-operate valve can become critical during an emergency. An instrument discrepancy deferred for later resolution can become the measurement an operator relies upon during start-up. A temporary arrangement understood during construction can become a forgotten hazard months later.

The feedback loop between Operations, Engineering and Construction must therefore be short:

- Find the issue.
- Challenge the condition.
- Correct it.
- Confirm closure.

Small deviations should not be allowed to accumulate into start-up problems.

Where design meets reality

Pre-commissioning and commissioning are among the most critical phases of any ammonia project. Years of engineering assumptions finally meet physical equipment, instrumentation, rotating machinery, control systems and operating teams.

For green ammonia, commissioning must achieve more than confirmation that individual items of equipment function correctly. It must build confidence that the integrated facility will behave safely under the dynamic conditions it is intended to experience.

For example:

- What happens when there is a rapid reduction in renewable generation?
- What happens when an electrolyser trips?
- How does hydrogen storage respond?
- What does the ammonia plant see?
- How does the plant recover?
- Where are the operating boundaries?
- What happens automatically and when does the operator intervene?

These scenarios should be addressed throughout the project lifecycle. They should be considered in design, assessed through dynamic simulation, reflected in control philosophy, translated into operating procedures, incorporated into OTS scenarios and validated during commissioning and start-up.

The first time an operator considers a serious upset should not be when it is happening in the plant.

First ammonia is not the finish line

Producing first ammonia is an important milestone, but it does not mean operational readiness is complete. Early operation is the period in which assumptions continue to meet reality. Procedures are improved, alarm settings are tested, equipment behaviour becomes better understood and operator competence develops across the real operating envelope. Weak signals and recurring operational issues begin to emerge.

For first-generation dynamic green ammonia facilities, this period will be particularly important.

The experienced ammonia personnel involved in design and commissioning should not disappear immediately after performance testing. Their knowledge and operational perspective should remain available while the plant organisation develops confidence in managing dynamic conditions.

Innovation demands discipline

Green ammonia introduces genuinely new challenges: renewable-power integration, electrolysers, hydrogen buffering, sophisticated controls, flexible synthesis technologies and new commercial operating regimes.

These innovations should be embraced. But they must be combined with the hard-earned operational discipline developed over decades in the ammonia industry.

Technology providers understand their technologies. Engineering, procurement and construction contractors understand project delivery. Equipment manufacturers understand their machines. Developers understand project economics.

Throughout the project, however, someone must continuously ask a more fundamental question:

How will all of this operate together – safely, dynamically and reliably?

That operational perspective must remain present from initial design until the facility has successfully passed through commissioning, start-up and early operation.

The hydrogen may be green but the ammonia is still ammonia.

As energy supply becomes more variable, plant operation becomes more dynamic and control systems become more sophisticated, operators will increasingly manage transitions that earlier generations of ammonia plants were designed to avoid.

The discipline required has not changed:

- Walk the line.
- Identify deviations while they are small.
- Provide immediate feedback.
- Involve experienced ammonia operations personnel from design – not only at commissioning.
- Understand the transient before experiencing it in service.
- Carry operational discipline through pre-commissioning, commissioning, start-up and early operation.

In ammonia, the safest problem is the one prevented before the plant ever starts. ■



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Durable alloys for ammonia cracking

Ammonia is expanding beyond its traditional role in the fertilizer sector to become a key option for transporting hydrogen worldwide. However, scaling up ammonia cracking has been challenging, as high-temperature creep and nitridation can combine to rapidly degrade structural materials.
Air Liquide has addressed this materials challenge and achieved production at an industrial-scale pilot. This article presents the validation results, showing how evidence from pilot plants and fundamental research has informed robust materials standards for the next generation of ammonia crackers.

M. Madelain, N. Ramenatte, B. Jung, D. Ulber, T. Wurzel (Air Liquide)

Material selection for ammonia cracking plants

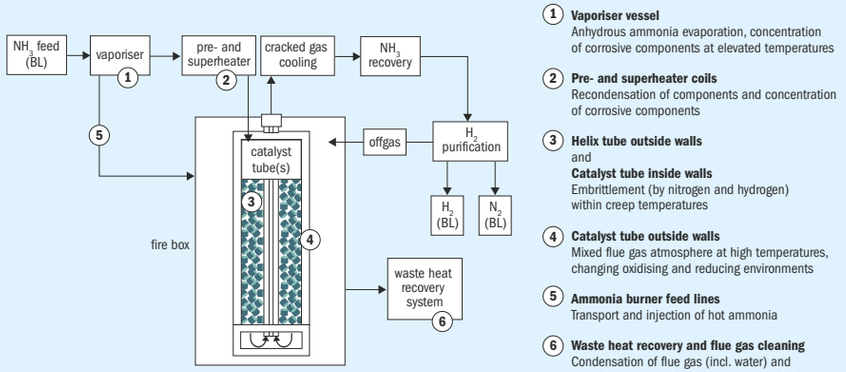
Building on its longstanding expertise in syngas and hydrogen production, Air Liquide was an early pioneer in understanding how materials behave under high-pressure conditions. As the industry gained experience with hydrocarbon feedstocks, Air Liquide helped define the metal-dusting behaviour of high-alloy materials exposed to high-carbon-monoxide atmospheres. This technical foundation informed the robust material standards that continue to support the reliability of high-pressure synthesis equipment today[1,2,3,4].

Today, hydrogen is increasingly expected to be transported globally as ammonia, then cracked back into hydrogen and nitrogen near its point of use. While many corrosion mechanisms in hydrogen production are well understood,[5] high-temperature nitridation of high-alloy materials during ammonia superheating and cracking remains less understood.

Nitridation and material integrity

Nitridation is commonly used to modify material surfaces and improve properties such as wear and corrosion resistance[6]. However, over the long-term the introduction of nitrogen into a metal matrix to increase hardness of the material can have serious consequences for equipment operating at high temperatures and pressures. If nitridation causes embrittlement, surface-layer spallation or progressive wall loss, it can ultimately lead to loss of containment[7].

Fig. 1: **Ammonia cracking block flow diagram and material degradation mechanisms**



1 **Vaporiser vessel**
Anhydrous ammonia evaporation, concentration of corrosive components at elevated temperatures

2 **Pre- and superheater coils**
Recondensation of components and concentration of corrosive components

3 **Helix tube outside walls** and **Catalyst tube inside walls**
Embrittlement (by nitrogen and hydrogen) within creep temperatures

4 **Catalyst tube outside walls**
Mixed flue gas atmosphere at high temperatures, changing oxidising and reducing environments

5 **Ammonia burner feed lines**
Transport and injection of hot ammonia

6 **Waste heat recovery and flue gas cleaning**
Condensation of flue gas (incl. water) and formation of corrosive components possible

Source: Air Liquide

To help prevent such failures, Air Liquide uses pilot-plant testing to generate analytical data and validate metallic materials under process-relevant conditions.

Design challenges for large-scale ammonia crackers

For the design of large-scale ammonia cracking furnaces producing more than 100,000 Nm^3/h of hydrogen, heat from the combustion of ammonia and waste gas is transferred indirectly through the heated walls of catalyst-filled, high-pressure cracking tubes. As a result, operating experience from today's mini ammonia crackers, which are typically used for the production of surface treatment gas mixtures in the order of a few hundred Nm^3/h, cannot be applied without qualification[8].

The differences extend beyond plant scale and the comparatively thick walls of mini-crackers. Large-scale fired crackers combine nitridation with high-temperature creep, conditions not present in small, internally electrically heated furnaces with a cold pressure shell.

Experience from heavy-water production for the nuclear industry also cannot be transferred directly. In this process, ammonia is synthesised, enriched in deuterium and subsequently cracked, without the water addition that may introduce trace components in other processes. Although the technology dates back to the 1970s, material degradation in high-temperature cracking tubes has been reported[9].

Air Liquide addresses these challenges through a comprehensive materials strategy that combines laboratory experiments, testing in an industrial-scale pilot plant and advanced modelling tools.

To explain the mechanisms of material degradation, we first outline the fundamentals of ammonia cracking, using the simplified flowsheet in Fig. 1.

Pressurised or subcooled liquid anhydrous ammonia is preheated and vaporised using waste heat from the process. Unlike conventional hydrogen production by steam methane reforming, the process does not require steam addition to the feedstock. Based on historical operating experience, small quantities of water, typically around 0.3%, are added to industrial ammonia feedstock to mitigate stress corrosion cracking (SCC) of carbon steel during storage and transport. SCC may nevertheless become relevant as the feed is heated during preheating. Trace contaminants, such as chlorine introduced during sea transport, may also increase corrosion risk and necessitate higher-grade materials.

Downstream, gaseous ammonia is superheated to temperatures above 400°C. Certain nickel-containing materials have been used in the ammonia synthesis industry, but temperatures in high-pressure synthesis loops and reactors are generally limited to below 550°C. Consequently, industry experience with nitridation at the higher temperatures used in ammonia cracking is limited.

Ruthenium-based catalysts may reduce the temperatures required for high ammonia-to-hydrogen conversion by around 100°C. However, practical nickel-containing catalysts require temperatures above 650°C to achieve reasonable single-pass conversion at the process pressures typical of industrial hydrogen production. The industry therefore has limited experience with the combination of high temperatures and high ammonia concentrations.

Air Liquide is demonstrating its ammonia cracking technology at an industrial-scale pilot plant in Antwerp, Belgium. The plant includes several industrial-size cracker tubes and burners. Commercial-scale capacity will be achieved by multiplying individual proven elements.

The numbered sections highlighted in Fig. 1 also indicate the corrosion monitoring points (CMPs) in Air Liquide's industrial-scale pilot plant.

This paper focuses on high-temperature nitridation of ammonia cracking tubes at high ammonia concentrations and presents initial results from Air Liquide's laboratory-scale material tests.

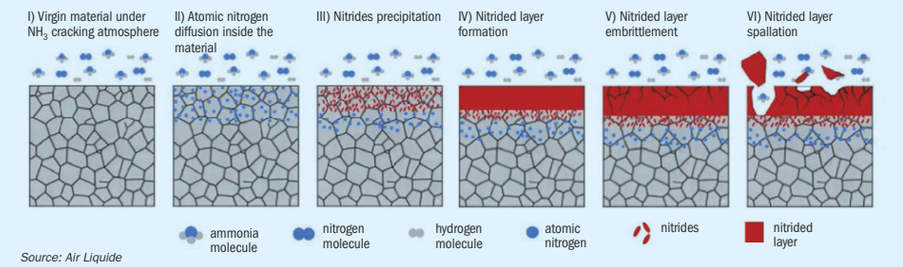
Material damage via nitridation

Gas nitridation is a chemical process, typically conducted at approximately 500°C using ammonia as a precursor, and is commonly used to increase the hardness of steels[10]. Ammonia decomposition is, in effect, the reverse of ammonia synthesis. It involves several steps, including ammonia adsorption on the material surface, dissociation of the adsorbed ammonia, and the formation and desorption of decomposition products[11].

This endothermic reaction requires an energy input and occurs at elevated temperatures, typically between 400°C and 900°C[12]. Although thermal decomposition of ammonia is kinetically slow, metallic elements can catalyse the reaction. Differences in chemical activity between the gas phase and the substrate can drive nitrogen and hydrogen diffusion into the material[13,14].

Provided the solubility limit is not exceeded, nitrogen can strengthen the microstructure by forming a solid solution.

Fig. 2: **Degradation of a metallic material undergoing high-temperature nitridation in an ammonia atmosphere**



Source: Air Liquide

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Above that limit, nitrides may precipitate within the material, both within grains and along grain boundaries. Fig. 2 illustrates the degradation mechanism.

In a large-scale ammonia cracking plant, materials are exposed to ammonia-rich feed at temperatures above 400°C after superheating, and to temperatures above 650°C in the fired cracker tubes. Nitridation potential increases with ammonia partial pressure, while nitrogen diffusion and nitride precipitation are promoted by higher temperatures.

As a result, high ammonia concentrations combined with elevated temperatures can drive greater nitrogen uptake, deeper diffusion and increased nitride formation, for example, at the inner surface of a catalyst tube. The larger volume of the surface nitride layer can generate tensile stresses. Combined with the reduction in fracture toughness associated with embrittlement, these stresses may initiate cracks or cause the layer to spall. Cracks may propagate from the nitrided layer into the base metal. Spallation exposes fresh material to the ammonia-rich environment, allowing the process to recur. Both mechanisms can progressively weaken the pressure-bearing wall. As catalytic cracking proceeds along the tube, ammonia activity declines, reducing the nitridation potential.

The likelihood of nitridation-related failure is strongly influenced by material composition, which affects nitrogen solubility and diffusion rates.

Nitrogen solubility depends on both alloy composition and temperature. At 800°C, for example, the solubility limit in a $Ni_{0.5}Cr_{0.5}$ alloy is approximately 1 vol-%, whereas in a $Ni_{0.2}Cr_{0.8}$ alloy it is an order of magnitude lower[15]. In pure iron, nitrogen solubility can reach 6 vol-%. Selecting materials with low nitrogen diffusivity is therefore important for the hot section of an ammonia cracker.

Although much of the published literature focuses on nitriding materials, material properties and their applicable operating ranges must be assessed specifically for this service. Air Liquide has therefore designed a laboratory-scale pilot test for long-term exposure of small specimens to high temperatures and high ammonia concentrations under controlled conditions. The results are used to establish nitridation kinetics and degradation mechanisms, supporting material lifetime assessments.

Laboratory testing is complemented by industrial-scale material tests in the pilot plant shown in Fig. 3. The plant incorporates the features required to produce hydrogen from ammonia in a fired cracking unit. It enables testing under internal tube pressure, potential creep and varying operating conditions representative of a process test matrix and typical operating envelope.

High-temperature ammonia corrosion testing at the Campus pilot

Campus pilot and materials

To study material degradation in high-temperature ammonia environments, Air Liquide developed a pilot facility at one of its Innovation Campuses (Fig. 4). The facility enables testing at temperatures up to 850°C and pressures up to 60 bar in an ammonia atmosphere.

The pilot consists of a tubular furnace fitted with a three-zone electrical resistance heater (Fig. 5a). Liquid industrial-grade ammonia is pumped from storage bottles, pressurised, vaporised and fed into the furnace at a low flow velocity (on the

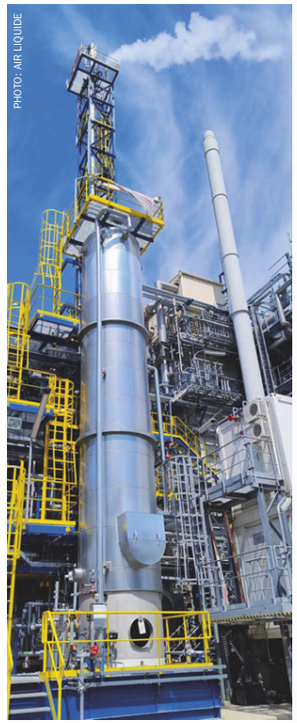
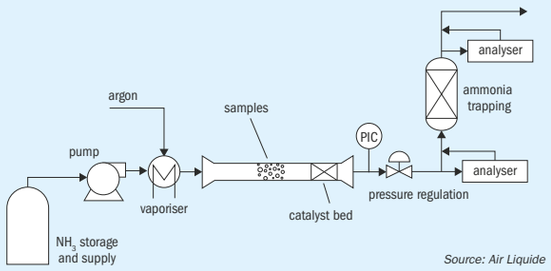


Fig. 3: Air Liquide's industrial-scale ammonia cracking pilot plant in Antwerp

Fig. 4: **Campus pilot diagram**



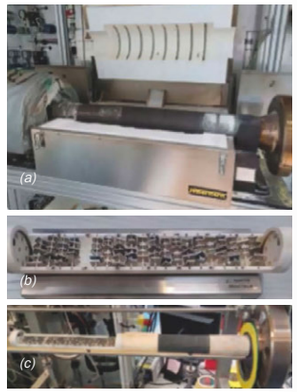


Fig. 5: Campus pilot tube furnace (a), sample holder and catalyst-basket arrangement (b), and sample holder (c)

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0.001 m/s) with a residence time exceeding 10 minutes. Samples are placed in an alumina holder within an isothermal zone of the furnace (Fig. 5b). The atmosphere within the sample holder has been validated for homogeneity.

A small amount of thermal ammonia cracking occurs inside the furnace tube. Remaining uncracked ammonia is further cracked in a downstream catalyst-filled basket and then fully removed in a detoxification cartridge. Gas analysis is carried out at the furnace outlet and downstream of the ammonia-trapping cartridge.

For any predefined and calibrated set of parameters like temperature, pressure, ammonia flow rate and ammonia fraction the Campus pilot can test multiple materials simulateously.

The test programme includes commercial nickel-based alloys, centrifugally cast alloys and coated materials selected for high-temperature service. This article presents results for two Alloy 224 and Alloy 60 HT R, to illustrate the assessment approach.

Material testing strategy

A multi-stage testing strategy was used to assess alloy performance in a high-temperature ammonia environment. It combines macroscopic kinetic measurements with microscopic characterisation to establish both comparative material performance and the mechanisms underlying nitridation-related degradation.

The core programme comprises long-duration isothermal exposure to high-concentration ammonia at representative service temperatures of 650–850°C. Metallurgical characterisation of the exposed materials provides insight into degradation kinetics and mechanisms.

Additional experiments address conditions that may occur in industrial service. To examine the effect of operating interruptions and temperature fluctuations, pre-nitrided samples are subjected to controlled thermal cycles. This tests the integrity and adhesion of the nitrided layer, including its susceptibility to cracking or spallation.

Because ammonia concentration decreases as cracking proceeds, a further series of tests examines the effect of lower ammonia concentrations on nitridation. Together, these experiments assess material behaviour across high-temperature ammonia environments, generate kinetic data and evaluate the influence of process conditions.

Results and characterisation

Samples exposed under different conditions underwent analytical, metallurgical and crystallographic characterisation. The following sections describe the main methods and representative results.

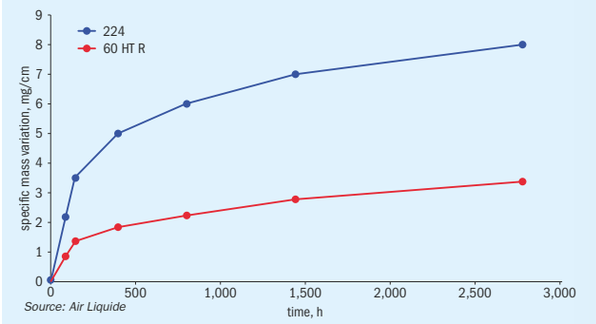
The first method, gravimetric analysis, provides a direct measure of overall reaction kinetics. Changes in specific sample mass over time are used to estimate nitrogen uptake associated with nitridation. Fig. 6 shows the specific mass change at 750°C. The observed parabolic kinetics are consistent with a diffusion-controlled process.

Gravimetric analysis also provides an initial means of comparing alloy performance. In this example, Alloy 224 shows a greater mass gain than Alloy 60 HT R, indicating lower resistance under the tested conditions. However, mass change alone cannot distinguish nitrogen uptake and nitride formation from potential mass loss caused by spallation. More detailed characterisation is therefore required.

The second method is X-ray diffraction (XRD), used to identify crystalline phases. The diffractograms in Fig. 7 indicate the presence of chromium nitride (CrN) and iron nitride (Fe_4N) in an austenite matrix, confirming nitridation and offers critical insights into the thermodynamic stability of the resulting compounds.

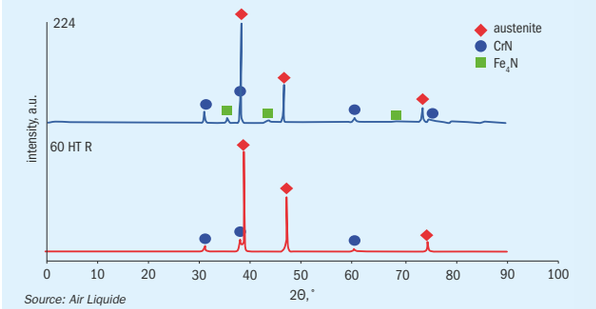
After XRD analysis, samples are sectioned and polished for optical microscopy. Cross-sectional images provide visual evidence of degradation penetration and enable measurement of the nitrided-layer thickness (Fig. 8). These measurements complement the mass-gain data and help establish a layer-growth kinetic law. Such a law can support component-lifetime predictions and the determination of corrosion allowances, subject to the assumption that critical spallation does not occur.

Fig. 6: **Specific mass change under ammonia at 750°C as a function of exposure time**



Source: Air Liquide

Fig. 7: **XRD diffractograms of materials exposed to ammonia at 750°C**



Source: Air Liquide

Cross-sectional micrographs also provide an initial view of the nitrided layer's microstructure and integrity. In the samples shown, Alloy 224 exhibits some superficial spallation, whereas the layer on Alloy 60 HT R appears stable.

The final characterisation method is scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDS), which provides high-resolution information on layer morphology, composition and elemental distribution. EDS maps (Fig. 9) can confirm and locate nitrogen and other elements, such as chromium and aluminium, in the layers identified by microscopy. The technique can also reveal phases, such as AlN, that may be too deep or present in quantities too small for detection by surface-sensitive XRD.

The results indicate a two-layer nitrided structure. The layer nearer the surface appears homogeneous, while the deeper layer contains more distinct features, including AlN. Nitrogen content then falls sharply to base-metal levels, marking the end of the nitrided region. Nitrogen also appears to destabilise chromium carbides, which transform into chromium nitrides.

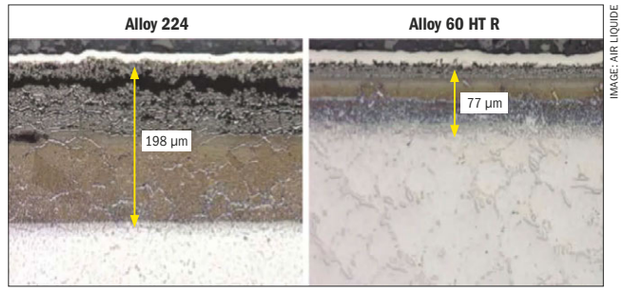


IMAGE: AIR LIQUIDE

Fig. 8: Optical microscopy images used to measure nitrided-layer thickness at 750°C

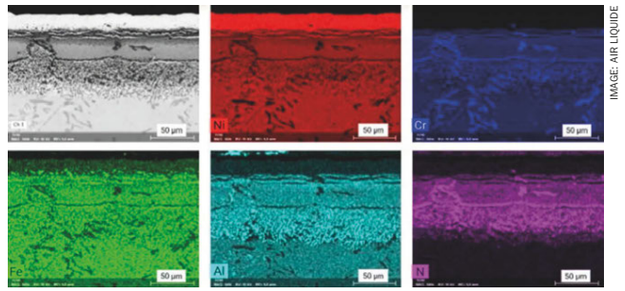


IMAGE: AIR LIQUIDE

Fig. 9: SEM cross-section and EDS elemental maps of Alloy 60 HT R after exposure at 750°C

Material testing in the industrial-scale pilot plant

Industrial cracker tubes

From the incoming battery limit to hydrogen export, the industrial-scale pilot plant offers a range of environments representative of future ammonia cracking units.

The plant includes several cracker tubes installed in a fired heater box with an industrially relevant heated length. The tubes include configurations with and without internal heat exchange (Cracker-X) and use different combinations of outer- and inner-tube materials.

The tube sections exposed to the highest nitridation potential are a particular focus of the testing campaign. As described above, two processes occur simultaneously along the heated length of the cracker tubes:

- Feed-gas temperature rises, increasing nitridation potential, diffusion rates and precipitation kinetics.
- Ammonia concentration falls as catalytic cracking proceeds, reducing ammonia partial pressure and, in turn, nitridation potential.

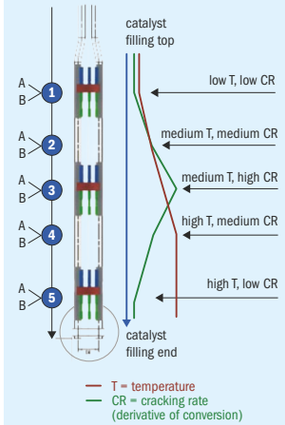
The competing effects mean that nitridation potential is expected to reach a maximum at some point along the tube, depending on temperature and ammonia partial pressure. Air Liquide used a firebox simulation to determine the temperature profile, cracking rate and corresponding ammonia concentration profile along the tube. This supports the placement of samples at representative locations, as illustrated schematically in Fig. 10.

To broaden the demonstration programme, the tubes contain several sample types, including tensile, hot-tensile, creep, toughness and metallography test samples.

The samples are scheduled for extraction after the first long-term campaign, following three thousand hours of operation. The industrial cracker tubes will undergo both non-destructive and destructive testing.

To relate observed damage to process conditions and laboratory-scale results, the pilot plant measures inlet and outlet stream temperatures, tube-skin temperatures and temperatures within the catalyst bed.

Fig. 10: **Material samples installed inside industrial cracker tubes**



Source: Air Liquide

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Summary

The experimental campaigns in the Innovation Campus pilot have generated important data for the design of ammonia cracking equipment. The results indicate that material degradation in ammonia cracking atmospheres differs from that observed in conventional steam methane reforming hydrogen production, underscoring the need for testing under conditions relevant to the intended application.

Nitridation of high-alloy materials was clearly observed, and initial comparisons distinguished performance among the tested alloys. Under the conditions examined, Alloy 60 HT R showed lower mass gain and a thinner nitrided layer than Alloy 224, indicating greater suitability for high-temperature ammonia service.

Characterisation of samples exposed to ammonia under isothermal conditions supports material selection and the evaluation of surface treatments. The observed layer morphology and phase distribution also reveal differences in integrity: the nitrided layer in some alloys, such as Alloy 224, is brittle and porous, while Alloy 60 HT R exhibits distinct sublayers with better apparent integrity, including AlN beneath CrN.

The thermal cycling tests provide vital information on the stability of the nitrided layer under fluctuating temperature conditions, mimicking real-world operational scenarios. The observed minimal change in nitrided layer thickness for both alloys after thermal cycling provides an indication of their resilience to thermal stresses, which is paramount for the safe and reliable operation of ammonia crackers.

Understanding the effect of ammonia concentration on nitridation kinetics, as demonstrated by the significant difference in mass gain between pure and low-concentration ammonia atmospheres allows for optimised design of cracker sections with varying ammonia concentrations, ensuring material suitability throughout the process while also respecting economic factors in the material selection process.

In parallel, Air Liquide has installed numerous samples along the process path and within the cracker tubes of its industrial-scale pilot plant. The sample programme – including tensile, hot-tensile, creep, toughness and metallography specimens – is designed to assess material behaviour across different process environments.

Analysis after extended exposure will provide insight into degradation under operating conditions that laboratory tests cannot fully reproduce, including internal tube pressure, potential creep and process fluctuations. The industrial-scale pilot also enables examination of the combined effects of nitridation and high-temperature creep under representative temperatures, pressures and ammonia concentrations.

Temperature measurements at the tube surface and within the tube, together with online gas-composition analysis, will help correlate process conditions with observed material degradation.

Comparing controlled laboratory tests with results from the industrial-scale pilot plant will help distinguish and quantify the effects of individual degradation mechanisms, refine kinetic corrosion models and improve lifetime assessments. Better predictions of nitrided-layer growth and embrittlement can inform corrosion allowances and maintenance planning, supporting risk-based inspection and helping to reduce unplanned downtime and maintenance costs.

Together, these laboratory and pilot-plant programmes provide a basis for material selection and equipment design informed by industrially relevant data. The aim is to support ammonia cracking plants that meet demanding requirements for reliability, safety and service life.

Outlook

Air Liquide's industrial-scale pilot plant in Antwerp has generated data across materials, reaction kinetics, catalysts, trace components, ammonia combustion, emissions abatement, heat transfer, modelling, ammonia safety, design and operational experience. The programme also incorporates a detailed approach to identifying and mitigating risks relevant to the first commercial ammonia cracker.

Following long-term operation, material samples and cracker tubes from the pilot plant will be analysed using non-destructive and destructive methods. Creep specimens and destructive testing of the cracker tubes are intended to help assess the interaction between creep and nitridation, which can also occur independently. This will support evaluation of how nitridation may affect conventional creep models. ■

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Proving the future of hydrogen imports

An ammonia cracking demonstration plant is being developed by thyssenkrupp Uhde and Uniper in Scholven, Germany, to test the full process of converting imported ammonia into purified hydrogen. **Dr. Christian Renk** and **Vaios Kitsos** of thyssenkrupp Uhde explain how the plant's planned testing programme will generate data on efficiency, flexibility, emissions and equipment performance to inform future commercial-scale projects, including the planned hydrogen import terminal in Wilhelmshaven.

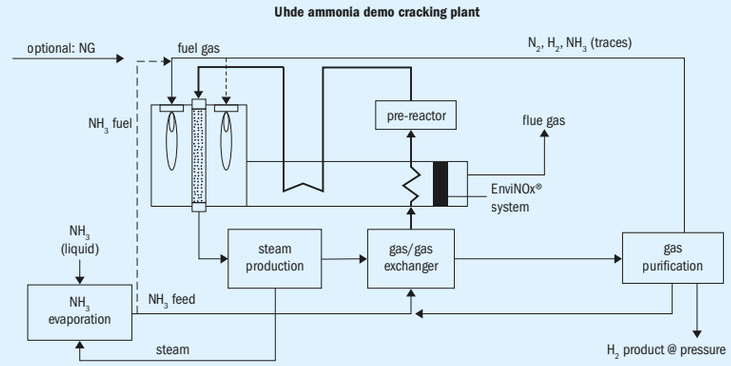


Uniper and thyssenkrupp Uhde Ammonia Cracking Demo Plant in Gelsenkirchen-Scholven, Germany (September 2026)

More than a stand-alone plant, the Ammonia Cracking Demo Plant developed jointly by thyssenkrupp Uhde and Uniper in Gelsenkirchen-Scholven/Germany provides a platform for testing and validating key process steps relevant to a future commercial ammonia-to-hydrogen plant: feed handling and evaporation, integrated heat recovery, a pre-reactor and fired cracking, hydrogen purification, off-gas recycling, flexible firing and emissions control. The challenge is to translate it into an efficient, reliable and commercially viable solution at the scale required for future hydrogen imports. The plant is based on Uhde proprietary technology and uses commercial-sized cracker tubes and burners, to investigate their performance under relevant conditions and to generate data for the development and design of future industrial-scale plants. This end-to-end configuration makes Scholven Ammonia Cracking Demo Plant an industrial proving ground for the complete process chain.

The project, which started at the end of 2023, is in its commissioning phase, with operation and tests to commence early 2027. It sets a demanding benchmark for both technology development and project delivery: research and development were advanced in parallel with engineering, procurement and construction. Catalyst qualification, burner development, materials testing, process modelling and plant integration therefore had to mature while the project itself was being executed. By advancing technology development and project execution in parallel, the project significantly shortened the path from laboratory research to commercial application, while enabling new findings to be included directly into the plant design.

Fig. 1: **Uhde Ammonia Cracking Technology – Simplified flow diagram**



Source: thyssenkrupp Uhde

From technology to execution

Engineering started in 2024. Components with long lead times were ordered and permits obtained in early 2025. Although it was a first-of-its-kind plant, the permitting process was straight forward. The experience gained during this process will be of high value for future commercial-scale projects. thyssenkrupp Uhde designed and erected the plant whilst Uniper provided the site, was responsible for permitting, site preparation, site integration, will operate the plant, and supply ammonia and utilities. In March 2026, Uniper handed over the prepared site to thyssenkrupp Uhde.

At the heart of the facility is an ammonia cracker containing seven tubes. Rather than being selected to achieve a specific capacity, the configuration represents the minimum viable arrangement (~4 t/d hydrogen) required to validate key process elements under realistic industrial conditions. The complete process is being de-risked under realistic operating conditions, including catalysts, burners, materials, energy integration, hydrogen purification and emissions. As a result, scale-up is achieved through numbering-up rather than redesign.

Keeping heat within the process

Liquid ammonia is fed into the system at ambient temperature and elevated pressure. Before reaching the cracking section, the feed is heated using energy recovered from the process itself. This high degree of heat integration is central to the commercial feasibility of ammonia cracking. In a future large-scale facility, ammonia consumption will account for the majority of the hydrogen production costs, making efficient energy utilisation a key parameter for overall plant economics.

To maximise thermal efficiency, the Uhde Ammonia Cracking concept combines feed evaporation and preheating, catalytic pre-reaction, heat recovery from the cracked-gas stream and the use of off-gas from the gas cleaning operation as fuel. One of the principal objectives of the Demo Plant is to validate this integrated energy concept under industrial operating conditions and to establish a robust basis for minimising external fuel demand in commercial installations.

The ammonia first enters a catalyst-filled pre-reactor, where a portion of the feed is already converted into hydrogen and nitrogen. After further heating, the gas is routed to the main cracker.

The cracking reaction takes place in catalyst-filled tubes heated by four burners. The seven tubes installed deliberately represent different positions within a future commercial reformer box. Tubes located near the centre are exposed to different heat fluxes than those closer to the walls, allowing the impact of these variations on conversion efficiency, thermal behaviour and long-term operation to be assessed.

After leaving the cracker and heat recovery systems, the crude product stream enters the gas purification system. During testing, the plant will operate across a wide range of conditions, including campaigns in which ammonia conversion is not maximised. The purification system reliably removes residual ammonia before downstream processing, enabling the plant to operate flexibly under these varied conditions.

The gas cleaning operation section produces the high-purity hydrogen required by downstream users while simultaneously generating an off-gas stream that can be utilised as process fuel. This integration links product quality and energy efficiency in a single process step. Depending on

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operating requirements, additional heat can be supplied using ammonia, hydrogen-rich cracked gas or, where necessary, natural gas.

The overall process concept builds on thyssenkrupp Uhde's extensive experience in fired reforming and large-scale hydrogen production. Combined with the integration of the unique EnviNOx® technology for ultra-low NO_x and N_2O emissions, the process is designed to support low-carbon hydrogen production while meeting the most stringent environmental standards.

Two years of testing campaigns

The Ammonia Cracking Demo facility will be operated in a two-year research, testing and validation programme. Individual test campaigns are expected to run for approximately 6 to 12 weeks. Throughput will be deliberately varied to investigate process flexibility, including dynamic plant output to investigate how far it can be reduced and subsequently increased again while maintaining stable operation.

After each campaign, the plant will be shut down and selected components exchanged or modified before restart. The programme will evaluate different catalysts, burner concepts, construction materials, gas cleaning operating conditions and flue-gas treatment configurations. Catalyst candidates have already undergone extensive laboratory qualification screening since 2022.

This reflects a broader development philosophy pursued by thyssenkrupp Uhde. Rather than optimising a single proprietary component, thyssenkrupp Uhde is assessing how different catalysts and technologies interact across the complete process chain within one integrated facility.

The resulting data provide a valuable basis for close collaboration with catalyst suppliers, allowing both sides to deepen their understanding of catalyst behaviour at industrial scale and jointly optimise future commercial solutions. At the same time, the supplier-flexible approach ensures that future customer projects can be configured on the basis of measured operating data and project-specific requirements. This not only reduces technical risk but also creates greater flexibility in the design and optimisation of commercial ammonia cracking facilities.

Particular attention will be paid to dynamic operation. Repeated start-up and shutdown sequences are of significant technical interest because they subject equipment to thermal and mechanical stresses that are rarely encountered during steady-state operation. While commercial ammonia crackers are expected to run as continuously as possible and respond to changing hydrogen demand primarily through part-load operation, the plant offers a unique opportunity to explore the operational limits of the technology. Understanding how the process responds to load changes, restarts and other transient conditions will provide valuable insights to inform the design and operation of future commercial facilities.

Turning operating data into industrial intelligence

The new Uhde Ammonia Cracker technology represents more than an innovative approach to Ammonia Cracking. From the very beginning, digitalisation has been an integral part of its development and reflects thyssenkrupp Uhde's commitment to combining engineering excellence with digital innovation. Digital tools and processes have therefore been integrated from the outset to capture, structure and interpret that data throughout the plant's development and testing.

For the prototype, Uhde is applying the same digital solutions used for large-scale industrial plants. The demonstration plant will be continuously connected and monitored, creating a consistent data foundation across test campaigns and operating states.

By combining operating data with engineering context, thyssenkrupp Uhde can assess how individual components and the integrated process behave under real operating conditions. Measurements can be interpreted in relation to process conditions, equipment behaviour and operational events, making it possible to evaluate performance, understand dependencies and assess the outcome of each test campaign systematically.

The resulting engineering insights will feed directly into the design, optimisation and operation of future commercial plants, supporting the transition from demonstration to reliable, continuous operation at industrial scale.

Reducing risk for Wilhelmshaven

The purpose of the Scholven demonstration plant extends far beyond the site itself. It is designed to support commercial-scale ammonia cracking infrastructure and provide the technology, execution and operating evidence required for large-scale hydrogen imports via ammonia.

The plant's significance is underscored by the broader partnership between Uniper and thyssenkrupp Uhde. Building on their strategic collaboration, the companies have signed a long-term framework agreement covering licence packages for up to six commercial ammonia cracking plants, with a combined processing capacity of 7,200 t/d. The technology is intended for Uniper's planned hydrogen import terminal in Wilhelmshaven, where pre-FEED has been completed and preparations for the next design phases are under way.

The key question is therefore no longer simply whether ammonia can be cracked into hydrogen. The focus lies on the parameters that ultimately determine project economics and operational reliability: hydrogen yield, energy efficiency, fuel consumption, flexibility under changing operating conditions and the long-term behaviour of critical equipment. Small deviations in any of these areas can translate into significant economic consequences over decades of operation in a future commercial facility. For this reason, the Scholven Ammonia Cracking Demo Plant serves as a testing and validation platform, assessing these parameters under industrially relevant conditions and generating data to support the development of future commercial-scale facilities.

The knowledge generated during the two-year test programme is expected to provide a foundation for future industrial-scale projects. Drawing on thyssenkrupp Uhde's experience in large-scale ammonia and reforming technologies – including EnviNOx® emissions control solutions – and its capabilities across feasibility studies, licensing, engineering, EPC execution and lifecycle support, the project will investigate and validate key elements of the route from imported ammonia to specification-grade hydrogen. The aim is to offer future customers an integrated solution spanning the entire value chain and supporting the development of ammonia-based hydrogen imports. ■



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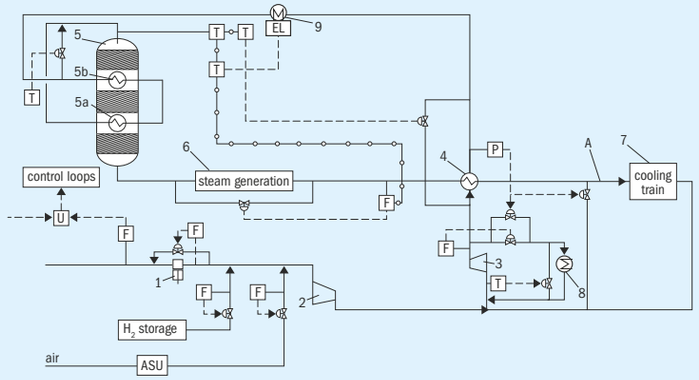
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A master controller for flexible ammonia synthesis

Bernd Keil and **Karan Bagga** of thyssenkrupp Uhde GmbH describe a proprietary thyssenkrupp Uhde master controller and synthesis loop design for adjusting green ammonia production as renewable power and hydrogen supply fluctuate. A dynamic simulation shows the plant can ramp from 10% to 100% of nominal capacity while keeping loop pressure and converter temperatures within safe operating limits.

Fig. 1: **Master controller for the synthesis loop**



Source: thyssenkrupp Uhde

Green ammonia produced using renewable energy can help decarbonise the fertiliser industry and can also serve as a carbon-free fuel or hydrogen carrier. It is synthesised from nitrogen and hydrogen in a classical Haber Bosch synthesis loop. In this process, the required nitrogen is extracted from air, while the hydrogen is produced by electrolysis of water, powered by renewable electricity. However, wind and solar generation can fluctuate significantly, preventing a green ammonia plant from operating continuously at steady state. Batteries or hydrogen storage can mitigate these fluctuations, but such measures are costly. It is therefore necessary to adjust the plant's production capacity in response to variations in renewable energy availability.

The master controller

This adjustment is performed by the so-called "master controller". It coordinates plant parameters; including temperatures, pressures and flow rates, so that hydrogen consumption in the ammonia synthesis section matches the hydrogen supplied by electrolysis and the storage system. Together with key modifications to the loop design, the controller maintains a constant pressure in the synthesis gas circuit, thereby limiting material fatigue caused by pressure cycling. It also regulates the temperature profile in the ammonia converter to sustain the reaction across all catalyst beds while preventing excessive temperatures that could cause nitriding of the reactor's pressure bearing shell.

In addition, the controller ensures that the recycle gas flow rate is maintained at a minimum, which prevents maldistribution and potential hot spots in the catalyst beds.

Fig. 1 shows the master controller configuration. Hydrogen from water electrolysis is compressed in a hydrogen compressor (1) and mixed with nitrogen from an air separation unit. The mixture is then compressed to loop pressure in a centrifugal compressor (2) before entering the synthesis loop. The circulator (3) conveys the recycle gas through the gas/gas heat exchanger (4) to the three-bed ammonia converter (5), which contains two internal heat exchangers (5a and 5b). The hot reactor effluent generates steam in unit (6), heats the cold recycle gas in the gas/gas heat exchanger (4), and is then cooled further in the cooling train (7), where liquid ammonia is separated from the synthesis loop. A heat exchanger (8) cools the recycle stream as it passes from the discharge side to the suction side of the recycle compressor (3).

The master controller comprises the following control loops:

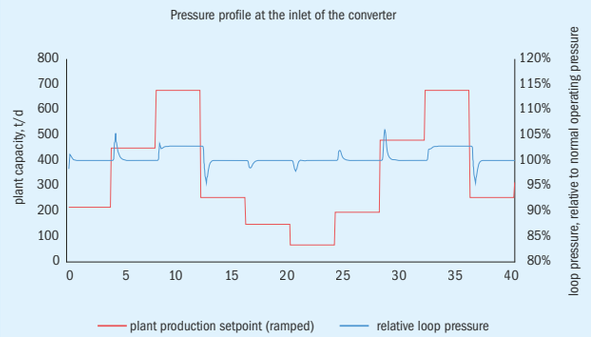
- Hydrogen withdrawal from the storage tank (the tank inventory itself is actively managed by the so-called "extended master controller"), with input from the overarching energy management system (third party).
- Synthesis-loop pressure control
- Inlet temperature control for the ammonia converter and the second and third catalyst beds.

The pressure in the synthesis loop remains constant when the quantity of synthesis gas consumed by the ammonia reaction equals the quantity of make-up gas entering the loop. This balance can be achieved by adjusting either the recycle flow rate or the ammonia concentration at the converter inlet. Both measures regulate the amount of ammonia formed during each pass through the converter.

The recycle flow rate is controlled by manipulating the so-called "spill-back valve", which regulates the bypass stream from the discharge side to the suction side of the circulator. The ammonia concentration at the converter inlet is adjusted by opening or closing the bypass around the cooling train. Opening this bypass reduces ammonia condensation in the cooling train and therefore increases the ammonia concentration in the loop.

The ammonia converter inlet temperature is controlled as follows: if the temperature is too high, the bypass around the gas/gas heat exchanger (4) is opened. If the temperature is too low, the bypass around the steam generator (6) is opened; at very low turndown ratios, the electric heater (9) is switched on.

Fig. 2: **Simulation of the master controller**



Source: thyssenkrupp Uhde

Master controller test

A dynamic simulation of a 675 t/d green ammonia plant was performed to evaluate the proposed master controller. The results are presented in Fig. 2. Using an actual renewable power profile, plant capacity was varied every four hours between 67.5 and 675 t/d, via a ramped setpoint (calculated by the master controller) as shown by the blue line. The master controller regulated the synthesis loop pressure to close to 100%, shown by the orange line, against variable setpoints and the consequent plant throughput.

The results show that the loop pressure remains within 5% below and 6% above the setpoint. This demonstrates that the proposed master controller concept can accommodate fluctuations in renewable energy supply while maintaining a safe operating envelope and stable synthesis-loop pressure. Under ASME Section VIII[1], pressure cycles below 15% of the design pressure do not require special design measures for synthesis loop pressure vessels. Uhde has nevertheless rigorously assessed and addressed additional mechanical and fatigue control measures[2, 3, 4].

Conclusion

The master controller maintains synthesis loop temperatures and pressure within acceptable limits despite fluctuations in hydrogen supply. This protects the catalyst from damaging thermal cycling and prevents loss of containment caused by pressure cycle fatigue. Ammonia production follows the cyclic hydrogen feed, enabling the plant to ramp between 10 and 100% of nominal capacity. ■

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A floating solution for alternative energy production

TOYO introduces its Blue Ammonia FPSO concept, combining offshore ammonia production from associated gas with CCUS, including CO_2 injection. **Nobuhiro Yoshida** and **Keisuke Sasakura** of Toyo Engineering Corporation outline the concept's key technical features and how it integrates ammonia production, FPSO design and CO_2 management technologies to support low-carbon ammonia production offshore.



PHOTO: TOYO

Ammonia is attracting growing interest as a carbon-free fuel and hydrogen carrier in the transition to a lower carbon energy system. Meanwhile, associated natural gas from offshore oil production is often reinjected into subsea reservoirs when nearby infrastructure or export pipelines are unavailable, particularly at remote FPSO locations. This can leave a potentially valuable resource underused. Against this background, offshore ammonia production is gaining attention as a possible alternative.

On 12 December 2024, Toyo Engineering Corporation (TOYO) and MODEC, Inc. (MODEC) received Approval in Principle (AiP) from the American Bureau of Shipping (ABS) for its innovative Blue Ammonia Floating Production Storage, and Offloading (FPSO) concept. It is one of the earliest offshore ammonia production concepts to receive AiP.

TOYO and MODEC developed the conceptual design by bringing together their expertise in the following areas:

- **Ammonia production process design:** TOYO collaborated with KBR to optimise the ammonia production process. TOYO has experience in the design and construction of more than 80 ammonia plants worldwide.
- **FPSO equipment design:** TOYO has developed expertise in equipment and topside layout design through involvement in nearly 20 FPSO projects.
- **Carbon capture and storage (CCS) technologies:** TOYO has capabilities in CO_2 separation, recovery, transportation, and storage, including enhanced oil recovery (EOR). The company has participated in more than ten CO_2-EOR and CCS projects to assess system configurations and feasibility.

The Blue Ammonia FPSO is designed to produce, store, and offload blue ammonia using associated gas that might otherwise be reinjected without productive use. The facility is designed to capture CO_2 generated during the conversion of associated gas into ammonia (NH_3), as well as CO_2 from gas turbine generators (GTGs), with the aim of reducing the facility's overall carbon footprint.

As part of the AiP process, layout studies examined the vessel's spatial constraints and the maintenance needs of an ammonia plant, which includes multiple reactors. A Hazard Identification Study (HAZID) also examined risks associated with handling ammonia offshore and identified potential countermeasures. This article summarises the study findings and the technical challenges to be addressed as offshore ammonia production concepts develop.

Blue Ammonia FPSO concept

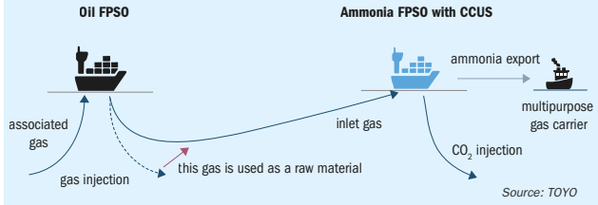
The concept is illustrated in Fig. 1.

The Blue Ammonia FPSO would be positioned alongside a new or existing oil FPSO. It would use associated gas from oil production to make ammonia, capture the resulting CO_2 and inject it into nearby oil reservoirs for storage or enhanced oil recovery. The ammonia would then be transferred to a multipurpose gas carrier for export.

Compared with conventional onshore blue ammonia plants, offshore production offers three potential advantages:

- **Lower feedstock costs:** Onshore ammonia plants commonly use pipeline natural gas or liquefied natural gas (LNG), making feedstock a significant operating expense (opex). An offshore facility could instead use associated gas that would otherwise be reinjected, potentially lowering feedstock costs compared with conventional onshore plants.
- **Improved access to CO_2 injection sites:** Onshore blue ammonia plants need access to oil fields or CO_2 pipeline infrastructure for CO_2 injection and to meet relevant certification criteria. Suitable sites and active projects exist in regions such as North America and the Middle East, while other regions may face infrastructure constraints. Offshore production could provide direct access to injection reservoirs, as oil FPSOs are typically located near oil fields that may be suitable for EOR.

Fig. 1: **Blue Ammonia FPSO concept**



- **Operational flexibility and relocatability:** If designed to accommodate a range of feed gas compositions, the FPSO could be redeployed to different offshore locations. This flexibility could help the facility adapt to changing resource conditions and project opportunities.

Although an offshore facility requires additional investment in the hull, mooring system and marine-specific design, these costs may be partly offset, depending on project conditions, by lower feedstock costs and reduced reliance on land-based gas and CO_2 infrastructure.

Process scheme

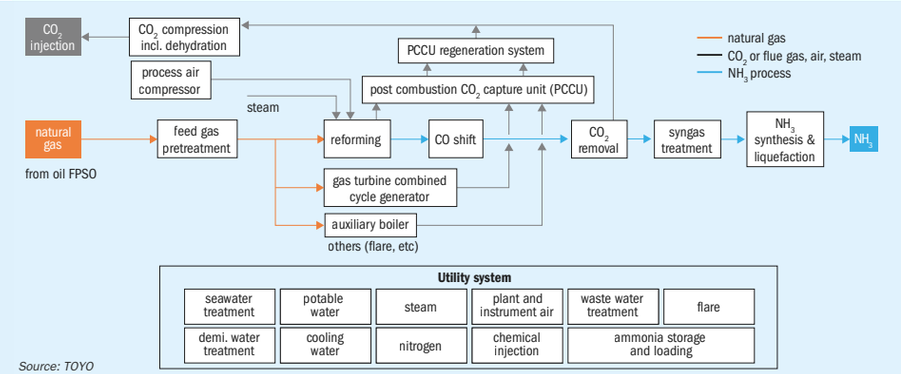
The Blue Ammonia FPSO process scheme is illustrated in Fig. 2. For this study, ammonia production capacity is set at 2,200 t/d, taking into account hull size constraints and TOYO's experience in ammonia plant design.

The onboard process follows the main stages used in conventional onshore plants: feed gas pretreatment, reforming, carbon monoxide (CO) shift, CO_2 removal, synthesis gas treatment, ammonia synthesis, and liquefaction.

Power is generated using a gas turbine combined-cycle (GTCC) system. Compared with a single-cycle gas turbine generator (GTG), the GTCC system offers higher power generation efficiency and can therefore help reduce CO_2 emissions.

Most CO_2 is generated during external combustion in the steam methane reformer (SMR), which supplies heat for the reforming reaction. To support a design focused on minimising emissions in anticipation of increasingly stringent blue ammonia definitions and certification standards, the process scheme includes a post-combustion CO_2 capture unit (PCCU). The PCCU uses chemical absorption with an amine-based solvent to recover CO_2 from flue gases produced by the SMR, GTCC, and auxiliary boiler.

Fig. 2: **Blue Ammonia FPSO process configuration**



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The CO_2 recovered by the PCCU is combined with CO_2 captured by the process-side CO_2 removal system. The combined stream is compressed to 550 barg, dehydrated and then injected into oil reservoirs or dedicated CO_2 storage formations.

Utility systems – including seawater treatment, demineralised water production, cooling water, steam generation, instrument air, nitrogen supply, and flare systems – are installed as in an onshore ammonia plant.

As discussed later, the FPSO hull offers more available space than a conventional oil FPSO, allowing some utility equipment to be installed within the hull to improve layout, access and maintainability.

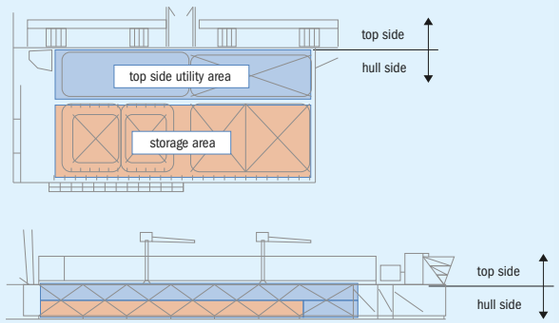
Hull concept

The Blue Ammonia FPSO hull is designed to be 400-m long, 60-m wide (excluding a 10-m deck overhang) and 30-m deep. Its ammonia storage capacity is 134,000 m^3, equivalent to approximately 40 days of production at the design capacity of 2,200 t/d. The concept retains space in the hull for additional equipment and systems.

To improve stability by lowering the centre of gravity, the design places as much topside utility equipment as practicable within the hull. This approach is intended to improve both vessel stability and space utilisation.

Fig. 3 shows a section view of the tank layout. The area previously dedicated entirely to ammonia storage has been divided into two levels. The upper section, shown in blue, is allocated to utility systems; the lower section, shown in orange, remains designated for ammonia storage.

Fig. 3: **Tank layout section views: midship (top) and side view (bottom)**



Source: TOYO

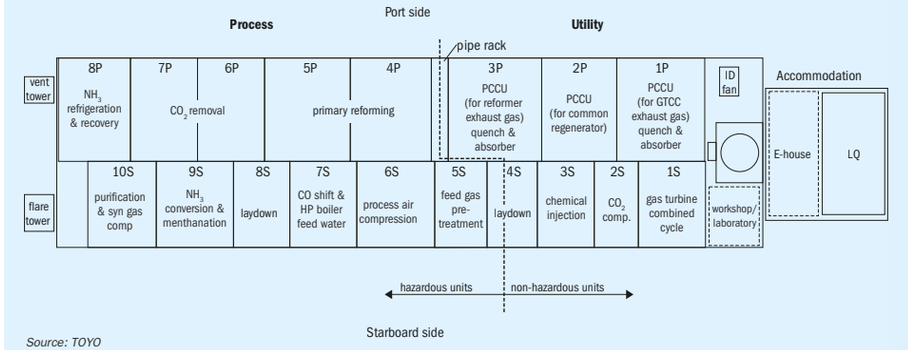
Plot plan study

For the preliminary design, each module envelope is assumed to be 40 × 40 m × 40 m, and weigh approximately 3,200 t. These assumptions are based on the lifting capacity of the module installation crane.

The FPSO concept uses a single-point mooring system, allowing the hull to rotate around the turret axis in response to wind direction. The turret side therefore remains windward. For safety, accommodation facilities – including living quarters and the E-House, which receives, controls, and distributes electricity across the FPSO – are located on the windward turret side. Utility systems and process equipment are arranged aft of these facilities, with the flare and vent stacks on the leeward side.

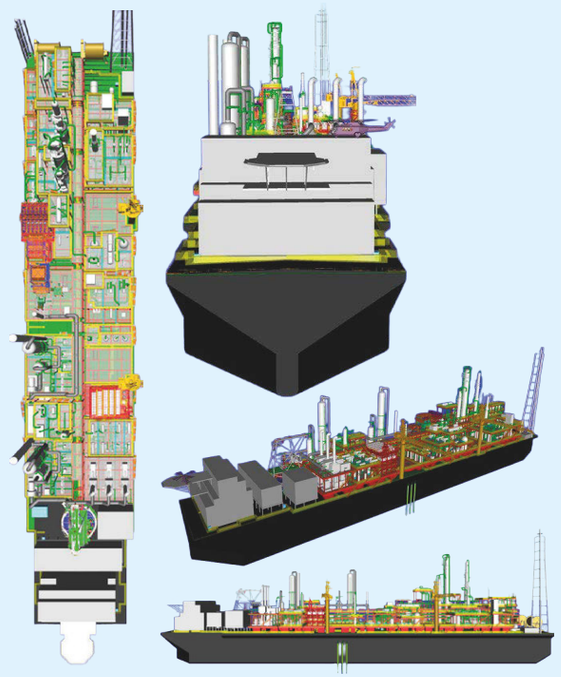
On conventional oil FPSOs, the turret and accommodation areas are typically placed at opposite ends of the vessel to reduce risks associated with associated-gas leakage. For this ammonia concept, the layout has been adapted to reduce the potential for ammonia to drift toward the living quarters under prevailing wind conditions.

Fig. 4a: **Module layout**



Source: TOYO

Fig. 4b: **Conceptual 3D model**



Source: TOYO

The module layout and conceptual 3D model are shown in Fig. 4. In line with the design objective of minimising CO_2 emissions, the layout includes a PCCU in addition to the process CO_2 removal units (Module 6P and 7P). The PCCU is distributed across three process modules:

- Module 1P: CO_2 capture from GTCC and auxiliary boiler flue gases.
- Module 3P: CO_2 capture from primary reformer flue gases.
- Module 2P: CO_2 regeneration for Modules 1P and 3P.
- CO_2 recovered in Modules 2P and 7P is compressed to 550 barg in Module 2S, dehydrated and then injected into subsea reservoirs.

The first floor of each module is elevated 6,500 mm above the main deck to account for draft, centre of gravity, and acceleration considerations.

Safety study

A comprehensive risk assessment was required as part of the AiP process for this FPSO concept. A HAZID study was conducted by a multidisciplinary team of specialists using a structured brainstorming method. Guided by predefined keywords, the team identified potential hazards, their causes and consequences, and existing safeguards.

The study assessed risks qualitatively using a corporate risk matrix across four dimensions: personnel safety, environmental impact, asset integrity, and reputational risk. Each hazard was assigned a High, Medium or Low risk rating.

The workshop produced 29 unique recommendations. No scenario was classified as High Risk, 27 were rated as Medium Risk, one was rated as Low Risk and one required action without a specific risk ranking.

Examples of the findings include:

- **Seawater contamination:** A Low Risk scenario concerned possible seawater contamination following a tube rupture in the ammonia refrigeration compressor condenser, which could result in an ammonia-seawater mixture being discharged overboard. Recommendations included reviewing the cooling configuration, assessing the feasibility of a closed-loop cooling system and implementing appropriate detection safeguards.
- **Firefighting across modules:** A Medium Risk scenario addressed possible fires involving catalyst, ammonia, hydrogen, hydrocarbons and flammable chemicals across different modules. Recommendations included providing appropriate fire-fighting systems for the identified scenarios, installing water spray systems for toxic ammonia, confirming adequate firewater capacity and paying particular attention to ammonia fire risks at the offloading area and on the main deck.
- **Escape route protection from ammonia exposure:** A Medium Risk scenario concerned the potential toxic effects of ammonia on personnel using escape routes. Recommendations included assessing the need for water sprays or water curtains along escape paths, incorporating protective systems where necessary and confirming that firewater capacity could support any additional spray systems if required.

All recommendations from the HAZID study will be tracked and addressed during subsequent engineering phases to support the implementation of appropriate risk mitigation measures.

Conclusion

Receiving AiP and completing the conceptual studies mark an initial milestone in developing a floating solution for alternative energy production. The next phase will focus on maturing the Blue Ammonia FPSO concept and addressing technical and commercial challenges identified during this work. The long-term objective is to develop a safe, reliable, and economically viable offshore solution for alternative energy supply that can contribute to global decarbonisation. ■

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From Raschig rings to precision nickel engineering

As hydrogen demand rises and sustainability pressures increase, catalyst innovation is entering a new era. **Jumal Shah** and **Ken Chlapik** of Honeywell Technologies explore how steam reforming catalysts have evolved over nine decades, from simple nickel pellets to structured catalysts and precision-engineered active metal distribution, delivering new gains in efficiency, cost reduction and carbon performance.

Steam methane reforming has been central to industrial hydrogen and synthesis gas production for around 90 years. During that time, reformers have developed from relatively modest units serving ammonia plants into large, highly efficient process reactors supporting the global production of ammonia, methanol, hydrogen and many downstream chemicals.

Much of this progress has been associated with advances in furnace design, metallurgy, burners, heat recovery and process integration. Yet reformer performance also depends on what happens inside each catalyst-filled tube. The shape, strength, chemistry and arrangement of the catalyst influence gas flow, heat transfer, methane conversion, pressure drop and the way performance changes throughout an operating cycle.

The history of reforming catalysts is therefore not simply a progression toward greater activity. It is a story of managing competing requirements. Increasing surface area can improve reaction rates but raise pressure drop. Greater porosity can improve access to active sites but weaken a pellet. A formulation that protects against carbon formation may not be required throughout the entire tube. Modern catalyst design addresses these trade-offs with greater precision, engineering performance at the scale of the material, pellet, catalyst bed and reactor.

From Raschig rings to engineered catalyst pellets

The first industrial nickel reforming catalysts introduced in the 1930s were simple by modern standards. Nickel became the preferred active metal because it combined high reforming activity with durability and an economically practical cost. Early catalyst beds used relatively simple forms, including Raschig rings, to provide exposed surface area while allowing process gas to pass through the bed.

As hydrogen and synthesis gas plants grew, the operating demands placed on catalysts also increased. Higher plant capacities, larger reformer tubes, more demanding heat fluxes and extended intervals between turnarounds required catalysts that could sustain activity without losing mechanical integrity or creating excessive resistance to gas flow. Successive generations of low-silica formulations, multi-hole pellets and more complex shapes were developed in response.

The economic effect of these improvements is cumulative. Catalyst operating cycles now typically extend for four to six years, around 50% longer than was common two decades ago. A longer cycle can allow a plant to move from replacing catalyst at every turnaround to every second turnaround, avoiding replacement and handling costs while reducing the operational risk associated with intervention. Achieving that result depends on maintaining activity, pressure drop and mechanical integrity together. A catalyst that begins with strong performance but fragments or loses stability cannot deliver the same value over the full cycle.

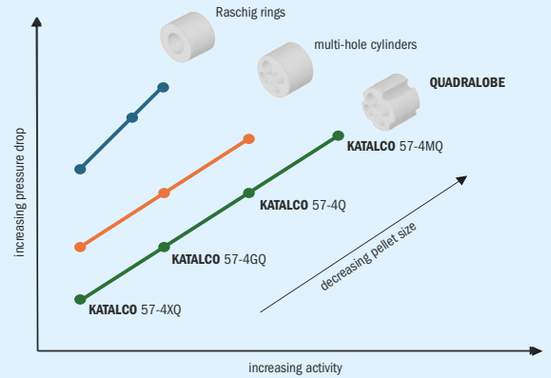
Pellet size illustrates the fundamental design compromise. Reducing pellet size provides more geometric surface area per unit of catalyst and shortens the distance reactants must travel to reach active sites. Both effects can improve apparent activity. However, smaller pellets also restrict gas flow and increase pressure drop. Catalyst development therefore requires geometries that create additional external surface without sacrificing bed voidage (the space available for gas to flow between the pellets).

Multi-channel designs were engineered to improve mass and heat transfer while maintaining strength and acceptable pressure-drop characteristics (Fig. 1). Details such as the pellet's length-to-diameter ratio also influence how particles orient during loading. A lower ratio can reduce pressure drop, while a higher ratio can encourage radial gas mixing and improve heat transfer. The appropriate balance depends on the reformer design, particularly as larger tube diameters increase the importance of radial gas mixing.

Pellet faces and fracture behaviour matter as well. Domed faces can help prevent regular stacking, preserving voids through which gas can flow. Modern pellets may also incorporate designed break points so that thermal or mechanical stress produces larger secondary fragments rather than fines (Fig. 2). This is important because fines can migrate into spaces between pellets, reduce local voidage and cause pressure drop to rise during the operating cycle.

Pressure drop is not only a hydraulic measurement. It affects the energy required to move process gas through the reformer and can restrict throughput where compression capacity is limited. Uneven fragmentation can also create local differences in flow, changing the distribution of heat and reaction within a tube. Pellet strength and controlled fracture behaviour therefore contribute directly to energy efficiency and operating flexibility, as well as reducing the risk of an early catalyst changeout.

Fig. 1: **Evolution of reforming catalyst shapes and the balance between activity and pressure drop**

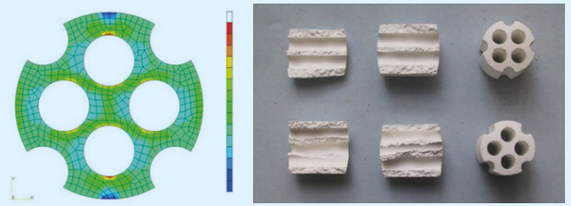


Source: Honeywell Technologies

These demands extend from geometry into the support itself. Porosity must provide sufficient surface area for nickel dispersion and limit diffusion resistance, while retaining the mechanical strength required for loading and long-term operation. The ceramic phases must remain stable under high-temperature steam exposure, minimising sintering, unwanted phase changes and the formation of inactive nickel compounds. Catalyst formulation, structural design and manufacturing conditions must therefore be considered together rather than optimised independently.

Carbon formation can deactivate the catalyst, increase pressure drop and create hot spots that may damage reformer tubes or force an unplanned shutdown. Surface chemistry therefore plays an important role in controlling this risk. Acidic sites on alumina supports can increase carbon formation, so basic promoters such as calcium may be used to neutralise surface acidity. In more demanding high-temperature or heavy-feed duties, potassium-promoted formulations can support the continuous gasification of carbon. Because promoted catalysts carry their own cost and operating-window considerations, the aim is not to use them indiscriminately, but to position them where the feed composition, heat flux and modelled carbon risk justify their use.

Fig. 2: **Finite stress analysis and controlled fracture behaviour of a QUADRALOBE™ multi-channel catalyst pellet**



Source: Honeywell Technologies

Precision at the particle and catalyst bed scale

Advances in modelling and catalyst characterisation have added another dimension to this engineering process. Although methane reacts rapidly once it reaches an active nickel site, the overall rate under many industrial conditions is constrained by the diffusion of reactants and products through the pellet's pore network. Much of the useful reaction can therefore occur in the outer region of the pellet, while nickel located deeper within it contributes less to performance.

Conventional manufacturing typically distributes nickel throughout the support. Precision manufacturing makes it possible to control its location, dispersion and density more deliberately. Honeywell Technologies' NiVARA™ technology concentrates active metal within the mass transfer-active region of the pellet, increasing the proportion of the nickel inventory that participates directly in methane conversion. The objective is not simply to reduce metal content, but to match the distribution of active sites to the physical conditions governing the reaction.

Commercial catalyst designs using this approach have achieved methane slip and approach-to-equilibrium performance comparable with conventional catalysts containing more than twice as much nickel (Fig. 3). By reducing the total nickel inventory without sacrificing performance, these designs can lower catalyst fill costs and reduce exposure to nickel-price volatility. Using less nickel also reduces the quantity of active metal that must be incorporated into each catalyst charge, lowering the material-related impact associated with catalyst manufacture. The benefit therefore extends beyond catalyst cost and resource use to the carbon footprint of producing the catalyst

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itself. In one comparison, the optimised design reduced the catalyst manufacturing carbon footprint by up to 29% relative to the previous generation catalyst.

This principle also demonstrates why catalyst design cannot be separated from its operating environment. Primary reformers, secondary reformers and autothermal reformers expose catalysts to different temperatures, heat-transfer conditions and reaction regimes. At the very high temperatures found in secondary reformers, for example, reaction is concentrated close to the pellet surface. A catalyst with a higher concentration of nickel sites at its periphery can provide the effect of greater geometric surface area without relying on a smaller pellet and the accompanying pressure-drop penalty.

In a typical secondary reformer, air introduced through a burner creates a fuel-rich combustion zone above the catalyst bed. Temperatures in this zone can reach approximately 1,000 to 1,300°C before the endothermic reforming reaction reduces the gas temperature to an outlet range of approximately 950 to 1,050°C. Under these conditions, the catalytic reaction is fast relative to diffusion through the gas film and pellet pores. Concentrating active sites near the surface is therefore a direct response to the governing reaction environment, rather than simply a strategy for reducing nickel inventory.

Conditions also change along the length of a single reformer tube (Fig. 4). Near the inlet, the loading may need to protect the bed against feed impurities. The middle section can experience high heat flux and an elevated risk of carbon formation, favouring a promoted, high-activity formulation. Further down the tube, where temperatures are higher and diffusion limitations have greater influence, a surface-enriched catalyst can improve approach to equilibrium and methane-slip performance. As molar gas flow increases along the tube, larger pellets may also be selected near the outlet to limit pressure drop.

The result is a zonal loading strategy in which different formulations, shapes and sizes perform complementary functions. This represents a significant change from treating the catalyst charge as a uniform bed. Improved process modelling and a wider range of catalyst grades allow the loading to be tailored to the feed, tube geometry, heat-flux profile and operating priorities of an individual reformer. Particle-level engineering is consequently reinforced by precision in where each catalyst is placed.

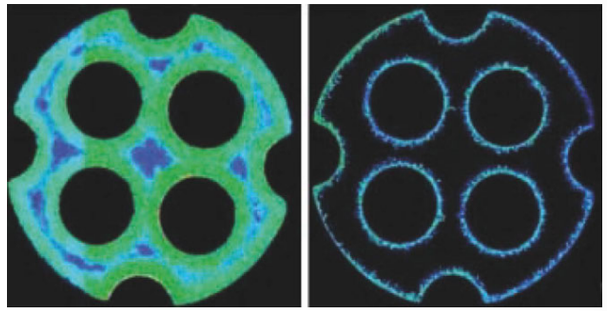


PHOTO: HONEYWELL TECHNOLOGIES

Fig. 3: Elemental map comparing nickel distribution in a conventional pellet (left) and a pellet with precision-engineered nickel distribution (right)

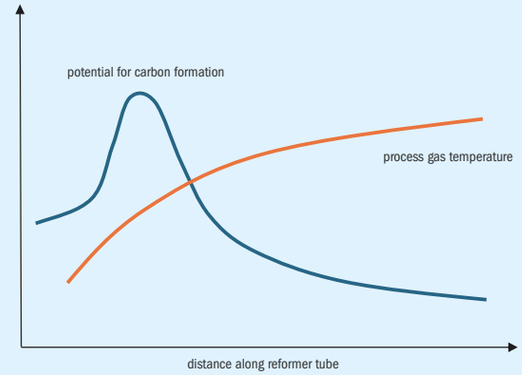
Extending precision engineering to the reactor scale

Even a carefully optimised pellet remains part of a randomly packed bed. This imposes inherent limits on the degree to which gas flow and heat transfer can be controlled. Heat enters a tubular reformer through the tube wall, but pellets near the centre of the tube are relatively distant from that surface. A gas boundary layer can also develop along the inside wall and act as a thermal barrier. At the same time, the spaces between randomly packed pellets create resistance to flow and can vary from tube to tube.

Structured catalyst technologies address these limitations by replacing random packing with an engineered reaction medium. Honeywell Technologies' CATACEL SSR™ catalyst technology, for example, uses thin metallic foils coated with catalytic material and formed into structures that stack inside the reformer tube. Their repeating geometry creates controlled flow paths, directs process gas toward the tube wall and disrupts the insulating boundary layer. The metallic substrate also conducts heat more effectively than a conventional ceramic pellet, while the high void fraction reduces hydraulic resistance.

These features allow catalyst geometry to influence the entire reformer rather than

Fig. 4: **Variation in process gas temperature and carbon-formation potential along a reformer tube**



Source: Honeywell Technologies

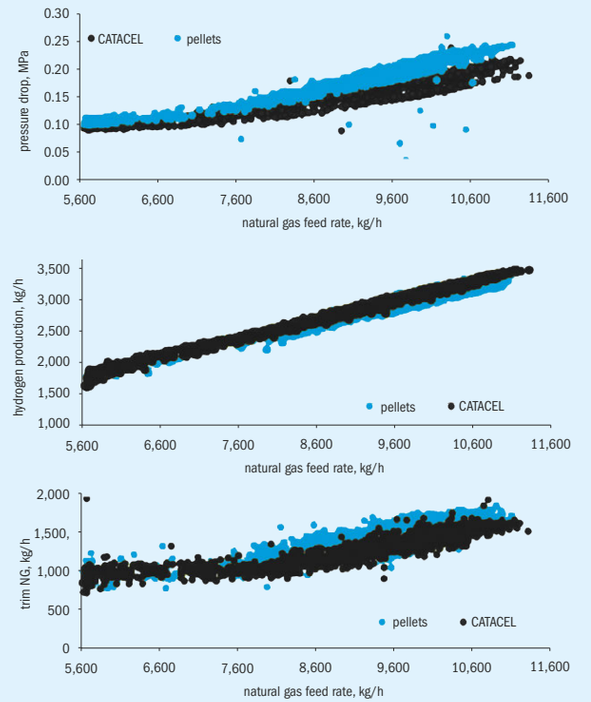
only the local reaction surface. Improved radial heat transfer can reduce the furnace firing required to achieve a given process duty. Lower process-side pressure drop can decrease compression requirements or provide additional operating flexibility at higher throughput. More consistent flow paths can also limit variation between tubes, making performance more predictable across the reformer.

The modular nature of the structure also makes the technology suitable for retrofit during a scheduled catalyst change. Individual elements are stacked within existing tubes, so the benefits can be introduced without redesigning the furnace. This matters because many operators need to improve the efficiency of installed hydrogen and syngas assets while avoiding the cost, disruption and project risk associated with major mechanical modifications.

Industrial operating experience shows the scale of the opportunity. In one side-fired steam reformer, replacement of conventional pellets with a structured catalyst reduced process-side pressure drop by approximately 25% and trim natural gas consumption by approximately 12% at maximum throughput. Over a catalyst operating cycle of nearly five years, the unit saved approximately 12,000 tonnes of natural gas and avoided around 31,000 tonnes of CO_2 emissions. The installation required no major mechanical modifications to the furnace.

The reduction in fuel use was greater at higher operating rates, when the improved transfer of heat into the process gas had the strongest effect. Hydrogen production remained broadly comparable with the previous catalyst system because the operator chose to prioritise energy efficiency rather than additional output. This illustrates an important feature of reactor-scale catalyst engineering: improved performance creates options. Depending on plant constraints and market requirements, the benefit may be taken as lower fuel consumption, higher production or additional operating margin (Fig. 5).

Fig. 5: **Performance comparison between conventional pellet catalyst and CATACEL SSR structured catalyst.**



Source: Honeywell Technologies

The next generation of reforming catalyst design

The progression from Raschig rings to multi-hole pellets, tailored active-metal distribution and structured catalysts reflects a steady expansion in the scale at which catalyst performance can be engineered. Early development concentrated on establishing activity and mechanical reliability. Later generations improved geometry, hydrothermal stability and carbon resistance. Current technologies add precise control over active-metal location, zonal loading, gas flow and heat transfer.

Future progress is unlikely to depend on a single catalyst formulation or architecture. It will come from combining materials science, manufacturing control, process modelling and operating data to design the catalyst and reactor as one system. This can mean using different pellet formulations along a tube, locating active metal only where it contributes effectively, or replacing random packing with a structure designed around the required flow and heat transfer behaviour.

As demand for hydrogen and synthesis gas grows, steam reforming will remain central to ammonia, methanol and hydrogen production, including lower-carbon plants incorporating carbon capture. Improving established reformers therefore offers an immediate route to reduce fuel use, operating costs, raw-material consumption and emissions while maintaining the reliability required by continuous-process industries.

After 90 years, the direction of catalyst innovation is clear. Performance is no longer defined only by what a catalyst contains, but by where its components are placed, how its geometry manages heat and flow, and how it works with every other part of the catalyst bed. From simple rings to precision-engineered reaction systems, the evolution continues at both the particle and reactor scale. ■

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