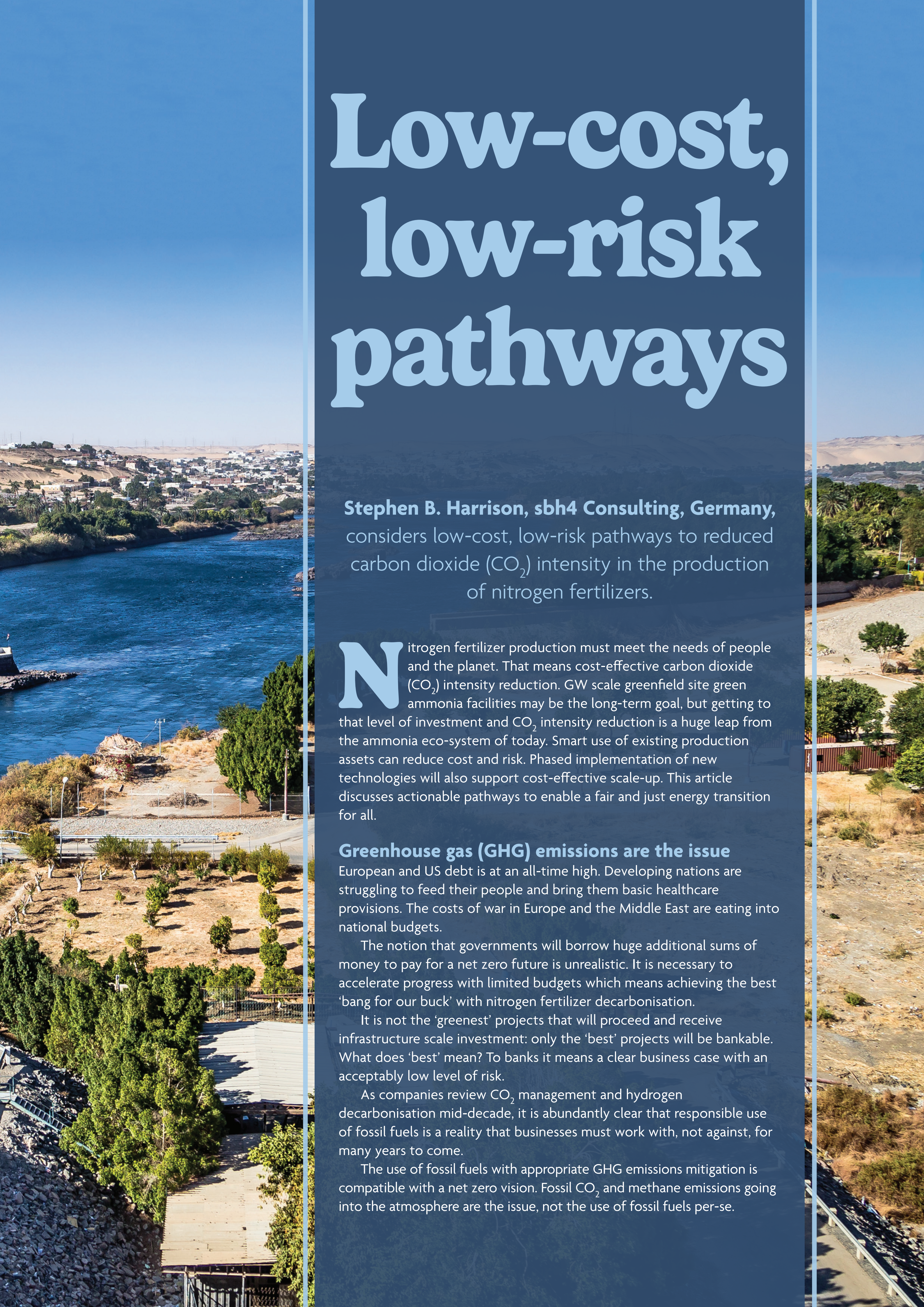

Low-cost, low-risk pathways

Stephen B. Harrison, sbh4 Consulting, Germany, considers low-cost, low-risk pathways to reduced carbon dioxide (CO_2) intensity in the production of nitrogen fertilizers.

Nitrogen fertilizer production must meet the needs of people and the planet. That means cost-effective carbon dioxide (CO_2) intensity reduction. GW scale greenfield site green ammonia facilities may be the long-term goal, but getting to that level of investment and CO_2 intensity reduction is a huge leap from the ammonia eco-system of today. Smart use of existing production assets can reduce cost and risk. Phased implementation of new technologies will also support cost-effective scale-up. This article discusses actionable pathways to enable a fair and just energy transition for all.

Greenhouse gas (GHG) emissions are the issue

European and US debt is at an all-time high. Developing nations are struggling to feed their people and bring them basic healthcare provisions. The costs of war in Europe and the Middle East are eating into national budgets.

The notion that governments will borrow huge additional sums of money to pay for a net zero future is unrealistic. It is necessary to accelerate progress with limited budgets which means achieving the best ‘bang for our buck’ with nitrogen fertilizer decarbonisation.

It is not the ‘greenest’ projects that will proceed and receive infrastructure scale investment: only the ‘best’ projects will be bankable. What does ‘best’ mean? To banks it means a clear business case with an acceptably low level of risk.

As companies review CO_2 management and hydrogen decarbonisation mid-decade, it is abundantly clear that responsible use of fossil fuels is a reality that businesses must work with, not against, for many years to come.

The use of fossil fuels with appropriate GHG emissions mitigation is compatible with a net zero vision. Fossil CO_2 and methane emissions going into the atmosphere are the issue, not the use of fossil fuels per-se.

Addressing the real problem will be the most cost-effective solution.

Sequester captured CO_2 from natural gas and coal

When ammonia is made from steam methane reforming (SMR) of natural gas, CO_2 leaving the reformer must be removed to enable the catalytic Haber-Bosch ammonia synthesis reaction to take place.

Every natural gas-fed ammonia plant already has a CO_2 capture facility. The capital expenditure (CAPEX) is spent and the energy costs for CO_2 capture are committed. Some of the CO_2 is reacted with ammonia to make urea. The remainder of the captured CO_2 can be sequestered to reduce the CO_2 intensity of nitrogen fertilizer production.

Coal-fed ammonia production is also low-hanging fruit. Immediately after coal gasification, the raw syngas is fed to a Rectisol unit where CO_2 and sulfurous gases are removed. At present, this CO_2 is generally blown into the atmosphere, unless a portion of it is required for urea production.

This captured CO_2 from coal gasifiers must also be a priority for sequestration, since the CAPEX and operational expenditure (OPEX) costs of the Rectisol plant are absorbed into the overall costs of fertilizer production. To reduce the CO_2 intensity of coal to ammonia, the only incremental costs are CO_2 transmission and sequestration.

Meaningful CO_2 reductions are being held back by 'tight' regulations

The 'blue' hydrogen CO_2 intensity levels are relevant for new-build ammonia and nitrogen fertilizer projects based on autothermal reformers (ATRs) or gas heated reformers (GHRs). This technology yields all of the CO_2 as a high-pressure stream with a high concentration of CO_2, enabling low unit costs of CO_2 capture.

However, the 'blue' hydrogen CO_2 intensity levels are not relevant for ammonia plant SMRs. This is the technology operating today in almost all gas-fed ammonia fertilizer plants. For an SMR to achieve the 'blue' certification, CO_2 must be captured from the low-pressure post-combustion flue gas in addition to the high-pressure syngas.

Post-combustion CO_2 capture is expensive since the stream pressure and CO_2 concentration are both low. On the other hand, capturing CO_2 from the high-pressure syngas stream of a SMR is cost effective, but results in only a 70% CO_2 capture rate – lower than the threshold required to hit 'blue'.

In essence, new blue ammonia ATR/GHR plants are too CAPEX intensive in a market where asset utilisations are not running at more than 90%. And, cost-effective decarbonisation retrofits to existing SMR plants will not meet the blue requirements. The tight definition of 'blue' ammonia has resulted in a stalemate.

In almost all parts of the world there has been significantly less progress to meet net zero targets than ambitions have declared. 'More of the same' is not the answer. The world needs high-impact action now. Ideas that can rapidly and cost-effectively be deployed.

Making rapid impact means the industry must accept that the next 30 years will be about rapid, retrofit decarbonisation of existing infrastructure in addition to progressive deployment of ultra-clean technology. To enable this, there must support for GHG emissions reduction in all forms rather than CO_2 intensity thresholds which indirectly promote certain technologies above others.

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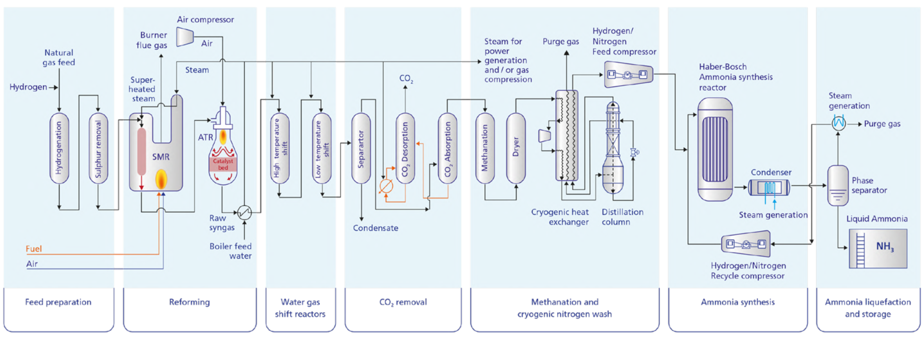


Compression duty for 1,000 tonne per day ammonia plant

Hydrogen/Nitrogen feed compression	11 MW
Air compressor (Air Separation Unit)	7 MW
Ammonia gas recycle	4 MW
Boiler water feet & cooling water pumps	1 MW

1. The SMR and the ammonia synthesis loop both generate steam, and the majority of the HP steam is from the SMR
2. Much of the compression energy is recovered from HP/MP steam expansion turbines which may either generate power and / or drive compressors on the same shaft
3. Heat energy (MP steam) for the CO_2 capture is recovered from within the process
4. The overall process, including the SMR, can export a small amount (circa 2 MW) of MP steam

Figure 1. Air-fed ammonia production process.

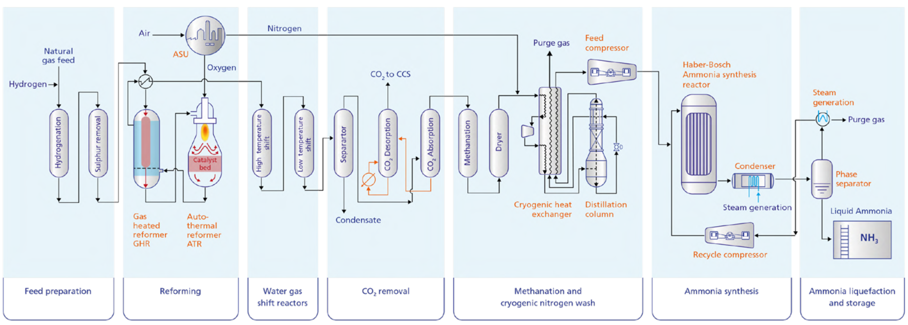


Figure 2. Blue ammonia production with GHR ATR.

Accepting the roles of carbon capture and storage (CCS), enhanced oil recovery (EOR), and enhanced gas recovery (EGR)

Despite some failures, disappointments and poor reporting in some geological CCS projects.

Figure 3. Ammonia, ammonium nitrate, and nitric acid complex.

Figure 4. CO_2 absorber and stripper on ammonia plant.

Figure 5. thyssenkrupp Uhde nitric acid plant, copyright MAN ES.

There have also been many successes. And the way to get better is to do more and learn faster. Enhanced oil recovery (EOR) and enhanced gas recovery (EGR) should also be seen as meaningful ways to store CO_2 in suitable geological formations.

Dismissal of EOR and EGR as valid CCS mechanisms due to concerns that they may increase fossil fuel production are not valid on a global scale. There is an abundance of crude oil and natural gas reserves in the Middle East and Russia: these nations will produce according to demand.

To say that EOR or EGR stimulate demand for fossil fuels is a flawed argument. And, local production avoids the cost and environmental impact of fuels distribution. Extending the life of wells can increase economic efficiency. Policy makers must take a more supportive view of EOR and EGR as valid means of CO_2 sequestration. Also, when taking into account the number of successful EOR schemes, underground geological storage of CO_2 has an overwhelmingly positive history.

A fair cost for CO_2 emissions

Excessive CO_2 in the atmosphere is the problem now and will remain a risk for eternity. At present, CO_2 emissions are too cheap: the tax penalties or incentives for CO_2 emissions reduction are too weak.

The EU Emissions Trading Scheme (ETS), Section 45Q of the US Internal Revenue Code (US 45Q), and other 'carrot or stick' schemes around the world must set a cost to CO_2 emissions which ensures there is a business case for decarbonisation investments. And, even if there is a degree of GHG emissions cost fluctuation, there must be a meaningful minimum to de-risk the business case. Higher avoided CO_2 emissions costs should be an upside, rather than a risk multiplier and business case killer.

To ensure a business case for CCS and low-carbon nitrogen fertilizers, the cost of CO_2 emissions must be in the order of €150 - 200/t. This is the approximate cost of CO_2 capture, transportation, and geological sequestration. This will represent a cost to producers, but concerns about overseas competition due to GHG emissions reduction policies moving at different speed around the world can be mitigated with embedded CO_2 cross-border tax adjustments.

The rich history of green ammonia

Almost 100 years ago, in the 1930s, ammonia was being produced from curtailed hydro power by the Hydro-Electric Power Commission of Ontario in Canada. At a similar time in Rjukan, Norway, 165 MW of electrolyser capacity across 150 modules produced 27 900 Nm^3/h of hydrogen to make ammonia through combination with nitrogen in the Haber-Bosch process. The ammonia was subsequently converted to ammonium nitrate fertilizer using the Ostwald Process.

In the 1960s and 70s, green hydrogen was produced on MW scale electrolyser schemes pulling renewable hydro power on the Aswan dam in Egypt. Green nitrogen-based fertilizers to develop local agriculture for food and cotton was the goal.

These 100 MW scale green fertilizer projects de-risked electrolyser production 50 years ago. However, the onset of cheap natural gas and a growing demand for hydro power to flow to local domestic and industrial users pushed these electrolytic hydrogen projects out of business.

For many years, electrolyser development and green ammonia production stagnated.

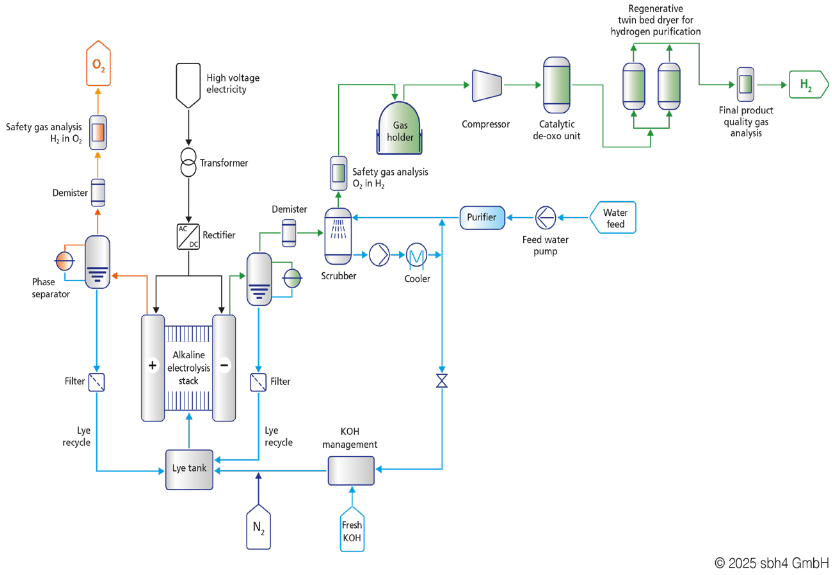
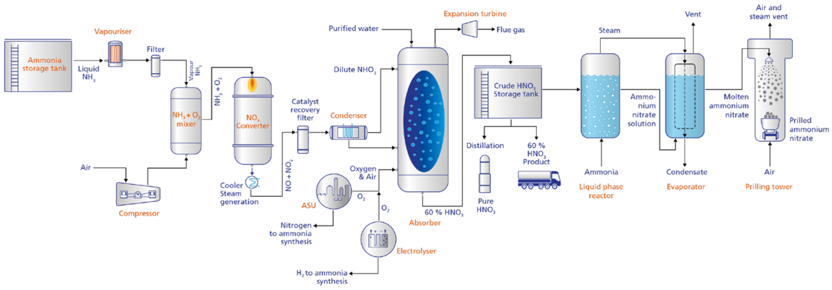


Figure 6. Low pressure alkaline water electrolysis process.

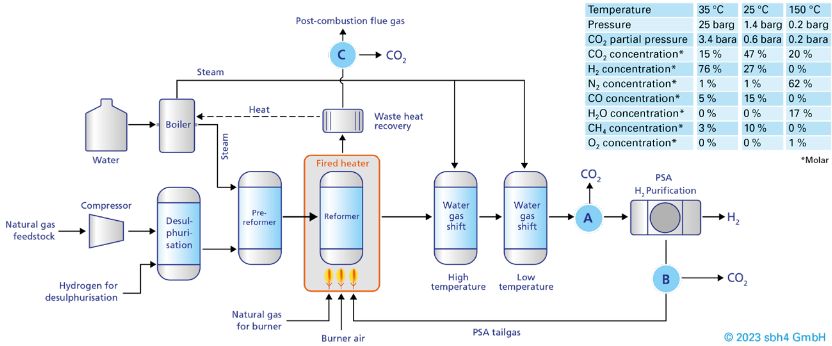


NO_x Converter	NO_x Absorber	Ammonium Nitrate Reactor
1. $4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O$	1. $6NO_2 + 3H_2O \rightleftarrows 3HNO_3 + 3HNO_2$	1. $HNO_3 + NH_3 \rightleftarrows NH_4NO_3$
2. $2NO + O_2 \rightarrow 2NO_2$	2. $3HNO_2 \rightleftarrows HNO_3 + H_2O + 2NO$	
3. $2NO_2 \rightleftarrows N_2O_4$	3. $2HNO_2 + O_2 \rightleftarrows HNO_3$	
	4. $2N_2O_4 + O_2 + 2H_2O \rightleftarrows 4HNO_3$	

Figure 7. Nitric acid and ammonium nitrate production.

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

*Molar



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

Figure 8. Potential locations for CO_2 capture from steam reforming.

GW scale green ammonia this decade

Helios is a 2.2 GW ammonia plant under construction in Neom, in the northwestern corner of The Kingdom of Saudi Arabia. Construction is more than 80% complete. Commissioning and commercial operation are due later in 2025.

The Helios project has been a visionary adventure. But has also needed to overcome challenges related to commercial, technical, and project risk. On the commercial side, the green ammonia cost is significantly higher than grey ammonia and insufficient offtakers are willing to pay the premium. As a result, the green ammonia capacity is not sold out.

On the technical side, the scheme will operate from variable wind and solar power. Late in the design phase, it was realised that the process would need to include battery energy storage to ensure the complex electrolyser, air separation, and ammonia synthesis processes remain at a stable operating load point. For this, and other reasons, the CAPEX costs escalated to more than twice the original business case estimate.

For the project execution, there have been delays in delivery of the electrolysers. These are the heart of the process and will convert desalinated sea water and renewable electricity to green hydrogen. Considering that the largest operational electrolyser park is 260 MW, producing 2200 MW (2.2 GW) of electrolyser capacity is a big ask.

The supply of critical components must be aligned to the electrolyser production plan. Delays in the electrolyser manufacturing supply chain had knock-on effects on the overall project timeline.

The realistic case for green ammonia

Given the lessons of Helios, it is becoming clear that additional GW scale projects for green ammonia production are unlikely to be funded in the short term. Furthermore, from a cost-effective climate policy perspective, it can be argued that they are not required until the world has decarbonised existing natural gas-fed SMRs on ammonia plants to a great extent.

However, proceeding with mid scale projects in the tens and low-hundreds of MW electrolyser capacity will enable learnings in green hydrogen and will represent strategic value. This scale of operation may be the default for green nitrogen fertilizer production for the next 10 - 15 years.

A compelling motivation to support green ammonia is to decentralise fertilizer production and reduce supply chain lengths. Ammonia produced on the Gulf Coast of the US must travel to mid-western corn belt.

Figure 9. The Yorke Peninsula in Australia, natural hydrogen source location.

Figure 10. Yara Sluiskil, copyright Yara International ASA.

Anhydrous ammonia is transported from the south to the north of the US by pipeline. Whilst this represents a low-cost modality to move large volumes of ammonia, farmers are not connected to the pipeline and 'last-mile' distribution costs can be material. The price to a farmer in Iowa, US can be around double the cost leaving a major production site in Texas or Louisiana.

Low cost natural hydrogen for affordable food

The extraction of natural hydrogen from underground sources could potentially revolutionise the nitrogen fertilizer sector. The number of companies active in natural hydrogen exploration and production has increased from a handful at the turn of this decade to more than 40 in 2025.

Several of the ongoing natural hydrogen exploration projects may commence commercial operations before 2030. The vision is to produce hydrogen with a low carbon intensity and at a cost less than grey or blue hydrogen derived from natural gas reforming.

The cost of natural hydrogen production is generally expended prior to commercialisation of the source. Exploration and drilling for the natural hydrogen are expensive and financially risky operations. Not all geological surveys find the pot of gold, and not every 'hunch' about the location to drill pays off.

Some natural hydrogen sources may be more dilute than had been expected making commercialisation marginal. So, the costs of failure must also be borne by the revenues generated by commercially viable natural hydrogen sources.

Depreciation of the exploration and extraction capital investment over the lifetime of the reserve is a major contributor to the cost of natural hydrogen. Well-head operating and capital costs of purification and transmission infrastructure must also be accounted for.

All in all, there are indications that natural hydrogen can be recovered at less than €1/kg from some reserves. This would be approximately 30 - 50% less expensive than blue hydrogen, and several times less expensive than green hydrogen.

Low-cost natural hydrogen means competitive ammonia and nitrogen fertilizer production. The dominoes continue to fall all the way to affordable food.

Natural hydrogen sources

The chemical and geo-mechanical mechanisms of natural hydrogen formation vary. One proposed reaction that produces natural hydrogen is between underground water and rocks which are not fully saturated with oxygen. Under the right conditions of temperature and pressure deep underground, the rocks pull oxygen out of water molecules to leave hydrogen gas. Some types of minerals in the rocks may catalyse this sub-surface reaction.

Over thousands of years, natural hydrogen may have been formed in this way. The resultant hydrogen may rise to the surface, where it may form so-called 'fairy circles'. Alternatively, it may be trapped in gas-tight underground geological formations, such as a rock dome or a salt dome. This is similar to how a natural gas or crude oil reservoir is trapped under non-porous rock.

Recent exploration has indicated that there are significant reserves of natural hydrogen under the ground. However, their replenishment rate is a lesser-known phenomenon.

The long-term sustainability of a natural hydrogen source depends on four factors: the amount of hydrogen stored in the rock formation; the rate at which fresh natural hydrogen is formed; the rate at which natural hydrogen is consumed through biological or other means underground; and the rate at which it is extracted during exploitation of the reserve.

Synergy between natural hydrogen and nitrogen fertilizers

In Europe, there are natural hydrogen sources being investigated in France and Spain. In the US, multiple locations are being drilled to validate the purity of natural hydrogen reserves and to estimated total amount of hydrogen they may contain. Parts of Africa, Australia, and Brazil are other locations where natural hydrogen has been found.

Many of these natural hydrogen sources are 'stranded' – meaning there is unlikely to be an offtaker near the source. Transportation of hydrogen will either require a capital-intensive pipeline, or operationally expensive distribution as pressurised gas or liquid. On the other hand, use of the hydrogen to produce nitrogen fertilizers will convert the hydrogen to a highly transportable product, for which there is likely to be a local or regional market.

We can expect to see a progressive transformation of the nitrogen fertilizer supply network over the next two decades as more natural hydrogen sources are commercialised with on-site fertilizer production. WF