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Erasmus Commodity & Trade Centre

Exploring the Business Case for Transatlantic Low-Emission Ammonia Trade

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Executive Summary

The aim of this project is to **explore and ex-ante evaluate the prospective business case for the trade of low-emission ammonia from the U.S. Gulf Coast (USGC) to the ARA region in comparison to other trade routes. Part of this is creating a better understanding of the necessary requirements for the market to scale. On this basis, strategic recommendations for interventions and investments are provided.**

The call for further exploring and ex-ante evaluating the business case resulted from the following observations, derived from previous CIEP and ECTC studies[1,2,3]; 1) The USGC and the ARA region are two similar port clusters with industrial complexes and large bunker markets, connected for over 50 years by molecule flows and trade spreads between WTI and Brent (crude oil) and between Henry Hub and TTF (gas). Both have related business ecosystems and are connected via trade, transactions and corporate networks,[4] with key players active at both sides of the Atlantic. 2) Europe is 'short' on renewable molecules that are needed for the energy transition. 3) Europe is 'short' on ammonia while the US is 'long', clearly indicating trade potential. 4) the trade lane further benefits from competitive transport costs and limited shipping risks.

Trade in ammonia, however, is still in an infancy stage; price mechanisms are not well established and market fundamentals beyond initial demand are poorly understood. Logistics chains are under-optimized and the articulation of regulatory frameworks in both the US and the EU is still complex and ambiguous. The current geopolitical landscape is characterized by trade wars and the ongoing conflict with Russia over Ukraine. Against this backdrop, both the US and the EU are prioritizing security of supply of key natural resources and industrial competitiveness as key policy concerns. This contemporary geopolitical landscape only further complicates the earlier set of pledges on decarbonization and energy transition by both governments and industry across the Atlantic and beyond. These developments call for action to make sure that future demand for ammonia in Europe is met. Security of supply is vital to new and existing industries to commit themselves to Europe and prosper.

This report builds on previous works of CIEP and ECTC. It takes a grounded theory approach, in which the concept of commodification pathways is embedded within the dynamic market theory of energy markets. This combined framework allows for inducing ideas about future pathways of the low-emission ammonia market by analyzing the complex interdependencies between 'structure' and 'agency' that shape the political economy of global energy trade in an evolutionary way.

Employing scenario planning techniques, the report addresses the central question: **What are the necessary requirements for the market to scale?** Four unique scenario logics were identified that follow a S-type curve typical of the dynamic market evolution:

I. Delayed market development; overcoming structural challenges

A delayed growth path of low-emission ammonia trade between the USGC and the ARA region, in which successful experiences elsewhere in the world lead the path for adoption more globally, including in the ARA region.

II. Thought it was the future, but it is replaced

An initial growth trajectory after which it plateaus; transatlantic low-emission ammonia trade is replaced by a combination of alternative, more competitive carriers (such as methanol, e-methane, and LOHC) and alternative supply centres. In this 'middle of the road' scenario, low-emission ammonia trade does provide for functionality in the demand for H_2 molecules but its relative value diminishes over time.

III. US Gulf Coast Ammonia is the future

An accelerated growth trajectory in which a 'bullish' attitude prevails. ARA-US Gulf Coast trade leads the way in what essentially is a full commodification pathway of low-emission ammonia as the leading energy carrier with increasing functionality in the identified use cases resulting in 'increasing returns'.

IV. No Business Case

A vector of combined forces and events results in a 'bearish' outlook on the overall business case.

The path forward

At the time of writing, given the regulatory landscape of the narrowly defined delegated act and the subsequent pushback from U.S. companies, coupled with the more advanced institutional demand case in Japan compared to Europe, we anticipate that the delayed market development pathway is the most plausible scenario at this moment.

In the second half of the 20th century Rotterdam became the main crude oil storage and refining hub, Amsterdam became specialized in fuel blending and storage while Antwerp developed into a fine chemicals processing hub. This emergence is not the intended result of formalized spatial planning, nor did the ARA ever become a frame of reference among planning agencies. Rather, it is the result of self-organisation (competition and cooperation) in the oil industry in correspondence and in reaction to local public policy initiatives that have culminated in the emergence of the ARA region as an internationally recognized spot market for crude oil and oil products.

Based on the analyses, we group the requirements to scale the ammonia market into three categories: physical infrastructure requirements, legal and policy requirements, and market arrangements. Physical infrastructure ensures that demand can be met, and concerns import terminals, storage, conversion facilities and transport modalities. Examples of legal and policy requirements are a permissive regulatory environment and robust CO_2 abatement targets. Market arrangements involve, for example, industry standards for the development of forward contracts, and the existence of Price Reporting Agencies (PRAs) that publish prices for low-emission ammonia.

Based on the necessary requirements identified and our assessment of the current pathway, the key recommendation is the adaptability of all stakeholders involved. The current landscape of geopolitics, trade, energy security, climate change does not allow for betting on one energy carrier, nor does it clarify the preferential energy mix of tomorrow. Thus, governments and industries must work together to create enabling conditions. This is important because ammonia is both a chemical as well as an energy carrier and could therefore contribute to both security of energy supply as well as the energy transition. Eventually, when external conditions are favourable, the USGC-ARA trade lane for low-emission ammonia could prove to be substantial. As an analogy, policy makers concluded at some point that the (socio-)economic cost of not being able to meet households or industries' gas demand was too high (value of lost demand). Therefore, infrastructure capacity was built to import LNG. Despite smaller initial volumes, LNG imports into Rotterdam saw rapid growth – due to decreasing domestic production and declining volumes of Russian gas. Even so, while liquidity of TTF was limited at the start, it has become the benchmark for the pricing of natural gas in Europe. Though the future path of low-emission ammonia remains uncertain, it can only copy natural gas' success if the necessary requirements to scale are met. Though the focus in this report is on the transatlantic route, initial volumes could come from other regions. This would nonetheless be positive for the ARA region and does not alter the requirements for the market to scale.

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1 Introduction

With the publication of the Draghi Report in 2024, competitiveness has been put firmly back on the European political agenda. The report highlights Europe's structural weaknesses and vulnerabilities. Europe runs the risk of falling further behind the US and China in terms of industrial base and output, technology & innovation and in finance & investments. Draghi's call for action is situated in an ongoing time of turbulence with trade wars, ongoing war in Ukraine, the risk of further escalating conflict in the Middle East and indeed the severe impact of climate change. All this complicates Europe's ambitions and policy pledges with regard to decarbonization and energy transition.

In this fast changing and turbulent landscape, many of the original targets set by, for example, RePowerEU will most likely not be met and are currently recalibrated. The EU originally aimed for 10 Mt of production of renewable hydrogen by 2030, complemented with another 10 Mt of renewable hydrogen imported from outside the EU. Also, the Dutch government committed itself to stimulating the production and distribution of renewable hydrogen. In April 2025, the government announced €2.1 billion to drive hydrogen production and €662 million to stimulate industrial uptake, with a renewable hydrogen obligation of 4% for industrial users, as part of the Green Growth package *(pakket voor Groene Groei).*[5] Now the initially bullish outlook on this 'green' hydrogen pathway has changed. Costs of energy have soared due to a lack of investments in legacy systems while the attractiveness of investments in offshore wind has deteriorated most notably due to worsened prospects for future electricity demand while CAPEX and financing costs have gone up. At the same time, the nitrogen regime complicates construction, maintenance and investment decisions. The business case for investment in the development of electrolysers needed for low-emission hydrogen is not there due to the lack of offtake agreements and the ongoing regulatory ambiguity. These developments call for action to ensure that future demand for ammonia in Europe is met. Security of supply is vital to new and existing industries to commit itself to Europe and prosper.

At some point, policy makers can decide that the (socio-)economic cost of not being able to meet ammonia demand becomes too high. The value of lost demand measures society's willingness to pay for security of supply. In this context, ammonia imports play an important role. Just as the case for importing LNG (see chapter 2), it can contribute to Europe's energy security while preventing losses associated with disrupted supply. This underscores the relevance of our report, which examines the pathways for ammonia market development through a scenario analysis, capturing the value of lost demand beyond solely cost considerations.

While the business case for domestic production of low-emission hydrogen is now problematic, the import potential remains (or even becomes stronger) under the current pledges. Ammonia as a hydrogen carrier holds good cards for trade and supply. Ammonia/fertilizer production was always a largely domestic affair, explaining the wide dispersion of production plants and limited international trade compared to world production. This structure is changing, in part because of rising feedstock costs in natural gas importing countries and the subsequent rationalisation and in part because of geopolitical developments. One example is the effect of current sanctions on Russia. Russia is converting more gas into ammonia due to difficulties to reach European markets and limited capacity to export the produced gas via pipelines or LNG. Since ammonia is not sanctioned, it offers an alternative avenue to monetise their gas reserves. As also new producers enter the market based on lower production costs, it is likely that international trade in ammonia will grow.

The Port of Rotterdam is well positioned to play a role in Europe's low-emission ammonia imports. It has long served as an entry – and pricing – point for commodities like crude oil, oil products, metals, while Europe's foremost natural gas price benchmark TTF is in the Netherlands. The fact that TTF offers the possibility to trade in a homogenous product (single quality) contributed much to its success. In relation to this, the import of LNG in the Netherlands did take off because the infrastructure was there and demand for gas already existed. As the Netherlands is well connected to neighbouring countries and the gas can be traded and indexed to the liquid TTF, market parties are keen to bring the gas to The Netherlands. Though different in terms of volume, Rotterdam is endowed with the infrastructure, capabilities, and demand for ammonia, and there is potential for new demand for ammonia in Amsterdam-Rotterdam-Antwerp (ARA): bunker fuels, petrochemicals, direct feedstock for power and heating generation and converting ammonia into hydrogen for a range of use cases. With the large potential demand in the ARA cluster and its throughput to the Rhine-Ruhr (sometimes referred to as ARRRA), supply and demand need to be matched in the ARA. This calls for the exploration of a business case for ARA as an ammonia trading hub that allows for transformations in time (through storage), space (through transshipment), and in form (through conversion and cracking). Trade in ammonia, however, is in an infancy stage; price mechanisms are not well established, market fundamentals beyond initial demand are poorly understood, optimized logistics chains are yet to be developed, and the articulation of regulatory frameworks is still complex and ambiguous.

Looking at near-term potential and project initiatives, Europe is likely short on ammonia, while the U.S. could be long on CCS-based ammonia. At the same time, electrolysis-based ammonia is clearly showing market potential as well. Although hydrogen development and ammonia trade may take off elsewhere too, we believe that the US Gulf Coast-ARA trade lane has the strongest potential to catalyze a hybrid market model - where long-term offtake agreements are complemented with the emergence of a spot market. Rotterdam (as the heart of the ARA cluster) and the ports in the US Gulf Coast (Houston, Corpus Cristi, Beaumont etc.) are two similar port clusters with industrial complexes and large bunker markets, connected for over 50 years by molecule flows and trade spreads between the WTI and Brent (crude oil) and between Henry Hub and TTF (gas). Both regions have therefore similar ecosystems with an exposure to transition and are connected via trade and business[6], with key players such as OCI, Shell, BP, VTTI, Vopak, Vitol, Aramco, Trafigura and Gunvor active at both sides of the Atlantic. The case for the US Gulf Coast-ARA trade lane further benefits from competitive transport costs and limited shipping risks.

U.S. based low-emission hydrogen is showing promise, and on the European side too, projects have been announced. In April 2025, Trammo, OCI and James Fisher Fendercare successfully carried out an ammonia bunkering pilot at the Port of Rotterdam.[7] Fortescue's 'Green Pioneer', a first-of-its-kind dual-fuel ammonia-powered vessel, received the Hydrogen Transport Award at the World Hydrogen 2024 Awards in Rotterdam.[8] However, significant uncertainty remains around the total addressable market size, offtake, access to financing – all of which continue to distort the business case. Our research aims to bridge the gap by giving a grounded assessment of the potential for transatlantic low-emission ammonia trade.

Therefore, the aim of this project is to explore and ex-ante evaluate the prospective business case for the trade of low-emission ammonia from the U.S. Gulf Coast (USGC) to the ARA region in comparison to other trade routes. Part of this is creating a better understanding of the necessary requirements for the market to scale. On this basis, strategic recommendations for interventions and investments are provided.

The report is organized as follows: It begins by introducing two complementary frameworks – the Commodification Pathway and the Dynamic Market Theory – which together provide a lens to analyze how market development may evolve. The key stakeholders, ongoing projects, and relevant regulatory frameworks are identified to contextualize the emerging transatlantic ammonia landscape, in Chapter 3. In chapter 4, we elaborate on how the trade of ammonia is governed by a complex web of regulatory frameworks, policies, and laws. Next, Chapter 5 compares the US Gulf Coast-ARA trade lane with alternative routes to Northwest Europe to offer insights into other potential demand and supply centers. A scenario-based approach is used to explore potential transatlantic market development pathways, anchored in key trends and uncertainties. In chapter 6, these scenarios help deduce what conditions are necessary for the market to scale. Finally, the report distils these insights to give parameters and considerations for model-based analyses of the business case.

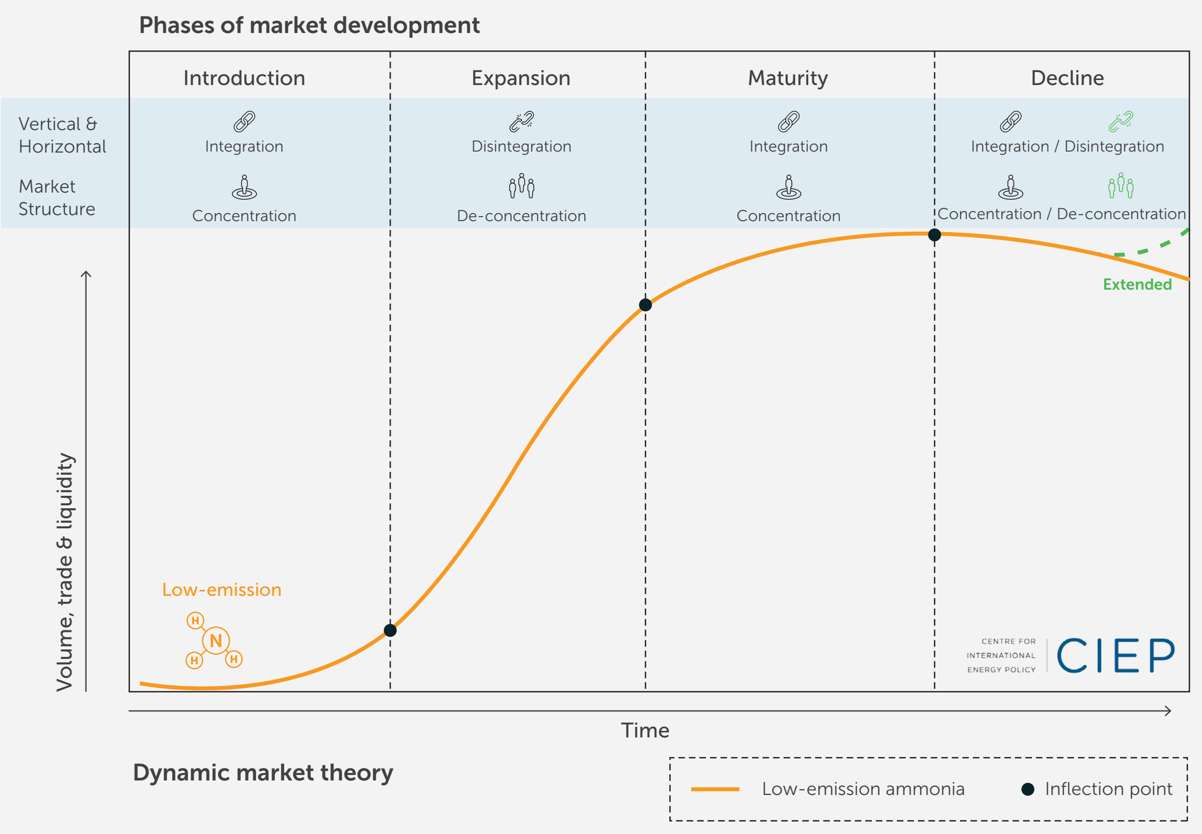
2 Theoretical framework

To examine potential transatlantic low-emission ammonia trade between the US Gulf Coast and the ARA region, the dynamic market theory and the commodification framework are used. These theories provide valuable insights into the phases of market development, how natural resources and raw materials become standardized commodities and essential conditions for the market to scale. The concept of Value of Lost Energy Demand (VoLED) is introduced at the end of this chapter to indicate that avoiding an interruption to meet energy demand comes with a cost first but that it can also avoid that economic activity (value) is lost.

2.1 The dynamic market theory

The dynamic market theory emphasises the changes that each product market undergoes throughout various stages in its lifecycle.[9] The market is viewed as a series of structures that evolve over time, rather than as a static structure.[10] A market typically progresses through four phases: introduction, expansion, maturity and decline (see figure 1). For this analysis, the focus will be on the first and second phase, as these are key to gaining a better understanding of the necessary requirements for the market to scale. The following section draws on CIEPs earlier study 'Securing Low Carbon Hydrogen Supply',[11] applying its insights on the dynamic market theory to development of the low-emission ammonia market.

Figure 1. Illustration of the Dynamic Market Theory

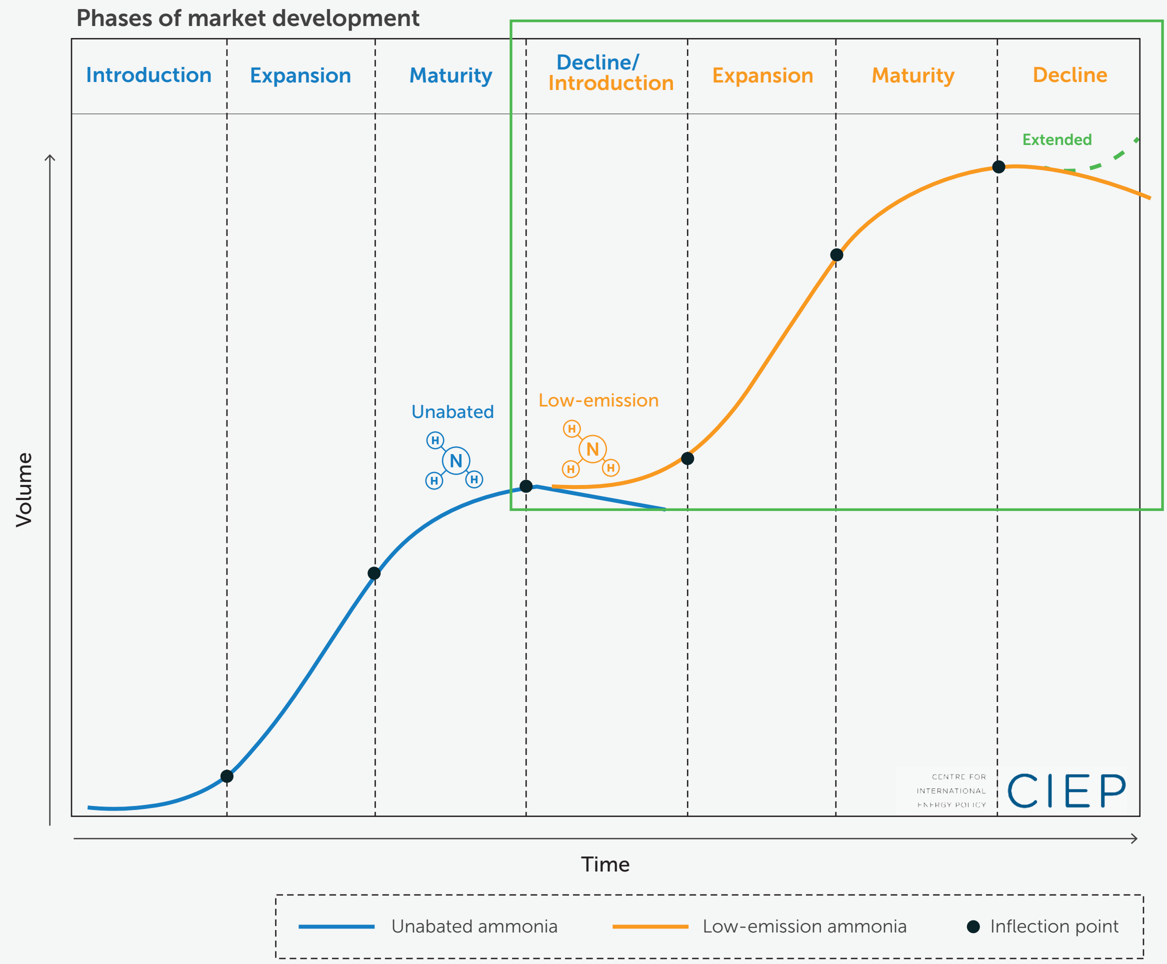


Introduction phase

The introduction phase is characterized by a relatively small-scale market, initially with minimal or no profits, and a limited number of (concentrated) suppliers and consumers.[12] It is the innovation stage of a product as the focus is initially on research, development, and experimentation with pilots, demonstration projects and scaling up to more industrial size in the later part of the introduction phase.

Ammonia has been used in fertilizer production for more than a hundred years and is by no means a new innovation. However, in light of the energy transition, low-emission ammonia — both from natural gas with CCS and via electrolysis — has emerged as a new product as an energy carrier. Low-emission ammonia necessitates new production processes and opens the door to new applications. The value chain and market players may differ from conventional ammonia producers and users. Currently, low-emission ammonia is a small market, with minimal profits and a limited number of suppliers and consumers. Most of the projects globally are in the concept and feasibility phase. Therefore, within this framework, low-emission ammonia is considered an innovation and currently in the introduction phase (see Figure 2).

Figure 2. S-curve for unabated and low-emission ammonia



In this phase, there is a high degree of chain dependency between stakeholders in the new value chain. The limited number of producers and producing countries limits substitution possibilities, which provides the supplying party with asymmetric market power and makes disruption of supply a significant risk to off-takers. At the same time, the pace of demand development and the pace of cost reduction pose long-term risks for suppliers who are early entrants in the low-emission ammonia value chain. Suppliers need demand security to mitigate the risks of high CAPEX investments, while off-takers simultaneously require supply security to gain the confidence necessary to make their own investments for applications.

To deal with the insecurities and abovementioned risks, effective cooperation between stakeholders in the value chain is necessary. This is typically done through vertical integration via integrated companies, consortia, joint ventures and long-term contracts or a combination of these. Long-term contracts with solid penalties on non-delivery can help guarantee delivery but also timely investments to avert future shortages. A form of horizontal integration, such as joint purchasing, could be beneficial in this phase of market development. The EU's plan to launch a joint purchasing programme for hydrogen carriers in September 2025 could help to increase leverage and enable especially small off-takers to secure volumes.[13] At this stage, competition authorities should permit a certain degree of cooperation between companies to enable for the market to scale along the value chain, while at the same time ensure that this does not lead to the abuse of market power for other market participants by increasing the barriers to entry.[14]

As the market scales and moves from the introduction phase to the expansion phase, supply issues might occur because of insufficient redundancy of capacity in the infrastructure, although existing market players will likely expand infrastructures when they can reach new clients. Nevertheless, smaller buyers may not generate sufficient incentives for such investments to materialise in a timely fashion. A more likely development is that demand will grow in the vicinity of the infrastructure and smaller demand centres further removed from the infrastructure will be served by other means of transportation first before large volume pipelines emerge. Smaller coastal or riverside demand centres can benefit from break-bulk supplies. Moreover, dedicated point-to-point connections that were sufficient for the introduction phase, may result in the inability to reach other customers as it does not allow for the rerouting of flows.

Expansion phase

The expansion phase is characterized by a rapidly growing market and new entrants that quickly diminish market concentration, increasing market competitiveness.[15] Incumbents are challenged by new organizations that can compete on price, with new volumes. This suggests that policy measures to reduce market concentration in the introduction phase are often not necessary because they are resolved by market dynamics. In the later stages of the expansion phase, it becomes more common for firms to disintegrate, specialize and focus on specific parts of the value chain to optimize their processes. Although there is still collaboration, there is a tendency towards de-concentration (horizontal) and de-integration (vertical). In this phase, prices are expected to decrease, and the low-emission ammonia market would likely expand beyond the current demand sectors, extending into new applications in energy, potentially as a direct fuel or indirectly for its hydrogen content.

Many of the risks from the introduction phase are also present in the beginning of the expansion phase. However, as the market grows new issues are likely to arise. While the introduction phase is about connecting production and consumption through vertical integration, in the expansion phase, the emphasis is on expanding demand and ensuring efficient ammonia or hydrogen distribution. Newcomers in this phase rely on accessibility of infrastructure and services such as storage, transportation and possibly conversion.

The EU's proposed joint purchasing could result in an oligopsony,[16] which potentially becomes problematic in the late expansion phase if it hinders newcomers from entering the market. Timely liberalisation of trade and access to infrastructure could offer a solution, however, implementing these measures too early could hinder value chain development.

Currently, the European Union is pursuing a regulatory framework for hydrogen modelled after the natural gas market, with unbundling and legal separation between networks, production and distribution.[17] Such an open access model can work well in the late expansion or maturity phase of a market, where multiple suppliers and buyers are actively participating. However, legal separation might form a barrier for market development in the introduction and early expansion phase, as it obstructs various forms of vertical integration, key for supply as well as demand security in a market with few participants.

Maturity phase

In the late expansion phase and early maturity phase, demand growth slows down and suppliers focus on maintaining or growing their market share through (international) mergers and acquisitions, again increasing market concentration. In this phase competition policy becomes more relevant. Where vertically integrated value chains were challenged by specialized firms in the late expansion phase, in the maturity phase vertical and horizontal integration is likely to increase again. Natural monopolies may be broken up by imposed competition policy along the lines of the gas and electricity market model, or alternatively no competition policy interventions are needed in what in essence are competitive markets at a global level such as the markets for crude oil and products.

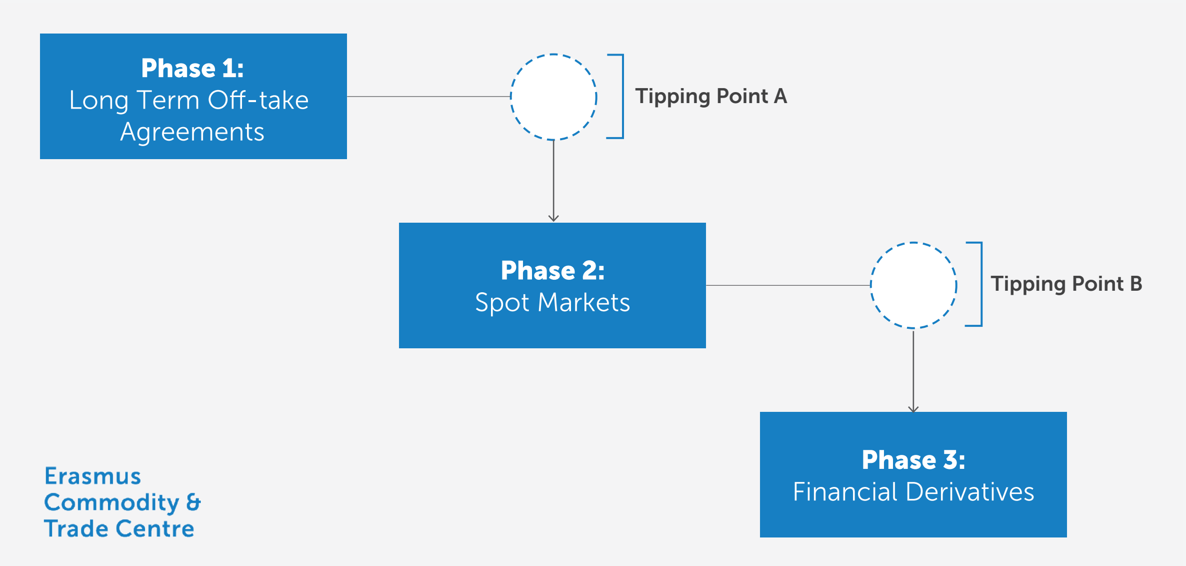
Decline phase

In the decline phase, demand stagnates or declines, only a few companies remain, and competition regulation becomes even more important. The remaining companies may be challenged by innovative newcomers, leading to the emergence of new applications and potentially extending the market lifecycle when new markets can be developed.

2.2 The commodification pathway

The three-phase commodification framework[18] provides a structural theory for assessing the development of a commodity market, and its progression through increased capacity for self-organization (see Figure 3 for an illustration).

Figure 3. The Commodification Pathway



Phase 1: Long-Term Offtake Agreements

The first phase of the commodification framework largely corresponds with the introduction and early expansion phase of the dynamic market theory as it is characterized by more rigid market fundamentals; there is limited and inflexible supply, and relatively inelastic and concentrated demand. The market is largely bilateral, with long term offtake agreements to mitigate supply risks. While spot trading can be present, it concerns the physical commodity only and is minimal in volume and activity. It can serve as a vent for conjunctural changes in demand. Interactions in this phase are informal, highly specialized, and/or incidental. There is a lack of price transparency. Prices could be linked to other commodities and can be fixed. Market infrastructure, including transport capacity, inventory, and manufacturing capital are largely optimized and locked in, which means it cannot quickly adjust to changes in market fundamentals. Provisions in the long-term contracts help to mitigate some of the inflexibilities but may not be sufficient to mitigate large swings in market fundamentals. As a result of these factors, the market is less efficient in adapting to large disequilibria than in a late expansion or more mature market.

Though demand-, value chain-, and financial risks are also present to a certain extent, the market structure is shaped by the need for market players to mitigate supply risks. Production projects are capital intensive with substantial upfront risks in capital expenditure, necessitating long-term financing. Transaction costs are managed through long-term offtake agreements or, alternatively, through vertical integration of the supply chain that allows market participants to internalize risks, rewards and transaction costs.[19]

Low-emission ammonia is currently in the first phase of the commodification pathway. Long-term offtake agreements and vertically integrated value chains are emerging as the dominant mode of trading, although trade volumes in this nascent market remain negligible as of now. Close to 20 Mt of traditionally produced ammonia, comprising merely 10% of total ammonia production, is for exports.[20] In 2019 and 2020, only around 500,000 to 675,000 tonnes of volume were exchanged on a fixed-price spot basis, much less than the 18-20 Mt traded through contracts.[21] ExxonMobil signed agreements with Trammo and Marubeni for the delivery of low-emission ammonia from its Baytown facility in Texas.[22,23] Previously, JERA had concluded a project framework agreement with ExxonMobil to procure 500,000 tonnes of low-emission ammonia from the same Baytown project to meet demand in Japan. With the Baytown facility expected to produce around 1 million metric tonnes of ammonia annually, these agreements exemplify the market's positioning in phase 1 of the commodification pathway, where long-term offtakes are the primary mechanism to de-risk investments. In such a landscape, there is a lack of price transparency and liquidity that constraints new entrants in the market. Supply is geographically concentrated based on the availability of natural gas or green electricity in a region.

Tipping Point A

The commodification pathway conceptualizes a tipping point after phase 1. Here the market undergoes a restructuring that propels the trade mechanism from long-term offtake agreements to include more variety in the duration of trade agreements and spot markets. This tipping point includes:

- Diversification of demand
- Expansion of infrastructure and hardware
- Development of information systems
- Permissive regulatory environment
- Introduction of forward contracts

Diversification of demand could take place both in terms of increased volume (to new and existing markets) and/or the emergence of new use cases that creates new demand markets. It could stem from top-down stimuli like government intervention and climate policies, or from bottom-up factors such as innovation within the value chain that introduces new efficiencies, technologies, or use cases for a commodity. These shifting demand factors may lead to scaling up of the infrastructure and hardware that support the commodity's supply and transformation across space, time, and form. Investments in the supply chain take shape and bottlenecks are alleviated through supply chain optimization and 'learning-by-doing'. Over time, information systems develop and evolve to become more transparent in response to new and a more diverse demand, challenging opaque pricing mechanisms. A permissive regulatory environment could develop to accommodate shifting demand patterns. The introduction of forward contracts at the exchange is an initial sign of market participants' willingness to diversify into other venues. Accompanied by this, PRA's (Price Reporting Agencies) start publishing quotes for products resulting the onset of price transparency. The commodification pathway theory views this stage as a potential 'make-or-break' element in the sophistication of a commodity market. Although, it is not given that the market evolves from the first phase, these elements and positive feedback mechanisms can tip the market towards phase 2.

In the context of low-emission ammonia, some recent developments have shown positive progress on certain factors within Tipping Point A. There are decarbonization targets for high-emission sectors espoused in national and international policies and laws. The potential use-cases for low-emission ammonia are expanding, with growing interest in its potential role as a clean energy carrier and direct fuel in maritime transport and power generation. On the regulatory front, the IMO has approved interim guidelines for the general use of ammonia as a fuel.[24] Changes to the IGC Code that are set to take effect on July 1, 2026, will officially permit the use of ammonia cargo as fuel.[25] Previously restricted by the IMO, these evolving regulations on the use of ammonia signal a shifting and more permissive regulatory landscape for ammonia.

Phase 2: Spot Markets

As the commodity market matures, exposure to supply risks decreases as more suppliers enter the market in response to new and diversified demand. This diversification makes production capacity more flexible, and hence more resilient to disruptions. With expanded upstream infrastructure and relatively fixed total costs, production volumes increase through efficiency gains. Incremental increase in yields allows producers to tap into new markets by selling excess supply on the spot market. This creates greater arbitrage opportunities. Supply flexibility enables trade to manage market disequilibria more effectively by leveraging better information systems and clearer price signals from the spot market.

In phase 2, the supply risk decreases whereas risks such as flat price, basis, spread, margin, volume, liquidity, and operational risks emerge. While phase one contracts typically had a very long duration, phase two is characterised by more variety in contract duration. In terms of the pricing of the contract, a small percentage of spot market indexation is introduced. Towards the end of phase two, the duration of contracts will tend to become a bit shorter whereas the percentage of spot indexation increases. Regarding market participants' ability to hedge against risks, the market develops more sophisticated trading instruments. Particularly, forward contracts emerge to hedge against spot price volatility. However, initially in phase two, these contracts remain highly customized bilateral agreements as there still is limited liquidity.

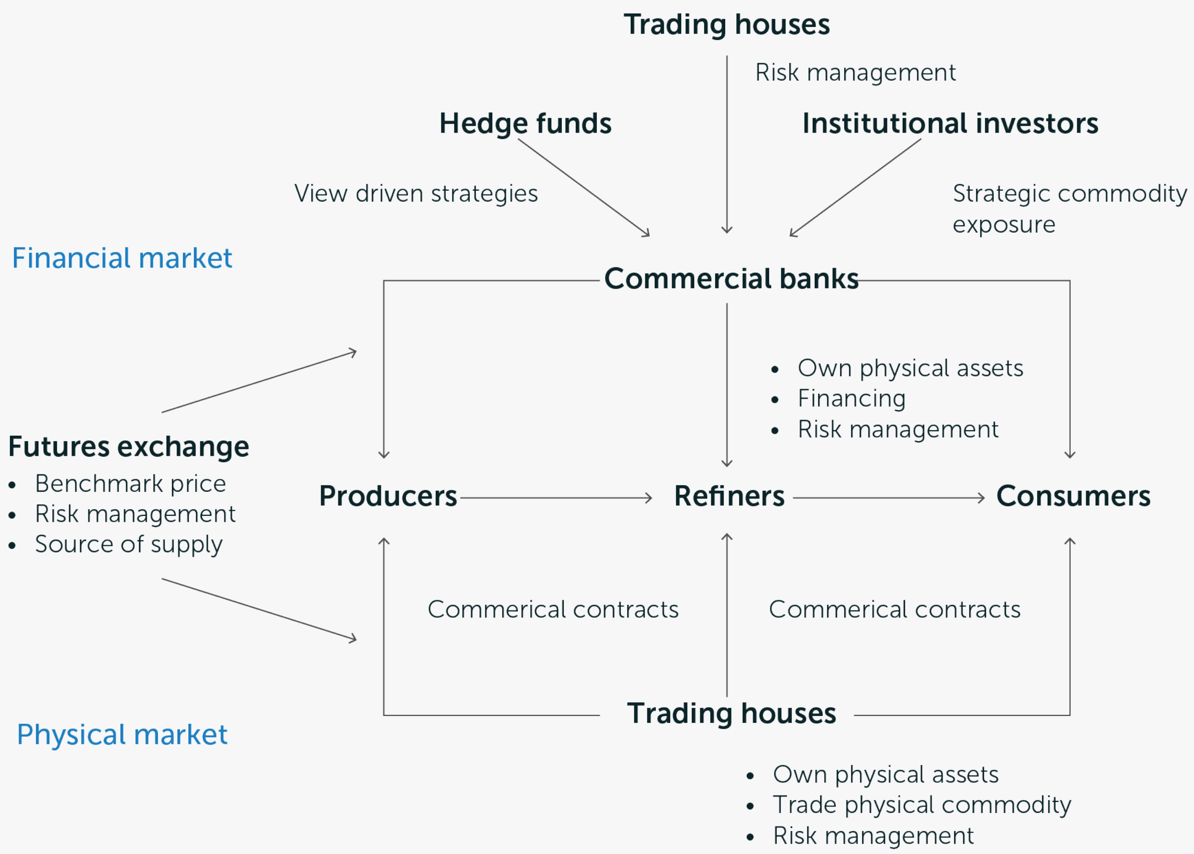
In the case of ammonia, currently initiatives are taken by the Association of International Energy Negotiators (AIEN) to design and market templates for forward contracts of US based blue ammonia trade.

Tipping Point B and the transition into Phase 3: Financial Derivatives

At this stage, market participants face diverse risks. They balance the transaction costs of striking contracts while responding quickly to price volatility in a market that yet has insufficient price transparency. Market players respond by trying to reduce transaction costs by standardizing forward contracts that enhance liquidity and are more readily transferrable. As the market matures in this direction, exchanges emerge and act as third-party clearing mechanisms, reducing counterparty risk. This shift to standardized, highly liquid futures contracts separate the contracts from delivery of the physical good, allowing for a broader range of actors to participate. Commercial banks, institutional investors, and hedge funds enter the space to trade futures contracts and financialization occurs. This enhances liquidity and trade frequency, allowing commodity traders and producers a more reliable mechanism for managing future price risks.

This tips the market into the third and final phase, where financialized instruments are introduced on commodity exchanges. Price discovery occurs on the exchange, driven by the liquidity provided. Price transparency is secured as the future price converges with the spot price as contracts mature. Contracts between producers and buyers could still have a long duration. However, due to the liquid and transparent nature of products traded on the exchange there may be less incentive to rely on long term contracts only. Instead of this, contracts with shorter duration and more spot price indexation may provide flexibility and optimisation possibilities to both parties. The final form of the commodity market resembles the one in Figure 4 below.

Figure 4. Commodity Market Overview[26]

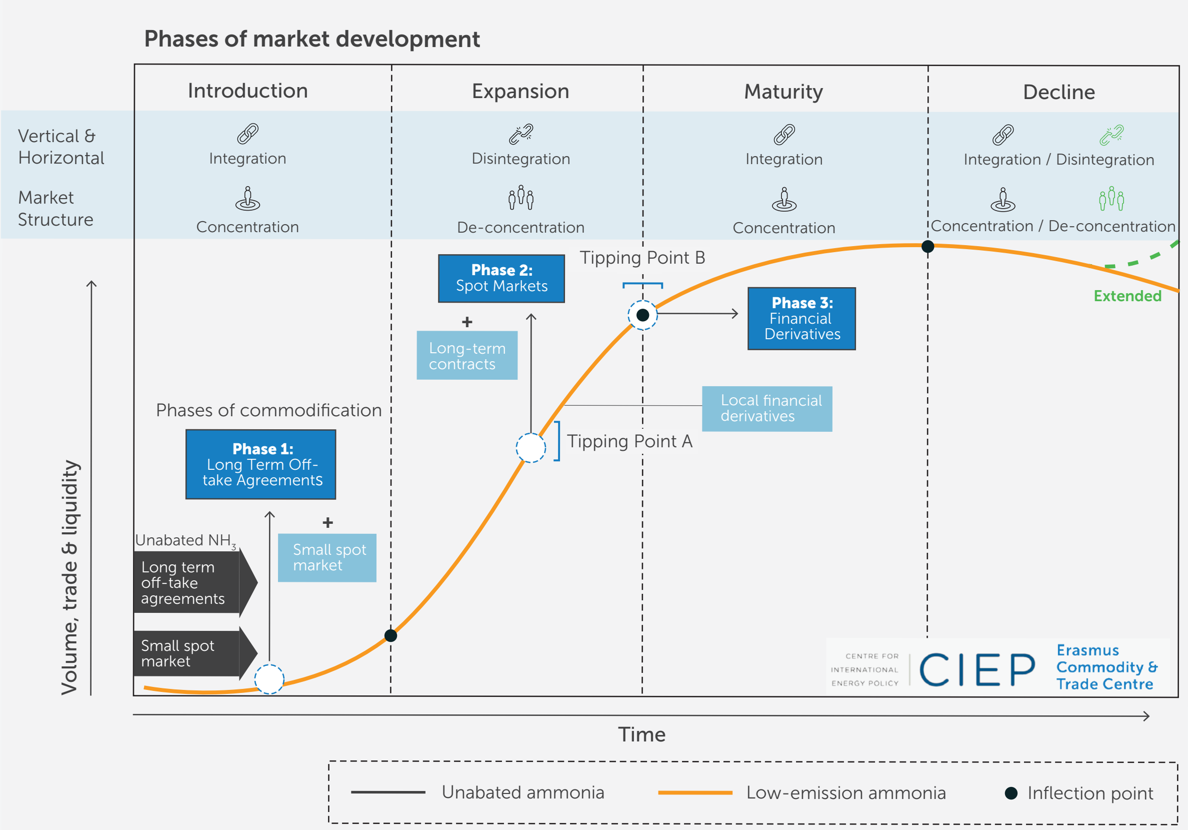


2.3 Integrating insights for market scaling

The dynamic market theory and the commodification pathway provide two distinct yet complementary perspectives on market development and commodification of goods. While the dynamic market theory focuses on market structure and competitive dynamics, the commodification pathway describes trade mechanisms and how goods become fungible commodities. Together, the two theories provide critical insights into how emerging markets transition into mature trade ecosystems, thus providing a valuable lens to examine the possible evolution of the low-emission ammonia market and its accompanying pre-requisites.

Figure 5 places the commodification pathway within the dynamic market framework, indicating how the dominant forms of trade in each phase of the commodification pathway align with the phases of market development.

Figure 5. Placing the commodification pathway in the dynamic market framework



The introduction phase of the dynamic market theory largely corresponds to phase 1 of the commodification pathway. At this stage, the market structure is characterized by limited supply, concentrated demand, and trade via specialized bilateral contractual structures. The current state of the low-emission ammonia market aligns with the first phase of both theories.

During the initial phase of market development, the regulatory environment must allow for a certain degree of cooperation so demand and supply security can be guaranteed along the value chain via vertical integration in the form of consortia, joint ventures or (bilateral) long term contracts. Policy support is necessary to incentivise early adoption of low-emission ammonia in sectors like the fertilizer, shipping and power sector.

As the market grows and moves into the expansion phase of the dynamic market theory, new suppliers emerge, and demand diversifies. Some spot trading may exist in the first phase of the commodification pathway but it increases and becomes more mature in phase 2. Positive feedback mechanisms, such as efficiency gains through 'learning-by-doing', may develop and shift market dynamics.

To support the growth of the market, sufficient infrastructure is essential. This infrastructure should be accessible to new entrants to enable competition. The timing of potential market liberalisation is key and must align with the market's development phase: if implemented too early, it may hinder participants from establishing value chains; if delayed too long, it could impede new entrants from accessing the market preserving an oligopolistic market structure, and limiting market growth. Additionally, to support the diversification of demand, permissive regulation for the handling and use of ammonia in new demand sectors will likely be necessary. If these conditions are met, the market may move further into the expansion phase and potentially tip it towards the second phase of the commodification pathway, where spot trading becomes increasingly common. It may also be complemented by the creation of the first localized financial derivatives.

As liquidity and standardization of contracts increase further, financialization occurs on a more global level and the market moves towards maturity, supported by sophisticated financial instruments. Exchanges and institutional players then take a central role in price setting and risk management. This is the final phase of the commodification pathway and the transition towards the maturity phase in the dynamic market theory. The low-emission ammonia market, still in a very nascent stage, is far from this phase of market evolution.

Value of Lost Energy Demand

In addition to the perspectives provided by the dynamic market theory and the commodification pathway, the concept of value of lost energy demand can also help explain why pathways may evolve in a certain way. The value of lost energy demand refers to the (socio-)economic cost of not being able to meet energy demand when and where it is needed. If (potential) demand exists, for example, from industries, households or power plants, but infrastructure capacity or supply to meet it is lacking, value is lost. This may result in forgone opportunities or blunt damage to the European economy and society as witnessed during the energy crisis in the wake of the invasion of Russia into Ukraine, when Europe ran out of gas. The concept is commonly used in the electricity sector under the term Value of Lost Load (VoLL), which serves as a quantitative measure to indicate the willingness to pay for avoiding power interruption and ensuring security of supply.[27] The value of lost energy demand is thus a quantitative measure of energy users' or society's willingness to pay for security of supply. It is a useful input for determining the optimal balance point between securing energy supply and ensuring its affordability.[28]

The analogy with LNG below illustrates how VoLED can help explain why certain pathways evolve differently than expected, shaping both their trajectory and intensity.

The Case for LNG

Implicitly, recognition of the value of lost energy demand was an important factor in the early liquefied natural gas (LNG) business case. Initially, in the 1990s and early 2000s, many viewed LNG imports as too expensive compared to alternatives. However, an institutional, policy, and regulatory framework materialized allowing for positive business cases for LNG-investments. Investments were made in import terminals, liquefaction plants and relatively expensive long-term contracts were signed, even though the short-term costs appeared high. Over time, the role of LNG for satisfying global gas demand – and the avoided costs of unmet energy demand or higher prices for end-users – have proven the strategic value of those investments. In short, the institutional policy and regulatory framework made the investments possible, despite cheaper energy supplies that might have been theoretically available, including pipeline gas that proved to be so problematic by 2022. Not being ready to import LNG, when the conditions changed unexpectedly, proved to be extremely problematic. Northwest European countries might want to be ready for low-carbon ammonia imports.

The analogy with the LNG market offers insights into the emerging low-emission ammonia market. The LNG market grew from long-term bilateral contracts with restrictions on cargo diversions. The price was indexed to oil and oil products.[29] Over time, trade between exporting countries and importing countries grew while the pricing of LNG shifted towards hub-based prices. The TTF in the Netherlands and the Henry Hub in the U.S. emerged as key price benchmarks. The share of spot sales in global LNG imports grew from under 5% in 2005 to 35% by 2022.[30] The LNG market has traditionally relied on long-term contracts that have been instrumental in financing large-scale LNG projects. In a significant development, the LNG market progressed towards greater commodification with the introduction of standardized financial derivatives. In June 2024, Singapore-based Commodity Futures Exchange and Clearinghouse Abaxx Exchange introduced centrally cleared, physically deliverable commodity futures contracts in LNG for key markets including the Gulf of Mexico, Northwest Europe, and North Pacific

Asia.[31,32] Notably, the first over-the-counter LNG cargo trade was indexed to Abaxx's Gulf of Mexico LNG future in March 2025, reflecting market confidence for the contract.[33] These contracts enhance the price discovery mechanism and offer sophisticated risk management tools to market participants, thereby enhancing liquidity in the LNG market. What was initially thought to be a market that would not take off due to the high costs can now be seen tipping towards the final phase of commodification.

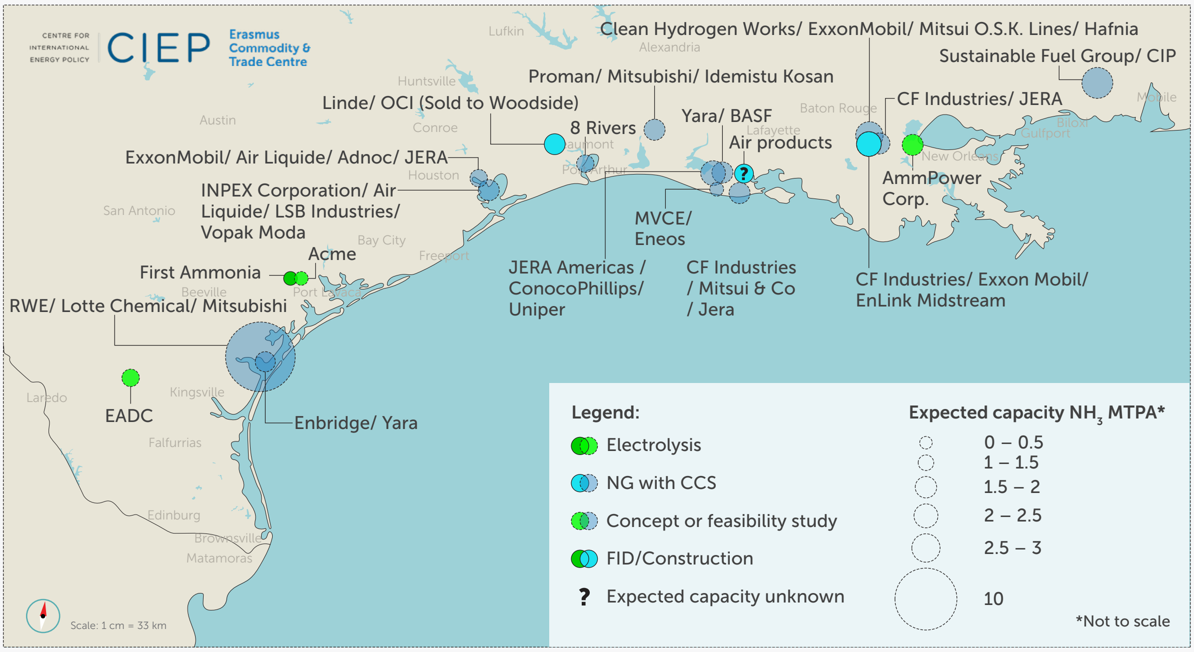
A similar case can be made for the role of low-emission ammonia in our future energy system. The Association of International Energy Negotiators (AIEN) is already in the process of setting up a Hydrogen taskforce with the aim of designing and marketing of standard templates for forward contracts While current cost estimates may suggest that importing low-emission ammonia is not (yet) competitive with alternatives, the strategic benefit and potential value it can offer in times of energy scarcity, can outweigh the upfront cost premium. Taking into account the value of lost energy demand into future business case evaluations (evaluations from a private perspective, but most certainly so from the public interest perspective) and model simulations can lead to a more realistic assessment of the low-emission ammonia import business case and its role in the wider energy system. The institutional, policy, and regulatory framework might be developed accordingly.

3 Current facilities, and status of announced projects in the US Gulf Coast and ARA region

3.1 Low-emission ammonia in the US Gulf Coast

A substantial number of low-emission ammonia export projects have been announced in recent years in the US Gulf Coast. As shown in Figure 6, most of the announced projects remain at the concept stage or are currently undergoing feasibility studies, with only a select few having taken a final investment decision (FID). The type of stakeholders involved, as well as the status of projects, appear to differ between those that aim to use natural gas and Carbon Capture and Storage (CCS) versus those intending to use electrolysis for hydrogen production. Projects relying on CCS typically have more established consortia and clearer partnership models, while electrolysis-based projects tend to be at earlier pre-development stages, with less clarity around the specific stakeholders and their role in the venture.

Figure 6. Low-emission ammonia export projects announced in the US Gulf Coast[34]



Note: *Graph is not exhaustive. Green bullets represent hydrogen projects based on electrolysis, blue bullets represent projects based on natural gas and CCS. The facilities shown include publicly announced projects that have expressed the intention to also export ammonia. Graph was made by CIEP and ECTC. Data sources: IEA, October 2024, Hydrogen Production and Infrastructure Projects Database, https://www.iea.org/data-and-statistics/data-product/hydrogen-production-and-infrastructure-projects-database, and company websites.*

Ammonia production via natural gas and CCS

Most of the announced projects in the US Gulf Coast focus on producing ammonia from natural gas combined with CCS technology. The consortia initiating these projects often include a mix of fertiliser producers, oil and gas companies, industrial gas firms, as well as storage and transportation infrastructure providers. Additionally, they often include a Japanese off-taker as a key partner. Together they form vertically integrated partnerships across the value chain to share the risks and allow for more efficient project development. A wide variety of collaboration structures are emerging. However, a review of these joint ventures shows that organizations tend to assume similar roles across various projects, reflecting their specific capabilities and strategic interests.

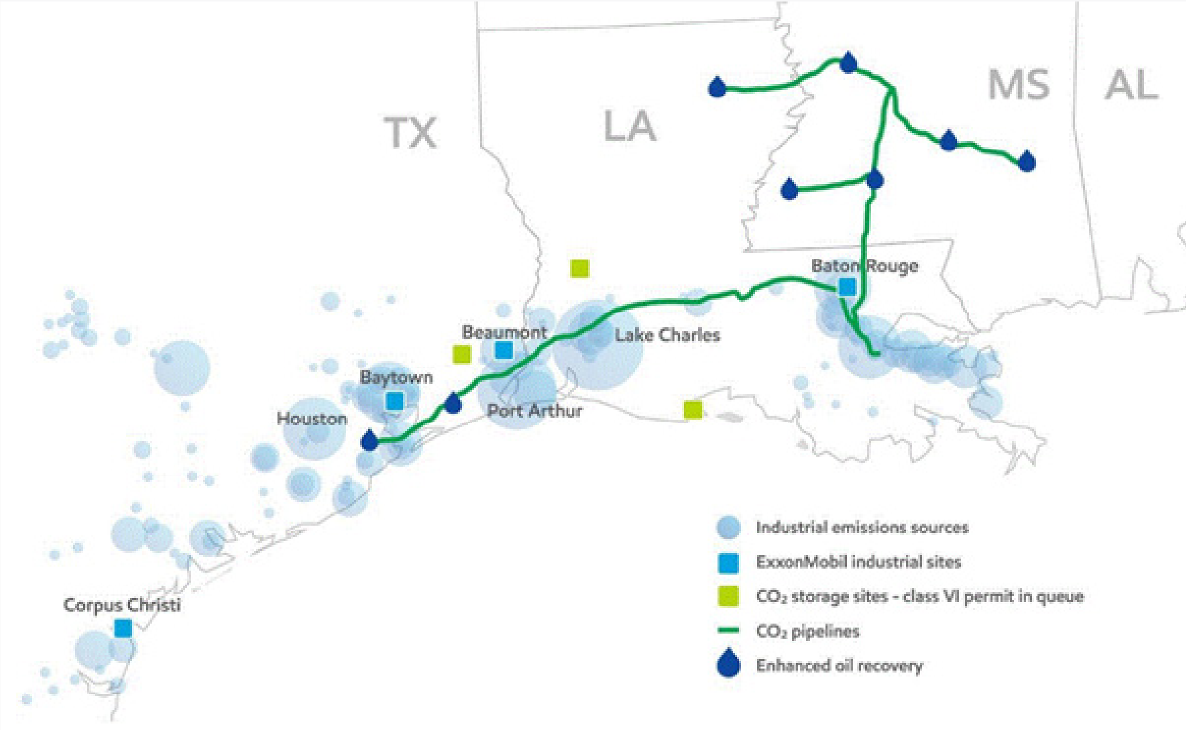
Multiple large fertiliser producers, such as CF Industries, Yara and OCI, are involved in projects in the Gulf Coast, leveraging their experience in ammonia project development, production, operations and distribution. CF Industries, the world's largest ammonia producer, is exploring several projects. A substantive project is the greenfield low-emission ammonia plant at CF Industries' Blue Point Complex in Louisiana.[35] The project is executed in a joint venture with JERA and Mitsui & Co. CF Industries holds a 40% stake in the project. JERA and Mitsui & Co. hold respectively 35% and 25%. The estimated costs to build the production facility will be funded by each partner according to their percentage of ownership. CF Industries will be responsible for operating the facility and maintenance. The offtake of the low-emission ammonia is handled by the three companies independently and is based on their percentage of ownership. It is expected to be the largest ammonia production facility by nameplate capacity in the world (1.4 million metric tons) and is expected to start producing in 2029.

Oil companies produce and use large volumes of hydrogen in their refining processes. This combined with their access to natural gas and experience with carbon capture and storage technology, positions them well to play a role in low-emission ammonia projects. Several oil companies are involved in low-emission ammonia projects in the Gulf Coast. For instance, ExxonMobil that executes a low-emission hydrogen and ammonia project at its refining and petrochemical facility at Baytown, Texas. According to ExxonMobil, this project will produce 1 billion cubic feet of low-emission hydrogen per day and produce over 1 million tons of ammonia annually, while capturing 98% of the CO_2 emissions produced in the process.[36] Marubeni will offtake 250,000 tonnes of the produced low-emission ammonia per year. Air Liquide has agreed to support the production of low-emission hydrogen and low-emission ammonia at the facility. The agreement will facilitate transportation of low-emission hydrogen through Air Liquide's existing pipeline network. Additionally, Air Liquide will potentially build and operate four Large Modular Air separation units (LMAs) to supply 9,000 metric tons of oxygen and up to 6,500 metric tons of nitrogen daily to the facility.[37] In a strategic move to diversify its portfolio, ADNOC signed an agreement on September 4, 2024, to acquire a 35% equity stake in the project.[38] Although the partnerships have brought the project closer to an FID, ExxonMobil has cautioned that its decision on the Baytown project depends on the release of final rules defining eligibility for the IRA's 45V tax credits.[39]

In contrast to the Baytown initiative, the FID for the greenfield ammonia facility in Beaumont, Texas, developed by OCI and Linde, has been taken and construction has started. According to OCI, this provides first-mover advantages, such as advantageous construction terms and favourable tax incentives. The project began engineering in late 2021 and construction in December 2022.[40] It aims to produce 1.1 million tons of ammonia per year in its first phase, using natural gas and CCS, with production expected to start in 2025. In this initiative Linde's hydrogen production and carbon capture technology is combined with OCI's expertise in ammonia production, storage, and transportation. Furthermore, Linde has teamed up with ExxonMobil for access to their CO_2 transportation and sequestration infrastructure. The first phase will capture and sequester 1.7 million metric tons of CO_2 annually. On August 5, 2024, OCI announced it had agreed to sell 100% of its equity in the project to Woodside Energy for USD 2.35 billion. OCI will manage construction and is responsible until the project is fully operational, after which control will transfer to Woodside.[41]

Furthermore, in various other Gulf Coast projects ExxonMobil plans to take charge of CO_2 transportation and sequestration.[42,43] ExxonMobil owns and operates the largest CO_2 pipeline network in the United States, spanning 1,500 miles across three states bordering the Gulf of Mexico (as shown in Figure 7),[44] making them a natural partner for ammonia production facilities that seek to capture and store carbon emissions.

Figure 7. ExxonMobil Gulf Coast industrial sites, CO_2 storages sites and CO_2 pipelines[45]



Industrial gas suppliers are interesting partners for future ammonia projects because of their existing infrastructure and expertise in handling and producing gases such as hydrogen, nitrogen, and carbon dioxide, which are essential for ammonia production. For instance, Air Liquide is exploring a possible collaboration with INPEX in the Houston Ship Channel project, where Air Liquide's Auto Thermal Reforming technology would be used for low-emission hydrogen production.[46]

Also, various storage and transportation providers are mentioned as partners in the announced projects. For example, Hafnia and Mitsui O.S.K Lines are involved in the ACE project in Donaldsonville, Louisiana, leveraging their extensive expertise in shipping gases such as LNG, LPG or ammonia. Their large fleets are set to support the project as it scales.[47] Vopak Moda is involved in the Houston Ship Channel project, at this same location it currently operates ammonia storage and handling infrastructure at a deepwater berth. The company intends to expand this storage capacity to accommodate the low-emission ammonia production from this new facility.[48]

A striking number of Japanese off-takers are partnering in low-emission ammonia projects along the US Gulf Coast. JERA, Mitsui & Co, Mitsubishi, Marubeni, ENEOS and Idemitsu Kosan all plan to invest in one or more projects in the region, aiming to secure a stable supply of low-emission ammonia for domestic use.[49,50,51,52,53,54] As an energy-short country, Japan is emerging as a major demand centre for low-emission ammonia, seeking dependable supplies of clean fuels to reduce emissions and enhance energy security.[55] The country lacks the renewable potential to produce large amounts of hydrogen via electrolysis, also it does not have the natural gas reserves and underground storage availability needed to produce the necessary volumes of hydrogen from natural gas and CCS. Besides, it is one of the few countries that has clear intentions to use ammonia in its (coal)power sector. Therefore, Japanese companies are actively entering into off-take agreements and considering investments in hydrogen projects overseas, targeting regions where supplies are either low cost or subsidized, among which the US Gulf Coast region.[56] With one of the strongest government supported demand-side programs, Japan offers the type of long-term off-take commitments (and institutionalised demand) that are necessary for hydrogen production initiatives to move forward. Unlike Europe, Japan has ready-to-use sectors that can accelerate the demand and uptake for low-emission ammonia, for instance, co-firing ammonia in coal plants. The country takes a technology neutral approach focused on finding low- cost, low-emission fuel supplies that can be used in existing energy assets.[57]

Ammonia production via electrolysis

To the best of our knowledge, there is currently one project running and producing ammonia via electrolysis in the US Gulf Coast. This is a 20MW electrolyser from CF industries located at their Donaldsonville Complex, which reached mechanical completion in April 2024 and is capable of producing up to 20,000 tons of ammonia annually. This project is not included in Figure 7, as the ammonia produced is utilized onsite at the complex for fertilizer production, with no indication that it will be used for export purposes. Only a few project announcements have been made by other developers planning to produce ammonia via electrolysis using (renewable) electricity.

First Ammonia, a Canadian low-emission ammonia developer expects construction works for a low-emission ammonia facility to commence in 2025. It is located at The Victoria Port's Texas Logistics Centre. The FID has been taken, and production is expected in 2027.[58] The plant will ultimately have a production capacity of 5 million metric tonnes (MMT/y) of low-emission ammonia by 2035. First Ammonia has partnered with Uniper as an off-taker of the low-emission ammonia.

ACME, an independent power producer from India, has also entered into an option agreement to lease a 245-acre site at the Port of Victoria. The company will carry out due diligence and feasibility studies for the development of an integrated clean hydrogen and ammonia facility, with a targeted ammonia production capacity of up to 1.2 MTPA.[59]

Energy Abundance Development Corporation (formally known as Green Hydrogen International), founded in 2019, is proposing the development of Hydrogen City a project located in Duval County, Texas. In its first phase, Hydrogen City aims to produce 280,000 tonnes of hydrogen annually, with storage in the Piedras Salt Dome. The hydrogen will be transported via pipelines to Corpus Christi and Brownsville for conversion into ammonia.[60]

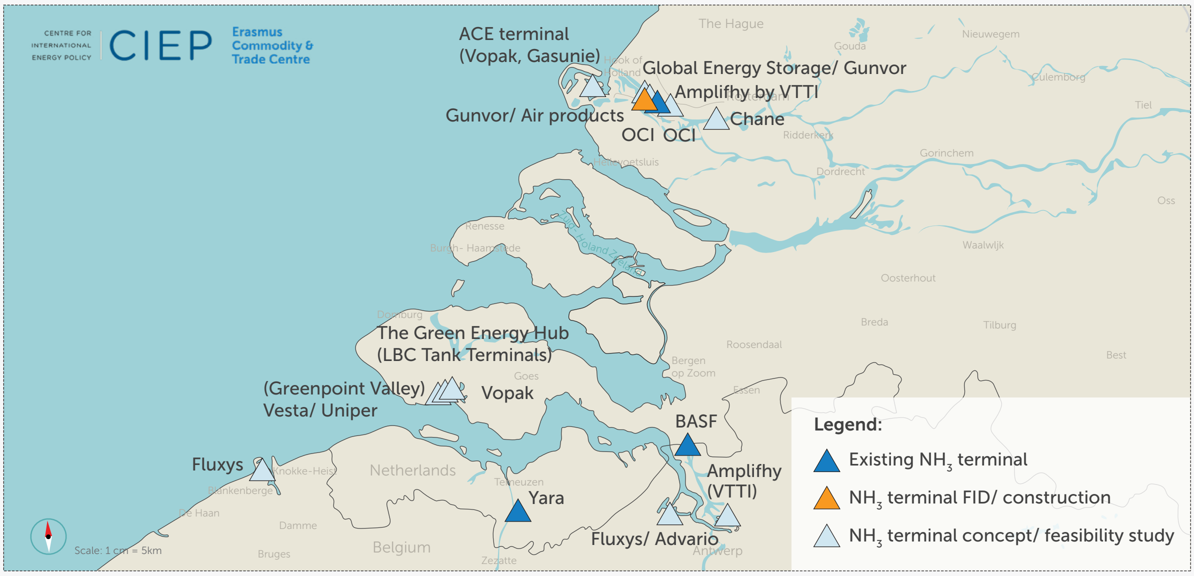
Furthermore, AmmPower Corp. has signed a Letter of Intent to develop a green hydrogen and ammonia facility at the Port of South Louisiana, with the goal of producing 4,000 tonnes of ammonia per day.[61]

In contrast to the ammonia projects that plan to use natural gas and CCS, projects in the US Gulf Coast intending to use electrolysis show less clarity on potential partnership structures and the stakeholders involved, and most of them remain in early pre-development stages.

3.2 Ammonia import terminals in the ARA region

Currently, there are three ammonia terminals operating in the ARA region: OCI Rotterdam, Yara Sluiskil and BASF Antwerp. These terminals offer access to international ammonia markets to fertiliser producers and other chemical demand sectors in the region. Although the region also hosts multiple ammonia production facilities, the terminals provide supply flexibility, which has proven invaluable in recent years for dealing with rising gas prices. Additionally, several new ammonia import projects have been announced by companies anticipating an increase of ammonia and hydrogen demand in Northwest Europe, driven by both the fertiliser sector and potential new energy applications. An overview of existing terminals and announced projects is shown in Figure 8.

Figure 8. Existing ammonia terminals and announced projects in the ARA region[62]



Note: *Graph is not necessarily exhaustive. Given the dynamic nature of the field, announced projects remain subject to frequent changes. The graph was made by CIEP and ECTC. Data sources: IEA, Hydrogen Production and Infrastructure Projects Database, October 2024, https://www.iea.org/data-and-statistics/data-product/hydrogen-production-and-infrastructure-projects-database, and company websites.*

Most of the announced projects remain in the concept or feasibility study phase. According to the IEA hydrogen infrastructure database, only one project, initiated by OCI, has reached a final investment decision so far.[63] This FID was taken for the first phase of an expansion of OCI's existing terminal in the Port of Rotterdam, tripling the ammonia throughput capacity, reaching a capacity of 1.2 million tons per year.[64]

Most of the companies involved in the announced import projects specialize in energy infrastructure, including storage, transportation, processing and logistics. Additionally, fertiliser producers, industrial gas suppliers, an international energy company and a trading firm are involved in projects in the region.

The stakeholders often own strategic locations in port areas, with access to international markets as well as connectivity for further distribution to end users within industrial clusters nearby or further into the Northwest European hinterland. In some cases, they already have terminals and storage facilities that can be repurposed.

Some projects have established (non-binding) agreements with potential clients. For example, the Chane project in the Port of Rotterdam has a non-binding agreement with Horisont Energi in place.[65] In certain cases, a future client is directly involved as part of the partnership or consortium.[66] This is true for the Gunvor-Air Products project in Rotterdam, where Air Products plans to import low-emission ammonia from overseas production sites operated by Air Products and its partners.[67] Similarly, in the Vesta-Uniper project in Vlissingen, Uniper intends to secure capacity at the terminal.[68] Air Products, Yara, OCI, Vopak and Uniper are involved in export projects on the US Gulf Coast as well as import projects in the ARA region, creating a strong foundation for potential transatlantic trade between these locations.

Many of the announced projects aim to address future uncertainties by designing terminals with optionality in both transportation methods and the range of services they plan to provide. With delays in the hydrogen pipeline network in the region, projects are allocating space for potential railcar loading and barge transport to move ammonia further inland. Since the realization of a hydrogen or ammonia pipeline between the Port of Rotterdam and the Ruhr area in Germany is unlikely in the near future, Chane is considering setting up an ammonia distribution hub in Duisburg, Germany. Ammonia would arrive at their terminal in the Port of Rotterdam and be transported by barge to Duisburg, where it would then be distributed further inland via pipeline, railcars and barges. Additionally, a cracking facility for hydrogen may be added in Duisburg.[69] Many of the proposed projects indicate plans to support both ammonia storage and throughput, as well as ammonia to hydrogen conversion and throughput of hydrogen.

4 Regulatory frameworks that govern investments, trade and shipping of ammonia

The trade of ammonia is governed by a complex web of regulatory frameworks, policies, and laws.[70] Some of the most relevant regulations from both sides of the Atlantic are discussed. On the European side this involves RED III, CBAM-ETS, Delegated Act on Low Carbon Fuels, and on the American side, it is the Inflation Reduction Act (IRA), which has undergone significant changes under the One Big Beautiful Bill (OBBB) that was passed by the second Trump administration in July 2025.

The Renewable Energy Directive was first introduced in 2009. The most recent revision of the directive (RED III) entered into force in 2023 and increased the EU's binding renewable energy target[71] to at least 42.5% for 2030, with an ambition for 45%.[72] Following its adoption on 20 November 2023, member states had 18 months to transpose most of the directive's provisions into national law. RED III establishes targets for the uptake of Renewable Fuels of Non-Biological Origin (RFNBOs); article 22a mandates that RFNBOs should account for at least 42% of the hydrogen used for final energy and non-energy purposes in industry by 2030, increased to 60% by 2035.[73] Additionally, RFNBOs should account for at least 1% of the total energy supplied to the transport sector in 2030, with a combined target of 5.5% for advanced biofuels and RFNBOs.[74] Member states with maritime ports (like the Netherlands) are encouraged to ensure that at least 1.2% of total energy supplied to the maritime transport sector comes from RFNBOs in 2030.[75] These mandates and sub-targets serve as key drivers for Europe to import renewable hydrogen, often referred to as 'green hydrogen', alongside domestic production.

The Delegated Act on RFNBO methodology outlines the conditions under which hydrogen, hydrogen-based fuels, and other energy carriers can qualify as RFNBOs. It sets two key criteria: The first is 'additionality', that requires hydrogen production to be matched with new, unsupported renewable electricity generation capacity through power-purchase agreements (PPAs). This means that the renewable electricity generating unit should begin operating no more than 36 months prior to the RFNBO unit, and it should not have received any (net) subsidy.[76] RFNBO production plants are allowed to enter into long-term renewable PPAs with existing renewable installations before 1 January 2028.[77] The second is 'temporal and geographic correlation', which ensures that the hydrogen is produced at the same time and in the same region as renewable electricity is available. This safeguards against a situation where hydrogen production drives demand for fossil-based electricity.[78] Until 2030, temporal correlation compliance requires the renewable electricity to be generated within the same calendar month as the electrolyser used for producing the RFNBO, while this changes to hourly-correlation after 2030.[79]

Only RFNBOs that reduce GHG emissions by at least 70% compared to fossil fuels will count towards the EU's renewable energy targets.[80.81] The requirements for renewable hydrogen production apply to both domestic and third countries that want to export to the EU. A certification scheme relying on 'voluntary schemes' will ensure compliance with these criteria. The schemes that have been recognised by the commission must be accepted by member states, thereby reducing the administrative burden for hydrogen producers and avoiding member state-specific procedures.[82]

Industry Obligations and Implementation into National Law

Member states were mandated to transpose the Renewable Energy Directive provisions into national law by 21 May 2025. However, there are delays in implementation and there is limited progress by countries.[83] On 24 July 2025, the European Commission sent out infringement notices to 26 member states – all

Note: *The overview of relevant regulations in this chapter is not exhaustive; there are other applicable regulations (such as the EU hydrogen and gas decarbonization package, CSDDD) that also govern ammonia trade and are not discussed in detail. Additionally, the regulatory landscape on both sides of the Atlantic is highly dynamic and subject to frequent changes, some of which may not be reflected at the time of writing this text.*

except Denmark – for not transposing RED III provisions into national law before the deadline.[84,85] The directive also had an intermediate deadline of July 2024 for transposing some provisions relating to permitting for renewables.[86] Earlier in February 2025, the European Commission released a package of infringement decisions and sent out reasoned opinions to some member states[87]- including The Netherlands - for not meeting this deadline and failing to address acceleration of permitting procedures.[88]

Article 22a of RED III states that RFNBOs must account for at least 42% of the hydrogen used for final energy and non-energy purposes in industry by 2030 and 60% by 2035.[89] A detail of note is that the obligation does not apply directly to hydrogen consumers but to the Member States. However, Member States can choose to impose RFNBO mandates on companies in their RED III transposition as a means to achieve this target.[90]

Article 22b in RED III offers some flexibility to member states to reduce the national RFNBO consumption target in industry by 20% in 2030 and 2035. The reduction applies if member states are on track to fulfil their national contribution to EU's overall renewable energy target, and when the consumption share of hydrogen (or its derivatives) in the member states produced from fossil fuels does not exceed 23% in 2030 and 20% in 2035. If both conditions are met, the RFNBO target can be reduced to 33.6% in 2030 and 48% in 2035.[91]

The Netherlands

The Netherlands has been one of the first countries to propose fulfilling the mandate through a mix of industry obligations at the company level and demand-side subsidies.[92] In April 2025 as part of the Green Growth package (pakket voor Groene Groei), the Dutch government announced €2.1 billion to drive hydrogen production and €662 million to stimulate industrial uptake, with a relatively low renewable hydrogen obligation of 4%.[93,94] In a letter to parliament dated July 2025, Sophie Hermans, Minister of Climate and Green Growth, stated that the Dutch government will introduce the annual obligation as of January 1, 2027, with a phased increase to 4% by 2030 and 9.9% by 2035.[95] The proposed 'Act on the Annual Obligation for Renewable Fuels of Non-Biological Origin in Industry' (Wet jaarverplichting hernieuwbare brandstoffen van niet-biologische oorsprong in de industrie, Annual Obligation Act) will introduce mandates for industrial users of hydrogen starting 1 January 2027 to meet the objectives of article 22a of RED III. Industrial companies would have to obtain a tradeable unit called a 'renewable hydrogen unit industry' (hernieuwbare waterstofeenheid industrie (HWIs) by using RFNBOs produced domestically in the industry, through imported RFNBOs, or by purchasing HWIs.[96] This obligation applies to industrial installations that consume more than 0.1 kt of hydrogen annually. The challenge, however, is that compliance is verified via a 'mass balance system' that requires the physical delivery of hydrogen – a tough requirement for hydrogen users, many of whom will not be connected to the Dutch hydrogen grid until at least 2027. To address this, the act includes a temporary exemption till 2029 which allows for claiming renewable hydrogen without the required proof of sustainability. This exemption will be reviewed again in 2028 to understand if an extension is needed.[97]

The Dutch ammonia producers will be partially exempt, and only 40% of their hydrogen use will be subject to the national RED III obligations.[98] Recital 63 (commonly referred to as the "ammonia recital") under RED III recognises the technical limits of decarbonising integrated SMR-based ammonia plants.[99] The recital does not provide a blanket exemption but opens the door to a case-by-case leniency in RED III implementation and will be relevant for the Netherlands.[100] Despite a motion calling for a full exemption of the ammonia sector, the government ultimately set it at 40%, arguing that RED III does not provide a clear legal basis for fully exempting ammonia production, and doing so could lead to infringement proceedings and fines from the European Commission.[101] Additionally, they maintained that it would disadvantage other industrial users and create an uneven playing field in the Netherlands. Beyond legalities, the government emphasized the strategic importance of investing in imports as a crucial component of strengthening supply security; converting existing grey ammonia imports to renewable ammonia imports can contribute to the mandates, and provide demand certainty to companies wanting to invest in projects for renewable hydrogen and hydrogen carriers supply. This prompts the question of whether imports replace domestic demand or are used for additional demand.

According to RED III, the RFNBO share of industry is calculated as follows[102]:

$$\frac{\textbf{Energy content of RFNBOs consumed in the industry sector for final energy and non-energy purposes}^{103}}{\textbf{Energy content of hydrogen for final energy and non-energy purposes}^{104}}$$

Since it is a consumption target, if renewable ammonia is produced by Member State A and exported to Member State B, only B can use it to count towards its RFNBO targets while A cannot claim the renewable hydrogen used to produce the renewable ammonia in its numerator.[105] Moreover, only the consumption of hydrogen (through all different pathways) is included in the denominator - not the consumption of its derivatives. So, if Member State A uses hydrogen to produce ammonia and exports it to Member State B, the hydrogen used to produce the ammonia is counted in the denominator of A while the resulting ammonia is not counted in the denominator for B.[106,107]

In its current form, there is uncertainty regarding how imports figure into the calculation of RFNBO share. A March 2025 paper by the Oxford Institute for Energy Studies states that it appears that imports are considered as following:

% RFNBO = (RFNBO domestic+ RFNBO imports) / H_2(Industry).[108]

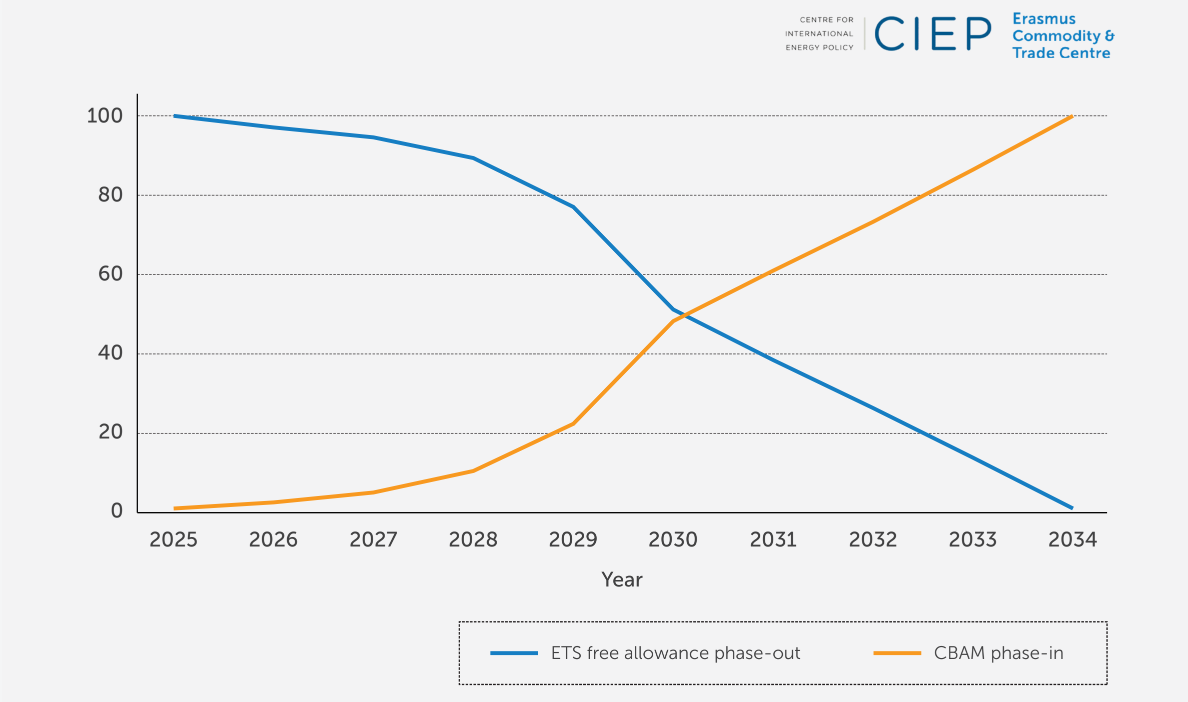
If this is the case, there appears to be a favourable set-up for importing RFNBOs like renewable ammonia, as it would increase the numerator (RFNBO consumption) without changing the denominator (domestic H_2 consumption), thereby helping member states comply with the 42% mandate. However, this aspect of RED III requires further clarification on calculation of imports.

In comparison to RED III, the Hydrogen production tax credits under the Inflation Reduction Act (IRA) are more pathway and technology agnostic; projects qualify for the tax credits solely on the basis of carbon emissions reduction achieved, without requirement of a particular production pathway to achieve it. On the other hand, hydrogen or ammonia produced using CCS would never qualify as a 'renewable' fuel of non-biological origin (RFNBO), by definition. This precludes it from being used to meet EU RFNBO mandates and sub-targets, and from accessing subsidies tied to the RFNBO classification.

4.1 Carbon Border Adjustment Mechanism (CBAM) and the EU Emissions Trading System (ETS)

The EU implemented the Carbon Border Adjustment Mechanism (CBAM) to put a price on carbon embedded in certain imported goods, aligning with the cost borne by domestic EU producers under the Emissions Trading System (ETS). CBAM was introduced to ensure a level playing field for (basic) EU industries that are subject to more stringent climate mandates, and to prevent carbon leakage. The regulation initially applies to certain sectors that are at a higher risk of carbon leakage: cement, iron and steel, aluminium, fertilizers, electricity, and hydrogen. In the future, the CBAM scope could be broadened to encompass other ETS sectors.[109] CBAM applies to ammonia while other hydrogen derivatives - such as methanol, electrofuels, and liquid organic hydrogen carriers (LOHCs) - are not yet included. As a result, the carbon emissions associated with the production of these hydrogen derivatives (other than ammonia) are not currently subject to a price when entering the EU.[110] CBAM is currently in its transitional phase (2023-2025) and the European Commission intends to implement it definitively in 2026. The phasing-in of CBAM is aligned with the gradual phase-out of free allowances under the ETS by 2034 (See Figure 9).[111]

Figure 9. ETS free allowances phase-out and CBAM phase-in[112]



A report by the Oxford Institute for Energy Studies highlights that U.S. low-emission ammonia is well placed to comply with European carbon intensity standards across regulatory frameworks such as CBAM and the EU ETS, thereby enabling a viable transatlantic clean ammonia trade.[113] While US renewable hydrogen easily meets the EU threshold, only the most environmentally stringent CCS-based production are likely to qualify. The study finds that by 2030, ammonia production with CCS in the U.S. is likely to be more cost-competitive than even depreciated SMR-based European production.[114] U.S. renewable ammonia will also, the study predicts, outperform Europe in cost-competitiveness by 2040 as a result of efficiency gains and decline in electrolyzer costs.[115] However, IRA incentives - the impact of their modification under the One Big Beautiful Bill (OBBB) as well as their future changes – remains crucial to watch out for.

Under the current EU ETS rules, only 50% of emissions for international shipping are accounted for. CBAM, which calculates emissions at the point of production and does not include the entire supply chain, leaves the remaining emissions unaddressed. As a result, imports from regions with lower emissions costs – such as the United States – can leverage this regulatory arbitrage and benefit from reduced emissions-related costs during transport. In April 2025, the IMO approved net-zero regulations and GHG emissions pricing for shipping.[116] This will increase compliance costs, and it remains to be seen how it relates to ETS-CBAM and hence the regulatory arbitrage for U.S. imports. Nonetheless, it incentivizes the use of low-emission fuels such as ammonia, and fuels compliant with the emission thresholds will be eligible for financial incentives from the net-zero fund.[117]

There are, still, weaknesses of CBAM that raise concern. While CBAM provides incentives for low-emission ammonia production (see box on Woodside Case Study on page 29-30), the Draghi report underscores how its success is still uncertain; it has a complex design and can be affected by fragmented, inconsistent implementation by member states.[118] The report recommends close monitoring in the transition phase and even postponement of the phase-out of ETS free allowances if its implementation is ineffective. Previous CIEP publications highlight the administrative burden associated with this product-based system – compared to the installation-based system of the ETS – and the possibility of circumvention.[119] For instance, in state-led economies, 'phantom' carbon pricing systems can be employed to bypass CBAM provisions.[120] Applying CBAM application in the chemical industry is also complicated by the challenge of tracking the carbon footprint of the approximately 350,000 registered chemicals, each used in diverse end-user products.[121] Re-exports from third countries presents further risks. The ineffectiveness of CBAM in such ways can undermine the incentive for low-emission projects.

4.2 Commission delegated regulation (EU) specifying a methodology for assessing greenhouse gas emissions savings from low-carbon fuels

The Delegated Act intends to provide a methodology to make the definition of low-carbon hydrogen and fuels, as already provided in the Hydrogen and Gas Market Directive as achieving GHG emissions savings of 70% compared to the fossil fuel comparator, operational.[122] It is a significant regulation for low-carbon hydrogen and its derivatives, including blue hydrogen and blue ammonia, but also hydrogen produced with electrolysis that does not fit into the strict definition of an RFNBO.[123]

In September 2024, the European Commission proposed a draft delegated act detailing the methodology for calculating GHG emission savings from low-carbon fuels.[124] The regulation has significance for the uptake of low-carbon fuels (such as blue ammonia) to replace fossil-based hydrogen. The proposed methodology considers the full lifecycle emissions and is consistent with the existing framework for renewable hydrogen and RFNBOs. Notably, the draft act permitted only default values for upstream CO_2 and N_2O emissions in the natural gas value chain.[125] For methane emissions, producers must comply with the Methane Regulation provisions. If the supplier does not report specific methane emission data, default values can be used for pipeline gas. For LNG as source, emissions from liquefaction and transport are additionally included.[126] The draft builds upon the EU hydrogen and gas decarbonization package, which was enforced in August 2024. Under this framework, the commission had a year since its entry into force to clarify the definition of low-carbon hydrogen, after which Member States will have until August 2026 to transpose the new rules into national legislation.[127] The final delegated act was published - before its stipulated deadline - on 8 July 2025. The regulation now moves to the European Parliament and Council, who have two months (with the possibility of extension) to either endorse or reject it.[128] The reliance on only default values for upstream CO_2 and N_2O emissions drew opposition during the commission's public consultation. Industry actors like Equinor argued that default values misrepresent actual emissions, ignore decarbonization efforts, and ultimately disincentive improvements in emissions performance. Equinor states that many low-carbon fuel projects – both domestic and import-based – could fail to meet the 70% emissions reduction threshold despite actually being within the threshold.[129] Similarly, the Oxford Institute for Energy Studies highlighted that CCS-based hydrogen likely would meet the 70% threshold only if the regulation deviates from the RFNBO methodology and excludes upstream emissions.[130] The draft act methodology may disqualify them from certain policy support and unintentionally undermine credible low-carbon options.

The final delegated act took some points of the consultation and feedback into consideration. For instance, the default value for the upstream CO_2 emissions of natural gas was reduced to 4.9 gCO_2/MJ.[131] It also introduced the possibility of region-specific default values for emissions after an assessment by mid-2028. The European Commission stated that they would safeguard existing projects against changes to the criteria.[132] However, the act did not allow deviation from default value for CO_2 and N_2O emissions.[133]

Given the narrowly defined delegated act in its current form, CBAM and ETS remain the key economic drivers of low-carbon hydrogen and ammonia. Though, another disparity is the EU exclusion of CCS with enhanced oil recovery (EOR). This could imply that the CBAM charge would be higher from US-based low-carbon hydrogen made with EOR.

Table 1. 'Standard Values' for GHG emission Intensities of Inputs[134]

Fuel	Upstream GHG Emissions (gCO_2eq/MJ)		
	CO_2	CH_4	N_20
Natural Gas*	4.90	0.190	0.00037

**excluding LNG liquefaction, shipping and regasification. For natural gas that was transported in liquid form additional GHG emissions (CO_2, CH4 and N_2O) due to liquefaction, shipping and regasification of natural gas shall be added.*

4.3 Inflation Reduction Act (IRA) and the One Big Beautiful Bill (OBBB) Act

On the other side of the Atlantic, the Inflation Reduction Act was signed into law in August 2022 by then-U.S. president Joe Biden, which sought to achieve carbon emissions reduction of 40% by 2030 compared to 2005.[135] Arguably one of the most significant climate and energy packages in U.S. history, the IRA functions through a comprehensive mix of grants, loans, rebates, incentives and other investments to drive the transition to clean energy. The IRA provisions most relevant for low-emission hydrogen and ammonia projects are the 45V – clean hydrogen production tax credit - and 45Q tax credits – the credit for Carbon Oxide Sequestration.

The U.S. House of Representatives passed the One Big Beautiful Bill in May 2025, and it was signed into law by President Donald Trump on 4 July 2025. The bill significantly modifies several provisions of the IRA, including changes to 45V and 45Q credits. Particularly, the bill accelerates the phase-out of 45V credits; facilities must now begin construction before 1 January 2028 to claim the credit, a five year advancement from the previous deadline of 1 January 2033.[136] This is nonetheless a two-year extension over the version that was passed by the House of Representatives which would have scrapped the credit from 2026.[137] 45Q credits retain most of their original form, with some foreign entity restrictions and parity for different utilizations of qualified carbon oxide for facilities or equipment that are commissioned after 4 July 2025.[138] Despite these changes, the IRA is a relevant legislation that has significantly governed investment decisions and low-emission ammonia projects over the past years. The 45V and 45Q credits, as outlined in the IRA, are discussed in the next section.

45V and 45Q

Section 45V provides a 10-year production tax credit (PTC) incentive for clean hydrogen at a qualified clean hydrogen production facility.[139] To qualify for 45V tax credits, the hydrogen production must achieve a lifecycle emissions rate of no more than 4 kilograms of CO_2e per kilogram of hydrogen produced.[140] A sliding scale of credits is offered based on the lifecycle GHG emissions rate:

Table 2. 45V Clean Hydrogen Production Tax Credits[141,142]

Carbon Intensity (kg CO_2e per kg H_2)	Maximum Hydrogen Production Tax Credit ($/kg H_2)
4-2.5	$0.60
2.5-1.5	$0.75
1.5-0.45	$1.00
<0.45	$3.00

Alternatively, projects can also elect for an investment tax credit (ITC) of up to 30% by claiming the hydrogen production facility as an "energy property".[143,144] The choice is irrevocable and prevents the project from claiming 45V or 45Q credits. The PTC typically always offers greater value than opting for the ITC.[145] The hydrogen must be produced in the U.S. to qualify for the investment or production credits. However, there are no such restrictions on its consumption, allowing for the export of hydrogen.[146]

Section 45Q is a provision for Carbon Capture, Utilization, and Sequestration (CCUS) tax credit. The IRA expands and extends the existing 45Q tax credits, complementing funding allocation in the Bipartisan Infrastructure Law (BIL) for CCUS and Direct Air Capture (DAC).[147] The facility must be placed in service before 1 January 2033 to qualify for the tax credits and can claim them for 12 years following the date it is placed in service.[148] The 45Q credits are awarded based on the amount of carbon a facility captures and sequesters – therefore available irrespective of lifecycle emissions[149]– and project developers can receive $85 per metric ton of carbon captured and sequestered.[150,151,152] 45V and 45Q credits are not stackable, however, a taxpayer is able to claim 45Q credits on electricity production and then use that electricity in a separate facility to produce qualified clean hydrogen that can claim 45V credits.[153]

Project developers make an irrevocable choice between claiming the 45V or 45Q tax credits. The 45Q credit of $85 per metric ton carbon translates to approximately $0.80 per kilogram hydrogen, commensurate with carbon capture rates.[154] According to an analysis by the Center for Strategic and International Studies (CSIS), an inflection point occurs at the third band, and 45V credits would be preferable over 45Q credits for projects that have lifecycle emissions of less than 1.5 kg CO_2e per kg H_2 (see table 3).

Table 3. 45V versus 45Q Tax Credit Values[155]

Project Lifecycle Emissions	45V Credit Value	45Q Credit Value
4 kg CO_2e	$0.60/kg	Up to $0.80/kg
2.5 kg CO_2e	$0.75/kg	Up to $0.80/kg
1.5 kg CO_2e	$1.00/kg	Up to $0.80/kg
0.45 kg CO_2e	$3.00/kg	Up to $0.80/kg

The 45VH2-GREET model is used to calculate the Well-to-Gate GHG emissions of hydrogen production pathways for the 45V tax credits. A revision of the methodology came out in January 2025 that assumed a methane leakage rate of 0.9% of methane consumed by the hydrogen producer.[156,157] While the January model assumed a fixed rate, another revision came out in May 2025 that allows users to "account for bespoke information (i.e. foreground data) to represent specific aspects of their natural gas supply chain."[158] According to CSIS's analysis, a fixed methane leakage rate of 0.9% implied that only projects that achieve a capture rate above 95% and those using clean electricity to power their operations will qualify for the $1/KG H_2 credit.[159] These regulations guide project developers' decision to choose between the 45V or 45Q credits.

It appears that the 45V credits are more accessible for green hydrogen producers who are likely to be eligible for the highest tax credit bracket of $3/kg hydrogen produced provided they are able to meet the electricity criteria for temporal matching, deliverability, and incrementality.[160] On the other hand, blue hydrogen producers have to demonstrate high capture rates to qualify for the higher 45V credits and may be better off claiming the 45Q carbon capture and sequestration credits in most cases. Higher upstream methane leakage rates would prevent blue hydrogen producers in the U.S. from accessing the higher brackets of the 45V credits.[161]

The regulatory uncertainty regarding the IRA tax credits under the Trump administration has kept many project developers in a state of limbo. The lack of clarity around long-term policy support and eligibility has stalled investment decisions and delayed project timelines. Exxon Mobil and BP lobbied for using project-specific methane data, which the revised 45VH2-GREET model incorporates.[162] Other companies, like CF Industries and Air Products opted to progress their blue hydrogen initiatives on the basis of the 45Q tax credits.[163] With the passage of the OBBB, 45V and 45Q are currently modified, but not repealed. Though, going forward, the challenge remains to not only respond to the updated rules but anticipate and adapt to future political shifts than might reshape the incentive landscape again.

The early sunset of 45V credits has implications for the development of low-emission projects which relied on it, obscuring already delayed project timelines. The OBBB impacts many clean energy tax incentives and could have broader consequences that affect investment and projects. Unfavourable political stance towards renewable energy and reduced policy support could, for instance, make it more challenging to meet the strict RFNBO standards for exports into the EU. Foreign entity restrictions increase administrative burden. However, unlike the other tax credits, the measures for 45Q are less stringent; it only applies to the entity claiming the tax credit, rather than the whole supply chain or input materials, making compliance relatively easier.[164] The 45Q credits can be claimed up until 2033 and are available for 12 years after operations begin, unlike 45V which need to now be claimed before 2028 and are applicable for 10 years. This may allow blue project developers to progress based on 45Q.

The Bipartisan Infrastructure Law (BIL) had appropriated funds to create H_2Hubs, which were to use renewable and nuclear power for hydrogen production. However, their future remains uncertain and coupled with the general de-prioritization of emission reduction goals, researchers at the Center on Global Energy Policy at Columbia stipulate that domestic demand for low-emissions hydrogen in the U.S. appears weaker. This may turn the U.S. to "competitive and limited" export markets.[165] The full implications of the OBBB are still unfolding and hard to ascertain.

4.4 Case Study: Woodside's Beaumont New Ammonia Project

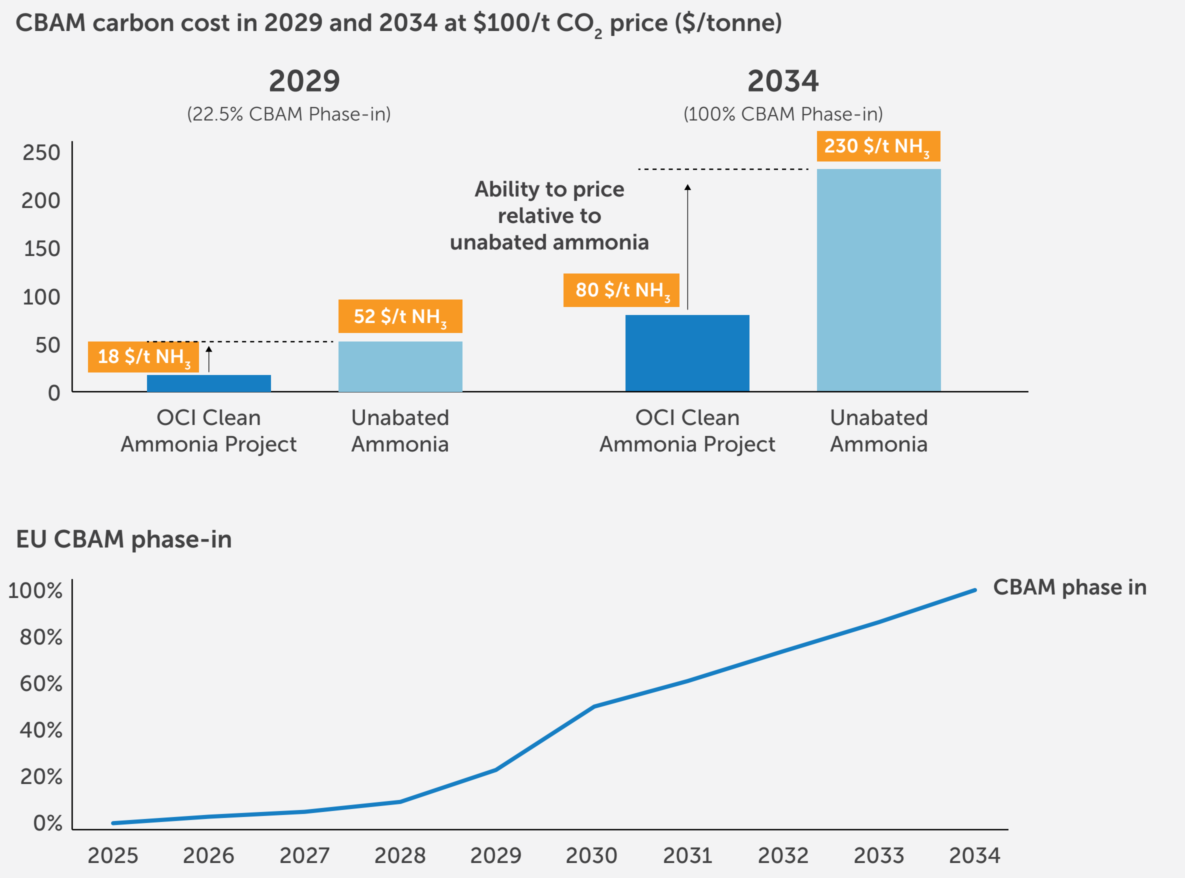
This section takes a closer look at the incentives for the Beaumont New Ammonia Project which was discussed in chapter 3.

45Q credits under the IRA offer $85 per tonne carbon captured and geologically stored. According to Woodside, the Beaumont New Ammonia project is expected to reduce emissions intensity from 2.3 t $CO_2e/t\ NH_3$ for unabated ammonia to 0.8 t $CO_2e/t\ NH_3$.[166] This capture of 1.5-tonne carbon per ton of ammonia produced implies that they could earn close to $130 per tonne ammonia produced using 45Q tax credits.

Woodside is targeting the European market initially, driven by the opportunity to leverage the EU Emissions Trading System (ETS) and Carbon Border Adjustment Mechanism (CBAM).[167] With free allowances under the EU ETS planned to be phased out by 2034 and CBAM imposing market ETS prices to imported CO_2 emissions, carbon intensity will become a key differentiator. Woodside estimates that its low-emission ammonia will fall within current and future EU benchmarks.[168,169]

Assuming a CBAM carbon price of $100 per tonne of CO_2 and 2.3 t $CO_2/t\ NH_3$ carbon emissions for an unabated project, Woodside estimates that by 2029 – when 22.5% of CBAM is supposed to be phased in – CBAM carbon costs of unabated ammonia will be $52 per tonne of ammonia, while the OCI Clean Ammonia project will incur a cost of $18 per tonne of ammonia.[170] By 2034, assuming a full phase-in of CBAM, the CBAM carbon costs rise to $230 per tonne for unabated ammonia and $80 per tonne for the OCI Clean Ammonia project (Figure 10).[171] The progressive removal of free allowances will increase carbon cost burden and increase the demand for low-emission ammonia.

Figure 10. Woodside's strategy for Leveraging ETS and CBAM Opportunities



Graph Source: *Rick Beuttel, presentation at the Ammonia Energy Association webinar, December 10, 2024, Woodside Energy, speaker slides available at https://ammoniaenergy.org/wp-content/uploads/2024/12/Project-Features-speaker-slides-Dec-2024.pdf, accessed through https://ammoniaenergy.org/webinars/woodside-energy-early-mover-advantage-in-the-growing-lower-carbon-ammonia-market/ (Orange textboxes added by CIEP and ECTC)*

Woodside is also looking to target Japan and South Korea, where supportive 'contract-for-difference' subsidy schemes cover the price gap between lower carbon fuels and conventional fossil fuels - schemes for which the project's carbon intensity is expected to qualify. By targeting both, they diversify their portfolio based on geography and contract-type.

5 Comparing the USGC-ARA trade lane with alternative routes to Northwest Europe

5.1 The US Gulf Coast compared to other supply centres

This section provides a high-level overview of potential future low-emission ammonia supply centres. We look at countries' natural gas production surplus, proven gas reserves and Carbon Capture, Utilisation and Storage (CCUS) projects. In addition to that, we show the amount of hydrogen projects countries are involved in, both in total numbers as well as how many of those are in more advanced phases such as FID, construction, or operational.

Many countries possess significant natural gas reserves, which is an indicator of potential production. However, a key differentiator for their export potential is their production surplus. For instance, China, the UAE, and Saudi Arabia have large reserves, but they currently consume more than they produce which limits their short-term export capacity. As table 4 indicates, Qatar stands out for the largest gas reserves – nearly double those of the second-largest holder in the selection of countries, the United States. It boasts established LNG and petrochemical infrastructure and has a relatively stable investment environment. Qatar' State-owned Energy is constructing a $1.2 Bn export-oriented blue ammonia facility, set to produce 1.2 million tonnes annually and capture and store 1.5 million tonnes of CO_2 per year. Currently under construction, the facility in Mesaieed could be one of the largest blue ammonia facilities once operational in 2026, positioning Qatar as a latent player in this space.[172] Apart from using natural gas in combination with CCS to produce low-emission ammonia, coastal countries could use a combination of wind and solar to produce green hydrogen and low-emission ammonia. Countries such as Saudi Arabia and Oman have potential here.

Norway benefits from proximity to the ARA region, uniquely positioned to export hydrogen directly (rather than ammonia), avoiding the need for energy-intensive cracking. The Dutch government signed a Memorandum of Understanding (MoU) for cooperating with Norway on hydrogen and CCUS in 2024.[175] Australia, despite its strong potential, has a disadvantage due to its distance from Europe and would rather transport its molecules to Japan. A gas surplus alone doesn't indicate export potential to the ARA region if it is already committed to long-term offtake agreements elsewhere. Australia is already geared towards other markets, with several offtake agreements and partnerships for exports to Asia-Pacific markets like Singapore, Japan, and South Korea.[176,177,178] Canada's natural gas production is concentrated in the Western Canadian Sedimentary Basin (WCSB).[179] Alberta and British Columbia accounted for 98% of Canada's total natural gas production in 2023.[180] Given their concentration on Canada's west coast, these regions are structurally more aligned to serve Asia-Pacific markets.

Table 4. Comparative Matrix for Different Supply Centres for Blue Hydrogen[173,174]

Supply Centres	US	Qatar	Norway	Australia	Canada	Algeria	Oman	Saudi Arabia	Egypt	Brazil	United Arab Emirates	China
Natural Gas Exports (Proxy*) 2023	148.83	136.78	112.84	111.65	69.52	55.20	13.64	0	-2.94	-6.57	-11.63	-170.58
Gas Proved Reserves by the end of 2020 (in billion cube metres)												
Total number of hydrogen production projects												
Total number of hydrogen production projects (FID/ Construction or Operation)												
Number of CCUS Projects (Only T&S and Full Chain)												
S&P Rating	AA+	AA	AAA	AAA	AAA		BBB-	A	B-	BB	AA	A+
Country Risk Premium (CRP)	0%	0.49%	0%	0%	0%	3.67%	1.64%	0.86%	8%	3.80%	0.66%	0.75%

**Calculated as production surplus (domestic natural gas production - consumption)*

Note: *The table highlights some key players in CCS-based ammonia production and export. Natural gas surplus and the number of Carbon Capture, Utilisation and Storage (CCUS) projects are used to gauge export potential and the maturity of CCUS technology deployment. Proven gas reserves indicate a country's long-term or future capability to support CCS-based hydrogen production. The number of hydrogen production projects in advanced stages gives an order of magnitude of development momentum in hydrogen and the availability of supporting infrastructure. S&P ratings and country risk premium reflect investor confidence and influence access to finance.*

The United States emerges as one of the most competitive supply centres. It has a significant natural gas surplus and many hydrogen and CCS projects in advanced stages. The U.S. has an estimated theoretical CO_2 storage capacity of 812 Gt, with the majority being onshore (68%).[181] In comparison, Australia and New Zealand together have an estimated storage of 595 Gt, and Canada 318 Gt.[182] The Norwegian continental shelf is estimated to have a theoretical storage capacity of 80 Gt of CO_2.[183]

To a lesser extent, the U.S. also has projects that use renewable electricity to produce low-emission ammonia. But, out of 38 proposed ammonia projects in the U.S. as of December 2024, 70-90% of the proposed capacity additions produce ammonia from fossil fuels with carbon capture.[184] China is currently the largest producer of green hydrogen, accounting for 58% of global operating capacity.[185] This dominance is driven by lower CAPEX compared to Western peers, as well as abundant low-cost solar and wind resources. Bloomberg NEF estimates that green hydrogen in China and India can compete with unabated hydrogen from the 2030s due to cheap renewables and electrolysers.[186] Other emerging supply hubs with strong green potential include Australia, Chile, Morocco, Namibia, UAE - and within the EU - Portugal, and Spain. If the first low-emission shipments to Europe come from NEOM, Egypt could be a bunkering location. Some export routes - such as from Qatar, Oman, Saudi Arabia, Australia - likely rely on the Suez Canal to reach Northwest Europe, adding additional transportation risks.

In general, the scale of green hydrogen projects is a lot smaller. In 2024, seven out of the largest ten blue or green hydrogen production projects by output that took an FID or started construction were green. However, the three blue hydrogen projects outpaced them with a combined annual output exceeding that of all seven green projects together.[187] The three blue projects were in Canada, Qatar, and Yara's Sluiskil project in the Netherlands. All produce hydrogen for use in ammonia production. There were fewer investment decisions in the U.S. in 2024 due to policy uncertainty around the 45V credits. The incremental nature of projects makes a difference, and having an existing base of infrastructure, industry, and supplies positions the USGC favourably to build on it. For blue or green hydrogen elsewhere in the world, entire value chains need to be built from scratch and that remains a major bottleneck.

While there are emerging centres of hydrogen and ammonia supply that could potentially compete with the U.S., this study focuses on the U.S. Gulf Coast-ARA trade route because we believe it offers the most immediate potential for commodification. As mentioned previously, there is a natural basis for transatlantic trade to efficiently match supply and demand. Globally, ammonia production with electrolysis remains nascent at the moment, and the EU's regulatory permissiveness for CCS-based ammonia will influence the role CCS-based ammonia imports can play in the region's decarbonization strategy. Some other regions, like the Middle East, are positioning themselves as strong exporters of ammonia with CCS. The Middle East has the advantage to potentially arbitrate between European and Asian markets. Looking now with regards to policy preference, the Middle East can supply Europe with electrolysis-based and Asia with CCS-based ammonia. It is not unthinkable that the commodification pathway happens earlier on the Middle East-Asia trade lane for CCS-based ammonia, as Middle Eastern companies set up their own trading arms and capabilities. However, that is in itself not disadvantageous for Europe and has the potential to accelerate commodification on the transatlantic route, as there will be a global market. As a buyer, Europe then has the optionality to arbitrate between the Middle East and U.S. Gulf origins.

5.2 Rotterdam compared to other potential demand centres in Northwest Europe

The position of the Port of Rotterdam in low-emission ammonia import, relative to other ports in the region, is to a large extent influenced by the location of future ammonia demand. Given the considerable uncertainty about where and to what extent ammonia will be used in the energy and feedstock sector in the future, Rotterdam's position as an import hub will be assessed by comparing it to other potential import locations.

The comparison focuses on ports in Northwest Europe, as they represent the primary competitors to the Port of Rotterdam due to their interconnected industrial clusters and established infrastructure.[188] Furthermore, Northwest Europe is the region where most of the newly announced ammonia import projects are located.

We assess the position of Port of Rotterdam in low-emission ammonia import as compared to other demand centres by looking at the current use and infrastructure of ammonia. After that, other potential ways of using low-emission ammonia are introduced. These other potential use cases are adopted in chapter 6.1 and included in various scenarios.

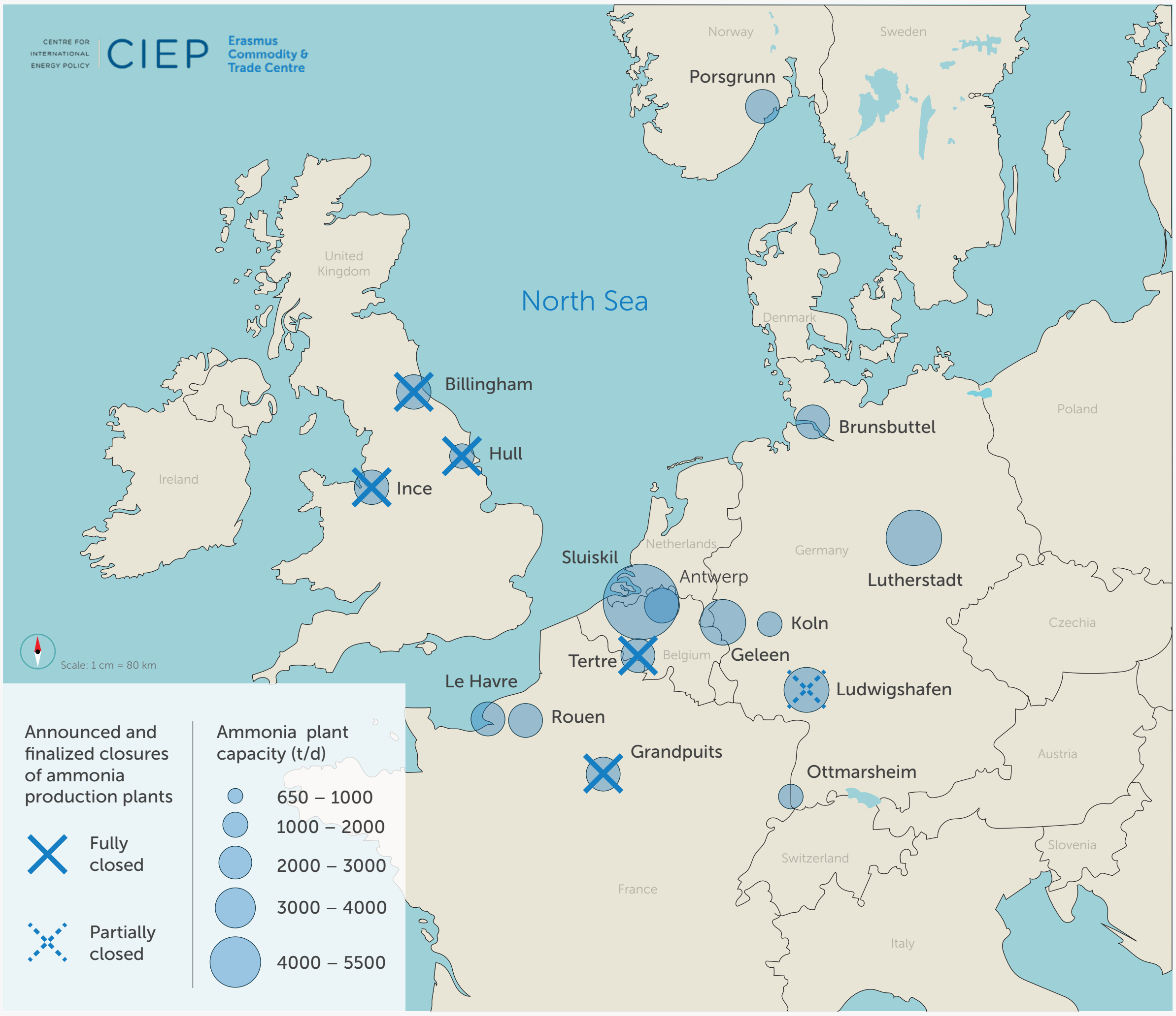
Low-emission ammonia in the fertilizer industry

Currently ammonia is primarily used in the fertiliser sector. If grey ammonia is substituted for low-emission ammonia imports, the Port of Rotterdam will initially compete with other Northwest European ports that also accommodate ammonia import facilities. Many of these ports are home to fertilizer production plants or serve as hubs for transportation further inland. Due to high natural gas prices in recent years, multiple ammonia production plants in the region have closed, as illustrated in Figure 11.[189] This has led to a greater reliance on imports and further increased the importance of import terminals in the region. It also underscores the need to be able- to transport to these new hinterlands that are not served domestically.

The ports with existing import terminals in the region include Porsgrunn, Rostock, Brunsbuttel, Sluiskil, Antwerp, Rouen, Le Havre, Montoir, Billingham, Hull and Rotterdam (see Figure 12).[190] With the anticipated growth of ammonia imports, several ports are also planning new terminals or expanding existing ones.[191] Many are concentrated in the ARA region, particularly at the Port of Rotterdam. Although most have not taken an FID yet, if these projects would come to fruition, the majority of ammonia import terminals will be situated in this region.

Europe is also home to various inland fertiliser producers and ammonia demand centres that sometimes lack direct access to global ammonia markets. These producers often make ammonia onsite from natural gas transported via pipeline. With rising gas prices, those without access to global ammonia markets have faced increasing challenges. In case an ammonia pipeline was to be realized in the Delta Rhine corridor – a cluster of underground pipelines and cables that is currently being developed connecting Rotterdam to western Germany – this could function as a new route to supply BASF[192] in Ludwigshafen and INEOS in Cologne with ammonia from global markets. This would further strengthen the position of Rotterdam in this case. Although an ammonia pipeline was initially part of the DRC project, it is currently no longer included. However, there is space reserved within the corridor for future pipelines, which would allow project developers to possibly realize an ammonia pipeline at a later stage.[193]

Figure 11. Announced and finalized closures of ammonia production plants in Northwest Europe between 2021 and January 2025



***Note:** Compiled by CIEP and ECTC, based on conversations with stakeholders, company announcements and data sources: European Commission, 2007. Large volume inorganic chemicals – ammonia, acids, and fertilisers. https://eippcb.jrc.ec.europa.eu/sites/default/files/2022-03/LVIC-AAF.pdf. Yara, 2020. Production capacities by segment. https://www.yara.com/siteassets/investors/057-reports-and-presentations/other/2020/production-capacities-by-segment-september-2020-pdf.pdf/. Agriland, March, 2023. BASF closes ammonia production plant in Germany. https://www.agriland.ie/farming-news/basf-closes-ammonia-production-plant-in-germany/.. Yara, October, 2024. Yara intends to transform Tertre plant to strengthen long-term competitiveness. https://www.yara.com/news-and-media/news/archive/2024/yara-intends-to-transform-tertre-plant-to-strengthen-long-term-competitiveness/. ACTU, January, 2025. Seine-et-Marne. "La seule solution" : 80 emplois affectés par l'arrêt de la production d'ammoniac à Grandpuits. https://actu.fr/ile-de-france/grandpuits-bailly-carrois_77211/seine-et-marne-la-seule-solution-80-emplois-affectes-par-larret-de-la-production-dammoniac-a-grandpuits_62131415.html. Yara, April, 2025. Yara International ASA 2025 first quarter results. https://www.yara.com/siteassets/investors/057-reports-and-presentations/quarterly-reports/2025/1q-2025/yara-1q-2025-presentation.pdf. CF Fertilisers Corporate Communications, July, 2023. CF Fertilisers UK Announces Proposal to Permanently Close Ammonia Plant at Billingham Complex. https://www.cfindustries.com/newsroom/2023/billingham-ammonia-plant Farmers Journal, n.d. CF Fertilisers to close one of its two UK plants. https://www.farmersjournal.ie/news/news/cf-fertilisers-to-close-one-of-its-two-uk-plants-702917#:~:text=The%20company%20will%20close%20its,(AN)%20and%20nitric%20acid.*

Of note, BASF has announced onsite production of renewable ammonia. see: https://www.basf.com/global/en/media/news-releases/2025/05/p-25-099

Figure 12. Ammonia import terminals and inland fertiliser production sites located along the proposed DRC corridor in Northwest Europe[194]

Note: *Graph is not exhaustive. The facilities shown include existing assets and publicly announced plans for the development of import projects. The existing facilities in Glomfjord and Ambes are not shown on the map given their considerable distance from Rotterdam. Data sources: IEA, Hydrogen Production and Infrastructure Projects Database, October 2024, https://www.iea.org/data-and-statistics/data-product/hydrogen-production-and-infrastructure-projects-database. Ammonia Energy Association, LEAD: Ammonia Energy Infrastructure, April, 2025, https://ammoniaenergy.org/lead/infrastructure/. Delta Rhine Corridor, n.d. For more movement on energy and climate in Europe. Retrieved April, 2025. https://www.delta-rhine-corridor.com/en. Company press releases and project announcements (various sources).*

Other use cases for low-emission ammonia

For most applications ammonia is not the most obvious fuel of choice due to its toxicity, challenging combustion properties, and technological immaturity. However, it is seen as a promising bunker fuel to reduce emissions in the shipping sector (bunkering).[195,196] Secondly, ammonia is being considered as a potential low-emission fuel for power stations.[197] As coal-fired power stations are being closed in Northwest Europe, this does apply primarily for gas-fired power stations. Thirdly, low-emission ammonia could also indirectly be used for its hydrogen content.

Ammonia bunkering

The majority of the bunkering activities in Northwest Europe are concentrated in the ARA region. The Port of Rotterdam is the largest bunkering port in the region, with approximately ten million tons of fuel sold annually.[198] The Port of Antwerp-Bruges follows as the second largest, with over six million tons fuel sold each year.[199] In contrast, the Port of Hamburg, which is the third largest container port in Northwest Europe, is estimated to supply only around 1 million tons of marine fuel annually.[200]

Although the ARA region is one of the largest bunkering markets in the world, this does not necessarily guarantee a dominant position in low-emission fuel bunkering in the future. Numerous other bunkering hubs in the world may have access to cheaper low-emission ammonia than the ARA region. However, due to its strategic position along major trade routes, high trade activity, large energy cluster, existing infrastructure and storage facilities, and proximity to key industrial centres, the ARA region - Rotterdam and Antwerp-Bruges in particular – remains well-positioned to play a significant role in a future global ammonia bunker market. In comparison to other ports in Northwest Europe, Rotterdam and Antwerp-Bruges seem best placed for future ammonia bunkering.

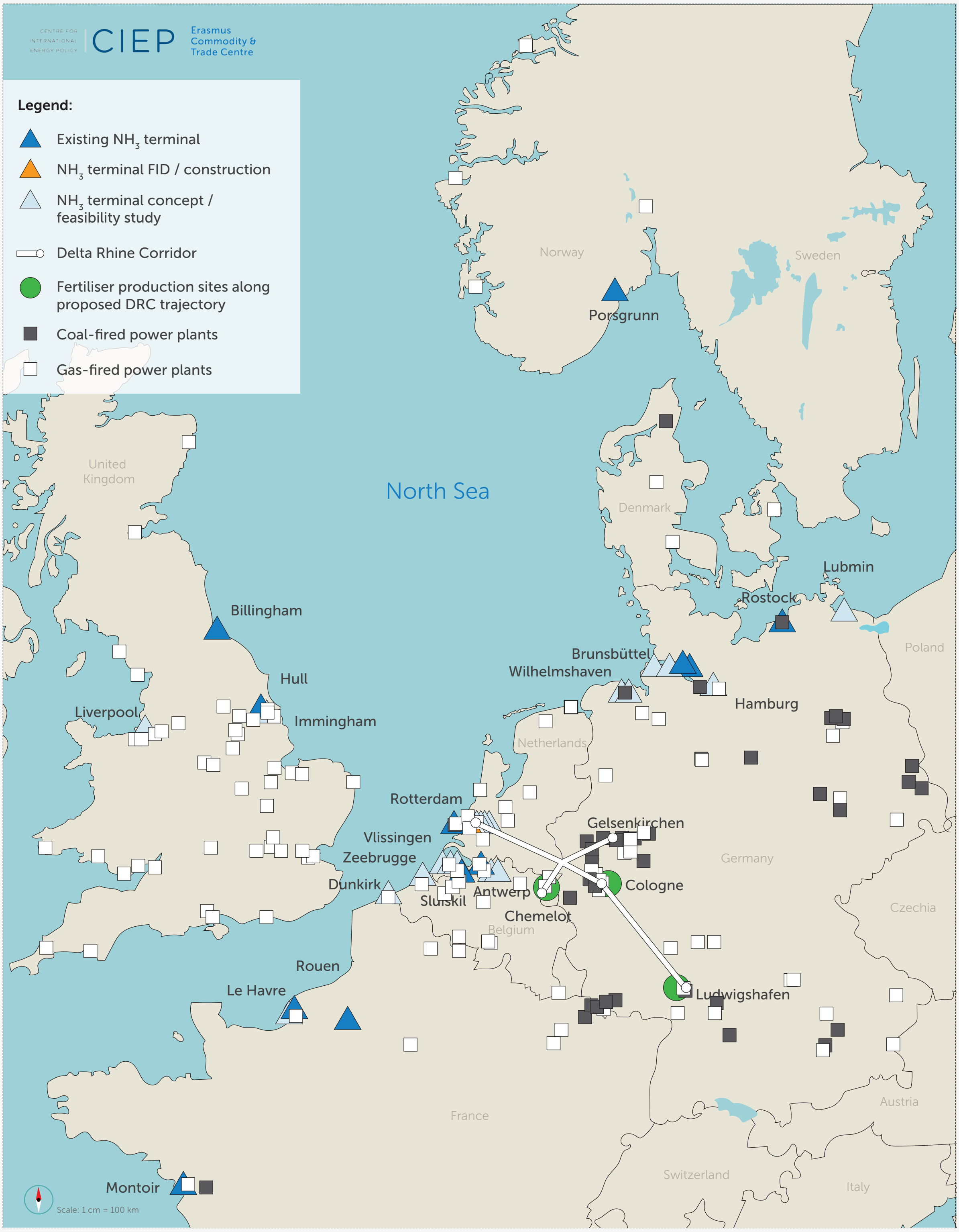
Ammonia (co-firing) in gas-fired power plants

Gas-fired power plants are currently undergoing ammonia (co-)firing tests. Various turbine manufacturers, predominantly from Asia, have announced plans to develop ammonia-fired gas turbines.[201,202] Although it is yet to be tested on a large scale, theoretically, current gas-fired power plants in Northwest Europe could be retrofitted to co-fire ammonia, with relatively minor adjustments.[203]

That said, not all power plants are equally positioned to be supplied with ammonia imports. Facilities located inland are unlikely candidates for these supplies, as there is no extensive pipeline network to deliver ammonia, while transport by train, truck or barge is often limited for safety reasons.

If ammonia co-firing in gas-fired power plants were to play a role in decarbonizing the electricity system in Northwest Europe, more locations could arise as viable entry points for imports (see Figure 13).[204] In the UK, several ports on both the east and west coasts may be well-positioned for ammonia import due to their proximity to gas-fired power stations. Similarly, ammonia imports through the ports of Antwerp-Bruges and Rotterdam could serve nearby gas-fired power plants as could ports in Northwest Germany and in France. Moreover, several gas-fired power plants are located along the proposed Delta Rhine corridor, which, if realised, would offer a potential supply route, further increasing the importance of the Port of Rotterdam as an ammonia import centre. Again, the feasibility of co-firing in these facilities would strongly depend on their economics, their proximity to populated areas and on whether safety regulations would allow it.

Figure 13. Ammonia import terminals, inland fertiliser production sites located along the proposed DRC corridor, and coal- and gas-fired power plants in Northwest Europe



Note: *Building on the data sources and assumptions described in figure 13 this graph additionally includes gas-fired power plants and coal fired power plants. Data source: European Commission Joint Research Centre (JRC), JRC Open Power Plant Database (JRC-PPDB-OPEN), 2019. https://data.jrc.ec.europa.eu/dataset/9810feeb-f062-49cd-8e76-8d8cfd488a05 Due to incomplete European power plant data, some plants might be missing or already decommissioned. The graph is intended for illustrative purposes only.*

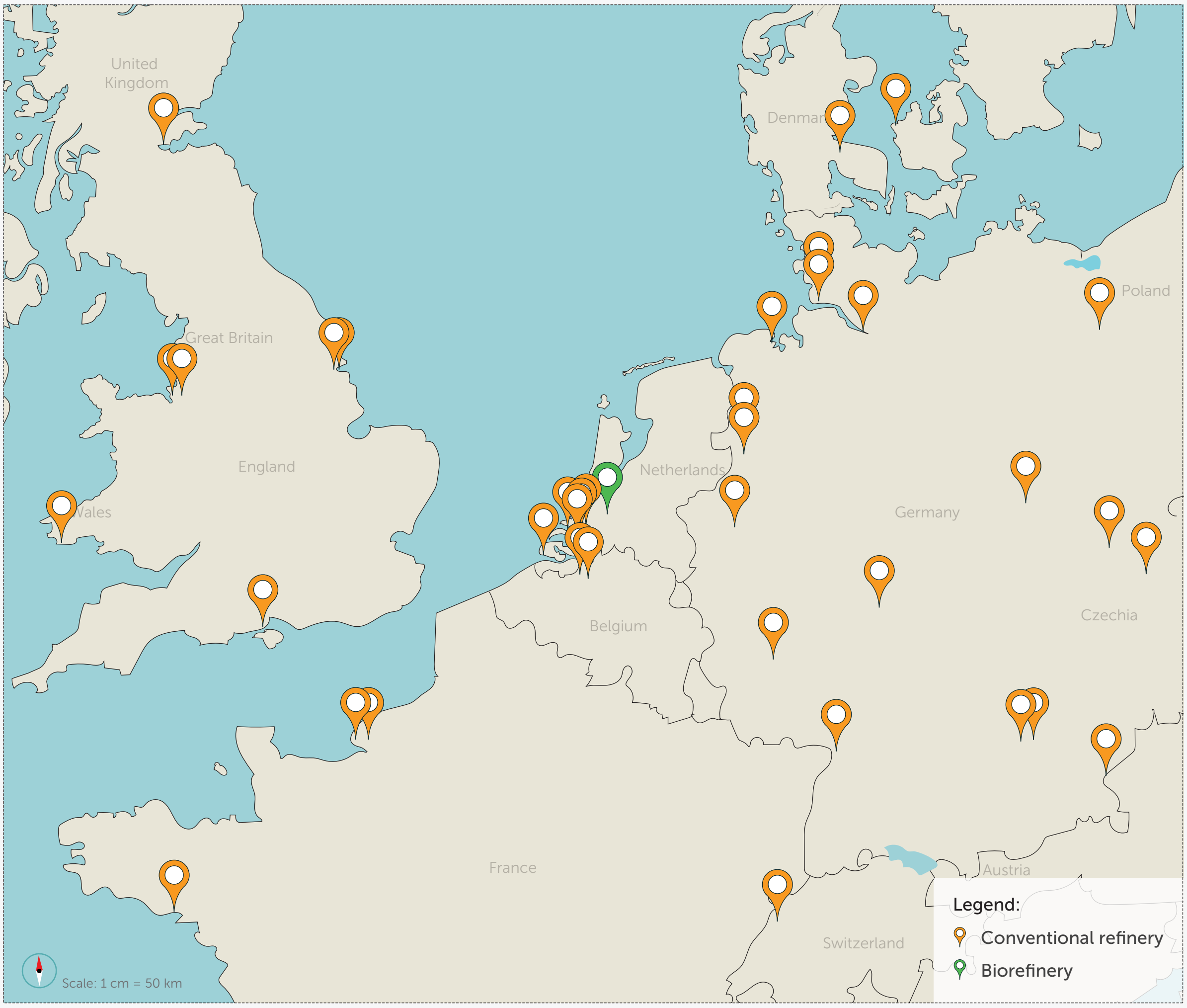
The third potential use case of imported ammonia is as hydrogen carrier, wherein the ammonia is converted back into hydrogen before it is used. Hydrogen has a wide range of potential applications in the energy sector, however, some are more realistic than others.

Currently, the total hydrogen demand in Europe is about 8 Mt per year.[205] The majority of this demand is concentrated in petrochemical clusters, with the refining industry being the largest consumer at 57%, followed by the ammonia industry at 25%, both using it as a feedstock. The remaining demand comes from the chemical industry (11%) and other industries (3%). In Northwest European countries (Germany, Netherlands, UK, France, Belgium and Denmark), the combined hydrogen demand is around 4 million tonnes per year. The majority of which is used in Germany (1.3 Mt) and the Netherlands (1.2 Mt).[206]

Presently, this demand is covered by hydrogen produced from fossil fuels, often produced at or near the facility where it is used. Porthos will abate some of the CO_2 emissions that result from the production.

Figure 14, provides an overview of refineries in Northwest Europe. Most countries in the region have refineries located in proximity to major ports.[207] Germany is an outlier, with the majority of their refineries located far inland, away from port areas.

Figure 14. Northwest European refineries[208]

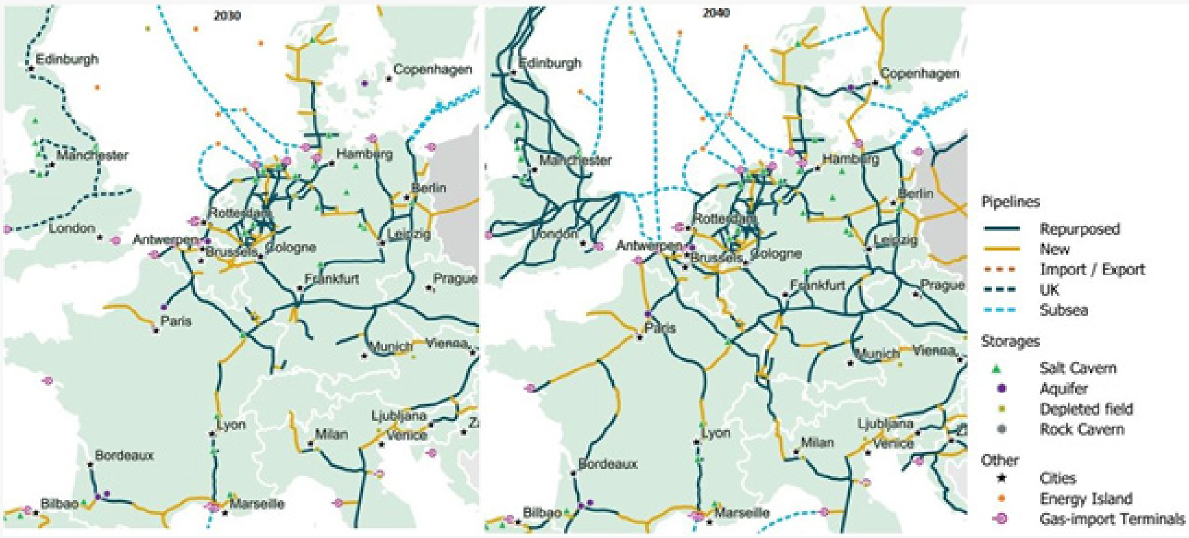


Source: *Concawe, n.d. Refinery and Biorefinery Sites in Europe. Retrieved April, 2025. https://www.concawe.eu/refineries-map/ (Graph adjusted for clarification by CIEP & ECTC)*

Potential future hydrogen application receiving significant attention, including its use in steel production and as a fuel in gas-fired power plants for flexible power supply, as low-emission alternatives are limited in these applications. It is however also important to note that the economics currently refrain steel producers from using hydrogen.

The European Hydrogen Backbone (EHB) initiative aims to establish a comprehensive pipeline network connecting most major ports in Northwest Europe to demand centres across the continent (see Figure 15).[209] The potential role of each port depends on its proximity to industrial demand, the capacity of that specific part of the network, and the timing and actual realisation of certain parts of the network built out. As clusters and ports become more connected to each other via the backbone, the competition among ports might shift merely from securing hydrogen flows to also competing for inland demand.

Figure 15. Proposed hydrogen backbone layout - 2030 ambition (left) and 2040 ambition (right)[210]



Source: *Concawe, n.d. Refinery and Biorefinery Sites in Europe. Retrieved April, 2025. https://www.concawe.eu/refineries-map/ (Graph adjusted for clarification by CIEP & ECTC)*

Regional strategies are emerging. French ports seem to be primarily focused on serving potential domestic demand.[211] Although France might have potential to export to neighbouring countries, most interconnections with neighbouring countries are only planned for a later phase, currently set for 2040. The Port of Rotterdam targets the broader Antwerp, Rotterdam, Rhine, Ruhr Area (ARRRA), aiming to act as a hub for inland hydrogen distribution to Belgium and western Germany.[212] The ARRRA forms the largest petrochemical cluster in the European Union and is already a major hydrogen consumer.[213] Additionally, the region hosts a large number of gas-fired power plants, and around 40% of German steel production takes place in North Rhine-Westphalia – both potential future users of low-emission hydrogen.[214] The ports of Antwerp-Bruges in Belgium, also have the ambition for import and throughput to Germany. At the same time, Germany seeks diversification of its hydrogen supply,[215] aiming to not rely solely on imports through neighbouring countries. In Germany, the Northwestern ports such as Wilhelmshaven and Brunsbüttel are geared towards Western Germany, notably the Ruhr Area, while the Northeast port of Rostock is oriented towards industrial demand in the east of Germany.[216,217,218]

If large-scale hydrogen conversion would become a reality, Rotterdam is well-positioned to serve a significant portion of the demand in the industrial clusters of Northwest Europe.

6 The necessary requirements for the market to scale: A scenario analysis

6.1 Scenario methodology

Scenario planning is a strategic tool to develop coherent and credible alternative stories about the future.[219] Rather than forecasting whereby historical data is extrapolated towards the future, scenario planning focusses on 'augmenting possible futures by anticipating major shifts in the business environment and think through a dynamic sequence of interacting events and trends'. It requires to think non-linearily in both positive and negative feedback loops. Although various scenario planning methodologies exist, in essence they follow a systemic approach in which external forces are mapped, assessed how these impact each other and how they are valued on the level of uncertainty and impact. The resulting scenario matrix allows for unique narratives about future worlds, that forms the basis for thinking in strategic implications and options.

In this project we did not execute a full scenario planning process but took advantage of recent work (2023) carried out in large part by the current research team. The *Hydrogen2Be*[220] report (H2B), a joint publication by ECTC, CIEP, TUDelft and DRIFT, applied scenario planning to analyse the imports of low-carbon hydrogen into Northwest Europe by the year 2040. Based upon the 8-step scenario planning approach, the H2B developed 4 unique scenarios: "Revival of the Rhineland", "Broken Bridges", "Europe's Eureka" and the "Right of Sun Tzu". The scenarios are defined by what were identified by the research team as the 2 critical uncertainties for the import of hydrogen: 1) the global geopolitical landscape defined by either an American-led West or a Chinese-led East rules-based order and 2) the social-economic prevalent public discourse on sustainability within the EU defined by either very idealistic or dogmatic versus more realistic or pragmatic. This resulted in 4 unique market evolutionary pathways in S-shapes and an assessment of the implications in terms of affordability, sustainability and security of supply. For a more detailed view on the scenarios and the analyses, we refer to the H2B report. Here we briefly discuss how we have recalibrated the groundwork of the H2B report in order to make it applicable to the current focal issue of transatlantic business case of low-emission ammonia trade. The starting point in our current analysis are the identified external forces (categorized according to the logic of the SEEPT analysis: Social, Economic, Environmental, Political and Technological external forces) of the H2B report (cf, table 2, page 39). We re-assessed the relative value and importance of the 20 identified SEEPT forces. Some of the forces were de-listed. Others were recombined based on intuitive logic and debate across the research team members on the one hand and discussions with external stakeholders on the other hand in various workshops. This resulted in re-calibrated SEEPT analysis of 15 forces from which ultimately the following six critical uncertainties were identified:

Table 5. Critical Uncertainties Identified

T2	Alternative Technologies	The development and commercial viability of competing technologies that could replace ammonia in its potential use cases. *(available versus unavailable)*
EC4	Industry Relocation	Location choice of (heavy) industries that already depend, or will depend on ammonia as feedstock, as a fuel, or for its hydrogen content. *(high versus low)*
EC5	Cheaper Alternative Supplier(s)	Availability of a cheaper alternative supplier for low-emissions ammonia import. *(available versus unavailable)*
P2	Energy Security in North-West Europe	The uninterrupted availability of energy sources at an affordable price in north-west Europe, including energy infrastructure resilience. *(high versus low)*
S3	Available Space	The physical availability of land as well as the presence of a permissive regime and a broader social license to operate for ammonia storage and handling within the port area. *(permissive versus restrictive)*
EC1	CO_2 Abatement Policies	Decarbonization regulations, mandates, and policies that shape the uptake of clean energy solutions. *(strong versus weak)*

Note: *For the full list of SEEPT forces from the H2B study and the recaliberated SEEPT forces, see appendix I.*

These critical uncertainties now underpin the logics of the scenarios. We applied these to narrate specific scenarios toward 2040 on the Transatlantic low-emissions ammonia trade resulting into specific pathways expressed in the S-curves identified earlier in the H2B report.

6.2 Scenarios

Europe has the ambition to decarbonize, secure its energy needs for the future and to revitalise its industries.[221] At the same time, it is surrounded by uncertainties regarding its own direct security, its terms of international trade, its competitiveness and decreasing public support for the energy transition.

Given the many uncertainties that Europe finds itself in we defined four storylines (scenarios) that explore potential pathways for the development of the low-emission ammonia market along the USGC-ARA trade lane from the end of this decade onwards. In the scenarios we introduce various use cases for low-emission ammonia to define the total addressable market. The storylines are based on the H2B scenarios that were adapted for low-emission ammonia trade and provide four unique S-shaped pathways. The six critical uncertainties[222], as identified in chapter 6.1 are presented as key drivers for the shape of the curves. The Dynamic Market Theory and the Commodification Pathway (chapter 2) provide us with a grounded theoretical lens to understand the unique pathways identified. Ultimately, each narrative examines a different pathway considering the development and interplay of political, economic and technical forces that have a large impact on how the market might evolve.

Scenario 1: Delayed market development: overcoming structural challenges

Throughout the second half of the 2020s, Europe took incremental steps towards a more pragmatic energy transition strategy, but these efforts proved insufficient to meet the urgency of the moment. When it came to import of low-emission molecules, regulatory policy remained restrictive. Despite *the growing global supply of hydrogen and ammonia, many international export projects failed to meet the EU's stringent RFNBO or low-carbon hydrogen criteria, slowing down the import of low-emission molecules to the region. At the same time CSRD and CSDDD regulation added an extra layer of complexity and costs, creating additional practical challenges for low-emission ammonia imports in the early stages of market development. This, combined with uncertainty about how EU regulation would evolve, created significant obstacles for investment.*

In the Netherlands specifically, safety concerns and permitting regime of the DCMR in the Rotterdam port area, including nitrogen emissions from construction played a major role in the slowing down of project development. Obtaining permits for import facilities was a large challenge. Additionally, the Dutch government was reluctant to facilitate ammonia transit to Germany, unwilling to assume responsibility for safety risks on Germany's behalf.

In the US, the post-Trump administration struggled with a spiralling public debt and inflation resulting in increased interest rates curbing final investment decisions. While the US Gulf Coast remained a promising export region, with arguably the world's most advanced project pipeline, few developers dared to move forward with investments at the close of the 2020s. In contrast, projects in the Middle East, Canada, China, and India moved ahead. In the Middle East several large-scale export projects reached FID, supported by government-backed investments and long-term policy commitments. Japanese and South Korean companies increasingly shifted their focus to this region, positioning themselves as key off-takers and equity partners in various projects. These offtake arrangements were backed by long-term contracts, enabled by state-led initiatives and favourable conditions in their domestic market that valued supply security and reducing emissions, helping buyers manage price and volume risks.

By the end of 2020s, multiple large-scale export projects completed construction. One of the first was the CCS-based ammonia project developed by TA'ZIZ (ADNOC), Fertiglobe and Mitsui in Al Ruwais, UAE. The project, with a capacity of 1 MTPA, used SMR technology with a near 100% CO_2 capture rate. It markets one of the first major low-emission ammonia shipments sent to Japan. These initial volumes were used to support Japan's fertiliser sector and to supply the first projects of co-firing ammonia in coal-fired power plants.

Meanwhile, Europe faced growing pressure as more major industrial players disinvested, scaled down operations or removed (EC4 – SEEPT forces) in response to an increasingly uncompetitive business climate for energy intense (base) industries and thermal power production. In an effort to restore Europe's attractiveness for investment and increase its energy security, the region radically shifted its climate agenda in the early 2030s. It embraced a truly pragmatic and colour agnostic approach, combining its CO_2 tax framework with straightforward, less bureaucratic subsidy scheme, and radical simplification of regulation (EC1, S3 and P2 – SEEPT forces). This improved investor confidence and removed some of the obstacles to project development.

In the first half of the 2030s, European fertilizer companies started to secure long-term contracts for low-emission ammonia. A leading European fertiliser portfolio player secured a long-term contract for CCS-based ammonia with ADNOC, covering 0.5 MTPA over a 20-year period. Backed by off-take guarantees from European, Japanese and South Korean buyers, ADNOC made significant investments in expansion of its existing low-emission ammonia facility.

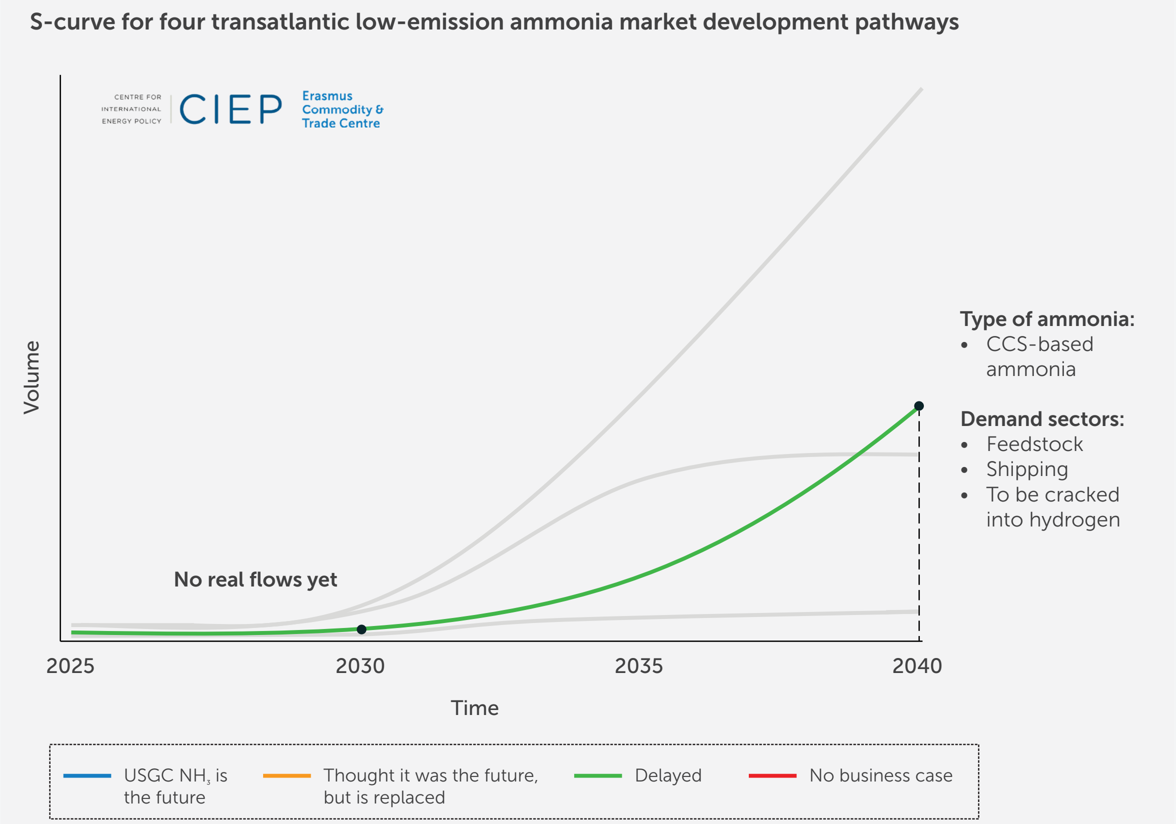
As the market expanded, new suppliers - both CCS- and electrolysis-based – as well as new off-takers entered the scene, though trade agreements continued to rely primarily on long-term contracts. Meanwhile, the role of ammonia in use cases beyond the fertiliser sector like shipping and transporting hydrogen slowly increased.

While the Netherlands grappled with regulatory barriers to project development, Northern German ports increasingly emerged as key hubs for transporting ammonia and hydrogen to the Northwest European hinterland, supported by Federal support provided under the 2025 Hydrogen Acceleration Act. Under *pressure to maintain its position as a key energy import hub, regulatory bodies in the Rotterdam port area became more flexible to accommodate rising import volumes, increasing the investment attractiveness of the port area. In 2035, discussions on the ammonia pipeline in the DRC, which would connect the ARA region with industrial clusters in the Northwest European hinterland, were restarted. Having fallen behind, the Netherlands played catch up to still secure a role as an ammonia and hydrogen hub for the Northwest European hinterlands.*

As this unfolded, US firms realized they were missing significant opportunities in the growing low-emission ammonia market and successfully lobbied for the reinstatement of the IRA 45Q tax credit. This prompted a wave of FIDs in the USGC for CCS-based export projects in the second half of the 2030s. The first contracts signed with EU off-takers followed. US suppliers offered shorter term contracts and more flexible volumes, without destination clauses. Backed by existing infrastructure and existing market demand in the USGC, the US producers were more willing to enter in flexible agreements with overseas off-takers than their middle eastern counterparts, given their different risk profile.

As increasing amounts of low-emission ammonia arrived in the ARA region in the late 2030s, spot trading increased and PRA's started reporting prices for various products. Moreover trading in forward products on the exchange increased while the first local ammonia derivatives were introduced as well. This supported basic price risk management in a still limited liquid market.

Figure 16. S-Curve: delayed scenario



Source: Adapted by Authors from H2B Report[223]

Scenario 2: Thought it was the future, but it is replaced

Looking back at the late 2020s and early 2030s, low-emission ammonia had appeared highly promising as an energy carrier. Yet by 2040, ammonia use had largely remained confined to its traditional role as a feedstock in the fertiliser and the chemical sector, with only limited uptake in a few niche energy applications and/or in some countries.

The late 2020s and the first half of the 2030s were a bullish period for the ammonia sector. Partly as a result of energy security concerns (P2 – SEEPT forces), policy incentives were strong, stimulating the necessary activity across the entire value chain – from production and transport to storage and end-use. Also, most of the regulation necessary for widespread adoption was put in place, addressing safety standards, emission accounting, infrastructure development and performance certification standards (EC1 – SEEPT forces). Around the world, numerous ammonia export projects (both CCS-based and electrolysis-based) reached FID and the first shipments arrived at ports in Japan, South Korea and the ARA region. In addition to conventional ammonia feedstock users, early adopters in energy began using ammonia as a fuel – particularly in shipping at major bunkering ports and co-firing in coastal power plants in Japan.

However, several significant problems with low-emission ammonia in the energy sector emerged throughout the second half of the 2030s. First, the anticipated cost reductions along the value chain failed to materialize at the expected pace. Also, the costs associated with ensuring safe handling and transport proved higher than anticipated. Therefore, continued policy support was projected to be necessary for an extended period, while high prices limited offtake interest.

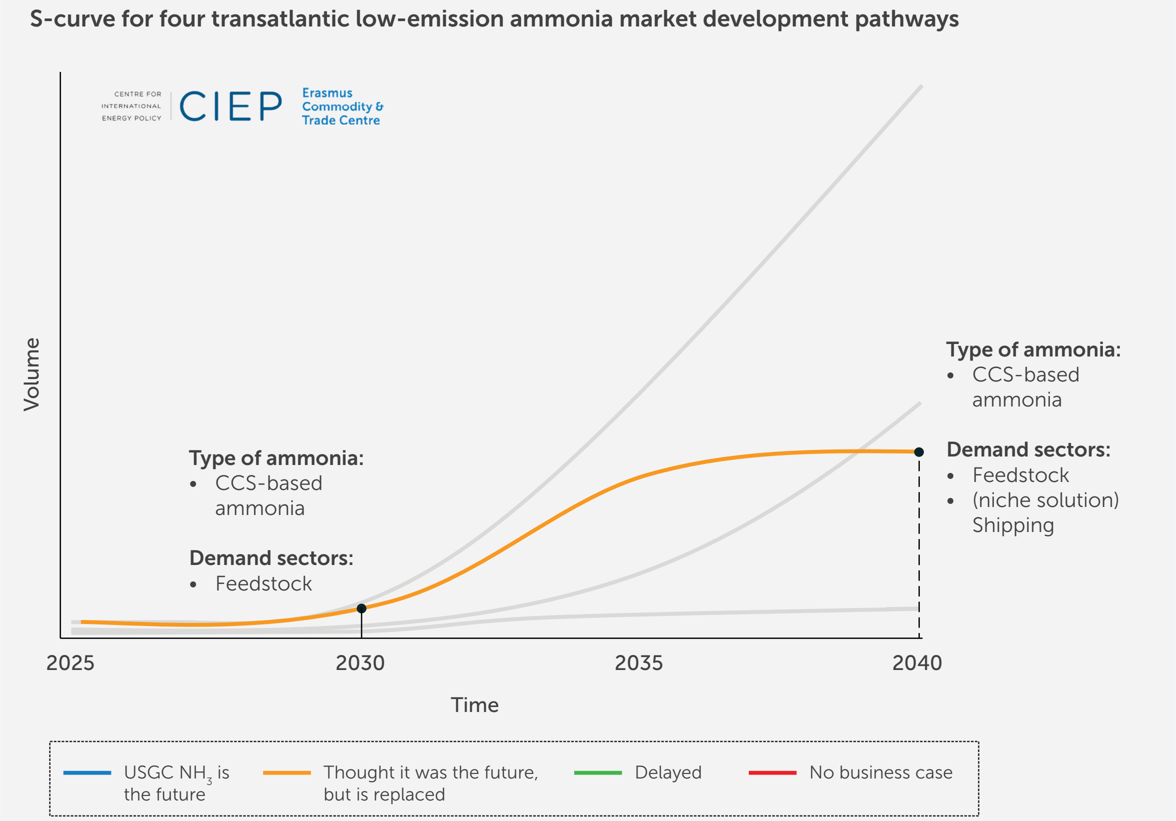
Furthermore, in 2035, major Japanese energy companies achieved 75% ammonia co-firing in an industrial scale coal-fired power plant, though NOx emissions remained far above acceptable levels for European standards. It turned out to be more challenging than initially thought to achieve high power output with low NOx emissions co-firing ammonia, limiting this carbon emission reduction solution to regions with more flexible environmental regulations.

Lastly, a series of safety incidents between 2035 and 2037 involving ammonia-fueled vessels prompted industry to reassess the viability of ammonia as a marine fuel. This increased the attractiveness of alternative solutions (S3, T2 – SEEPT forces). Especially, methanol gained significant traction as a marine fuel, driven by safety advantages, operational simplicity and infrastructure readiness. Ammonia still played a role but was surpassed by methanol as the leading clean fuel for shipping.

In the meantime, in Europe, local low-emission energy production was scaled up at an impressive pace. The offshore wind sector gained new momentum, and deployment fell only marginally short of 2030 targets, despite earlier concerns over grid integration, financing and workforce limitations. The rapid expansion of offshore wind capacity enabled significant domestic electrolysis-based hydrogen production. This was complemented by hydrogen production from natural gas and CCS in Norway and the Port of Rotterdam. In the mid-2030s, a couple of nuclear power plants were under construction. Additionally, instead of increasingly relying on low-emission ammonia imports to deal with energy shortages, LNG imports from the global market continued to play a prominent role. A portion of those flows were converted to hydrogen using CCS domestically.

By the end of the 2030s, the use of low-emission ammonia in the ARA region was largely limited to fertiliser use and shipping while only small volumes were used for energy applications. Shipments came from a handful of suppliers and long-term contracts dominated trade while spot trade remained limited. Amid growing safety concerns, public perception of ammonia had deteriorated. EU policymakers became more restrictive and discouraged its use where alternative solutions were available. The ammonia pipeline in the DRC was ruled out. At the same time, meaningful volumes of other alternatives for low-emission energy transport, such as carbon neutral LNG, liquid organic hydrogen carriers and methanol entered the market, offering a less controversial solution for low-emission energy transportation and storage.

Figure 17. S-Curve: thought it was the future, but is replaced



Source: Adapted by Authors from H2B Report[224]

Scenario 3: US Gulf Coast ammonia is the future

Faced with the serious threat of large-scale decline in energy-intensive industries, the European Commission and national governments responded with a sense of urgency throughout the second half of the 2020s, implementing far-reaching policy changes. Substantial financial aid to the industry was provided (EC4 – SEEPT forces), while regulations on sustainability, EU investments and permitting were significantly simplified. Additionally, large-scale investments were made to strengthen the EU's energy security, its energy infrastructure and long-term industrial transformation towards low-emission technologies was encouraged, taking a pragmatic and technology-neutral approach (EC1, P2, – SEEPT forces).

Europe's efforts to strengthening its competitiveness through reduction of complexity and regulatory pressure and reducing energy costs for the industry, while maintaining a focus on climate, turned out to be largely successful although for consumers/citizens the cost of energy as share of income went up. Indeed, some disinvestment occurred throughout the first half of 2030s. The EU industrial base remained largely intact but only with considerable support from governments financed from a combination of debt and increased taxes.

On the other side of the Atlantic, the adoption of the OBBB by the Trump administration in early 2025, significantly modifying the IRA, did impact investment appetite in particular for green hydrogen production. Nonetheless, the tax exemption schemes provided by the OBBB did allow for low-emissions projects to move forward. The post-Trump administration installed in the late 2020's gained bi-partisan support for the re-introduction of some of the IRA's funding provisions though rebranded to fit the new administration's narrative. This ultimately enabled the US to secure its competitive edge in global markets, becoming a first mover and low-cost supplier of ammonia based on natural gas with CCS.

As a result, the first flows of low-emission ammonia based on natural gas with CCS from the USGC arrived in ports in the ARA region in the early 2030's. The first customers were fertilizer producers active in both the USGC and ARA region. During these years early adopters in the shipping industry started to bunker ammonia in the port of Rotterdam and Antwerp-Bruges. Initial trade was driven by close cooperation across the value chain, via strategic partnerships or long-term contracts. The incremental nature of the investments in the USGC, rather than total greenfield investments, implied that not the entire production volumes were locked into long-term agreements. Moreover, the presence of industrial clusters with multiple potential users in both regions also made it easier to arrange flexible offtake arrangements. Portfolio players with long-term supply positions added to this flexibility by offering spot volumes.

Meanwhile, in Northwest Europe, the scale up of low-emission domestic energy production experienced growing challenges throughout the 2030s. Despite ambitious plans by North Sea countries for offshore wind expansion, progress was limited due to a lack of financing appetite from the private sector. Additionally, structural concerns regarding workforce shortages, environmental regulation and a lack of public support to devote more space for this purpose (S3 – SEEPT) caused the domestic production of low emission energy to remain subdued. At the same time, hopes for a nuclear renaissance never fully materialized. Limited public acceptance prevented a large-scale revival of the sector. As a result, Northwest Europe remained more import dependent than it might have envisioned in the 2020s and domestic hydrogen production remained constrained.

At the same time, the global market for low-emission ammonia expanded as new suppliers and off-takers entered the market. Alongside CCS-based ammonia, electrolysis-based ammonia export projects started to come online, further diversifying supply. Flows from the USGC to the ARA region were complemented by shipments from other regions of the world (EC4 – SEEPT forces). PRA's started reporting prices on various low-emission ammonia products, spot trading increased and market makers on the exchange started providing liquidity for an increasing range of products for delivery in the ARA region. Simultaneously, the first local financial derivatives were created and traded.

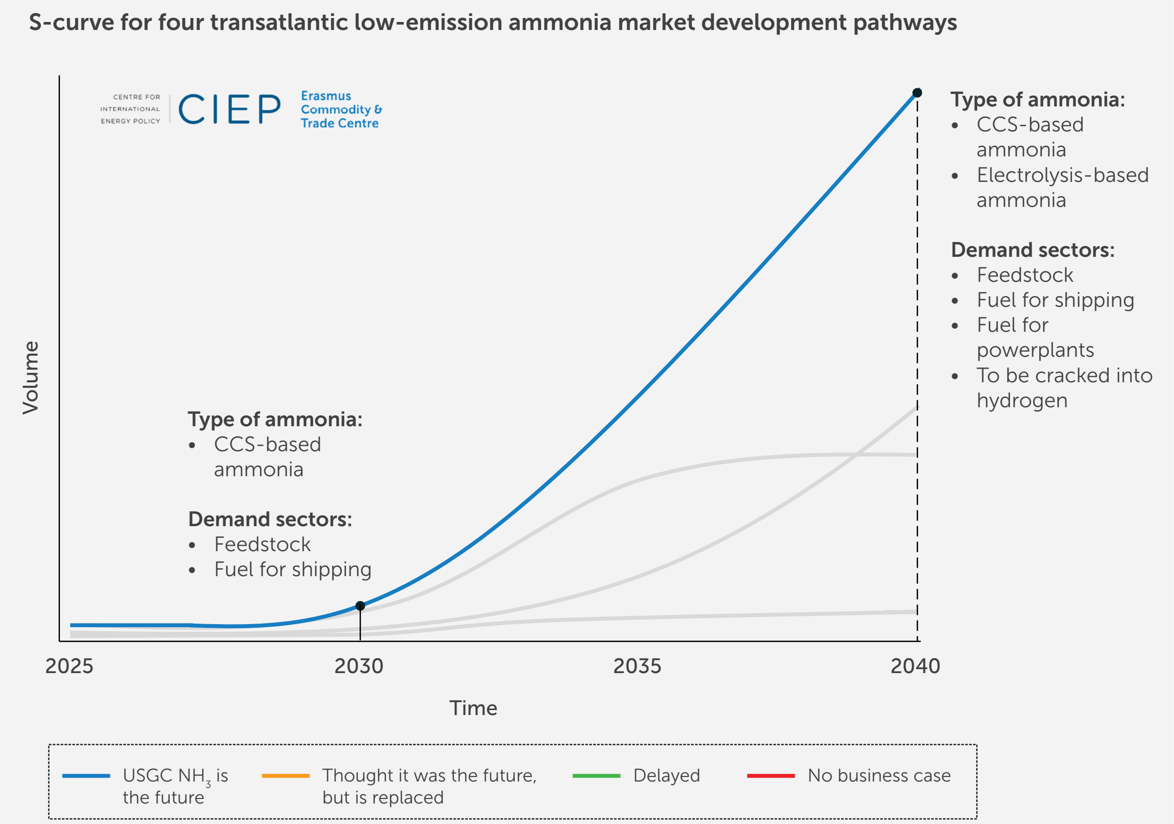
In the mid 2030's, faced with limited domestic alternatives, the EU continued to rely on LNG imports. Yet it became more permissive towards ammonia, allowing for greater imports and use in the energy sector. To accommodate the expansion of ammonia use while mitigating potential accidents, safety measures were strengthened through regulation, technological improvements and enhanced personnel training. Safety remained a priority as the region balanced energy security and protecting the public from safety hazards.

Use of ammonia as a shipping fuel further picked up in the mid-2030s. Rotterdam and Antwerp-Bruges started to establish themselves as key ammonia bunkering hubs in Northwest Europe. As trade expanded, import terminals were adding conversion facilities to absorb the abundant hydrogen from solar and wind and facilitate arbitrage between the ammonia and hydrogen market. The first industrial-scale tests regarding co-firing in gas-fired power plant took place around 2035. Ongoing engineering advancements enabled higher co-firing rates driving further emission reduction over time.

In 2035, after several years of delays, the ammonia pipeline through the Delta Rhine Corridor was completed, connecting the ARA region to the German hinterland. This pipeline quickly became a strategic asset for the region, facilitating the flow of ammonia to Chemelot, Gelsenkirchen, Cologne and Ludwigshafen, for fertilizer production, co-firing in coal plants, and as a hydrogen source for industrial use.

In the second half of the 2030s, low-emission ammonia—both CCS- and electrolysis-based—gained further commercial traction as standardized and liquid physically-settled futures contracts developed by global exchanges such as ICE, CME and Abaxx with the ARA region as main delivery point, supporting price transparency, solidifying ARA and USGC as main price reference points allowing major traders and financials to enter the financial derivatives market and boosting further spot market trade of low-emission ammonia. As ammonia completed the full commodification pathway (see chapter 2), price signals and the spread between USGC and ARA (and Japan-Korea) now governed international trade while the financial derivatives market allowed for the warehousing and transferring of price risk.

Figure 18. S-Curve: USGC NH_3 is the future



Source: Adapted by Authors from H2B Report[225]

Scenario 4: No business case

The second half of the 2020s proved to be highly problematic for Europe's heavy-industry. Fears of Europe losing it competitiveness for energy-intensive industry as articulated in the famous 'Draghi report' became a stark reality (EC4 – SEEPT forces). The relocation and disinvestment of key industrial players marked the beginning of the collapse of energy-intense industrial ecosystems in Northwest Europe. Attention fully shifted to retaining European industry and safeguarding the continent's security.

In response, Europe weakened some of its climate ambitions in order to reduce pressure on industry. Key policy measures, such as CBAM and the phase-out of free emission rights, were delayed due to the complexities of implementation and concerns that it could exacerbate economic slowdown (EC1 – SEEPT forces). With CBAM delayed, the ARA region lost a lot of its attraction for first-mover low-emission ammonia projects. The anticipated business case for large-scale imports of low-emission ammonia to the region failed to materialize.

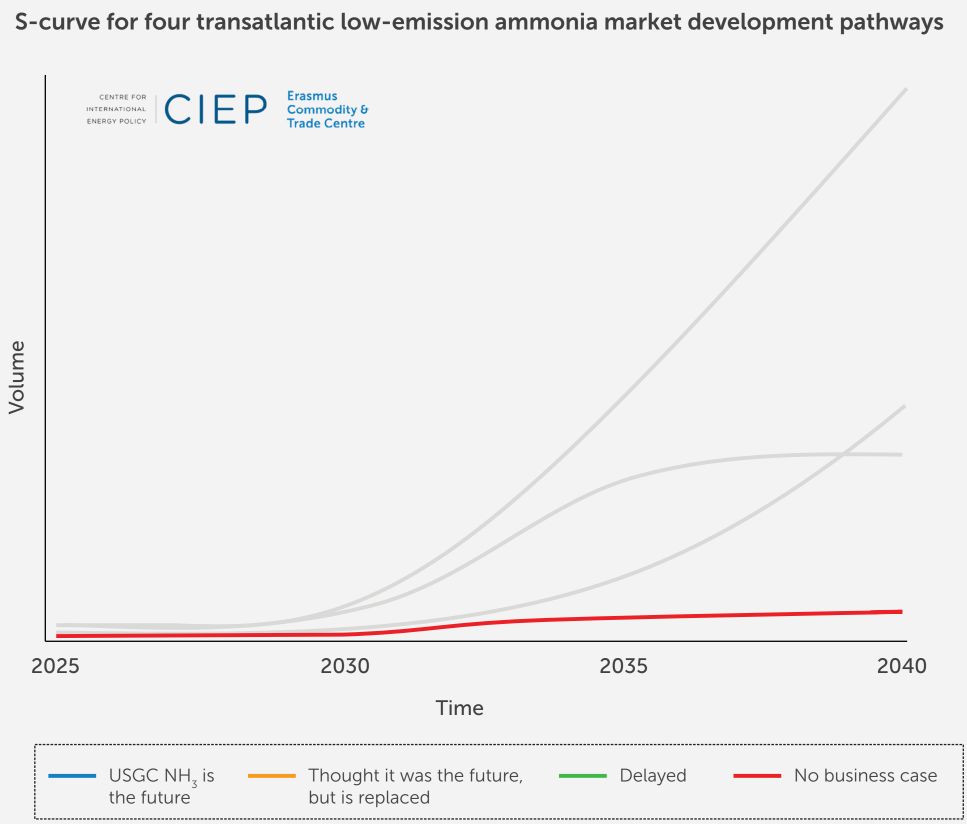
In other regions, low-emission hydrogen and ammonia ambitions were likewise scaled back. High costs and low demand persisted as key issues. The necessary policy to plug the gap was not strong enough in most places and binding offtake agreements remained lacking. By the late 2020s, the global vision of a quickly emerging low-emission hydrogen economy had largely proven unrealistic, with progress falling far short of expectations. Despite a decade of global strategies, roadmaps and numerous pilot projects, most large-scale low-emission hydrogen projects never reached an FID, other than those connected to local offshore wind and large-scale solar production. As a result, the global focus gradually shifted to other carbon emission reduction options. In the second half of the 2030s, when a renewed interest in low-carbon supply chains emerged in Asia, the newest bets were on the e-methane route rather than on ammonia, because the use of existing gas infrastructure was seen as beneficial from a cost perspective (T2 – SEEPT forces).

Meanwhile, in the early 2030's, global LNG supply increased as major new liquefaction projects in the US Gulf Coast and Qatar came online. Chinese LNG demand levelled off as a result of saturation in key demand sectors and policy support for domestic energy production. This caused a state of oversupply, continuing well into the mid- 2030s. Europe leveraged this situation by relying on natural gas for longer, combined with efforts to reduce network costs and taxes, easing some of the burden of high energy prices on its industrial base.

In the 2030s, following numerous closures and disinvestments, stability gradually returned to Europe's industrial landscape. The region adopted a brownfield-oriented approach to the energy transition, focusing on incremental emission reductions through existing infrastructure rather than full system overhauls. Europe started to blend increasing amounts of bio- and e-methane with its conventional methane supply. This allowed Europe to gradually reduce emissions, while continuing to use its existing infrastructure without needing to heavily invest in complex and costly behind-the-meter solutions. At the same time, biofuel mandates in the transport sector were gradually increased, supporting emission reduction in road and aviation again avoiding rapid infrastructure shifts. These measures also provided much needed relief to the electricity grid. Combined with CCS in the industry, this approach helped reduce emissions in more difficult-to-abate sectors.

Worldwide, flows from low-emission ammonia projects that did materialize were solely restricted to feedstock applications, such as fertiliser, refining and other chemical use cases where alternatives simply do not exist. As a result, ammonia trade did not see any significant increase. The ambition of using hydrogen or ammonia at scale for mobility, power generation or high temperature heat, did not materialize.

Figure 19. S-Curve: no business case



Source: Adapted by Authors from H2B Report[226]

6.3 Overview of requirements for the market to scale

A mix of global and local, exogenous and endogenous factors influence the viability of the transatlantic business case. Based on current developments in the low-emission ammonia landscape, the scenario analysis of potential market development, and insights from the theoretical framework, several necessary conditions for scaling the transatlantic low-emission ammonia market have been identified. Though the focus in this report is on the transatlantic route, initial volumes could come from other regions. This could nonetheless be positive for the ARA region and does not alter the requirements for the market to scale. The requirements have been categorized according to their characteristics into one of the three groups; physical infrastructure requirements (A), legal and policy requirements (B), market arrangements (C).

Necessary requirements for the market to scale

A. Physical infrastructure requirements

Whether Rotterdam can capitalise on its potential depends on the successful development of receiving, storing, refining and transporting low-emission ammonia. This requires **import for ammonia terminals, storage facilities, conversion facilities and transport modalities.** This physical infrastructure ensures that local demand and demand in the hinterland can be reached. Building a hydrogen backbone in The Netherlands could be very beneficial to low-emission ammonia as well. Storage facilities for ammonia are a solution to volatility in demand while at the same time they enable trade optimisations.

Safety of people and safety of the physical infrastructure are crucial to scaling the market. Incidents contribute crucially to public perception of ammonia and therewith the formation of the market. Safety protocols and measures should be in place by companies along the value chain to demonstrate safe handling of ammonia.

B. Legal and policy requirements

In order to make sure that physical requirements can be implemented, legislation, policies and permits should be in place and be aligned. At the same time, policy makers have to create a level playing field, including a technology neutral approach, supporting companies and small end-users to make the transition.

Robust CO_2 abatement targets, pricing mechanisms (E.g. CBAM) and targeted subsidies along the whole value chain together stimulate demand for low-emission energy carriers by making them more competitive. These should be sufficient to make sure that the attractiveness of EU as a target market does not diminish.

Regulatory consistency is also essential, both between nations, as well as the harmonization of local and global standards. For example, under legislation such as RED III, lack of uniformity in its transposition into national law fragments the market undermining the business case. If the Netherlands enacts obligations at the company-level but Germany does not, the lack of level-playing field acts as a hinderance. The same applies to discrepancies in carbon accounting methodologies, for example in relation to a scheme for trading low-emission ammonia.

Permissive regulatory space concerns a regulatory environment that is flexible and conducive to energy transition projects including low-emission ammonia projects. This could encompass various factors, some of which are:

- Pragmatism in the selection of decarbonization pathways; such as the treatment of CCS and electrolysis pathways under RED III, the Delegated Act for low-emission fuels, and the IRA
- Conducive/feasible safety and compliance regulations (E.g. CSRD, CSDDD)
- Allowing for the possibility to use ammonia in other potentially promising demand segments (e.g. supporting its adoption in the maritime and shipping sectors and for flexible/firm low-carbon power production to supplement renewables)

- Support of inland pipeline transportation to move ammonia beyond port areas reaching demand centres in the hinterland
- A pragmatic approach to NOx emissions during the construction phase of a project, recognizing the potential for the net reduction of emissions once the project is put into operation.

A **dynamic approach to competition policy** that adapts to the evolving needs of the market at its different stages of market development supports the development of a low-emission ammonia market. For example, during the introduction phase, allowing for a certain level of collaboration between players along the value chain enables players to deal with the significant risks that come with setting up new supply chains. In later phases it can, if necessary from the competition viewpoint, support the development of open-access infrastructure to lower barriers to entry for new market participants.

Policy mismatch between the U.S and the EU can make or break the business case for low-emission ammonia. The continuation of the hydrogen relevant tax credits under the IRA (45V and 45Q) makes low-carbon ammonia production cost-effective in the U.S., and their long-term certainty incentivizes investment decisions. 45V credits, after amendments made by the OBBB, can only be claimed until 1 January 2028, while facilities placed in service before 1 January 2033 remain eligible for 45Q. On the EU side too, there are time-sensitive provisions; RFNBO production plants have until 1 January 2028 to secure long-term PPAs with existing renewable installations, thereafter strict additionality requirements apply. Until 2030, renewable electricity for RFNBOs can be matched on a monthly basis, after which hourly-matching applies. In the Netherlands, the exemption from the mass-balance system of verification under the Annual Obligation Act is until 2029, and may or may not be extended after a review in 2028. As a result, the conditions to qualify as an RFNBO become stricter after 2030 under the present regulatory framework. Recent policy changes and economic logic will favour CCS-based ammonia production in the US - which cannot be used to fulfil RFNBO mandates in the EU. This policy mismatch presently undermines the business case. On both sides of the Atlantic, the shrinking time window may either push project developers to accelerate efforts, or deter final investment decisions given the regulatory uncertainty.

It is in the interest of governments to **diversify supply** of feedstocks and energy, for example, by including low-emission ammonia in the energy transition solution space. This creates a more robust future energy system, a diverse set of technologies and diverse supply lines that increase security of energy supplies.

C. Market arrangements

An important enabler for trading low-emission ammonia is the existence of a **reliable scheme for trading low-emission ammonia certificates.** Certificates can prove the origin of molecules and are a step towards avoiding double counting. Companies, owners of ships or small end users that aim to reduce their footprint will only buy certificates that are trustworthy. It will be up to the EU and national governments to create clarity on the requirements of such a scheme and who will be responsible for the roll-out of it. It involves various questions concerning the issuance, warehousing, adapting, and the trading of certificates. This non-physical infrastructure is critical for the market to develop.

Price Reporting Agencies (PRA's) publish price quotes for all kinds of commodities. These quotes are typically used in long term contracts between buyers and sellers and provide for independent pricing. If these agencies publish price quotes for (low-)emission ammonia delivered in the ARA region it becomes easier for market participants to agree to a price for (low-)emission ammonia being delivered. **Traders** typically enter the market when arbitrage opportunities (location/time) exist. A result of these parties becoming active on the market is that liquidity increases and bid-ask spreads decrease. Additionally, **brokers** play a crucial role in connecting supply and demand for a commodity. For kickstarting the trading of low-emission ammonia these intermediaries could play an important role. **Market makers** have an important role in **providing liquidity** in markets and products that have limited liquidity. In the gas market, exchanges had market maker programmes for futures with the aim to increase liquidity and reduce costs for market participants. This could be supportive for increasing the traded volume for low-emission ammonia once it becomes tradable on the exchange.

Initiatives for **industry standards on forward contracting** need to be supported as they result in reduced transaction costs and allow for risk management on bi-lateral trades. Overall institutional mechanisms in support of price discovery through the design of financial instruments that allows for the warehousing and transferring of price risk further supports the business case around CAPEX and Net Present Value of investment in ammonia assets.

Conclusion

In the second half of the 20th century, the initial emergence of ARA as polycentric port system connected infrastructure (pipelines), trade flows, transactions and a division of labour.[227] Rotterdam became the main crude oil storage and refining hub, Amsterdam became specialized in fuel blending and storage while Antwerp developed into a fine chemicals processing hub. This emergence is not the intended result of formalized spatial planning, nor did the ARA ever become a frame of reference among planning agencies. Rather, it is the result of self-organisation (competition and cooperation) in the oil industry in correspondence and in reaction to local public policy initiatives that have culminated in the emergence of the ARA region as an internationally recognized spot market for crude oil and oil products. This was only later institutionally formalized in delivery contracts (oil futures) traded on international commodity exchanges. With regards to low-emission ammonia and the development of a hydrogen economy we might see the same emergence taking place: Amsterdam has taken the route of methanol and LOHC and does not pursue any ammonia investments, while Rotterdam, Antwerp and NorthSea Port are more or less in competition with each other.

At the time of writing, given the constraining regulatory landscape and the subsequent pushback from U.S. companies, coupled with the more advanced institutional demand case in Japan compared to Europe, we anticipate Japan offers more regulatory clarity and signals, with better-organized ready-to-use sectors for low-emission ammonia. In contrast, the EU market remains fragmented and lacks demand aggregation, driven by varied (and currently delayed) national transpositions of RED III. The use-cases for direct use are currently weaker in Europe than elsewhere. The demand gap could be alleviated by adopting a more pragmatic approach to the low-carbon policies for the next 10-15 years. The outcomes are not set in stone. The evolutionary pathway will eventually be shaped by building on the existing successful self-organised port system while stakeholders remain adaptive to the changing landscape. As was seen in the case of LNG, informed by the value of lost energy demand (VoLED), exogenous factors and external events can rapidly shift the trajectory from one pathway to another, underscoring that ammonia's future role may be shaped by more than economic calculus alone. In a world where geopolitics comes into play more prominently, such a concept becomes more prevalent and relevant.

Taking the four potential pathways and the requirements to scale the market into consideration, we therefore conclude that for all stakeholders involved it is important to be adaptive. The current landscape in terms of geopolitics, trade, energy security and climate change does not allow for betting on one energy carrier. Neither does the current landscape tell what the preferential energy mix of tomorrow is. Therefore, governments and industries should collaborate to make sure that the necessary conditions for a low-ammonia market to scale are in place. This is important because ammonia is both a chemical as well as an energy carrier and could therefore contribute to both security of energy supply as well as the energy transition. Eventually, when the external conditions are favourable, the trading of low-emission ammonia via the USGC – ARA trading lane could prove to be substantial. The import of LNG in Rotterdam serves as an analogy. Policy makers concluded at some point that the (socio-)economic cost of not being able to meet households or industries' gas demand was too high. To mitigate damage (lost value) to the European economy, infrastructure capacity was built to import LNG. Initially volumes were small. However, as a result of declining volumes of both domestic production and Russian gas, imported LNG volumes increased sharply. Even so, while liquidity of TTF was limited at the start, it has become the benchmark for the pricing of natural gas in Europe. Though the future path of low-emission ammonia remains uncertain, it can only copy natural gas' success if the necessary requirements to scale are met.

7 Considerations for future research

Based on the insights of this study, we offer some considerations for further research.

We do not consider further quantification of the identified pathways to add significant value at this stage, given the high level of regulatory uncertainty in Europe – as captured in the pathways of this study. This includes ambiguity around the Delegated Acts and the recalibration of policy pledges by individual member states (in particular Germany). There is more clarity in the US with the OBBB, which clearly undercuts green hydrogen production but still accommodates low-emission hydrogen carriers (ammonia) in combination with CCS. Likewise, developments in the Middle East, China, and Japan may also influence global market dynamics, and inevitably, Europe's policy preferences, regulatory regime and market design. For instance, Japan's continued offtake commitments of low-carbon ammonia from the Middle East and the US Gulf Coast may further optimize supply chains and generate incremental tonnage to be traded spot for a diversifying demand in power generation and marine fuels.

Therefore, we believe at this stage it will be more relevant to monitor early indicators that signal tipping points in market evolution, commodification pathways, and the implications for Rotterdam's position as a port-industrial hub. Rather than quantifying pathways, it would likely be more useful to conduct a simulation based on a real-world trade flow, with committed involvement of industry players in production, shipping, trade, financing, and offtake. Such a simulation should consider how institutional design affects optionality and liquidity, scalability and offtake, price discovery and price risk transfer mechanisms, and ultimately policy targets on decarbonization. Project-based learning with industry stakeholders is therefore key as it will generate the crucial agency to overcome various barriers through collective action.

Future research in this area could strategically connect academic expertise with these applied industrial initiatives around simulating market developments and institutional design. Applied scientific research would then contribute to the actual realization of market development and commodification processes that are critical for the Port of Rotterdam and ensuring a secure, sustainable, and affordable energy and feedstock supply for Dutch society and its neighbors.

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1. Natural gas surplus is calculated as production minus consumption (2023 figures), sourced from Statistical Review of World Energy 2024.
2. The number of hydrogen production projects is counted from the IEA Hydrogen Production Projects database (Updated October 2024). Decommissioned projects excluded.
3. The number of CCUS projects, counted from the IEA CCUS Projects database (Updated April 2025), reflects the broad carbon management landscape, including all end-use sectors, not just hydrogen/ammonia. Only 'Transport & Storage (T&S)' and 'Full Chain' projects are counted to avoid duplication with standalone capture, transport, storage, or utilization initiatives. This approach also ensures that only projects with well-established or integrated value chains are included. Different project phases are counted separately (aligning with the IEA methodology) for simplicity. Cancelled and decommissioned projects excluded.
4. S&P Rating and Country Risk Premium (CRP) (Based on CDS) sourced from () (January 2025). For the UAE, the country risk premium based on rating was used, as CDS (Credit Default Swap) data was not available.

[174] *The table highlights some key players in CCS-based ammonia production and export. Natural gas surplus and the number of Carbon Capture, Utilisation and Storage (CCUS) projects are used to gauge export potential and the maturity of CCUS technology deployment. Proven gas reserves indicate a country's long-term or future capability to support CCS-based hydrogen production. The number of hydrogen production projects in advanced stages gives an order of magnitude of development momentum in hydrogen and the availability of supporting infrastructure. S&P ratings and country risk premium reflect investor confidence and influence access to finance.*

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Appendix I

1 Overview of SEEPT Forces – Hydrogen to Be Report

Social

- **S1** Social structure
- **S2** Public acceptance of the energy transition
- **S3** Energy (distribution) justice
- **S4** Availability of human capital

Economic

- **EC1** CO_2 abatement policies
- **EC2** Stability of global financial markets
- **EC3** Extent of globalisation
- **EC4** Industry relocation

Environmental

- **ENV1** Climate change-induced extreme weather events
- **ENV2** Scarcity of raw materials
- **ENV3** Land and water availability
- **ENV4** Sustainability pathways

Political

- **P1** Leadership in hydrogen and hydrogen technology development
- **P2** Degree of global cohesion
- **P3** Rules setters in global markets
- **P4** Energy security in north-west Europe

Technological

- **T1** Learning curve for non-H_2 electricity storage
- **T2** Access to key hydrogen technologies
- **T3** Emergence of intercontinental energy supergrids
- **T4** Emergence of high-energy digital appliances

2 Overview of SEEPT Forces – Recalibrated

Social

- **S1** Public Acceptance of Ammonia
- **S2** Availability of Human Capital
- **S3** Available Space

Economic

- **EC1** CO_2 Abatement Policies
- **EC2** Stability of Global Financial Markets
- **EC3** (Economic) Rule Setters in Global Markets
- **EC4** Industry Relocation
- **EC5** Cheaper Alternative Supplier(s)

Environmental

- **ENV 1** Sustainability Policy/ Transition Regulation
- **ENV 2** (International) Consistency of Sustainability Standards

Political

- **P1** Political Rule Setters
- **P2** Energy Security in North-West Europe
- **P3** Food Security in North-West Europe
- **P4** Willingness to be dependent on a single supplier country (Eg. U.S.)

Technological

- **T1** Viability of Alternative Carriers
- **T2** Alternative Technologies