CommodipHy

The commodification of ammonia and the role of Rotterdam as a global pricing centre

van Son, Liam; Arkhipov-Goyal, Amit; Van den Berghe, K.B.J.; den Ouden, Bert; van Vliet, Robert-Jan; Jacobs, Wouter

Publication date
2023

Document Version
Final published version

Citation (APA)
van Son, L., Arkhipov-Goyal, A., Van den Berghe, K. B. J., den Ouden, B., van Vliet, R.-J., & Jacobs, W. (2023). *CommodipHy: The commodification of ammonia and the role of Rotterdam as a global pricing centre*. Delft University of Technology.

CommodipHy

The commodification of ammonia and the role of Rotterdam as a global pricing centre

Research Report
March 2023

Erasmus Commodity & Trade Centre

Erasmus

TU Delft

Acknowledgements

This report was conducted by the Erasmus Commodity & Trade Centre (ECTC; part of Erasmus Urban, Port and Transport Centre; Erasmus UPT) and the TU Delft Faculty of Architecture and the Built Environment. This research was funded by Resilient Delta.

Project team: Amit Arkhipov-Goyal (ECTC), Bert den Ouden (ECTC), Liam van Son (lead author; Erasmus UPT), Dr. Karel van den Berghe (TU Delft), Robert Jan van Vliet (independent consultant), Dr. Wouter Jacobs (ECTC).

Interim research findings were presented at the Nationaal Waterstof Congress in Jaarbeurs, Utrecht, on 15 December 2022.

Cover image credit: Suriyapong Thongsawang | iStock by Getty Images

Executive Summary

Ammonia's future in the energy system

The upheaval in energy markets and energy systems, accelerated by Russia's invasion of Ukraine in February 2022, has complicated the trade-offs between energy security, sustainability and affordability. European Commissions' REPowerEU plan was intended to accelerate Europe 's independence from Russian-based fossil fuels. Hydrogen and hydrogen carriers, such as ammonia, have the potential to displace hydrocarbons in the energy mix and secure supplies for Europe's energy transition. Rather than overly relying on domestic production of green hydrogen, REPowerEU emphasizes the role of trade in managing regional imbalances in supply and demand. Trade in hydrogen carriers, however, is in an infancy stage: price mechanisms are not well established, market fundamentals beyond initial demand are poorly understood, optimized logistics channels are yet to be implemented, and regulatory frameworks are still to be articulated.

Potential for ammonia is extensive – demand for the commodity may rise to 688 Mt by 2050, more than triple the current market size. This growth is expected to be driven by ammonia's use as a hydrogen carrier, and as a bunker fuel in place of fossil fuels to decarbonise the shipping industry. The eventual size of the market and its geographic distribution remain uncertain, but its use is increasingly stimulated by government policies, particularly those aimed at introducing hydrogen into the energy mix and decarbonising industries, especially in the EU, the US and Japan. However, for ammonia to service this demand, the market for the commodity will need to become more sophisticated.

The commodification of ammonia, and the establishment of pricing centres, will be fundamental to positioning ammonia as an energy carrier in the zero-to-low-carbon energy future. This report conceptualises commodification as a process, situates the ammonia market within it and considers the potential for Rotterdam to become ammonia's European pricing centre. This informs a set of next steps to position Rotterdam and the Amsterdam-Rotterdam-Antwerp (ARA) region as a leader in the future ammonia market.

Commodifying ammonia

The report conceptualised a three-phase commodification framework to illustrate phases of commodity market sophistication, and the tipping points that enable the transition of the market from one phase to another. According to the commodification framework, the ammonia market is currently in the first phase, whereby it is an untransparent market comprised largely of long-term contracts between producers and consumers. Moreover, much of the current production is co-located with demand, meaning only about 10% of all ammonia produced is traded internationally. However, the growth and (geographic and sectoral) diversification of demand, as well as changing means of producing ammonia, may create further variation between locations of supply and demand.

This may tip the market into the second phase, where it is dominated by more transparent spot market trading, which balances supply and demand, introduces customised forward contracts, and sets the benchmark for long-term contracts. This is a critical step for building confidence for the use of the commodity in key parts of the energy system, as market players can access more and better information, leading to improved price discovery, and therefore further balancing of supply, demand, and price. Feedback loops that attract more market players, volumes of the commodity and financial liquidity then nudge the market to phase three.

The third phase, far removed from the current state of the ammonia market, is where the market establishes standardised financial derivates and thus increases financial liquidity. These steps enable market players to further mitigate risks associated with trading the commodity. The extent to, and the pace at which the transition to the second phase occurs depends in part on the role ammonia will play vis-à-vis hydrogen. There are three possible pathways, should ammonia be chosen over competing carriers. It can 1) reinforce local hydrogen production by acting as a price equalizer, 2) serve as a direct feedstock for hydrogen, or 3) become a direct energy source alongside hydrogen.

Rotterdam as a pricing centre

Pricing centres in commodity markets are fundamental mechanisms: they enable financial liquidity and price discovery that account for variations across geographies, often serving as benchmarks for contract prices settled in the market. Pricing centres often co-locate with concentrations of supply or demand, or both, because of the volume of the commodities and trade deals that are settled in these locations. They attract trade volumes as the benchmark price and preferred delivery location locks-in value to markets and contracts: locations of superior optionality in time, space and form attract liquidity and returns of investments in these markets.

The Port of Rotterdam has long served as an entry – and pricing – point for numerous commodities, particularly crude oil, oil products and natural gas. This has endowed Rotterdam, and the wider ARA port-industrial cluster, with the infrastructure, institutions and demand for current and future ammonia value chains. There is also potential for new demand for ammonia in the ARA: bunker fuels, petro-chemicals, converting ammonia into hydrogen for use in power markets, and the inland transfer of ammonia into the industrial areas of the Rhine-Ruhr region. Through a combination of these reasons, Rotterdam is well positioned to become a pricing centre for ammonia.

With Rotterdam as a pricing centre, market players will seek to sell against Rotterdam prices, because of regular demand on the spot market. This will drive more suppliers to move volume to the Rotterdam price and endorse the price discovery process. A financial derivative contract will then consider the underlying physical volume traded on a benchmark price to settle future physical delivery terms, as it will attract the most liquidity in the contract. This places Rotterdam in the advantageous position to secure recurring flows of ammonia, by capitalising on the virtuous cycle produced by the advancement in the commodification pathway.

Strategic recommendations

To continue unravelling the complexity of this market and its development, the report recommends building understanding of the competing hydrogen carriers, the two main sources of demand – ammonia for hydrogen and ammonia for bunker fuel, as well developing a business case for Rotterdam in this market:

- **Assessing the role of competing (and complementing) hydrogen carriers:** Ammonia's function as a hydrogen carrier depends in part on the maturity of competing carriers, such liquid hydrogen, liquid organic hydrogen carriers (LOHC) and methanol. Their future market size, as well as technical and cost improvements may challenge ammonia's potential. Research into the commodification of competing carriers will provide insight into ammonia's longer-term standing vis-à-vis the other carriers.
- **Understanding the development of the ammonia bunker fuel market:** Rotterdam is the largest bunker fuel market in Europe, and shipping constitutes a large share of potential demand growth for ammonia. The Port of Rotterdam is already witnessing an expansion of bio-blended bunker fuels, particularly as the push for decarbonisation in shipping intensifies. Research into the bunker fuel market, as well as carbon offsets and green certification trading, both of which are complimentary to this market, will render a clearer picture of ammonia's prospect as a bunker fuel.
- **Understanding the costs of converting ammonia to hydrogen:** Ammonia's function as a hydrogen carrier presents the second largest potential growth market for ammonia. However, to realise this prospect, unknowns around the costs of conversion need to be better understood. There is a need for research into the conversion spread (price difference between price of hydrogen, and the price of ammonia with the cost of conversion) of imported ammonia into pipelined hydrogen. This includes the study of the economic relationship between the two options and the cost of environmental compliance under the EU's Delegated Acts on Renewable Hydrogen, since ammonia converted to hydrogen would be traded in the mass balance system separately from the Guarantees of Origin.
- **Making the market in the ARA:** H2Global has solidified Germany's position as a leading hydrogen, and by proxy, ammonia, importer. However, with the large potential demand in the ARA and its throughput to the Rhine-Ruhr, supply and demand need to be matched in the ARA. The Netherlands is already active in establishing connections with future hydrogen and ammonia export countries, through both government and commercial initiatives. However, this needs further development, to commercialise these connections into actual traded volumes, for the eventual commodification of ammonia. This calls for the creation of a business case for ARA as an ammonia hub, and eventually as a pricing point. The business case should identify the necessary steps to make the market, catalogue key market actors, especially in shipping, storage, trading and demand, and address the potential to consolidate a knowledge base in The Netherlands that enables these efforts.

Table of contents

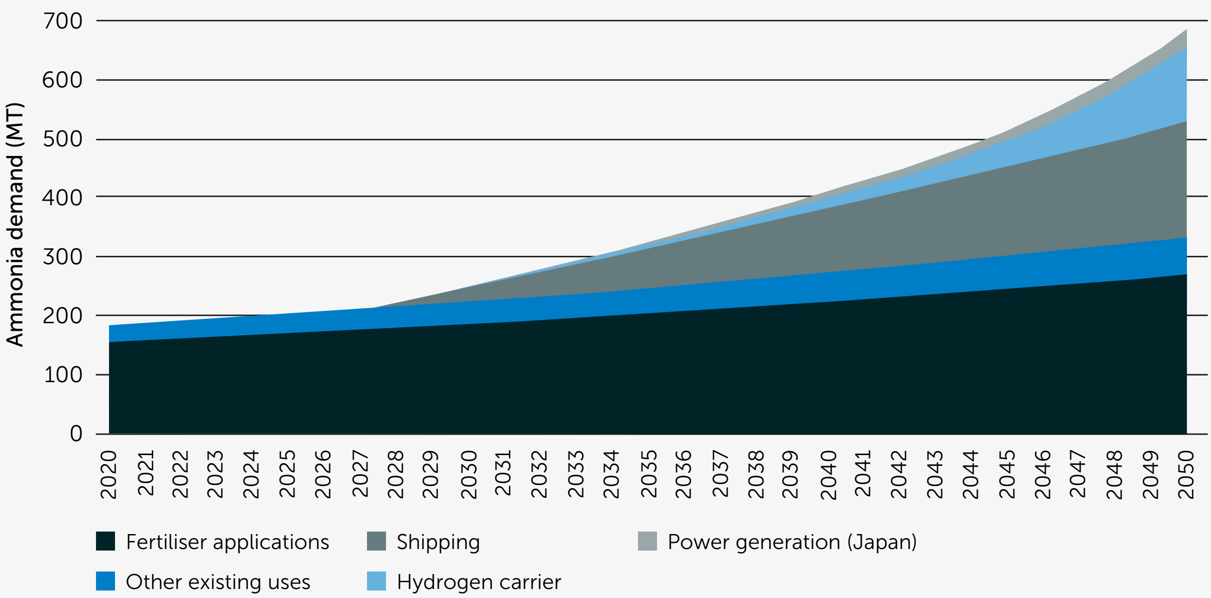
1 Introduction

1.1 Background and problem statement

As the world transitions towards reliance on renewable energy sources, energy systems are being adjusted or outright redesigned to accommodate for new sources and flows. In regions where molecular energy sources will need to complement the intermittently generated renewable electricity, such as in northwest Europe (NWE), new molecular carriers will be needed.[1] Ammonia is one of the considered carriers in the molecular segment of this future energy system, in part due to its potential as a hydrogen carrier. Its application as an energy carrier and fertilizer will drive global demand for the commodity to an estimated 688 Mt by 2050 – roughly three times of today's demand.[2]

Its promising role in the energy system and as a fuel for long-distance shipping will contribute much of the new demand from 2027 onwards, as shown in Figure 1 below.[3] However, for ammonia to satisfy this potential new demand, the trading of the commodity needs to evolve. The commodification of ammonia and the establishment of pricing centres are essential steps for its contribution to a successful energy transition and the realization of carbon emission abatement strategies.

Figure 1: **Expected ammonia demand up to 2050 for the 1.5 degree Celsius scenario).[4]**



1 P. Stapersma, Market Coordination of Dynamic Energy Flows, 2020, Clingendael International Energy Program.

2 IRENA and AEA, *Innovation Outlook: Renewable Ammonia.* Abu Dhabi, 2022.

3 DNV GL, *Energy Transition Outlook 2022* DNV GL, 2022.

4 IRENA and AEA, *Innovation Outlook: Renewable Ammonia.*

Besides its use as a direct fuel source, there is growing recognition of ammonia's potential application in the hydrogen economy. The interface between the two commodities - hydrogen as feedstock for ammonia, and ammonia as a potential carrier for hydrogen - could spur a virtuous cycle for hydrogen's role in the future energy mix. There is a growing prominence of green hydrogen in emission abatement strategies such as the European Commission's REPowerEU plan, proposed in May 2022. The EU Hydrogen Accelerator program forms an integral part of REPowerEU, and it aims to establish a 20 Mt annual consumption capacity of green hydrogen in the EU. 10Mt of this is to be produced domestically, and 10Mt is to be imported, as domestic production is unlikely to satisfy domestic demand.

The capacity to deliver on the EU's hydrogen ambitions is hamstrung by inefficiencies in transporting gaseous hydrogen over long distances without pipeline infrastructure. Pipeline imports alone will not meet the import target of 10 Mt and will rather be responsible for moving hydrogen within the continent. Forecasts suggest that 45% of hydrogen traded internationally in 2050 will be by ship, predominantly in the form of ammonia, as well as other carriers such as methanol, liquid organic hydrogen carriers (LOHC) and liquified hydrogen.[5] Ammonia is a promising carrier because it densifies hydrogen at relatively low cost using well-understood technologies and existing infrastructure.[6]

The prospective changes in demand for ammonia merit research for three reasons. First, to note what changes could be on the horizon for the ammonia trade. Second, to review how commodity markets function and derive implications for government and commercial actors of a growing liquid market for ammonia. This includes a discussion on the need for new institutions to facilitate the trade of ammonia, how this might happen, and where a burgeoning market can take advantage of existing industry and infrastructure. Third and final, to understand what role Rotterdam can play as a pricing centre in this growing market.

1.2 Research Aim and Questions

The aim of this research is to explore the commodification of ammonia and identify the conditions needed for the emergence of a dynamic ammonia market. To address this aim, this report poses two main research questions:

1. What stages will the commodification of ammonia follow, and what tipping points are likely to drive this process?
2. What is the importance of establishing a pricing centre to develop an international trading hub?

5 IRENA, *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part I – Trade Outlook for 2050 and Way Forward.* Abu Dhabi, 2022a.

6 N. Salmon and R. Bañares-Alcántara, "Green Ammonia as a Spatial Energy Vector: A Review," *Sustainable Energy & Fuels 5,* no. 11 (Jun 01, 2021): 2814-2839.

This report describes the ammonia market at present and discusses how the anticipated growth of the market's fundamentals will both necessitate and shape robust institutional arrangements for efficient price formation. A key issue in this respect is the need for price benchmarks, which tend to form out of trade hubs with a spatially concentrated supply and demand of the physical commodity. The anticipated growth of the ammonia market will thus give rise to strategic considerations for public and private stakeholders in the Amsterdam-Rotterdam-Antwerp (ARA) region.

The report is structured as follows. Section 2 develops the theoretical foundations of the research, outlining the basic functions of commodity markets and the pathways that they take in their development. Section 3 delves into the ammonia market, placing emphasis on production, trade, important market players, emerging markets, and regulation. Section 4 analyses the commodification of ammonia, addresses the need for security of supply and demand, and presents the potential for the ARA region to become a key pricing point for Europe. Section 5 concludes the report.

2 Commodity markets, commodification, and pricing

2.1 Introduction

This chapter discusses how commodity markets evolve from a theoretical perspective. This is done to firstly conceptualize the mechanisms that drive commodification, and secondly to understand why certain geographical locations are more likely to emerge as pricing points over others. Key theoretical frameworks – transaction cost economics, institutional economics, evolutionary economics and complexity theory – that inform this discussion, are addressed in logical order.

2.2 Theoretical foundations

Transaction costs economics (TCE) places emphasis on how economic actors seek to minimize costs resulting in particular governance mechanisms, varying from vertically integrated corporate bureaucracies to spot markets. In commodity and shipping markets, for example, there can be situations in which vertical integration is preferred over lengthy negotiations over prices and contract terms.

Closely related to TCE is *institutional economics*, that looks at how institutions - sets of rules and conventions governing human interaction - evolve via deliberate design or via 'spontaneous order'. Delineation of property rights, Incoterms[7], standardized contract specifications and the clearing mechanisms on exchanges are all examples of institutional designs to minimize transaction costs in international trade. The basic assumptions within TCE of fully informed and rational agency often obscures how arguably inefficient or suboptimal resource allocation continues to prevail. Institutional economics argues how transaction costs minimization is not the only driver for institutional change, as sunk costs can lock-in development pathways in which it is not in everybody's utility to change the status quo. The concept of spontaneous order (or what is referred to as self-organization in complexity thinking), on the other hand, argues that only free markets with no government intervention will allow for price signals to convey aggregate information that no individual participant in the market is likely to gain by themself.

Evolutionary economics and its focus on routines and skills in which organizations are constrained by bounded rationality, cognitive limitations, and incomplete information, helps to understand how through selection, adaptation and chance, certain business models or industries evolve do not necessarily evolve in the most efficient way. Despite the widespread

7 Incoterms are a set of commercial/trade rules established by the International Chamber of Commerce ("ICC") that are used in international sale contracts.

availability of digital technologies and tools, for example, physical commodity trades are still largely executed via cumbersome exchanges of paperwork (bills of lading, warehouse receipts, insurance certificates), which are prone to fraud and misinterpretations.

A specific concept derived from evolutionary economic thinking is '*the principle of relatedness*', that postulates the likelihood of industries evolving through novel combinations (technologies, practices, business models) with other industries, that together form unique product spaces. The degree to which such novel combinations are likely to happen is based upon the degree of relatedness between two sets of industries: in terms of technology, skills, business models, asset specificity, etc. For example, the introduction of transferrable delivery contracts – so-called 'futures' – on the Chicago Board of Trade in 1848, can be considered a novel combination of commerce and the financial industry that arose from the practice of wholesaling in context of risk.

Essential to the relatedness principle and evolutionary economic pathways is the role of geographical proximity, in the sense that tacit forms of knowledge do not travel far and thus diffusion of novelty is geographically constrained. The extent to which externalities of co-location favour geographical concentration of industries will define and lock-in regional economic compositions. These are consequently bound to similar institutional arrangements such as the rule of law, culture, political representation, and tax policies. On a regional level, the 'principle of relatedness' – or diversification from one 'product space' to another – refers to the empirical probability that a region enters or exits an economic activity as a function of the number of related activities present in that location.[8]

Finally, complexity theory, or the study of complex systems, looks at the behaviour and properties of systems understood broadly as a set of interacting and interdependent entities that form a together unified whole. Systems are considered complex when they are governed by self-organization (cf. Hayek's spontaneous order) in which no entity has the agency to control the behaviour of the entire system. They are further characterized by non-linearity, in which positive and negative feedback loops can accelerate or dampen interactions and interdependencies. The interactions also lead to the phenomenon of emergence, whereby they create novel characteristics and behaviours in the system.

Commodity markets can be considered as complex. They regulate relative prices of various commodities across the world, yet no player in the market has the capacity to control the market's fundamentals upon which decisions are taken. No agent in the commodity market, be they physical commodity merchants, investors or speculators can have full knowledge on the market fundamentals of each commodity in the market and on their interactions. Exogeneous shocks due to weather (a drought destroying crop yields), pandemics (crunching demand) or geopolitical events (trade or kinetic wars constraining access) add to the complexity. The key trait of complex adaptive systems, a sub-set of complex systems, is the capacity to "change and reorganize their component parts to adapt themselves to the problems posed by their

8 C. A. Hidalgo et al., "Product Space Conditions the Development of Nations," *Science* 317, no. 5837 (2007): 482-487; César A. Hidalgo et al., "The Principle of Relatedness," in *Unifying Themes in Complex Systems IX* (Cham: Springer International Publishing, 2018), 451-457.

surroundings."[9] This is particularly applicable to commodity markets, as their components consist of several interconnected subsystems listed below.[10]

1. The production and extraction of the commodity;
2. The shipping and distribution of the commodity;
3. The processing and delivery of the commodity to customers for end use;
4. Inputs in further manufacturing processes;
5. A financial and technological system that facilitates transactions, the settlement of (forward) prices and the data analytics in support of decision-making.

Each of these subsystems performs an integral function for a commodity market's capacity to adapt to internal and exogenous problems – or *shocks*. Specific to commodity markets, adaptation and self-organization is a result of, and reflected by, changes to a commodity's relative price. Price fluctuations should, in principle, both indicate market disequilibria and help restore disequilibria as the behaviour of the self-organizing subsystem responds to the price. Price discovery is thus a crucial aspect of a commodity market's capacity to adapt and self-organize as a system.

The degree to which price discovery is an unfettered process corresponds to the ability of the system to restore disequilibria. Poor transparency, market manipulation, or imperfect information that leads to irrational decision-making will hamper the process of price discovery to the detriment of the commodity market.[11] In other words, the complex adaptive system fails to adapt. This may lead to serious supply and demand shocks because prices – crucial signals for decision-making among the system's disparate actors – do not, or only partially, represent market fundamentals.

2.3 Commodities, commodity trading and commodity markets

A commodity is a product that it is indistinguishable from any other product of the same type in the eyes of the purchaser, regardless of its origin. This frequently applies to raw materials such as (non) ferrous metals, oil and gas, and agricultural products. However, transformed raw materials and manufactured products, including ammonia, can also be classified a commodity under certain conditions.

The distinguishing feature of a commodity is that it is a good with a standard quality whose product characteristics are, in principle, verifiable before purchase.[12] Information on the

9 J. H. Holland, Hidden Order: *How Adaptation Builds Complexity*, Reading, Mass: Addison-Wesley, 1995.

10 W. Jacobs and R. Horster, "Commodity Supply Networks as Complex Adaptive Systems: How Commodity and Freight Markets Respond to a Supply Shock," in *Geographies of Maritime Transport*, Edward Elgar Publishing, 2020, 87-99.

11 W. Jacobs and R. Horster, "Commodity Supply Networks as Complex Adaptive Systems: How Commodity and Freight Markets Respond to a Supply Shock," in 87-99.

12 A. Berg, D. Valiente, and C. Egenhofer, *Price Formation in Commodities Markets: Financialization and Beyond*, Brussels: CEPS, 2013.

product characteristics – including production, storage, transport, and substitutability factors – is available at low cost to prospective purchasers of a commodified good. This entails that the demand for commodities is intrinsically sensitive to price fluctuations. Actors looking to purchase a commodity can 'shop around'.[13]

In effect, unlike with differentiated products, commodity prices are based on the supply and demand function of the market, rather than the properties of the individual product.[14] The reducibility of commodities to relatively homogenous products means that product characteristics do not generally translate to competitive advantages or disadvantages to businesses trading in the good. Standardization of a commodity lends itself to relatively high substitutability, and hence price generally becomes the main determinant for transactions to take place. Price itself is influenced by a variety of factors shown in Table 1, which have lent commodity prices a high degree of volatility. This means price discovery and setting functions are key to the formation and operation of a commodity market.

Table 1: **Key drivers of price formation.**[15]

Product Characteristics	Supply Factors
Quality	Product convertibility and capital intensity
Storability	Horizontal and vertical integration
Renewability	Storability and transportability
Recyclability	Industry concentration
Substitutability	Geographical concentration (emerging markets)
(Final) usability	Technological developments
	Supply peaks and future trends
Demand Factors	**Exogenous Factors**
Income growth and urbanisation	'Financialization process' and monetary policies
Technological developments and alternative uses	Subsidies programmes
Long-term habits and demographics	General government intervention (e.g. export bans)
Economic cycle	The economic cycle and other macroeconomic events
	Technological developments
	Unpredictable events (e.g. weather)
Demand Factors Exogenous Factors	
Micro-structural developments (e.g. competitive setting)	
Functioning of internationally recognised benchmark futures or physical prices	
International trade	
Expansion of commodities futures markets and 'non-commercial' investors	
Futures markets infrastructure	

13 A. Berg et al., *Price Formation in Commodities Markets: Financialization and Beyond*, p. 12.

14 Fredrik Andrén-Sandberg, *Commodities Pricing and the Bulk Trap*, Springer, 2018.

15 A. Berg et al., *Price Formation in Commodities Markets: Financialization and Beyond.*

Commodity exchanges[16] are key institutions for the trade of these otherwise undifferentiated products. Historically, commodity exchanges have played a central role in reducing the costs of transaction between buyers and sellers of commodities. Exchanges act as institutional arrangements that offer services that help to define and enforce property rights, offer commodity measurement, enforce contractual obligations and agreements, mitigate information asymmetries between various market actors, and provide public goods too costly to be borne by individual actors.[17] These services are thus transaction-cost reducing and thus essential to the trade of commodities.

2.4 Price discovery, price benchmarks and price assessments

Fundamental to the functioning of commodity markets is price discovery. Price discovery emerges every time a seller and buyer interact in a transaction. At an individual level, these interactions are influenced by the factors enumerated in Table 1. Price formation is further influenced by the frequency and volume of these individual transactions, which, when aggregated, convey information to market actors about the market fundamentals. In general, more buyers and sellers for a particular product leads to more transactions, which in turn leads to more liquidity in the market and a narrower the bid-ask spread, which therefore arguably leads to a better price discovery mechanism in the market.

In commodity trading there are two different market types:

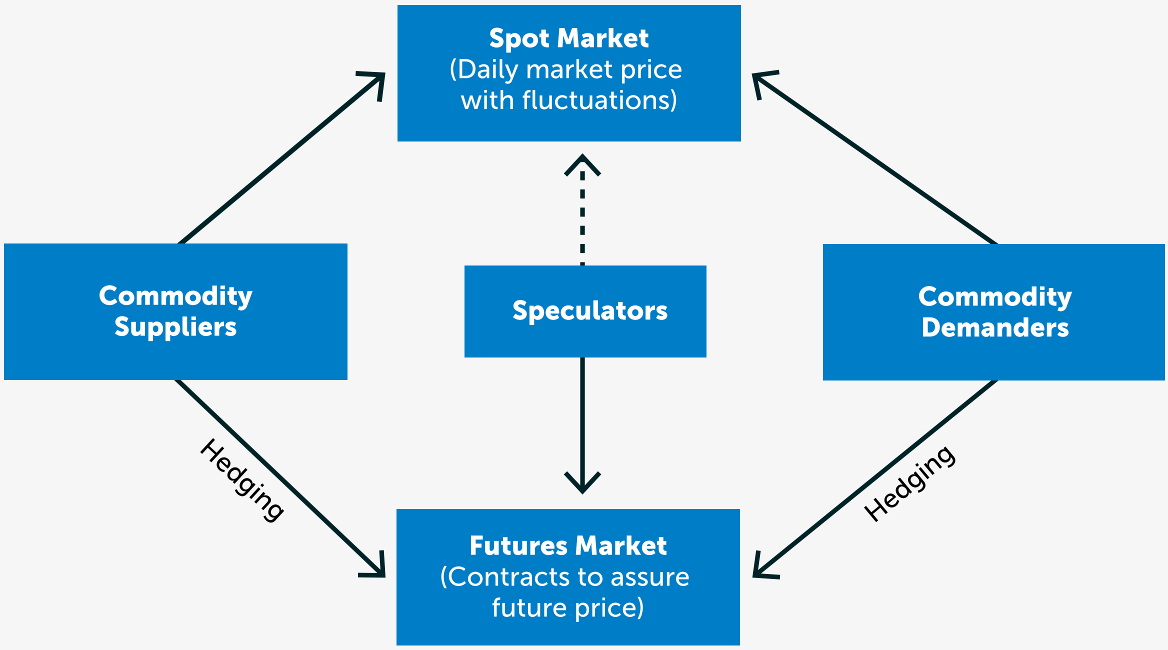
- ***Spot or 'cash' markets*** consist of over-the-counter, bilateral, day-to-day transactions between buyers and suppliers (either directly or sometimes through commodity exchanges) and in which the physical commodities change ownership immediately with undisclosed prices and customized contracts. Since a physical exchange takes place (which can be coordinated from a distance), these spot markets tend to locate near ample supply and demand locations, with optionality for transformations in time, space, and form. As is often the case, spot markets may be located at large port-industrial clusters where the conditions of ample supply, concentrated demand, and sufficient optionality for transformations are met. Examples include the ARA, New York Harbor or the US Gulf Coast for oil products (gasoline, LPG, kerosene, naphtha).

- ***The futures market*** is the trade in future delivery contracts with standardized dates, volumes and delivery locations on exchanges. It is mainly used to hedge against or mitigate price risks (by commodity merchants, large suppliers, and off-takers) and to speculate on price fluctuations (by investment banks, investments funds, private equity). It is a centralized market in which the exchange is the counterparty for both buyer and seller, and transactions are centrally cleared by the exchange or by a certified clearing house.

16 "Commodities Exchange." Available from https://www.investopedia.com/terms/c/commoditiesexchange.asp.

17 C. Pirrong, "The Efficient Scope of Private Transactions-Cost-Reducing Institutions: The Successes and Failures of Commodity Exchanges," *Journal of Legal Studies* 24 (1995).

Figure 2: **Relationship between Spot and Futures markets for the trade of commodities.**[18]



Both markets strive to address and accommodate demand and supply disequilibria by way of providing a market clearing price at all times, for all traded quantities, and within reasonable time frames.[19] To that end, it is necessary that both of these markets are competitive and aim to achieve high liquidity. Market structure is an important variable in allowing both physical and futures markets to scale and develop. The market structure should reduce barriers to entry to allow for greater participation, a higher frequency of transactions, and thus greater liquidity. These in turn reduce transaction costs of conducting business in the commodity space, which has the effect of driving competition in the market. In turn, the commodity value chains benefit from improved market efficiency.

2.4.1 Risk Mitigation: Raison d'être of the two market types

The relationship between the two commodity markets – spot and futures markets – is one of risk mitigation measures. **Spot markets** are physical markets where market actors in possession of the physical commodity are exposed to price risk, transportation risk, and transaction risk.[20] These risks are complex, diverse, and impossible for any individual actor to fully control. Due to the systemic complexity of commodity markets, individual commercial actors are limited in their capacity to limit exposure to risks on the physical market.

18 M. A. Ehlen and A. J. Scholand, *An Agent Model of Agricultural Commodity Trade: Developing Financial Market Capability within the NISAC Agent-Based Laboratory for Economics (N-ABLE),* Department of Homeland Security, 2005.

19 A. Berg, et al., *Price Formation in Commodities Markets: Financialization and Beyond*

20 Ibid., pp. 25-26.

The most important among them is price risk, whereby a market actor risks exposure to price trends by holding inventories of a commodity. Transportation risk results from changes in transportation costs and options, which may fluctuate because of real and artificial bottlenecks; for example, a shortage of vessels can amplify freight rates.[21] Transaction-related risk refers to risk in aspects that facilitate the transaction, such as the product quality delivered, counterparty's credit risk, or disadvantageous currency trends. In essence, a delivery can be rejected based on poor quality, a buyer can go bankrupt, or exogenous factors may cause a currency to depreciate, thus rendering a trade unexecuted or executed at a loss to one or both of the parties.

Managing exposure to these risks may take different forms. Holding inventories of a commodity is a particularly crucial mechanism for managing exposure to price volatility. Inventories offer a buffer function to commodity markets by reducing the costs of responding to fluctuating demand and supply. At a macro-level, the storage levels of a commodity will help to balance supply and demand over time by allowing for a market to respond to foreseen and unforeseen changes in supply and demand.

At a company level, producers and traders can build up, hold, or sell-off inventories to respond to price fluctuations. This implied advantage is referred to as the convenience yield. With the physical asset in possession, the owner can respond to situations with immediate effect without the costs associated with obtaining the physical asset. In effect, manufacturers can keep production going and merchants can take advantage of demand rise and price increase, or simply satisfy long-term customers.

However, inventories are an imperfect buffer. The uncontrollability of price fluctuations is not merely assuaged by holding or selling a physical stock. A commodity trading firm must contend with price risk while managing other factors like transportation or transaction-based risks, which may impact the liquidity of a stock. For instance, transport bottlenecks can restrict an actor's ability to sell off inventory. Moreover, commodity merchants require a mechanism to be able to reliably forecast price fluctuations to justify storage or sale against the price of storage and insurance.

The **futures market** addresses the exposure of actors in physical commodity markets to these risks. Futures contracts are an important tool for market actors to transfer this risk across time and space. Risk transfer occurs in futures contracts by fixing an agreed price of sale of a commodity in the future at a standardized delivery point. This allows producers, traders, and users to reduce their exposure to price fluctuations on the spot market by offering a mechanism to hedge potential losses.[22] Holding an inventory that is subject to spot price fluctuations can be buttressed by engaging in liquid futures contracts to manage a range of potential loss depending on how the spot price fluctuates.

21 C. Pirrong, *The Economics of Commodity Trading Firms*, Trafigura, 2014.

22 I. Cheng and W. Xiong, "Financialization of Commodity Markets," *Annual Review of Financial Economics* 6, no. 1 (Dec 1, 2014): 419-441.

Actors can buy or sell futures contracts to cover loss. To illustrate, for agricultural producers in a season-bound market that is relatively illiquid, this may mean hedging against a plummeting spot price of an agricultural good occurring before the crops have been harvested, by fixing the price of sale in advance. For traders of 'hard' commodities, such as metals and minerals, the futures market offers a mitigation strategy to uneven demand caused by weather (e.g., for energy) or GDP growth/stagnation (e.g., for industrial metals).

In addition to transferring risk by fixing prices, futures markets are also integral to the function of inventories as buffers, through the price signals that futures markets send to holders of the physical commodity.[23] This relationship is explored further in the following section.

2.4.2 Price discovery in the two market types, and the role of inventory

Price formation emerges from interactions on both physical and futures markets, which feed back into the market as price signals. Formation thus depends on the efficient functioning of the market organization for physical commodities and linked futures contracts."[24] Physical markets are structured in one of two ways, either as exchanges or bilateral markets. Due to the practical requirements of the physical commodity trade – such as the influence of product characteristics – spatial concentration of these exchanges tends to reflect regional supply and demand factors. Hence, regional fragmentation of an ostensibly global market adds a layer of complexity to the determination of price.

Bilateral markets are market hubs with sufficient concentration of demand and supply where bilateral over-the-counter spot or forward contracts are struck between two parties, usually the producer and end user.[25] Contracts can be immediate or long-term agreements. The result is that bilateral contracts tend to be highly customized and can therefore lack transferability, which ultimately exposes the parties to flat price risk.

Price discovery in physical transactions is beholden to a variety of factors that each contribute to informational friction. The specific factors such as geographic fragmentation and variety of contracts influence an actor's decision-making process depend on the market structure. Nevertheless, the variable factors and the resultant imperfect information leads to inefficient price discovery. For actors in physical markets to accrue more accurate information, more frequently, therefore requires higher transaction costs.

23 H. Working, "The Theory of Price of Storage," *American Economic Review* 39, no. 6 (1949): 1254-1262; H. Geman and W. O. Smith, "Theory of Storage, Inventory and Volatility in the LME Base Metals," *Resources Policy* (2012).

24 A. Berg et al., *Price Formation in Commodities Markets: Financialization and Beyond.*

25 Ibid.

Futures markets play a key role in price discovery. Trading in physical goods on the spot market comes with practical considerations related to the heterogeneity of the market. The variety of products and quality grades translates to a larger spread of traded prices, compounded by the spread of prices available for the sale of a commodity at different locations across the world.[26] In contrast, futures contracts are standardized, rendering the prices of futures contracts easier to evaluate by incurring lower transaction costs than would be necessary for evaluating spot prices for physical goods with a larger set of distinct variables.

To add, futures contracts are often traded without the intention of completing the underlying transaction of the physical good. In fact, a seller of the future contract may not be in possession of the physical good, and the buyer may have no intention of receiving a physical delivery.[27] This detachment from the physical good is, in essence, a reduced barrier to entry into the market, allowing actors across the world to trade in futures contracts on centralized futures exchanges.[28] Futures markets generally enjoy higher liquidity for this reason.

The trade in futures contracts serves to aggregate disparate, fragmented information on centralized platforms, rendering a clearer picture of market fundamentals of a commodity. In doing so, futures trading helps to overcome information frictions more present in physical markets. This makes futures prices for a given commodity an important price signal guiding demand and providing feedback that influences spot prices.

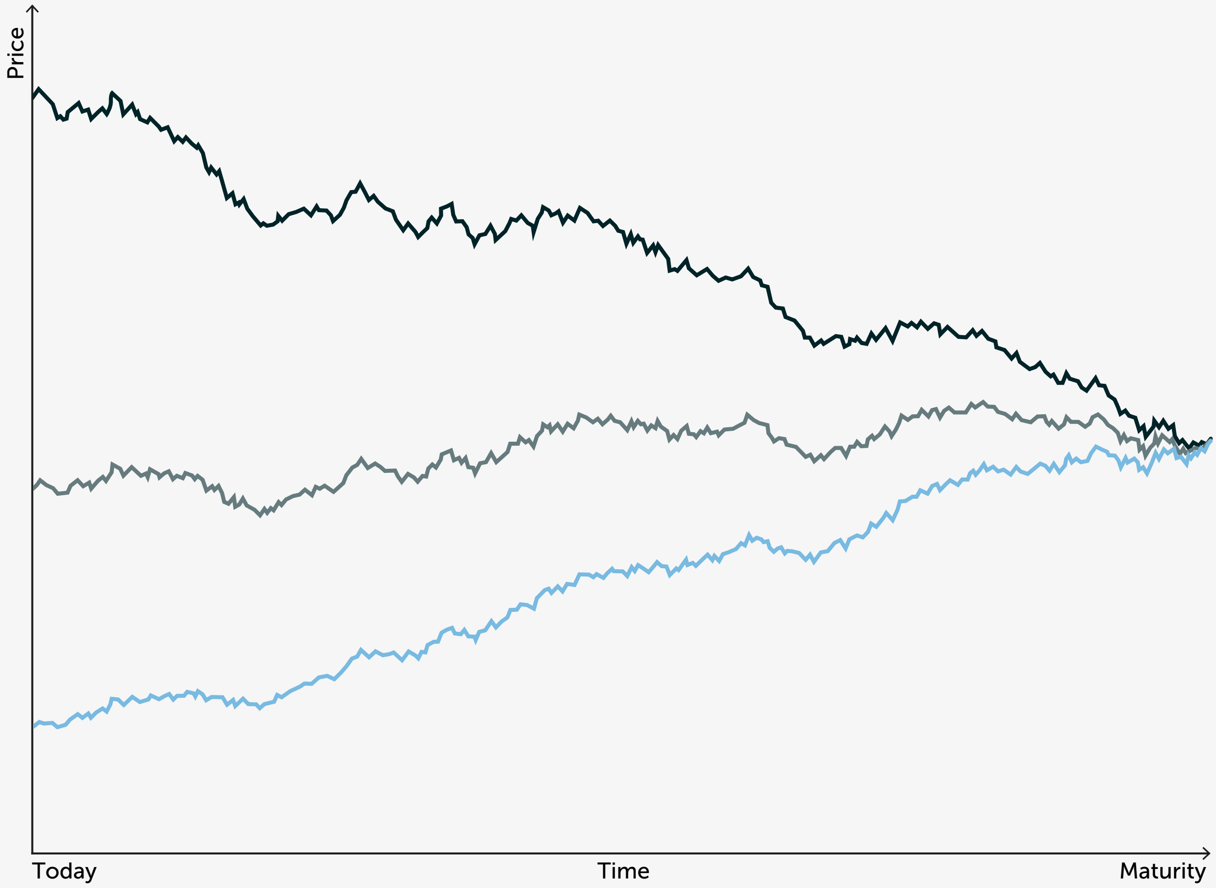
However, this relationship between futures and spot prices, known as a temporal spread, is more than a mutual signal devoid of other factors. Price behaviour is affected by the temporal relationship of the spot prices and futures market contracts. The prices of futures markets and the spot price will converge at the point of maturity of the futures contract, as shown in Figure 3. That said, spot and futures prices are not two substantially independent prices, their relationship is influenced by the role of inventory.

26 I. Cheng and W. Xiong, "Financialization of Commodity Markets,": 419-441.

27 G. Poitras, "From Antwerp to Chicago: The History of Exchange Traded Derivative Security Contracts," *Editions Sciences Humaines* (2009): 11-50.

28 I. Cheng and W. Xiong, "Financialization of Commodity Markets,": 419-441.

Figure 3: **Price convergence of Futures and Spot.**[29]



The relationship between storage and price is bidirectional. Previously, storage was introduced as a mechanism to mitigate exposure to risk through the implied convenience yield that inventories offer to actors on the market. However, the level of storage sends important signals that influence price formation in both spot and futures markets. The Theory of Storage maintains that the level of storage of a given commodity will impact its temporal price spread, i.e., the spread between futures and spot prices.[30] The theory holds that when situations of scarcity arise for a given commodity, reflected in low inventories, the spot prices will tend to exceed futures prices and that the spot prices will contend with greater volatility than the futures prices. Conversely, ample supply, as measured in part by inventories, will generally depress the spot price in relation to the futures price and will subdue price volatility on both the spot and futures markets.

29 "Contango and Backwardation." Available from https://en.wikipedia.org/wiki/Normal_backwardation#/media/File:Contangobackwardation.png.

30 H. Working, "The Theory of Price of Storage,": 1254-1262; H. Geman and W. O. Smith, "Theory of Storage, Inventory and Volatility in the LME Base Metals."

These premises hold for two reasons. First, the relationship between futures and spot prices is impacted by the level of inventory, because of the signal it sends to actors on the spot market. Scarcity begets tight markets. In response, buyers on the spot market will drive prices up by bidding whatever price is necessary to secure supply.[31] Second, the degree of price volatility is dependent on the levels of storage because in moments of scarcity, any news concerning short term supply will have an aggravated effect, with a potentially large impact on the spot market.

The influence of storage on price formation implies the importance of informational signals on the level of inventory of a given commodity. Geographical proximity facilitates access to accurate and transparent information. For this reason, disparate commodity hubs tend to emerge where there is a concentration of production or storage, and therefore a greater access to reliable information and the ability to act on this information (both at a lower transaction cost). These areas naturally accumulate a higher frequency of interaction through positive feedback loops that ensure increasing returns.

2.4.3 Making sense of prices: Benchmarks

Ultimately, price discovery, or the act of setting the price of a contract, is a negotiation between parties that results in an agreed price that is acceptable to both parties. This can be an onerous task with high transaction costs, due to the number of variables at play (see Table 1). There is a variety of physical commodity deals that are customizable to volumes, product characteristics, destinations, and timings, to name a few. Setting the price per deal can therefore be costly.

As a matter of simplifying trades, reference prices are often used as points of departure for bilateral deals. A benchmark is an external reference price that is accepted by the transacting parties.[32] The development of price benchmarks benefits commodity markets by establishing a reference for numerous bilateral trades that would otherwise incur high transaction costs on the transacting parties. These benchmarks tend to emerge in disparate geographical locations to reflect the market circumstances of the region. Liquidity is the main factor in determining whether a market price will become a reference point. Hence, benchmarks tend to emerge where there is:[33]

1. Sufficient supply in the underlying reference physical market;
2. Sufficient market access (demand);
3. Efficient price discovery.

When met, these characteristics tend to translate into high liquidity. Owing to the diversity of traded commodities, the level of standardization, centralization, and maturity of these markets can differ, so not all commodity markets have established benchmarks. The existence of many underdeveloped commodity markets can be attributable to factors such as a high production costs, which necessitate a close link between the producer and the buyer, with the latter guaranteeing offtake over extended periods. In these circumstances, long term contracts, prices of which are revised at agreed-upon intervals in bilateral negotiations, may be preferred.

31 H. Geman and W. O. Smith, "Theory of Storage, Inventory and Volatility in the LME Base Metals."

32 A. Berg et al., *Price Formation in Commodities Markets: Financialization and Beyond.*

33 Ibid.

These long-term contracts are generally opaque to external parties as they can be based on sensitive information, such as the marginal cost of producing the traded volume of the commodity, and can expose either party to unwanted competition. These prices can also be linked to external benchmarks for other (related) products.

However, in both benchmarks and bilateral contracts issues with price transparency can hamstring the development of the commodity market, if its fundamentals are due to shift rapidly. For benchmarks, the risk may be that the underlying conditions of the traded commodity no longer reflect agreed prices. This can be driven by exogenous, demand and supply factors, or a market reorganization that leads to sudden disequilibria. For long term bilateral contracts, efficiency gains could lead to surplus product – dubbed the *incremental ton* – or the demand for the commodity swings rapidly due to an exogenous factor. As commodity markets develop due to shifts in the market fundamentals, the need for efficient pricing mechanisms becomes more apparent. Institutional arrangements, like regional benchmarks, serve to facilitate the continued growth of the market by reducing transaction costs, creating positive feedback and spatially concentrating related industries.

2.5 Commodification

A commodity develops a market where it is assigned an economic value upon which it is traded between market actors. Commodities differ in the organization of their market based on the specificities of the commodity itself, its product characteristics, its use cases, and all manner of supply and demand factors that shape the market's structure. The organization of a commodity market is thus subject to change as a function of changes in these specificities.

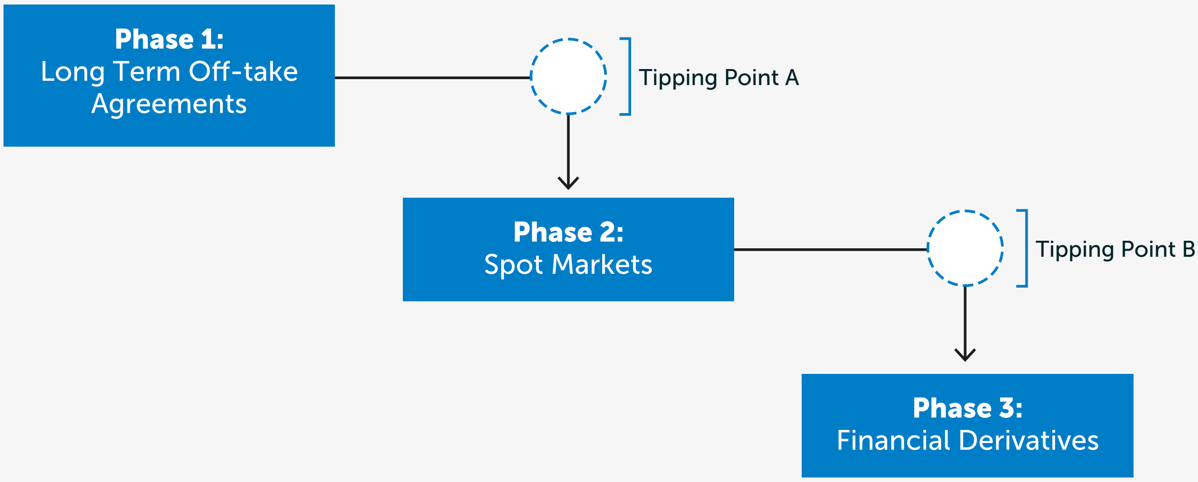
The evolution of commodity markets tends to follow a distinctive pathway. The conceptualisation of this commodification pathway is recognizable by three stages that, simply put, increase in the level of a commodity market's capacity for self-organization. The first recognizable phase encompasses markets dominated by the practice of long-term offtake agreements between suppliers and buyers to reach market equilibrium. The second phase emerges as the physical spot market gains increasing relevance in the balancing of supply and demand, whereby exposure to price risk is more pronounced. As forward contracting emerges to mitigate this price risk, the need for greater liquidity demands standardization of contracts. The resulting standardization characterizes the third phase, whereby a market for financialized derivative contracts emerges.

The different phases mark a general progression in trends, like higher participation and traded volumes, and increases in liquidity of the traded products. The emergence of these recognizable phases follows a dynamic where *"path dependencies, increasing returns to scale and learning-by-doing cost reductions can produce sudden, tipping-point-like transitions that cannot be extrapolated from past system behaviour."*[34] In other words, tipping points resulting

34 F. C. Moore et al., "Determinants of Emissions Pathways in the Coupled Climate–social System," *Nature*, no. 603 (2022): 103-111.

from positive feedbacks within a system lead to new institutional arrangements. These improve the self-organizing capacity of the market, generally through greater transparency of price setting and added mechanisms to mitigate risk exposure. The phases and the tipping points, as shown in Figure 4, are described in greater detail below.

Figure 4: **The Commodification Pathway.**



Source: authors

2.5.1 Phase 1: Long Term Off-take Agreements

Phase one in the evolution of a commodity market is characterized by inflexible market fundamentals. A notable lack of price transparency and liquidity are compounded by rigid supply and demand factors, leading to the market taking time to adapt to disequilibria. Generally, few suppliers are active in the market, meaning that the flexibility of supply is absent in the case of endogenous or exogenous shocks. A supply shock, for instance, cannot be readily mitigated by relying on alternate suppliers or products. Conversely, demand is concentrated in a few buyers, or in a circumscribed sector, meaning that demand is predictable and relatively inelastic.

Furthermore, the market's infrastructure, hardware and assets are locked in. That is to say that transport capacity, inventory or manufacturing capital is efficiently utilized and thus not readily adaptable to rapid shifts in the market's fundamentals. The dominant mode of market clearance is through long-term off-take agreements to ensure market stability. Spot trade can exist in this market, but it is negligible in volume and activity. Interactions tend to be informal, highly specialized, and/or incidental.

The reason for this market structure is the need faced by actors to primarily mitigate supply risk, though demand, value chain and financial risks exist too. Additionally, transaction costs are reduced by either engaging in long-term off-take agreements or in vertical integration of the supply chain. Producers face various constraints in establishing commodity production projects, as these are generally capital-intensive processes with major upfront risk in capital expenditures (capex), which require long-term financing.

Long term off-take agreements allow suppliers to access fixed, long-term investment that allows them to produce a base load of the product. Purchasers can be confident of a security of supply for an extended period provided by the base load. In turn, these types of agreements de-risk the investment, and are thus instrumental in securing the necessary capital needed to overcome a veritable chicken-and egg problem. Another route to mitigating risks and uncertainty is through vertical integration of the value chain. Vertical integration allows market players to internalize risk, reward and transaction costs.

2.5.2 Tipping Point A

Though it is not a given that markets evolve from the first phase, certain feedback mechanisms can lead to increasing returns, greater scale, and reduced transaction costs that tip the market towards restructuring. Tipping Point A, as shown in Figure 4, is point at which the market embraces a rapid shift toward Phase Two. First, the commodity market begins to experience a diversification of demand. This can occur both in term of volume (i.e., a greater demand for the commodity or its downstream manufactured products) or new use cases are developed for the commodity that lead to new demand markets.

Second, the infrastructure and hardware for the commodity's supply and transformation in space, time, and form may scale up in response to shifting demand factors. On the supply side, demand signals can be addressed by upstream investment in production facilities to increase supply. As investments in the supply chain materialize as ships, storage facilities, terminals as transport nodes, as well as manufacturing plants, to support demand growth. Bottlenecks ease as a result of supply chain optimization and learning-by-doing.

Third, information systems develop and become more sophisticated. Information on market fundamentals gradually becomes more transparent in response to the diversification of demand. As noted, new and diverse demand puts pressure on opaque pricing mechanisms. Information systems are installed to address this need. An example of this occurring is when price reporting agencies extend their services to cover the commodity through new pricing methodologies.

Finally, a permissive regulatory environment develops in response to the diversification of demand. Though this is not a given, this final element can often be the 'make or break' element in the evolution of a commodity market towards greater sophistication. Examples of this can be found in the issuing of environmental permits, the standardization of certain products, or the development of a customs regime for import and export.

Combined, these four dynamics may develop into a tipping point if they lead to significant positive feedbacks or a reduction in transaction costs.

2.5.3 Phase 2: Spot Markets

Phase 2 describes a commodity market that is significantly less exposed to supply risk. In general, more suppliers are in the market and demand has diversified. Production capacity has become more flexible as a result of this. Assuming upstream infrastructure has expanded, and total costs are now relatively fixed, the volumes produced will gradually increase through efficiency gains. The incremental increase in yields allows the producers to capture new markets by selling excess volumes on the spot market. With a diversified demand for the commodity, this spot market has grown significantly. There is greater opportunity for arbitrage as lower marginal costs lead to increased interest in the spot market from commodity traders in search of large price spreads. Shipping and storage infrastructure allow for spot trading in places that can mitigate differences in price and timing.

The supply flexibility ensures that trade is capable of reconciling market disequilibria through more robust information systems and price signals from the spot market. Supply risks are swapped with different forms of risk, such as flat price, basis, spread, margin, volume, liquidity and operational risks. This exposure leads market players to establish more sophisticated trading instruments to hedge against these different forms of risk. The most prominent are forward contracts designed to hedge against price volatility on the spot market. However, these are limited in their liquidity, as they are highly customized, bilateral agreements.

2.5.4 Tipping Point B

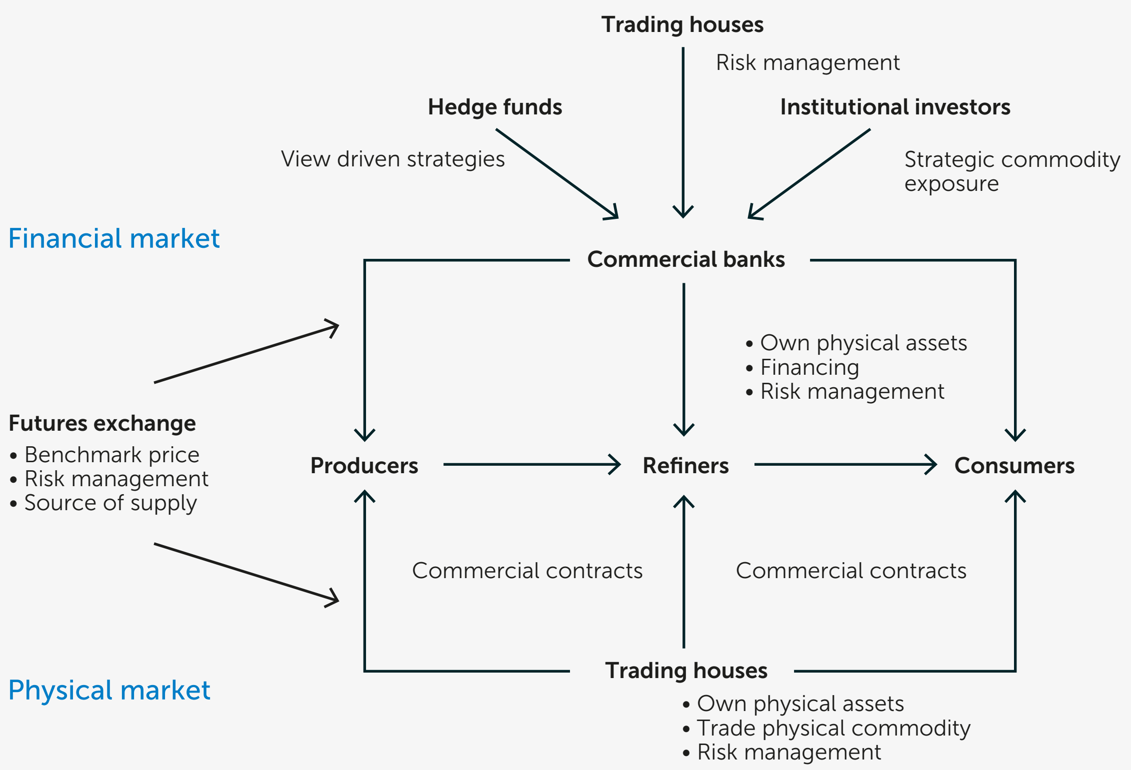
The needed volume and volatility on the spot market is a problem associated with Phase 2, which can leave market players exposed to significant risk. The trade-off becomes more pronounced between the transaction costs required to strike contracts with reasonable risk exposure, and the need to respond quickly to a volatile market with improved, but insufficient, price transparency. Price formation becomes fraught because of this trade-off. In response, market players act to reduce transaction costs through the standardization of forward contracts to ease liquidity. These standardized contracts, known as futures contracts, are more readily transferable. Exchanges emerge to issue these *futures contracts* as third-party facilitators and provide a centralized clearing mechanism for trades. The mechanism reduces the risk born by the engaged parties if contracts cannot be fulfilled.

The advent of standardized, highly liquid futures contracts based on the exchanges removes the contract from the delivery of the physical good, which allows a broader array of actors to engage in the market for futures contracts. Financialization occurs as commercial banks, institutional investors and hedge funds step into trade futures contracts. As a result, the liquidity and trade frequency for futures contracts provides commodity traders and producers a more reliable mechanism to mitigate future price risk.

2.5.5 Phase 3: Financial Derivatives

In the third and final stage, financialized instruments are introduced on commodity exchanges. Price discovery takes places at the exchange through the liquidity provided. Price transparency is secured with the futures price converging to the spot price as contracts mature. The elements and actors of the commodity market in final form, Phase 3, is shown in Figure 5.

Figure 5: **Commodity market overview.**[35]



35 N. C. Schofield, *Commodity Derivatives: Markets and Applications*, John Wiley & Sons, Ltd, 2021.

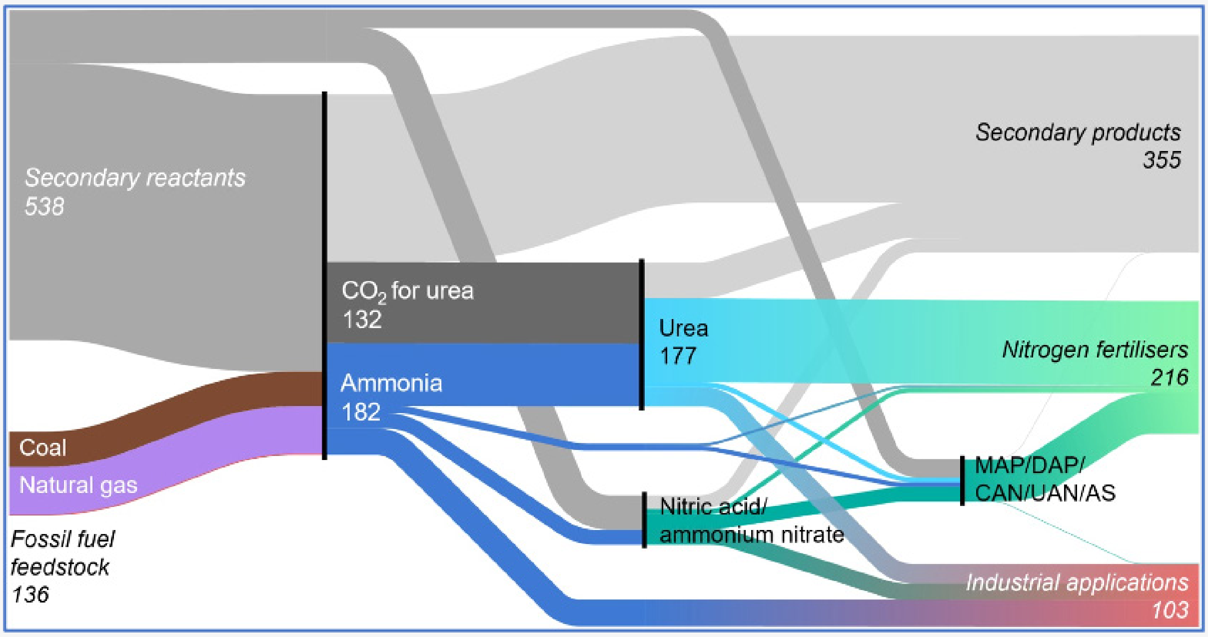
3 Ammonia Market

This section establishes the current market fundamentals of ammonia, and discusses the nascent shift towards low-to-zero carbon production pathways and new use-cases of ammonia as an energy carrier.

3.1 Contours of the market

Ammonia already has an established market.[36] As a chemical, it is the starting point for all mineral nitrogen fertilizers, with approximately 85% of current ammonia production used for fertilizer applications.[37] The remaining flow of ammonia is destined for various industrial applications, among which plastics, explosives and synthetic fibres are the most common (see Figure 6). At present, the direct and indirect use of ammonia as an energy carrier is still nascent, accounting for less than one percent of total global ammonia demand.[38] These markets comprise ammonia's potential use as a maritime fuel, feedstock for power generation, or hydrogen carrier for the emerging hydrogen economy.

Figure 6: **Mass flows in the ammonia supply chain. Numeric values are in million tonnes per year of production using data from 2019. Only fossil fuels used as feedstock shown.**[39]



36 IEA, "Ammonia Technology Roadmap," Available from https://www.iea.org/reports/ammonia-technology-roadmap/executive-summary.

37 IRENA and AEA, *Innovation Outlook: Renewable Ammonia.*

38 Ibid.

39 IEA, "Ammonia Technology Roadmap."

3.1.1 Production

Due to its energy intensive production, the ammonia industry is currently reliant on fossil fuels.[40] Its production revolves around two steps, isolation of hydrogen and synthesis, the latter of which requires high heat and pressure to synthesize ammonia.[41] Consequently, ammonia production today requires 8.2 EJ, or approximately 2% of total global energy consumption.[42] Of this amount, 40% is used as feedstock (fossil fuels for isolating hydrogen), and the rest is consumed as process energy.

The greening of ammonia production is therefore a defining challenge for the industry and its projected demand growth in the context of a zero-carbon economy. The levelized cost of grey ammonia ranged between USD 250-450/t in the past decade, while green ammonia can be 2-3x more expensive, making it much less cost competitive.[43] Ammonia's main use case as a feedstock for nitrogen-based fertilizers presents an additional issue. Approximately 130 Mt of CO_2 are injected each year in direct use for the manufacture of urea.[44] The CO_2 required for urea synthesis is sourced from the ammonia production, which currently accounts for most of the world's use of captured carbon. As such, the main product of ammonia is dependent on current grey/blue production pathways.

The key determinant of where ammonia is currently produced – and where it will be produced in future using zero/low-carbon technology – is the availability of feedstock and abundant, low-cost process energy. As nearly all of ammonia production is sourced from either natural gas (70%) or coal (26%), the most prominent producing countries and regions tend to enjoy an abundance of these resources (see Table 2). The access to large reserves of natural gas have allowed the United States, the Middle East, and Russia to account for 8-10% of the world's ammonia production each. China, with its abundant coal reserves, produces the largest share of global output at approximately 29%, as well as 45% of all ammonia related emissions.[45]

40 Ibid.

41 IEA, *Ammonia Technology Roadmap: Towards More Sustainable Nitrogen Fertiliser Production*, 2021b.

42 Ibid.

43 IRENA, *Green Hydrogen for Industry: A Guide to Policy Making*, 2022b.

44 "Carbon Capture, Utilisation and Storage - Fuels & Technologies." Available from https://www.iea.org/fuels-and-technologies/carbon-capture-utilisation-and-storage.

45 Ibid.

Table 2: **Ammonia production by region/country in 2019.**[46]

Country/Region	Share (%)
China	29
Russia	10
United States	9
Middle East	9
European Union	8
India	8

The major issue associated with the production of ammonia is the emissions intensive process.[47] Ammonia production accounts for approximately 1.8% of CO_2 emissions globally.[48] At around 2.4 tons of CO_2 per ton of ammonia, the emissions intensity is twice that of crude steel production and four times cement production. In terms of direct emission, global ammonia production emits 450 Mt CO_2 per year, equivalent to the footprint of total energy system emissions of South Africa.[49] This is not surprising, considering ammonia's energy requirements and its current reliance on fossil fuels (98-99%). Indirect emission along the value chain account for a further 170 Mt CO_2 per year.

3.1.2 Trade

Ammonia is a globalized commodity. Around 10%, or around 20 Mt, of ammonia's total production is destined for export.[50] This trade of ammonia is the result of the large variation in production costs that exist between regions. Another factor is the distance to centres of demand, which impacts the costs of transportation. Countries and regions with a comparative advantage have, as a result, specialized in ammonia production for export. Trinidad and Tobago, Russia, and countries across the Middle East are notable examples of export driven strategies (see Table 3 and Figure 7).

46 IEA, "Ammonia Technology Roadmap."

47 IRENA, *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part I – Trade Outlook for 2050 and Way Forward.*

48 The Royal Society, *Ammonia: Zero-Carbon Fertiliser, Fuel and Energy Store*, 2020.

49 IEA, *Ammonia Technology Roadmap: Towards More Sustainable Nitrogen Fertiliser Production.*

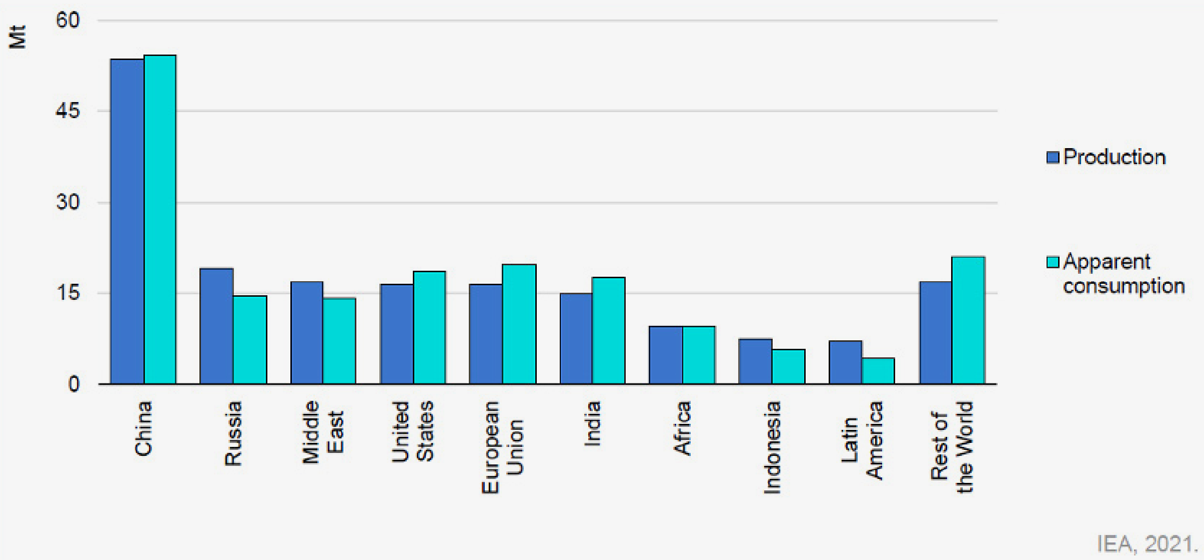
50 Ibid.

Table 3: **Top exporting and importing countries/regions.**[51]

Export		Import	
Country/Region	**Global Share (%)**	**Country/Region**	**Global share (%)**
Russia	24	European Union	24
Trinidad and Tobago	23	India	14
Middle East	15	United States	13

The top importing regions and countries are the European Union, India, and the United States, accounting for 24%, 14%, and 13% of the global share of imports, respectively. The European Union imported about 4 Mt of ammonia in 2020, approximately 89% of which was dedicated to fertilizer applications. India and the US imported approximately 3 Mt and 2 Mt, respectively.

Figure 7: **Apparent consumption and production of ammonia in 2019.**[52]



Notes: The apparent consumption of a region is equal to its production plus imports minus exports.

Well-established Infrastructure exists to support this trade.[53] Storage and transport infrastructure have a high level of maturity due to its century-long importance as a feedstock for fertilizers. Around 90% of produced ammonia is used onsite as a feedstock for derivative products and thus only about 25-30 Mt is transported (both domestically and internationally). Most of this amount, around 18-20 Mt, is transported by ship. Although estimates vary, approximately

51 IEA, "Ammonia Technology Roadmap."

52 IEA, "Ammonia Technology Roadmap."

53 The Royal Society, *Ammonia: Zero-Carbon Fertiliser, Fuel and Energy Store;* IEA, *Ammonia Technology Roadmap: Towards More Sustainable Nitrogen Fertiliser Production.*

170-200 vessels are currently in operation with the capacity to carry ammonia, of which at least 40 are deployed with ammonia cargo at any given time.[54]

International shipping routes are supported by a comprehensive network of ports with largescale handling capacity for ammonia, typically near ammonia production facilities. There are currently some 270 ammonia sea terminals across the world, of which around 30 are found in the European Union.[55] Considering that the European Union is the top importer of ammonia globally, these terminals play a direct role in serving Europe's approximate 19.2 Mt per annum consumption of ammonia.[56] The ARA region in particular is home to a concentration of six ammonia terminals with varying levels of storage capacity.[57]

The benefit of established infrastructure is that there are minimal technical limitations beyond extending global ammonia infrastructure needed to meet the expected increase in demand to a 688 Mt market in 2050 from today's 183 Mt.[58] The existing infrastructure will be able to accommodate the phasing-in of green ammonia as low-to-zero-carbon production technologies develop.

3.1.3 Ammonia price formation

As previously stated, approximately 90% of ammonia is used onsite following production. Only 10%, around 20 Mt, is destined for trade or export. The relatively low volumes traded compared to the total production and consumption has, until recently, curtailed the need for the further commodification of ammonia. The market for traded ammonia has predominantly run on (long-term) contracts and bilateral agreements to secure the offtake of principally excess supplies.[59] This has left the spot market for ammonia comparatively small. Assessments of fixed-price spot trading in 2019 and 2020 saw that around 500,000t and 675,000t of volumes exchanged hands, a marginal amount compared to the 18-20 Mt that was traded on contract.[60] Relative stability of demand and production, the latter of which is linked to a decade of stable natural gas prices, means that there is little liquidity and hence a historically negligible interest in engaging on spot markets.

54 DNV, "Harnessing Ammonia as Ship Fuel." Available from https://www.dnv.com/expert-story/maritime-impact/Harnessing-ammonia-as-ship-fuel.html; IRENA and AEA, *Innovation Outlook: Renewable Ammonia.*

55 Euractiv, "Why Green Ammonia Will be the Workhorse of EU's Future Hydrogen Economy," 2022. Available from https://www.euractiv.com/section/energy/opinion/why-green-ammonia-will-be-the-workhorse-of-eus-future-hydrogen-economy/.

56 The apparent consumption of a region is equal to its production plus imports minus exports. "Production, Consumption and Trade of Ammonia in Selected Countries and Regions, 2020 – Charts – Data & Statistics." Available from https://www.iea.org/data-and-statistics/charts/production-consumption-and-trade-of-ammonia-in-selected-countries-and-regions-2020.

57 DNV, "Alternative Fuels Insights," Available from https://afi.dnv.com/Map.

58 IRENA and AEA, *Innovation Outlook: Renewable Ammonia.*

59 Argus Media, *Argus White Paper: Ammonia Market Volatility,* 2022b

60 Ibid.

Due to the illiquidity of the physical ammonia market, several benchmarks have emerged in locations where concentrations of volume can be found from supply or for demand. Prices of ammonia are generally assessed either as free on board (FOB) in export markets or as cost and freight (CFR) in main demand regions.[61] The latter accounts for the cost of the spot purchase in addition to freight rates. Price reporting agencies like Argus Media offer price assessments and projections based on a public methodology.[62] Said methodology takes into account units, lot and cargo size, product specifications, and freight rates, among others. Prices are assessed for various FOB or CFR hubs using this methodology and available data.

The Black Sea FOB – sometimes called Yuzhny FOB ammonia price, or Pivdenny more recently – was until recently deemed the global price benchmark for ammonia.[63] Located in Odessa, Ukraine, Black Sea FOB materialized as a convenient benchmark for global ammonia spot trade due to its concentration of large volumes of marginal tonnage that was surplus to demand in Russia's and Ukraine's domestic industries and agriculture, as well as robust hinterland infrastructure for transport to the site and storage. The concentration of volume at this location was, until the war in Ukraine, large, owing to the significant market share of Russia and Ukraine in global ammonia exports. Combined, the two countries accounted for approximately 20% of global exports.[64] These volumes guaranteed a security of supply – a crucial element for benchmarks to emerge.

In addition to the security of supply, another factor necessary for the emergence of benchmarks is security of demand, or market access. The location of the Black Sea FOB benchmark lent it access to demand centres in Europe through its relative proximity to them and its direct access to the coast. Besides its access to Europe, the region itself is the agricultural heartland of Eastern Europe, which has in the past ensured a steady flow of ammonia to the region through existing hinterland pipeline infrastructure. These factors combined gave Black Sea FOB considerable weight on global ammonia prices. Other benchmarks exist, but these were influenced by the price signals sent from Black Sea FOB. Changes to this hierarchy are underway as a result of Russia's invasion of Ukraine. The corresponding supply shocks and a looming long term demand growth has exposed the vulnerability of price discovery on the ammonia spot market.

---

61 Argus Media, *Argus Ammonia Methodology and Specifications Guide,* 2022a.

62 Ibid.

63 ICIS, "IFA '22: Global Ammonia Market Unsettled and Uncertain," May 2022. Available from https://www.icis.com/explore/cn/resources/news/2022/05/31/10770070/ifa-22-global-ammonia-market-unsettled-and-uncertain.

64 S&P Global, "Unpacking Ammonia's Market Landscape and its Role in the Energy Transition." Available from https://www.spglobal.com/commodityinsights/en/market-insights/blogs/energy-transition/091622-ammonia-prices-supply-demand-hydrogen-power-bunker-fuel.

Table 4: **Other price benchmarks of spot ammonia.**[65]

Region	Name	Price (Q1 2022)	Price (Q2 2022)	Price (Q3 2022)	Price (Q4 2022)
North America	Anhydrous Ammonia CFR Tampa (USA)	USD 1177/Mt	-	USD 1323/Mt	USD 1150/Mt
APAC	Aqueous Ammonia FOB-Qingdao	USD 812/Mt	-	USD 840/Mt	-
Europe	Anhydrous Ammonia CFR Hamburg	USD 1550/Mt	USD 1645/Mt	USD 1602/Mt	-

In sum, the arrangements in place for price formation, based on small-scale physical spot markets and low liquidity, were sufficient to facilitate the market conditions for ammonia trade if they remained stable. Yet, the period of 2021 to 2022 saw rapid endogenous and exogenous changes to the market that bore significant repercussions for price formation. Both short-term and long-term factors have shifted these market conditions, leading to a forecasted period of price volatility.[66] These factors are briefly explained here.

Short-term factors

Firstly, short term supply disruptions have set the underlying conditions of a tight market for ammonia, meaning that prices are projected to be volatile in the near term. The volatility is in part due to the sensitivity of market actors to news, which in conditions of imperfect information can lead to frenzied responses. The tight market conditions first emerged in 2021 following an "unusual"[67] drop in production that led to a supply crunch. By December 2021, ammonia was trading at record-high prices. The condition was compounded by Russia's invasion of Ukraine, which both cut the ammonia supply coming from one of the world's largest exporters and instigated an energy crunch that drove up production costs of ammonia in Europe. As a result, these volumes have all but dried up, leading to questions of what the new global benchmark for the ammonia trade should be.[68] According to the International Fertilizer Association (IFA), the conflict has led to "very challenging" conditions for price formation.[69]

An additional element impacting supply is the availability of vessels designed to transport ammonia. Ammonia is transported as a liquid in refrigerated conditions at -33 degrees Celsius, due to its toxicity at ambient temperatures. Liquid Petroleum Gas tankers (LPG) are used to transport anhydrous ammonia under the required conditions, which means that ammonia transport flows must contend with other liquid bulk energy commodities. This exposes ammonia transport flows to changes in other markets, which creates the potential for transport

65 ChemAnalyst, "Ammonia Price Trend and Forecast." Available from https://www.chemanalyst.com/Pricing-data/ammonia-37.

66 Argus Media, *Argus White Paper: Ammonia Market Volatility.*

67 Argus Media, *Argus White Paper: Ammonia Market Volatility.*

68 Argus Media "Ammonia most Exposed Fertilizer to Ukraine Conflict." Available from https://www.argusmedia.com/en/news/2307380-ammonia-most-exposed-fertilizer-to-ukraine-conflict.

69 ICIS, "IFA '22: Global Ammonia Market Unsettled and Uncertain,"

bottlenecks. Ammonia traders have noted a shortage of vessels.[70] This is likely due to the spike in energy prices, that has driven tanker owners to seize on rising transport costs for petrochemical products.[71]

Interestingly, spot trade has increased following the sharp upward price movements. The spiking prices have turned traders to the spot market in search of arbitrage opportunities around the sharp price movements.[72] Spot activity grew by some margin in 2021 to 1.5 Mt in fixed-price spot trades due to sustained high prices at the end of 2021. The number amounts to 8% of the total volume of ammonia traded in that year, up from the 675,000t traded in 2020.[73] Such increases suggest a growing relevance of the spot market and an increase in liquidity, which will in turn impact price formation if these trends maintain themselves.

Long-term factors

Secondly, long term factors are also at play. Exogenous factors such as the energy transition has inspired interest in both low carbon ammonia production, and ammonia as an energy carrier for hydrogen transport or as a direct fuel source in power and maritime shipping. Producers and potential consumers in new markets are responding to this interest, particularly as various regulatory frameworks and incentive schemes are being rolled out to create (force) the necessary supply and demand conditions.

These factors will shift the location and size of export markets, as well as of demand centres of ammonia. However, combined with regulatory uncertainty, the implications for the ammonia market are not yet clear. In principle, the growth and diversification of both supply and demand will likely entail a more dynamic commodity market with greater liquidity. Accordingly, the arrangements for price formation are likely shift in the long term in response to the increased liquidity.

3.1.4 Safety

Ammonia is a toxic chemical that requires safe handling, storage, and transport. At ambient conditions, ammonia is a toxic gas that can life-threatening upon inhalation at concentrations above 0.1 volume-percent.[74] In addition, ammonia is a corrosive substance. These risks are mitigated by industry practices, with centuries-long experience in developing standards for the safe handling of ammonia in different applications. The safety risks are barriers to the development of new use cases for ammonia, such as a maritime fuel. Interviews carried out in support of this research confirm this: interviewees maintain that technological challenges are

70 S&P Global, "Higher Ammonia Prices Prompting European Restarts, but Shortages Remain: Traders," Available from https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/040122-higher-ammonia-prices-prompting-european-restarts-but-shortages-remain-traders.

71 Marine Insight, "Worldwide Gas Ship Shortage Leads to Vessel Rates Surging at Record Levels." Available from https://www.marineinsight.com/shipping-news/worldwide-gas-ship-shortage-leads-to-vessel-rates-surging-at-record-levels/.

72 Argus Media, *Argus White Paper: Ammonia Market Volatility.*

73 Ibid.

74 IRENA and AEA, *Innovation Outlook: Renewable Ammonia.*

not the issue.[75] Rather, public perception of safety risks may hamstring regulatory approval of ammonia in certain applications. Long distance transport of ammonia over land is not seen as a viable option for scaling up due to the safety consideration associated with leakages – especially were said transport to be near population centres.[76]

3.2 Developing sector demand

Due to the new potential applications of ammonia, the demand for it is expected to increase fourfold by 2050.[77] More than half of the projected demand will be from the use of ammonia in energy markets as a maritime fuel, a feasible and scalable hydrogen carrier, a form of energy storage, and a potential back-up source for power generation. In short, the product characteristics of ammonia lend it potential as a key node of future zero carbon industrial sectors. Its usability, storability, and substitutability are commonly considered strong advantages in contrast to other prospective low-to-zero carbon molecular energy carriers.

It is particularly interesting as an energy carrier due to its comparably high energy density.[78] For example, DNV and the Singapore National Hydrogen Strategy expressly signal a market developing for ammonia as a maritime fuel.[79] Singapore will aim to accelerate deployment in international shipping, and define safe and operational envelopes to facilitate a regulatory sandbox for ammonia bunkering trials.[80] Ammonia's promise as a maritime fuel has prompted leading engine manufacturers, MAN and Wärtsilä, to develop internal combustion engines designed to run on ammonia-fuel, which are expected to be commercially viable by 2024.[81] Retrofitting packages will follow in 2025. For this sector's expected ammonia demand to flourish, large scale investments are required: IMO sets out the need for an approximate USD 1-1.4 trillion in cumulative investment between 2030 and 2050.[82] Most of the investments, around 87%, will manifest upstream from shipping in production, storage and bunkering activities.[83]

75 Based on interviews with a business development director at a technology company specializing in ammonia related technologies and products, an executive director at an engineering company specializing in the design and construction of industrial plants, and a global director of alternative energy at a tank storage company.

76 Ibid.

77 IRENA and AEA, *Innovation Outlook: Renewable Ammonia.*

78 The Royal Society, *Ammonia: Zero-Carbon Fertiliser, Fuel and Energy Store.*

79 Ibid; DNV GL, Energy Transition Outlook 2022; Argus Media "Singapore's MPA Partners on Ammonia-Fuelled Tankers." Available from https://www.argusmedia.com/en/news/2339087-singapores-mpa-partners-on-ammoniafuelled-tankers; Energy Market Authority and Maritime and Port Authority of Singapore, *Expression of Interest to Develop an End-to-End Low Or Zero-Carbon Ammonia Power Generation and Bunkering solution ("project") in Singapore* 2022.

80 Ibid.

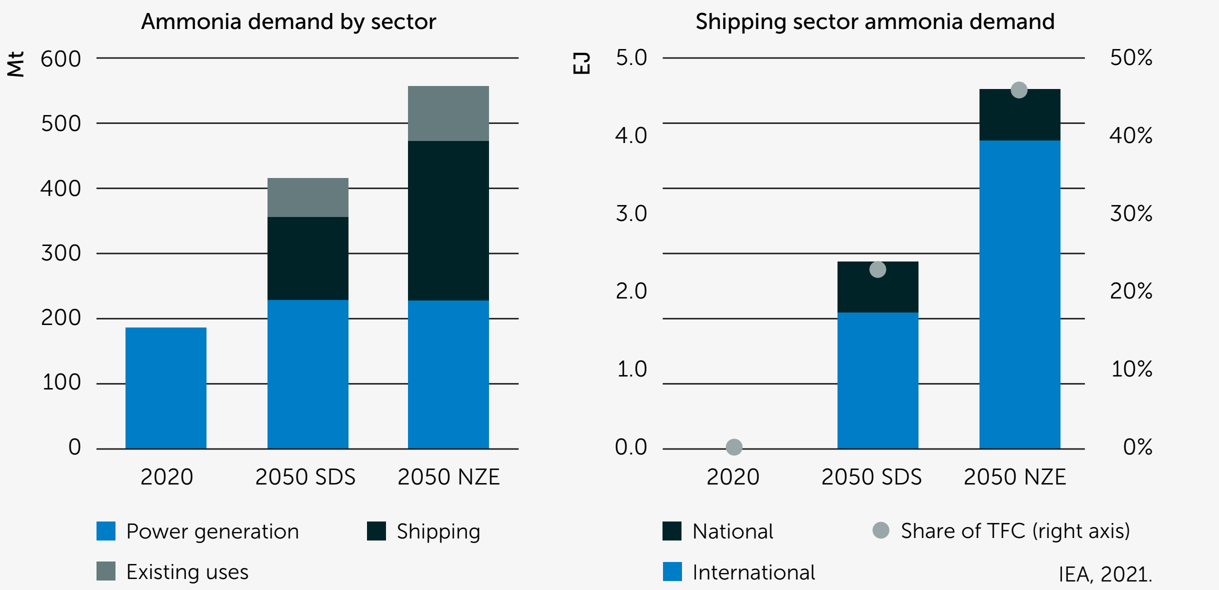
81 Ibid. "Ammonia as a Shipping Fuel." Available from https://www.globalmaritimeforum.org/news/ammonia-as-a-shipping-fuel.

82 "Ammonia as a Shipping Fuel,"

83 Ibid.

Ammonia can also be used in the power sector as a substitute for coal, as is currently being tested in Japan.[84] Coal and ammonia co-firing was successfully demonstrated in 2017 by Chugoku Electric Power Corporation, and plans to commercialize gas turbines that can combust 100% ammonia by 2025 have been announced by Mitsubishi Heavy Industries.[85] Despite the promise in power sectors, the application these markets will not be uniform across the world. Due to safety considerations, it is not likely that ammonia will substitute either fossil or future fuels at large scale for power generation in Europe.[86]

Figure 8: **Ammonia use as an energy carrier across two sustainable development scenarios.**[87]



Note: SDS = Sustainable Development Scenario; NZE = Net Zero Emissions by 2050 Scenario; TFC = total final energy consumption in the maritime shipping sector. "Existing uses" refers to current argicultural and industrial uses, coinciding with the core analytical scope for this technology roadmap.

As a hydrogen derivative, it is considered a comparatively low-cost solution to issues with the storage and overseas transport of the hydrogen molecule. The International Renewable Energy Agency (IRENA) purports that by 2025, 45% of traded hydrogen will be shipped, predominantly in the form of ammonia.[88] Interviews with industry experts confirmed this to varying degrees. Some opined that ammonia presents the most probable pathway for this activity for the near to medium term, until technical barriers surrounding the transport of

84 IEA, *Ammonia Technology Roadmap: Towards More Sustainable Nitrogen Fertiliser Production.*

85 Ibid.

86 Based on an interview with the global director of alternative energy at a tank storage company.

87 "Ammonia Technology Roadmap,"

88 IRENA, *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part I – Trade Outlook for 2050 and Way Forward.*

Liquid Organic Hydrogen Carriers (LOHC) and liquid hydrogen can be addressed over the next decades.[89] Another expert suggested that methanol and ammonia will compete until liquid hydrogen becomes scalable in the long term.[90] Regardless of the competition for other hydrogen derivatives, the consensus remains that ammonia is the most immediately scalable low-carbon derivative. Of a total of 15 hydrogen export projects with over 1 GW electrolysis capacity highlighted in a recent report by Hydrogen Europe, 12 indicated they would export hydrogen by conversion to ammonia.[91]

However, barriers exist in the alignment of the immediately scalable potential of ammonia and the low carbon requirements of the governing bodies pushing for said development. This new market for ammonia is linked to strategic ambitions for emission abatement in energy intensive sectors like transport, industry, and power. The most notable is the REPowerEU package proposed by the European Commission in May of 2022, following Russia's invasion of Ukraine. REPowerEU seeks to accelerate the scale up and adoption of a hydrogen-based economy, aiming to import 10 Mt and locally produce 10 Mt of hydrogen by 2030.

Taking this initiative as an example, it has been argued that such scale is unachievable before 2030. First, REPowerEU necessitates that the hydrogen imported is certifiably 'green,' hence, the import of hydrogen through the medium of ammonia entails that the ammonia is certifiably green of origin. Notwithstanding, the regulatory framework and standards that still require development – an issue addressed in the next section – there is a significant chance that the required supply of these 'green' hydrogen volumes will not be available before 2030.

A key challenge in this regard is in investing and developing electrolyser production capacity. To illustrate this, the Global Maritime Forum expects 44% of cumulative investment required to be dedicated to hydrogen production.[92] Ammonia synthesis facilities, as well, will require heavy investment, taking up a considerable slice of the expected 43% (see Figure 9). An exhaustive list of green and low carbon ammonia synthesis plants – existing or planned – can be found in Appendix A.

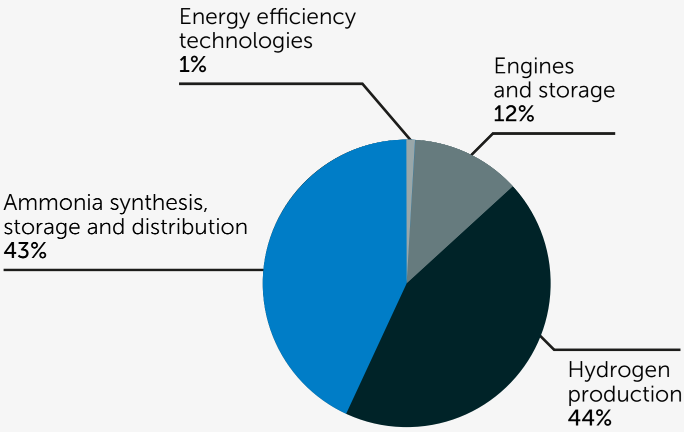
89 Based on an interview with the global director of alternative energy at a tank storage company.

90 Based on an interview with the executive director at an engineering company specializing in the design and construction of industrial plants.

91 Hydrogen Europe, *Clean Hydrogen Monitor* 2022.

92 "Ammonia as a Shipping Fuel."

Figure 9: **Investment breakdown across vessels and land-based infrastructure.**[93]



Hydrogen Europe suggests that only 5 Mt/year of renewable hydrogen and derivatives will be available for import to Europe by 2030, representing 50% of RePowerEU targets.[94] These potential volumes are, in addition, marked by uncertainty as MoUs securing trade routes between these projects and Europe currently only cover 2.8Mt, or 28% of the RePowerEU target.[95] The numbers reflect unclear project timelines. To illustrate, only 2.4 Mt/year out of the 11.5 Mt projected to be supplied post-2030 are in the engineering/design or construction phase (as of August 2022). Two ambitious projects in the feasibility stage are worth highlighting; the Western Green Energy Hub in Australia and the Green Energy Oman project in Duqm, Oman, could provide 5.4 Mt/y, or just over half of the projected 11.5 Mt per year beyond 2030.

More generally, a notable shift is occurring in the industry towards the deployment near-zero emission ammonia technologies in the production process. As suggested in Figure 10, the number of projects in the pipeline, and their capacities, are growing and could potentially push the amount of near-zero emission ammonia production capacity to 8 Mt by 2030.[96]

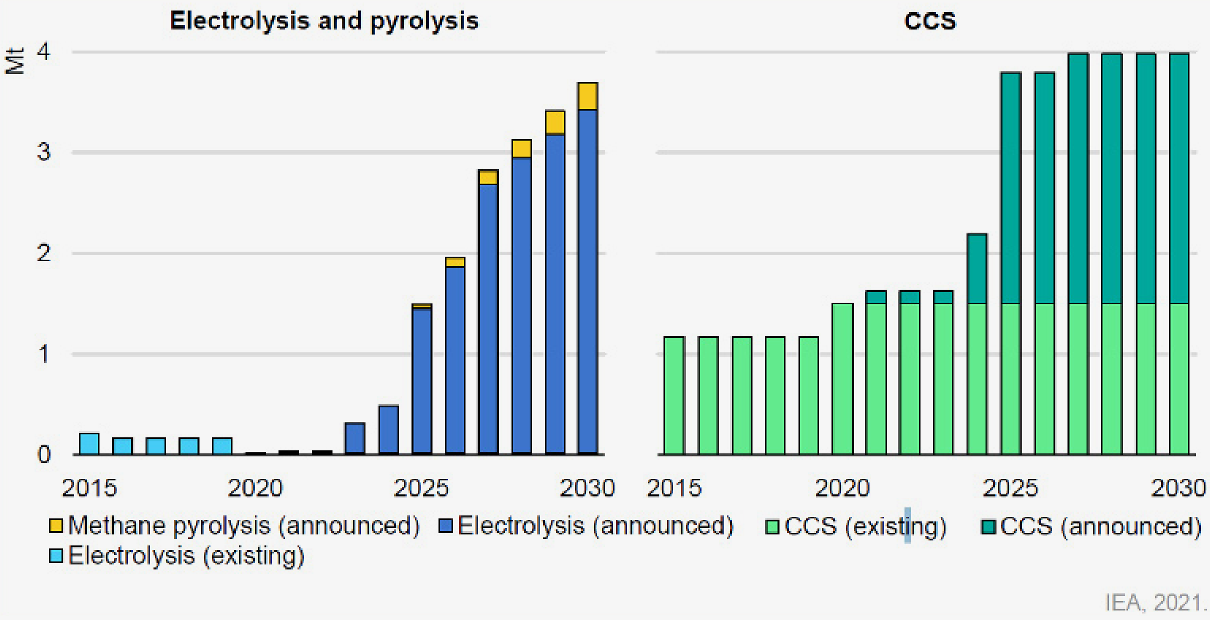
93 Ibid.

94 Hydrogen Europe, *Clean Hydrogen Monitor.*

95 Ibid.

96 IEA, *Ammonia Technology Roadmap: Towards More Sustainable Nitrogen Fertiliser Production.*

Figure 10: **Current and announced projects for near-zero-emission ammonia production, IEA (2021).**



There are several bottlenecks and uncertainties that can impact the development of demand and supply of low carbon ammonia in the future:[97]

- Unaligned or lacking government incentives to decrease CO_2 emissions;
- Sufficient electrolyser production capacity (as stated previously);
- Existence of expansive ammonia transport infrastructure;
- Ammonia's approval as a maritime fuel by inter-governmental bodies.

97 IRENA and AEA, *Innovation Outlook: Renewable Ammonia.*

4 The commodification of ammonia

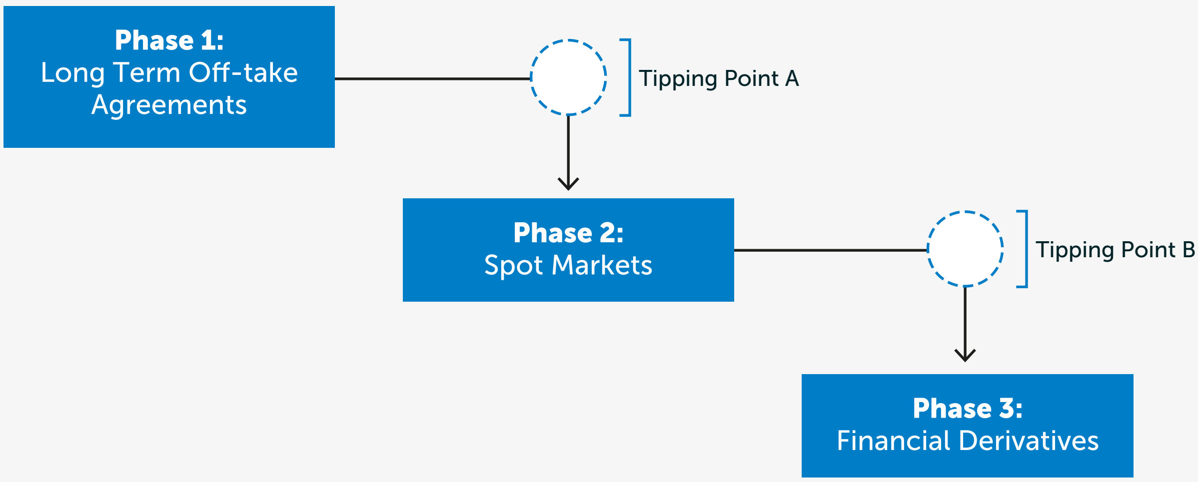
This section addresses the commodification of ammonia and identifies the conditions needed for the emergence of a highly dynamic ammonia market that is capable of self-organization. Building on the Commodification Pathway framework, the following section takes up the argument that certain conditions for the commodification of ammonia are developing favourably. These conditions are signalled by the increased interest in ammonia, the likely growth and diversification of its demand, a recognition of the need to invest in infrastructure and hardware, a developing policy and regulatory landscape, and the increasing sophistication of related information systems. Owing to these signals, a tipping point may be on the horizon for the ammonia market. That said, the further commodification of ammonia is not a given.

The following section introduces the signals of the commodification pathway in the ammonia market. Second, the section elaborates on the relationship between ammonia and hydrogen. Finally, the section indicates how the commodification of ammonia can be steered by stakeholders in the Rotterdam port-industrial cluster (and the wider ARA region) to realize a robust ammonia market and gain an advantageous position therein. This report maintains that the ARA region holds potential as a future ammonia hub. By pursuing objectives to draw market activity, secure import volumes of ammonia to the ARA region, and establish a forward market, Rotterdam could emerge as a new benchmark price hub with global appeal.

4.1 Ammonia and the Commodification Pathway

For the ammonia market to mature, it will need to develop a greater capacity for self-organization to respond to the expected large-scale change in demand and supply fundamentals. A robust market tends to involve greater price transparency, a certain level of financialization to minimize risk to market players, sufficient hardware and infrastructure to 'transform' the commodity, and recognized hubs of trade where volumes of the commodity are concentrated. These features enable the reduction of market friction so that price discovery – the crucial self-organizing mechanism to restore disequilibria – can be an unfettered process.

Figure 11: **Phases of the Commodification Pathway.**



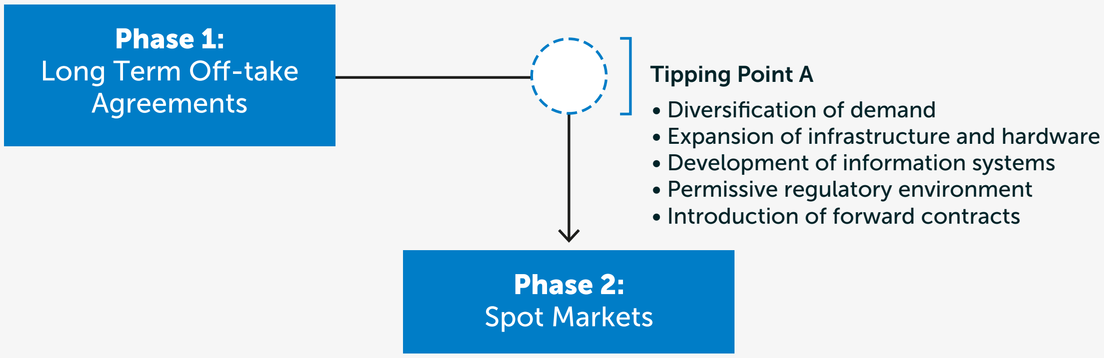
Source: authors

At present the ammonia market is fairly one dimensional and thus resembles Phase 1 of the Pathway. It is characterized by marginal volumes of the total production traded, and yet a smaller fraction of traded volumes occurring through physical spot markets. A relatively small number of buyers and sellers trade about 10% of the ammonia produced globally, the rest being locked-in for immediate use onsite. Most of the ammonia is destined for fertilizer applications.[98] Supply and demand fundamentals are relatively inflexible, so consumers of ammonia tend to mitigate supply risk via long term offtake agreements or vertical integration. An effect of these arrangements is the lack of price transparency and liquidity, which limits market entrance. The price discovery mechanism has until recently been sufficient to balance the market fundamentals. The projected growth of demand and supply of ammonia emphasizes that the market needs a more robust price discovery mechanism.

The Commodification Pathway recognizes four generic conditions for a tipping point to shift the weight of a market's main trade mechanism from long-term offtake agreements to spot markets. Figure 12 shows that this tipping point consists of a commodity's diversification of demand, the expansion of supporting infrastructure and hardware, the development of robust information systems, and the presence of a permissive regulatory environment. Ammonia seems to be experiencing movement on each of these conditions, though at different rates and with varying success. Identifying which of these conditions to facilitate could allow market players in the ARA region prioritize certain objectives over others.

98 IRENA and AEA, *Innovation Outlook: Renewable Ammonia.*

Figure 12: **Tipping Point A.**



Source: authors

4.1.1 Diversification of demand & expansion of infrastructure and hardware

Diversification of demand and the expansion of infrastructure and hardware are mutually reinforcing conditions and are thus considered together. These conditions are both concerned with the physical capacity of a market to deliver equilibrium and reflect a market's increasing need for flexible capacity to respond to disequilibria. The driving logic behind these two conditions is that they break the status quo of a path-dependent commodity market and offer alternative avenues for increasing returns.

Diversification of demand may be viewed as a systemic response top-down and, or bottom-up stimuli that can either force or encourage a shift in market preferences or technological substitution.[99] Top-down factors tend to be exogenous, macro level factors such as government intervention in response to climate change. Conversely, bottom-up factors may refer to innovation within a commodity value chain – or a parallel value chain – that shifts preferences of market players through new efficiencies, technologies or use cases for a commodity. That the ammonia trade is experiencing a diversification of demand is signalled by two related factors: structural energy transition policy and use case innovation.

The energy transition has set the policy agenda to espouse decarbonization strategies in high emission sectors like transport, power, and steel production. Within the scope of decarbonizing these sectors, new fuels and technologies have been artificially put forward to substitute energy-dense, highly efficient carbon-based fuels. Among these, are ammonia and hydrogen, in part due to the absence of carbon in their molecules.[100]

From a bottom-up innovation perspective, industries have taken up the challenge to deploy ammonia as a direct fuel in transport and power generation or as a hydrogen carrier for the future hydrogen economy. As a shipping fuel, commercial-scale demonstrations are expected

99 F. W. Geels and J. Schot, "Typology of Sociotechnical Transition Pathways," Research Policy 36, no. 3 (2007): 399-417.

100 IRENA and AEA, *Innovation Outlook: Renewable Ammonia*

to take place in the mid-2020s.[101] Both two-stroke and four-stroke engines will likely be commercially available by the mid-2020s.[102] The Maritime and Port Authority of Singapore has signalled its intent to focus on ammonia as its future fuel of choice.[103] There are approximately 130 ammonia-ready vessels on order as of October 2022.[104]

However, ammonia has not been embraced unanimously. For instance, the IMO has not yet approved ammonia as a maritime fuel, and fleet owners Maersk and Cargill have focused their resources on methanol-fuelled ships.[105] Similarly, ammonia's use in power faces regulatory uncertainty in Europe.[106] Nevertheless, Japan, for instance, has become a front-runner in experimenting with new ammonia co-firing technologies for use in the power sector.[107] Following successful tests in 2021, JERA Co., Inc. (JERA) expects to have commercial-scale co-firing of up to 20% ammonia in a 1 GW coal-fired power plant ready by the mid-2020s.[108] JERA is aiming for 50-60% co-firing by 2030 and 100% by 2040. To meet this demand, JERA has already begun procurement for ammonia, having sent a request for proposals to 30 companies.[109] The conditions for the proposals stipulate that procurement will be based on long-term contracts from 2027 to the 2040s of 500,000 tons per year to be delivered FOB.

The potential market for ammonia in hydrogen production faces the least uncertainty. Technology is not a bottleneck, nor is the regulatory environment. Instead, frontrunners, particularly in the Netherlands and Germany, have announced several gigawatt-scale ammonia-import terminals with conversion cracking facilities. Investment and regulatory frameworks will be the more challenging bottlenecks to address. Statements of intent to invest in upstream, midstream, and downstream infrastructure and hardware are beginning to take shape, but are not in line with the aspirational demand targets. At this relatively nascent phase in the commodification of ammonia, the scale-up of supply and infrastructure faces enormous investment requirements in capital, which must simultaneously deal with the risk of several interwoven challenges.

101 Ibid.

102 Ibid.

103 Argus Media, "Singapore's MPA Partners on Ammonia-Fuelled Tankers"; Energy Market Authority and Maritime and Port Authority of Singapore, *Expression of Interest to Develop an End-to-End Low Or Zero-Carbon Ammonia Power Generation and Bunkering solution in Singapore.*

104 "Clarksons: There are 130 Ammonia-Ready and 6 Hydrogen-Ready Vessels on Order." Available from https://www.offshore-energy.biz/clarksons-there-are-130-ammonia-ready-and-6-hydrogen-ready-vessels-on-order/.

105 "A.P. Moller - Maersk Continues Green Transformation with Six Additional Large Container Vessels." Available from https://www.maersk.com/news/articles/2022/10/05/maersk-continues-green-transformation; "Cargill Orders Methanol-Powered Kamsarmax Pair." Available from https://www.offshore-energy.biz/cargill-orders-methanol-powered-kamsarmax-pair/.

106 Based on an interview with the global director of alternative energy at a tank storage company.

107 T. Yoshizaki and H. Kobayashi, ed. *CO_2 Free Ammonia as an Energy Carrier,* 1st ed., 2023, 601-611

108 IRENA and AEA, *Innovation Outlook: Renewable Ammonia.*

109 JERA, "JERA to Conduct International Competitive Bidding for the Procurement of Fuel Ammonia | Press Release." Available from https://www.jera.co.jp/english/information/20220218_853.

Challenges to investment

First, is the context of the energy transition that, as a driving factor in the ambitions to grow the ammonia market, necessitates emissions reductions related to the production of ammonia. The risk is that emission reduction related to the production and use of ammonia is desired but not immediately economically attractive.[110] Projects for low carbon hydrogen and ammonia production will require access to renewable energy at competitive prices or will need to have access to caverns to store captured carbon, which limits where these projects can take place.[111]

Second, the scaling up of ammonia volumes is directly linked to the expansion of production of hydrogen, its main feedstock. Projections for the needed cumulative investments in the zero-carbon hydrogen value chain amounts to around USD 700 billion by 2030.[112] Projects proposed to meet the targets have not materialized. Only around 10% of proposals have reached final investment decision, are under construction or are already operational.[113] Required investments in midstream and downstream are similarly large in scale. Estimates of the required investments for ammonia storage facilities globally will amount to around USD 20 billion.[114] For transport, the fleet of LPG and liquid ammonia carriers will need to expand to approximately 235 ships with 85,000 m^3 capacity per ship – with voyages every two weeks – to meet projected demand in 2050.[115]

Despite the challenge, there is evidence of expansion of both midstream and downstream capacities by several frontrunners. Concerning the fleet of LPG/ammonia carriers, examples include Nippon Yusen Kaisha Line (NYK) that announced its order of a fourth LPG Dual-Fuel Very Large LPG/NH3 Carrier to be built by Kawasaki Heavy Industries Ltd.[116] Regarding storage and import terminals, the Netherlands and Germany will likely host several new projects. Notable projects are being announced in Vlissingen and Rotterdam in the Netherlands, and Wilhelmshaven and Hamburg in Germany.[117]

---

110 Based on an interview with the business development director at a technology company specializing in ammonia related technologies and products.

111 Based on an interview with a vice president of hydrogen at an integrated energy company.

112 Hydrogen Council and McKinsey & Company, *Hydrogen Insights 2022,* 2022.

113 Ibid.

114 IRENA and AEA, *Innovation Outlook: Renewable Ammonia.*

115 Ibid.

116 "Kawasaki Receives an Order for an 86,700 M^3 LPG-Fueled LPG/ NH3 Carrier." Available from https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20211202_9041; "NYK to Build its Fourth LPG Dual-Fuel very Large LPG / NH3 Carrier." Available from https://www.nyk.com/english/news/2022/20220804_01.html.

117 "Bp Reveals Plans to Evaluate Expansion of Germany's Green Energy Port with a New Hydrogen Hub." Available from https://www.bp.com/en/global/corporate/news-and-insights/press-releases/bp-reveals-plans-to-evaluate-expansion-of-germany-green-energy-port-with-new-hydrogen-hub.html; "NEWS - Vopak Prepares for Import of Green Ammonia in North Sea Port, the Netherlands." Available from https://www.vopak.com/newsroom/news/news-vopak-prepares-import-green-ammonia-north-sea-port-netherlands; "Germany to Build First Green Ammonia Import Terminal." Available from https://www.gtai.de/en/meta/press/germany-to-build-first-green-ammonia-import-terminal-923268; "New Ammonia Import & Export Terminals: The Greenpoint Valley Project, Netherlands." Available from https://www.ammoniaenergy.org/articles/new-ammonia-import-export-terminals/; "OCI Expands Import Terminal for (Green) Ammonia." Available from https://www.portofrotterdam.com/en/news-and-press-releases/oci-expands-import-terminal-for-green-ammonia; "Development of Import Terminal for Hydrogen Carrier in Port of Rotterdam." Available from https://www.portofrotterdam.com/en/news-and-press-releases/development-of-import-terminal-for-hydrogen-carrier-in-port-of-rotterdam.

Another concern from industry is the lack of arrangements that de-risk CAPEX and OPEX investments, such as loans, grants, and investment guarantees, as well as procurement contracts and off-take agreements. Regulatory frameworks and policy support are sought to address this gap to fast-track access to public funding and facilitate demand-matching through the long-term off-take agreements needed for project finance. It is uncertain where this legislation and regulatory frameworks will be most clear or beneficial to producers.[118] Legislative packages in the United States or the European Union, for instance, will differ in the transaction costs imposed on market players in terms of technical requirements and access to capital or incentives. However, as is shown in the next subsection, progress on regulation and policy support has been made to help market players access investments.

4.1.2 Progress on regulatory permissibility

The United States and the European Union (EU), including some of its member states, are leading the way in stimulating supply and demand factors through policy and legislation. These initiatives will likely entail a competition to provide the most attractive incentives, as illustrated by the EU's response to the US' Inflation Reduction Act. Beyond incentives to stimulate supply and demand, there remains a significant gap in legislation to support the introduction of new use cases for ammonia at commercial scale.

European Regulations

The EU has been a frontrunner with a series of legislative packages and proposal under the initial Green Deal designed to give a clear signal on how the EU will pursue decarbonization in key sectors of importance for the hydrogen and ammonia industries. The recent legislative package REPowerEU proposes to amend the Renewable Energy Directive (REDII) as it appears in Fit for 55. The amendments aim to establish binding targets for the production and import of hydrogen at 10 Mt each, as well as quotas for consumption. The EU Commission's initial proposal aims for increases in share of Renewable Fuels of Non-Biological Origin (RFNBO) in transport to 5% and industry to 75% by 2030, though counter offers from the Parliament are under negotiation.[119] In addition, REDII will likely mandate member states to choose between a 13 % reduction in GHG intensity or a 29 % renewable energy source share in the final energy consumption of the transport sector by 2030.[120]

To buttress the development of targets, the EU has made major steps to defining what 'renewable' or low carbon means. The Delegated Acts on RFNBOs are considered 'make or break' for industry and transport. REDII will set the targets, but the delegated acts will supplement REDII by determining what can be counted as RFNBO. These proposed delegated acts are still in the process of consultation, which could continue into 2023. As it stands, the round of consultation revealed concern that the delegated acts would impose unnecessary

118 Based on an interview with the senior vice president of product management at a chemical company specializing in production and distribution of fertilizers.

119 Hydrogen Europe, *Clean Hydrogen Monitor.*

120 European Parliament, "Revision of the Renewable Energy Directive in "A European Green Deal." Available from https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/file-revision-of-the-renewable-energy-directive.

burdens – both technical and financial – on the nascent green hydrogen production industry.[121] This will likely have direct impact on the local production of ammonia.

Carbon Border Adjustment Mechanism

Another element in the European market is the Carbon Border Adjustment Mechanism (CBAM). CBAM deals with the risk of carbon leakage resulting from the EU Emissions Trading System (ETS). This addresses the risk of EU-based companies moving carbon-intensive production abroad to take advantage of lax standards, or that EU products are replaced by carbon-intensive imports.[122] The basic principle is that CBAM equalizes the price of carbon between domestic production and imports, by requiring EU importers to purchase carbon certificates corresponding to the carbon price that would have been paid had the goods been produced under the EU's carbon pricing rules. It is relevant specifically to hydrogen and ammonia imports because a deal has been reached to extend the scope to hydrogen.[123]

H2Global

These European regulatory initiatives aim provide clarity to market actors. They are designed to alleviate uncertainty, in part, by providing a permissive regulatory environment for the development of ammonia production. However, the costs of scaling up remain prohibitive to actors seeking to scale up production. Security of demand, as well as a mechanism to reduce capital is needed to kickstart upstream investments in hydrogen projects. The necessity arises within this permissive regulatory environment to match, and lock in, off-takers to unlock investment for production. The European solution is H2Global.

H2Global is a German initiative launched in May 2021 to kickstart both demand and supply of green hydrogen and derivatives by concluding long-term offtake agreements with prospective hydrogen producers and facilitating short term sale contracts with hydrogen consumers in industry, transport and energy sectors.[124] The aim of the initiative is to stimulate supply by ensuring access to funding and offtakers, while signalling to consumers a security of supply over the long term at reduced costs.

The mechanism functions by way of an intermediary – the Hydrogen Intermediary Network Company GmbH (HINT.CO) – that concludes purchase agreements with electrolysers (producers) and short term sale contracts for green hydrogen products and derivatives. The lowest cost long-term offtake agreements and the highest purchase offers will be awarded contracts under the scheme, offering an incentive for producers to continue reducing costs of production while increasing industrial off-takers' willingness to pay premium for green

121 Hydrogen Europe, *Clean Hydrogen Monitor*; "Commission Launches Consultations on the Regulatory Framework for Renewable Hydrogen." Available from https://ec.europa.eu/info/news/commission-launches-consultation-regulatory-framework-renewable-hydrogen-2022-may-20_en.

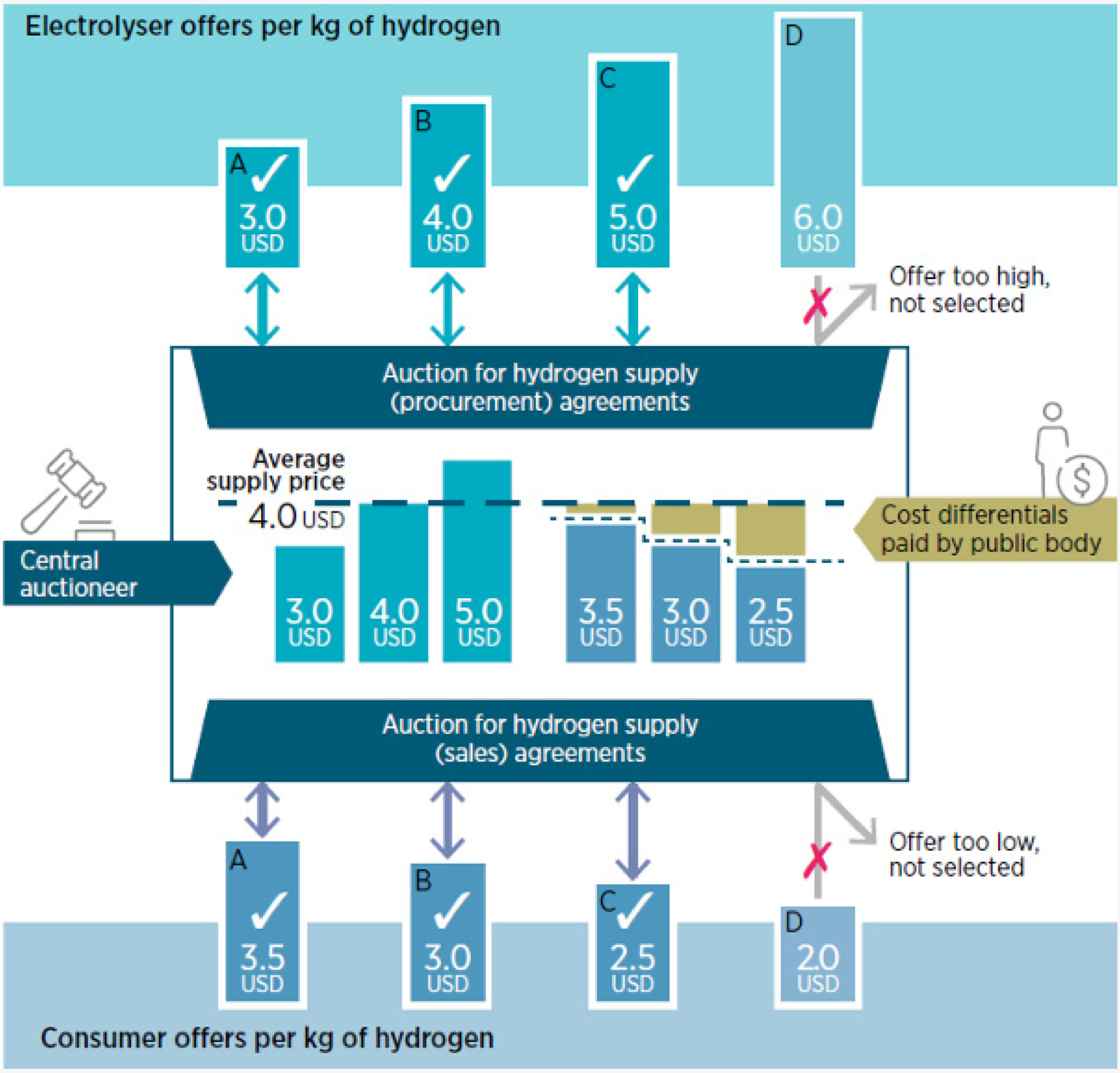
122 "Commission Launches Consultations on the Regulatory Framework for Renewable Hydrogen."; "Carbon Border Adjustment Mechanism." Available from https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_3661.

123 "Deal Reached on New Carbon Leakage Instrument to Raise Global Climate Ambition." Available from https://www.europarl.europa.eu/news/en/press-room/20221212IPR64509/deal-reached-on-new-carbon-leakage-instrument-to-raise-global-climate-ambition.

124 Hydrogen Europe, *Clean Hydrogen Monitor.*

hydrogen.[125] The intermediary HINT.CO covers the price difference between the sale and purchase agreements, a form of Contracts for Difference (CfD). HINT.CO will be funded by different funding bodies, and at present the German Federal Ministry for Economic Affairs and Climate Action has contributed EUR 900 million to H2Global's first funding cycle.[126] This compensation will be funded by HINT.CO until such time that demand and supply prices are aligned – thus removing the necessity for an intermediary. See Figure 13 for a visual overview.[127]

Figure 13: **Schematic overview of H2Global's functionality.**



125 IRENA, Green Hydrogen for Industry: *A Guide to Policy Making.*

126 Hydrogen Europe, *Clean Hydrogen Monitor.*

127 IRENA, Green Hydrogen for Industry: *A Guide to Policy Making.*

For flexibility in the creation of tailored funding windows, specific parameters are set for product (hydrogen, ammonia, methanol), geographic area (country, regional, global), and sustainability criteria.[128] Purchase agreements are standardized to 10-year contracts. At present, the focus is on establishing foreign trade partnerships with countries where green hydrogen production is cost-efficient. The first auction window seeks to secure 10-year contracts for the import of green ammonia. Trade of liquid hydrogen and other derivatives will follow as these markets develop further. Dutch Minister for Climate and Energy Policy, Rob Jetten, has indicated the Netherlands' intention to participate in H2Global to his counterpart in Germany.[129]

Though an important step to kickstarting the scale up of the industry, the dual auction system poses certain barriers.[130] The first concern is the administrative burden that this scheme puts on prospective participants, relative to the requirements set by competing schemes, such as the US' IRA for instance. The second is the impact of the mechanism on price formation, if the artificial price remains in place for extended periods of time. Related to this is that the auction system will incentivize supply projects to bid at a price lower than is economically feasible.[131] A key concern noted by industry leaders is the complexity of the European approach, which may undo the current lead EU has built up in upstream investment in hydrogen. In contrast, the US proposes a straightforward framework that may to leapfrog the EU in attracting commercial activity. The main benefit to the US system is that access to finance is far less complex.

The US is seeking to reduce the costs of clean hydrogen production by approximately 80% to USD 1 per kg in one decade to make it competitive in the market with fossil hydrogen.[132] To that end, the US Department of Energy (DOE) has launched H2Hubs, a platform for securing federal funding for hydrogen projects. For this initial launch, DOE envisions selecting six to ten H2Hubs for a combined total of up to $6-7 billion in federal funding. DOE may issue a second launch of funding to solicit additional H2Hubs.[133]

Furthermore, the IRA, passed with much fanfare, is a legislative package that includes mechanisms to make (green) hydrogen projects more competitive. Signed into law in August 2022, the IRA provides a Hydrogen Production Tax Credit. The new maximum $3/kg production tax credit (PTC) could undercut grey hydrogen production, according to S&P. The

128 Hydrogen Europe, *Clean Hydrogen Monitor.*

129 "Antwoord Op Vragen Van De Leden Erkens En Klink Over Het Bericht Dat De Europese Unie Voornemens is Een Waterstofbank in Het Leven Te Roepen." Available from https://www.rijksoverheid.nl/documenten/kamerstukken/2022/10/24/beantwoording-kamervragen-over-het-bericht-dat-de-europese-unie-voornemens-is-een-waterstofbank-in-het-leven-te-roepen.

130 Based on an interview with the senior vice president of product management at a chemical company specializing in production and distribution of fertilizers.

131 Based on an interview with the senior vice president of product management at a chemical company specializing in production and distribution of fertilizers; IRENA, *Green Hydrogen for Industry: A Guide to Policy Making.*

132 US Department of Energy, *DOE National Clean Hydrogen Strategy and Roadmap*, 2022; OECD, "Regional Clean Hydrogen Hubs Funding Opportunity Announcement." Available from https://oced-exchange.energy.gov/Default.aspx#FoaId4dbbd966-7524-4830-b883-450933661811.

133 "Regional Clean Hydrogen Hubs Funding Opportunity Announcement."

full $3/kg PTC will be available to hydrogen manufactured with lifecycle emissions of 0.45-1.5 kg, by producers which meet the federal government's wage standards.[134] The immediate pricing effect of the tax credit may drive finances into the sector, leading to long-term cost reductions. Though the power price variable will have to be considered (in many cases this has not been favourable in the US over the past year), this is still a promising piece of legislation for the hydrogen sector in the US.

4.1.2.1 Emission accounting and the guarantee of origins

Certification is needed for emissions accounting, purity grading of ammonia and feedstocks, and for the creation of a level playing field.[135] The most important aspect relates to both the quantification and reduction of carbon emissions in the lifecycle of ammonia. Establishing the CO_2 equivalent footprint of ammonia is a necessary step to decarbonization in the value chain. The process differentiates products based on emissions and quality. Without this differentiation, it is difficult for intermediaries or end users to ensure that the ammonia they purchase is low-carbon, because the molecules themselves are the same regardless of the process used to derive it.[136]

In addition to accounting for the related emissions of the molecule, certification is essential to determining the value of low carbon ammonia. Certification schemes like 'Guarantees of Origin' justify a higher price of green or low-carbon ammonia to purchasers as the price can be veritably linked to the positive externality of decarbonizing a value chain. The traceability and verification that these schemes offer allows producers and consumers to reach agreement on the value of green or low carbon ammonia.[137] Certification schemes could also support the levy of a carbon tax on ammonia produced outside the EU and redistribute the accrued revenues to support other aspects of the value chain.

A possible barrier in the development of certification schemes could be the administrative burden of accounting for lifecycle emissions in an often-complex chain of custody. To ease the potential administrative burden, certification schemes could be developed on a book-and-claim framework similar to that used in European power markets, whereby certificates are traded separately from the physical product.

4.1.2.2 Shipping fuel

Regulation for new use cases is still lagging. For instance, though preparations for ammonia's use as a shipping fuel are underway, fully developed international regulations for its use, storage, and bunkering have not yet been established.[138] Gaps exist in the IMO's safety and environmental regulations as well as in the international ISO standards referenced by IMO

---

134 "Revealed | how Biden's $3/kg Green Hydrogen Tax Credit could Break Open US Production | Recharge." Available from https://www.rechargenews.com/energy-transition/revealed-how-bidens-3-kg-green-hydrogen-tax-credit-could-break-open-us-production/2-1-1279955.

135 IRENA and AEA, *Innovation Outlook: Renewable Ammonia.*

136 Ibid.

137 Ibid.

138 ClassNK, *Part C "Guidelines for the Safety of Ships using Ammonia as Fuel,"* 2022; EMSA "Classification Societies." Available from https://www.emsa.europa.eu/inspections/90-classification-societies.html.

requirements.[139] In the absence of international regulations at the IMO level for the use of ammonia as a shipping fuel, many class societies have issued Approval in Principle for the design of ammonia-fuelled bulk carriers and container ships.[140] These societies develop technical standards for the design and construction of ships and are authorized by political bodies to act on their behalf to certify and survey ships. The EU, for instance, recognizes 11 of the world's 50 classification societies, among which are the American Bureau of Shipping, DNV GL, Bureau Veritas, Korean Register, and Nippon Kaiji Kyokai (Class NK).[141] Each of these named societies has published guidelines on the design of ammonia-fuelled ships.[142]

4.1.2.3 Land-side regulatory frameworks

Due to ammonia's toxicity, its handling and use are highly regulated to prevent contact with humans and the environment. In the context of the EU, the comparatively strict Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation controls commercial and industrial use, transport, handling and storage of ammonia and ammonia-based substances.[143] REACH places the burden of proof on companies engaging in commercial or industrial use of ammonia, to ensure that all associated risks are adequately addressed. Without authorization, companies may not use the substance. The measure places emphasis on the risks being demonstrably eliminated, which places the potential large-scale inland transport and development of new use cases, such as with ammonia-to-power in Europe, in doubt for the foreseeable future.[144]

4.1.3 Development of information systems

The development of information systems that track the trade of a commodity is a final enabling condition for the shift to a physical spot market. Sophisticated information systems render a clearer, more accessible picture of the market's fundamentals.[145] Information systems increase in sophistication through the frequency of assessments, through the variety of elements assessed related to the commodity, and through the amount of input and data available. A non-exhaustive list of elements assessed by information systems for commodity markets may be price of the commodity in major import and export markets, freight rates along major transport routes, general news that may impact fundamentals, production rates, and storage. The frequency of, and amount of available input for, these assessments will increase or decrease the accuracy of these assessments.

The ammonia market's information systems are showing signs of growing sophistication in response to the forecasted demand diversification and growth, as well as to exogenous shocks

139 American Bureau of Shipping, CE Delft, and Arcsilea, Potential of Ammonia as Fuel in Shipping, 2022.

140 ClassNK, *Part C "Guidelines for the Safety of Ships using Ammonia as Fuel"*

141 EMSA "Classification Societies."

142 American Bureau of Shipping, CE Delft, and Arcsilea, *Potential of Ammonia as Fuel in Shipping*

143 "Ammonia, Anhydrous - Substance Information – ECHA." Available from https://echa.europa.eu/substance-information/-/substanceinfo/100.028.760.

144 Based on an interview with the global director of alternative energy at a tank storage company.

145 W. Jacobs and R. Horster, "Commodity Supply Networks as Complex Adaptive Systems: How Commodity and Freight Markets Respond to a Supply Shock," in 87-99.

faced in 2021 and 2022.[146] The increased attention to ammonia from potential market entrants has brought with it unprecedented focus on the pricing mechanisms currently in place and how they are assessed. In the context of anticipated price volatility over the near term, this presents problems for both traditional market players and new entrants who are exposed to the relatively frequent price swings experienced of recent.[147] A standardized approach based on a flat price reference is sought by new entrants, according to Argus Media – preferably with a higher frequency.[148]

Two price reporting agencies have sought to address this need. Both Argus Media and S&P Global have launched daily price assessments of the ammonia cargoes for several of the largest import and export markets.[149] The former's assessment currently covers East Asia CFR (excluding Taiwan) and Middle East FOB, though they intend to cover NW Europe (duty paid/duty free) and US Gulf CFR. S&P Global will cover the same markets. As of January 2023, it is not clear if other price reporting agencies have followed suit. These daily price assessments offer market participants greater certainty and lower their risk.

4.1.4 Phase 2 and beyond

At present, the ammonia market has not yet reached Phase 2 along the pathway. It is therefore difficult to foresee how the ammonia market will look in such a context. Nevertheless, the following section highlights the generic features and risks that come with Phase 2 and suggests important changes the ammonia market may face and what the most important conditions for further development will be.

At Phase 2, a commodity market is less exposed to supply risk and participants enjoy greater market access along with reduced informational friction. Demand has diversified or is continuing to do so. In the case of the ammonia market, this would entail that new use-cases for the commodity are successfully demonstrated and beginning their commercial deployment. The regulatory frameworks and guidelines governing increased human interaction with ammonia enable deployment in different operational contexts, for instance in bunkering operations at seaports.[150]

Production, transport, and storage capacity has expanded and thus become more flexible in response to the growing and diversified demand. For instance, clear regulatory mechanisms are in place to bridge the capital cost gap for hydrogen and ammonia production projects and the required energy – renewable or otherwise – for operation is available, leading to

146 Argus Media, *Argus White Paper: Ammonia Market Volatility.*

147 ICIS, "Nitrogen Fertilizer Prices Nosedive as Buyers Go Missing." Available from https://www.icis.com/explore/resources/news/2023/01/27/10848720/podcast-nitrogen-fertilizer-prices-nosedive-as-buyers-go-missing/.

148 Argus Media, *Argus White Paper: Ammonia Market Volatility.*

149 "S&P Global Platts Launches Ammonia Cargo Price Assessments | S&P Global Commodity Insights." Available from https://www.spglobal.com/commodityinsights/en/about-commodityinsights/media-center/press-releases/2021/101321-platts-launches-ammonia-cargo-price-assessments#; "Argus Ammonia - NEW: Daily Price Assessments," Available from https://www.argusmedia.com/en/fertilizer/argus-ammonia.

150 American Bureau of Shipping, CE Delft, and Arcsilea, *Potential of Ammonia as Fuel in Shipping.*

increased supply.[151] The cycle of efficiency gains begins and incremental increases in yielded tonnage produce excess volumes that are easier to trade on a more liquid physical spot market. The combination of robust demand emanating from different geographical hubs and diverse user markets allows for greater arbitrage opportunities as different needs in timing and delivery points can be met. Trade is thus more capable of reconciling market disequilibria, making use of sophisticated information systems and more robust price signals from the spot market.

The ammonia market will likely change in several ways. The certification of carbon intensity levels of the upstream value chain will impact trade and price of ammonia, adding an extra layer of complexity, albeit necessarily. The drive to decarbonize ammonia will create markets for different classifications of ammonia based on carbon emission intensity. The idea is that ammonia will be differentiated on the basis of emission intensity and production methodology, leading to three general classifications – grey, low carbon, and zero carbon ammonia.[152] Furthermore, standardization of gradations within these general classifications will be required, so that prices can be differentiated between ammonia cargoes of certifiably different carbon emissions levels.[153] In addition to this, certification schemes will need to be created and widely adopted to prevent a fragmentation of standards between regions that could feasibly distort the market and lead to carbon leakage.[154]

S&P Global forecasts that approximately 57% of global grey ammonia will be displaced by low-carbon ammonia by 2050.[155] In this case, the pricing of ammonia will likely become less dependent on natural gas prices as production pathways decarbonize. The growth of a related market for various classes of hydrogen – based on emission intensity and production pathway – will likely be an important price signal, which in turn will be increasingly influenced by the cost of renewable power and carbon pricing mechanisms. The geographical fragmentation of hydrogen prices will potentially drive ammonia pricing as traders utilize ammonia cargoes to seek arbitrage opportunities between price spreads of the different hydrogen markets.

As such, the coupling of ammonia and hydrogen offers a mutually reinforcing mechanism in support of robust physical spot markets. The interplay between the two markets ensures a sophistication of both demand, supply, and informational factors. In this context, the central challenge faced by Phase 2 markets is that supply risks are swapped with different

---

151 "EU Green Hydrogen Plans in Stalemate as Nine Member States Lobby for Inclusion of 'Low-Carbon' H2: Report." Available from https://www.hydrogeninsight.com/policy/eu-green-hydrogen-plans-in-stalemate-as-nine-member-states-lobby-for-inclusion-of-low-carbon-h2-report/2-1-1396840.

152 Based on an interview with the senior vice president of product management at a chemical company specializing in production and distribution of fertilizers.

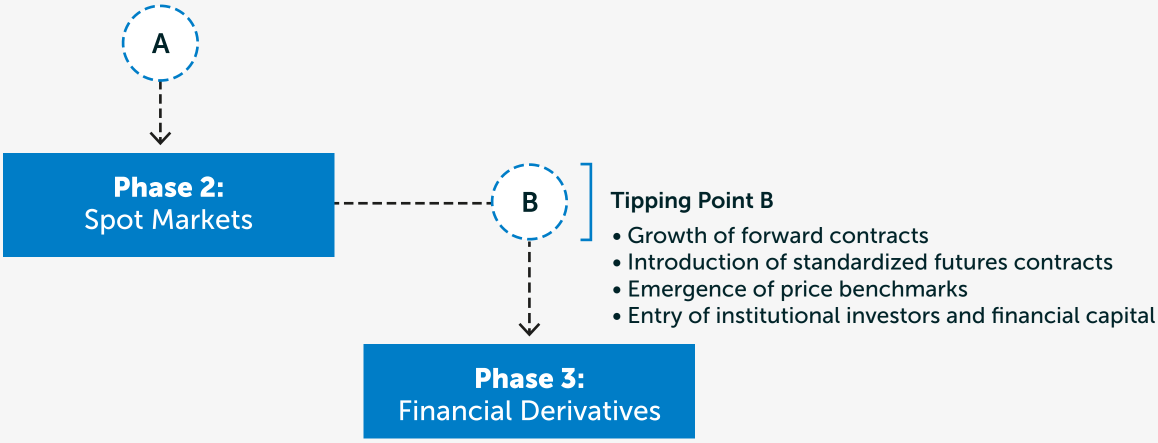
153 Based on an interview with the business development director at a technology company specializing in ammonia related technologies and products.

154 Based on interviews with the business development director at a technology company specializing in ammonia related technologies and products and the executive director at an engineering company specializing in the design and construction of industrial plants.

155 "S&P Global Commodity Insights Launches New Platts Renewable 'Green' Ammonia Prices." Available from https://finance.yahoo.com/news/p-global-commodity-insights-launches-080900447.html.

forms of risk that require more sophisticated trading instruments for risk mitigation to allow market participants to hedge against these different forms of risk. The most prominent trade instruments are forward contracts designed to hedge against price volatility on the spot market. However, these are limited in their liquidity, as they are highly customized, bilateral agreements.

Figure 14: **Tipping Point B in the Commodification Pathway.**



Source: authors

The conditions for further commodification, Tipping Point B (see Figure 14), will depend on a standardization of forward contracts to ease their liquidity. Exchanges will emerge to design and issue futures contracts and facilitate their trade. The second condition would be that commercial banks, institutional investors, and hedge funds step in to offtake future price risk by participating on these exchanges – thereby financializing the commodity market.

It is not certain how specific conditions of the ammonia market will form in Phase 2, but it is reasonable to assume that spot markets will grow in relevance and that the necessities of risk mitigation increasingly demand contract standardization. However, for this to take place, ammonia's commodification towards Phase 2 must be deliver on the conditions of diminished supply risk, robust demand, and strong spot markets with greater transactions and volumes.

Premature efforts to set up exchanges without said liquidity or market size will likely struggle for relevance. The recent announcement that ICE would expand its alternative fuels complex by launching an ammonia futures contract in early 2023 is one to pay attention to. The proposed contract will be based on Argus Media's daily price assessment for ammonia cargoes delivered to northwest Europe.[156] The context for the launch, according to ICE, is the commodity's

156 "ICE Plans to Launch its First Ammonia Futures Contract." Available from https://www.ice.com/insights/ice-plans-to-launch-its-first-ammonia-futures-contract.; L. Walton, *Circular 22/183 Introduction of Additional Cleared ICE Futures Europe Contract - Argus Ammonia NWE CFR Future* ICE, 2022.

potential growth in multiple applications. To the authors' knowledge, the futures contract was not launched at the target date of 16 January 2023. Presumably, regulatory approval may have been a barrier. Nevertheless, the contract may struggle to gain traction in the absence of liquidity and market size.

4.1.5 Destination ARA

The potential importance of ammonia is recognized by the signals outlined in the previous subsection. Yet, its commodification still contends with certain barriers that, if left unaddressed could hamper the development ammonia's trade. This report argues, through the 'principle of relatedness' that public and private actors in the ARA region can leverage the region's advantages to drive the commodification of ammonia and build a robust import (spot) market with global relevance.

The ARA region enjoys a natural advantage as an import hub and potential benchmark for the ammonia and hydrogen markets. The ARA polycentric port region may be viewed conceptually as a complex system of local and non-local assets, actors, and institutions that has emerged as a gateway and hub for trade through decades of interaction, competition, and specialization between its constituent parts.[157] The geographical proximity and concentration of related economic activities – key features of the principle of relatedness – fostered the growth of the petrochemical industry, specifically the product space of oil.

Though the petrochemical industry is not the focus of this report, its presence lends the ARA region considerable promise as the future European hub of alternative energy carriers like hydrogen and ammonia.[158] The degree of relatedness between the fossil and hydrogen/ammonia is evidenced in similar skills, demand markets, business models, infrastructure, technologies, organizational routines, and institutional arrangements (see Table 5). This relatedness and subsequent concentration of market players in direct and related industries is an advantage that public and private actors can leverage to draw in more volumes and actors to foster demand creation and security of supply.

157 K. van den Berghe et al., "Friends with Benefits: The Emergence of the Amsterdam-Rotterdam-Antwerp (ARA) Polycentric Port Region," *Territory, Politics, Governance* 11, no. 2 (Feb 17, 2023): 301-320.

158 K. van den Berghe et al., "Friends with Benefits: The Emergence of the Amsterdam-Rotterdam-Antwerp (ARA) Polycentric Port Region": 301-320.

Table 5: **Relatedness between Fossil Fuels, Hydrogen, and Ammonia.**

Related features	Description
Skills	Handling molecules, hazardous materials, ships, risks, and financialized contracts
Infrastructure	Facilities for storage, transport, conversion and transformation of liquids and gasses.
Institutional arrangements	Contracts, exchanges, certificates, GO, Insurance liabilities, warehouse receipts.
Organizational routines	Systems for trade, arbitration, risk taking, hedging, of valuable chemicals and their financial derivatives.

4.2 The relationship between ammonia and hydrogen

A crucial element of the commodification of ammonia is its relationship with hydrogen. No assessment of ammonia's commodification pathway would be complete without an analysis of this relationship. How this develops will have a significant impact on the development of energy markets, particularly in how both hydrogen and ammonia's main use cases and pricing mechanisms become institutionalized. The following subsection addresses these interlinkages and proposes several potential scenarios with distinct and profound significance for the future hydrogen economy, for ammonia's other demand markets, and for conventional energy commodities' relevance in the medium to near term.

With several interrelated compounds in a certain industrial setting there is often a tendency for the market parties to choose one of these as the "central" commodity to trade. The prices for the other compounds are then merely derived from this central commodity. Considering this pricing dynamic, it remains to be seen how the close chemical, industrial, and economic relationship between ammonia, hydrogen and natural gas will dictate pricing. The following discusses how the dynamic may evolve and which of these markets will be "central" to price formation.

It is known from experience that this can evolve over time. For instance, as natural gas was being phased-in as an energy carrier during the 1950s, 1960s, and 1970s, its price was derived from the price of oil. Originally, gas was not considered an independently priced commodity. This changed during the 1980s and 1990s, as the supply of natural gas grew steadily, and technological and infrastructural transportation bottlenecks eased, leading to gas-to-gas competition. Only then it became a frequently traded commodity with a pricing in its own right - it became more central.

Market parties and commodity traders prefer to trade in commodities that are:

1. Transported across a wide geographical range;
2. With pricing in their own right, not derived directly from another commodity;
3. With a multitude of applications as a feedstock and energy carrier;
4. Not hampered by natural monopolies or regulatory obstacles

This is motivated by the economic drivers of market parties (profit margin, portfolio management, risk hedging) and commodity traders (earning capability, ease of trade). The next subsections analyse this dynamic in the context of the ammonia market for different situations: the ammonia production historically, and after the change towards renewable and carbon neutrality in different prospective pathways.

4.2.1 The traditional production of ammonia from hydrogen and natural gas

Historically, ammonia (NH_3) has been produced industrially by the Haber-Bosch process from nitrogen (N_2) and hydrogen (H_2), where the hydrogen is coming mostly from steam methane reforming of natural gas (CH_4). Natural gas is the main feedstock commodity, which is widely transported through an open-access infrastructure (pipelines, ships, terminals). There may be limited transportation of hydrogen (by pipeline and trucks) and ammonia (by pipeline, rail and ships); those pipelines are mostly industry-owned with a natural monopoly, prohibiting open access.

Chain sequence: Gas and LNG (transported) > H_2 (local) > NH_3 (local) > local feedstock applications. In this situation, the empirical criteria of each involved commodity is as follows:

Table 6: **Traditional value chain of ammonia production.**

	Criterion	Gas and LNG	H_2 pipelines	NH_3
A.	Transported across a wide geographical range	**++ (large pipelines, global LNG)**	- (limited regional pipelines)	+- (some global shipping)
B.	Pricing in its own right, not derived directly from another commodity	++	-- (dependent on natural gas)	-- (dependent on natural gas)
C.	Multitude of applications as a feedstock and energy carrier	**+ (mostly energy, some feedstock)**	- (mostly feedstock, diverse applications)	-- (only feedstock, a few main applications)
D.	Not hampered by natural monopolies or regulatory obstacles	**+ (open access infrastructure)**	-- (pipelines producer owned)	+- (shipping, terminals)

Source: authors.

Under traditional circumstances, natural gas is the predominant 'central' commodity. In this context, hydrogen and ammonia are not independently priced commodities. Despite this, ammonia does show more activity than hydrogen in some of the criteria. This stems from the observation that there has been regular activity for many years in shipping and trading of ammonia – not yet in hydrogen.

4.2.2 Commodities in three pathways for carbon neutral ammonia and hydrogen

In the instance of energy transition towards carbon neutrality, one would expect changes in the above situation. As the hydrogen and ammonia value chains decarbonize, the traditional dominance of natural gas prices will likely waver. The extent to which either hydrogen or ammonia become the more dominant will depend on the pathway towards carbon neutrality. There are at least three optional pathways:

I. Producing "green" hydrogen nationally, from renewable electricity and electrolysis, used as feedstock for producing ammonia and other chemicals, and as an energy carrier replacing gas.
II. Importing ammonia ("green" and blue") as direct feedstock, and as a source of hydrogen.
III. Importing ammonia with applications as in II.; and in addition, as a direct energy source.

At this point in time, it is not clear which pathway will prevail; a mixture is also possible or even likely. Initially, the main thinking was along pathway I, but this has evolved recently towards pathway II and lately also pathway III, accelerated by the energy crisis in the aftermath of the Ukraine war. The changes in commodity perspective for each of these pathways is analysed below.

I. Producing "green" hydrogen locally, from renewable electricity and electrolysis

This pathway was most discussed until a few years ago. In this pathway, renewable electricity is sourced to produce hydrogen. Hydrogen is used both for its original role as feedstock and as a new energy carrier to replace natural gas. Due to this broader role for hydrogen, a common infrastructure (new pipelines and storage, or repurposed natural gas infrastructure) is expanded and geared towards its transport. In this pathway, the role of ammonia remains unchanged.

Pathway I. Chain sequence: Renewable electricity (regional) > H_2 (transported regional) > NH_3 (local) > local feedstock applications:

Table 7: **Value chain of ammonia production under Pathway I.**

	Criterion	Renewable Electricity	H_2 pipelines	NH_3 local and shipped
A.	Transported across a wide geographical range	+/- (European electricity grid)	**+/- (European pipelines)**	+ (global shipping)
B.	Pricing in its own right, not derived directly from another commodity	+ (price widely varying in time and geographical)	**+- (derived from regional renewable electricity)**	- (dependent on hydrogen)
C.	Multitude of applications as a feedstock and energy carrier	+	**+ (energy and feedstock, diverse applications)**	-- (feedstock, a few main applications)
D.	Not hampered by natural monopolies or regulatory obstacles	+ (open access electricity grid)	**+ (pipelines are open access)**	+ (shipping, terminals)

Source: authors.

In this pathway, the central commodity role of natural gas is largely replaced by hydrogen. However, there is a key difference in the pricing dynamic. In the natural gas-dominant context, hydrogen had the same price everywhere, as it was produced from natural gas with limited price differences across the world, owing to the global LNG trade. There was, in other words, a shipped liquid global equalizer: LNG.

In the new situation, with hydrogen produced from renewable electricity, electricity prices will differ across the globe. Thus, the pricing of hydrogen will be diverse and geographically spread. This opens opportunities for ammonia, as a globally shipped liquid commodity, to provide price arbitrage across the globe between the different regional hydrogen markets. In other words: there will be a new shipped liquid global equalizer: Ammonia. The advent of such a dynamic would suggest that pathway II is the more likely scenario.

II. Importing ammonia (green and blue) as direct feedstock and as a source of hydrogen

In this pathway, both hydrogen and ammonia are not (only) produced from local renewable electricity, but (mainly) imported from locations with more favourable conditions for renewable electricity generation. This hydrogen is then converted into ammonia for transportation. Making this conversion in the exporting country removes the need for ammonia production in the importing country. There, the original sequence is reversed: instead of converting part of the hydrogen into ammonia, the imported ammonia is partly reconverted into hydrogen and partly used as feedstock.

Pathway II. Chain sequence: Renewable electricity (global) > NH_3 (transported) > NH_3 use and re-conversion into H_2 (regional) > energy applications

Table 8: **Value chain of ammonia production under Pathway II.**

	Criterion	Renewable Electricity/H_2	NH_3 shipped globally	H_2 regional
A.	Transported across a wide geographical range	+/- (Regional electricity grids)	**+ (Global shipping)**	**+/- (European pipelines)**
B.	Pricing in its own right, not derived directly from another commodity	+ (price widely varying in time and geographical)	**+ (diverse electricity prices, global arbitrage)**	**- partly derived from global ammonia market**
C.	Multitude of applications as a feedstock and energy carrier	+	**+ (feedstocks and conversion into hydrogen)**	**+/- (mostly energy, some feedstock)**
D.	Not hampered by natural monopolies or regulatory obstacles	+ (open access electricity grids)	**+ (shipping, terminals)**	**+ (pipelines are open access)**

Source: authors.

In this pathway, ammonia can become a more central commodity. Ammonia, as the most easily shipped commodity, provides price arbitrage across the globe between the different regional hydrogen markets, much like the function of LNG today as an arbitrage commodity between the diverse regional gas markets across the globe. Under these circumstances, liquid ammonia would become a key global commodity, with hydrogen price spreads split in different price regions across the world. Nevertheless, hydrogen maintains its prime importance as a valuable and versatile *energy* commodity in this scenario, assuming that ammonia itself has limited energy applications. In this pathway, ammonia is converted into hydrogen upon import. Hydrogen in turn drives other prices, in particular the local electricity market in the import countries.

IV. Importing ammonia with applications as in II and, in addition, as a direct energy source
In this pathway, ammonia is the global commodity as in pathway II. In addition, ammonia forms part of regional energy markets and is treated as an energy commodity. This could be the case, for instance, in industrial settings and large-scale applications like power plants or in the long-distance maritime shipping sector as a marine bunker fuel.

Pathway III. Chain sequence: Renewable electricity (global) > NH_3 (transported) > NH_3 use as feedstock and energy source, and re-conversion into H_2 (retail)

Table 9: **Value chain of ammonia production under Pathway III.**

	Criterion	Renewable Electricity/H_2	NH_3 shipped globally	H_2 regional
A.	Transported across a wide geographical range	+/- (Regional electricity grids)	**+ (Global shipping)**	+/- (European pipelines)
B.	Pricing in its own right, not derived directly from another commodity	+ (price widely varying in time and geographical)	**+ (diverse electricity prices, global arbitrage)**	- partly derived from global ammonia market
C.	Multitude of applications as a feedstock and energy carrier	+	**++ (feedstocks, some energy application, conversion into hydrogen)**	+/- (mostly energy, some feedstock)
D.	Not hampered by natural monopolies or regulatory obstacles	+ (open access electricity grids)	**+ (shipping, terminals, pipelines)**	+ (pipelines are open access)

Source: authors.

This pathway assumes that ammonia becomes a more central commodity both for global shipping and wholesale energy. As such, ammonia may become an important price driver for the energy market in the import countries. This is also caused by ammonia taking a more central place in energy storage.

4.2.3 The storage roles of hydrogen and ammonia to provide balancing

Next to transportation, storage may become an important function of ammonia. It is generally assumed that hydrogen is easily storable, but this may turn out to be too optimistic. Hydrogen storage in tanks is expensive and limited in size. Underground storage of hydrogen in old gas fields seems attractive from both a cost and volume perspective, but this still faces several technical and conceptual difficulties which need to be overcome.

In the short term, the main, proven option for hydrogen storage is in underground salt caverns. The Netherlands, Germany, and the UK can make such salt caverns, in contrast to many other European countries. Still, this salt cavern storage is limited in size. The main Dutch storage site, Hystock in Zuidwending, will have the capacity of four caverns of 6 kt each – 24 kt in total. This is considered by many in the market as rather limited compared to the size of the hydrogen market in 2030, estimated to reach the size of around 700-1000 Kt/year.[159] The salt cavern storages would cover a few weeks of non-production ("Dunkelflaute") of green hydrogen from offshore wind.[160]

For this reason, parties are considering other dispatchable storage and back-up options. Ammonia import terminals are an option, both providing storage of ammonia and a cracking

159 Nationaal Waterstof Programma, *Routekaart Waterstof 2022,* 2022.

160 Presentation of HyXchange initiative, 2022.

facility to convert this ammonia into hydrogen. Such a cracking facility can be operated in a flexible manner to satisfy the needs of hydrogen balancing for individual market parties and/or the hydrogen grid.[161] HyXchange, the project for establishing an exchange for the free trade of hydrogen, has incorporated this in *its Hydrogen spot market simulation* project.[162] This ongoing project aims to find out more about the market dynamics of the hydrogen market. It considers several options including ammonia storage and cracking to stabilize the balancing of the hydrogen grid. In the preliminary presentations to market participants, this turned out to be an important feature.[163] Further simulations will be carried out to find out more.

4.2.4 Conclusions about the roles of hydrogen and ammonia

From the analysis above, it shows that the hydrogen and ammonia will both be important commodities in the future, potentially replacing the role of natural gas and LNG.

If these pathways are realized, hydrogen will take over the role of natural gas and, correspondingly, ammonia will take over the role of LNG. The balance of importance between those two commodities will depend on the precise pathway taken. These pathways show that, at the very least, ammonia could be an important global commodity providing arbitrage between (as well as balancing to) the regional hydrogen markets. At minimum, ammonia may develop into a facilitating commodity for the hydrogen economy.

161 Bert den Ouden, *The Hydrogen Market Boosted by Ammonia: Feed, Standards & Balancing,* 2022b.

162 Bert den Ouden, *Hydrogen Spotmarket Simulation,* 2022c.

163 Bert den Ouden, *H2 Spotmarket Simulation Results 2026m* 2022a.

5 Conclusion

This report set out to understand the potential of ammonia as a globally traded commodity and the role Rotterdam can play as a pricing point for it. For the former, the report conceptualised a three-phase commodification framework, to illustrate phases of market sophistication, and the tipping points that enable the development of the market. For the latter, the report explored what predisposes Rotterdam to be a hub, and thus a pricing centre.

The global ammonia market is at an inflection point – demand for the commodity may triple by 2050. This growth will most likely occur from the use of ammonia as a hydrogen carrier and its direct use as a bunker fuel to decarbonise the shipping industry. This potential, although still uncertain with respect to size and geography, is increasingly stimulated by government policies, particularly those aimed at introducing hydrogen into the energy mix, especially in the EU, the US and Japan. However, for ammonia to service this demand, the market for the commodity will need to become more sophisticated.

According to the commodification framework, the ammonia market is currently in phase one – an untransparent market comprised largely of long-term contracts between producers and consumers. However, the growth and (geographic and sectoral) diversification of demand may tip the market into phase two, where the market is dominated by spot market trading, which balances supply and demand, and sets the benchmark for long-term contracts. Phase three, where the market establishes financial derivates, would be the final phase.

The extent to, and pace at which the transition to phase two occurs depends in part on the role ammonia will play vis-à-vis hydrogen. It can 1) reinforce local hydrogen production as a price equalizer, 2) serve as a direct feedstock for hydrogen, or 3) become a direct energy source alongside hydrogen. In this context, the report maintains that Rotterdam's advantageous location and experience with related (liquid) products enables it to become a pricing centre for the trading of ammonia.

6 Appendix 1: Existing and planned facilities for renewable ammonia

Overview of existing and planned facilities and technology providers for renewable ammonia production (existing capacity of 0.02 Mt/yr; planned capacity of 15 Mt/yr (2030) and 71 Mt/yr (total).[164]

Location	Company	Start-up year	Capacity (kt/yr)	Electrolysis technology	Electricity source	Source
Commercial plants						
Cusco, Peru	Enaex	1965	10	Alkaline	Hydro	(Brown, 2020d)
Taranaki, New Zealand	Ballance Agri-Nutrients, Hiringa Energy (revamp)	2021	5	-	Wind	(Ayvalı, Tsang and Van Vrijalden-hoven, 2021; Brown, 2020e)
Puertollano, Spain	Fertiberia, Iberdrola (revamp)	2021 2025	6.1 57	-	Solar, battery	(Brown, 2020f; Fertiberia and Iberdrola, 2020)
Duqm, Oman	ACME, Tatweer	2021 TBD	TBD (pilot) 770	-	Solar	(Zawya, 2021)
Port Lincoln, Australia	H2U, Mitsubishi, Government of South Africa, ThyssenKrupp	2022 Unknown	40 705 – 1 410	Alkaline	Wind, solar	(Brown, 2018d; Pendlebury, Meares and Tyrrell, 2021)
Porsgrunn, Norway	Yara (revamp)	2022 2025-2026	5 500	Alkaline	Hydro	(Brown, 2019c; Tullo, 2020)
Western Jutland, Denmark	Skovgaard Invest, Vestas, Haldor Topsøe	2022	5	-	Onshore wind, solar	(Ravn, 2020)
Ogata Village, Japan	Tsubame BHB	2022	TBD	-	Wind, solar	(Atchison, 2021a)
Rabat, Morocco	Fusion Fuel	2026	183	PEM	Wind, solar	(Fusion Fuel, 2021)
Pilbara, Australia	Yara (revamp and new)	2023 2026 2028 2030	< 8 48-160 480 800	Alkaline or PEM	Onshore wind, solar	(ENGIE and Yara, 2020) Feasibility study
Louisiana, US	CF Industries, ThyssenKrupp (revamp)	2023	20	-	Grid electricity	(Brown, 2020b)
Palos de la Frontera, Spain	Fertibaria, Iberdola (revamp)	2023 2027	62 100	-	Solar	(Ludecke, 2021)
Northern Germany	Haldor Topsøe, Aquamarine	2024	105	Solid oxide	Offshore wind	(Frøhlke, 2021a)
Sluiskil, Netherlands	Yara, Ørsted (revamp)	2024-2025	75	Alkaline	Offshore wind	(Brown, 2020c)

164 IRENA and AEA, *Innovation Outlook: Renewable Ammonia.*

Location	Company	Start-up year	Capacity (kt/yr)	Electrolysis technology	Electricity source	Source
Commercial plants						
Antofagasta, Chile	Enaex, ENGIE	2024 2030	18 700	-	Solar	(Power Engineering International, 2020) Feasibility study
Abu Dhabi, UAE	KIZAD, Helios Industry	2024 2026	40 200	Alkaline	Solar	(KIZAD, 2021)
NEOM, Saudi Arabia	NEOM, Air Products, ACWA Power	2025	1 200	Alkaline	Onshore wind, solar	(Brown, 2020g)
Berlevåg, Norway	Varanger Kraft	2025	90	-	Wind	(Hydrogen.no, 2020)
Bell Bay, Australia	Origin	2025	420	-	-	(Origin, 2020)
Gladstone, Australia	H2U	2025	1 750	-	-	(Brown, 2020h)
Tasmania, Australia	Fortescue	2025	250	-	-	(Crolius, 2020a)
Lake Naivasha, Kenya	Maire Tecnimont	2025	45	-	Solar, geothermal	(Stamicarbon, 2021a)
Norway	Grieg Edge, Arendals Fossekompani	2025	TBD	-	Wind	(Atchison, 2021b)
Quebec, Canada	Hy2Gen	2025	183	Alkaline or PEM	Hydro	(Hy2Gen AG, 2021)
Chile	AustriaEnergy, Ökowind	2026 or before TBD	TBD 850 – 1 000	-	Onshore wind	(Atchison, 2021c; Trammo, 2021)
Esbjerg, Denmark	Copenhagen Infrastructure Partners, Maersk, DFDS	2026	650	-	Offshore wind	(Barsoe, 2021)
Duqm, Oman	DEME Concessions, OQ	2026 TBD	150 520	-	Solar, wind	(DEME, 2021)
Pilbara, Australia	InterContinental Energy	2030 2035	3 000 9 900	Alkaline, and/or PEM & solid oxide	Onshore wind, solar	(Brown, 2020b; Tancock, 2020)
Murchison, Australia	MRHP, Copenhagen Infrastructure Partners	2028	1 900	PEM	Onshore wind, solar	(Matich, 2020) Final decision for ammonia not made, can also be liquid hydrogen
Al Wusta, Oman	OQ, InterContinental Energy, EnerTech	2028 2038	TBD 9 500 – 11 400	-	Onshore wind, solar	(OQ, InterContinental Energy and EnerTech, 2021)
Canarvon, Australia	Province Resources, Total-Eren	2030 or before	2 400	-	Onshore wind, solar	(Province Resources Limited, 2021)
Gladstone, Australia	Austrom Hydrogen	TBD	1 125	-	Solar	(Brown, 2020i)
Western Australia	InterContinental Energy	TBD	20 000	-		(Burgess and Washington, 2021)
Moranbah, Australia	Dyno Nobel, Incitec Pivot	TBD	60	-	Solar	(Brown, 2019d, 2020d) Feasibility study

Location	Company	Start-up year	Capacity (kt/yr)	Electrolysis technology	Electricity source	Source
Commercial plants						
Skive, Denmark	Siemens Gamesa, Energifonden Skive	TBD	TBD	-	Wind	(Brown, 2018e)
Moura, Australia	Queensland Nitrates, Incitec Pivot, Wesfarmers JV, Neoen, Worley	TBD	20	-	Onshore wind, solar	(ARENA, 2019; Brown, 2020d; Crolius, 2020b) Feasibility study
Port Adelaide, Australia	TBD	TBD	170-450	-		(Pendlebury, Meares and Tyrrell, 2021)
Geraldton, Australia	BP, GHD, ARENA	TBD TBD	20 1 000	-	Wind, solar	(Brown, 2020j)
Canarvon, Australia	HyEnergy	TBD	300	-	Onshore wind, solar	(Peacock, 2021)
Portland, Australia	Countrywide Energy, Glenelg Shire Council, Port of Portland	TBD	56	-	-	(Pendlebury, Meares and Tyrrell, 2021)
Orkney, Scotland	Eneus Energy	TBD	7	-	Wind	(Brown, 2020k; reNEWS.BIZ, 2021a)
Laos	Tsubame BHB	TBD	TBD	-	Hydro	(Tsubame BHB, 2020)
Abu Dhabi, UAE	TAQA Group, Abu Dhabi Ports	TBD	1 200	-	Solar	(TAQA Group, 2021)
Finnmark, Norway	St1 Nordic Oy, Horisont Energi	TBD	TBD	-	Wind	(Atchison, 2021b)
Mauritania	CWP	TBD	11 425	-	Wind, solar	(CWP, 2021)
Egypt	ThyssenKrupp	TBD	TBD	-	-	(Egypt Today Staff, 2021)
Espírito Santo, Brazil	AmmPower	TBD	TBD	-	-	(AmmPower, 2021)
Iowa, US	Maire Tecnimont	TBD	84	-	Onshore wind, solar	(Stamicarbon, 2021b)
Technology demonstration plants (past and current)						
Morris, US	University of Minnesota	2014 TBD	0.025-0.035 0.35	Alkaline	Onshore wind	(Brown, 2020d; RTI International, 2021)
Koriyama, Japan	FREA, JGC Corporation	2018	0.007	-	Onshore wind, solar	(Brown, 2020d)
Harwell, UK	Siemens, Cardiff University, University of Oxford	2018	0.010	-	Onshore wind	(Brown, 2020d)
Kawasaki, Japan	Tsubame BHB	2019	0.020	-	-	(Crolius, 2021)
Foulum, Denmark	Haldor Topsøe	2025	0.3	Solid oxide	Onshore wind	(Brown, 2020d)
Ben Guerir, Morocco	OCP, Fraunhofer IMWS	TBD	0.7	-	Solar	(Ayvalı, Tsang and Van Vrijaldenhoven, 2021; Brown, 2018c)

Location	Company	Start-up year	Capacity (kt/yr)	Electrolysis technology	Electricity source	Source
Selected technology providers						
Germany	ThyssenKrupp	Technology provider	2 – 1 750	Alkaline	N/A	(Will and Lüke, 2018)
Denmark	Haldor Topsøe	Technology provider	-	Solid oxide	N/A	(Hansen and Han, 2018)
Switzerland	Casale	Technology provider	-	-	N/A	(Casale, 2021)
US	KBR, Cummins	Technology provider	-	PEM	N/A	(KBR, 2021)
Netherlands	Stamicarbon	Technology provider		-	N/A	(Stamicarbon, 2021c)
Netherlands	Proton Ventures	Technology provider	1-20	-	N/A	(Proton Ventures B.V., 2019)
Japan	Tsubame BHB	Technology provider	1-100	-	N/A	(Crolius, 2021)
US	Starfire Energy	Technology provider	17.5	-	N/A	(Starfire Energy, n.d.)

7 Appendix 2: Existing and planned facilities for lower-carbon ammonia

Overview of existing and planned facilities for fossil-based ammonia with a lower carbon footprint (existing capacity of 2.6 Mt/yr; planned capacity of 17.4 Mt/yr).[165]

Location	Company	Start-up year	Capacity (kt/yr)	Carbon footprint reduction relative to SMR (%)	Hydrogen source	Source
Enid, US	Koch Nitrogen Company, Chaparral Energy	1982	285	62.5%	CO_2 is used for enhanced oil recovery.	(MIT, 2016)
Joffre, Canada	Nutrien	1987	490	25%	By-product hydrogen from ethane cracker.	(Adair, 2020)
Beulah, US	Dakota Gasification Company	1991	355	62.5%	CO_2 is used for enhanced oil recovery.	(Brown, 2016)
Kawasaki, Japan	Showa Denko	2003	60	35%	65% of hydrogen is from recycled plastic.	(Showa Denko K.K., n.d.)
Coffeyville, US	CVR Energy, Chaparral Energy, Blue Source	2013	375	62.5%	CO_2 is used for enhanced oil recovery.	(MIT, 2016)
Geismar, US	Nutrien	2013	200	62.5%	CO_2 is used for enhanced oil recovery.	(Adair, 2020)
Freeport, US	Yara, BASF	2018	750	25%	By-product hydrogen from ethane cracker.	(Brown, 2018b)
Sluiskil, Netherlands	Yara, Dow	2019	22 (only part of existing facility)	25%	By-product hydrogen from ethane cracker.	(Brown, 2019b)
Redwater, Canada	Nutrien	2020	245	62.5%	CO_2 is used for enhanced oil recovery.	(Adair, 2020)
Jubail, Saudi Arabia	SAFCO	2021	1 160	62.5%	CO_2 is used for methanol synthesis and enhanced oil recovery.	(Herh, 2020)
Beaumont, US	OCI Nitrogen	2021	365	≥ 70%	Hydrogen is produced from natural gas with CCS.	(Ewing, 2021)
Nebraska, US	Monolith Materials	2024	275	≥ 70%*	Hydrogen is produced by methane pyrolysis.	(Brown, 2020c)

165 IRENA and AEA, *Innovation Outlook: Renewable Ammonia.*

Location	Company	Start-up year	Capacity (kt/yr)	Carbon footprint reduction relative to SMR (%)	Hydrogen source	Source
Pilbara, Australia	Yara (revamp)	2024-2025 or earlier	≤ 800	≥ 70%	Hydrogen is produced from natural gas with CCS, to be used by JERA (Hasegawa, 2021).	(Hasegawa, 2021)
Finnmark, Norway	Horisont Energy, Haldor Topsøe	2025	1 000 - 1 400	≥ 70%	Hydrogen is produced with ATR with CCS.	(Horisont Energi, 2021a)
Ruwais, UAE	ADNOC	2025	1 000	≥ 70%	Hydrogen is produced from natural gas with CCUS.	(ADNOC, 2021)
Central Sulawesi, Indonesia	PAU, Mitsubishi, Jogmec, Bandong IoT	2026 or before	≤ 660	≥ 70%	Hydrogen is produced from natural gas with CCS.	(Argus Media, 2021b)
Western Australia	Hazer Group	TBD	TBD	≥ 70%*	Hydrogen is produced by methane pyrolysis.	(Hazer Group Ltd., 2021)
Billingham, UK	CF Industries (revamp)	TBD	595	≥ 70%	Hydrogen is produced from natural gas with CCS; 700 000 tonnes of CO_2 sequestered annually.	(Reed, 2021)
Ince, UK	CF Industries (revamp)	TBD	280	≥ 70%	Hydrogen is produced from natural gas with CCS; 330 000 tonnes of CO_2 sequestered annually.	(CF Fertilisers, 2021)
Port Bonython, Australia	TBD	TBD	16 – 1 235	≥ 70%	Hydrogen is produced by CCS.	(Pendlebury, Meares and Tyrrell, 2021)

Note: SMR = steam methane reforming; ATR = autothermal reforming; CCS = carbon capture and storage; CCUS = carbon capture, utilisation and storage; TBD = to be determined; US = United States; UAE = United Arab Emirates; UK = United Kingdom.

* This concerns the CO_2 emissions from the methane feedstock. The carbon intensity also depends on the electricity source (Bicer et al., 2016); see also section 3.2.

8 Appendix 3: Planned facilities for large-scale ammonia decomposition

Overview of planned facilities for large-scale ammonia decomposition.[166]

Location	Company	Start-up year	Ammonia feed (Mt/yr)	Hydrogen output (kt/yr)	Hydrogen application	Sourcew
Commercial plants						
Rotterdam, Netherlands	Transhydrogen Alliance	2024 long-term	- 3.7	- 500	One-third of current Dutch hydrogen demand	(Proton Ventures B.V., 2021)
Wilhelmshaven, Germany	Uniper	2030	2.2	295	10% of German hydrogen demand by 2030	(Uniper, 2021)

166 IRENA and AEA, *Innovation Outlook: Renewable Ammonia.*

9 Appendix 4: List of Interviews

In support of the research, this study drew invaluable insights from interviews with senior industry experts.

#	Title of interviewee
i)	Business development director at a technology company specializing in ammonia related technologies and products
ii)	Executive director at an engineering company specializing in the design and construction of industrial plants
iii)	Global director of alternative energy at a tank storage company
iv)	Senior vice president of product management at a chemical company specializing in production and distribution of fertilizers
v)	Vice president of hydrogen at an integrated energy company
vi)	Head of decarbonisation at a major trading and transportation company
vii)	Head of business development at a major fertilizer production and distribution company
viii)	Former CEO of a major trading company

10 Bibliography

"Alternative Fuels Insights." Available from https://afi.dnv.com/Map.

American Bureau of Shipping, CE Delft, and Arcsilea. *Potential of Ammonia as Fuel in Shipping*. 2022.

"Ammonia, Anhydrous - Substance Information - ECHA." [cited 2023]. Available from https://echa.europa.eu/substance-information/-/substanceinfo/100.028.760.

"Ammonia as a Shipping Fuel." [cited 2022]. Available from https://www.globalmaritimeforum.org/news/ammonia-as-a-shipping-fuel.

"Ammonia Market Outlook, 2021-2031." [cited 2022]. Available from https://www.transparencymarketresearch.com/ammonia-market.html.

"Ammonia most Exposed Fertilizer to Ukraine Conflict | Argus Media." [cited 2022]. Available from https://www.argusmedia.com/en/news/2307380-ammonia-most-exposed-fertilizer-to-ukraine-conflict.

"Ammonia Price Trend and Forecast." Available from https://www.chemanalyst.com/Pricing-data/ammonia-37.

"Ammonia Technology Roadmap." Available from https://www.iea.org/reports/ammonia-technology-roadmap/executive-summary.

Ammonia Technology Roadmap: Towards More Sustainable Nitrogen Fertiliser Production. 2021b.

Andrén-Sandberg, Fredrik. *Commodities Pricing and the Bulk Trap: Learnings from Industries at the Forefront*. Sweden: Springer, 2018.

Ann Berg, Diego Valiente, and Christian Egenhofer. *Price Formation in Commodities Markets: Financialization and Beyond.* Brussels: CEPS, 2013.

"Antwoord Op Vragen Van De Leden Erkens En Klink Over Het Bericht Dat De Europese Unie Voornemens is Een Waterstofbank in Het Leven Te Roepen.". Available from https://www.rijksoverheid.nl/documenten/kamerstukken/2022/10/24/beantwoording-kamervragen-over-het-bericht-dat-de-europese-unie-voornemens-is-een-waterstofbank-in-het-leven-te-roepen.

"A.P. Moller - Maersk Continues Green Transformation with Six Additional Large Container Vessels." Available from https://www.maersk.com/news/articles/2022/10/05/maersk-continues-green-transformation.

"Argus Ammonia - NEW: Daily Price Assessments." Available from https://www.argusmedia.com/en/fertilizer/argus-ammonia.

Argus Media. *Argus Ammonia Methodology and Specifications Guide.* 2022a.

Argus Media. *Argus White Paper: Ammonia Market Volatility.* 2022b.

"Benchmark (Price)." [cited 2022]. Available from http://www.mckinseyenergyinsights.com/resources/refinery-reference-desk/benchmark-price/.

Bert den Ouden. *H2 Spotmarket Simulation Results 2026.* 2022a.

Bert den Ouden. *The Hydrogen Market Boosted by Ammonia: Feed, Standards & Balancing.* 2022b.

Bert den Ouden. *Hydrogen Spotmarket Simulation.* 2022c.

"$7 Billion in Funding, New Roadmap for the US Hydrogen Industry – Ammonia Energy Association." [cited 2022]. Available from https://www.ammoniaenergy.org/articles/7-billion-in-funding-new-roadmap-for-the-us-hydrogen-industry/.

"Bp Reveals Plans to Evaluate Expansion of Germany's Green Energy Port with a New Hydrogen Hub." Available from https://www.bp.com/en/global/corporate/news-and-insights/press-releases/bp-reveals-plans-to-evaluate-expansion-of-germany-green-energy-port-with-new-hydrogen-hub.html.

"Carbon Border Adjustment Mechanism." [cited 2022]. Available from https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_3661.

"Carbon Capture, Utilisation and Storage - Fuels & Technologies." [cited 2022]. Available from https://www.iea.org/fuels-and-technologies/carbon-capture-utilisation-and-storage.

"Cargill Orders Methanol-Powered Kamsarmax Pair." [cited 2023]. Available from https://www.offshore-energy.biz/cargill-orders-methanol-powered-kamsarmax-pair/.

Cheng, Ing-Haw, and Wei Xiong. "Financialization of Commodity Markets." *Annual Review of Financial Economics* 6, no. 1 (Dec 1, 2014): 419-441. CrossRef, .

"Clarksons: There are 130 Ammonia-Ready and 6 Hydrogen-Ready Vessels on Order." [cited 2023]. Available from https://www.offshore-energy.biz/clarksons-there-are-130-ammonia-ready-and-6-hydrogen-ready-vessels-on-order/.

"Classification Societies." [cited 2023]. Available from https://www.emsa.europa.eu/inspections/90-classification-societies.html.

ClassNK. *Part C "Guidelines for the Safety of Ships using Ammonia as Fuel"*. 2022.

Choi, Thomas Y., Kevin J. Dooley, and Manus Rungtusanatham. "Supply Networks and Complex Adaptive Systems: Control Versus Emergence." *Journal of Operations Management* 19, no. 3 (2001): 351.

"Commission Launches Consultations on the Regulatory Framework for Renewable Hydrogen." Available from https://ec.europa.eu/info/news/commission-launches-consultation-regulatory-framework-renewable-hydrogen-2022-may-20_en.

"Commodities Exchange." [cited 2022]. Available from https://www.investopedia.com/terms/c/commoditiesexchange.asp.

"Contango and Backwardation." Available from https://en.wikipedia.org/wiki/Normal_backwardation#/media/File:Contangobackwardation.png.

Craig Pirrong. *The Economics of Commodity Trading Firms.* Houston: Trafigura, 2014.

"Deal Reached on New Carbon Leakage Instrument to Raise Global Climate Ambition." 13-12-Available from https://www.europarl.europa.eu/news/en/press-room/20221212IPR64509/deal-reached-on-new-carbon-leakage-instrument-to-raise-global-climate-ambition.

"Development of Import Terminal for Hydrogen Carrier in Port of Rotterdam." Available from https://www.portofrotterdam.com/en/news-and-press-releases/development-of-import-terminal-for-hydrogen-carrier-in-port-of-rotterdam.

"Differential Price Behavior as a Subject for Commodity Price Analysis." *Econometrica* 3, no. 4 (Oct 01, 1935): 416-427.

DNV GL. *Energy Transition Outlook 2022*. DNV GL, 2022.

Energy Market Authority and Maritime and Port Authority of Singapore. *Expression of Interest to Develop an End-to-End Low Or Zero-Carbon Ammonia Power Generation and Bunkering solution in Singapore*. 2022.

"EU Green Hydrogen Plans in Stalemate as Nine Member States Lobby for Inclusion of 'Low-Carbon' H2: Report." [cited 2023]. Available from https://www.hydrogeninsight.com/policy/eu-green-hydrogen-plans-in-stalemate-as-nine-member-states-lobby-for-inclusion-of-low-carbon-h2-report/2-1-1396840.

Frances C. Moore, Katherine Lacasse, Katharine J. Mach, Yoon Ah Shin, Louis J. Gross, and Brian Beckage. "Determinants of Emissions Pathways in the Coupled Climate–social System." Nature, no. 603 (2022): 103-111.

Fredrik Andrén-Sandberg. *Commodities Pricing and the Bulk Trap.* Springer, 2018.

Geels, Frank W., and Johan Schot. "Typology of Sociotechnical Transition Pathways." *Research Policy* 36, no. 3 (2007): 399-417.

Geoffrey Poitras. "From Antwerp to Chicago: The History of Exchange Traded Derivative Security Contracts." *Editions Sciences Humaines* (2009): 11-50.

"Germany to Build First Green Ammonia Import Terminal." Available from https://www.gtai.de/en/meta/press/germany-to-build-first-green-ammonia-import-terminal-923268.

Green Hydrogen for Industry: A Guide to Policy Making. 2022b "Harnessing Ammonia as Ship Fuel - DNV." [cited 2022]. Available from https://www.dnv.com/expert-story/maritime-impact/Harnessing-ammonia-as-ship-fuel.html.

Hélyette Geman, and William O. Smith. "Theory of Storage, Inventory and Volatility in the LME Base Metals." *Resources Policy* (2012).

Hidalgo, C. A., B. Klinger, A. -L Barabási, and R. Hausmann. "Product Space Conditions the Development of Nations." *Science* 317, no. 5837 (2007): 482-487. PubMed.

Hidalgo, César A., Pierre-Alexandre Balland, Ron Boschma, Mercedes Delgado, Maryann Feldman, Koen Frenken, Edward Glaeser, Canfei He, Dieter F. Kogler, Andrea Morrison, Frank Neffke, David Rigby, Scott Stern, Siqi Zheng, and Shengjun Zhu. "The Principle of Relatedness." In *Unifying Themes in Complex Systems IX*. Edited by Anonymous Cham: Springer International Publishing, 2018a, 451-457.

Hidalgo, César A., Pierre-Alexandre Balland, Ron Boschma, Mercedes Delgado, Maryann Feldman, Koen Frenken, Edward Glaeser, Canfei He, Dieter F. Kogler, Andrea Morrison, Frank Neffke, David Rigby, Scott Stern, Siqi Zheng, and Shengjun Zhu. "The Principle of Relatedness." *Unifying Themes in Complex Systems IX* (2018b): 451.

"Higher Ammonia Prices Prompting European Restarts, but Shortages Remain: Traders." Available from https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/040122-higher-ammonia-prices-prompting-european-restarts-but-shortages-remain-traders.

Hydrogen Council, and McKinsey & Company. *Global Hydrogen Flows: Hydrogen Trade as a Key* Enabler for Efficient Decarbonization. 2022a.

Hydrogen Council and McKinsey & Company, Hydrogen Insights 2022. 2022b.

Hydrogen Europe. *Clean Hydrogen Monitor.* 2022.

"ICE Plans to Launch its First Ammonia Futures Contract." Available from https://www.ice.com/insights/ice-plans-to-launch-its-first-ammonia-futures-contract."Ice to Launch Ammonia Futures Contract." Available from https://www.argusmedia.com/en/news/2395229-ice-to-launch-ammonia-futures-contract.

"IFA '22: Global Ammonia Market Unsettled and Uncertain." [cited 2022]. Available from https://www.icis.com/explore/cn/resources/news/2022/05/31/10770070/ifa-22-global-ammonia-market-unsettled-and-uncertain.

IHS Markit. *The World's Top 40 Ammonia Buyers.* 2020.

IRENA. *Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part I – Trade Outlook for 2050 and Way Forward*. Abu Dhabi: 2022a.

IRENA, and AEA. *Innovation Outlook: Renewable Ammonia*. Abu Dhabi: 2022.

"JERA to Conduct International Competitive Bidding for the Procurement of Fuel Ammonia | Press Release." [cited 2023]. Available from https://www.jera.co.jp/english/information/20220218_853.

John H. Holland. *Hidden Order: How Adaptation Builds Complexity*. Reading, Mass: Addison-Wesley, 1995. NDL-OPAC.

"Kawasaki Receives an Order for an 86,700 M^3 LPG-Fueled LPG/ NH3 Carrier." Dec. 02, [cited 2023]. Available from https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20211202_9041

Laurence Walton. *Circular 22/183 Introduction of Additional Cleared ICE Futures Europe Contract - Argus Ammonia NWE CFR Future*. ICE, 2022.

Mark A. Ehlen, and Andrew J. Scholand. *An Agent Model of Agricultural Commodity Trade: Developing Financial Market Capability within the NISAC Agent-Based Laboratory for Economics (N-ABLE).* Department of Homeland Security, 2005.

"Mauritania, CWP Global Sign Deal for Green Hydrogen Project." [cited 2022]. Available from https://energycapitalpower.com/mauritanias-30gw-green-hydrogen-cwp-deal/.

Nationaal Waterstof Programma. *Routekaart Waterstof 2022*. 2022.

Nayak-Luke, R. M., C. Forbes, Z. Cesaro, R. Bañares-Alcántara, and K. H. R. Rouwenhorst. "Chapter 8 - Techno-Economic Aspects of Production, Storage and Distribution of Ammonia." *Techno-Economic Challenges of Green Ammonia as an Energy Vector* (2021): 191-207.

"New Ammonia Import & Export Terminals: The Greenpoint Valley Project, Netherlands." Available from https://www.ammoniaenergy.org/articles/new-ammonia-import-export-terminals/.

"NEWS - Vopak Prepares for Import of Green Ammonia in North Sea Port, the Netherlands." Available from https://www.vopak.com/newsroom/news/news-vopak-prepares-import-green-ammonia-north-sea-port-netherlands?language_content_entity=en.

"Nitrogen Fertilizer Prices Nosedive as Buyers Go Missing." Available from https://www.icis.com/explore/resources/news/2023/01/27/10848720/podcast-nitrogen-fertilizer-prices-nosedive-as-buyers-go-missing/.

"NYK to Build its Fourth LPG Dual-Fuel very Large LPG / NH3 Carrier." [cited 2023]. Available from https://www.nyk.com/english/news/2022/20220804_01.html.

OCI, and Hinicio. *White Paper: The Decarbonization Potential of Ammonia as Fuel for Co-Firing.* 2022.

"OCI Expands Import Terminal for (Green) Ammonia." Available from https://www.portofrotterdam.com/en/news-and-press-releases/oci-expands-import-terminal-for-green-ammonia.

"OCI to Expand Rotterdam Ammonia Terminal Capacity." Available from https://www.argusmedia.com/en/news/2341464-oci-to-expand-rotterdam-ammonia-terminal-capacity.

"Production, Consumption and Trade of Ammonia in Selected Countries and Regions, 2020 – Charts – Data & Statistics." [cited 2022]. Available from https://www.iea.org/data-and-statistics/charts/production-consumption-and-trade-of-ammonia-in-selected-countries-and-regions-2020.

"QAFCO Ammonia Storage Tanks." [cited 2022]. Available from https://www.mcdermott.com/What-We-Do/Project-Profiles/QAFCO-Ammonia-Storage-Tanks.

"Regional Clean Hydrogen Hubs Funding Opportunity Announcement." Available from https://oced-exchange.energy.gov/Default.aspx#FoaId4dbbd966-7524-4830-b883-450933661811.

"Revealed | how Biden's $3/kg Green Hydrogen Tax Credit could Break Open US Production | Recharge." [cited 2022]. Available from https://www.rechargenews.com/energy-transition/revealed-how-bidens-3-kg-green-hydrogen-tax-credit-could-break-open-us-production/2-1-1279955.

"Revision of the Renewable Energy Directive in "A European Green Deal." Available from https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/file-revision-of-the-renewable-energy-directive.

Salmon, Nicholas, and René Bañares-Alcántara. "Green Ammonia as a Spatial Energy Vector: A Review." *Sustainable Energy; Fuels* 5, no. 11 (Jun 01, 2021): 2814-2839.

"Saudi Arabia's $5bn Green Hydrogen-Based Ammonia Plant to Begin Production in 2025." [cited 2022]. Available from https://energy-utilities.com/saudi-arabia-s-5bn-green-hydrogenbased-ammonia-news111872.html.

Schofield, Neil C. *Commodity Derivatives: Markets and Applications*. John Wiley & Sons, Ltd, 2021.

"Singapore's MPA Partners on Ammonia-Fuelled Tankers | Argus Media." [cited 2023]. Available from https://www.argusmedia.com/en/news/2339087-singapores-mpa-partners-on-ammoniafuelled-tankers.

Stephen Craig Pirrong. "The Efficient Scope of Private Transactions-Cost-Reducing Institutions: The Successes and Failures of Commodity Exchanges." *Journal of Legal Studies* 24 (1995).

"S&P Global Commodity Insights Launches New Platts Renewable 'Green' Ammonia Prices." 1 December [cited 2023]. Available from https://finance.yahoo.com/news/p-global-commodity-insights-launches-080900447.html.

"S&P Global Platts Launches Ammonia Cargo Price Assessments | S&P Global Commodity Insights." [cited 2023]. Available from https://www.spglobal.com/commodityinsights/en/about-commodityinsights/media-center/press-releases/2021/101321-platts-launches-ammonia-cargo-price-assessments#.

Stapersma, Pier. *Market Coordination of Dynamic Energy Flows*, Clingendael International Energy Program. 2020. https://www.clingendaelenergy.com/inc/upload/files/CIEP%20Briefing%20Paper%202020-02%20WEB-2.pdf

The Royal Society. *Ammonia: Zero-Carbon Fertiliser, Fuel and Energy Store*. 2020.

"Unpacking Ammonia's Market Landscape and its Role in the Energy Transition." [cited 2022]. Available from https://www.spglobal.com/commodityinsights/en/market-insights/blogs/energy-transition/091622-ammonia-prices-supply-demand-hydrogen-power-bunker-fuel.

"Unpacking Ammonia's Market Landscape and its Role in the Energy Transition." [cited 2023]. Available from https://www.spglobal.com/commodityinsights/en/market-insights/blogs/energy-transition/091622-ammonia-prices-supply-demand-hydrogen-power-bunker-fuel.

"U.S. Ammonia Prices Rise in Response to Higher International Natural Gas Prices." Available from https://www.eia.gov/todayinenergy/detail.php?id=52358.

US Department of Energy. *DOE National Clean Hydrogen Strategy and Roadmap*. 2022.

Van den Berghe, Karel, Antoine Peris, Evert Meijers, and Wouter Jacobs. "Friends with Benefits: The Emergence of the Amsterdam-Rotterdam-Antwerp (ARA) Polycentric Port Region." *Territory, Politics, Governance* 11, no. 2 (Feb 17, 2023): 301-320.

White Paper: Ammonia as a Marine Fuel. DNV GL, 2020.

"Why Green Ammonia Will be the Workhorse of EU's Future Hydrogen Economy." [cited 2022]. Available from https://www.euractiv.com/section/energy/opinion/why-green-ammonia-will-be-the-workhorse-of-eus-future-hydrogen-economy/.

"Worldwide Gas Ship Shortage Leads to Vessel Rates Surging at Record Levels." October. Available from https://www.marineinsight.com/shipping-news/worldwide-gas-ship-shortage-leads-to-vessel-rates-surging-at-record-levels/.

Working, Holbrook. "The Theory of Price of Storage." *American Economic Review* 39, no. 6 (1949): 1254-1262.

Wouter Jacobs, and Robert Horster. "Commodity Supply Networks as Complex Adaptive Systems: How Commodity and Freight Markets Respond to a Supply Shock." In *Geographies of Maritime Transport*. Edited by Anonymous Edward Elgar Publishing, 2020, 87-99.

Yoshizaki, Tsukasa, and Hideaki Kobayashi ed., *CO_2 Free Ammonia as an Energy Carrier*. 1st ed. ed.2023.

Erasmus University Rotterdam (EUR)
Erasmus Commodity & Trade Centre
Burgemeester Oudlaan 50
3062 PA Rotterdam, The Netherlands
www.eur.nl/erasmusctc