ERASMUS UNIVERSITY ROTTERDAM
ERASMUS SCHOOL OF ECONOMICS

MASTER THESIS
ECONOMICS AND BUSINESS
MASTER IN PORT, URBAN AND TRANSPORT ECONOMICS

# What are the critical success factors for commodifying hydrogen and launching a hydrogen and ammonia market.

DATE: 08/12/2022

**Author:**
Antonios Kyrtzalis

**Student Number:**
617933

**Supervisor:**
Wouter Jacobs

**Second Assessor:**
Liam van Son

# ABSTRACT

In a world dominated by fossil fuels for transportation, heating, and industrial usage, governments and private companies are looking for renewable energy sources aiming to decarbonize the world. Hydrogen appears to be one of the best candidates to replace fossil fuels in every sector. However, it is not yet considered a commodity which makes the energy transition even more challenging. This thesis analyzes the most critical factors for commodifying hydrogen and making it a tradable commodity. Furthermore, the role of ammonia is examined in more depth for hydrogen commodification as one of the best hydrogen carriers for transportation and storage and as an already established and mature market. Oil and natural gas as commodities are taken as examples in order to draw lessons about how they evolved over the years and became tradable commodities. After conducting semi-structured interviews with experts from the ammonia and hydrogen sector, results show that hydrogen is expected to grow even faster than expected in the next few years. Certification systems and cooperation between private and public sectors are undoubtedly crucial for launching a hydrogen market. Finally, ammonia will play a vital role in the short term in transporting hydrogen overseas.

# Table of Contents


**1. INTRODUCTION....4**

1.1. CONTEXTUAL BACKGROUND....4
1.2. RESEARCH AIM AND QUESTIONS....7

**2. LITERATURE REVIEW....8**

2.1 . COMMODITY MARKET FUNCTION....8
2.2. DERIVATIVE CONTRACTS....10
*2.2.1. Forwards and Futures....10*
*2.2.2. Options contracts....12*
*2.2.3. Freight contracts....12*
2.3. STAKEHOLDERS....12
2.4. PRICE DISCOVERY....15

**3. METHODOLOGY....18**

3.1. EXPLORATORY RESEARCH AND DEDUCTIVE ANALYSIS....18
3.2. EX-ANTE EVALUATION....19
3.3. INTERVIEWS....20

**4. CRUDE OIL AND LNG MARKET EVOLUTION....20**

4.1. CRUDE OIL....20
*4.1.1. Contracts....22*
*4.1.2. Price discovery....23*
*4.1.3. Price drivers....25*
4.2. LNG....25
*4.2.1. Contracts....27*
*4.2.2. Price discovery....29*
*4.2.3. Price drivers....30*

**5. HYDROGEN....31**

5.1. PRODUCTION....32
5.2. TRANSPORTATION....33
5.3. AMMONIA AS A HYDROGEN CARRIER....34
*5.3.1. Ammonia prices and volumes....35*
*5.3.2. Ammonia Production, Transportation and Storage....36*
*5.3.3. Current projects....38*
5.4. CHALLENGES AND SOLUTIONS FOR HYDROGEN COMMODIFICATION AND TRADE....38

**6. RESULTS....41**

6.1. AMMONIA ROLE....41
6.2. HYDROGEN COMMODIFICATION AND TRADE....43
*6.2.1. Certification schemes....43*
*6.2.2. Market liquidity....43*
6.3. BLUE HYDROGEN AND AMMONIA IMPORTANCE....44
6.4. HYDROGEN AND AMMONIA PRICE BENCHMARK....44
6.5. NETHERLANDS AS THE MAIN HYDROGEN HUB....45

**7. CONCLUSION....46**

**8. REFERENCES....49**

# 1. Introduction

## 1.1. Contextual background

In the last few years, climate change has made governments, companies, policymakers, and regulators search for alternative fuels to reduce emissions and prevent the sustainability of the planet. Consequently, the energy transition from harmful fuels to more sustainable ones has become necessary.

More and more governments have recently started implementing regulations and strategies to reduce greenhouse gas emissions (Nousan et al., 2020). In Europe, great examples are the European Green Deal and the Paris Agreement. The Paris agreement is a global initiative to mitigate global warming below 2°C helping countries to manage climate change issues and assist their efforts (European Commission, 2014). European Green Deal is an initiative from the European Union that includes policy packages to enhance the green transition and climate neutrality by 2050. One of the major packages is the Fit for 55, whose aim is to convert the policies of the European Green Deal into law (European Council, 2022).

Furthermore, governance arrangements are becoming more essential since countries must follow a low-carbon path that will eventually change the business and commodity exchange function (Bhattacharyya, 2020). Due to the Russian invasion of Ukraine and, thus, the energy crisis that has resulted in geopolitical tensions between Europe and Russia, the European Union has launched the REPowerEU plan. The purpose of this initiative is twofold and consists of the independence of Europe from the Russian energy supply and overcoming climate change. The main actions include energy saving, supply from other international producers, and reliance on renewable energy sources. The acceleration of renewable sources in heating, power production and transportation gives the appropriate room for renewable hydrogen to establish itself as a primary energy source. European Union has set a target to produce and import ten million tonnes of domestic renewable hydrogen respectively until 2030. This, combined with the accelerated actions from the European Commission to publish the appropriate acts that verify the production source of hydrogen and the 200 million euro funding for testing purposes, increases the importance of a hydrogen market (European Commission, 2022).

Researches show that hydrogen is one of the best candidates to replace fossil fuels. It is the most abundant element on the planet and is considered one of the most promising choices since it can be produced by renewable energy sources (Kovac et al., 2021). Today, hydrogen is mainly produced by coal or gas and is primarily used in industrial sites, with the potential to be used in transportation and heating in the upcoming years (IEA, 2019). Additionally, hydrogen is primarily used for producing plastics and fertilizers after natural gas processes (European Commission, 2022).

In 2020, the global hydrogen demand reached around 90 metric tonnes (Mt). Almost half of this demand came from the consumption of refineries as feedstock and energy sources. The other half was dedicated to chemical production and, more specifically, ammonia and methanol. Finally, a small portion was used for steel and iron production. By 2050, the demand is expected to be six times greater than the current one, with industrial and transportation usage being the leading consumption sectors (IEA, 2021).

From the supply side, fossil fuel hydrogen production plants were responsible for 79% of demand, while the rest was by-product hydrogen made by transformations of naphtha to gasoline (IEA, 2021).

Despite the global pandemic, hydrogen remained stable regarding supply and demand volumes. Investments of a total of 11 billion USD from companies related to production, transfer and consumption, as well as government recovery packages, give the perception that investments in the hydrogen industry will grow substantially in the upcoming years. Companies already listed on the stock exchange increased their shares for investors to gather the appropriate capital and invest in constructing facilities for hydrogen production. A great example is plug power, a US company specializing in producing and selling electrolyzers, which sold 4.8 million new shares in the last two years, while other companies from the same industry also raised remarkable funds. Apart from the electrolyzers sector, other private companies from the production, pipeline, storage, engine manufacture, energy, steel and transportation sector are interested and involved in the hydrogen market offtaking.

Hydrogen is considered a feedstock commodity mainly used in the industrial sector. Since the 1970s, hydrogen has been trying to establish itself as a clean energy carrier exploiting the shortages and the high prices of oil in different periods as well as climate change. However, discoveries and lower oil and natural gas prices did not let hydrogen have the expected effect. Today, its price varies between 1 and 3 USD per kilogram (Nousan et al., 2020).

Three different primary colors characterize hydrogen regarding how it is produced. Grey hydrogen is produced by fossil fuels and emits CO2 when made. Blue hydrogen is also produced by fossil fuels, but the CO2 emissions are captured and stored in specialized underground facilities. Finally, green hydrogen is produced by renewable energy using electrolyzers (Deloitte Netherlands, 2022).

Hydrogen is stored in tanks in a liquid or gas form for small-scale applications, while underground storage is preferred in large-scale applications (Scita et al., 2020). Salts caverns are also used to store hydrogen for extended periods as well as ammonia. The latter is also used to ship hydrogen and transport it worldwide if pipeline infrastructure is absent (IRENA, 2022). Additionally, ammonia has a comparative advantage over liquid hydrogen since it is able to liquefy easier after chemical processes. Moreover, it is safer to transport and store because of its high boiling point and low vapor pressure (Chatterjee, 2021). Methanol is another carrier of hydrogen that is constructed after hydrogen reaction with CO2, and then it can be transformed back to hydrogen through chemical processes (Andersson et al., 2020).

Hydrogen is distributed to different locations for different purposes. Pipelines are the identical solution for large-scale hydrogen transportation, exploiting the already existing ones from natural gas transportation or making minor modifications. However, due to its density, hydrogen distribution is considered difficult and expensive (Scita et al., 2020).

Even though the technology, infrastructure and regulatory framework are becoming more mature each year, the major problem is the need for a hydrogen market that will establish itself as a tradable commodity (Scita et al., 2020). Liquification, transportation, price determination, reliability, production, storage, supply, and demand are factors that should be identified to commodify hydrogen and create a global market that will allow its exchange. For all that reasons, creating a hydrogen market is becoming increasingly essential.

A massive effort has been started in the Netherlands where Gasunie and the ports of Rotterdam, Amsterdam Groningen and North Sea Port are collaborating in order to make hydrogen trade possible. The project is called HyXchange. This project examines the ways of creating a hydrogen market and exchange. The port authorities of the aforementioned locations cooperate with Gasunie to produce, distribute and store hydrogen. Additionally, HyXchange is working on publishing certifications for hydrogen, a hydrogen exchange index, a spot market, and trading instruments to establish hydrogen as a tradable commodity (Gasunie, 2021).

The European Union, apart from the projects that aim to decarbonize industries and climate change, also launched the IPCEI Hy2Tech projects, whose primary interest is the hydrogen sector. This project includes 35 companies and 15 countries of the European Union. Its main purpose is to develop hydrogen technologies and decarbonize the industrial and transportation sector. Additionally, it provides the involved member states with the needed funds and resources to develop production, transportation and storage applications. The total investment of IPCEI Hy2Tech is estimated at around 14.2 billion euros (European Commission, 2022).

To examine the factors mentioned above, different energy carriers such as Liquified Natural Gas (LNG) and crude oil are set as examples to investigate the elements that contributed to commodifying them and making them exchangeable. LNG has been one of the most important energy sources for over half a century. Its liquefaction capacity is growing rapidly. Traditionally, the LNG market is based on long-term contracts between the producers and the buyers, and its price is directly linked with oil prices. However, long-term contracts have the disadvantage of not providing flexibility, so the LNG market has launched to emerge in short-term or spot markets (Craig Pirrong, 2017).

This shift from long-term to short-term contracts is due to the fact that the market cycle becomes more liquid, which increases the spot trading activity and the fluidity of the spot market. As a result, long-term contract reliance seems to be unnecessary (Craig Pirrong, 2017).

In general, the energy market experiences price fluctuations for supply and demand due to different factors such as weather, shortage of production, lack of storage capacity, logistic inefficiencies, etc., generating risks and uncertainty for producers and buyers. For that, financial derivative contracts give the solution to mitigate the risk for both parties. In that way, producers and buyers sign an agreement to exchange the product at a specific price and date, reducing the risk of future rise or fall in the prices that would lead to losses (Craig Pirrong, 2017).

IEA identifies some of the significant challenges of launching a hydrogen economy. First, hydrogen production from sustainable or low-carbon sources is expensive. This relies upon the fact that renewable electricity and electrolyzers essential to produce green hydrogen are costly. Secondly, hydrogen facilities and infrastructure are evolving at a low pace. Pipelines, production plants, carbon capture storage and ships are not entirely available at the moment. This slow development also affects the dependency of hydrogen production on fossil fuels instead of clean energy sources resulting in high CO2 emissions. Finally, the regulatory framework regarding a clean hydrogen economy is not consistent and exact yet (IEA, 2019).

To sum up, the discussion above reveals the relevance of this thesis which is mainly based on business, financial and transport economics. Regarding the latter, it is essential to define how hydrogen commodities can be exchanged and what is needed for this to happen. As for the business and financial economics relevance, a price benchmark for hydrogen and trading hubs that will allow hydrogen exchange are fundamental factors for the commodification process. Additionally, commodity markets are highly correlated with the financial world (Schofield, 2021). Yet, this thesis relates to complexity theory and systems. That is, the commodity market and commodification of a product are highly related to uncertainty, exogenous shocks and assimilation (van den Berghe et al., 2022). Finally, institutional economics is also relevant since they allow for organizing the prices, the necessary financial instruments needed for trading, standardized contracts and trading platforms.

## 1.2. Research aim and questions

The research aims to analyze how commodity markets evolve, focusing on the energy market in order to provide recommendations and strategic implications for stakeholders on how a hydrogen and ammonia market could emerge. The stakeholders could be governments, private companies related to the hydrogen industry, investors such as banks, ports, storage companies and companies that operate in the commodification sector.

Therefore, the research question that this thesis will address is the following:

*"In light of hydrogen's emergence as a source of energy, what are the critical success factors of launching hydrogen and ammonia exchange as tradable commodities?*

The structure of this thesis is as follows. The second chapter is the literature review and discusses how markets emerged and evolved, what are the fundamental characteristics from the past and the mechanisms of the commodity markets commodity in terms of contracting, price discovery and parties involved. The third section involves the methodology, which includes the necessary steps to answer the research questions that emerge. The fourth chapter analyzes the market evolution of two main energy carriers, LNG and crude oil. In this chapter, the analogy of both is discussed, aiming to draw lessons and apply this information to commodifying and launching a hydrogen and ammonia market. The fifth section is dedicated to hydrogen and ammonia, their forms, production, transportation and infrastructure, giving insights into the current situation. In the sixth section, the critical factors are identified and validated with interviews with experts from the hydrogen and ammonia industry. This chapter answers the main research question of how the commodification of hydrogen and ammonia can take place. Finally, the last chapter includes conclusions.

# 2. Literature Review

## 2.1. Commodity market function

Commodities are physical goods that are not differentiated and fulfill a variety of economic needs. They are standardized results of production processes and can be traded through financial instruments. Their supply and demand are considered liquid, and the time of production and availability usually need a long period (Clark, 2014). Commodities are heterogeneous, meaning they vary in type, production location, characteristics, grade and quality (Schofield, 2021). This heterogeneity of the commodities has made investments in the commodity market more attractive in recent years (Ielpo, 2018). The commodities are characterized as upstream when available for industrial use, such as oil, and downstream when delivered directly to the end-user, e.g., gold (Clark, 2014). All the available commodities in the market, meaning agricultural, energy and industrial, need to go through different transformations to be consumable. Craig Pirrong (2014) distinguishes the transformation of the commodities into three categories, namely in space, time and form (Pirrong, 2014).

Transformation in space consists of transporting the commodities from the suppliers to the consumers. Usually, the production regions are located far away from the final consumption destination. Spatial transformation is a fundamental process that allows for the transportation of commodities from one point to another, and it is considered a core activity of commodity trading (Pirrong, 2014). Schofield (2021) agrees that production and consumption do not always occur at the same location, which means that the commodities need to be transported. Additionally, claims that the transportation of the commodities varies depending on the location and the type of the commodity. For instance, oil in the U.S. is mainly transported through pipelines or trains, while in Europe, ships are used more frequently.

The storage of the commodities is also an important characteristic of the commodity market since the demand and the supply do not usually occur at the same time (Schofield, 2021).

Transformation in time includes the inconsistencies that may occur in the supply and demand of a commodity. Different factors create these situations, such as weather conditions and macroeconomic events. For instance, gas production is constant throughout the year. Still, weather conditions decrease the demand for gas consumption when the temperature is higher and increases the demand when the temperature is lower. Inventories provide a solution to such shocks in supply and demand. Storing commodities allows flexibility to the market when the supply and demand for a product are low or high throughout the year (Pirrong, 2014).

Plenty of commodities need to be transformed to be consumed in their final form. For example, soybeans have to go through a process to produce oil or meal. Another example is crude oil which has to be refined in gasoline or diesel or blended and mixed to form the final product. All the above transformations are essential steps for the commodity trade process (Pirrong, 2014).

Commodity trade is an investment strategy where raw materials or production inputs are traded. It is associated with the field of financial economics as well as with the sectors of production, storage and transportation. The most common commodities traded are wheat, coffee, sugar, oil and ore (Jacobs & van Bergen, 2014).

Throughout the years, the commodity market has been subject to several changes, such as modifications to the way of trading, dramatic increases in demand from China, and amendments to the legislative framework. In the past, vendors and buyers used to meet face to face to complete a transaction. However, the necessity of standardization regarding quantity, quality, the guarantee of origin and the delivery date of the commodity established the creation of exchange markets in the 19th century. (Geman, 2009). Some of the most essential commodity exchanges are Chicago Mercantile Exchange (CME), New York Mercantile Exchange (NYMEX) and the Intercontinental Exchange (ICE) (Jacobs & van Bergen, 2014).

In the physical market, where the commodities are exchanged, also called the spot or cash market, the transaction between the seller and the buyer occurs immediately and is done at the spot price (Priolon, 2019). According to Geman (2009), spot trading represents the immediate delivery of the product accompanied by a signed contract between the buyer and the seller, which shows, amongst others, all the parties involved in the transaction (Geman, 2009). Additionally, Bern and von Bern (2012) highlight that the spot market represents all the transactions that occur when the prices have several fluctuations and when the delivery has to be realized in a short period (Bern & von Bern, 2012). There might be delays in the payment and the delivery of the commodity, but the transaction is considered when the agreement is done (Priolon, 2019). In the commodity market environment, the spot market definition is usually ambiguous, mainly because different commodities have different maturity (Schofield, 2021).

Furthermore, although the spot market functions as a reference, nowadays, commodity trading focuses on paper instead of physical trading (Bern & von Bern, 2012). Today commodity exchanges take place on online trading platforms (Priolon, 2019). It is rare to see buyers and sellers meet with each other and agree on the delivery time and the price of the commodities. For that reason, intermediaries are responsible for receiving the commodity, storing it and transferring it to the buyer (Geman, 2009).

Commodity derivatives markets allow for standardized contracts meaning futures, forwards and options and work as financial instruments whose price depends on the spot price of the commodity. The financial instruments that have as a reference an underlying asset are called derivatives since their price is derived from the price of the spot market. Derivative financial instruments for commodities are distributed between the over-the-counter (OTC) and organized markets via an exchange such as ICE or CME (Priolon, 2019).

## 2.2. Derivative contracts

Three main contract types exist in the commodity derivatives market. Forwards, futures and options. In the existing literature, authors highlight different characteristics and purposes of derivative contracts.

In general derivative contracts are detained delivery agreements that have a value based on another underlying transaction. This transaction can occur in the spot market or another derivative market. Since the economic condition will not remain the same over time, this will affect the derivative contract making it more or less valuable. Derivative contracts are mainly used to manage risks (Koppenhaver, 2009). They can be standardized and traded in the Over The Counter (OTC) market. OTC derivatives can be agreed upon privately, which exposes the parties involved to credit and liquidity risk (Brown-Hruska, 2009).

### 2.2.1. Forwards and Futures

Forwards and futures are signed agreements between the buyer and the seller of a commodity at a given quantity, quality, price and date of delivery (Geman, 2009). Priolon (2019) points out some characteristics of the forward and the futures contracts. These contracts represent an obligation of the buyer and the seller to fulfill their commitments on a future date. One of their main differences is that futures contracts occur in organized markets while forward contracts are in over-the-counter (OTC) markets. Another difference is that futures contracts are considered more liquid than forwards, but this norm has some exceptions. Since forwards are negotiated in OTC markets, it is difficult to compensate for a loss if one of the involved counterparties will not respect the commitment and default (Priolon, 2019). Futures oblige the two parties to exercise the contract and fulfill their commitment, meaning pay or deliver the commodity at maturity. It is not common for a futures contract to be terminated at an earlier date than the agreed expiration date (Koppenhaver, 2009). Producers, traders, and their clients buy futures contracts to hedge their vulnerability to the price movements in the commodity market (Chevaliers & Ielpo, 2013).

Geman (2009) agrees that futures are used to hedge price risk and trade commodities as financial instruments. Futures contracts are price transparent and have low transaction costs, while they generate a necessity to terminate or deliver the commodity physically before the expiration date. The transaction of futures contracts takes place in futures exchanges where the clearinghouse is responsible for taking away any trade credit risk by being the intermediate between the buyer and the seller, guaranteeing that the transaction will happen even if a counterparty defaults (Geman, 2009). Futures contracts are more volatile thus, they are more exposed to significant losses or gains (Baker et al., 2018).

On the other hand, forward contracts are usually used to replace spot transactions, mostly in cases where the commodity is non-storable such as electricity. Additionally, in forwards, credit risk is fully present (Geman, 2009). That is because the contract's price is agreed upon at the contract's expiration date, and there are no payments that occur until the contract's maturity. This credit risk represents the possibility that the contract sellers might default on their obligations when the price in the spot market is higher than the price that has been settled at the begging of the agreement (Koppenhaver, 2009).  Credit risk can be distinguished into two main categories. The first is the presettlement risk, while the second is the settlement risk. The former represents the risk of a counterparty defaulting before the expiration date of the contract, while the latter represents the possibility of a counterparty defaulting at the maturity date of the contract.

Schofield (2021) marks that futures contracts have the same purpose as forwards, meaning that they offer price certainty for a specific period in the future; however, the way they are traded differs (Schofield, 2021). Forwards are derivative contracts that convey possession obligations of a commodity on the cash market and deliver it at a future date. They agreed only once at a price that will be transferred on the day of the delivery and not before that (Koppenhaver, 2009).

The quality and grade specification are some of the main characteristics of futures contracts, especially when the commodity is heterogeneous. Since commodities vary in shape, grade and quality, it is essential to guarantee an element of standardization so that the consumer knows the origin and the characteristics of what he receives. In contrast, regarding forwards, if a commodity is bought forward at a higher price than the spot price at the time of delivery, none of the parties can terminate the contract and buy it in the current market. Nevertheless, there is a possibility of a mutual termination earlier than the contract's expiration date after the buyer and seller agree on a break amount that represents the current value of the contract. Finally, according to Schofield (2021), evidence from the market shows that most futures contracts are terminated before the expiration date, indicating that they are used for risk management purposes instead of supply sources (Schofield, 2021).

### 2.2.2. Options contracts

In terms of the options contracts, the buyer is allowed to walk away in the case of a price reduction of the underlying commodity, and there is protection under the contract if the prices move in the buyer's favor. The options are defined as the right – and not the obligation – of a buyer or a seller to make a transaction in the future for a price that has been agreed upon today. The option contracts can be both cash and physically settled, meaning they can be delivered. In such agreements, the buyer pays a premium, usually up front, to the holder, while higher flexibility is offered to both sellers and buyers (Schofield, 2021). Bern and von Bern (2012) add that the holder of the option contract can decide whether they want to exercise the contract autonomously or not. Most of the time, the exercise of the options contract includes payment in cash (Bern & von Bern, 2012).

### 2.2.3. Freight contracts

Apart from the futures, forwards, and options contracts, there are also freight contracts that nowadays can only be traded under the Forward Freight Agreement (FFA). The main purpose of these contracts is to hedge the fluctuations in freight rates. The contract specifies the route that the ship will follow, the size of the cargo and the expiration date. The transactions of the FFA market are not shared in public (Geman, 2009).

Regardless of the route that the commodities will follow and the commodity type, the transaction includes the transportation of the cargo, mostly by ship. For that reason, trading companies also function as logistics companies. Their main purpose is to buy a commodity, transfer it from the start to the finish destination and finally sell it at a higher price in order to make a profit (Bern & von Bern, 2012).

## 2.3. Stakeholders

The traders play a key role in commodity trading. They aim to create a competitive advantage based on their knowledge, information and instinct in order to negotiate a premium and make a profit. At the same time, it is essential for them to be aware of the specifics of the logistics function since commodities are transferred worldwide, and it is crucial to know the right delivery time (Jacobs & van Bergen, 2014). One of the main tasks of commodity traders is to optimize the commodity transformations. An important aspect of optimization is the costs of transportation, inventory and processing (Pirrong, 2014).

Commodity traders try to find and exploit arbitrages that emerge when the value of the transformation exceeds the cost of making it. Moreover, while traders buy and sell physical commodities aiming to make a profit, there is a risk associated with these transactions, which is usually overcome via future markets (price risk-management) (Pirrong, 2014).

Commodity traders have started to be integrated vertically in the last few years since logistics and inventory management are becoming more essential. A great example of vertical integration is Vitol, one of the most popular energy traders, functioning its own tank storage division since 2006. (Jacobs & van Bergen, 2014).

The commodity futures market incorporates two main categories of traders; speculators and hedgers. Speculators prefer to act in the futures market rather than buying the commodity in the spot market and then expecting the price to increase. Additionally, they prefer to keep the commodity for an extended period rather than having a private agreement with the buyers to transfer the products at a specific date, at a price that they anticipate to be higher than the spot price. On the other hand, hedgers are involved in spot and futures markets. Hedgers pay a risk premium to speculators to avoid price risk, while speculators participate in the futures market when they anticipate a chance to receive a premium from hedgers (Johnson, 1960).

The hedging technique is used to mitigate the risks that may occur in a transaction or transportation. The trader concludes an offsetting deal to compensate in a loss case. Priolon (2019) believes that by hedging, market participants try to find profit in the financial market since a transaction delivered on a later date incurs risks. By hedging, potential losses that are challenging to avoid on the physical market can be compensated, while the risks that occur in the financial – and the physical – market due to the fluctuation of the prices of commodities can be mitigated (Priolon, 2019). When traders hedge, they take the opposite position of the spot market in the futures market. The most commonly used hedging tools are forward future and option contracts. Producers use hedging against adverse shifts that may occur in prices by selling their futures contracts. Using futures contracts to hedge, the price is fixed, and only the difference between the spot and the futures price needs to be defined. A reduction in the futures price will cause a reduction in the spot price, allowing the trader that has already sold the contract to buy the same futures contract at a lower price (Tauser & Cajka, 2014).

As mentioned above, one of the main differences between forwards and futures contracts is that the latter are standardized in terms of the quality, delivery date, length of the contract etc. In contrast, forwards can be customized depending on the needs of the parties involved. Additionally, most of the time, forward contracts are not physically delivered. Forward contracts consist of another hedging technique. The producer makes an agreement with the bank for the commodity price, which is compared to the spot price. If the spot price at the expiration date of the contract is lower than the agreed price, then the producer receives the difference between the two prices. Next, the producer sells at the spot market in order to be protected from the reduction of the spot price on that day. On the opposite occasion, the producer has to pay the difference between the prices and would be better to not have the forwards contract (Tauser & Cajka, 2014).

It is essential for hedgers and speculators to identify whether the market is in contango or normal backwardation. Normal backwardation is when the futures price is below the expected futures spot price. On the other hand, contango is when the futures price is above the expected futures price. Keynes

(1930) claimed that for the normal backwardation to hold, the futures price must be lower than the expected futures price, allowing speculators to have a risk premium. (Keynes, 1930)

In paper trading, some buyers and sellers transact physical commodities using hedging to cope with price variations. On the other hand, financial parties such as banks and hedge funds aim to speculate on the futures contracts and make a profit (Bern & von Bern, 2012). Furthermore, traders speculate about the price fluctuations in the market without owning the commodities themselves. Those belong to banks, hedge funds and institutional investors. Commodity houses own the commodities, and their main responsibility is shipping them to the final market destination (Jacobs & van Bergen, 2014).

Transformations are optimized by commodity trade firms trying to restore supply and demand inconsistencies. Additionally, they buy and sell commodities in different forms at the same time and react to price signals in order to invest and make the transformations happen. The process of making transformations in commodities is dependent on the available technology and infrastructure. For example, transportation technology meaning ocean freight, rail, barges, and pipelines, defines the potential spatial transformations (Pirrong, 2014).

The diversity of commodity trading firms is extensive. There are commodity trading companies such as Trafigura and Vitor that are independent entities specializing in transformation activities. On the other hand, some banks operate trades, such as J. Aron, which is part of Goldman Sachs, the commodity trading sector of Morgan Stanley, J. P. Morgan Chase etc. Many famous energy companies have trading operations, such as BP, Shell and Total. Some commodity trade companies are specialized in trading specific commodities, such as Trafigura, which trades energy, while others trade a broader set of commodities. Moreover, trading companies also differ in their involvement in the marketing chain. Some are involved upstream, meaning that they own farms or mineral production, midstream, meaning that they are involved in the transportation and the storage of the commodities and downstream, dealing with processing into the final product (Pirrong, 2014).

Another key player in the commodity exchange is the trading hubs. In the past, the commodity trading hubs were buying the products from the producers and then selling them to the final consumer. Nowadays, the trading hubs have developed by owning and operating significant divisions of different commodity supply chains (Schofield, 2021). The clearinghouses are also crucial by functioning as an intermediate between the seller and the buyer. The clearinghouse covers the commitments of the buyers and the sellers in case one of them cannot fulfill the agreement (Priolon, 2019). Commodity houses try to reduce the risk from price fluctuations by implementing future trading. If future prices are expected to be higher than the spot ones, the trader attempts to store the commodities and sell them when the prices increase. In the opposite case, traders want to sell as soon as possible to avoid losses and not store the commodities in tanks or warehouses (Jacobs & van Bergen, 2014). They offer guarantees and mitigate the risks for both parties regarding their obligations. In OTC markets, the buyer and the seller are in direct contact, and usually, their transactions are exercised by an intermediary bank (Priolon, 2019).

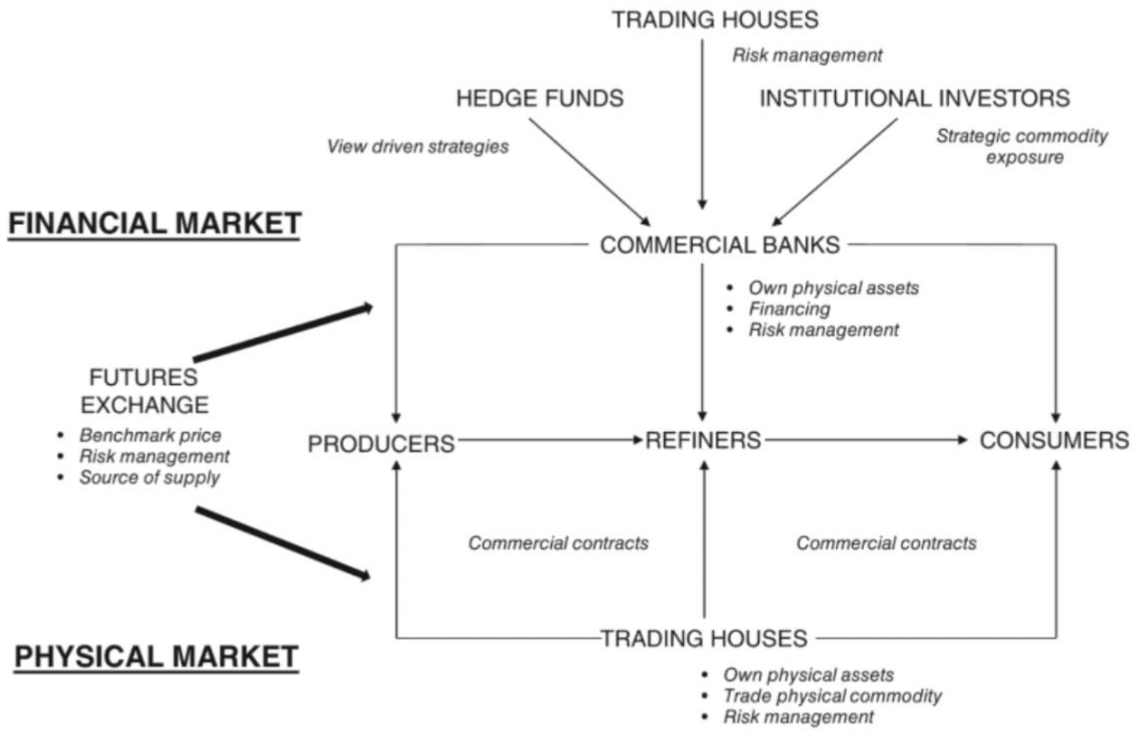


*Figure 1: Commodity market overview, Source: Schofield, N. C. (2021). Commodity Derivatives: Markets and Applications*

Neil C. Schofield (2021) gives an overview of the commodity market in the figure above. On the physical side of the market, there are three key participants; producers, refineries and consumers. Along with the trading hubs, those include the physical side of the market. In contrast, the financial side of the market consists of those organizations that offer financing and risk management services as well as investors. Price discovery is a core process of the commodity market, making future exchanges an essential operation (Schofield, 2021).

## 2.4. Price discovery

Commodity prices are essential from a socio-economic perspective since they affect social development, poverty, and stability. Macroeconomic events, demand and supply are crucial factors influencing commodity prices (Staritz, 2013). There are major differences between the trading of physical commodities and transformed products. Since commodities are standardized, price differentiation is more decisive than the transformed products, which can compete on differentiation. In the commodity market, the characteristics of the commodity are agreed upon by all the involved parties, and then the negotiations are mainly based on the price. Commodities experience several price fluctuations both in the short and long term. This is known as price volatility and defines the variations of the price. Price volatility is usually a major problem for the market participants, and the final consumer is the one who is affected the most (Priolon, 2019).

To minimize the size of the price volatility problem, public authorities intervene by offering strategies. They define measures to balance the prices and provide the operators with the appropriate tools for private risk management (Priolon, 2019). Additionally, Staritz (2013) adds that countries implement policies in the commodity derivatives market environment in order to improve the transparency of the transactions, minimize the risk of OTC trading and prevent any market misapplying, protecting the parties involved. Regulations in the commodity market are essential to prevent any impaired functions that may occur. Different parties regulate the commodity market, such as the European Securities and Markets Authority (ESMA) and the U.S. Commodity Futures Trading Commission (CFTC) (Priolon, 2019).

In economic growth periods, commodity prices increase, so consumers will need a higher income to purchase a commodity. As a result, imbalances in supply and demand will occur, especially when a market has a slow response to this kind of change. Supply and demand imbalances will therefore cause production and storage problems. When the demand for a commodity increase, the production should increase to meet the demand, or the prices will increase to restrain the demand. The latter will cause inflation, while the former will create a surplus. It is shown that, in general, the prices of commodities are directly affected by macroeconomic events as well as by the production and inventory circumstances. Additionally, commodity prices are important measures of inflation since they respond rapidly to shocks (Chevalier & Ielpo, 2013).

Since commodities are not homogeneous, the pricing practice of having a single benchmark has become widely accepted. Pricing benchmarks have contributed to the tradability of the commodities. Price benchmarks are reference points based on the market activity and are examined by the market participants. A commodity's price is considered a benchmark only if different, and various participants use it (Schofield, 2021).

Regarding the future prices, Geman (2009) underlines that they are constructed either from the supply and demand of the underlying commodity or the expected prices that a commodity will have at different periods. Mostly on liquid markets such as crude oil and electricity, the future prices show the path that the prices will follow. The information for the anticipated future spot prices is essential for storable commodities since the prices will define the inventory options for companies. In the case of increased future prices, more storage is needed, while in the opposite case, less inventory is needed (Geman, 2009).

Inventories are essential for the business world and companies to be prepared for the risks that arise because of the fluctuations in supply and demand. Companies that trade storable commodities such as oil, steel, metals, corn and sugar face financial risks if they cannot transfer that risk to their customers.

Traders not only use financial hedging by using derivative contracts, but they also use inventories to hedge the so-called consumption volume risk that occurs because of the volume inconsistencies in commodity demand.  Firms should decide how much volume of the commodity will store and how much will be available for production. Inventory consists of two natures; one is the long-term supply of the commodity, while the second is the availability in the spot market. Regarding the former, the supply with fixed prices for an extended period allows for mitigating the risk of price volatility of commodities. The latter protects the company from the consumption commodity risk. According to Kouvelis et al. (2013), the interaction of inventory and financial hedging leads to increased inventory levels only if the financial hedge is effective and efficient. Finally, the procurement of the physical market maximizes the efficiency of the inventory hedging, which involves the supply and demand volatility risk (Kouvelis et al., 2013).

The imbalances regarding the production and supply of commodities made people involved in trading activities create trade routes in order to overcome the scarcity and abundance in different regions and satisfy the demand. Trade routes include the shipping of commodities and the transportation from a start to a finish point (Clark, 2014). In the last few years, ocean shipping rates have increased dramatically, adding one more issue to the already increased commodity prices and making the transportation of goods even more expensive worldwide. This can be noticed in the rising prices in oil transportation, where the price for tankers insurance has risen significantly. This might be due to the fact that the demand for goods in China has increased considerably, and more tankers/vessels are required. As a result, a supply shortage occurs and therefore, the prices increase since even fewer tankers are available to meet the demand of other countries. Moreover, since China, Europe and the U.S. import more goods than they export, they experience inflation issues. This domino effect also impacts the ship manufacturers in South Korea, Japan and China, who are obliged to follow the European regulations and safety requirements regarding oil tankers (Geman, 2009). Kanavussos and Nomikos (2001) found that the spot and forward freight prices are correlated with each other, and more specifically, spot prices follow those in the forwards market (Kavussanos & Nomikos, 2001).

Additionally, regarding factors that influence commodity prices, Chevaliers and Ielpo (2013) found that economic news releases influence the commodity market prices. More specifically, they show that in periods of recession, the commodity market prices are highly impacted, while in expansion periods, they are not. However, since growth periods are longer than recessions, the authors suggest that the findings might indicate that the business cycle does not affect the commodity markets. Indeed, the energy commodity market is not sensitive to economic news. Additionally, the recession period news has a greater impact than growth periods (Chevalier & Ielpo, 2013).

The supply chain function is heavily dependent on the energy market since oil, natural gas, and electricity constitute major inputs for industrial usage. Energy can be traded in spot and futures markets for immediate and later delivery. However, the storage facilities for energy carriers are circumscribed, causing uncertainty about the supply and demand. The costs of transactions tend to be higher in the spot market than in the futures market near the contract's expiration date. That is because the trading volume in the spot market is lower, and therefore, the availability of the commodity is reduced. This fact allows companies involved in energy transactions to fulfill their need in the futures markets instead of in the spot market (Secomandi & Kekre, 2014).

# 3. Methodology

In the previous chapter, the commodity market function was explained together with the evolution of the markets in general. In addition, derivative contracts, price discovery techniques and the main parties involved were analyzed to provide information regarding the fundamentals of the commodity markets and how they operate.

In this chapter, the methodology process is discussed to give insights into the needed methodology that has to be followed to answer the main research question. The methodology of this thesis consists of exploratory research and deductive analysis by examining the analogy of the commodity markets and the evolution of LNG and crude oil. Additionally, it uses the ex-ante evaluation method to identify the appropriate strategies and policies that have to be implemented to launch a hydrogen and ammonia market. Lastly, it consists of interviews with experts from the energy and trading industry in order to validate, clarify and nullify the gathered information.

## 3.1. Exploratory research and deductive analysis

The exploratory research method constitutes the core of this thesis combined with the analogy of LNG and crude oil market evolution and the deductive research method. The deductive analysis allows for explaining all the related information regarding a topic aiming to answer the main research question. It also expands the understanding of all the associated problems phenomena (Reiter, 2013). Finally, the primary purpose of the deductive analysis is to generate new ideas and better theories than the current researchers have concluded (Casula et al., 2020).

Exploratory research consists of the investigation of unknown processes, activities or situations that are worth exploring. The main aim of the exploratory study is to obtain empirical generalizations about the examined process, activity or condition. The exploratory technique is mainly used as a method when the subject for investigation has not experienced empirical research (Stebbins, 2001).

Exploration allows for collecting both qualitative and quantitative data. Even though qualitative data collection is more common in exploratory research, it also consists of descriptive statistics such as volumes, percentages and indexes (Stebbins, 2001).

A fundamental element of exploratory research is the investigation of new ideas around a research subject contributing to the development of sciences. In order to get the final answer, this research method requires a deep examination of the topic. The purpose of exploratory research has two aspects. The first is examining an issue that has not been investigated before. The second is the investigation of already existing studies aiming to generate new ideas (Elman et al., 2020).

The exploratory research aim is to answer questions regarding how and why things happen. The deductive approach is the core of exploratory research, explaining general matters and concluding with specific ones. The exploratory research focuses on discoveries for topics that are relatively new. Additionally, it generates questions to be further examined in more extensive studies (Casula et al., 2020). Finally, exploratory research relies on previous theories and tests the plausibility of implementing them to a new model or idea (Reiter, 2013).

This thesis uses exploratory research and deductive analysis to draw lessons from LNG and crude oil market function and evolution. The main goal is to generate new ideas for the yet unexplored hydrogen and ammonia market by examining previous information and policies from other commodity markets.

## 3.2. Ex-ante evaluation

Ex-ante evaluation has many characteristics providing tools for various purposes. First ex-ante evaluation allows for optimally implementing a policy or program by minimizing the cost and maximizing the impact. Secondly allows for identifying effective and efficient ways of implementing a policy or program. In that way, the range of the anticipated effects is determined. Finally, ex-ante evaluation can be used to examine how the impacts have been affected by shifted parameters of the analyzed program. The ex-ante evaluation method collects information from previous experience to implement them in a hypothetical policy or program and derive the potential effects (Todd & Wolpin, 2006).

Samset and Christensen (2015) agree with Todd and Dolphin (2020) that one of the significant ex-ante evaluation benefits is avoiding inefficient solutions by identifying the best solution beforehand. Ex-ante evaluation is based on assumptions since the information available is limited. This lack of information makes the ex-ante method rely on the intuition and opinion of the parties involved in a project or theory. Even though this may be considered a drawback, the ex-ante evaluation process allows for systematic progress of this kind of limited information on a topic. Usually, this method is used when there is a high level of uncertainty in the evolution of a project and when the available data for such a topic is restricted. Therefore, the type of retrieved information is crucial for a successful outcome. Flexibility, imagination and intuition can lead to better results in such situations. Several studies claim that decision-making is more based on experience and feeling than quantitative information or analyses. In complex cases, intuition based on experience and training is preferable to logical analysis. However, this needs deep knowledge and a solid base on the relative topic (Samset and Christensen, 2015).

The main aim of the ex-ante evaluation is to define the effect of possible new policies. These new strategies can be an extension of existing ones by shifting parameters. Policy and decision-makers use ex-ante evaluation by comparing the impact of previous policies before they conclude the final strategy (Wolpin, 2013).

In this thesis, the extrapolation includes information about how LNG and crude oil markets have evolved in terms of contracts, price discovery and trading aiming to take lessons and implement the most efficient characteristics in the launching of a hydrogen and ammonia market.

### 3.3. Interviews

Interviews are mainly used in qualitative research to collect information and data from the participants' experiences over the years (Ryan et al., 2009). Generally, there are three interview types: standardized, unstandardized and semi-standardized (Williams & Babbie, 1976). Ryan et al. (2009) define standardized interviews as a comprehensive list of questions. This type of interview indirectly obliges the participant not to deviate from the nature and scope of the questions. On the other hand, unstandardized questions are based on open-ended questions allowing for deviation and further discussion of the topic. Finally, semi-standardized interviews consist of a mix of both previous types of interviews (Ryan et al., 2009). Since this thesis uses exploratory research and ex-ante evaluation methods that require flexibility and precision simultaneously, the latter type of interview is used, taking into account other aspects that may be helpful and may deviate from the original question list.

The interviews' primary purpose is to clarify the identified critical factors for launching a hydrogen and ammonia market from field experts.

## 4. Crude oil and LNG market evolution

### 4.1. Crude oil

Crude oil is the most consumed energy commodity among the other energy carriers. According to Platts, the term crude oil does not explain any specific type of oil but consists of 130 crude oils. Each class has different qualities and is attractive for various reasons and purposes. Crude oil elements are carbon atoms and molecules consisting of hydrogen. An interesting fact about crude oil is that usually, it is not used by itself but, after refining processes, generates other products. Some examples are gasoline, diesel, naphtha, kerosene and fuel oils. (Schofield, 2021).

Crude oil has different characteristics that define its final usage, such as density, sulfur content, acidity, etc. Additionally, crude oil is distinguished into different categories, light, sweet crude, heavy and sour. These categories have different refining results and location production. They are used for various purposes and have different characteristics (Schofield, 2021). Light crude oil is characterized by low viscosity and density, allowing for smooth flow at room temperature. Additionally, together with sweet crude oil, they are less expensive to refine. Heavy crude oil has a higher density than light crude oil, and sweet crude oil has lower sulfur content than sour crude oil (Baker et al., 2018).

Crude oil started being globally tradable in the USA, with American oil companies playing a significant role in exporting the commodity. The prices were correlated with the Gulf of Mexico region. However, after 1973 and for the next decade, Saudi Arabia became the leading source of light crude oil, becoming a price benchmark. Today NYMEX, Western Texas Intermediate (WTI), International Petroleum Exchange (IPE) in London and Singapore International Monetary Exchange (SIMEX) are the reference points for different types of crude oil exchange (Braginskii, 2009).

Crude oil benchmarks are mainly generated because of the production location and the presence of significant derivative markets. A great example is Dared Brent crude oil which has approximately only 0.3% of the total international production. Still, its location and support from the WTI derivative market establish them as a benchmark (Schofield, 2021).

Crude oil is transported through pipelines or specialized tankers. The former is the most preferred way to transfer crude oil and its refineries, although they have high construction costs. On the other hand, ship tankers carry liquid products of crude oil, and they are distinguished into different categories depending on their capacity (Schofield, 2021).

In Europe, there are specific routes that crude oil and its refineries follow, such as the Suez and Panama canals and the Rhine, Seine and Maas rivers. After refining, the crude oil can be distributed to wholesale buyers such as airports that accommodate airlines or to gas and petrol inventory locations (Schofield, 2021).

Usually, the production location differs from the location of the reserves. Production and consumption of crude oil have risen significantly over the last four decades. China has the highest consumption shares, over 8.5% in 2005 and over 14% in 2019. The figure below shows the production and consumption locations and the demand in these regions (Schofield, 2021).

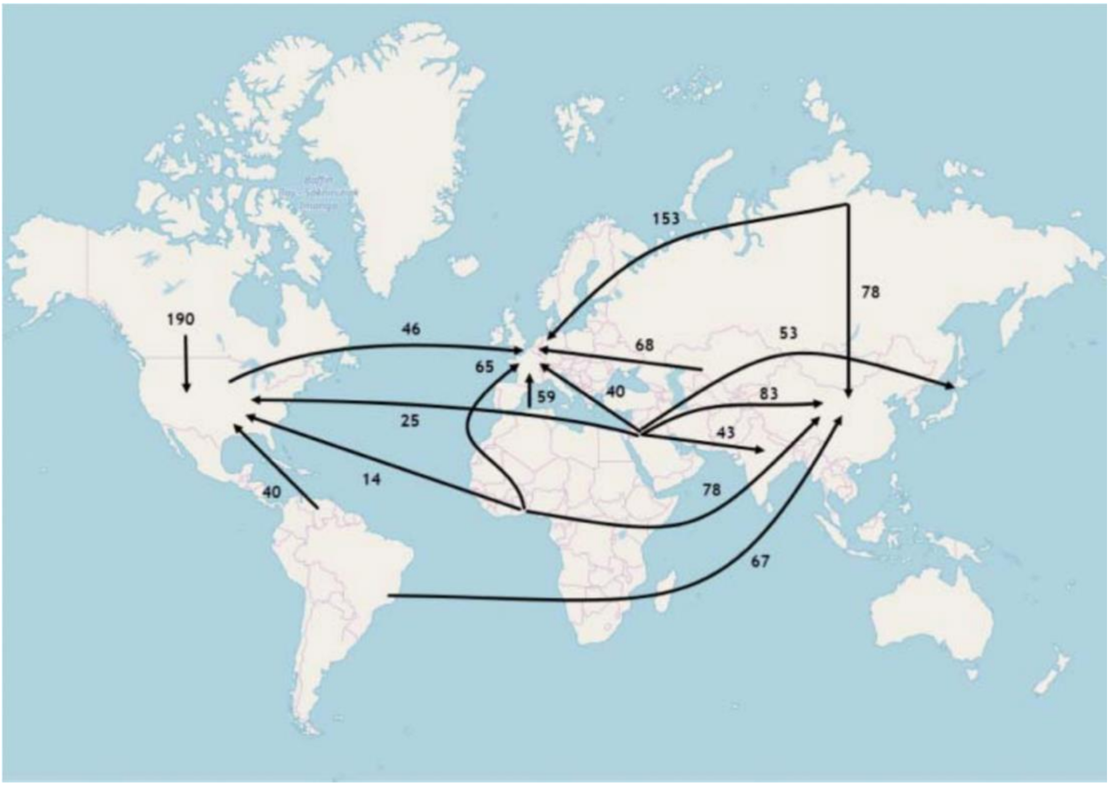


*Figure 2: Crude oil movement. Source: Schofield, N. C. (2021). Commodity Derivatives: Markets and Applications*

The Organization of Petroleum Exporting Countries (OPEC) plays a crucial role in crude oil supply, demand and pricing. It is an organization that includes countries with high production volumes of crude oil, such as Iraq, Saudi Arabia, Kuwait, Algeria, Ecuador, Venezuela, Nigeria etc. The organization's purpose is to manage the petroleum policies, including efficient supply, demand, storage and pricing for producers and consumers involved in the industry (opec.org, 2022).

Several crude oil markets worldwide have different contracts, quality, and liquidity characteristics, with North Sea Oil and WTI being the leading ones. Trading depends on various circumstances involving producers, consumers, traders and the balance between the supply and demand. Even though a company might produce crude oil, it may be necessary to buy products from various sellers to balance supply and demand, which is the origin of trading (Schofield, 2021).

### 4.1.1. Contracts

The trading process includes various parties. Notably, in crude oil trading, the main participants are national oil companies, integrated oil companies, producers, refiners, financial institutions capable of trading the commodity in the spot market, and trading houses. Similar to other commodities, the trading mechanisms include participation in the derivatives market. Crude oil trading can happen in the spot market, over-the-counter forward contracts, or future delivery with futures contracts (Schofield, 2021).

Energy derivatives started to function as financial instruments after the 1970s. They can be exchanged in both the OTC market and on exchange markets. Crude oil contracts are included in the category of petroleum derivatives, with sweet crudes from WTI and Brent being the most popular ones (Pirrong, 2009).

During the oil shocks in the 1970s and the conflicts between the production countries and the oil companies regarding long-term agreements, the emergence of a physical oil market was necessary. As a result, energy derivatives occurred for mitigating risk purposes and price discovery (Pirrong, 2009). Crude oil derivatives started to emerge in the 1970s. They are usually long-term, and their price is dependent on different benchmarks. These benchmarks can be indices of future, spot or near-term prices published by Price Reporting Agencies (PRAs) (Baker et al., 2018).

After the Arabic oil embargo in 1973, which caused a significant price increase, crude oil futures contracts were introduced in 1974 by New York Cotton Exchange (NYCE) futures in the USA. In 1978 NYMEX was offered the most successful contract for heating oil in 1979 and gasoline in 1981, which are the most prevalent refined crude oil products. (Baker et al., 2018).

Today, a contract agreement for heating oil and gasoline has a predetermined delivery of 42.000 gallons to the New York Harbor. This shipping port allows the storage and trading of commodities, and the contracts are fulfilled the day before the maturity date. However, these arrangements are usually terminated before the delivery date. If the contract is concluded, it can still be traded through the Exchange of Futures for Physical (EFP), following the exchange rules that generally allow the transaction the day after the last trading day (Baker et al., 2018).

NYMEX and the Chicago Board of Trade made numerous efforts to upgrade crude oil futures contracts and its refined products. The Commodity Futures Trading Commission (CFTC) was responsible for accepting the futures contracts' characteristics. Both contract markets got approval from the CFTC, and they launched crude oil contracts in 1983. After the inefficient price management from OPEC in the mid-1980s, the emergence of price risk management instruments made NYMEX WTI crude oil futures contracts the most significant futures contracts in the market (Baker et al., 2018).

Today, the WTI and Brent are the most popular futures contracts of crude oil, traded in NYMEX and ICE futures, respectively, with WTI considered the leading global price benchmark. For instance, WTI light sweet crude oil contracts have fixed features delivering 1000 barrels of the commodity at Cushing, Oklahoma, in the delivery month. Both contracts function as price discovery tools for the oil market. (Pirrong, 2009).

### 4.1.2. Price discovery

In the past, crude oil prices have gone through four pricing system stages. The first one was in the 1940s, when prices were defined according to the production costs. The second stage was in the 1950s until the early 1970s, when the prices were determined according to the so-called "oil basket" and the principle of cost plus. In the third stage, OPEC was responsible for setting the prices from the early

1970s until the mid-1980s. Finally, the last stage, which is in implementation until today, includes exchange centers such as NYMEX, WTI etc. (Braginskii, 2009).

The OPEC countries are free to have their pricing policy. For instance, Saudi Arabia sets the prices based on the final delivery location. If the final destination is the USA, it uses the benchmark of WTI (Schofield, 2021).

It is interesting to notice that despite OPEC countries having the highest export and inventory capacities of crude oil, none of them are considered global benchmarks. The reason behind that was generated back in the 1980s when the leading producing countries advocated that crude oil prices are directly dependent on the prices of refined products. Back then, the prices of refined products were high; thus, producers set crude oil prices in the same direction. This pricing system allowed refineries to take high margins regardless of production; therefore, they tried to increase their performance and capacity. The exceeded supply generated resulted in lower refined products and crude oil prices. As a result, OPEC countries find it more rational to set their prices based on the final delivery location of the commodity (Schofield, 2021).

According to Hotelling and his theory of exhaustible sources, the prices should be increased based on the interest rate in different periods (Hotelling, 1931). This theory applies to crude oil prices since it is considered a finite source. As a result, crude oil prices should be in a contango situation, meaning that the spot price should be higher than the future price. Nevertheless, since futures contracts established themselves in crude oil trading, the market experiences normal backwardation meaning that the spot prices are lower than the future prices. The dominant theory of why there is backwardation in the oil market is that since price fluctuations generate uncertainty, oil owners try to postpone the extraction of the commodity, anticipating that the prices in the future will rise. However, this increases the inventory costs of carrying the oil. There are only a few examples of contango in the crude oil market, with the Asian economic crisis in 1998 being one of the most significant (Pirrong, 2009).

Crude oil prices are directly related to its refined products. For instance, extreme cold weather conditions in a region will increase the demand for heating oil and its price. As a result, the demand for crude oil will also rise as well as its price. An indirect effect will experience other refined products, such as gasoline, whose price will decrease because of the predetermined capacity that crude oil refined products have (Pirrong, 2009).

Finally, it is important to mention the price relationship between WTI and Brent since, as mentioned above, they are considered global price benchmarks. According to Elder et al. (2014), the identical case for WTI and Brent oil pricing is to be equal since, otherwise, there are profit opportunities in the futures and physical market from arbitrageurs. Normally, WTI should have a higher price than Brent oil because its density and sulfur context is lower. However, in the last few years, Brent crude oil has been traded at a premium to WTI. This is due to several factors, such as the dramatic increase in oil production in the USA and the circumscribed inventory and transportation capacities of national crude oil. For that reason, people involved in the crude oil market doubt that WTI is still a leading price benchmark for crude oil (Elder et al., 2014).

### 4.1.3. Price drivers

According to Tsoskounoglou et al. (2009), supply and demand forces, as well as geopolitical events, are major factors that define crude oil prices. An example of a dramatic price increase of crude oil due to geopolitical events was the war in Iraq and Lebanon, which are considered leading suppliers of crude oil. Additionally, the dramatic increase in demand from countries such as China and India also hugely impacts the price rise. Moreover, the inventory capacity of crude oil, the discoveries regarding potential oil extraction locations, and the global economic development also influence crude oil prices. Another factor has emerged in the last few years and is related to the depreciation of the US dollar, which represents the price of crude oil. Finally, according to Ji and Fan (2016), the increased liquidity of the oil market and the augmented demand for oil worldwide, combined with the unsuccessful involvement of OPEC, made various countries play a role in oil pricing (Ji & Fan, 2016).

Schofield (2021) distinguishes these factors into three categories: supply chain considerations geopolitical, and macroeconomic events. Regarding the macroeconomic events, economic growth, meaning that the Gross Domestic Product (GDP) increases, then crude oil prices will also increase. In contrast, crude oil prices would decrease in a case of a possible substitution such as gas. A great example of such a case was back in the 1980s when oil prices went down due to the promotion of alternative fuels. Other factors influencing crude oil prices are the prices of other crude oil and the supply and demand of refined crude oil products (Schofield, 2021).

Finally, regarding the supply chain considerations, the extracted and refined capacity impacts the price of crude oil. For example, if the demand for a refined product increase, then the capacity of the product must fulfill the demand; otherwise, the prices will go up. Additionally, the storage and inventory capacities influence the prices. If there are not enough storage and inventory facilities, the production will decrease, and therefore the price of short-term delivery of the commodity will rise. Finally, the cost of production and distribution also directly affects prices (Schofield, 2021).

## 4.2. LNG

Over the last few years, governments and companies have been looking for clean energy sources and gas demand has increased dramatically. Liquefied natural gas (LNG) allows natural gas transportation from production countries to those that do not produce or are connected with pipelines (Energy.Gov, 2016).

The transportation of LNG started back in 1959 from the U.S. to the UK. The first shipment showed that large quantities of LNG can be transported by sea and that an LNG market can start to operate.

LNG is a product generated from natural gas and offers an alternative delivery way. It is formed after cooling it to -161°C and after detaching the oxygen and carbon dioxide elements to constitute pure methane (Schofield, 2021). The LNG is transported through specialized tankers to regasification facilities. Asian countries are the major manufacturers of such tankers/ships. Normally, shipping companies own the ships/tankers and rent them to suppliers or buyers. For effective delivery, the parties have to cooperate and ensure that the terminals that are able to handle the LNG cargo are ready to operate. The LNG is converted again to its initial gaseous form in the regasification process. Regasification facilities usually take place in specialized terminals that receive the LNG, and through cryogenic storage tanks, LNG is stored. Again, the parties involved have to arrange the process and ensure that the necessary regasification capacity is at hand (Energy.Gov, 2016). Regarding the responsibilities of the parties involved, producers are responsible for the liquefaction process, while consumers are for the regasification. Additionally, the necessary tankers for LNG transportation can be handled by the producers, buyers or another third party. Finally, in the FOB contracts, consumers are responsible for the potential risks that may occur during the delivery of the LNG  (Nikhalat-Jahromi et al., 2017).

There is evidence that transporting natural gas in a liquified form is more efficient and less expensive than transporting them via off or onshore pipelines for distances longer than 1100km and 3500km, respectively (Nikhalat-Jahromi et al., 2017). More specifically, it reduces the storage capacity that natural gas occupies by 1/600, allowing for transfer over large distances (Schofield, 2021).

The leading importers of natural gas are Japan, South Korea and China, while the top exporters are Qatar, the USA, Australia and Russia (Schofield, 2021).

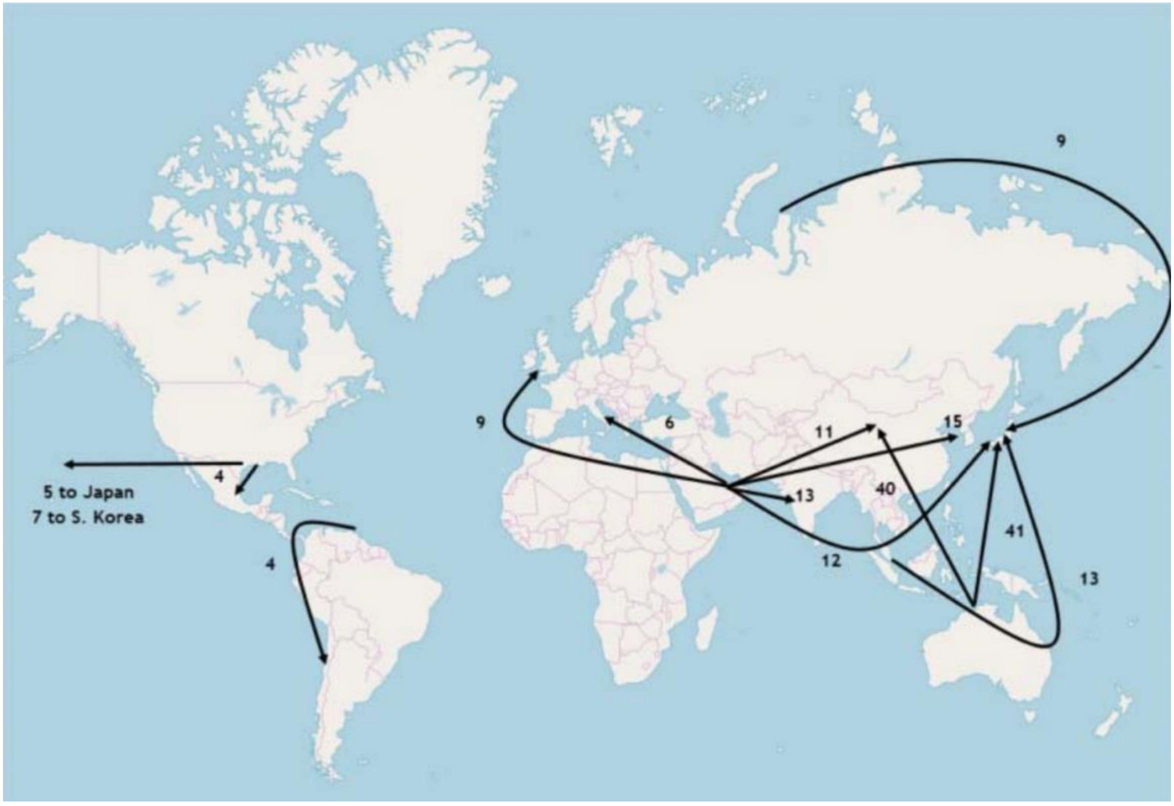


*Figure 3: LNG movement. Source: Schofield, N. C. (2021). Commodity Derivatives: Markets and Applications*

The map above shows the LNG movements in billion cubic meters from the exporters to importers. Only Qatar delivers LNG to Europe, while Japan receives LNG from Australia, the USA, and Russia (Schofield, 2021).

LNG is an exchangeable commodity that has evolved dramatically over the last few years. More and more countries want to construct LNG supply chains for several reasons, such as higher gas prices, energy security issues and obligations for clean and flexible energy sources. Wood (2012) underlines that it is challenging to forecast the future LNG trade activity because of the rapidly changing regional LNG market situation and technological advancements. In the last two decades, large energy companies have started to build LNG supply chains by investing in the necessary infrastructure to allow LNG import, export, and shipping. LNG trade benefits are becoming more well-known, and as a result, they attract new entrants to the market. The increased competition caused technological developments such as floating regasification and the improvement of LNG infrastructure with advanced liquefaction trains and ships. Energy companies such as BP, Shell, Total, Petronas etc., have recognized the significance of managing LNG infrastructure since it gives them the flexibility to utilize their gas reserves and cover any possible margins (Wood, 2012).

### 4.2.1. Contracts

LNG trading started to grow after the 1960s based on long-term contracts with a duration between 20 and 25 years. The agreement consists of two parties, the producer and the consumer. LNG contracts specify the delivery location, the amount and the price of the commodity. These contracts are also known in the markets as sale and purchase agreements (SPA) (Schofield, 2021). Various companies are responsible for the LNG trading system. From the investment side, national and international oil companies are responsible for financing the LNG supply sector, while commercial banks and credit agencies work as loaners (Nikhalat-Jahromi et al., 2017).

Investors cooperate with each other and buy the product from the producers. Then, they make long-term agreements with the buyers, and the revenues of these agreements are divided among all the sponsor parties involved. LNG buyers are usually state-owned companies or private enterprises from developed nations that supply their country. Commercial banks and credit agencies loan money to buyers to build or improve the necessary capacity for receiving and converting LNG (Nikhalat-Jahromi et al., 2017).

LNG contracts also include some more specific elements. The first is the duration of the contracts. In the past, LNG contracts were mainly long-term agreements between producers and consumers (Schofield, 2021). Since the LNG market is characterized by high capital investments necessary for converting natural gas to LNG and reverse, producers and lenders make long-term agreements with the buyers to ensure they have the proper cash flow to cover their capital expenditures. Take or pay clauses in the contracts guarantee that the lenders or the producers will be paid a certain amount of money from the buyer to cover their debts and high fixed costs. In the case that there is an agreement between the producer and the seller, the lenders of the LNG production process evaluate the buyers since there are possibilities of incompetence in fulfilling the contract, which will lead to problems regarding the coverage of the capital investments and debts (Nikhalat-Jahromi et al., 2017).

Destination clauses are another essential feature of LNG contracts. Their purpose is to eliminate any possibility of buyers re-selling the delivered product to a market where the price is higher than the price they paid and thus make a profit. As a result, these clauses specify the delivery location of the LNG product without allowing for change (Hartley, 2014). However, In the last few years, this element has been slowly eliminated from the contract agreements as it is considered anti-competitive. The pricing terms are also stated in the LNG contracts, indicating whether the price is based on FOB or CIF, such as in the crude oil contracts. Finally, the pricing basis is also indicated. This shows whether the price is based on crude oil prices or a gas index such as the Henry Hub gas futures (Schofield, 2021).

It is important to mention that the long-term contracts that used to emerge in the LNG market have been slowly eliminated or used for specific purposes. In contrast, short-term contracts with a duration of fewer than four years have started to occur and occupy a significant share of LNG trading. The main reason for the elimination of long-term contracts is that they deteriorate the flexibility of the buyers and the sellers to exploit advantageous situations in the short-term market. However, recently, long-term contracts have become more flexible regarding modifications during the arrangements (Hartley, 2014).

They allow for volume modification, more pricing and delivery options. With that development, parties involved in LNG trading are also more flexible in disruptions (Hartley, 2015). Other factors that helped the emergence of short-term contracts instead of long-term, as well as the emergence of more flexible long-term contracts, are the increased competition, geopolitical and commercial reasons that generate high uncertainty (Energy.Gov, 2016). Finally, the augmented demand fluctuations and spot market liquidity also played a crucial role (Agerton, 2017).

The LNG spot market has seen a dramatic increase in liquidity in the last few years, making the market more efficient and flexible and providing the appropriate security as in the past (Pirrong, 2014). LNG spot market includes two sale categories. One is the spot transaction of LNG, and the other is the short-term agreement between the buyer and the seller. The latter is a less than four years contract that differs from the long-term contracts in two main features. The take or pay clause that still exists in the contract obviously cannot cover the costs of the necessary infrastructure, and the price is usually fixed since the contract is less than four years (Nikhalat-Jahromi et al., 2017).

### 4.2.2. Price discovery

The formulation of prices in the LNG market varies in different countries worldwide. In Europe, Northeast Asia, India and China, the LNG prices are directly related to the prices of other energy sources such as crude oil. In contrast, prices in the USA and UK depend on the competition between the supply and demand of the parties involved (Nikhalat-Jahromi et al., 2017).

LNG prices are correlated either with natural gas benchmarks such as Henry Hub in the USA and the NBP in the UK or with oil or other energy sources prices or indices. In Europe, the LNG prices follow gas indices and prices because of the augmented competition in gas flow from pipelines. In Northeast Asia, China and India, the LNG prices follow those of oil. The main reason is because of the Japanese policy in the 1960s to replace electricity generation from coal and oil with natural gas. Therefore, the LNG imports increased dramatically, establishing LNG as the primary source of electricity generation. After decades that Taiwan, China and South Korea started to be involved in the LNG exchange, JCC prices are the benchmark for Asian LNG prices up until today. However, the dramatic rise in oil prices made Asian countries consider the creation of an LNG Asian hub that will allow for independent pricing formulas for LNG (Nikhalat-Jahromi et al., 2017).

Since Asian countries are significant importers of LNG, it is interesting to see how the prices and the contracts are defined. Before the oil crisis in the 1970s, LNG contract pricing was considered fixed. After the 1970s, the prices inclined to index formulas. One of Asia's most crucial price indexes is the Japan Customs-cleared Crude (JCC), also called the Japanese Crude Cocktail (Schofield, 2021).

The LNG price is US dollars and measured in Metric Million British thermal units (MMBtu). The JCC price formula indicates that LNG prices correlate directly with crude oil prices (Schofield, 2021).

$$LNG\ Price = X * Crude\ oil\ Price + Y$$

This equation consists of three parts. The obvious one is the crude oil prices, which directly influence LNG prices. X represents a coefficient for the oil and natural gas equivalence in the market, usually between 11 and 15%. Finally, Y represents other related fixed costs, such as LNG insurance or shipping costs, to ensure that the prices fluctuate between a particular range (Schofield, 2021).

Apart from the above formula, which is highly specified for Japan, usually, LNG prices follow natural gas benchmark indices such as the Henry Hub in the US, the National Balancing Point in the UK and the Japan Korean Market (JKM) (Schofield, 2021).

For example, trading LNG based on Henry Hub as a benchmark allows the trader to re-sell the product to another trading hub, such as the NBP. This allows the trader to make a profit or lose depending on transportation costs between the two locations (Schofield, 2021).

There are various reasons why LNG pricing cannot split entirely from oil pricing. Currently, reference pricing for gas is not considered reliable and transparent, making it difficult to be independent. Additionally, LNG can only be transported through ships and not blended into a pipeline system, such as gas, decelerating the evolution of gas-on-gas applications (Energy.Gov, 2016). Another reason is that LNG is considered a not-liquid market, leading to dramatic price fluctuations, which increase the price risk of the involved parties. Tying to a liquid market decreases price volatility (Agerton, 2017). Therefore, this decrease in price volatility provides security to consumers and buyers.

On the other hand, the main disadvantage of linking LNG prices with other commodities is that it creates inaccuracies in pricing and estimating supply and demand. The separate paths that LNG and oil have taken in the last few years, with the latter becoming transportation fuel and the former feedstock for electricity generation, as well as the dramatic rise in gas demand, achieved the launching of LNG prices independence from those of oil (Pirrong, 2014). As a result, LNG has started to implement gas-on-gas pricing, which estimates the supply and demand of natural gas without taking into account the oil prices and the balance in that market (Energy.Gov, 2016).

### 4.2.3. Price drivers

According to Schofield (2021), LNG derivatives are similar to natural gas derivatives. Since LNG is produced from natural gas, the price drivers of the latter directly affect LNG. From the supply side, adverse weather conditions that affect production, such as hurricanes in the US, can drive prices (Schofield, 2021). More specifically, in cases where severe weather conditions occur and demand is augmented, the prices may be pressed upward. Additionally, extremely hot or cold weather conditions affect commercial and residential demand and therefore increase or decrease prices (EIA, 2021).

Another important factor is the storage volumes of natural gas. As mentioned above, LNG is produced by modifications of natural gas. Since the commodity market is unpredictable and several fluctuations occur, storage capacity plays a crucial role in cases of unexpected increases in demand. In the months with low demand, large volumes of natural gas are stored and used when the demand occurs again (EIA, 2021).

Prices of competing energy sources also have an impact on LNG prices. Industries that use high volumes of natural gas, petroleum or coal to produce steel or iron look for low prices. Therefore, if the prices of other fuels decrease, the demand for natural gas will also decrease, and the prices will follow the opposite direction (EIA, 2021).

Finally, the available infrastructure for liquefaction and regasification processes, as well as specialized vessels, play a significant role in the formulation of LNG prices. Specialized vessels for LNG transportation, LNG terminals and gasification facilities might not be available because of the high demand for LNG or the infrastructure inflexibility that needs a long time to be manufactured (Schofield, 2021).

# 5. Hydrogen

In the last few years, the rapidly increasing population has affected the energy demand, which is anticipated to increase by 50% by 2030. In addition, the industrialization of developing countries combined with the domination of oil and gas, which occupy a share of 80% of global energy demand, have also contributed to the production of vast amounts of greenhouse gas emissions, increasing the concerns about climate change. Therefore, policymakers are looking for clean, secure and sustainable energy sources that will reduce pollution and retain energy supply and demand at a level able to sustain economies (Ball & Wietschel, 2009). Hydrogen, the most abundant element on the planet, is considered one of the best candidates to replace fossil fuels and provide industries, transportation systems and households with a nonpolluting option. However, the hydrogen market and trade are still in process and need to mature (Lubitz & Tumas, 2007).

The idea of a hydrogen economy is not new. Until 1960, hydrogen was widely used for domestic purposes, specifically for street lighting, heating and cooking. This idea was even more developed after the oil crisis in the 1970s. Hydrogen is mainly used as a feedstock for the hydrogenation of crude oil or ammonia composition (Ball & Wietschel, 2009). Today, hydrogen is used primarily for industrial purposes. The majority of hydrogen usage is dedicated to ammonia production and oil refining (IRENA, 2019).

The two main benefits that hydrogen offers is the zero emissions and energy security. Even though most hydrogen production is done from fossil fuels, it provides the potential to be produced exclusively from renewable energy (Ball & Wietschel, 2009).

Currently, the production volumes of hydrogen reach 120 million tonnes annually, of which approximately 66% is pure hydrogen, and 33% is blended with other fuels. This volume represents 4%

of final energy usage. 95% of the total production relies on fossil fuels, while the rest 5% on renewable sources or by-products (IRENA, 2019).

## 5.1. Production

Hydrogen is mainly found as a chemical element in water and hydrocarbons. There are plenty of sources and processes to produce hydrogen. In terms of sources, fossil fuels, renewable and nuclear energy are the main sources, while methods include gasification of coal and biomass, water electrolysis, natural gas reforming, and water splitting. Today, fossil fuels are the main source of hydrogen production (Ball & Wietschel, 2009).

Two main processes allow the production of hydrogen from fossil fuels. The first is Steam Methane Reforming (SMR) which emits approximately 9.5 grams of CO2 per hydrogen kilogram. The second is coal gasification which emissions reach almost 675 grams of CO2 per kilowatt of hydrogen. Even though these are the most cost-effective ways to produce hydrogen, they are not sustainable. Therefore, since hydrogen production from renewable sources is still expensive and not widely used, other methods must be implemented to achieve the energy transition (IRENA, 2019).

One solution is hydrogen production with Carbon Capture Storage (CCS), also known as blue hydrogen. CCS allows for capturing and storing CO2 emissions from fossil fuels. However, although blue hydrogen production is a reliable solution for sustainable hydrogen and thus a solution for energy transition, some aspects have to be considered (IRENA, 2019).

Blue hydrogen production is not 100% sustainable. There is a range between 5 and 15% of leakages while capturing the CO2. Nevertheless, today, CCS has been improved, resulting in lower leakages. It is vital for CCS projects to have monitoring, reporting and verification (MRV) applications to make sure that the CO2 capturing and storing volumes are correctly calculated (IRENA, 2019).

Despite the rapid growth of CCS technologies and projects, the volumes of capturing and storing CO2 from the power and industry sector are far from the anticipated ones. More specifically, the expected volumes for the power sector are 350 Mt/year reaching only 2.4 Mt/year, while for the industry sector are 400 Mt/year, reaching 32 Mt/year (IRENA, 2019).

Currently, in the Netherlands, there are two big CCS projects. The first is the H-vision initiative, located at the Rotterdam harbor. The vision of this project is to construct four steam reforming plants producing 15-20 tonnes of hydrogen per hour, capturing and storing approximately 8Mt of CO2/year until 2030. The produced hydrogen is planned to be distributed to parties within the harbor or to other customers inside the Netherlands. The second project is called Hydrogen to Magnum, located in Eemshaven in Groningen. The three parties involved are Gasunie, Nuon and Equinor. Nuon will convert its 440MW Magnum plant into hydrogen, while Equinor will construct an Auto Thermal Reforming (ATR) plant to produce hydrogen from natural gas transferred from Norway. The produced hydrogen will be distributed via pipelines of Gasunie, and the CO2 will be captured and stored (IRENA, 2019).

Finally, green hydrogen is produced via renewable sources such as wind and solar. Electricity is generated by renewable sources and produces hydrogen through the electrolysis process. Electrolysis plays a crucial role in the production of green hydrogen. Through electrolysis, the chemical substances of water are split, and pure hydrogen is produced (IRENA, 2020). Currently, there are various investments in the electrolyser sector from companies that are interested in producing renewable hydrogen. (IRENA, 2019).

One of the main factors that helped hydrogen to grow in the last few years is the cost reduction of green hydrogen (IRENA, 2019). Firstly, the cost reduction of electrolysers to approximately USD 200/kw. This decline is expected to be realized by 2030. The main reason for this reduction is the rapid growth of the electolysers supply chain with more producers and distributors involved. A second major factor is the reduction of levelized energy costs. That is, renewable sources are becoming cheaper, mainly in countries with a vast amount of wind and sun exploiting wind turbines and solar panels. Finally, the rapid increase in production and utilization of technologies also play a significant role. By 2030, optimal locations in renewable sources are anticipated to reach hydrogen production costs of approximately USD 1.5/kg (Hydrogen Council, 2021). According to IRENA (2019), using low-cost electrolyzer hydrogen production from wind power is the cheapest way to produce hydrogen.

## 5.2. Transportation

Hydrogen can be transported via pipelines, trucks or specialized ships. Today, liquid hydrogen ($LH_2$) and ammonia ($NH_3$), provide the most sustainable transport option for hydrogen. Even though optimal distribution choice depends on the end-use purpose and the distance that should be covered, general rules distinguish the best transportation option (Hydrogen Council, 2021).

Trucks can carry compressed gaseous hydrogen and liquid hydrogen. They are mainly preferred for distributions of low volumes and high distances (Ball & Wietschel, 2009).

Pipelines allow for the flow of gaseous hydrogen. Pipelines have been widely used for hydrogen distribution for over 50 years, connecting production sites with refineries and chemical plants. Germany, Belgium and the Netherlands have extensive pipeline networks that allow hydrogen to flow.

In the case of transporting high volumes of hydrogen for short and medium distances, pipelines are the best solution. The transportation costs reach approximately USD 0.1/kg for 500km. Nevertheless, this is the optimal solution after guaranteeing no leakages. It is also important to mention that since pipeline infrastructure is capital intensive, demand for hydrogen should be constant for pipelines to be considered the most efficient distribution mean. On the other hand, trucks are the next best solution in fluctuating or low-demand cases. The main advantage is that they can transfer hydrogen in gaseous and liquid forms, reaching costs of about USD 1.2/kg per 300km (Hydrogen Council, 2021).

Subsea pipelines are the most efficient way for hydrogen transportation for long distances. However, there are a few networks that allow for such a distribution. For that reason, ships are employed for long distances transporting different hydrogen forms (Hydrogen Council, 2021).

The most widely used are ammonia and liquid hydrogen. Both carriers have approximately the same costs; therefore, the best choice depends on the purpose of usage and the purification and pressure levels needed. Liquid hydrogen is mainly used in cases where the end-user needs high-purity hydrogen or trucks are required to transport hydrogen after it arrives at the port. The main advantage of liquid hydrogen is that it does not need any cracking or modification processes resulting in a high-purity outcome. On the other hand, the main disadvantage of liquid hydrogen is its low energy density, deteriorating the load capacity per ship. Additionally, liquid hydrogen storage causes great amounts of boil-off losses. It is important to mention that even though liquid hydrogen technology has been realized, it is still in its infant stages of implementation (Hydrogen Council, 2021).

Considering the cost reduction of hydrogen production, transportation is becoming more critical in commodifying hydrogen as a widely used product. Distribution costs are directly dependent on the hydrogen production costs and the way of production, meaning grey, blue or green, and the available infrastructure in terms of pipelines and CCS facilities. Additionally, since the hydrogen economy is not mature yet, infrastructure establishment and the time needed to realize such facilities also play a role. As a result, since there are no well-established production sites and connection infrastructure, the increased demand will be met by exporting hydrogen (Hydrogen Council, 2021).

## 5.3. Ammonia as a hydrogen carrier

Hydrogen's main limitation is its low energy density, especially when it is stored or transported. There are several investigations on other chemical elements that can accommodate hydrogen, and ammonia is one of the best candidates.

Ammonia ($NH_3$), is a chemical element that consists of hydrogen and nitrogen. Almost 1/5 of its mass is hydrogen (Thomas & Parks, 2006). When ammonia is cracked, hydrogen and nitrogen are decomposed. After that, hydrogen is separated and purified, reaching high costs (IEA, 2022).

Ammonia is a commodity that is used in various applications. Primarily, it is used to produce synthetic nitrogen fertilizers. It is also used in refrigerators, pharmaceuticals, plastic, and fibers. (IRENA & AEA, 2022). After cracking, hydrogen can be derived and used on itself. (Thomas & Parks, 2006).

The main advantages of ammonia are that it has a high energy density, can be shipped quickly to specialized ammonia ships, increasing its effectiveness compared to liquid hydrogen, and can be stored at cheap pressure levels (Thomas & Parks, 2006).

### 5.3.1. Ammonia prices and volumes

Current volumes of ammonia production reach about 183 Mt per year, with the majority being produced by fossil fuels. In the last few years, ammonia has been used as a hydrogen carrier, covering almost half of its demand volumes (33 Mt) in 2020. Prices of fossil fuel-based ammonia vary between USD 0.11 and 0.34 per kilogram, depending on the used fossil fuel. On the other hand, renewable ammonia, produced via green hydrogen, has emerged in the last few years. The anticipated volumes of renewable ammonia are around 15Mt by 2030. In 2022, renewable ammonia prices reached USD 0.72 per kilogram in locations with plenty of solar and wind resources. By 2030 considering renewable energy development, the prices are anticipated to decrease by almost 50% in 2050. It is obvious that electricity prices will affect the competitiveness of renewable ammonia compared to ammonia based on fossil fuels. An electricity price of around USD 20 megawatt/hour is considered able to make renewable ammonia prices competitive (IRENA & AEA, 2022).

Below, Figure X shows the path of fossil fuel ammonia production from 2010 until today, while figure X compares the anticipated production costs of fossil fuel and green ammonia until 2050 in USD (IRENA & AEA, 2022).

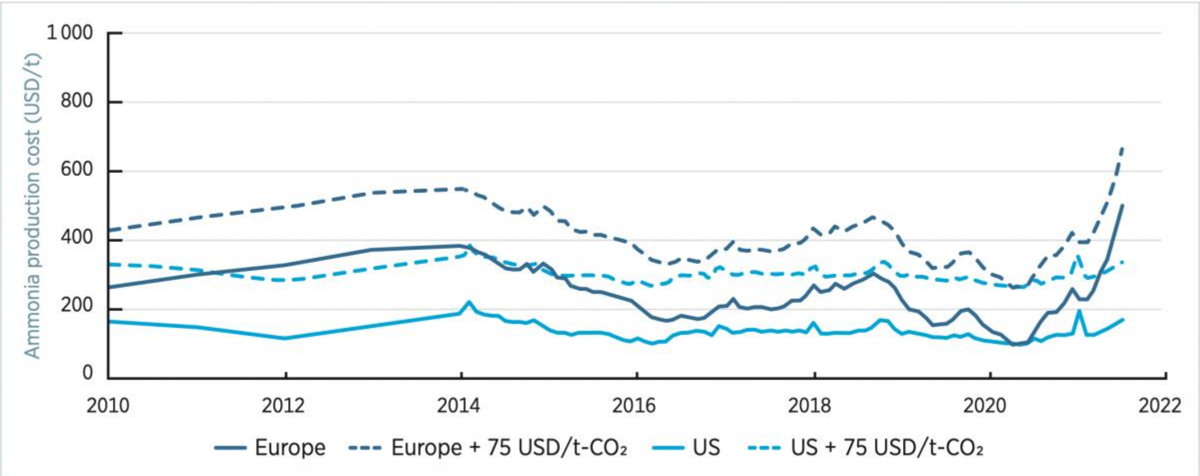


*Figure 3: Production costs of natural gas-based ammonia. Source: IRENA & AEA (2022), Innovation Outlook: Renewable Ammonia.*

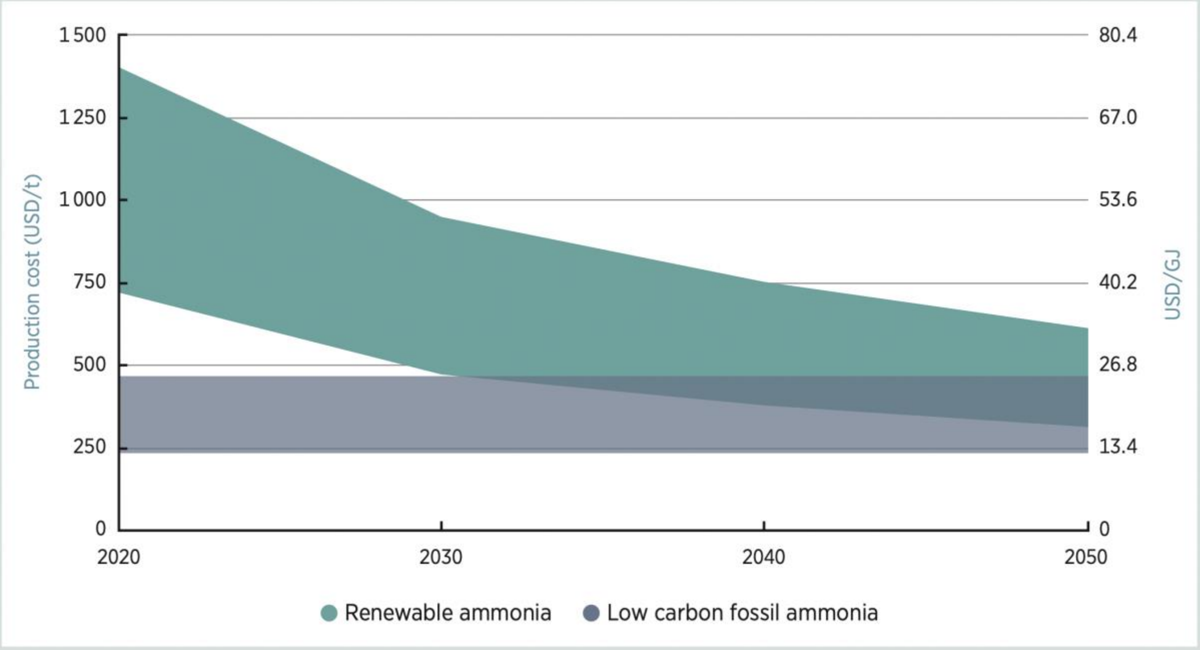


*Figure 4: Fossil fuel and renewable ammonia production costs. Source: IRENA & AEA (2022), Innovation Outlook: Renewable Ammonia.*

From the figures above, it is essential to notice that renewable ammonia is anticipated to reach the prices of fossil fuel-based ammonia by 2030 (IRENA & AEA, 2022).

### 5.3.2. Ammonia Production, Transportation and Storage

The increasing interest in renewable energies and the urgency for an energy transition away from fossil fuels make renewable ammonia and hydrogen even more vital for the upcoming years. It is now certain that ammonia as a hydrogen carrier will play an essential role in the next few years. That is because ammonia is a mature commodity from trading, storing and technological perspectives since it is used as a fertilizer feedstock (IRENA & AEA, 2022).

According to IRENA, the demand for ammonia as a hydrogen carrier will reach approximately 125Mt per year by 2050 in the 1.5°C scenarios, as seen in the figure below.

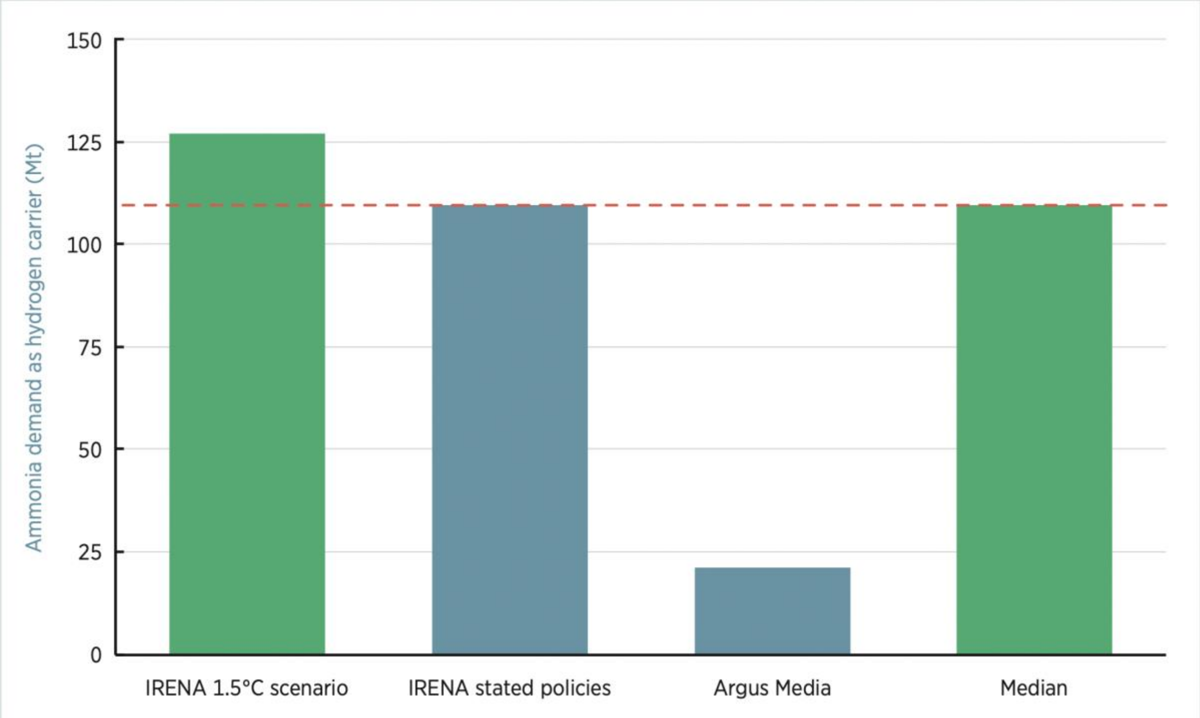


*Figure 5: Ammonia demand as a Hydrogen carrier. Source: IRENA & AEA (2022), Innovation Outlook: Renewable Ammonia.*

Ammonia infrastructure is well established, having over 190 terminals at 120 ports globally. Those handle around 20 million tonnes of ammonia annually (IRENA & AEA, 2022).

Transportation can be fulfilled by road, train, pipeline and ship. The latter occupies over half of the total transported ammonia, which reaches approximately 25 to 30 Mt per year. Pipelines are also widely used, mainly in the U.S.A. The main advantage of pipelines is that gas and liquid pipelines can be used to distribute ammonia after little modifications. Trains are used primarily in Europe and transport almost 1.5Mt per year (IRENA & AEA, 2022).

Large scales are liquified and refrigerated at -33°C with atmospheric pressure for ammonia storage. Ammonia is stored in tanks, and the facilities are located at ports near production facilities. On a smaller scale, ammonia is liquified using pressure (IRENA & AEA, 2022).

From a technical perspective, ammonia, hydrogen and nitrogen are produced after cracking. In the case of pure hydrogen production from ammonia, apart from the decomposition, a hydrogen purification process is also required. Partial decomposition results in a mixture of ammonia and hydrogen, allowing for usage in many applications (IRENA & AEA, 2022).

Ammonia decomposition systems, also known as ammonia crackers, are becoming more and more critical in large-scale hydrogen production, especially in northern Europe. The hydrogen distribution can occur when connected with the European hydrogen network, which is anticipated to reach about 23000 kilometers by 2040. It is essential to mention that the already existing natural gas network will accommodate almost two-thirds of the European hydrogen grid (IRENA & AEA, 2022).

Since ammonia is already an international commodity distributed via ships and pipelines, its transportation technologies are more mature and, therefore, less expensive than hydrogen. This is one of the most important reasons behind the preference for using ammonia for hydrogen transportation. Also, hydrogen transportation requires conversions into liquid hydrogen, which necessary infrastructure is not present yet (IRENA & AEA, 2022).

### 5.3.3. Current projects

Currently, various projects and research regarding ammonia as a hydrogen carrier exist. ThyssenKrupp Uhde, a German company, has developed a technology for ammonia cracking that allows for almost 80% efficiency and 100% hydrogen purity. Together with AmmoRef and Clariant, they have received 14 million euros in funds from Germany's government to continue their research on cost reduction and efficiency increase of ammonia cracking (IEA, 2022).

At the Port of Rotterdam, Gasunie, Vopak, and HES International are developing the potential of an import terminal known as the ACE terminal, which will include ammonia crackers (IEA, 2022). Additionally, The Port of Rotterdam, together with Trammo, Varo Energy and Proton ventures, have created the Transhydrogen Alliance, aiming to achieve 500 kt of hydrogen production per year through ammonia cracking. Today, hydrogen demand for industrial usage reaches approximately 1500 kt per year. Finally, Another big ammonia project takes place in Germany. Uniper will establish an ammonia cracker at the Port of Wilhelmshaven, anticipating approximately 295kt of hydrogen production after input of 2.2 Mt of ammonia annually, able to cover one-tenth of Germany's demand for hydrogen (IRENA & AEA, 2022).

## 5.4. Challenges and solutions for hydrogen commodification and trade

Decarbonization targets, climate change and the need for other energy sources have made the public and private sectors involved in the hydrogen industry. This can be shown by financial support, regulations, strategies and policies that have been implemented at a rapid pace in the last few years. However, since the hydrogen industry is still in its early stages, plenty of other actions should be implemented and challenged to be overcome in order to succeed and establish itself as a significant energy commodity. (Hydrogen Council & McKinsey & Company, 2021).

First, hydrogen production is dominated by natural gas and coal. Even though hydrogen is used on an industrial scale, currently, its production depends on fossil fuels. Secondly, the costs of producing hydrogen from renewable sources are still expensive, resulting in a slow-growing pace. Another challenge for hydrogen is that it is not yet widely used apart from industrial sites for oil refining and ammonia production. In order to grow even more, it should be used in more sectors, such as power production and transportation. However, one of the main reasons for the absence of hydrogen from other sectors is the lack of the appropriate infrastructure, such as the construction of pipelines and ships that will allow for easier distribution (IRENA, 2019).

Another significant barrier that should be overcome is the further reduction of production and transportation costs. According to Hydrogen Council, a 65GW electrolysis process will equalize the costs of grey and green hydrogen. The estimated required capital reaches around USD 50 billion. Another way to achieve a reduction of the expenses is the construction of large-scale hydrogen clusters that will allow for the involvement of various off-takers that will be able to share risks, investments and technological improvements. Those clusters could be port areas, industrial companies and export/import hubs (IRENA, 2019).

The global hydrogen network is expanding rapidly, with approximately 680 hydrogen projects worth around USD 240 billion announced to take place until 2030. However, the actual implementation of investments is absent, with only 1/10 of them being realized. China and North America are leading in the production of low-carbon hydrogen, with Europe occupying almost 30% of the total hydrogen projects globally. The main reason behind quicker development in China and North America is the strong government support (Hydrogen Insights, 2022). Many countries worldwide have started developing hydrogen import and export projects aiming to align with climate objectives. Governments have begun to implement frameworks to ensure that hydrogen supply from exporting countries is low-emission. European Union is an excellent example of such actions. In March 2022, European Commission launched the RepowerEU plan, which focuses on reducing fossil fuel consumption, independence from Russia's energy supply and enhancing the European Green Deal. The main goal of ReEpowerEU is the production of 10 Mt of green hydrogen per year and the import of another 10 Mt by 2030. Apart from these targets, the plan has also announced two delegated acts which include production methods and process suggestions for hydrogen to be accounted as green. Those proposals were agreed from member states of the EU in the Renewable Energy Directive (RED II). (IEA, 2022).

Even though the public sector has already taken action, another obstacle derives from this low proportion of investment realization. It indicates that the hydrogen market lacks final investment decisions. According to Hydrogen Council, the main reason behind the lack of final decision investments in hydrogen projects is the absence of demand visibility. Regulatory framework and funding around hydrogen are still lagging, discouraging offtakers from making final investment decisions and making long-term agreements. Long-term contracts are able to offer certainty around the hydrogen economy. Hydrogen's maximum potential should be fully exploited to reach the 2050 net zero emissions target. For that, around USD 700 billion is required by 2030. That is, USD 460 billion should still be invested until 2030 for targets to be met. These enormous amounts of money might be discouraging, but they only occupy approximately one-fifth of the total investments for oil and gas in the last 10 years (Hydrogen Insights, 2022).

Cooperation between the public and private sectors is required for global hydrogen trade to materialize. Hydrogen demand should be visible from the public sector, and a regulatory framework should be implemented around hydrogen usage. Fossil fuel consumption measures should be applied to end users to make hydrogen more competitive and attractive. Additionally, governments should announce the availability of loans, grants, tax credits, and financial support to hydrogen projects. This will attract more offtakers to take action. Finally, reliable certification schemes should be formulated. This will allow for a transparent hydrogen trade, ensuring hydrogen's origin, production process and performance (Hydrogen Insights, 2022).

From the private sector, project developers should ensure the conduction of long-term relationships between buyers and sellers. The primary purpose is to mitigate the risks and cover the capital costs for hydrogen network facilities and infrastructure. Moreover, hydrogen-related infrastructure should grow even more with storage, hydrogen conversion facilities and terminals to allow for efficient and effective global trade. In that way, both supply and demand volumes will increase, with private entities responsible for matching them efficiently (Hydrogen Insights, 2022).

The commodification of hydrogen and the realization of a hydrogen market requires stakeholders that are able to implement strategies and projects into solid actions. Short and long-term targets have to be set, accompanied by the appropriate regulatory framework. In addition, investors, governments and companies must build a core of developing infrastructure, find the proper workforce, and form the right partnerships. Obviously, these actions require effective strategies, research and huge investments (Hydrogen Council & McKinsey & Company, 2021).

Certification systems are also vital for the hydrogen trade to be established, Those include the different production and process methods and the guarantees of the origin of hydrogen. Certifications provide parties with transparency and security. Additionally, they give the relevant stakeholders with clarity to implement their projects and investment decisions. Currently, there are just a few standards and certification systems regarding hydrogen, and governments should take action to build those vital instruments. CertifHy, a certification system funded by the EU, is currently applied in voluntary markets and has the potential to be used as a regulatory instrument for hydrogen in the future. More specifically, it is an electronic certification that proves that a certain amount of hydrogen is produced at a specific location with a certain production method (IEA, 2022).

Finally, another important factor for realizing the hydrogen trade is the financial instruments and market structure. Currently, transactions between sellers and buyers are fulfilled by bilateral agreements, or they are managed by brokers. However, hydrogen is considered a capital-intensive product with enormous infrastructure and facilities needed. As a result, the parties involved want to ensure that their investments will finally pay off, and they ask for long-term contracts which offer more transparent prices. Implementation of take or pay contracts used in the gas and oil market can provide parties with security. On the other hand, there are parties that prefer more flexibility in the contracts without destination clauses included (IEA, 2022).

It seems that long-term contracts will dominate the hydrogen market in the short-term, but spot or resale mark. For that, ammonia will play a significant role since it is a mature commodity that already has the necessary infrastructure and financial instruments (IEA, 2022).

Regarding price discovery, hydrogen does not have a price benchmark yet. Open Hydrogen Initiative (OHI), a consortium by S&P Global Commodity Insights, GTI Energy and the National Technology Energy Laboratory, tries to measure the carbon intensity of a kilogram of hydrogen at the production level, providing customers with transparency and credibility. Therefore, the main goal of OHI is to create a benchmark for low-emission hydrogen. Finally, it can be applied to create contract and sport market prices (IEA, 2022).

Apart from OHI, another project aims to tackle high emissions and enhance hydrogen usage. H2Global mechanism by Hydrogen Intermediary Network Company (HINT.CO) provides solutions to buyers and sellers regarding the uncertainty of the hydrogen market, which requires huge investments. More specifically, HINT.CO conducts long-term purchase agreements with the vendors and short-term sales contracts with the buyers. The core of these agreements is based on the contracts for differences (CfD) approach with HINT.CO covers any price differences between supply and demand using German grants. The German government has agreed to make available around 1 billion euros. Through this project, hydrogen investments will be safer, and hydrogen trade will be eased (IEA, 2022).

# 6. Results

After analyzing how commodity markets function in theory, examining well-established commodities such as oil and natural gas and describing the current situation for hydrogen and ammonia, this section will provide insights and answers to the main research question about the critical factors in terms of price discovery, infrastructure, market liquidity for commodifying hydrogen and launching a successful hydrogen and ammonia market.

As mentioned in the third chapter, data were collected after conducting semi-standardized interviews with experts in the field of hydrogen and ammonia. Additionally, part of the data was provided from the research of the Erasmus University of Rotterdam conducted by Wouter Jacobs and his colleagues named Commodiphy.

## 6.1. Ammonia role

As described in chapter 5, ammonia is an important hydrogen carrier. One of the advantages is that it can be transported easily, and its cooling process does not require extreme temperatures. Ships, infrastructure and terminals already exist to facilitate ammonia, but it requires a lot of energy for cracking to release hydrogen. Nevertheless, in the last few years, hydrogen is not used in the form of hydrogen but in the form of ammonia, for instance, as a fertilizer or as a source of chemical feedstock. European targets for decarbonization and the war between Russia and Ukraine have made imports much more important, with ammonia becoming a key commodity for hydrogen storage and transportation unexpectedly. Large volumes of ammonia are anticipated to be imported by regions with abundant renewable energy sources and cheap electricity and energy sources. Middle East, the USA, Chile, South and North Africa and Australia are considered the best candidates for ammonia exporting.

These are the main reasons why ammonia is the fastest-appearing transportation mode for hydrogen, at least in the short term. The reason behind its short-term efficiency is that it requires a lot of energy to crack it and convert it back to hydrogen. As a result, regions that lack energy sources, mainly fossil fuels, are not able to use them continuously. Additionally, if hydrogen wants to grow and be used purely as fossil fuels for several applications, then it needs to be transported as hydrogen because ammonia cracking for hydrogen release will not be able to handle huge volumes. Finally, since ammonia is toxic and dangerous, regulations might cause uncertainty about its effectiveness in the long term. A great example of regulations is the transportation of ammonia through pipelines since any leakage may have severe consequences.

People from the ammonia sector see that in the next 10 years, trading volumes are anticipated to double. Until 2050, ammonia trading is expected to increase by 10 times, reaching approximately 400 Mt annually. Ammonia business is expected to grow, with initially Europe being the frontrunner and then the US taking the lead. This is mainly a result of less complexity and taxation in the US when a party meets the characteristics.

The ammonia spot market already exists, and around 20 Mt are traded annually. These volumes are a result of spot and long-term contracts trading under the spot price. However, even though price transparency of the ammonia spot market is necessary due to the anticipated extreme increase in demand in the next few years, clarity of the price formation of ammonia has not been achieved yet. The majority of ammonia today is produced by natural gas. Therefore, its price is highly dependent on the prices of natural gas, which is exceptionally high. This energy crisis has increased the urgency of deploying renewable sources to produce green ammonia and hydrogen. Pricing is currently a huge barrier for final investment decisions to be realized. The ammonia market for fertilizers will continue to exist, but in order for this to be expanded, the right price should be formulated and applied. Currently, ammonia price is an obstacle to using it as the main hydrogen carrier for transportation. The price is between EUR 3 and 4/kg, with cracking technology prices not taken into consideration yet.

Since different grades characterize ammonia due to different production processes, such as hydrogen (blue, green etc.), the transparency of the market will be highly dependent on the certification schemes around it. Therefore, clarification of the standardization based on origin and other characteristics is significant.

## 6.2. Hydrogen commodification and trade

Commodification means that standardization must exist. In fact, there are two bases of commodification. The one is for hydrogen to become a shipping commodity or a pipeline commodity. According to Bert den Ouden CEO of the HyXchange project, the most critical success factor for a hydrogen market is to become open and integrated for everyone, which means a third-party access network. A network needs to be there and be independent. Otherwise, third-party access to the network will not be viable. If the network exists, then stakeholders from market parties can participate.

### 6.2.1. Certification schemes

The majority of interviewed parties demonstrated certification as one of the most critical factors in enabling hydrogen trade. Certification schemes will play a vital role in developing ammonia and hydrogen trading. More specifically, they will not incentivize vendors to produce low-carbon hydrogen and ammonia but mainly verify the product's origin. It will be key for the hydrogen market to become transparent and fair for all the parties involved. Additionally, the presence of trading agreements between certifications will also be vital. So, there will be trading instruments for the certificates. And then, there will be trading instruments for the spot market.

A simulation will take place by a spot market across the already existing pipelines in the Netherlands. Therefore, this will be a spot market trading system to provide balance so that each party can balance themselves every hour. Balancing the hydrogen market on the pipelines will not be easy. So, balancing will be a tool that will be of great importance and is already developing. Balancing tools are already there for electricity and natural gas. Therefore, the project is to take one of those and adapt hydrogen exchange to them. Governments can be helpful in the certification schemes and traceability around ammonia, guaranteeing the origin and the characteristics of the commodity and setting up the legal basis.

Finally, according to Roman van Riel Junior Business Manager Electrification & Hydrogen New Business Development of Port of Rotterdam, a hydrogen trading platform will also enhance the hydrogen exchange as a commodity since off-takers will have the necessary information to find each other and trade hydrogen.

### 6.2.2. Market liquidity

At the moment, hydrogen and ammonia market liquidity face obstacles. Both supply and demand sides lack actual project and investment implementation since they are waiting for someone to take the first step. From the supply side, engineering and capacity absence cause problems. On the demand side, investors want to ensure that they will take their money back. However, still, the lack of actual project implementation discourages them to invest even though they are willing to support financially even with a low Internal Rate of Return (IRR). If the hydrogen market wants to be liquified, then infrastructure plays a vital role. A market is considered liquid when pipelines and infrastructure exists. Therefore, hydrogen should follow the natural gas example. Infrastructure absence was the main reason behind the slow pace of growth of LNG liquidity. Hydrogen should be traded inside a network, such as electricity and natural gas, so any party can participate.

Currently, hydrogen and ammonia markets depend on long-term bilateral agreements between the off-takers. The main reason behind this is that there is high uncertainty and a need for guaranteed demand and supply for both producers and buyers to mitigate investment risks. Furthermore, investors and buyers want to verify that they can indeed decarbonize and then generate a certain framework for their future projects. As a result, market liquidity is expected to be achieved after 2030, when the market will be more well-established, and the risk will be lower in the spot market trade.

## 6.3. Blue hydrogen and ammonia importance

Hydrogen production from renewable energy sources is growing at a rapid pace, with several investments in solar and wind infrastructure taking place. This rapid growth generates questions regarding blue hydrogen's importance and role in the energy transition since the required infrastructure for CCS and storage facilities are extremely expensive. In addition, after the war in Ukraine and the energy crisis globally, blue hydrogen has been diminished even more.

However, despite the obstacles and questions around blue hydrogen is importance is vital for hydrogen to become a tradable commodity. Green hydrogen is produced from renewable sources using natural phenomena such as wind and sun. The main disadvantage is that the sun and wind do not always exist, and as a result, energy production from those sources may cause uncertainty. Consumers need a constant base load that can guarantee their supply. Therefore, blue hydrogen will be used as a flexible backup that will cover any production inconsistencies that may occur.

Another opinion is that the main purpose of blue hydrogen and ammonia is to make the transition smoother and easier when green is ready to take place. Green needs huge power capacity, electrolysers and renewable energy facilities that are not currently in place to meet the demand and make the energy transition reality.

## 6.4. Hydrogen and ammonia price benchmark

The question regarding an establishment of a price benchmark around hydrogen and ammonia generated unclear answers since it is a challenging topic that cannot be easily predicted.

A representative of a company related to hydrogen and ammonia production stated that an important factor in whether will be a pricing point for the hydrogen and ammonia market is whether the market design will be centralized or decentralized. A centralized market means, for instance, that there will be a central cracking facility for ammonia in Rotterdam to convert it into hydrogen. As the current situation stands, Australia seems to have the role of the leading hub. However, there are also other regions, such as Rotterdam, that have the potential to become a major hub, but this depends on the market design that is not set yet.

Other opinions stated that it is very likely that hydrogen will be able to develop a pricing center. A price center for ammonia will only be viable as a corollary of the hydrogen index. Before all the carriers, hydrogen itself will take a price, and then carriers will follow depending on various factors.

Finally, Roman van Riel said that there are a lot of different factors on whether a price benchmark for hydrogen should exist or not. Since it is anticipated to be imported from all around the world, it is extremely challenging to have only one pricing point to define all the prices.

## 6.5. Netherlands as the main hydrogen hub

The transition from fossil fuels to hydrogen cannot take place immediately. It needs to emerge gradually. Even though there are several countries around the world that already have pipeline network infrastructure, the Netherlands has the potential to become the price center of hydrogen trading. It is able to build a hydrogen pipeline system much faster that any other country.

Most countries worldwide only have one pipeline that distributes natural gas. For that reason, it is impossible for a country to dedicate its pipeline network only to hydrogen since that will mean that gas will not be able to flow anymore, and therefore the transition will not take place in the right way.

Figure X below shows the pipeline infrastructure of the Netherlands, with the yellow lines representing the already existing pipelines and the blue that are anticipated to be built by 2030.


*Figure 6: The Netherlands pipeline network. Source: Gasunie*

The greatest advantage of the pipeline network of the Netherlands is that it has four pipelines. As a result, one of them can easily be taken and transformed into hydrogen, and the gas flow can remain. That's why the Netherlands is suitable because it is one of the only countries which is ready on a country-wise basis for a dedicated hydrogen-only network. Also, it is very connected to other countries, especially Germany and Belgium.

In addition to the above advantage, the Netherlands is the most hydrogen-intensive economy in the world. currently, it is mainly grey hydrogen, but in the future, it will be blue or green.

Figures X below depict the hydrogen consumption per country and per capita. Someone can easily see that the Netherlands has the greatest consumption of hydrogen per capita, reaching 10GJ per year.

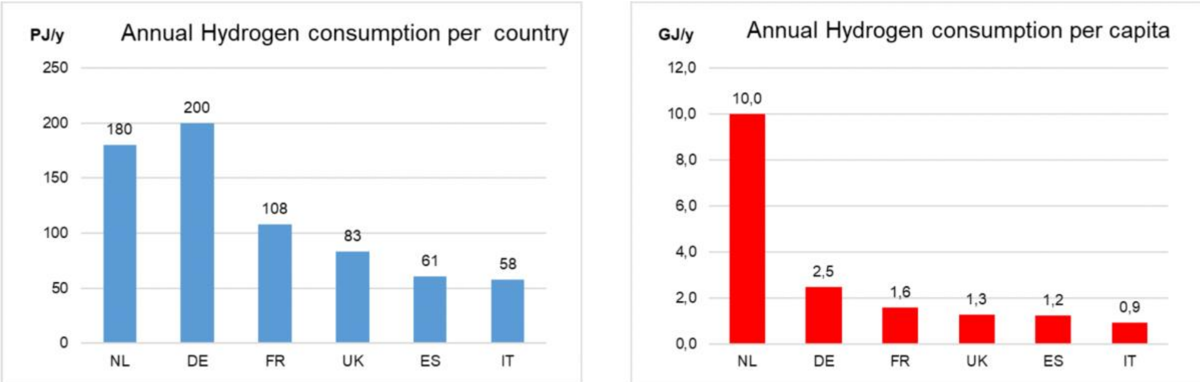


*Figure 7: Annual hydrogen consumption per country and per capita in Europe. Source: Update HyXchange*

# 7. Conclusion

Climate change, the energy crisis and the urgency for decarbonization of the world have incentivized the public and private sectors to find renewable sources to replace fossil fuels. Hydrogen is one of the best candidates to replace fossil fuel usage in the transportation heating and industry sector. However, hydrogen is not considered a tradable commodity yet. In addition, since hydrogen production, transportation and usage are extremely challenging, ammonia as a hydrogen carrier is also examined as one of the best solutions to accommodate hydrogen. Therefore, this research purpose is to identify the critical success factors of commodifying hydrogen and launching a hydrogen and ammonia market.

First, commodity markets were analyzed to introduce how they function in terms of trading, price discovery and contracting. Next, the methodology of the thesis is analyzed, which includes ex-ante evaluation of hydrogen and ammonia trade, deductive analysis and exploratory research of other commodities and finally, semi-structured interviews with experts on the ammonia and hydrogen sector to identify the steps that should be followed in order to answer the main research question. The fourth chapter consists of the deductive analysis of crude oil and liquified natural gas (LNG), aiming to take examples of how they function and grew over the years. The fifth chapter includes an analysis of hydrogen and ammonia as products examining the production, storage transportation, prices and current projects. Finally, chapter six identifies the factors that will play a significant role in making the hydrogen and ammonia market a reality.

Various conclusions have been drawn after the research, some of which are contradictive. Hydrogen is growing at a rapid pace, even faster than was expected. The first anticipation for specialized ships was for 2030 and then for 2027. Now, projects have been announced, with the first hydrogen ships arriving in 2024.

The hydrogen production process (grey, blue, green) will depend on the location. That is where the cheapest energy sources exist. For example, green hydrogen will be mainly produced in Australia, where renewable energy sources are abundant, while blue hydrogen is expected to be produced in locations where CCS facilities are available.

Liquid organic hydrogen (LOH) is one of the main hydrogen carriers for transporting hydrogen by trucks or ships. It is easy to transport, and it does not need cooling. However, liquid hydrogen carries a lot of dead mass that is not needed in the end, and the process of releasing hydrogen requires a lot of energy. Therefore, a great amount of electricity is required at the source.

Liquid hydrogen and ammonia will be the best candidates for hydrogen trading. Ammonia trading is expected to increase in the next few years, mainly transported via ships and rail. Also, ammonia is considered a mature commodity that already has a well-established infrastructure and technology, a factor that enhances the commodification of hydrogen. For that reason, it is anticipated that its volumes will increase before the other hydrogen carriers. Hydrogen will be accommodated by pipelines and ships, most probably in a liquid hydrogen form or ammonia. Low-carbon hydrogen carriers and ammonia will play a key role in energy supply and security. Additionally, ammonia is considered to be the best hydrogen carrier for transportation and storage in the short term because of its toxicity and the regulations that are anticipated around it in the next few years.

Hydrogen price is linked to other sources depending on how it is produced. Grey and blue hydrogen are related to natural gas prices and green hydrogen to the green electricity costs from renewable sources. Green hydrogen is anticipated to be the price driver of hydrogen. Blue will play the role of balancing power but not as a price driver. Green hydrogen prices are dropping fast after the natural gas prices increase due to the energy crisis and the general expansion of the economies after the covid-19 wave.

Cooperation between the public and private sectors is mandatory. Firstly, governments can support hydrogen commodification with several actions. First, they can help with financing research studies on how hydrogen efficiency can be improved. Additionally, they can support the creation of certification schemes that will indicate the characteristics of the tradable product and the country of origin. This will enhance the transparency of the market. On the other hand, commercial partners and trading parties should be responsible for setting up the necessary trading facilities for hydrogen exchange.

Finally, as Bert den Ouden, CEO of HyXchange, stated, hydrogen commodification will be realized when the market is available for everyone. This means that an independent third-party access network should exist. If the network exists, then stakeholders can participate.

Hydrogen and ammonia trading is growing but at a slower pace. The targets that the public and private sectors have set are highly ambitious and unrealistic for the short term. However, essential steps are taking place, and projects have started to be implemented successfully. Additionally, since the first steps are always the most difficult, there is an optimistic perception that the hydrogen and ammonia market will grow in an exponential rhythm and that energy transition will be realized through those commodities.

# 8. References


Agerton, M. (2017). Global LNG Pricing Terms and Revisions: An Empirical Analysis. The Energy Journal, 38(1). https://doi.org/10.5547/01956574.38.1.mage

Andersson, J., Krüger, A., & Grönkvist, S. (2020). Methanol as a carrier of hydrogen and carbon in fossil-free production of direct reduced iron. Energy Conversion and Management: X, 7, 100051. https://doi.org/10.1016/j.ecmx.2020.100051

Baker, H. K., Filbeck, G., & Harris, J. H. (2018). Commodities. Oxford Scholarship Online. https://doi.org/10.1093/oso/9780190656010.003.0001

Ball, M., & Wietschel, M. (2009). The future of hydrogen – opportunities and challenges. International Journal of Hydrogen Energy, 34(2), 615–627. https://doi.org/10.1016/j.ijhydene.2008.11.014

Braginskii, O. B. (2009b). Crude oil prices: History, forecast, and impact on economy. Russian Journal of General Chemistry, 79(11), 2486–2498. https://doi.org/10.1134/s1070363209110371

Bern, V. E., & von Bern, E. (2012). Rohstoff - Das gefährlichste Geschäft der Schweiz (German Edition) (2., ed.). Salis Verlag. Retrieved from: https://www.yumpu.com/en/document/read/5359983/commodities

Bhattacharyya, S. C. (2020). Energy Economics: Concepts, Issues, Markets and Governance (2nd ed. 2019 ed.). Springer.

Brown-Hruska, S. (2009). The Derivatives Marketplace: Exchanges and the Over-the-Counter Market. Financial Derivatives, 21–42. https://doi.org/10.1002/9781118266403.ch2

Casula, M., Rangarajan, N., & Shields, P. (2020). The potential of working hypotheses for exploratory deductive research. Quality & Quantity, 55(5), 1703–1725. https://doi.org/10.1007/s11135-020-01072-9

Chatterjee, S., Parsapur, R. K., & Huang, K. W. (2021). Limitations of Ammonia as a Hydrogen Energy Carrier for the Transportation Sector. ACS Energy Letters, 6(12), 4390–4394. https://doi.org/10.1021/acsenergylett.1c02189

Chevalier, J., & Ielpo, F. (2013). Commodities and the Business Cycle. The Economics of Commodity Markets, 115–116. https://doi.org/10.1002/9781118710098.part2

Chevalier, J., & Ielpo, F. (2013a. Commodities and Fundamental Value. The Economics of Commodity Markets, 169–176. https://doi.org/10.1002/9781118710098.part3

Chevalier, J., & Ielpo, F. (2013). Individual Dynamics: From Trends to Risks. The Economics of Commodity Markets, 3–50. https://doi.org/10.1002/9781118710098.ch1

Clark, I. J. (2014b). Commodity Option Pricing: A Practitioner's Guide (The Wiley Finance Series) (1st ed.).

Deloitte Netherlands. (2022). What is hydrogen? Retrieved by https://www2.deloitte.com/nl/nl/pages/energy-resources-industrials/articles/what-is-hydrogen.html?id=nl:2ps:3gl:4always-on-broad::6er:20220309:foe-topic&gclid=CjwKCAjwj42UBhAAEiwACIhADv8lRRHzmSS-v43NA2wvmlv-Tn71jyQfK7CR3NZ5s4YPz6DgUn6puBoCI_8QAvD_BwE

Elman, C., Gerring, J., & Mahoney, J. (2020). The Production of Knowledge: Enhancing Progress in Social Science (Strategies for Social Inquiry). Cambridge University Press.

Elder, J., Miao, H., & Ramchander, S. (2014). Price discovery in crude oil futures. Energy Economics, 46, S18–S27. https://doi.org/10.1016/j.eneco.2014.09.012

Energy.Gov. (2016). "Understanding Natural Gas and LNG Options" Handbook. Retrieved from https://www.energy.gov/ia/articles/understanding-natural-gas-and-lng-options-handbook

European Council. (2022). Fit for 55. Retrieved from https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/

European Commission. (2022). Hydrogen. Energy. Retrieved from https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en

European Commission. (2022). Remarks by Executive Vice-President Vestager on Important Project of Common European Interest in the hydrogen technology value chain. Retrieved from https://ec.europa.eu/commission/presscorner/detail/en/SPEECH_22_4549

European Commission. (2022). REPowerEU: A plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition. European Commission - European Commission. Retrieved from https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131

European Commission. (2014). Paris Agreement. Retrieved from https://ec.europa.eu/clima/eu-action/international-action-climate-change/climate-negotiations/paris-agreement_en#eus-role

European Council. (2022). European Green Deal. Retrieved from https://www.consilium.europa.eu/en/policies/green-deal/

Gasunie. (2021). Creation 'HyXchange' hydrogen exchange a step closer. Retrieved from https://www.gasunie.nl/en/news/creation-hyxchange-hydrogen-exchange-a-step-closer

Geman, H. (2009). Commodities and Commodity Derivatives: Modeling and Pricing for Agriculturals, Metals and Energy (The Wiley Finance Series Book 464) (1st ed.).

Hartley, Peter R. (2014). Recent Developments in LNG Markets. James A. Baker III Institute for Public Policy of Rice University: http://bakerinstitute.org/research/recent-developments-lng-markets/

Hartley, P. R. (2015). The Future of Long-term LNG Contracts. The Energy Journal, 36(3). https://doi.org/10.5547/01956574.36.3.phar

Hotelling, H. (1931). The Economics of Exhaustible Resources. Journal of Political Economy 39, 137–175 https://www.jstor.org/stable/1822328

Hydrogen Insights (2022). An updated perspective on hydrogen market development and actions required to unlock hydrogen at scale. Hydrogen Council. Retrieved by https://hydrogencouncil.com/en/hydrogen-insights-2022/

IEA (2021). Global Hydrogen Review 2021. IEA, Paris. Retrieved from https://www.iea.org/reports/global-hydrogen-review-2021

IEA (2019). The Future of Hydrogen. IEA, Paris. Retrieved from https://www.iea.org/reports/the-future-of-hydrogen

IEA (2022). Global Hydrogen Review 2022. IEA. Paris https://www.iea.org/reports/global-hydrogen-review-2022

Ielpo, F. (2018). The Economics of Commodities and Commodity Markets. Oxford Scholarship Online. https://doi.org/10.1093/oso/9780190656010.003.0002

IRENA. (2019). Hydrogen: A renewable energy perspective. https://www.irena.org/publications/2019/Sep/Hydrogen-A-renewable-energy-perspective

IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, International Renewable Energy Agency, Abu Dhabi.

IRENA. (2022). World Energy Transitions Outlook: 1.5°C Pathway. https://www.irena.org/publications/2022/Mar/World-Energy-Transitions-Outlook-2022

IRENA & AEA (2022), Innovation Outlook: Renewable Ammonia, International Renewable Energy Agency, Abu Dhabi, Ammonia Energy Association, Broo

Jacobs, W., & van Bergen, T. (2014). Understanding the Economic Geography of Commodity Trade.

Ji, Q., & Fan, Y. (2016). Evolution of the world crude oil market integration: A graph theory analysis. Energy Economics, 53, 90–100. https://doi.org/10.1016/j.eneco.2014.12.003

Johnson, L. L. (1960). The Theory of Hedging and Speculation in Commodity Futures. The Review of Economic Studies, 27(3). https://doi.org/10.2307/2296076

Kavussanos, M. G., & Nomikos, N. K. (2001). Price Discovery, Causality and Forecasting in the Freight Futures Market. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.271072

Keynes, J. M. (1930). A Treatise on Money. Vol. I. The Pure Theory of Money. Journal of the Royal Statistical Society, 94(4), 618. https://doi.org/10.2307/2341941

Koppenhaver, G. D. (2009). Derivative Instruments: Forwards, Futures, Options, Swaps, and Structured Products. Financial Derivatives, 1–20. https://doi.org/10.1002/9781118266403.ch1

Kouvelis, P., Li, R., & Ding, Q. (2013). Managing Storable Commodity Risks: The Role of Inventory and Financial Hedge. Manufacturing & Service Operations Management, 15(3), 507–521. https://doi.org/10.1287/msom.2013.0433

Kovac. A., et al. (2021). Hydrogen in energy transition: A review. International Journal of Hydrogen Energy, 46(16), 10016-10017. https://doi.org/10.1016/j.ijhydene.2020.11.256

Lubitz, W., & Tumas, W. (2007). Hydrogen: An Overview. Chemical Reviews, 107(10), 3900–3903. https://doi.org/10.1021/cr050200z

Nikhalat-Jahromi, H., Angeloudis, P., Bell, M. G. H., & Cochrane, R. A. (2017). Global LNG trade: A comprehensive up-to-date analysis. Maritime Economics & Logistics, 19(1), 160–181. https://doi.org/10.1057/mel.2015.26

Noussan, M., Raimondi, P. P., Scita, R., & Hafner, M. (2020). The Role of Green and Blue Hydrogen in the Energy Transition—A Technological and Geopolitical Perspective. Sustainability, 13(1), 298. https://doi.org/10.3390/su13010298

Pirrong. C. (2014). Fifty years of global LNG. Trafigura.

Pirrong. C. (2017). Liquefying a Market: The Transition of LNG to a Traded Commodity. Journal of Applied Corporate Finance, 29(1), 86-91. https://doi.org/10.1111/jacf.12222

Pirrong, C. (2014). The economics of commodity trading firms. Trafigura.

Pirrong, C. (2009). Energy Derivatives. Financial Derivatives, 125–133. https://doi.org/10.1002/9781118266403.ch9

Priolon, J. (2019). General Observations on the Physical Trading of Commodities. Financial Markets for Commodities, 1–11. https://doi.org/10.1002/9781119579274.ch1

Priolon, J. (2019). The Financial Commodity Markets. Financial Markets for Commodities, 13–23. https://doi.org/10.1002/9781119579274.ch2

Priolon, J. (2019). Futures Contracts and Forward Contracts. Financial Markets for Commodities, 25–54. https://doi.org/10.1002/9781119579274.ch3

Reiter, B. (2013). The Epistemology and Methodology of Exploratory Social Science Research: Crossing Popper with Marcuse. Government and International Affairs Faculty Publications. Paper 99.

Ryan, F., Coughlan, M., & Cronin, P. (2009). Interviewing in qualitative research: The one-to-one interview. International Journal of Therapy and Rehabilitation, 16(6), 309–314. https://doi.org/10.12968/ijtr.2009.16.6.42433

Samset, K., & Christensen, T. (2015). Ex Ante Project Evaluation and the Complexity of Early Decision-Making. Public Organization Review, 17(1), 1–17. https://doi.org/10.1007/s11115-015-0326-y

Schofield, N. C. (2021). Commodity Derivatives: Markets and Applications. (The Wiley Finance Series) (2nd ed.). Wiley.

Scita, R., Raimondi, P. P., & Noussan, M. (2020). Green Hydrogen: The Holy Grail of Decarbonisation? An Analysis of the Technical and Geopolitical Implications of the Future Hydrogen Economy. SSRN Electronic Journal. http://dx.doi.org/10.2139/ssrn.3709789

Secomandi, N., & Kekre, S. (2014). Optimal Energy Procurement in Spot and Forward Markets. Manufacturing & Service Operations Management, 16(2), 270–282. https://doi.org/10.1287/msom.2013.0473

Staritz, C. (2013). EconStor: Re-regulation of commodity derivative markets: Critical assessment of current reform proposals in the EU and the US. Retrieved from https://www.econstor.eu/handle/10419/98792

Stebbins, R. (2001). Exploratory Research in the Social Sciences. SAGE Publications, 2–17. https://doi.org/10.4135/9781412984249

Taušer, J., & Čajka, R. (2014). Hedging techniques in commodity risk management. Agricultural Economics (Zemědělská Ekonomika), 60(4), 174–182. https://doi.org/10.17221/120/2013-agricecon

Thomas, G., & Parks, G. (2006). Potential Roles of Ammonia in a Hydrogen Economy. U.S. Department of Energy.

Todd, P., & Wolpin, K. I. (2006). Ex Ante Evaluation of Social Programs. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.931393

Tsoskounoglou, M., Ayerides, G., & Tritopoulou, E. (2008). The end of cheap oil: Current status and prospects. Energy Policy, 36(10), 3797–3806. https://doi.org/10.1016/j.enpol.2008.05.011

van den Berghe, K., Peris, A., Meijers, E., & Jacobs, W. (2022). Friends with benefits: the emergence of the Amsterdam–Rotterdam–Antwerp (ARA) polycentric port region. Territory, Politics, Governance, 1–20. https://doi.org/10.1080/21622671.2021.2014353

Williams, D. G., & Babbie, E. R. (1976). The Practice of Social Research. Contemporary Sociology, 5(2), 163. https://doi.org/10.2307/2062956

Wolpin, K. I. (2013). Ex Ante Policy Evaluation—The Role of Theory. The Limits of Inference without Theory. https://doi.org/10.7551/mitpress/9258.003.0004

Wood, D. A. (2012). A review and outlook for the global LNG trade. Journal of Natural Gas Science and Engineering, 9, 16–27. https://doi.org/10.1016/j.jngse.2012.05.002