TNO innovation for life

Renewable Ammonia

VALUE CHAIN ANALYSIS

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Executive Summary

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Blue and green ammonia stand out as promising solutions to drive global decarbonization initiatives. The upcoming ACE Terminal in the Port of Rotterdam aims to further enhance and exploit ammonia's role in the energy transition.

Understanding the value chain of ammonia is crucial for its full development and integration into the industry. While prior studies addressed production and import, there is a gap in understanding and establishing post-arrival phases.

Main objectives

1. Conduct a comprehensive **value chain analysis** from import stages to end-use applications, and **identify obstacles** involved in transitioning to ammonia.
2. **Evaluate** different **distribution methods** for ammonia.
3. Investigate the **present and future applications** of ammonia and assess business opportunities.
4. Conduct **market research**, including **interviews** with relevant stakeholders, to understand perspectives and preferences of the ammonia industry.

Key findings

Interviews were conducted and participants shared their opinions:

- Strong preference for **cracking** ammonia into hydrogen for multiple uses.
- Ammonia as a **shipping fuel** has the most potential as a future application.
- An **ammonia pipeline** for inland distribution is the safest option.
- Two big fertilizer companies have no interest in buying renewable ammonia through the ACE Terminal.

The **main obstacles** involved in transitioning to ammonia are:

- **Cost competitiveness.**
- **Safety** concerns, especially in terms of distribution.
- The need for **governmental cooperation** and support to implement **policies and certification.**
- Lack of **off-take agreements** and **market uncertainty.**

Main conclusions

- Renewable ammonia needs a stronger value proposition because aspects like safety, price, certification, conversion losses and combustion gases need to be addressed.
- Market research should not be based on the biggest ammonia producers and consumers in the Netherlands but should instead look into the smaller plants in industrial clusters, which probably have less resources to import the ammonia themselves.
- Demand is too unclear to justify the construction of an ammonia pipeline.
- Cracking is likely to play a role in the transition considering Europe's preference for hydrogen as an energy carrier and the hydrogen pipeline network under development. However, while the technology and markets mature, two central pilot cracking plants in Antwerp and Rotterdam might be the best strategic decision.
- Gradual integration of ammonia, first in existing markets and then in new ones, poses a lower risk. However, integration of industrial processes and inability to switch off individual plants will limit opportunities in current ammonia markets.

Recommendations

- **Consider the Betuweroute** rail infrastructure to develop a distribution strategy and critically assess the **viability of a pipeline** in the near future.
- **Educate and advise the government** on policies to drive and facilitate the transition, especially for customers.
- Foster dialogue and collaboration among companies and governments to **address value chain bottle-necks** and ensure off-takers.
- Adopt **standardized procedure** frameworks for the handling and distributing of ammonia.
- Further explore the opportunities and challenges of **power generation** as a new application of ammonia.

Abbreviations

APAC	Asia-Pacific
BE	Belgium
CapEx	Capital Expenditure
CCS	Carbon Capture and Storage
CO_2	Carbon dioxide
DE	Germany
EMEA	Europe, Middle East, and Africa
EU	European Union
EU-27	European Union - 27 member states
FEED	Front-End Engineering Design
FID	Final Investment Decision
H_2	Hydrogen
IRA	Inflation Reduction Act
LNG	Liquefied Natural Gas
LOHCs	Liquid Organic Hydrogen Carriers
LPG	Liquefied Petroleum Gas
MoU	Memorandum of Understanding
Mt	Million tons
N_2	Nitrogen
N_2O	Nitrous oxide
NH_3	Ammonia
NG	Natural Gas
NO_x	Nitrogen oxides
NL	Netherlands
OpEx	Operational Expenditure
Q&A	Question and Answer

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1

Introduction

Company Profile

Introduction

This section provides background information about TNO in order to contextualize the topic of the thesis. It introduces the company, its vision and mission, strategy, structure, core competencies, products and services, customer base, innovation activities, financial analysis, environmental analysis, partnerships, and values. Finally, it describes the motive for the thesis and relevance of the topic in the context of the current climate crisis.

1.1. Company overview

The Netherlands Organization for Applied Scientific Research (Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek) is an independent research organization striving to drive innovation, and create economic and social value[1]. TNO was founded by the Dutch government in 1932 with the goal of making information accessible to businesses and governments[1], developing knowledge for practical application, boosting the competitive strength of industry in a sustainable way, and improving the well-being of society[2]. See a summary of TNO's history in Appendix 1.

The company, headquartered in Den Haag, has around 3,900 employees[3] in 24 different locations across the country and three abroad, including offices and laboratories[1]. See overview of locations in Appendix 1, Table A1.

TNO has an international presence and collaborates with organizations and partners worldwide. While it is primarily based in the Netherlands, it actively engages in international research, innovation and consultancy projects. These activities allow TNO to establish a network, foster knowledge exchange and contribute to technological advancements at a European and global level.

1.2. Vision and mission

TNO's **vision** is to be a leading research organization and ensure a safe, healthy, sustainable, and digitally connected society[3].

TNO's **mission** is to generate innovative and practical solutions that create impact and value for society at large, and contribute to a more sustainable future[4]. In doing so, the company tackles challenges such as security, sustainable energy supply, circular use of raw materials, and IT technology that respects public values[3].

1.3. Strategy

TNO aims to achieve its mission by performing two core tasks[3]:

- **Support the Dutch government** in carrying out statutory government tasks in the public interest, and provide policy advice for all ministries.
- **Strengthen the earning power of the Dutch economy** and increase employment through innovation, collaboration, licensing, and founding of new companies (spin-offs).

Moreover, the company's strategic priorities in 2022 were the following[5]:

(1) **Develop systems solutions** that consider the consequences for the greater whole and the long-term.
(2) **Create innovation ecosystems** by involving many different parties and ensuring a common strategy.
(3) **Achieve technological breakthroughs** to solve societal challenges and create opportunities for the economy.
(4) **Dynamic innovation** to ensure success in the rapidly changing global environment and give employees the opportunity to realize their full potential.

TNO has also defined some key strategic elements to help achieve its objectives, including the four societal themes[4] (safety, health, sustainability, and digitalization):

Table 1. TNO's key strategic elements

Client focus to increase impact	**SMEs** small and medium-sized enterprises, and the challenges they are facing
Valorization and implementation for successful market launch	**Time-to-market** is crucial to maintain competitiveness
Focus and mass (moonshot targets) for key enabling technologies and the four societal themes	**Systems thinking and systems innovation** to grasp many perspectives and understand complex systems
Demonstratable impact on complex societal challenges	**Fit and healthy organization** equality, diversity and inclusiveness

1.4. Organizational structure

TNO consists of a Supervisory Board, Executive Board, Council for Defense Research, services organization, and 6 units[6] (see Figure 1).

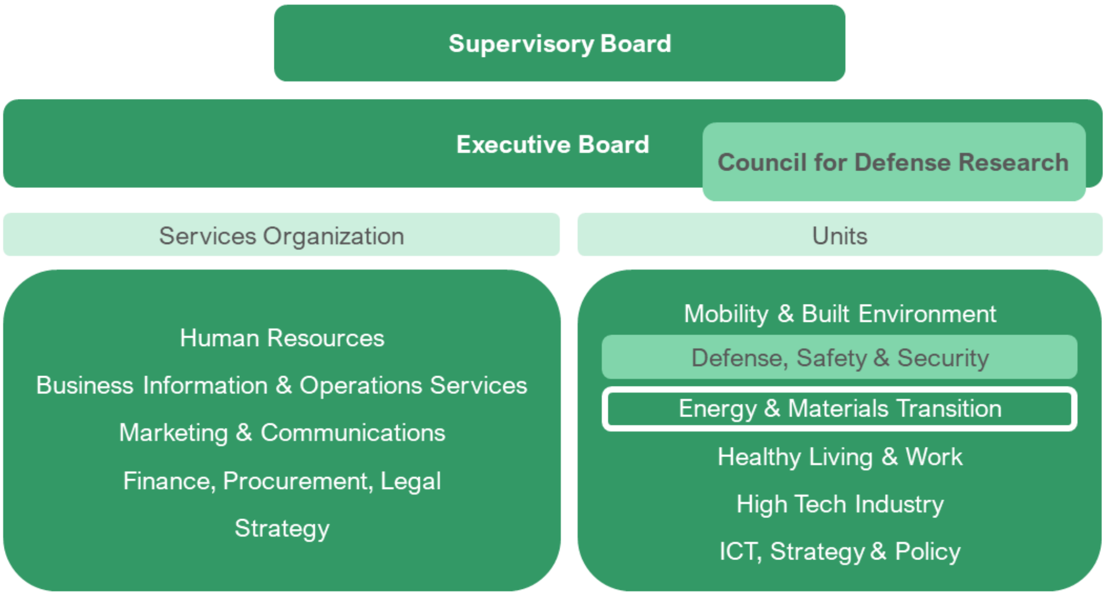

Figure 1. Organizational structure of TNO

The Supervisory Board has an advisory role while the Executive Board manages the organization with full authority except for some specific responsibilities[7]. The latter currently consists of three members: CEO (Chief Executive Officer), CFO (Chief Financial Officer), and COO (Chief Operating Officer). In addition to the Executive Board, the Council for Defense Research also decides on policies regarding the Defense unit of TNO.

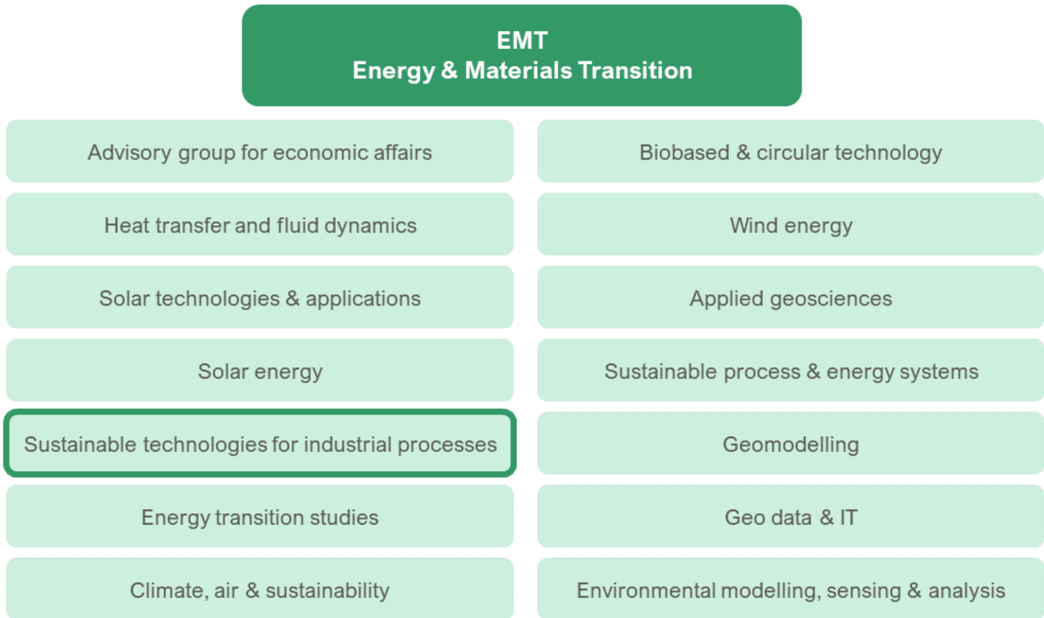

Figure 2. Structure of EMT unit

As seen in Figure 2, Energy & Materials Transition (EMT), one of the units, is composed of 14 expertise groups. One of the groups, Sustainable Technologies for Industrial Processes (STIP), is part of the roadmap *Towards CO_2 neutral industry*, which is composed of several research clusters. The Seed Early Research Program (ERP) for *Ammonia – Future Proof Commodity,* from which the idea for this thesis originated, is a contribution to the *Synthetic Fuels & Chemicals* cluster. This ERP is led by a group of scientists, consultants, project managers, an engineer, and an LCA (Life Cycle Assessment) expert.

1.5. Stakeholders

TNO offers a diverse range of products and services (Appendix 1, Table A2) that leverage its expertise in applied research and technological innovation to create value for all its stakeholders[3], seen in Figure 3.

Figure 3. TNO's stakeholders

- Demonstrable impact on the four societal themes with innovations.
- Knowledge development and advice for public policies.
- Products and services for greater earning power.
- Knowledge development through collaboration.
- Revenue generation and encouragement of responsible business practices.
- Self-development, engagement and equal opportunities for employees.

1.6. Environmental analysis

The following analysis examines the external factors that shape TNO's strategic landscape and influence its operations, research endeavors, and future trajectories[8].

Table 2. PESTLE analysis of TNO

Political factors	Economic factors	Sociocultural factors
Changes in government **policies** and funding priorities can affect TNO's research budgets and activities **Geopolitical instability** might affect international collaboration projects	National and global conditions such as inflation or investment climate can influence TNO's **funding** Fluctuations in the **private sector** can affect commitment to collaborative initiatives and demand for services	The level of technological **acceptance** influences TNO's ability to implement innovative solutions **Demographic** trends can impact the demand for specific research areas (healthcare, sustainability, cybersecurity)

Technological factors	Environmental factors	Legal factors
Rapid advancements in the private sector impact the relevance of TNO's offerings Identifying **global trends** is crucial to benchmark research initiatives and identify gaps	**Climate action** and **circular economy** initiatives drive demand for TNO's expertise and research efforts Responsibility to demonstrate **commitment** to sustainable goals through TNO's practices and influence	**Intellectual property** rights and **patent** laws influence the commercialization and transfer of TNO's knowledge **Ethical conduct**, data privacy, and **compliance** with protocols impact the integrity of the research outcomes

The analysis extends to the focal point of this thesis: ammonia. Ammonia production and use, with its potential to reduce CO_2 emissions, is a relevant contender in combatting climate change. Therefore, it captures aligns perfectly with the company's commitment to innovation and exploration.

Ammonia's trajectory depends on an interplay of governmental policies and incentives, influencing its sustainable integration into the Dutch industry's decarbonization efforts. Also, public perception plays an important role due to significant concerns about the toxicity of ammonia and safety aspects of its distribution.

Gaining traction and relevance within this context is pivotal as it influences the funding to carry out research activities on ammonia production and cracking. Additionally, collaboration with industry partners is necessary to expand and transfer TNO's knowledge, and accelerate technological advancements. Lastly, understanding market trends and predicting the evolution of the sector is pivotal for TNO to get involved in the dynamic and competitive landscape of the energy transition effectively.

However, it is not only about innovating but also about securing these advancements through commercialization. The process of patenting and licensing is strategic in ensuring the adoption of ammonia-related technologies and a consistent revenue stream to sustain ongoing research.

1.7. Seed ERP

The Energy & Materials transition unit is focused on six critical areas, including "carbon-neutral industry" [9]. In this regard, ammonia is clearly a topic of interest for TNO since it is an opportunity to develop innovations to make the energy-intensive industry carbon neutral. It aligns perfectly with the company's focus on industrial energy supply, carbon capture and reuse, and sustainable fuels.

In Early Research Programs, TNO develops new knowledge to strengthen its technology position and the Dutch economy[3]. These programs need to involve fields with clear scientific challenges and high societal relevance. The Seed ERP on Ammonia was approved in 2023 with the ambition to develop a vision of the role of ammonia in achieving a net-zero industry. The main challenges were the systemic analysis of green ammonia value chains globally, ammonia-to-hydrogen reforming techniques, novel direct ammonia utilization technologies, and minimization of harmful emissions and critical material use. Consequently, the idea for this thesis originated as a means to gain knowledge on opportunities for ammonia and contribute to strengthening the Seed ERP's official proposal in order to be selected for a Full ERP kick-off, which is a four-year program.

This Ammonia Seed ERP also contributes to achieving the United Nations' Sustainable Development Goals (SDGs), which are a universal reflection of the societal challenges the world is facing, and a priority of TNO's strategy. Four different goals (Figure 4) are potentially influenced by ammonia's role in the energy transition because it constitutes a clean energy source, and considerable efforts are underway to establish a viable business case for cost-effective production and import.

The successful integration of ammonia into the industry and the adoption of novel applications could have significant economic benefits and enhance the Dutch industrial landscape. The research group aims to foster innovation and offer effective solutions to ammonia-related challenges, including infrastructure for its distribution. Ultimately, the objective is to combat climate change by reducing CO_2 emissions and promote low-carbon fuels both nationally and globally.

Figure 4. Ammonia Seed ERP alignment and contribution to four SDGs

As previously mentioned, TNO's objective is to be a technology innovator and frontrunner in knowledge supply to the Dutch industry, which entails the licensing or sale of intellectual property rights (IPR) to exploit the results of the ERP, or the creation of spin-off entities. Moreover, the program can provide policy advice to the Ministry of Economic Affairs and Climate Policy.

The potential business size of such program can be estimated on the assumption of a licensing model. License incomes for the chemical industry are usually around 1-3% of the investment of a new plant. For example, the Port of Rotterdam recently commissioned a feasibility study for an ammonia cracker to produce 1 million tons (Mt) of hydrogen[10]. TNO estimates a needed investment of around 3 billion euros. This would translate into a licensing income of 60 million euros based on a 2% licensing fee. What's more, considering the port's ambition to supply 4.6 Mt of hydrogen by 2030, this could result in a license income of about 300 million euros for TNO.

Consequently, this topic holds significant relevance and immense potential for TNO, making this research thesis a valuable contribution to the group and the program's objectives.

2

Problem Statement

Problem Statement

The decarbonization of various sectors such as energy, transport, industry, buildings and agriculture is an urgent global imperative in the face of climate change. Ammonia production currently accounts for 1.8% of global carbon dioxide emissions. That is why the ammonia industry, with the potential of blue/green ammonia as a low-carbon alternative, can play a significant role in achieving decarbonization goals. However, the lack of a comprehensive understanding of the ammonia value chain and uncertainties surrounding the market evolution hinder its full development and effective integration into the industry.

The problem lies in the need for a thorough value chain overview and analysis of blue/green ammonia, specifically in the case of the Port of Rotterdam in the Netherlands. As a major European port, it already possesses ammonia terminals, and the upcoming ACE Terminal will further enhance its role as an ammonia importer in the coming years. The required analysis should encompass the entire lifecycle of ammonia, from production to end-use, while also considering future applications. Several studies have provided valuable insights into clean ammonia production and import routes to European countries. However, a crucial aspect that still requires further investigation and understanding is the post-arrival phase of ammonia, once it has reached the Port of Rotterdam. The lack of knowledge regarding the ammonia market's future evolution, the demand for specific types (green, blue, grey), uncertainties surrounding near-future off-takers, large-scale distribution, policy frameworks, options for cracking, hydrogen demand and applications, and the required infrastructure to accommodate the anticipated growth of the industry pose challenges to strategic decision-making and investment planning. Addressing these uncertainties and knowledge gaps is essential to facilitate the industry's transition to ammonia-based solutions and to maximize the benefits of a sustainable and decarbonized ammonia value chain.

As mentioned before, this problem statement emphasizes the need for a comprehensive value chain analysis, addressing market uncertainties, policy gaps, distribution methods, and infrastructure requirements within the specific context of the Port of Rotterdam. The present study aims to evaluate the full potential of ammonia as a key player in the energy transition, with a view to promote its widespread adoption and facilitate the industry's decarbonization goals.

Research question

What are the opportunities, challenges, key aspects, and determining factors involved in developing, establishing, and adapting the value chain of ammonia from the Port of Rotterdam, considering the potential growth of the market and future applications?

3

Objectives

Objectives

This section gives an overview of the main objectives of this study. It provides a roadmap for addressing the problem statement and research questions, setting the direction of the research and shaping the methodology and analysis that will follow. The main objectives are:

1. Conduct a comprehensive **value chain analysis** of blue and green ammonia, focusing on the stages **from import** at the Port of Rotterdam, specifically the ACE terminal, **to end-use** applications. These include storage, transportation, cracking options, and potential off-takers.

2. **Identify obstacles** involved in transitioning to ammonia, particularly low-carbon ammonia, analyzing factors such as technological challenges, market dynamics, policy implications, and economic viability.

3. Evaluate different **distribution methods and routes** for ammonia to optimize the transportation aspects of the value chain considering safety and cost-effectiveness.

4. **Investigate the present and future applications** of ammonia as an energy carrier, assessing feasibility, benefits, disadvantages, and compatibility with existing infrastructure.

5. Obtain insight into the **opinions and perspectives of relevant stakeholders** within the ammonia industry, value chain, technological advancements, policy frameworks, and potential solutions for decarbonization.

6. Adopt a **critical and unbiased approach** to provide a thorough assessment of the risks, safety and environmental issues, obstacles, and bottlenecks involved in this study.

7. Understand the **market** including preferences and priorities of ammonia producers, consumers, licensors, and facility providers.

8. Provide informed **advice and recommendations** to TNO and interested parties on the best strategies and approaches in different scenarios, and the successful integration of ammonia in the energy sector.

4

Theoretical Framework

Theoretical Framework

This introductory section provides a conceptual foundation for the report by offering a comprehensive examination of the current climate situation, ammonia's potential to decarbonize the industry sector, transport, storage and cracking technology, and the theories and models that support the research study, including value chain, environment and market factors, and business development. It aims to provide a broad understanding of the topic and its complexities, and the concepts presented here will guide the analysis and interpretation of the research findings.

4.1. Energy transition and decarbonization

The climate challenge

Climate change is a global challenge that requires urgent attention and coordinated efforts from nations worldwide. Over the past few decades, as the awareness of its extensive impact and consequences has grown, nations have come together to tackle this problem through international agreements and policies. Europe is a frontrunner in climate action, with the European Union (EU) introducing directives and regulations for transitioning to a low-carbon economy, increasing renewable energy uptake, and improving efficiency[11].

Climate pacts, such as the Paris Agreement of 2015, have set ambitious targets in order to limit global warming to well below two degrees Celsius[12]. However, implementing and translating these agreements into tangible actions at regional and national levels pose significant challenges. Developing effective policies involves balancing economic growth, social considerations, and environmental sustainability. Moreover, stakeholder interests have to be addressed and collaboration between sectors and industries fostered.

In the Netherlands, the government strives to deal with the complex network of scientific, economic, and political considerations to develop effective strategies. The difficulty also lies in the interdependencies among global systems, and the need for both short-term and long-term planning and investment. Additionally, addressing climate change requires making trade-offs, and managing the risks and uncertainties associated with transitioning to a low-carbon future.

Uniting efforts and introducing initiatives

The National Climate Agreement (2019) placed particular emphasis on reducing greenhouse gas emissions by 49% in 2030 compared to 1990[12]. In order to facilitate the transition and give concrete measures, five different discussion tables were established to address each sector separately: built environment, mobility, industry, agriculture and land use, and electricity. These goals and actions affect the everyday life of both citizens and businesses. We are now facing a series of decisions that affect our consumption habits, our mobility and lifestyle, and how we earn our livelihood.

One year following the Climate Agreement, by approving the European Green Deal (2020), the European Commission raised the target to - 55% by 2030 and committed to making the EU climate neutral in 2050[13]. Net zero means that the total emissions are equal to or less than the emissions removed from the environment. Furthermore, in the COP26 international climate conference (2021) in Glasgow, nearly 200 countries negotiated and signed the Glasgow Climate Pact, and the Paris Agreement's Rulebook was completed[14]. However, these measures and objectives do not specifically stipulate what each country must do and the pact is not legally binding.

It is also worth noting that the Russian-Ukraine war, which increased natural gas prices in Europe, simultaneously accelerated the transition from fossil fuels to renewable energy sources. Lastly, and most recently, the COP27 was held in Sharm El-Sheikh (Egypt) and placed the focus on providing funding for developing countries to combat climate change as well as vulnerable countries affected by climate disasters[15]. In addition, the central theme was also about limiting global warming and switching toward implementation and accountability.

Decarbonizing the industry sector

As the urgency to combat climate change and reduce greenhouse gas emissions intensifies, the industrial sector is increasingly focusing on decarbonization as a fundamental objective. Decarbonization refers to the process of reducing or eliminating carbon dioxide and other greenhouse gas emissions associated with industrial activities. It implies system changes in the field of energy and raw material use in order to transition away from fossil fuel-based energy sources and adopt low-carbon alternatives, such as renewable energy and energy-efficient technologies[12].

The concept of decarbonization is not only driven by environmental concerns but also presents significant opportunities for industries to enhance their sustainability, improve operational efficiency, and capitalize on emerging clean technologies. By adopting a future-oriented public-private approach and setting ambitious decarbonization goals, the industry sector can not only contribute to a greener future but also to create new value and achieve long-term competitiveness and resilience in the evolving global landscape of sustainable development[12]. Several studies have been carried out at a national and international level to assess and develop decarbonization strategies for different sectors, including steel[16], fertilizers[17], and power[18].

In the summer of 2021, the 'Fit for 55' legislative package was proposed as a means for the EU to reach climate neutrality by 2050[19]. More specifically, it makes the goal of reducing emissions by at least 55% by 2030 a legal obligation[20]. Overall, the package aims to provide a framework for a just and balanced transition that strengthens innovation and competitiveness of the EU industry.

4.2. Ammonia

The molecule and its properties

Ammonia (NH_3) is a molecular compound that exists naturally in living organisms and the environment, and is part of the nitrogen cycle, but it is also commonly produced artificially. It has a carbon-free chemical structure and it is a gas under standard conditions, which means that it dissipates into the atmosphere but it may take enough time to generate significant concentration in the site of release. That poses a concern because ammonia is toxic and corrosive, and so it requires strict safety measures for handling it[21]. On the other hand, ammonia serves as a precursor for many chemicals used in a wide range of applications and is therefore a globally traded commodity. It can be easily liquified at -33.4 °C (atmospheric pressure) and, given its extensive and prevailing presence in the chemical industry, there is already a substantial amount of expertise and infrastructure in place to ensure safe handling.

Every year, about 185 Mt of ammonia are produced globally[21]. The artificial production of ammonia requires hydrogen (H_2) and nitrogen (N_2) as feedstock, and an energy source, which is usually a fossil fuel such as natural gas (72%) or coal (22%)[22]. Therefore, producing hydrogen is the initial step in ammonia production and is typically obtained through a steam methane reforming process.

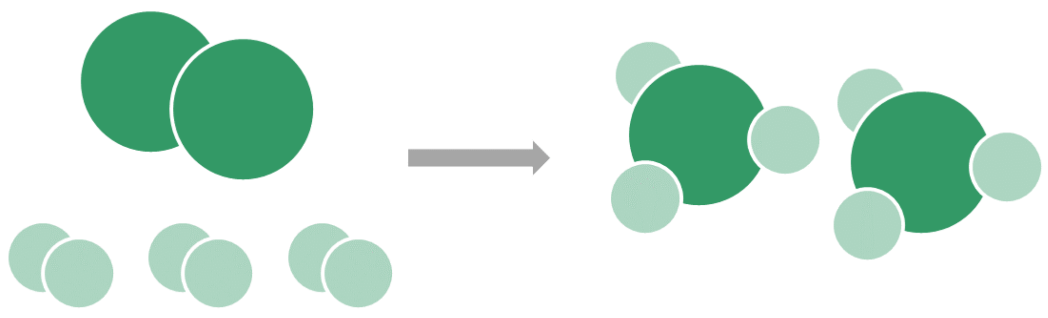

Figure 5. Nitrogen and hydrogen molecules (left), ammonia molecules (right)

H_2 is a colorless, odorless gas and the lightest element on the periodic table. It is highly flammable and has low density. On the other hand, NH_3 is colorless but strong-smelling, it has a higher density and can be easily liquified. Table 3 shows an overview of the basic properties of both compounds.

Table 3. Basic properties of ammonia and hydrogen[21]

	NH_3	H_2
Molar mass (g/mol)	17.03	2.02
Boiling point (°C)	-33.4	-252.9
Melting point (°C)	-77.8	-259.1
Density (kg/m^3) at 0 °C, 1 atm	0.77	0.09
Energy density (MJ/l), liquid	12.7	8.5

Applications and consumption

Out of the total ammonia global demand, around 70% is used in nitrogen-based fertilizers and the remaining 30% is used for various industrial applications[23] such as commercial explosives, textile industry, durable resins, reducing NO_x emissions, household cleaning products, plastics and fibers, and cooling agents[21].

Ammonia is widely consumed in the APAC region (49%) and EMEA region (26%), followed by the Americas (15%) and EU-27 + UK (10%)[21]. Global consumption matches global production, which has been increasing steadily over the past decade and will continue to do so due to fertilizer demand, which is linked to the growing world population and the need to satisfy the global demand for food. Similarly, demand for industrial applications should also increase as industrialization intensifies across the world.

A hydrogen carrier and low-carbon fuel

Hydrogen plays a crucial role in decarbonizing since it can be used as a means of storing excess renewable energy from intermittent sources like solar and wind power. Therefore, it can contribute to energy independence by diversifying energy sources and reducing reliance on fossil fuels. However, despite its high gravimetric energy density when compared to electricity storage, hydrogen still has a high volumetric energy density and requires large storage volumes. Furthermore, there is limited existing infrastructure.

Ammonia has recently been regarded as an advantageous energy carrier because it contains 17.6 wt% of hydrogen, has higher volumetric energy density, and there is already a globally established infrastructure for transporting it. It can be brought to its destination and then split back into hydrogen and nitrogen through a cracking process[24]. For this reason, and because it shows little energy loss from transportation, ammonia has great potential in supporting the decarbonization of the world energy system.

Furthermore, not only can ammonia be used as a hydrogen carrier but also as a direct low-carbon fuel. Its combustion or utilization in fuel cells does not produce CO_2 emissions, thereby eliminating the need for cracking it back to hydrogen and enabling enhanced energy efficiency. As a result, ammonia has emerged as a promising contender and a significant potential fuel and energy carrier in the ongoing energy transition. Nevertheless, the challenge lies in producing green ammonia and the need to generate hydrogen from renewable energy sources or via a carbon-neutral production process that eliminates CO_2 emissions.

Decarbonizing ammonia

Ammonia synthesis is the single biggest carbon-emitting chemical production process worldwide, contributing approximately 1% of global CO_2 emissions as it relies heavily on fossil fuels[25]. The production of one ton of ammonia leads to 1.6 to 4.0 tons of Scope 1 CO_2 emissions, along with emissions of Scope 2 and 3 (see Figure 6). As a result, the yearly production of 185 Mt of ammonia leads to CO_2 emissions that are up to six times greater.

Scope 1	Direct emissions from on-site production
Scope 2	Indirect GHG emissions from electricity generation
Scope 3	Indirect GHG emissions from end-use and other value chain activities

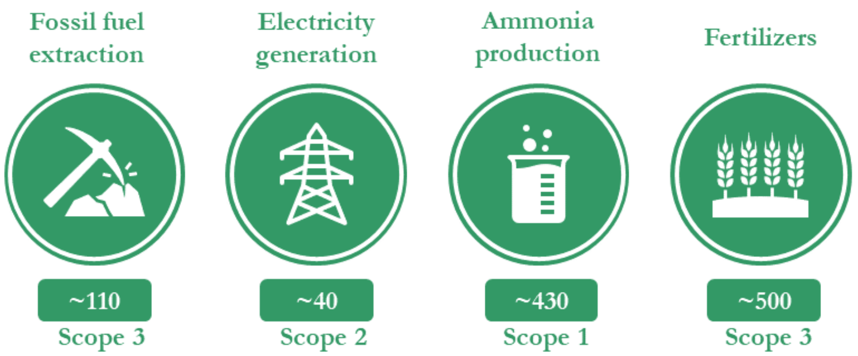

Figure 6. GHG emissions along the supply chain in 2020 (in Mt CO_2e)[25]

Decarbonizing the ammonia production process can be achieved through the production of green and blue ammonia. Green ammonia is produced using renewable energy sources, typically through the electrolysis of water powered by wind, solar, or other renewable sources. The electricity from renewables is used to split water into hydrogen and oxygen, with the hydrogen then being combined with nitrogen from the air, a process called Haber-Bosch, to produce ammonia, as shown in Figure 7.

Blue ammonia is produced using fossil fuels, but with carbon capture and storage (CCS) technology (Figure 7). This approach involves capturing the CO_2 emissions produced during ammonia production and then storing them underground or utilizing them for other industrial processes, effectively preventing the release of CO_2 into the atmosphere. Blue ammonia is generally seen as an intermediate step towards fully decarbonized production, as it allows for emissions reduction while transitioning to greener alternatives and leveraging existing infrastructure and technologies.

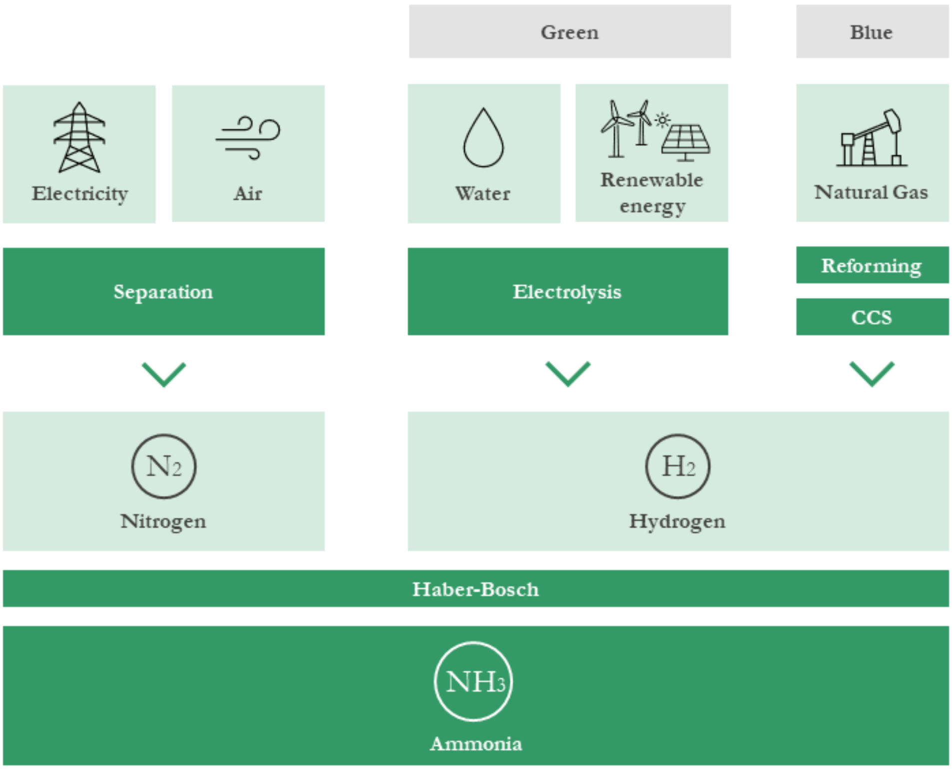

Figure 7. Production process of green and blue ammonia

The goal of decarbonizing ammonia production involves scaling up green ammonia production by phasing out the use of fossil fuels and increasing the adoption of renewable energy sources. By transitioning from conventional methods to green and blue ammonia production, the industry can significantly contribute to the global efforts of mitigating climate change. Besides, approximately 80 Mt of the current ammonia production capacity presents an early opportunity for decarbonization[22].

Ammonia in the energy transition

Given the opportunities provided by ammonia, its role could change as the energy transition unfolds. Clean ammonia production can help decarbonizing the fertilizer industry, be a vector for long-distance hydrogen transport, a fuel for power generation, or become the main zero-emissions fuel for shipping[25]. According to the IEA, the demand for ammonia for the new applications by 2050 is set to be twice as high as the demand for its current applications[18]. However, initiating this transition requires strong policy support, and large-scale investments in both supply and demand-side technologies to enable the use of ammonia as a fuel. That includes, for example, building production plants in regions with abundant and cheap renewable energy, and developing ammonia terminals and cracking facilities in resource-scarce countries.

4.3. Ammonia infrastructure and technology

This summary provides an overview of the current infrastructure and technologies associated with ammonia shipping, storage, distribution and cracking.

Shipping and storage

Ammonia shipping involves the transportation of ammonia from production centers to destinations around the globe. Each year, about 18 to 20 Mt of ammonia are transported by specialized vessels known as ammonia carriers or ammonia tankers[22]. These vessels are adapted to the properties of ammonia, including handling its odor and toxicity, and the need for specific temperature and pressure conditions to maintain its liquid state during transport. Ammonia carriers come in different types and sizes, ranging from small coastal vessels to large ocean-going tankers. The capacity of these ships can vary, from 10,000 to 50,000 tons[26].

In addition to the ships themselves, the shipping infrastructure includes terminals and ports equipped with storage facilities and loading/unloading systems specifically designed for handling ammonia. Ammonia storage tanks are constructed from materials such as carbon steel or stainless steel[27] and have a capacity of up to 50,000 tons.

ACE Terminal

Gasunie, HES, and Vopak have partnered up to develop an ‘open access’ terminal for importation of ammonia on the Maasvlakte in the Port of Rotterdam, which is expected to be operational by 2026. The terminal offers strategic advantages, including direct access from the North Sea and connectivity to Rotterdam's industrial hub and Gasunie's pipeline infrastructure in Northwest Europe[28].

The project focuses on reusing existing facilities, allowing for a shorter time-to-market and promoting sustainability. ACE terminal will utilize Gasunie's storage tanks and pipeline infrastructure, HES International's land and dock, and Vopak's ammonia storage expertise. Moreover, the terminal has ample space for potential capacity expansion[29].

The end goal is to "crack" the ammonia and convert it back into hydrogen. The hydrogen will then be fed into the energy system through Gasunie's hydrogen network, which is planned to be operational in the coming years[29]. Alongside, imported green ammonia is also expected to attract interest from sectors currently relying on grey ammonia such as the fertilizer industry, or the heavy transport sector, thus enhancing the viability of ammonia as a fuel option.

Distribution

Despite the long history of large-scale ammonia transport compared to hydrogen, distribution is currently avoided where possible because of ammonia’s toxicity, corrosiveness and potentially large impact area in case of an accident[30]. That is why the Dutch government has made efforts to reduce the risk to citizens by seeking to limit or phase out inland transport.

Thus, transport of ammonia by road is rare because of its relatively small capacity and high associated risk. On the other hand, there used to be regular transport of ammonia by rail until about 2010, but has decreased significantly in the recent years due to strong discouragement from the national government for the same safety reasons. For example, an average of 2,000 rail tanks cars drove every year from Geleen to Ijmuiden via cities such as Eindhoven, Utrecht and Amsterdam. Currently, there is restricted, smaller-scale transport only between the Port of Rotterdam and Delfzijl, Krefeld, and Geleen (Chemelot)[30]. Moreover, the Dutch government encourages inland waterway transport over rail.

Consequently, transport by water emerges as the most compelling choice, facilitating large-scale distribution of ammonia to industrial locations and neighboring countries. Notably, Chemelot possesses a loading jet designed specifically for ammonia[30]. Nonetheless, the projected large growth of ammonia imports could potentially strain existing capacity, compromising safety protocols and environmental regulations[30]. This circumstance accentuates the necessity for additional safe distribution methods.

A promising alternative that yields benefits in terms of safety, costs, and sustainable connections and development, is a pipeline. There are currently no operational pipelines for ammonia in the Netherlands, with the exception of the ammonia pipelines at chemical complexes and a short pipeline from the port of Urmond to Chemelot[30]. Moreover, there are only about 25 ammonia pipelines in Europe, mostly ranging from 1 to 10 km, and used only for transport within industrial complexes and ports[31].

Despite the lack of experience with long ammonia pipelines in the Netherlands, the US and Russia can be used a reference. The US has three main systems that add up to 5,000 km, and Russia's 2,400 km long pipeline, which also crosses Ukranian territory, has been in operation since 1983 [31]. A feasibility study was recently carried out to assess the value and possibilities of the Delta Corridor (Figure 8), the construction of four pipelines from the Port of Rotterdam to Chemelot and North Rhine-Westphalia[32]. This pipeline bundle was initially set to transport C4-LPG, propylene, hydrogen and CO_2, but now ammonia is also being considered as a candidate. Several parties could benefit from these pipelines because there would be fewer trains carrying hazardous materials, and Rotterdam and Chemelot's leading role in the transition of the Dutch industry would be strengthened. Moreover, it would contribute to a robust distribution network and avoid potential future bottlenecks. Lastly, link options for several companies and regions would develop.

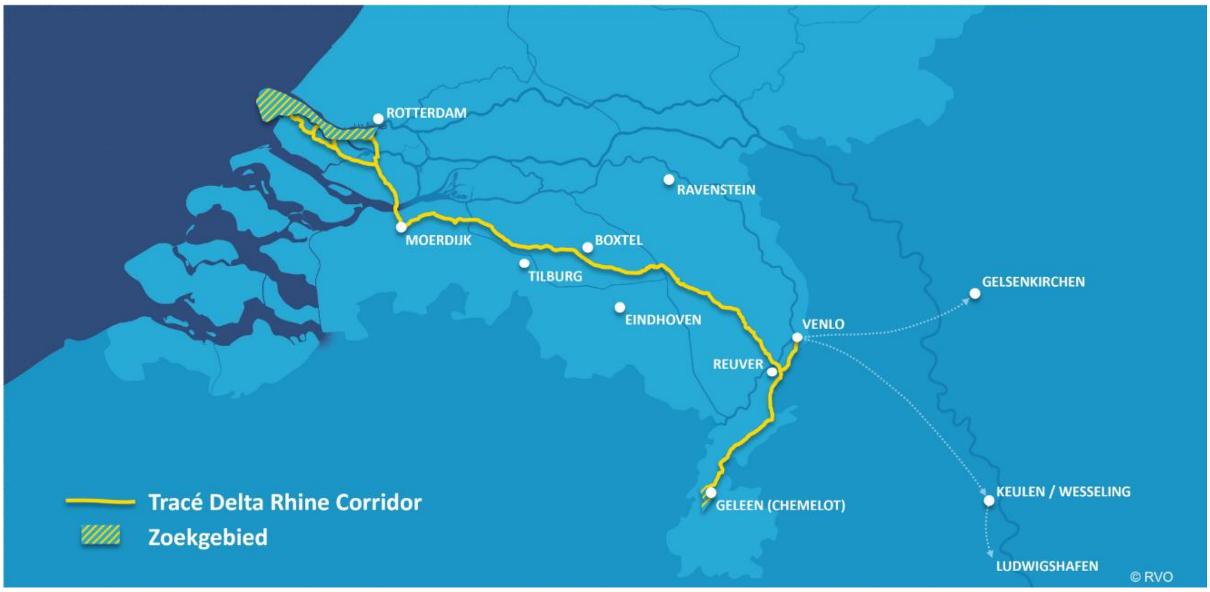

Figure 8. Intended route of the Delta Rhine Corridor[33]

Cracking

Ammonia cracking, the catalytic decomposition of ammonia into hydrogen and nitrogen, is going to be an important step in the ammonia value chain in order to meet hydrogen demand. Until now, the small-scale cracking of ammonia has mostly been used for the chemical and refining industry. However, the need for large-scale ammonia cracking has been gaining attention as a means to support decarbonization efforts while avoiding the challenges of hydrogen shipping.

Currently, several companies around Europe (Air Liquide, Duiker Engineering, Proton Ventures, AFC Energy, Linde, Aramco) are working on the development of cracking plants[34]. Some of the main obstacles when trying to crack volumes ranging from 300,000 to 1 million tons per year are catalyst efficiency and durability, hydrogen purity, cost competitiveness, and energy efficiency[35]. Even though progress is being made in research and pilot projects to address these challenges, further technological development is needed to scale up ammonia cracking.

Fluor, along with other companies, was commissioned to perform a pre-feasibility study this year for a large-scale industrial ammonia cracking plant in the Port of Rotterdam. The study investigated the possibilities to generate 1 million tons of hydrogen per year from imported ammonia. The focus was also placed on safety, centralized and decentralized options, capacity, space requirements, costs and emissions[10].

4.4. Evaluation of appropriate models

As mentioned in the problem statement, there is a clear need for an analysis of the activities, infrastructure, applications, supply and demand, and stakeholders involving ammonia imports in the Netherlands. In order to make a thorough assessment, a robust model that encompasses all steps and operations is needed, and several business models appear useful, relevant, and potentially effective in achieving this goal. The concepts of supply chain, value chain, business model canvas, and blue ocean strategy take into account a broad range of factors for defining a business idea, creating product value, or optimizing logistics (Table 4).

A **supply chain** is a network of parties that are involved in creating a product and delivering it to the consumer. Supply chain management is a crucial process for companies to reduce their costs, improve production efficiency, and remain competitive[36].

Value chain refers to all the business activities and processes involved in creating a product or performing a service. It helps companies gain insight into each of their transactions, maximize value at each point in the chain, and better understand their competitive advantage[37].

The **Business Model Canvas** is used to visualize all the building blocks when starting a business, including customers, route to market, value proposition, and finance[38].

The **blue ocean strategy** is an approach that focuses on creating uncontested market spaces and finding innovative ways to create value for customers[39].

Table 4. Advantages and disadvantages of the business concepts

	✓	✗
Supply chain	Includes components such as producers, vendors, warehouses, transportation, distribution centers and retailers	No specific focus on value creation, understanding customer demands and preferences, emerging technologies, or the broader strategic context
Value chain	Well suited to identify value-adding stages, customer needs, new markets, and opportunities for improvement and innovative technologies	Complexities of real-world business operations are oversimplified
Business model canvas	Flexible tool that focuses on the value proposition, identification of opportunities, and risk assessment	Overlooks interdependencies and market dynamics, high-level view with very limited focus on chain of activities
Blue ocean strategy	Identification of new uses and market spaces, and creation of innovative propositions for unmet customer needs	Not suited for already established markets with existing competition

The supply and value chain models allow for a comprehensive overview of activities, possibilities and challenges, which fit the scope of the thesis. On the other hand, the applicability of the business model canvas and blue ocean strategy to the case of ammonia is limited. While there are prospects for new ammonia applications involving innovative technologies and new customer segments, it is important to note that ammonia has a well-established global market and a long history of trade. Therefore, the focus of this study is on the transition from conventional ammonia production and distribution methods to renewable alternatives and safer options, considering near-future large-scale imports. To do that, a more practical and logistical evaluation of ammonia's potential is needed.

In conclusion, the value chain model is the most appropriate approach as it allows for a holistic perspective on the entire range of activities, from ammonia import to its ultimate end use. By adopting this model, various critical aspects, such as stakeholder interests, safety considerations, the energy transition context, existing and future ammonia markets, and business strategy elements, can all be taken into account. Oversimplification and limited scope are disadvantages of using the value chain model because it is quite challenging to address the complexities of all interactions and external factors. Consequently, the research will be based on three general concepts: a value chain overview, environmental and market factors, and business development and strategy.

4.5. Value chain model

Porter's Value Chain Model (Figure 9), which was conceived by Harvard Business School Professor Michael Porter, states that all of the activities that make up a firm's value chain can be split into two categories: primary activities, those that go directly into the creation of a product or execution of a service, and secondary activities, those that help primary activities become more efficient and create a competitive advantage[37].

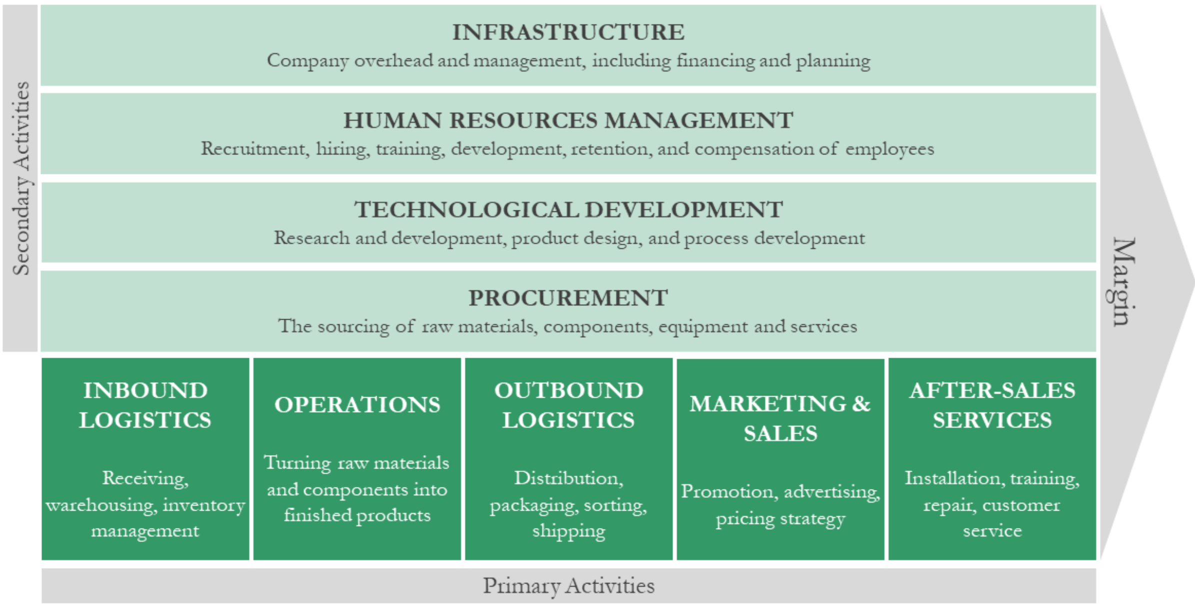

Figure 9. Components of a value chain according to Porter's definition[37]

Despite Porter's Value Chain Model being primarily tailored to individual firms producing products or executing services, it can still be adapted for the case of ammonia. By identifying the key focus steps and defining the scope of the research, a custom-made, optimized value chain can be formulated for the Netherlands and, more specifically, for ammonia imports in the Port of Rotterdam.

In addition, there are more models that adjust to and build upon the traditional value chain and can be useful for the analysis:

- The **global value chain** (GVC) model explores how organizations and countries coordinate and integrate activities across borders[40].
- The **extended value chain** model expands beyond the internal activities of the organization to include external partners and stakeholders[41].
- The **social value chain** model incorporates social well-being and environmental impact considerations[42].
- **Value stream mapping** (VSM) focuses on specific processes to identify inefficiencies and optimize flow[43].
- **Value chain mapping** provides a high-level illustrative view of the interactions between major activities[44].

Environment and market factors

In the context of this thesis, while the value chain model provides some coverage, it is essential to include and place emphasis on the environment and market factors surrounding ammonia. The dynamic nature of business environments requires careful consideration when planning and conducting operations, as challenges and potential drawbacks may come up[45]. Additionally, understanding consumer behavior and economic trends is crucial, as they can significantly influence the market and evolve over time[46]. The following is an overview of the most important factors to analyze in order to provide valuable insights that will aid in formulating robust strategies for the successful integration of ammonia into different sectors.

- **Economic** factors include energy prices, renewable energy investments, government subsidies, carbon pricing, market demand, and investments in infrastructure.
- **Social** factors entail public perception and acceptance, consumer awareness of environmental issues, workforce training and skills, community engagement, health and safety.
- **Regulatory** factors, such as standardized safety measures for ammonia handling, and government policies for carbon pricing and emissions targets, play a critical role in shaping the ammonia value chain. Considerable debate surrounds the methods of inland transportation of ammonia, such as concerns regarding trains traversing urban areas.
- **Technological** factors include advancements in renewable ammonia production, carbon capture techniques, cracking technologies, and ammonia combustion systems.
- **Sustainability** has a great influence due to, for example, greenhouse gas emissions involved in the production and transport of ammonia, resource availability, or the revamp and reuse of existing infrastructure.
- **Competition** factors, in terms of technological advancements, alternative energy carriers, market entry barriers, and cost competitiveness, determine the market share and positioning of ammonia.

- **Speculation** regarding the future of ammonia markets and applications can affect investor behavior, research efforts, consumer interest, government policies, and the securing of off-takers.
- **Supply and demand** play a pivotal role by considering the drivers, consumer preferences and market trends within different sectors such as fertilizers, the chemical industry, energy storage, and fuels.
- **International conditions** can impact the market in terms of supply chain, competition, buyer behavior, trade and investment opportunities.

Demographics, seasonal fluctuations, and ethical factors are out of the scope. Demographics are not central because the focus is on industrial applications rather than consumer-based demographics. Also, while there might be a future seasonal dependence of hydrogen on electricity demand, it falls beyond the project's scope, which is specifically focused on the uses of ammonia. In addition, in this context, it is more appropriate to prioritize safety and environmental implications over ethical considerations as the former is more relevant and inherently encompasses the latter.

Business development and strategy

In addition to exploring the impact of environmental and market factors, another vital component to consider in this study, as part of the value chain, is business development and strategy. By incorporating this in the theoretical framework, further insights can be gained beyond the operational aspects, thus helping ensure the long-term success of ammonia ventures.

Business development is a strategy used to find new prospects and nurture them to help drive business growth[47]. It aims to improve all departments of an organization and create long-term value from customers, markets and relationships. On the other hand, a business strategy outlines the plan of action to achieve the vision of an organization and guides the decision-making processes to improve financial stability in a competing market[48]. Overall, they provide a method to address aspects such as strategic decision-making, market adaptability and response to competition, identifying growth opportunities, mitigating risks, and aligning with sustainability goals.

While these approaches are typically designed for individual companies seeking to nurture their competitive advantage and generate profits, the scope of this study extends beyond the confines of a single company, involving numerous organizations and stakeholders. Despite this broader context, the fundamental principles underlying these business concepts remain highly relevant and adaptable. By leveraging and tailoring them to ammonia, a robust analysis of the industry's dynamics can be achieved.

5

Research Methods

Research Methods

This section serves as a guide for the data collection process and analysis. It begins by explaining the data collection methods employed. To further delve into the extended value chain, the subsections are dedicated to specific topics, including the evaluation of similar projects in Europe, gathering essential insights on the ammonia market and its associated business opportunities, conducting a comparative assessment of various distribution methods, and utilizing scenario planning to envision future possibilities.

5.1. Data Collection

The data collection combines primary and secondary data. Primary data is original, specific for the research at hand, and is not obtained from any pre-existing sources. It is collected through semi-structured interviews, expert opinion and consultation, and focus groups. On the other hand, secondary data involves consulting various sources to gather information that has been collected for different yet similar purposes.

Literature research

- Sources included feasibility studies, reports, presentations, scientific papers, company websites, new articles, and white papers.
- Ammonia Energy Association website[49] provided valuable insights on ammonia-related projects, news and developments. It also helped determine the selection of companies for interviews.
- Online investigation was conducted using search engines *Google* and *Microsoft Edge*.
- Other sources of information were colleagues and ammonia experts that gave recommendations, valuable input, or references to relevant studies and reports.

Semi-structured interviews

Interviews allow gathering first-hand information, gaining in-depth understanding, and capturing diverse perspectives from different players in the value chain. Moreover, they offer a means to validate findings from literature research and other sources, identify emerging trends and issues, and build professional connections that can be beneficial for future collaboration.

The aim for the interview process was to cover the different parts of the value chain by targeting six groups or types of companies: infrastructure, technology solutions, energy, industrial players, research and consultancy, and government. Overall, a total of 27 companies, including TNO, were approached for an interview because of their relevant role in the ammonia sector, as seen in Table 5. The goal was to conduct at least 10 interviews.

Table 5. Companies that were approached for an interview

Category	Company
Infrastructure	Port of Rotterdam
	Port of Amsterdam
	Port of Antwerp
	Gasunie
	Vopak
	Koole Terminals
	Fluxys
Technology solutions	Duiker CE
	Stamicarbon
	Company #10
	Proton Ventures
	Future Proof Shipping
	Air Liquide
Energy companies	Company #14
	Uniper
	RWE
	Horisont Energi
	Shell
Industrial players	Yara
	OCI Nitrogen
	ICL Fertilizers
	TATA Steel
Research & consultancy	TNO
	Greenpeace
	Oostkracht10
Government	Ministry of Economic Affairs and Climate Policy
	Ministry of Infrastructure

The reasons for conducting semi-structured interviews were mainly flexibility, diversity and engagement[50]. The goal was to provide enough freedom to explore additional topics, follow up on interesting points, reflect different views, and motivate participants to express their opinions.

Confidentiality and Privacy: all interviews were recorded and treated as private to safeguard participants' identities and sensitive information. Participants were given the option to remain completely confidential, and they were also provided the opportunity to review the final report before submission, ensuring their consent and participation were respected.

Each interview included a pre-determined set of approximately ten open questions and was designed to last between thirty minutes and one hour, depending on the amount of follow-up questions and level of detail in the answers. Interview questions were adapted to each company and participant, but most of them touched upon the same topics. Table 6 is an overview of the questions grouped into different topics, and the questions in bold were included in almost all interviews:

Table 6. Set of questions used in the semi-structured interviews

Introductory	**Can you describe your job and function within your company?**
	What is your company's general strategy regarding the energy transition?
	Can you give an overview of the ammonia-related projects that the company is currently involved in?
ACE Terminal	What ammonia demand is expected?
	Considering potential future demand growth, are there sufficient space and provisions for both the ACE Terminal and existing ammonia terminals to accommodate expansion?
	What is the conversion process for NG pipelines to H_2? What are the challenges?
Ammonia market	**Who are the expected off-takers (and applications)?**
	What is the current and expected future demand?
	What is the current price of grey ammonia and the projected price range for blue and green ammonia?
Ammonia production & consumption	Is there an interest to switch to blue and green ammonia?
	Has the company considered importing ammonia or hydrogen?
	Is it purely an economic decision?

New applications	**Do you think the ammonia market will grow significantly due to new uses such as maritime fuel or power generation?**
	What are the advantages and challenges of ammonia as a maritime fuel?
	What are the advantages and challenges of ammonia for power production?
Safety	What are the risks of ammonia shipping, storage and distribution?
	What are the risks of ammonia as a shipping fuel?
Distribution	**In terms of distribution methods and routes for imported ammonia, what are the key factors influencing the selection, considering aspects such as cost, safety, logistics and infrastructure?**
	Is the inclusion of an ammonia pipeline within the Delta Corridor something you would recommend?
	Will the imports go mostly to the industry in the Netherlands or will they be further transported to Germany and Belgium?
Cracking	**What is your perspective on cracking ammonia at the Port? Specifically, with considerations of centralized vs decentralized cracking, and hydrogen demand and availability?**
Concluding	**Which aspects of the transition to green ammonia and the adoption of new ammonia applications do you perceive as progressing well, and which aspects are impeding the process?**
	How do you anticipate industries evolving and transitioning in terms of grey and green ammonia usage?
	Is it feasible to generate supply before there is a clear and significant demand?

A thematic analysis was used to identify common ideas and patterns that came up repeatedly in the interviews[51]. The procedure was the following:

- Familiarization with the data by transcribing, reading through the texts and taking notes of relevant information.
- Codification of the data by highlighting short sections of the text and labeling them according to the idea that is expressed.
- Generation of themes by identifying patterns among codes. These are broader and allow the combination of several codes into a single theme.
- Inclusion of these concepts in the results as a complement and improvement of the analyses described in this section, and also addressed each theme in turn.

Additionally, some of the information obtained from the interviews was summarized in a table by company and topic. Moreover, all the answers collected from the question "*Which* *aspects of the transition to green ammonia and the adoption of new ammonia applications do you perceive as progressing well, and which aspects are impeding the process?*" were represented in a comparative way to give a qualitative and visual insight into relevant topics.

Expert opinion and consultation

In the data collection phase of the methodology, a significant emphasis was placed on gathering expert opinions and conducting consultations within the ammonia industry. By engaging with experts, the research aimed to capture insights, industry trends, and emerging developments.

The NH_3 Event[52], a two-day conference about business cases, technological advancements and opportunities for ammonia, was held in Rotterdam on June 8 and 9, 2023. International speakers addressed innovation and the future of working with ammonia. Attendance offered opportunities to acquire valuable insights, interact with diverse stakeholders, establish professional connections, and refine the scope and focus areas of this study.

- Internal consultation within TNO: scientists, business managers and consultants.
- External consultation with industry experts at NH_3 Event.
- Presentations from companies at NH_3 Event (see Table 7).

Table 7. List of companies that presented at the NH_3 Event and provided relevant information

Port of Rotterdam	TU Delft	Antea Group
Institute for Sustainable Process Technology	Stamicarbon	HyXchange
Proton Ventures	Argus	Duiker CE
Ammonia Energy Association	AFRY	IHI Corporation
Erasmus University Rotterdam	Fertiberia	Honeywell
Bureau Veritas	Saipem	Swagelok
Yara International	GES	Starfire

Focus group

A focus group is a qualitative research method that involves a small group of individuals brought together to discuss a specific topic or issue under the guidance of a moderator[53]. The purpose of a focus group is to gather in-depth insights, perceptions, and opinions from participants regarding the research topic.

In this project, the focus group sessions were composed by a group of six to nine people from the Seed-ERP NH3 (see Introduction 1.7). The moderator and semi-structured format of the meetings allowed group interaction, valuable discussions, and exploration of different ideas.

The following are the three types of focus group sessions that took place:

- Research proposal where the objectives and approach for this study were presented, and participants were encouraged to give advice and suggestions.
- Short weekly meetings to update on project developments, engage in discussion and obtain feedback.
- Final presentation of the results of the study, and Q&A, where the audience was invited for an open discussion. For this concluding session, attendance was extended to colleagues from various clusters within TNO with the dual aim of disseminating the research findings to professionals in related fields and gathering feedback from a broader, impartial audience. The participants could offer fresh insights and pose novel questions that might not have come up within the smaller focus group.

5.2. Extended value chain mapping

The scope for the value chain was defined in order to create an overview of activities and considerations for the context of this research. An adapted version of the traditional value chain model discussed in section 4.5 was used to identify the primary and secondary activities relevant to this study, and to map the extended value chain of ammonia from import terminal at the Port of Rotterdam to the end-user. Setting these limits allowed a custom-made and more in-depth analysis of the key activities. A schematic was created where each activity was addressed individually to identify key questions regarding the possible options, stakeholders, potential and bottlenecks.

5.3. Multiple case study

A brief multiple case study was done as a way of comparing projects that are similar to the ACE Terminal at the Port of Rotterdam. The goal was to obtain a general idea of the plans and strategies in other Dutch and European ports that have recently announced their plans for new ammonia terminals and cracking considerations. Moreover, some of the interviews provided insight into the state of these projects.

Criteria for choosing ports

- Major energy and industry hubs.
- Ports with newly announced ammonia terminal projects.
- In close proximity: Netherlands, Germany, Belgium and the UK.

Criteria for the study

- Reasons for and against an ammonia terminal.
- Strategy regarding inland distribution.
- Cracking considerations.
- Availability of necessary ammonia-suited infrastructure.

5.4. Business development

On the practical side, several visual analysis frameworks were used to analyze business opportunities, understand strategies, and provide the opportunity for discussion.

The **Ansoff Matrix** (Figure 10) was used to help plan and evaluate growth initiatives, and conceptualize the associated level of risk[54]. It considered the attractiveness of four different growth strategies by leveraging both existing products and markets with new ones.

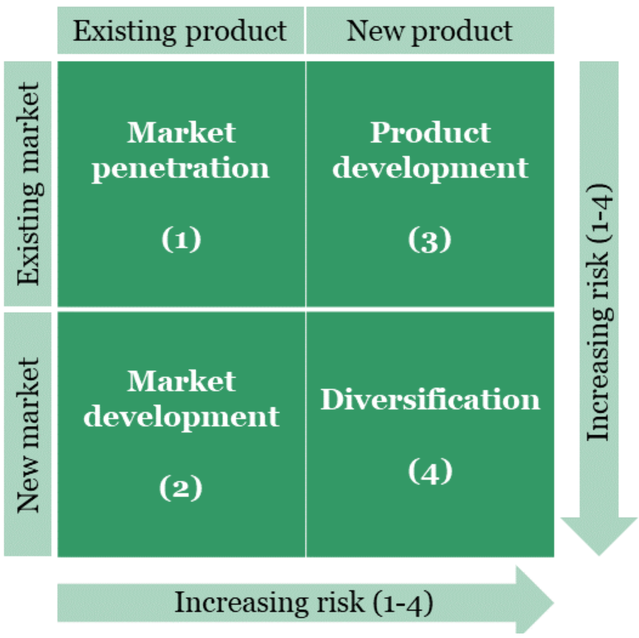

Figure 10. Ansoff matrix[54]

The **SWOT Analysis** was used to evaluate the competitive position of ammonia and to develop strategic planning by assessing internal and external factors, as well as current and future potential[55]. This tool helps in analyzing the strengths, weaknesses, opportunities and threats of a company or business.

Lastly, a graph illustrating the level of **Readiness versus Confidence** was created to assess the perceived role of ammonia in existing and potential application opportunities, along with the technological readiness. Each application was represented by a different circle with size corresponding to the estimated potential future demand.

5.5. Market research

In the context of examining of environment and market factors, demand plays a key role because it drives the sector and has significant impact on the other factors. Since social, regulatory and technological considerations were addressed in other sections of the study, the market research approach was based on two main aspects:

1. Off-takers → Location and interests

2. Cracking → Advantages and disadvantages

In addition to literature research, this section combines insight obtained from interviews and segmentation research in terms of ammonia and hydrogen use. Mapping the potential off-takers in the Netherlands and neighboring countries facilitated the evaluation of their interests and their connection opportunities to future hydrogen and ammonia pipeline networks. Moreover, it highlighted the significance of the dynamic interplay between the demand for ammonia versus hydrogen, and cracking processes. Therefore, an assessment of the implications of cracking and the role it could assume within the sector was also included.

5.6. Comparative analysis

This comparative analysis aimed to assess the various inland distribution methods in a visual and comprehensive way. The objective was to gather valuable insights and information through the interviews and literature research to facilitate an informed evaluation of the different options.

By weighing the advantages and disadvantages of each method, the aim was to identify the most viable and optimal approaches for ammonia distribution, while considering key factors such as stakeholder preferences, import volumes, routes, safety considerations, cost implications, and existing infrastructure. Additionally, the analysis involved projecting potential future infrastructure and making comparisons with distribution practices in neighboring countries to derive valuable recommendations for effective ammonia distribution strategies.

5.7. Scenario planning

Scenario planning was well-suited for the case of ammonia, particularly in the context of the energy transition and the uncertainty surrounding its development, because it allowed for the exploration of multiple possible futures based on potential end uses. Given the dynamic nature of the energy sector, scenario planning can help prepare for different outcomes, as well as identify strategic responses to potential challenges and opportunities. It enables a proactive approach in navigating the complexities of potential future developments and making informed decisions.

By constructing different scenarios based on varying factors and assumptions, the objective was to create a range of plausible future situations. Information and insights were gathered from relevant literature and expert opinions to create these scenarios. To envision the different possible trajectories for the ammonia sector, a flowchart of implications was created based on the most probable applications.

6

Results & Discussion

Results & Discussion

This section presents the findings from the interviews and assessment of the ammonia extended value chain, including business development and market research. Furthermore, as described in the Research Methods section, it includes an overview of the European ports currently looking into importing ammonia, along with an analysis of the distribution methods. Additionally, it contains the discussion of the results, which serves as the foundation for formulating conclusions and recommendations.

6.1. Extended value chain (from import terminal to end-user)

Figure 11 shows a reduced version of the classic value chain model made specifically for the case of ammonia taking into account the scope of this study. The range of activities go from inbound logistics, in the import terminal, to the off-take from customers, including operations and outbound logistics. Secondary activities also covered by this research are infrastructure, specifically distribution methods, and technological developments regarding cracking processes. Consequently, marketing, customer service, human resources management, and procurement fall out of the scope and therefore have not been included in the extended value chain map.

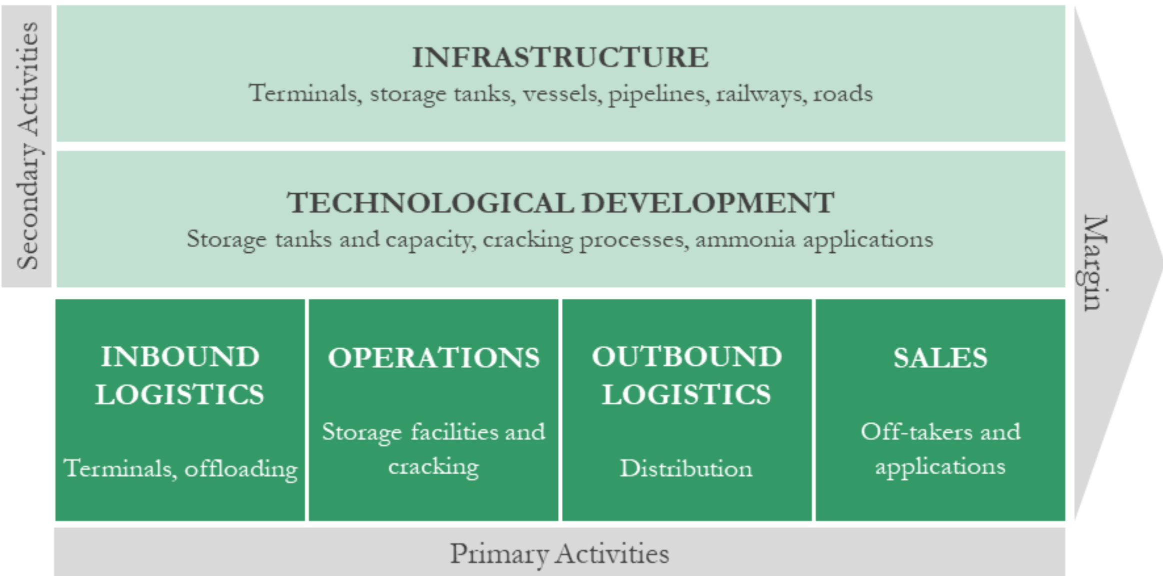

Figure 11. Adapted value chain: ammonia, from import terminal to end-user

Figure 12 is a map of the value chain from the ACE Terminal in Rotterdam to the end-user, including the different possibilities in terms of storage, distribution, cracking and applications.

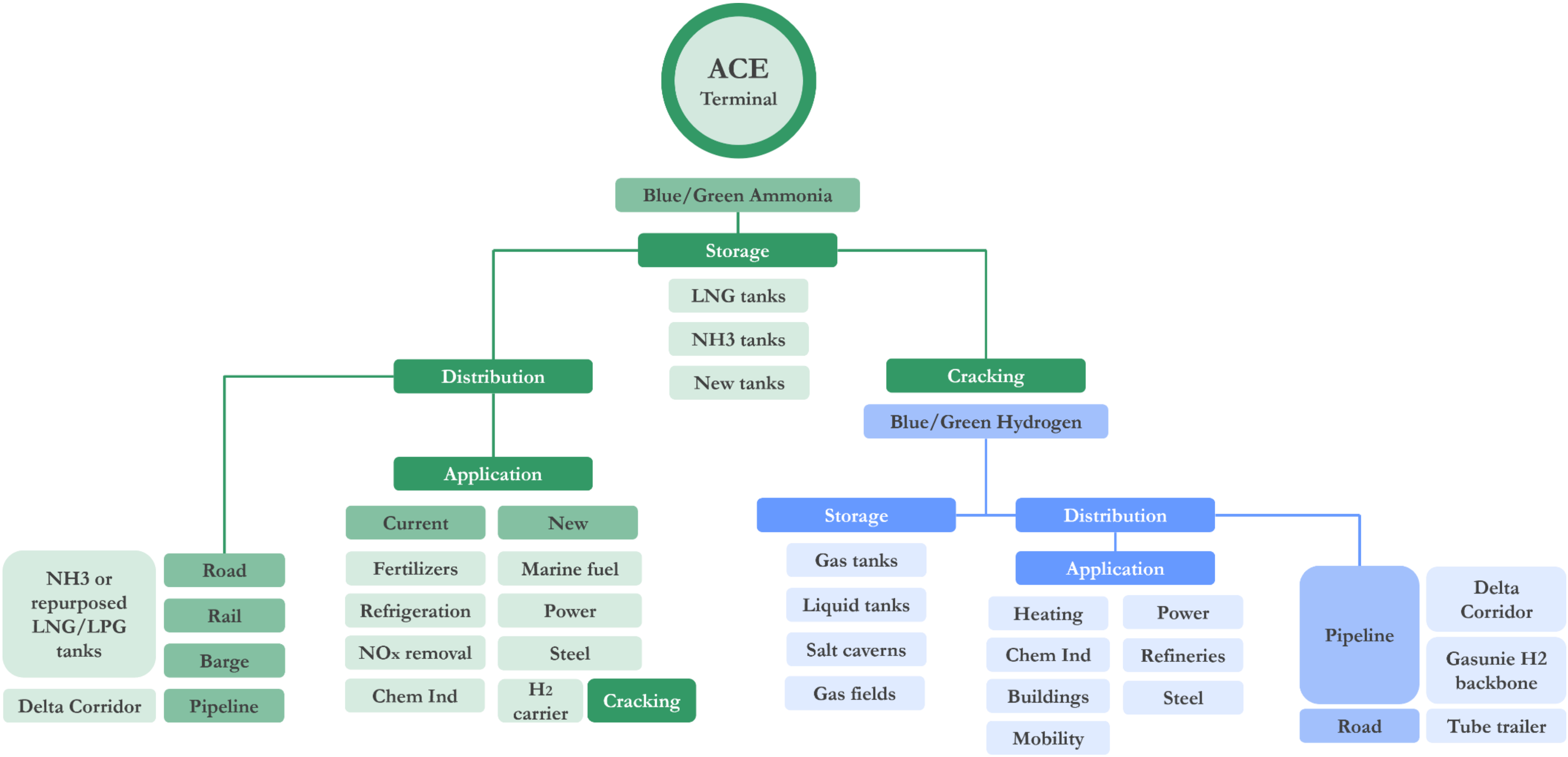

Figure 12. Extended value chain mapping of ammonia from ACE Terminal to end-user

This visual representation raised a set of questions for each step of the chain and highlighted the main concerns and obstacles. Consequently, the results of this study tried to provide answers, consider all the possible options, and gather information that can be useful when making strategic decisions.

Here are the fundamental aspects that require resolution or attention during the development of the value chain:

Ammonia storage

- What are the challenges of adapting LNG storage facilities?
- What will be the storage capacity?

Distribution of ammonia

- What distribution method is best?
- What are the key factors to consider?
- Will the current system suffice?
- Will there be a connection with Germany and Belgium?
- Should the Delta Rhine Corridor include an ammonia pipeline?

Ammonia off-takers

- Where will the main off-takers be?
- What will be the applications of ammonia?
- Will new ammonia markets develop?

Cracking

- Will cracking be necessary/feasible?
- Should cracking be centralized or de-centralized?
- What is the desired cracking capacity of the potential pilot plant in Rotterdam?

Hydrogen storage

- How will the Port of Rotterdam store hydrogen?

Distribution of hydrogen

- What are the challenges of converting Gasunie's NG pipeline network?
- Will Germany and Belgium be connected to the Dutch hydrogen backbone?

Hydrogen off-takers

- Where will the main off-takers be?
- Will new hydrogen markets develop?

The storage aspects of the value chain are the least challenging ones. The interviews with Gasunie and Vopak provided relevant information on the storage plans at the ACE Terminal. The other aspects of the value chain are more complex and require a more thorough analysis, provided in the following results subsections.

Ammonia storage

Gasunie owns two LNG tanks on location with a capacity of 55,000 m^3 each. These do not require any modifications to store ammonia. The only disadvantage is that, because ammonia is heavier than LNG, capacity decreases about 40%. Though the current storage capacity is around 65,000 m^3, the plan is to build four new ammonia tanks to store 85,000 m^3 in each. Therefore, it is expected that the ACE Terminal will have a total storage capacity of 400,000 m^3.

Hydrogen storage

Hydrogen storage will be necessary not only to accommodate cracked ammonia but also to store the hydrogen produced at the port. Shell has reached a Final Investment Decision (FID) to construct Europe's largest green hydrogen facility, which is expected to be operational by 2025.

Small-scale hydrogen storage is possible with both gaseous and liquid tanks. These are useful for small daily fluctuations in demand or supply, but large-scale facilities are currently not feasible. Salt caverns and depleted gas fields are effective solutions for storing large volumes of hydrogen. There are around 700 salt caverns in the Netherlands with a combined estimated capacity of 100,000 to 300,000 m^3. Even though no caverns are in direct reach of the Port of Rotterdam, it is the only current possibility for long term storage because the feasibility of storing hydrogen in depleted gas fields is still unclear. However, future developments might make it feasible and the Port will be able to benefit from offshore gas fields located nearby.

6.2. Results from interviews

The interview process consisted of 20 interviews and a total of 22 interviewees. The latter were business developers, directors, managers, and analysts, and the vast majority had a background in engineering (see Table 8). Unfortunately, only five of the six categories were covered since an appointment with government entities could not be scheduled due to time and resource constraints. Moreover, two interviewees expressed a preference for maintaining the confidentiality of their company's name.

Table 8. Companies and job positions of all participants of the interview process

Category	Company	Field	Position of interviewee
Infrastructure	Port of Rotterdam	Trade & shipping	Business manager
	Port of Amsterdam	Trade & shipping	Strategic advisor energy transition
	Gasunie	Gas infrastructure	Hydrogen import business developer
			ACE Terminal market intelligence
	Vopak	Storage solutions	Business development analyst
			Project engineer new energy & LNG
Technology solutions	Duiker CE	Engineering services	Process development lead
	Stamicarbon	Fertilizer technology	Product portfolio manager
	Company #10	Industrial engineering	Deputy head of technology development
	Proton Ventures	Ammonia solutions	Manager sales engineering
	Air Liquide	Industrial gases	Change leader / engineer
Energy companies	Company #14	Oil & gas	Operations manager
	RWE	Energy production	Commercial project manager hydrogen
	Horisont Energi	Energy exploration	Process specialist
Industrial players	Yara	Fertilizers & Chemicals	Director decarbonization industrial solutions
	OCI Nitrogen	Nitrogen products	Manager technology and energy
	TATA Steel	Steel manufacturing	Director strategy, programs and external relations
Research & consultancy	TNO	Research & innovation	Business director gas technology
			Scientist sustainable transport and logistics
			Strategic business analyst
			Researcher energy transition
	Oostkracht10	Sustainable solutions	Consultant

Covering the entire value chain

Figure 13 depicts the subjects discussed in each interview, showing that the complete value chain, as previously defined, was explored multiple times during the interview process. This enhances the validity of the research findings and conclusions. The green dots indicate that the interviewee was asked about the subject and provided their perspective or knowledge. It is important to acknowledge that, in each case, the level of familiarity would vary depending on the company's field of expertise. Despite this variability, the overall goal was to capture general opinions while also gathering valuable insights whenever possible.

Throughout the course of the approximately 7-week interview period, this table served as a tool to monitor the distribution of covered topics and identify any gaps in information. For instance, by the third week, there was minimal data gathered on new ammonia applications, particularly as a shipping fuel. Consequently, subsequent interviews placed greater emphasis on this aspect, and an internal meeting with a sustainable transport specialist was included.

Among the topics discussed, the *ACE Terminal* and *similar projects* received relatively less input, leading to a multiple case study with fewer results and insights for analysis. On the other hand, the topics of cracking, distribution, ammonia applications, and safety garnered more engaging debates, as interviewees possessed substantial information as well as more established opinions on these matters. These discussions delved beyond surface-level insights typically found in literature.

	ACE Terminal	Cracking	Distribution	Current applications	Future applications	Safety	Similar projects
Port of Rotterdam	●	●	●				
Port of Amsterdam		●			●	●	●
Duiker		●	●		●		
Gasunie	●	●	●		●		
Vopak	●	●	●		●		●
Horisont Energi		●	●			●	
RWE		●	●				●
Air Liquide		●	●			●	●
Yara		●	●	●			●
OCI Nitrogen	●		●	●			
Tata Steel				●	●		
Company #10			●			●	
Stamicarbon		●	●	●	●	●	
Proton Ventures		●				●	
Company #14		●	●				
Oostkracht 10			●			●	
TNO (1)		●	●	●		●	
TNO (2)		●		●	●		
TNO (3)			●		●	●	
TNO (4)				●	●		

Figure 13. Subjects discussed in the interview process

Summary of key aspects

Figure 14 is a summary of the key aspects within the extended value chain that were addressed during the interviews. It encapsulates four major subjects that significantly impact supply chain establishment, i.e. ammonia distribution, handling, and usage. Notably, interviewees had flexibility in their responses for cracking modes, distribution methods, and new applications, enabling them to combine different options.

This summary visually represents interviewee ideas and opinions even though it is important to acknowledge the complexities of their responses, which often hold various perspectives and arguments. Respondents took into account factors such as feasibility, cost, efficiency, and safety, alongside interconnected relationships. Instead of providing clear-cut solutions, they expressed ideas that align with their perception of relevance, market evolution, and the broader context. These ideas and options were presented as likely scenarios and strategies that cater to the interests of stakeholders.

The value of this summary is that it shows shared viewpoints and differing opinions within the industry. For example, while most interviewees favored pipelines as the most cost-effective and secure distribution method, some of them highlighted unique advantages of alternative methods, sparking interesting debate. Similarly, regarding cracking, centralized facilities might seem logical initially, but a couple of interviewees emphasized how it would greatly depend on ammonia and hydrogen end-uses.

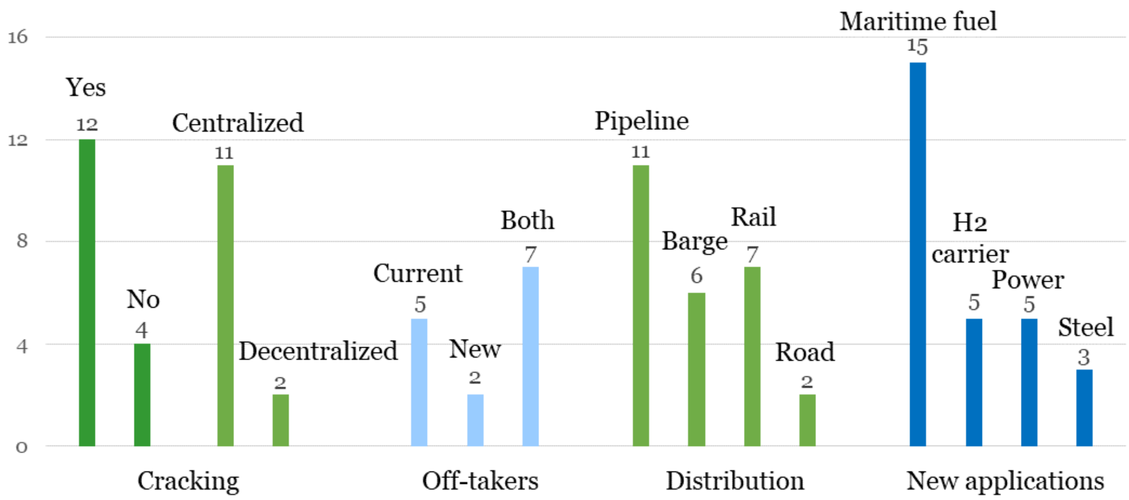

Figure 14. Subjects discussed in the interview process

Twelve participants viewed cracking as a necessary step in the transition. Despite potential expenses and energy loss, respondents valued the existing hydrogen infrastructure and the potential benefits for hydrogen applications. Those who supported centralized cracking emphasized the potential cost savings due to economies of scale, a point that was reaffirmed in the pre-feasibility study by Fluor for a large-scale industrial cracker in the Port of Rotterdam[10].

Two participants leaned towards decentralized cracking, emphasizing its suitability for specific regions like rural areas in Germany. One participant favored decentralized cracking alone, while another opted for a combination of centralized and decentralized cracking. This approach, despite ammonia transport risks, seemed viable and cost-effective for customers with potential demand for both ammonia and hydrogen.

On the other hand, four respondents advocated for using ammonia directly whenever possible, reserving cracking as a last resort. Some expressed skepticism about the future relevance of hydrogen, stating the lack of clear applications.

The perspectives on potential off-takers for imported ammonia offered a varied spectrum of viewpoints among participants. Five respondents had an inclination towards established uses, which is attributed to the dependability and familiarity of these current sectors. Adopting a strategy exclusively focused on existing applications would probably result in smaller volumes of ammonia imports and limited market opportunities. In contrast, two respondents displayed a more forward-looking approach, advocating for exploration of untapped sectors that could become potential off-takers.

Notably, a substantial majority of seven respondents supported a hybrid approach, envisioning a fusion of current and future applications. This convergence implies that simultaneously catering to established and emerging uses of ammonia could lead to a more diversified and resilient market, thus increasing import volumes. Interestingly, this aspect on potential off-takers showcases the industry's willingness to transcend traditional boundaries and promote market growth.

Figure 15. Responses from interviews on ammonia distribution methods

Figure 16 provides more detailed information on each company’s individual response regarding distribution options. Interviewees were openly asked about the influencing factors in the selection of distribution methods and encouraged to give their own opinion on how it should and probably would be done.

Port of Rotterdam	●			
Duiker	●	●		
Gasunie		●		
Vopak	●			
Horisont Energi	●			
RWE			●	●
Air Liquide	●			
Yara	●			
OCI Nitrogen		●	●	
Company #10	●		●	
Stamicarbon		●	●	
Proton Ventures	●		●	
Company #14		●	●	
Oostkracht 10	●			
TNO (1)	●			
TNO (2)	●	●	●	●

Figure 16. Responses from interviews on ammonia distribution methods

The majority of interviewees preferred pipelines as the distribution method for ammonia. While some of them believed that a pipeline would be the sole choice, others mentioned that it might not be entirely feasible. The former had serious safety concerns and were convinced that, given the anticipated import volumes, transportation methods like barges, rail, and especially road transport would not be permitted by the government.
Building a pipeline poses challenges as it requires substantial demand and a large investment. The upcoming Delta Corridor project presents an opportunity to include an ammonia pipeline. However, the decision is pending, and its strategic viability is a topic of debate. Its feasibility relies on consumer locations but the route has already been established. However, if ammonia demand rises in industrial clusters as some forecasts suggest, a pipeline will become indispensable.

Opinions on rail transport were mixed. Some considered trains safe while others viewed them too dangerous to pass through urban areas. Despite, most acknowledged that negative public perception is a main concern. A comparison was made with Germany's use of rail for ammonia transport considering the lack of intention to build an ammonia pipeline.

Similar considerations arose for distribution via barges. While already established and proven effective, increasing ammonia volumes also increase accident risks. Many interviewees emphasized that the ammonia industry cannot afford accidents in these early development stages. Another argument was the current compatibility of barge and rail setups with neighboring countries, Germany and Belgium, which are anticipated to be major off-takers.

While pipelines were most frequently cited, a comparable number of interviewees mentioned barges, rail, or combinations thereof. Road transport appeared in two interviews, not as a standalone method but coupled with other methods, to deliver small volumes of ammonia to plants outside the large industrial clusters.

OCI Nitrogen, already importing ammonia in the Port of Rotterdam, distributes through barges and rail. The company plans to continue this approach unless a direct link between the Delta Corridor in Geleen is established. In such case, OCI would opt for pipelines for safety reasons and government compliance.

The interviewees generally assumed increased ammonia import volumes, although this is not guaranteed. They implied that if the market doesn't grow significantly, the current distribution system will remain viable. Therefore, distribution is directly related to ammonia usage.

As illustrated in Figure 17, participants talked about projections for market growth and the leading novel applications of ammonia. The vast majority were optimistic about its viability as a shipping fuel for seagoing vessels specifically and not for inland shipping. On the other hand, the option of ammonia for power generation was not similarly embraced.

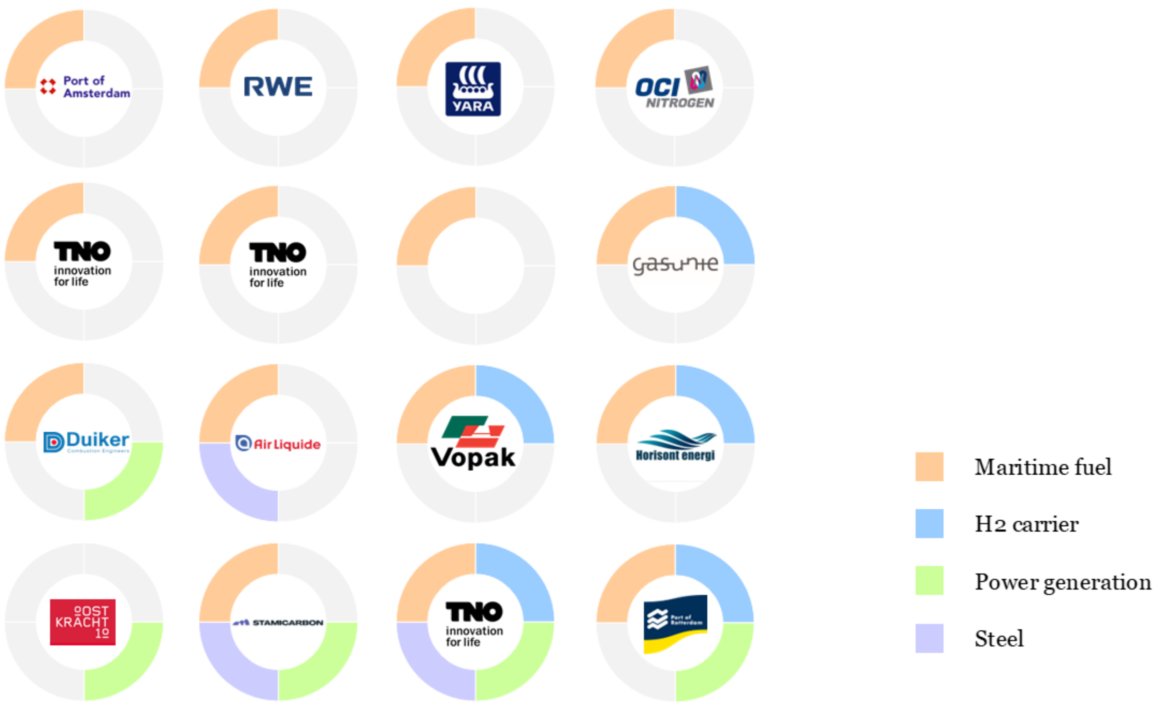

Figure 17. Responses from interviews on future applications of ammonia

Even though interviewees were asked specifically about ammonia as a shipping fuel and its use in power generation, some also mentioned the use of ammonia as a hydrogen carrier, but that topic was discussed separately, when addressing cracking options.

Moreover, three participants included the idea of directly using ammonia for steel production instead of hydrogen. However, it is worth mentioning that Tata Steel has already outlined plans to transition to hydrogen and has no intention of incorporating or utilizing ammonia in their operations.

Recurring themes

Table 9 is a compilation of recurring themes observed throughout the interviews that were not addressed by the interviewer. Therefore, it offers a valuable and realistic representation of the global concepts and drivers, including industry players' perspectives and concerns. This approach is useful to maintain a general outlook on the issue at hand, as going too much into detail can sometimes divert focus from the broader context.

Table 9. Recurring themes in interviews

Uncertainty	Complexity
Difficult to assess and predict the future due to uncertainty regarding applications, safety, policies, public acceptance, and cracking. Stakeholders are hesitant to make decisions and commitments in such variable environments.	Decarbonization goals pose many questions with no easy or clear answers. This is not a problem with a specific or simple solution. It is a big challenge because there are many stakeholders and interdependencies involved.
Global energy demand	**Renewables**
The huge energy demand worldwide has a big impact on all strategic decisions and evolution of the energy sector and overall transition.	One of the biggest obstacles, and the reason for exploring different energy carriers, is the limited availability of renewables in Europe, which makes import activities a must.
Cost effectiveness	**Safety**
It all comes down to the business case because cost considerations are a main driver of all business decisions. This must also be taken into account because the transition affects many industries that need to be able to survive.	The risks of ammonia are clear and it is a general opinion that it should be used only within the industry, not for individual use. Moreover, safety measures are extremely important because one accident can end the ammonia sector at a global level.
Carrot & stick	**Chicken & egg**
The US offers companies more support and subsidies but no real push to take action, while the EU is implementing more restrictive policies but offering no incentives. The latter might risk market development and possibly push production away from the EU.	Supply and demand are tricky because buyers want asset availability and market certainty but providers first need to secure off-takers to make investments bankable.

The first four recurring themes all revolve around the central challenge of the ongoing global energy transition. Themes of uncertainly and complexity underline the attention and collaborative efforts required from both public and private entities to innovate and take action, especially for ammonia, since its potential as an energy carrier is still untapped. Despite ammonia's drawbacks, the need for large quantities of renewable energy predominates. Consequently, most interviewees did not focus on whether ammonia should be imported and used, but on how to integrate it effectively, because it will be crucial to achieving decarbonization goals.

The other four themes are centered around more practical considerations. For instance, many participants emphasized the importance of acknowledging cost implications despite the willingness to decarbonize, and how the industry needs to be able to sustain growth while navigating the transition. Additionally, the risks involved in ammonia handling and utilization were unavoidable addressed. The consensus was that a well-defined protocol for ammonia management, along with staff training and standardized procedures, was crucial. Despite these risks, most interviewees believe that they are not enough to dismiss ammonia as an important element in the transition.

In terms of policies, the belief among industry players that US companies are receiving more support and incentives should be a matter of concern for the European Union. There is a possibility that certain plants might relocate in search of more cost-effective renewables and advantageous legislations, such as the Inflation Reduction Act (IRA) in the US. This law provides funding for carbon capture and storage (CCS) projects, which is why participants mentioned that blue ammonia will play a significant role.

Factors like low gas prices were acknowledged as potential obstacles for the competitiveness of green ammonia, particularly in the short term[22] (see Figure 18). Moreover, the fact that blue technologies, unlike green ones, extend the lifetime of current infrastructures, will solidify the presence of blue ammonia in the market and avoid early decommission of plants.

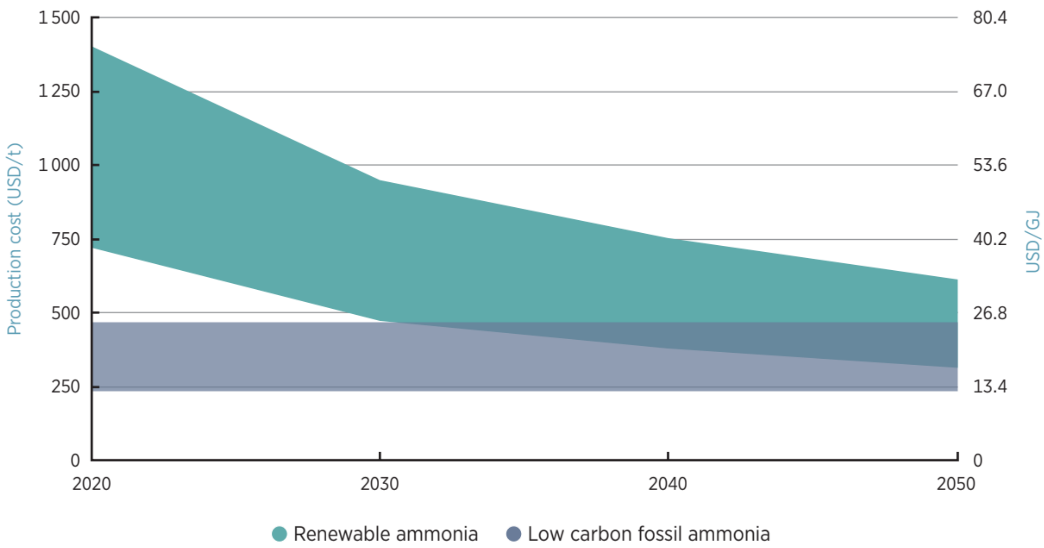

Figure 18. Estimated costs of low-carbon ammonia up to 2050 obtained from the IRENA report[22]

A clear example is OCI's project to build a blue ammonia production plant in Texas, intended for export. This strategic move aims to produce over 1 million tons of ammonia annually and phase out a significant part of their grey ammonia production in the Netherlands.

Comparatively, the European Union's Green Deal focused on imposing stricter limits on greenhouse gas emission, while the IRA aimed to make new climate-neutral technologies more competitive than conventional ones through tax credits and subsidies.

Lastly, the recurring phrase 'chicken & egg' came up when participants wanted to show concern regarding the evident lack of secured off-takers. While attention is currently directed toward global projects for renewable ammonia production and importation, no agreements with off-takers have been announced. For instance, in early 2023, Cepsa and ACE Terminal signed a Memorandum of Understanding (MoU) for the supply of green ammonia to the Port of Rotterdam's import terminal[56].

Progress and impediments in ammonia transition and adoption of new applications

This analysis revolves around the responses provided by nearly all participants when asked about the positive and negative aspects of the transition to green ammonia and the adoption of new applications. The answers were organized based on prevalence, resulting in two word clouds (Figure 19): one showcasing areas seen as progressing well and the other representing current obstacles. Interestingly, some concepts were found in both word clouds.

Progressing aspects

Among the progressing aspects, technology garnered attention from eight participants. They expressed that numerous technologies within the ammonia value chain have been demonstrated and that the focus now lies in their scale-up rather than development. However, three interviewees suggested that technology, particularly in relation to green ammonia production and cracking processes, is not entirely ready yet. These participants emphasized that enhancing performance and reducing costs remain barriers to the successful integration of ammonia into the energy sector.

Momentum, investments, projects, and safety were also highlighted as progressing aspects. However, while one interviewee noted that several projects were reaching the Final Investment Decision (FID) stage, two others contradicted this, indicating that many projects were still in feasibility or preliminary design stages, and no actual construction had really started.

Similarly, safety and investments also garnered differing opinions. Some participants drew attention to DCMR's (Environmental Protection Agency of the Port of Rotterdam) decision to put all ammonia applications on hold and also to the fact that the port has more experience with Liquid Organic Hydrogen Carriers (LOHCs) than with ammonia. In contrast, other interviewees emphasized the collective awareness of involved parties regarding safety considerations and a sense of responsibility, in addition to ammonia's good safety track record. Nevertheless, it was acknowledged that increasing ammonia transport volumes will correlate with increased risk of accidents.

Figure 19. Progress (left) and impediments (right) in the ammonia transition and adoption of new applications, according to interviewees

Impediments

Policies and certifications were widely cited as obstacles to ammonia implementation. The absence of clear governmental guidelines, the need for a sufficiently high carbon price, and stronger support for the development of the value chain were emphasized. Moreover, participants stressed the importance of a straightforward classification for low-carbon ammonia similar to that for hydrogen. A certification framework accounting not only for carbon intensity but also overall environmental impact.

Challenges related to financeability of projects and the gap between grey and blue/green ammonia also came up. The cost of green ammonia is influenced by electricity prices, while blue ammonia costs are dependent on natural gas prices. Cracking processes were also identified as potential contributors to higher hydrogen prices. In an industry where price is vital to differentiate a product from competitors, both these factors are seen as significant obstacles.

Six participants showed concern about public perception and considered it a decisive and pivotal factor for the successful growth of the ammonia market, specifically influencing distribution within the Netherlands. Numerous questions were raised regarding distribution, including the feasibility of bringing ammonia inland, viability of pipelines, projected ammonia volumes for distribution, and ensuring safe transport to remote areas beyond the major industrial clusters.

As already mentioned, this final subject is closely linked to both off-takers and demand, both of which remain unclear. While one participant predicted a surplus of supply over demand, another stated that supply would struggle to meet the anticipated high demand. However, many agreed on the need to support the phase out of fossil fuels on the demand side, thus securing off-takers.

6.3. Ammonia import terminals in Europe

This multiple case study investigates 14 import projects for ammonia across 10 different European ports, including major hubs like Rotterdam and Antwerp, which are among the top five European ports based on size and activity. Table 10 provides an overview of the information that was found on throughput volumes, storage capacity, development stage, project type, expected suppliers and off-takers, cracking considerations, companies involved in the project, and projected operational start-dates.

Given that most projects are in early development stages, the availability of information was limited, making this evaluation preliminary and general. Nevertheless, this section reaffirms the current interest in ammonia and momentum of the sector. The following overview provides insights into the strategies and plans for each terminal.

Table 10. Overview of ammonia import projects in Europe

	Future throughput (Mt)	Storage capacity (m3)	Project type	Development stage	Suppliers	Cracker	Distribution	Off-takers	Companies	Ready
Rotterdam (NL) [56, 57, 58, 59]		65,000 to 400,000	Reuse and expand	Design, FID	Cepsa (Spain)	Yes	Barge and/or pipeline	Fertilizers, shipping fuel	Gasunie, Vopak, HES, ACE Terminal	2026
	1.2 and up to 3		Expand	FID	Middle East, North Africa			Fertilizers, H_2, shipping fuel	OCI Nitrogen	2023
Vlissingen (NL) [60, 61]	1 and up to 2	60,000	Reuse	Feasibility study, FEED		Yes	Barge, rail		Vesta, Uniper, Proton Ventures	2026
		110,000	Reuse	Considering		Yes		Fertilizers, H_2, shipping fuel	Vopak	
Antwerp (BE) [62]	1.5			FID		Yes	Rail, truck, barge, pipeline		Fluxys, Advario	2027
Brunsbüttel (DE) [63, 64, 65]	3 (combined with Rostock)		Expand					Yara	Yara	2024
	0.3		Build		Hyphen (Namibia)	Maybe	Rail		RWE	2026
Wilhelmshaven (DE) [66, 67]	2.6		Reuse	Feasibility study		Yes		NRW industry	Uniper	
			Reuse	Exploring possibilities	bp Australia	Yes		Ruhr industry	bp	2028
Hamburg (DE) [68]			Reuse	MoU	Air Products	Yes			Air Products, Mabanaft	2026
Duisburg (DE) [69]			Build	Letter of intent, MoU				Rhine-Ruhr industry	Duisport, Koole Terminals	
Rostock (DE) [70, 71, 72]	3 (combined with Brunsbüttel)	600,000	Reuse	Cooperation agreement	Total Eren	Yes			Yara, VNG	2028
Immingham (UK) [73, 74]			Build	Second statutory	Air Products	Yes		Humberside industry	Air Products, Associated British	2026
Stanlow (UK) [75]	1		Reuse and expand	Feasibility study		Yes			Essar Group, Stanlow Terminals	2027

Rotterdam

The ACE Terminal benefits from existing infrastructure, dock facilities, and storage tanks, positioning it as potentially one of the largest ammonia import terminals in Europe. Its strategic location enables direct access from the North Sea and connection to Rotterdam's industrial sector. Moreover, ACE Terminal plans to link with Gasunie's national hydrogen pipeline network through an industrial-scale cracker. While green ammonia imports are the primary focus, the initial phase also contemplates blue ammonia.

Simultaneously, OCI strives for carbon neutrality by 2050 and aims to expand throughput capacity at the terminal in Rotterdam. The company's strategy involves collaborating with the business community and public authorities to establish ammonia bunkering operations. OCI seeks to exploit the potential of Europe's largest bunkering port to enhance the ammonia value chain.

Vlissingen

Vesta's terminal in Vlissingen is well located for supply by seagoing vessels, along with reloading into barges and rail tank cars. The company's plan involves utilizing the existing 60,000 m^3 of refrigerated storage capacity and connecting it to the Dutch hydrogen backbone through an ammonia cracker. Proton Ventures is leading the Front-End Engineering Design (FEED) project, further developing the details and preparing for implementation.

Additionally, Vopak, with its refrigerated LNG storage tanks and available space for expansion, is considering the prospect of storing imported ammonia, engaging in cracking, and connecting to the backbone for hydrogen supply across the Netherlands, Germany and Belgium. A final investment decision will be made on the basis of market interest.

Antwerp

The ongoing project at the Port of Antwerp entails multiple send-out solutions, possibly including an ammonia pipeline to industrial sites. What's more, the project also involves the first large-scale cracker, which will be operational by 2024. This pilot plant will connect to Fluxys' open-access hydrogen network, ensuring supply throughout Northwest Europe.

Brunsbüttel and Rostock

Yara's expansion plan covers both the Brunsbüttel and Rostock terminals, with a combined target of importing 3 million tons of ammonia annually, sourced form plants like Total Eren's production site in Chile. Regarding distribution, Yara is interested in collaborating with VNG to make use of its extensive hydrogen pipeline network. Similarly, RWE intends to import from Namibia to Brunsbüttel and is working with VTG, an experienced global logistics company, to facilitate delivery by rail in Germany and neighboring countries.

Wilhelmshaven

Uniper and BP are exploring the reuse of existing infrastructure for ammonia import. The former wants to leverage the port's deep-water facilities and access to Germany's largest hydrogen cavern. The terminal will be connected to the European hydrogen backbone to support the Nort-Rhine Westphalia industrial clusters, potentially supplying 10-20% of German demand by 2030.

It is worth noting that not all projects are based on revamping and reusing existing facilities. There is a balance between reusing infrastructure, expanding import capacity, and building new terminals. This reflects the sector's anticipation of significant future ammonia imports and growing demand.

Many projects are structured in two phases, with the second involving throughput capacity expansion and cracker construction. However, while most project announcements anticipate cracking, only a few organizations are currently deploying and demonstrating these technologies at the required scale. Furthermore, there is emphasis on connections to the hydrogen network but no details about early ammonia imports prior to cracking readiness.

There is another noticeable gap in information regarding suppliers but especially off-takers. Indications are vague, only referring to industrial areas near the ports but no specific companies or applications. Similarly, there is little information about inland distribution of ammonia.

6.4. Ammonia opportunities and prospects

Growth strategies

The Ansoff Matrix for ammonia can be divided into two categories:

Existing product → **Grey** ammonia

New product → **Green and blue** ammonia

Grey ammonia is widely used for various applications. Its growth strategy over past decades has mainly focused on market penetration in industries such as fertilizers and chemicals, which have experienced steady growth. Moreover, the later inclusion of ammonia in sectors like refrigeration, metal treatment, textiles, food products, polymers and explosives, can be categorized as market development, as ammonia expanded its presence into new industries.

Therefore, both green and blue ammonia fall under the classification of new products due to their value proposition of reduced environmental impact and contribution to decarbonization goals. Low-carbon ammonia presents two potential growth strategies, each with clear potential but also significant risk.

Product development → New product in existing market

This approach involves increasing the adoption of green and blue ammonia in markets where ammonia is already in use. In the near-term, this is a good strategic approach because the level of risk is moderate and the market is already established. Understanding the added value for customers, potential incentives, and switching costs is essential.

A significant consideration is the fact that about 55% of global ammonia demand comes from urea production, which requires both NH_3 and CO_2. As a result, replacing fossil-based ammonia entirely might not be feasible because some ammonia and urea plants are integrated.

Diversification → New product in new market

This strategy involves exploring entirely new applications or industries for renewable ammonia, and also the highest level of risk. For example, Japan's use of ammonia as a stationary fuel in the power sector highlights the potential of diversification.

Identifying sectors where ammonia can drive transformation and demonstrating clear value to customers is key. This approach also needs to consider factors like regulations, safety and switching costs for potential customers.

Internal and external factors

The SWOT analysis in Figure 20 shows the numerous benefits that low-carbon ammonia offers for achieving decarbonization goals due to its well-established global trade and existing infrastructure. The handling of ammonia, though challenging due to toxicity and water solubility, is countered by specialized training, the compound's distinctive smell, and high ignition energy, which reduce the risk of an accident. Opportunities include production initiatives, the stability and growth of the agricultural sector, and emergence of new applications.

However, there are certain vulnerabilities and challenges. Ammonia faces technological obstacles in the fields of fuels, production efficiency, management of combustion gases, and large-scale cracking. Industry stakeholders, though optimistic about technology readiness, acknowledge the time-sensitive nature of the energy transition and its competitive landscape. Moreover, public perception as well as governments' have the capacity to shape ammonia's trajectory.

Strengths	Weaknesses
→ High **hydrogen density** → **Low carbon** footprint → Global **trade network** → **Existing** storage and transportation **infrastructure** → **Ease of handling** (mildly cryogenic) compared to hydrogen → Existing **production** methods → **High ignition** energy (safety) → Early **detection** possible due to odor and reactivity	→ **Toxicity** and hazardous properties → **Little experience as fuel** for any sector → Codes and **standards not** fully **developed** → **High ignition** energy (combustion engines) → Low **energy density** → Risk of **combustion gases** (NOx, N_2O) → Energy **conversion losses** → Water **solubility** → Specific **training** required for handling → Large **investments** in production plants

Opportunities	Threats
→ **Carbon neutral** energy carrier → **Hydrogen storage** solution (efficient use of surplus renewable energy and less power fluctuation) → Industry **decarbonization** efforts (replace fossil fuel use) → Development of **new applications** → Increasing number of industrial projects for **production** of green and blue **ammonia** → Growing **agricultural industry** (increased sustainable fertilizer demand)	→ **Public perception** and acceptance → Proximity of ammonia operations to **populated locations** → No operational **large-scale crackers** yet → **Competition** of other hydrogen carriers → **Price gap** between grey and blue/green → Regulatory and **policy changes** → **Supply chain** not ready for expected future demand

Figure 20. SWOT analysis of low-carbon ammonia

Readiness vs. confidence

The graph in Figure 21 illustrates the perceived role of renewable ammonia across existing and potential applications, along with the level of technological readiness. Each circle represents a different application, with its size reflecting estimated potential future demand. This analysis is qualitative and draws on both literature and insights from interviews to offer an informed estimation.

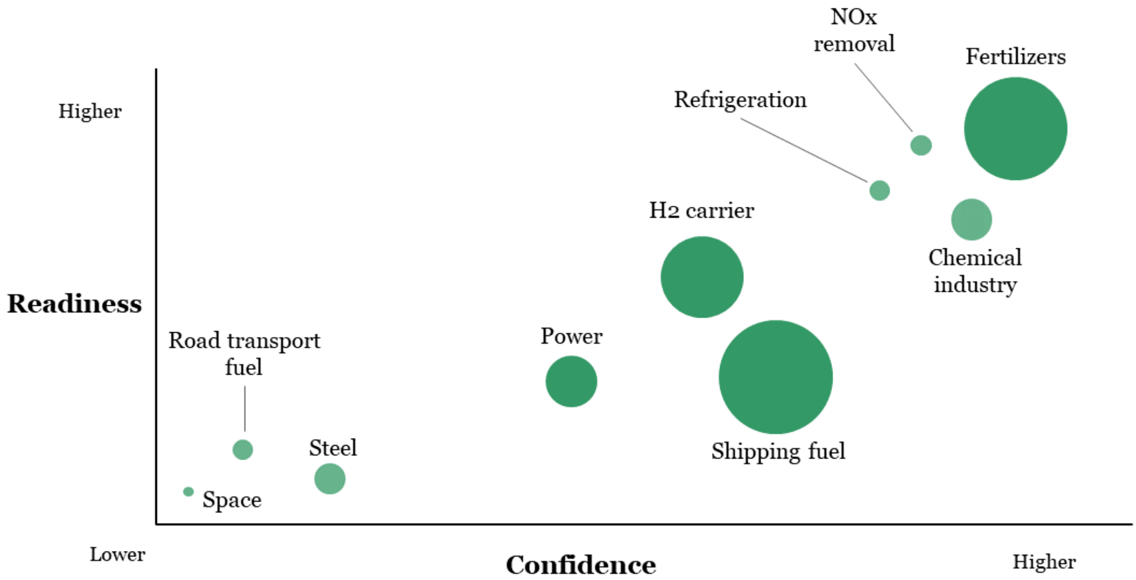

Figure 21. Renewable ammonia applications Readiness vs. Confidence

The application with the highest potential appears to be shipping fuel even though it is sparking considerable debate due to safety concerns and N_2O emissions. Another disadvantage is ammonia's low energy content compared to methanol, a strong competitor. Ammonia requires more storage space for the same amount of energy and thus leaves less space for cargo. Additionally, a technical study determined that, although retrofitting vessels to operate on ammonia is technically feasible, the costs are higher than 50% of the ship's market value[76]. Despite these challenges, risk assessments conclude that crew risks can be kept at a tolerable level through proper guidelines[77], which solidifies ammonia's position as a strong contender. Moreover, the main advantage of ammonia over methanol is that it does not require a source of CO_2 for production and is carbon free.

A complete shift to ammonia for the maritime sector could amount to a demand of 400 million tons[78], although the shipping industry will probably opt for a diversification strategy. Nonetheless, supplying a significant part of the global maritime shipping energy would potentially double, tripe, or even quadruple current demand and production capacity. Various estimates show shipping as the biggest driver of ammonia consumption, with projections reaching 150 million tons by 2050[78]. Similarly, IEA's ammonia technology roadmap suggests that, in a net-zero emissions by 2050 scenario, maritime fuel would account for 44% of global ammonia demand, translating to roughly 200 million tons[79].

Fertilizer applications display higher confidence and readiness levels but share a similar potential with shipping fuel due to constraints caused by the dominance of urea in the nitrogen market. On the other hand, Japan is driving ammonia demand for power generation, but lack of clear indication on whether it will be green and limited interest from other countries lower the confidence and potential levels of this sector. Lastly, ammonia's prospects as a hydrogen carrier are dependent on cracking technologies, although stakeholders are certain that cracking operations are imminent.

6.5. Ammonia and hydrogen markets

Off-takers

Figure 22 presents an overview of potential off-takers for ammonia, with particular focus on industrial areas. This decision to concentrate on industrial areas aligns with a practical approach as it encompasses the existing consumers of ammonia, such as the fertilizer, chemical and other industries. The OCI and ICL fertilizer production plants are located in Chemelot while Yara's and Rosier's are in Terneuzen. These applications have the highest confidence levels and relatively low associated risks. Moreover, this approach considers the view of interviewees that ammonia should primarily serve industrial applications.

In the prospect of new applications for ammonia, the same conceptual framework remains applicable. For instance, ammonia's utilization as a shipping fuel does not require inland distribution, as refueling occurs at ports. Similarly, ammonia serving as a hydrogen carrier is expected to be integrated into the existing hydrogen pipeline infrastructure. Additionally, in the case of using ammonia for power generation, the demand is likely to originate from these industrial areas as well.

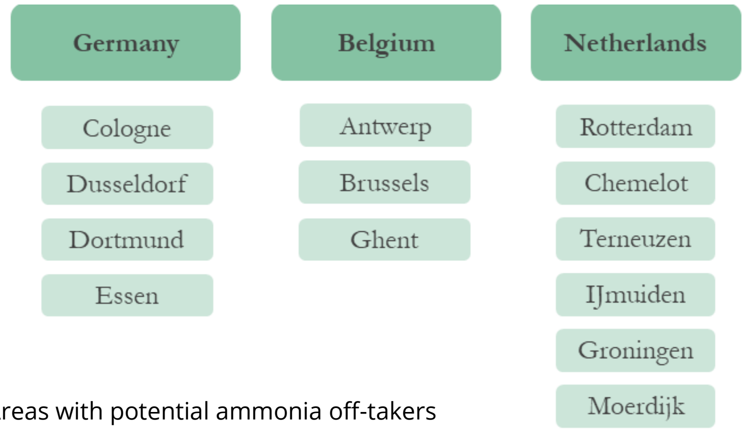

Figure 22. Areas with potential ammonia off-takers

The assessment of off-takers extends to the Netherlands, Germany, and Belgium. This is grounded in the anticipation that neighboring countries will have significant demand, leading them to rely on the Netherlands, specifically the Port of Rotterdam, as a key source of supply.

However, the assumption that all industrial clusters, and specifically the four biggest fertilizer production plants, have interest in importing ammonia through the ACE Terminal may need reassessment. During interviews, OCI, for instance, did not show interest as the company already imports ammonia through its own terminal in Rotterdam. Similarly, it is probable that Yara will not opt for ammonia imports at its Sluiskil (Terneuzen) location due to highly integrated processes at the site, i.e., various processes are closely connected and interdependent. Therefore, Yara has no plans to switch off any plants. Nevertheless, at the Brunsbüttel (DE) location, the transition to renewable ammonia seems more feasible as ammonia and urea are the sole products. These factors indicate the need to also consider smaller fertilizer companies and other applications of ammonia within these clusters since basing the transition on the demand from big fertilizer plants solely, while seemingly logical, may not be the most viable approach.

This information regarding potential off-takers is also presented in a map to provide geographical perspective (Figure 23). The map considers both the existing hydrogen backbone and the Delta Corridor, which could potentially accommodate both hydrogen and ammonia distribution. However, it is evident that the hydrogen network will be significantly more extensive and with wider reach.

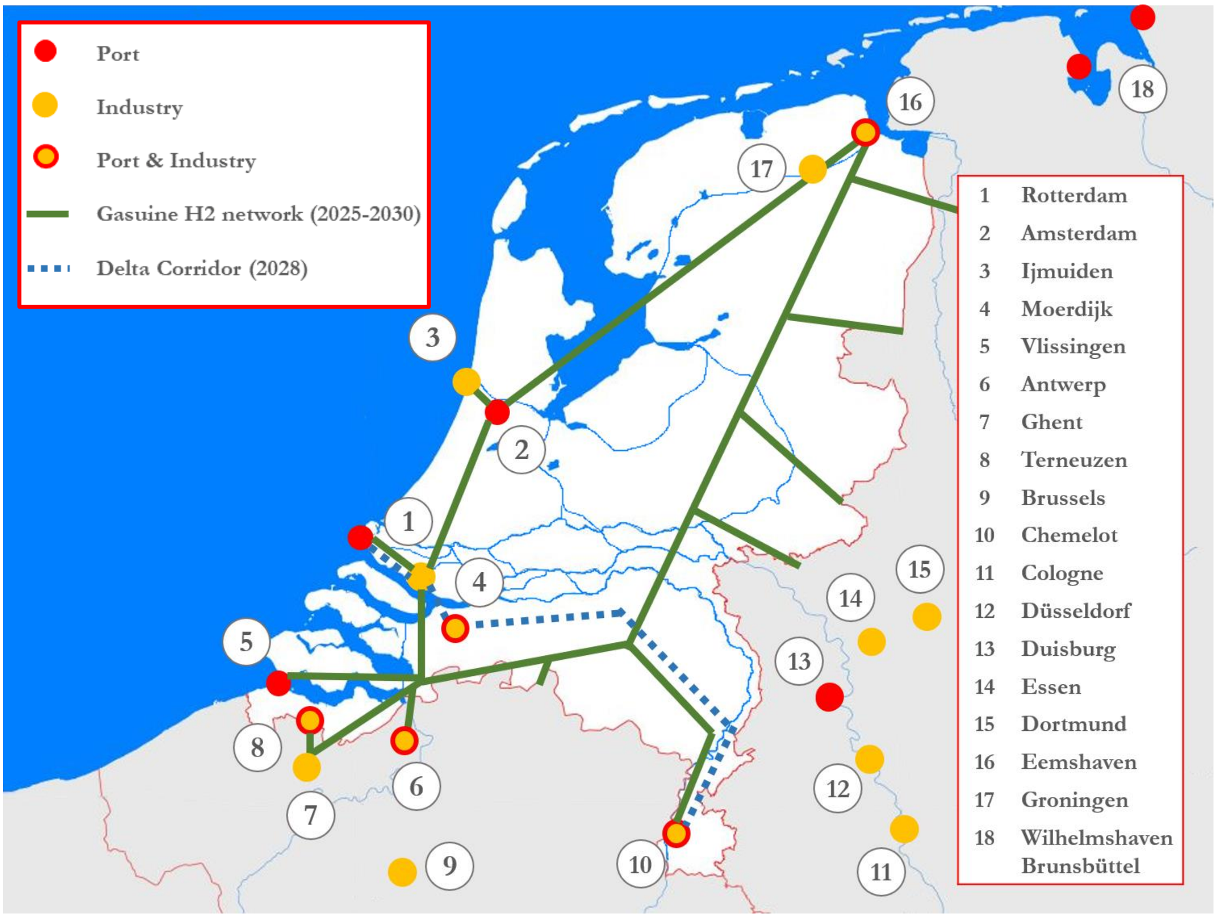

Figure 23. Map of potential ammonia and hydrogen off-takers

In addition to the ammonia market, it is important to evaluate the hydrogen market, as it plays a pivotal role in the current energy landscape and has a direct connection to ammonia. While hydrogen initiatives have faced challenges in the past, the current dynamics of renewable energy technology and government collaboration suggest a more promising outlook. Global demand for hydrogen stands at 94 million tons annually, with a recent increase driven by traditional applications in refining and industrial processes.

Similar to ammonia, the potential of the hydrogen market lies in the shift towards green and the expansion of industrial uses. New applications, such as transport and heating, are emerging as key areas of growth. For instance, renewable hydrogen demand from refineries pursuing decarbonization, though limited, could boost the green hydrogen market. While individual customer demand remains uncertain, the focus should be on monitoring the evolution of hydrogen developments.

The existing natural gas pipeline infrastructure, which will be adapted for hydrogen, will probably influence customer preferences, favoring the adoption of hydrogen due to its ease of supply compared to other fuels or energy sources like renewable electricity, which may be constrained and subject to fluctuations.

A notable example of a future hydrogen off-taker in the Netherlands is Tata Steel in the Ijmuiden area. Tata Steel is actively planning to transition to hydrogen, and their existing grid connection makes this transition feasible. Their operations are expected to drive substantial demand, and they are collaborating with Nouryon and the Port of Amsterdam to develop a hydrogen cluster, anticipating significant future demand. However, it is worth noting that this is a long-term project, as Tata Steel is initially transitioning from coal to natural gas, a move that will already result in major improvements in terms of climate impact.

Shell is also taking proactive steps to introduce new hydrogen solutions for industrial customers in energy and chemical parks near Cologne, as well as at Shell sites in Rotterdam and Moerdijk. Additionally, RWE and Shell are exploring the integration of hydrogen into the mobility sector in Germany, the Netherlands, and the UK. They are evaluating the feasibility of establishing a hydrogen station network for heavy trucks connecting Rotterdam, Cologne and Hamburg.

Furthermore, Germany's inauguration of a railway line with 14 trains powered entirely by hydrogen in 2022 serves as compelling evidence that the hydrogen market will experience substantial growth in the coming years.

Cracking

In this context of the hydrogen market, it is crucial to assess its direct connection to ammonia, particularly in the context of cracking. Moreover, Rotterdam has ambitious plans to crack 7 Mt of ammonia to supply 1 Mt of hydrogen to the backbone.

Figure 24 delves into the advantages and disadvantages of ammonia, categorized into four main blocks: costs, market, energy considerations, and technological aspects.

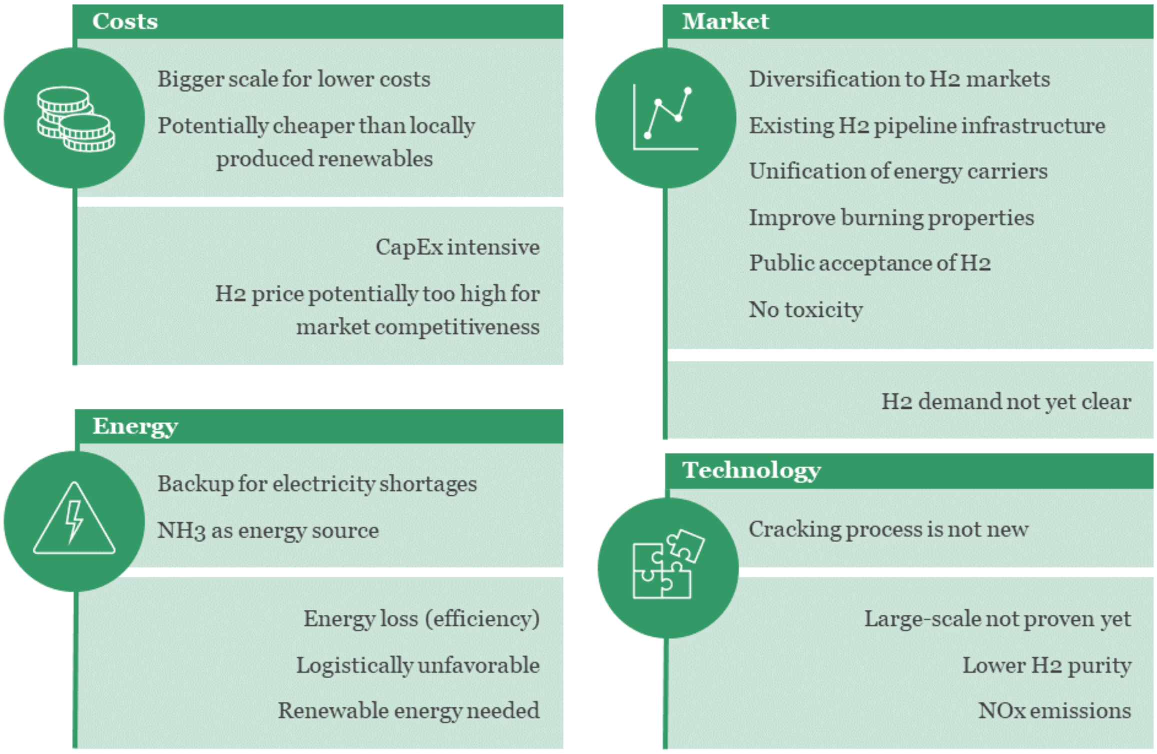

Figure 24. Cracking advantages and disadvantages

Regarding costs and technical considerations, these should be acknowledged as challenges rather than barriers. The development of technologies for managing hydrogen purity and emissions is of high importance and time-sensitive. These challenges will be addressed in the upcoming large-scale pilot plant in Antwerp. As for costs, while large investments would be required, the prospect of a high hydrogen demand might help offset these initial investments, ultimately driving down operational costs and the final price of hydrogen.

In terms of energy, while small crackers can effectively operate on electricity, larger units would need to rely on ammonia or hydrogen as an energy source. Duiker is already working on such solutions involving the utilization of the ammonia itself as the primary heat source for the cracking process. This approach stands out as the most advantageous option both from a technical and economic perspective.

Furthermore, market considerations for ammonia cracking are predominantly positive. Ammonia would be able to penetrate new markets within the hydrogen sector and accessibility for customers would be greatly facilitated through the hydrogen backbone. Additionally, public acceptance leans favorably toward hydrogen. An interesting prospect lies in cracking operations to offer a blend of ammonia and hydrogen as a fuel source, thereby enhancing combustion properties and delivering a value-added product to customers.

6.6. Distribution of ammonia

This section presents a comparative analysis of the four considered methods for ammonia distribution. Table 11 details the various key aspects associated with distribution.

A significant concern, particularly in the Netherlands, revolves around proximity to urban areas and the potential pollution of rivers, which could have adverse effects on aquatic life. Over the past decades, there have been few accidents related to ammonia distribution, primarily involving train derailments, leakages, and truck collisions[80]. While these accidents have not resulted in casualties, affected areas had to be evacuated, and some people required medical assistance due to inhalation. It is worth noting that accidents also occur with pipelines, often due to digging, ground works, corrosion, and material failures[31]. Therefore, stringent guidelines and regulations are essential for pipeline inspection, leak detection and mitigation.

In terms of cost-effectiveness, barge transport emerges as the most economical option due to its lower capital expenditure (CapEx) and operating expenses (OpEx), with costs being relatively independent of distance. Pipelines, however, exhibit higher initial investment costs, but for short distances they offer lower operating expenses. The decision on whether to include an ammonia pipeline within the Delta Corridor is tied to future ammonia demand, as it requires a minimum volume and constant supply. In contrast, other transportation methods possess lower capacities but greater flexibility regarding volume. If ammonia demand were to grow exponentially, the existing transportation modes would struggle to handle the imported quantities, potentially saturating networks and increasing the chance of an accident.

The uncertainty surrounding future ammonia applications and off-takers complicates the pipeline decision, as it has a fixed route and modifying it is cost-intensive. Additionally, the absence of ammonia pipelines in Germany and Belgium presents challenges for connecting with these countries, whereas connection via rail is already established. It is important to note that the Dutch government presently favors barge transport over rail[81] and its stance on the possibility of a pipeline remains unclear.

An option to consider is the Betuweroute (see Figure 25), particularly in the near term. Launched in 2007, the Betuweroute is a significant Dutch infrastructural project designed exclusively for freight traffic, connecting Rotterdam to the German border. This route, which avoids passing through cities, boasts high capacity, accommodating around 90 freight trains daily. In 2014, over 25,000 trains utilized this route. Most importantly, Germany secured funding in 2016 to extend the route to the Ruhr area by 2030[82].

Table 11. Comparative analysis of ammonia distribution methods (part 1 of 2)

	Safest Most efficient	Most feasible Logical	Most convenient Best connected	Most dangerous Least efficient
Safety	Safest	Risk of accident	Risk of accident - debatable	Higher risk of accident
	Strategy for leak detection necessary		History of leakages (US)	
	Low carbon footprint	Goes near urban areas	Goes through urban areas	
Cost	High CapEx (≈ 1.5M €/km)[83]	Low CapEx (lease/rental)	Low CapEx (lease/rental)	Low CapEx (lease/rental)
	Cheapest below 300km[84]	Cheapest for long distances	Cheaper than truck	Most expensive
	Low OpEx	Low OpEx	Low OpEx	High OpEx
	High distance sensitivity	Low distance sensitivity	Significant distance sensitivity	Significant distance sensitivity
Infrastructure	No existing pipeline	Established	Established	Established (small-scale)
	Delta Corridor construction 2026		Betuweroute extension ready by 2030	
	Need to require rights of way		Ijsselroute and Brabantroute operational	

Table 11. Comparative analysis of ammonia distribution methods (part 2 of 2)

				
Route	Fixed route	Flexible route	Flexible route	Most flexible route
	No connection to Germany and Belgium	Connection with Germany and Belgium	Connection with Germany and Belgium	Connection with Germany and Belgium
	No need for water connection	Susceptible to droughts	No need for water connection	No need for water connection
Volume	Flexible capacity (for scale-up)	Limited capacity	Limited capacity	Low and limited capacity
	Depends on pipe diameter	≈ 1000 - 2000 tons	≈ 50 tons/RTC, 22 RTCs/train	≈ 20 tons
	Minimum demand required	Fit for fluctuating demand (small growth)	Fit for fluctuating demand (small growth)	Fit for fluctuating demand (small growth)
Regulations	Government support required	Currently preferred by government	Discouraged by government	Government efforts to reduce
		ADN (dangerous goods)	RID (dangerous goods)	ADR (dangerous goods)
Public acceptance	High	Medium	Low	Very low

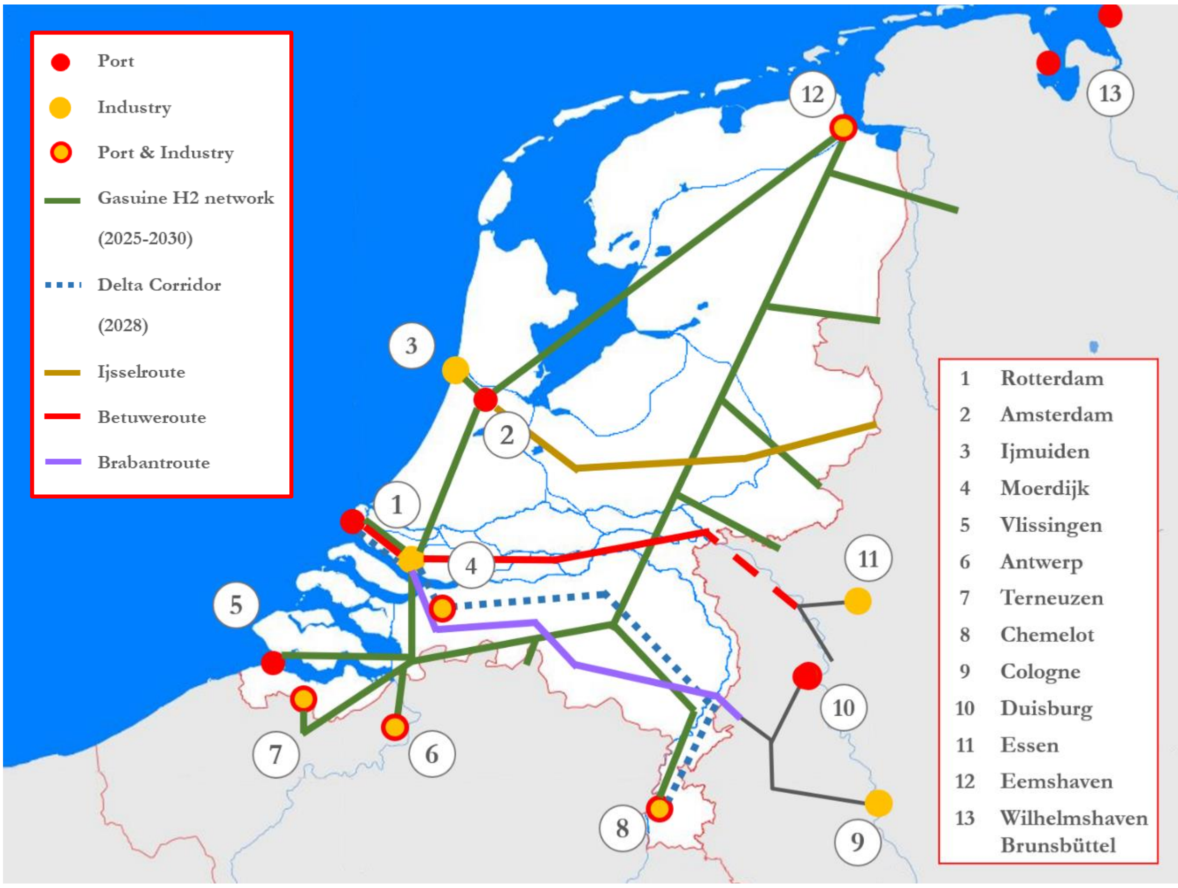

Figure 25. Map of Dutch pipeline networks, rail routes and waterways

6.7. Potential scenarios

This section offers an examination of potential scenarios that depict the future of ammonia. Four distinct scenarios (Figure 26), derived from different combinations of four primary application blocks (Figure 27), have been defined to provide insights into the landscape of ammonia utilization. The first application block is the current ammonia market, and the other three are based on the applications with the highest confidence and potential future demand, as shown in Figure 21. Moreover, in Figure 27, horizontal arrows outline the interdependencies within individual applications and various distribution methods.

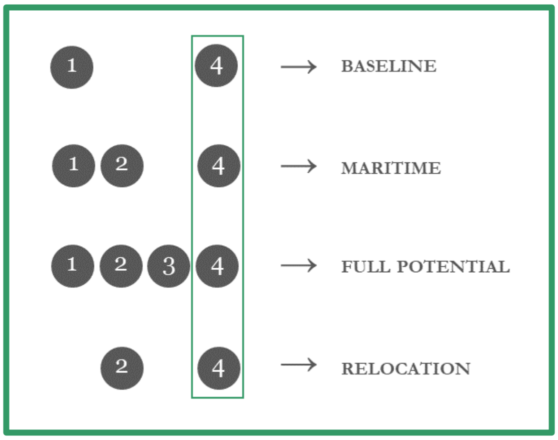

Figure 26. Four scenarios for ammonia

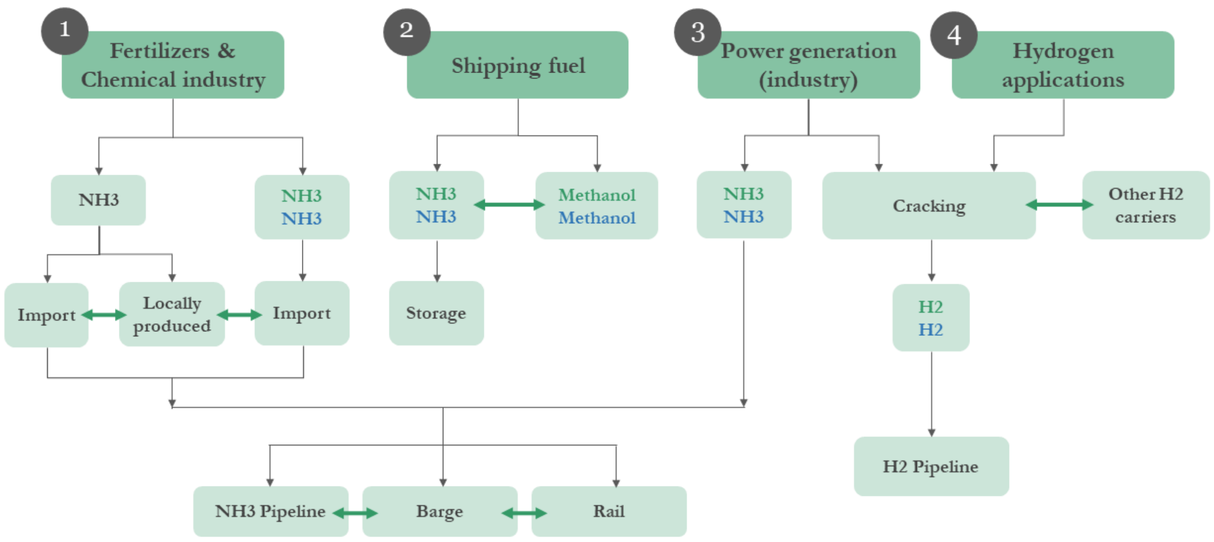

Figure 27. Four main application blocks for ammonia scenario planning

It is important to note that these scenarios emphasize implications and critical aspects concerning infrastructure and distribution methods, rather than delving into expected demand figures, as multiple studies have already addressed this[22, 30].

Baseline scenario

The baseline scenario is the most probable, especially in the short term, and represents a conservative approach. Stakeholders and interviewees agree that targeting the current market should be the initial priority, considering lower risks in terms of business development. That is why the first block (fertilizers and chemical industry) is included in three of the four scenarios. Furthermore, the fourth block, ammonia's role as a hydrogen carrier, is featured in all scenarios, given Europe's significant investments in unifying energy trade through hydrogen. The scale of this is still not clear but it will have direct impact on hydrogen storage capacity and cracking facilities. Depending on demand, perhaps a cracker at the Port of Rotterdam will be enough, or perhaps other ports will also have their own cracking facilities.

Causes for the baseline scenario might be strong opposition from the public or strict safety regulations impeding its use as a fuel. Considering a steady growth of current ammonia industries, gradual adaptation of the existing value chain might be possible without an ammonia pipeline because it is highly unlikely that the entire ammonia industry will decarbonize and that a grey ammonia baseline will not remain. Therefore, a combination of barge and rail transport may suffice, provided continued governmental support for barge transport and consideration of the Betuweroute.

Maritime scenario

This second scenario envisions the successful adoption of ammonia as a shipping fuel, building upon de baseline scenario. The interviews indicated that this application holds enormous potential due to the substantial size of the shipping market. Over the long term, the market could shift from the baseline scenario to this maritime scenario.

Implementing this scenario translates to an expansion of storage facilities at the ports, a potential challenge if the ammonia market triples in size, as predicted in some studies. Additionally, ports would need to develop refueling systems while governments would be required to establish rigorous safety regulations. Notably, this scenario also does not necessarily mandate the construction of an ammonia pipeline.

The widespread adoption of ammonia as a shipping fuel would also be influenced by the cooperation of ports, particularly major ones like the Port of Rotterdam although, for instance, the Port of Amsterdam is at the moment reluctant to handle ammonia within its facilities. However, this position could change in the face of significant market growth. If the Port of Rotterdam were to receive ammonia-fueled vessels, it could set a precedent for other ports to follow suit.

A report by IRENA projected that, in a scenario aligned with the goals of the Paris Agreement, ammonia demand from the maritime sector would surpass the combined demand of all existing ammonia markets by 2030. However, under current policies, fossil-based ammonia production would double, and by 2050 less than 10% of the market would consist of renewable ammonia[22]. Therefore, the realization of this maritime scenario heavily depends on the effective implementation of policies aimed at promoting and facilitating decarbonization, particularly within the shipping sector.

Full potential scenario

This scenario delves into the full potential of ammonia, a future where the government strongly supports its use across various applications. Consequently, this is the scenario carrying the highest level of risk. However, it is important to acknowledge that it is less probable than the previous scenarios because, at present, only Japan has demonstrated significant interest and commitment to investing in the development of ammonia as a stationary fuel. Furthermore, this full potential scenario would entail the need for an ammonia pipeline to supply industries in the Netherlands and neighboring countries.

The transition of industries from fossil-based fuels to renewable ammonia holds the potential to significantly boost demand. Companies such as Duiker are actively working towards realizing this transformation. It is worth noting that this scenario would likely require the most extensive supply chain development efforts and long-term investments. However, an ammonia pipeline would be more cost effective than in the previous scenarios.

It should be noted that this highly inclusive scenario, encompassing all four main application blocks, closely aligns with the scenarios examined in other studies, which consistently incorporate all potential applications when forecasting ammonia demand.

Relocation scenario

This last scenario represents a possibility that some interviewees were concerned about although they also believed that Europe will strive to avoid it. However, there is no guarantee of its avoidance. With the development of green and blue ammonia production worldwide, it is quite certain that, over time, the price of low-carbon ammonia will significantly decrease, making it competitive with grey ammonia. Some companies, such as OCI, already see importing ammonia as a more cost-effective option than producing it in-house. While this pertains to grey ammonia, blue ammonia is expected to catch up, especially in the US. In such a scenario, companies may begin importing larger quantities of ammonia, and some might even relocate their production plants to countries where renewable energy is more economical, opting to import the final product instead of the ammonia feedstock. However, in this scenario, with a competitive price, ammonia could still find opportunities as a hydrogen carrier and shipping fuel.

Although this scenario is not as likely, as Europe aims to preserve its industrial sector, and many ammonia plants are integrated with other industrial activities, companies will inevitably always prioritize the most cost-effective solutions. Thus, some plants will probably eventually relocate, which will certainly harm the Dutch industry and economy.

7

Conclusions

& Recommendations

Conclusions

Fulfillment of objectives

The following conclusions and key findings are presented as an evaluation of the eight proposed objectives of this research:

Objective 1 → Value chain

The value chain analysis and multiple case study identified two critical bottlenecks: the distribution of ammonia, which is the most challenging, and the cracking processes, with technological developments underway. Until these two bottlenecks are resolved, it will be challenging to secure off-takers.

Objective 2 → Obstacles in the transition

Interviews revealed, in addition to overall uncertainty, five main obstacles in transitioning to renewable ammonia:

1. Cost competitiveness.
2. Safety concerns and public acceptance of distribution pathways.
3. The need for policies and certification.
4. Lack of off-take agreements.

Objective 3 → Distribution methods

Currently, it is unclear whether there will be enough demand to justify an ammonia pipeline. If a pipeline were to be built, it should include a direct connection to the German industry, as it is expected to drive significant demand.

Should the government support the utilization of the rail Betuweroute, a combination of barge and rail transport could serve as a viable and flexible solution, offering reliability in a fast-changing environment.

Directing efforts toward improving safety and risk management in rail transport might be a more strategic course of action compared to investing in a pipeline whose profitability remains uncertain.

Objective 4 → Applications of ammonia

There are three future applications of ammonia with significant potential but uncertain in terms of readiness and confidence. Renewable ammonia needs a stronger value proposition to secure its position as a leader in the transition because its future is highly dependent on government intervention.

While the shipping market offers more opportunities due to its size, the power sector might be a more pragmatic alternative, utilizing the same distribution infrastructure as current ammonia consumers in industrial clusters. In this context, a pipeline could be a more profitable option.

Objective 5 → Interviews

20 interviews, instead of the 10 initially proposed, covered the entire value chain, with the exception of governmental institutions, and provided valuable insights. General opinions include:

1. Centralized cracking.
2. Incremental approach from existing markets to diversification.
3. Preference for ammonia pipeline, though a combination of barge and rail was also considered viable and relatively safe by some.
4. Maritime fuel as the future application with the most potential.

Objective 6 → Critical approach

Achieving this objective presented significant challenges. The study attempted to present contrasting opinions and remain unbiased but lacked input from stakeholders with no specific interest in ammonia.

Four scenarios were proposed with an aim to maintain realism and deliberately avoiding demand forecasts based on potentially biased assumptions. However, the study proactively explores opportunities to facilitate the adoption and establishment of ammonia as a leading green fuel.

Objective 7 → Market research

This objective also presented challenges due to the need for extensive consumer engagement, which remains highly uncertain. Nonetheless, notable findings include that OCI and Yara Sluiskil showed no inclination toward procuring green ammonia via the ACE Terminal.

Although ammonia cracking poses logistical inefficiencies, the likelihood of industrial clusters transitioning to ammonia instead of hydrogen, considering that the hydrogen value chain is more mature, seems low. Nevertheless, developing the ammonia value chain and consolidating its position in direct application markets would result in increased availability, offering a competitive advantage over other hydrogen carriers.

At present, focus on two primary crackers in Antwerp and Rotterdam seems the best strategic decision. In the future, once the technology is more mature, and if ammonia has a high potential market share within the hydrogen landscape, the consideration of smaller crackers in other European ports will make more sense.

Objective 8 → Advice and recommendations

The thorough analysis and research carried out generated relevant advice for TNO, industry players and governments, and is presented separately in the conclusions section.

Other key findings

The main challenges to reach the maritime or full potential scenarios are as follows:

- **Limited government cooperation** and support to incentivize the decarbonization of fertilizer and chemical industries.
- **Uncertainty regarding the market** sizes of green hydrogen and ammonia, off-takers and cost-competitiveness.
- Significant efforts and investments in increasing green ammonia availability are at odds with the lack of focus on **developing distribution strategies** and infrastructure.

Solving these three key issues will not only unlock opportunities in current markets but also in new ones, particularly the shipping and power sectors. This can help increase government backing for these novel applications and reduce both risk and switching costs for prospective customers, thus making ammonia more attractive than the alternatives. In both the current and future markets, infrastructure reconversion can only occur once ample availability is established.

Figure 28 shows the key challenges in the chain of events that promotes the successful adoption of renewable ammonia in several markets, thus achieving the maritime or full potential scenarios.

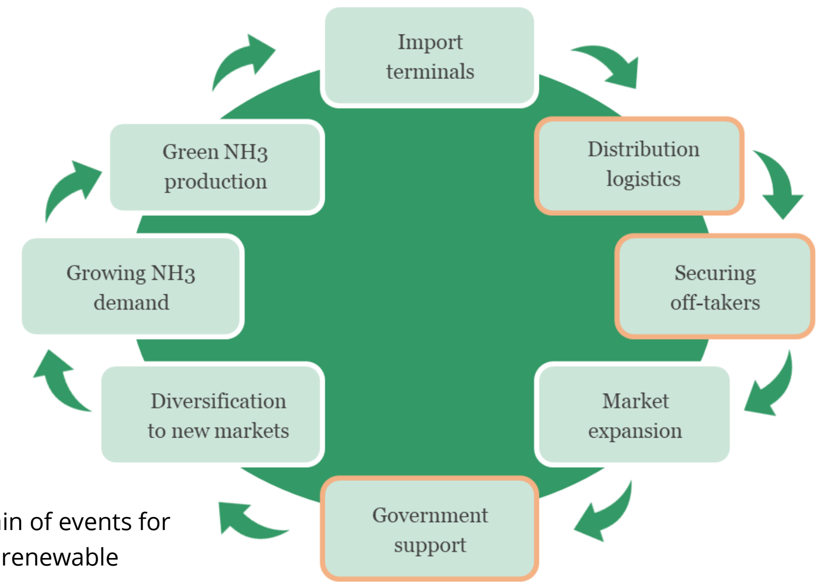

Figure 28. Chain of events for the success of renewable

Recommendations

The advice derived from this study is structured into three categories, tailored for each of the recipients i.e., industry players, governments and TNO.

Industry players

- **Facilitate collaborative dialogue** among suppliers, providers and buyers to collectively address the bottlenecks within the value chain. Focus on ensuring long-term off-take contracts.
- **Delay the decision for a pipeline**. Instead, encourage Dutch and German industries to collaborate, in coordination with governments, to assess future demand and make a well-informed decision regarding the feasibility of an ammonia pipeline.

Governments

- Take action in the form of **incentives and subsidies** to facilitate the transition, especially for consumers. Recognize the gap between decarbonization goals and current policies, and develop national and European policies that actively support the transition towards renewable ammonia.
- Consider the viability of **leveraging the Betuweroute** and enhancing ammonia transport via rail within the Netherlands.
- Publicly support the ammonia industry and provide informative resources to **improve public perception** and understanding of ammonia's role in decarbonization efforts.
- Adopt internationally **recognized certification and standardized procedure** frameworks for producing and handling renewable ammonia.

TNO

- Serve as a knowledge channel to **educate the government** on the potential of ammonia and risk mitigation strategies, bridging existing knowledge gaps to enable more informed governmental decisions.

- Act as a consultant to **advise the government** on policies and regulations that drive the transition. Collaborate with Ammonia Energy Association to develop renewable ammonia certification standards.
- **Forge partnerships** with key industry players, such as Air Liquide, involved in cracking technology. Combined efforts can be channeled towards mutual knowledge enrichment.
- Allocate research resources to enhance the **purity, cost-efficiency, and emissions aspects of cracking technologies** rather than scaling up. Consider the potential of technology licensing to support smaller-scale cracking projects in other European ports since hydrogen demand in these locations may not match the scale of Antwerp and Rotterdam.
- Invest in **research** related to alternative ammonia-to-energy technologies, such as **power and heat generation**. Collaborate with industrial partners to further develop this application and contribute to the establishment of ammonia trading systems.

8

Limitations

& Future Research

Limitations

This study is subject to several limitations in terms of both the research methodology employed and inherent limitations of the subject, which posed certain challenges and led to gaps in the study's coverage.

Research methods

- **Interviews** provided personal and subjective opinions, which may not represent the views of all stakeholders or reflect realistic scenarios. However, efforts were made to address this by conducting interviews with TNO personnel who had no vested interest in promoting ammonia, thus offering more balanced perspectives. Doubling the number of interviews also helped incorporate varied opinions and professional profiles. Moreover, focus groups and consultation activities were also potentially biased, especially those from the ammonia conference.
- **Scenario planning** involves numerous assumptions and often lacks specificity, failing to explore various possibilities within each scenario. For this study, the analysis could have benefited from deeper examination of interdependencies between government and other stakeholders, pricing dynamics, demand variations, and competitive forces.
- **Value chain mapping**, while serving as the study's foundation, is a static representation that cannot capture the dynamics, trends, or evolving market requirements. However, for this study, supplementary analyses were conducted to complement the evaluation of critical aspects.
- This study provides a **broad overview** but lacks in-depth exploration. It serves as preliminary research that should be followed by more comprehensive investigations into identified key areas.

Research topic

- The **uncertainty** surrounding the energy transition and government actions poses challenges in predicting future trends and developments.
- **Competing alternatives** to ammonia, such as hydrogen, methanol, and LOHCs, were not examined in detail, although they exert substantial influence on the industry landscape and cannot be disregarded.
- **Generalization** is based on the main industrial clusters and primarily the four major fertilizer producers, which may not entirely reflect the realities and preferences of

potential off-takers. Moreover, only two interviews were conducted with companies using ammonia as feedstock, which is not representative of the entire market.

- The multiple case study was less extensive than anticipated due to **information limitations** and uncertainty surrounding project realization, as most projects were still in the feasibility stage.

Future Research

This research has identified several avenues for future research that can expand upon its findings and provide valuable insights for supporting and advancing the adoption of ammonia in the energy transition.

Market research → Diversifying industry analysis

In addition to the major fertilizer production companies in the Netherlands, future market research should encompass smaller enterprises that may lack the resources for independent ammonia imports. It should also delve into other chemical applications of ammonia, examining whether these industries produce ammonia in-house and exploring their decarbonization plans. Gaining insight into the interests and projected demands of these industries will be crucial for assessing their significance.

Interviews → Expanding interview pool

Conducting more interviews can serve a twofold purpose: gaining direct access to information on ongoing projects and developments, and expanding TNO's collaborative opportunities.

Cost analysis → Pipeline investment evaluation

Evaluate the cost difference between constructing an ammonia pipeline in the Delta Corridor now versus deferring it to a later stage if it becomes necessary. This analysis should consider:

- The cost of pipeline installation during the construction of the Delta Corridor, including the pipeline itself and associated labor costs. Exclude investments related to Delta Corridor construction that would occur regardless of the ammonia pipeline. Factor in potential expenses associated with maintaining a non-profitable pipeline.
- The complete costs of reopening the entire Delta Corridor to build an additional ammonia pipeline.

Future applications → Shipping and stationary fuels

- Conduct a comparative analysis of ammonia and methanol to determine ammonia's position and competitiveness as a potential shipping fuel, and whether TNO could be interested in conducting research to develop ammonia as a shipping fuel.
- Investigate ammonia's viability as a stationary fuel, including an analysis of potential retrofitting costs for combustion furnaces. Examine Japan's strategy and explore means of enhancing confidence levels in this application.

Scenario planning → Further elaboration

Expand the development of the four potential scenarios, delving deeper into the determining factors and interdependencies. Consider how each scenario would play out under varying demand conditions, government policies, distribution systems (including the presence or absence of a pipeline), and the adoption of competing energy-carriers. A more comprehensive approach can offer richer insights into future possibilities.

9

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Appendix

Appendix 1

History of TNO

Throughout the course of 90 years, TNO has been part of and led many innovative projects that have significantly contributed to society in terms of health and safety, quality of life, defense, and sustainability, among others (1). The following are some examples and key achievements:

Health and safety

Since 1955, TNO has monitored and researched the growth of youths regularly, and contributed to the development of vaccines, especially for the protection of children. Moreover, throughout the 60s and 70s, vehicle safety studies and car crash simulation software decreased fatalities significantly. TNO was also involved in computer screenwork safety (1985) and noise-cancelling research (1999). In 2009, TNO was the only organization in Europe with a biomedical Accelerator Mass Spectrometer, which enabled faster medication development and approval.

Quality of life

TNO contributed to the reconstruction of Rotterdam after the Second World War with experimental and innovative houses, and had a key role in the Delta Works project (1955) due to the development of sensor instruments and sea measuring stations. Furthermore, the organization was a pioneer in areas and concepts such as self-scanning at Albert Heijn (1987), greenhouse design and technology (1993-2006), and mobile payment testing (2007).

Defense

Many technologies have been developed by TNO in the defense sector such as a listening device for aircraft positioning (1935), a digital fire control unit for projectile aim calculations (1960), and a radar system for detecting and tracking targets (1979). This organization has also been involved in research programs dedicated to image recognition (1980), long-range sonar technology (2001), cybersecurity (2011), laser satellite communication (2018), and high-energy laser weapons (2019).

Sustainability

In the field of sustainability, TNO has long been paving the way for innovation, from registering emissions as early as 1971 and participating in a national research program on wind energy (1975), to experimenting with solar homes (1976) and alternative fuels (1990). Additionally, the organization developed smart grids for energy sharing and optimization (2009), thus anticipating the now widely used smart meter, and designed a satellite for greenhouse gas and air pollution monitoring at a city level.

TNO locations

Table A1. **All TNO locations**

Amsterdam	Geleen	Soesterberg
Bergen op Zoom	Groningen (2)	Utrecht
Brussels, Belgium	Helmond	Zeist (2)
Delft (4)	Leiden	Yokohama, Japan (2)
Den Haag (3)	Petten	
Eindhoven (3)	Rijkswijk (2)	

Products and services

Table A2. Main key areas in which TNO delivers its products and services

Research & Development	Create innovative solutions tailored to specific needs
Consultancy & Expertise	Strategic advice, feasibility studies, market assessments and technology roadmaps
Testing & Certification	Evaluate performance, quality, safety, and compliance of products and processes
Technology Transfer & Licensing	Industry partners can access and implement TNO-developed technologies and innovations
Training & Education	Enhance the skills and knowledge of professionals in various fields
Demonstrations & Pilot Projects	Showcase the feasibility and benefits of new technologies and concepts
Policy support & Impact Assessments	Develop evidence-based policies and assess the impact through data analysis and modeling

Appendix 2

Personal reflection

Throughout my internship, I encountered both challenges and rewarding moments, and I can confidently say that this experience has been crucial in shaping my professional trajectory. It marked the end of my academic journey, and it was here, at TNO, that I gained valuable insights into my future career path and personal development.

One of the most significant aspects of my internship was the opportunity to contribute to a research program aimed at fostering sustainable global energy systems. While my background was not directly related to the topic, I knew it was the direction I wanted to take in this final stage of my studies. I delved into an unfamiliar domain and, through my research, I got interesting insights into the current state of ammonia production in the Netherlands and the challenges companies face in transitioning to renewable ammonia.

Setting deadlines for myself and planning the timeline of my research was crucial for staying on track and ensuring my objectives were met. Initially, tackling this subject was intimidating and I struggled with the autonomy I had to define the project's scope and approach. Additionally, I had to move away from my scientific mindset and adopt different research methods. However, as the project progressed, I learned to trust my judgment and became more confident in making decisions. The fact that my suggestions were taken seriously and sparked interesting debates during interviews boosted my confidence.

I also worked on my interpersonal skills, recognizing the importance of asking questions and being proactive. While my work primarily involved desk research, I made a conscious effort to maintain open communication with my supervisor, regularly updating on my progress and presenting findings in a clear and visual manner.

Conducting interviews posed a set of challenges. Distinguishing between facts and subjective opinions, and understanding that one person's perspective does not necessarily represent an entire company's strategy, was difficult. Navigating these complexities required me to remain impartial and objective, a task made even more challenging given that most interviewees had a vested interest in ammonia. Striking the right balance was crucial.

This thesis has given me a great opportunity to work on my networking skills, especially at the conference and with the interviews. Starting conversations, making connections, and maintaining professional relationships were valuable aspects of this journey.

What I enjoyed most about this thesis was the opportunity to delve deep into a topic while simultaneously maintaining a broader perspective. Condensing vast amounts of information, creating visuals, and drawing conclusions were fulfilling tasks. Structuring, optimizing, adapting information, and making it understandable for different audiences was a highlight. Presenting is something that I really like and that I want to continue to do.

I am happy with my performance and overall experience. Achieving my research objectives and discovering my strengths in conducting interviews, presenting, and synthesizing information has been enlightening. This experience has not only prepared me for my future career but also given me valuable insights into the dynamics of a professional workspace.