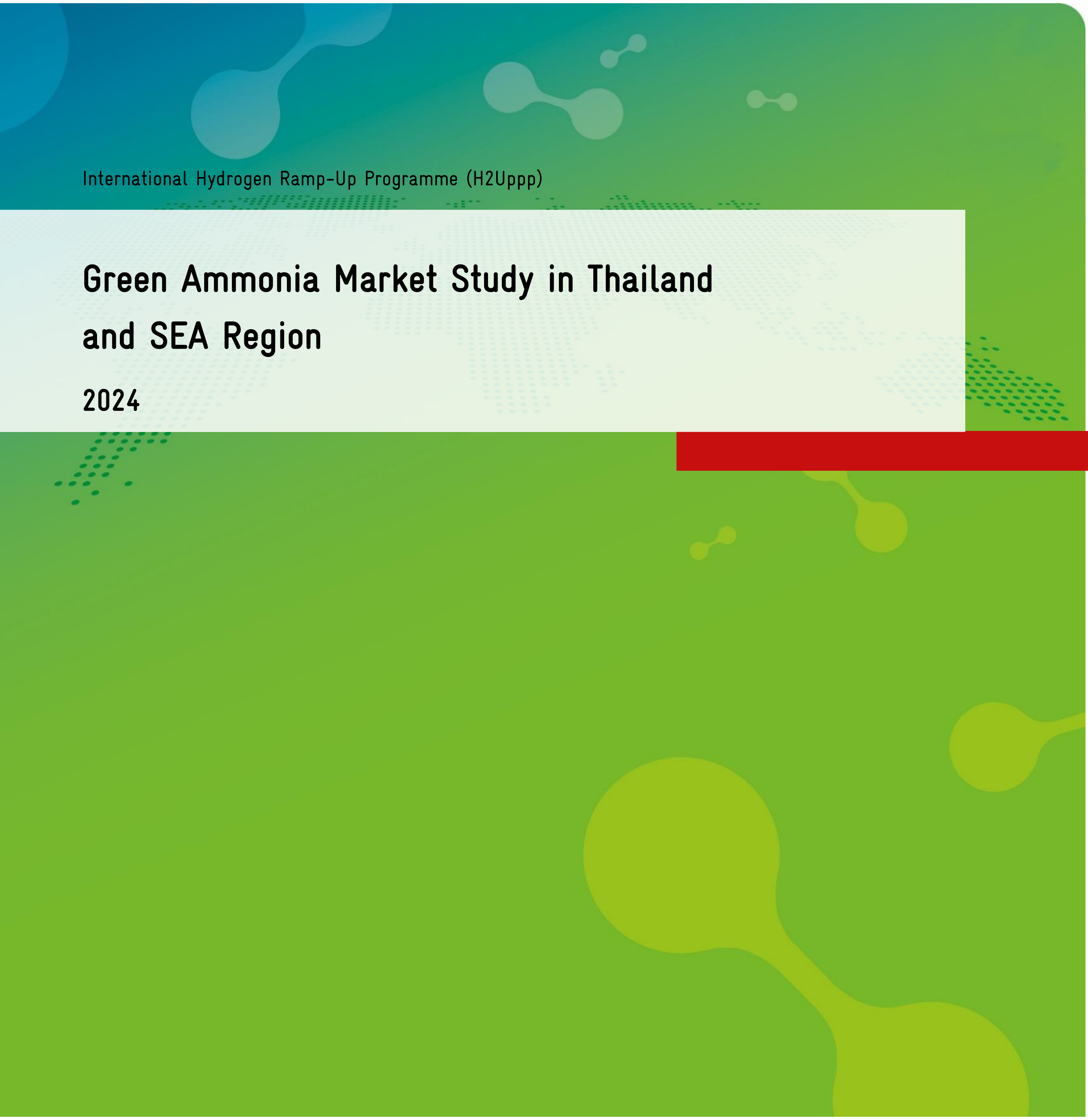

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Preface

Welcome to this comprehensive technical study exploring the future of green ammonia in Thailand's energy landscape, conducted in collaboration with DNV under the International Hydrogen Ramp-Up Programme (H2Uppp). As the Project Manager leading this initiative, I am thrilled to present this study, a testament to collaborative efforts dedicated to advancing sustainable energy solutions.

Thailand's commitment to carbon neutrality by 2050 and net zero emissions by 2065 positions hydrogen and ammonia as an essential pillar of its energy transition. This study focuses on the potential applications of green ammonia, analyzing its contributions to decarbonizing power, industry, and transport sectors within Thailand's unique context. We begin with a global perspective on the ammonia market, production dynamics, and international trade, laying the groundwork for an in-depth exploration of Thailand's role within Southeast Asia.

Ammonia, integral to Thailand's agriculture and industry, is undergoing a transformative phase, evolving from a cornerstone in fertilizer manufacturing to a green energy carrier. The study unveils Thailand's status as an ammonia-importing nation, emphasizing the imperative for a strategic shift towards sustainable practices.

We delve into policy and regulatory frameworks crucial for supporting green ammonia production and trade, aligning Thailand's efforts with global best practices. The study examines hydrogen standards and certifications, offering insights into navigating this evolving landscape in the pursuit of decarbonization.

Concluding with a forward-looking perspective, we assess the cost dynamics of domestic production versus imports, exploring potential scenarios and highlighting opportunities and challenges. From being a green ammonia importer to contemplating value addition and export, the study provides a comprehensive view of Thailand's evolving position in the green ammonia landscape.

Finally, we explore potential risks associated with technology, market dynamics, economics, and policy. Acknowledging and addressing these risks will be pivotal as Thailand ventures into uncharted territories in its pursuit of integrating green ammonia into its energy portfolio.

I extend sincere gratitude to the dedicated team, collaborators, and contributors who have shaped this study. It is my fervent hope that this endeavor not only contributes to academic discourse but also serves as a practical guide for stakeholders invested in Thailand's sustainable energy future.

Thank you for joining us on this transformative journey.

Tim Nees

Project Manager, H2Uppp Southeast Asia

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EXECUTIVE SUMMARY

Thailand has committed to reach carbon neutrality by 2050 and net zero emissions by 2065, with hydrogen and ammonia both playing a potentially pivotal role. Hydrogen will be required to decarbonize hard-to-abate sectors, while ammonia is already an essential commodity in Southeast Asia (SEA) and Thailand in particular that is expected to see several additional use cases develop as ammonia becomes increasingly green. This study will assess the focus on the potential use cases for green ammonia in decarbonizing the power, industrial and transport sectors, and outlining the resulting projected developments in the ammonia market and ammonia trade within Thailand and SEA.

Global ammonia market

The ammonia industry started development with the Haber-Bosch process developed in the 20th century (1900s), transforming agriculture and addressing global food shortages through its key role in the production of fertilizer. Despite its historical success, the process's energy intensity has sparked interest in more sustainable production methods, including renewable energy and novel catalysts.

Globally, 80% of ammonia demand is used for fertilizer and 20% for industrial applications like chemicals and fuel. The APAC region, particularly China and India, consumes over half of the world's ammonia, mainly for agriculture. China is the largest global consumer and producer, making up 40% of both. India is the second-largest consumer at 30%, and the United States follows as the largest consumer outside Asia. The production of ammonia is currently nearly 100% reliant on fossil fuels, mostly from natural gas and the remainder from coal, naphtha, and heavy fuel oil. Renewable ammonia however remains a negligible share.

The global demand outlook for ammonia is that demand is expected to increase, driven by the maritime sector and international trade of ammonia as a hydrogen carrier. The production outlook could also lead to a significantly expanded market for low-carbon ammonia, driven by decarbonization. The global ammonia production capacity is expected to rise, with new facilities in the Middle East, North Africa, and the United States. Import and production strategies vary globally, with the United States relying on domestic production due to abundant natural gas, while Japan, with limited domestic resources, plans to transition to renewable ammonia imports beyond 2030. Import decisions for the production of ammonia or ammonia products like urea hinge on factors such as feedstock availability, energy costs, and transportation expenses, showcasing diverse approaches based on specific country circumstances.

Current ammonia market in Southeast Asia and Thailand

In Thailand, the demand for ammonia encompasses a wide array of industries, spanning agriculture, fertilizers, petrochemicals, and industrial chemicals, which extends across different geographical regions. The core of Thailand's ammonia demand centres around fertilizer manufacturing as the agricultural sector is pivotal to the nation's economy.

Thailand's position in the ammonia market is currently that of an importing nation. The substantial disparity between imports and exports underscores the nation's current reliance on external sources to fulfil its demand for ammonia-related products. Urea and Anhydrous Ammonia stand as the pivotal constituents of Thailand's ammonia imports. The significance of urea imports lies in its critical use as a fertilizer, addressing nitrogen-deficient soils resulting from prevalent agricultural practices.

Within the broader SEA region, the demand for ammonia is driven by fertilizer production and utilization. Interregional trade flows occupy a pivotal role in shaping the ammonia market within the region. Nations with surplus ammonia production actively participate in cross-border trade to meet the diverse demands of neighbouring countries. Indonesia is the largest exporter, followed by Malaysia, Thailand, Vietnam, and Singapore, while the rest of the countries in SEA are primarily net importers of ammonia-related products. In the urea market, Indonesia, Vietnam, Thailand, Philippines, and Singapore are the only countries with urea production. Indonesia and Malaysia are the largest exporters, with nearly half of their exports within SEA. Being the largest exporter in the region, Indonesia also has the highest number of ammonia plants, close to 20 operational plants, which collectively contribute to the country's exports. Thailand is the primary importer, yet only less than 30% come from SEA. The Philippines sources the most urea imports from the SEA region, followed by Myanmar and Cambodia.

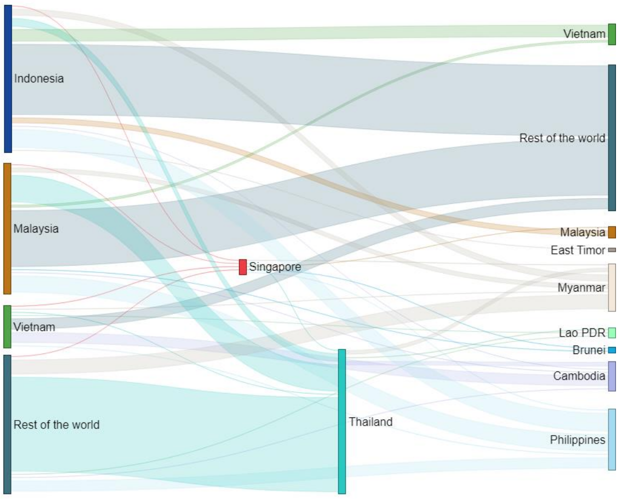

Figure ES-1. Trade Flows of Urea within Southeast Asia and the rest of the world

Policy and regulatory framework to support green ammonia

Governments and regulators are developing policy, regulations and standards to support green ammonia. These are important for supporting existing ammonia producers to achieve emissions reductions as well as for incentivizing new green ammonia projects. Several nations, particularly the major ammonia-producing countries, have progressed in developing advanced policies and regulations for applications related to green ammonia. The development of global policies and regulatory frameworks for ammonia as a new bulk commodity is actively underway, reflecting a shared commitment to its potential as a sustainable energy carrier. Germany, Japan, Australia, the Netherlands, the United States, Norway, South Korea, the United Kingdom, and Singapore are at the forefront of this effort.

Ensuring safety and environmental protection is of paramount importance when it comes to ammonia infrastructure in Thailand. Thailand's regulatory framework plays a crucial role in ensuring the safe deployment, operation, and maintenance of ammonia infrastructure. Local regulations provide a foundation for safety protocols that must be meticulously followed during the design, construction, and operation phases of ammonia facilities. As ammonia markets become increasingly interconnected, adhering to international norms ensures that Thai ammonia infrastructure is compatible with global supply chains and industry best practices. Organizations such as the International Code Council (ICC), the International Maritime Organization (IMO), and the United Nations Economic Commission for Europe (UNECE) have developed guidelines and protocols that shape the safe transport, storage, and utilization of ammonia worldwide. These organizations provide comprehensive frameworks for assessing and managing risks associated with ammonia, offering insights into process safety, risk communication, and emergency preparedness.

Role of hydrogen standards and certification

Hydrogen, including ammonia, has been increasingly considered a decarbonization pathway for hard-to-abate sectors. However, not all hydrogen is low-carbon, and the choice of production pathways significantly impacts greenhouse gas emissions. Some pathways may even surpass emissions from fossil-based alternatives like coal, oil, or natural gas. Since ammonia is a hydrogen derivative, emissions in its value chain are closely tied to hydrogen production. The key difference between conventional and lower-carbon ammonia production lies in hydrogen production methods (e.g. electrolysis via renewables).

Numerous jurisdictions are establishing criteria and standards for renewable and low-carbon hydrogen and ammonia, with frameworks like Green Hydrogen Standards (GH2) internationally and specific standards in regions like the European Union, Australia, and the USA. Thailand, particularly, should consider the ASEAN taxonomy which is applicable for the Southeast Asian (SEA) region. Varying threshold values in standards can guide investment decisions along the value chain. The EU RED II standard, with a stringent carbon threshold of 3.38 kg CO_2e/kg H_2, sets limits on production, transport, and processing pathways, translating to 0.6 kg CO_2e/kg NH_3 for ammonia. The GH2 standard, with a 1.0 kg CO_2e/kg H_2 threshold, is complemented by upcoming ammonia production emissions limits (current draft states 0.3 kg CO_2e/kg NH_3) expected in late 2023[1].

To quantify the associated lifecycle emissions of the ammonia value chain for the Thailand context, a high-level life cycle assessment (LCA) for two applicable scenarios was conducted:

- Thailand domestic green ammonia production
- Import of green ammonia from Australia

Based on these calculated values, green ammonia, as well as blue ammonia with a high capture rate (94%) at a lower range value from both scenarios will be able to meet the current most rigorous threshold (RED II limit, assuming the limit is extended to derivatives processing).

Future role of ammonia in Thailand

An evaluation of the cost to produce green ammonia domestically, versus the landed cost to import green ammonia from Australia was performed to determine Thailand's position in the green ammonia landscape. In addition to the levelized cost of ammonia (LCOA) calculated, the levelized cost of hydrogen (LCOH) was also determined for both scenarios to investigate how the end product affects the strategies to be adopted in terms of cost basis.

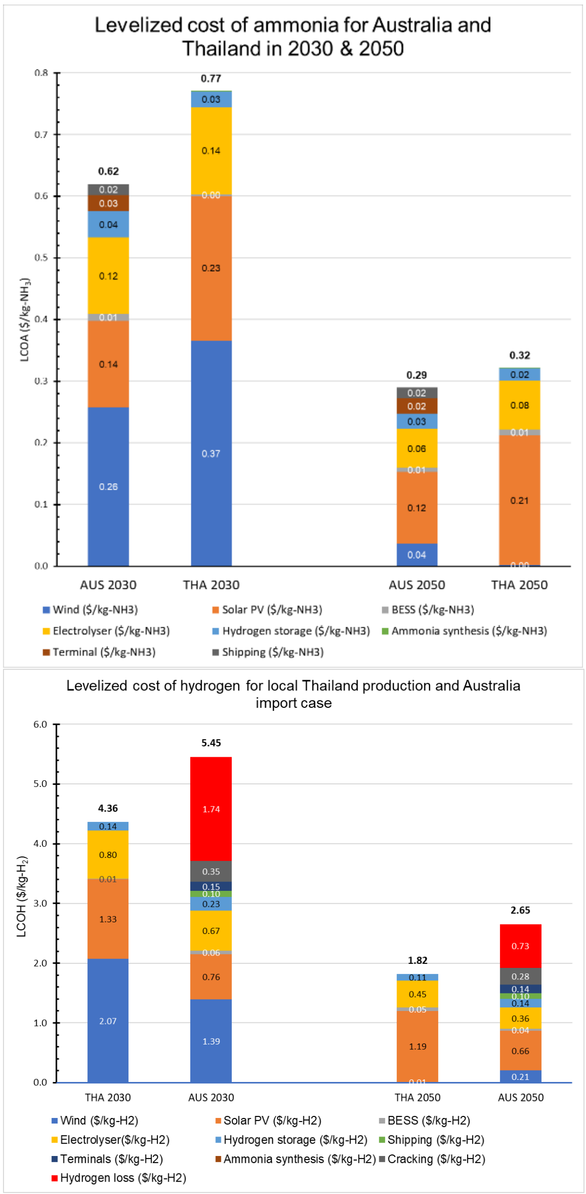

Figure ES-2. LCOH for production in Thailand and import from Australia

- **Green ammonia** – By 2030, it is more economical for Thailand to import ammonia from Australia rather than produce it domestically due to cheaper renewable resources in Australia. The landed cost of ammonia from Australia is \$0.62/kg-NH_3 while that of producing domestically is \$0.77/kg-NH_3. By 2050, the cost for both options reduce to almost the same level, at around \$0.30/kg-NH_3. Therefore, a gradual

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[1] Standard | Green Hydrogen Standard

shift towards domestic production could be considered in the long run as it will also enhance supply security.

- **Green hydrogen** – Domestic production in Thailand is favoured due to high losses for the cracking process from ammonia to hydrogen when importing from Australia. This applies to both the short and long term. The LCOH in Australia is cheaper than in Thailand in 2030 and 2050. However, the cracking results in high hydrogen losses, thus raising the overall landed cost of hydrogen to \$5.45/kg-H_2 and \$2.65/kg-H_2 for 2030 and 2050 respectively. The equivalent cost of local production in Thailand is around \$4.40/kg-H_2 and \$1.80/kg-H_2 for the two years.

Opportunities for Thailand as a green ammonia importer

Green ammonia is anticipated to contribute to the decarbonization of power generation through co-firing, as a chemical feedstock for various industries, and to be utilized in the marine fuel sector. The analysis indicates that green ammonia in Thailand will primarily be employed for decarbonization in existing use cases, particularly in the industry feedstock sector as a chemical feedstock. The overall potential demand for green ammonia in Thailand would be 12.10 – 43.71 Mton NH_3 annually by 2050, depending on the carbon price scenarios. In a broader context, in the Southeast Asia region, green ammonia will also be employed for new use cases, serving as a fuel. This is particularly relevant for countries with limited access to renewable energy resources. Given the limited access to renewables, the cost of green hydrogen production from renewables would be high. Therefore, importing green ammonia provides a viable alternative for achieving decarbonization. Another use case is for countries aspiring to become bunkering hubs, where the demand for green ammonia may increase due to its potential as a substitute for marine gas oil (MGO).

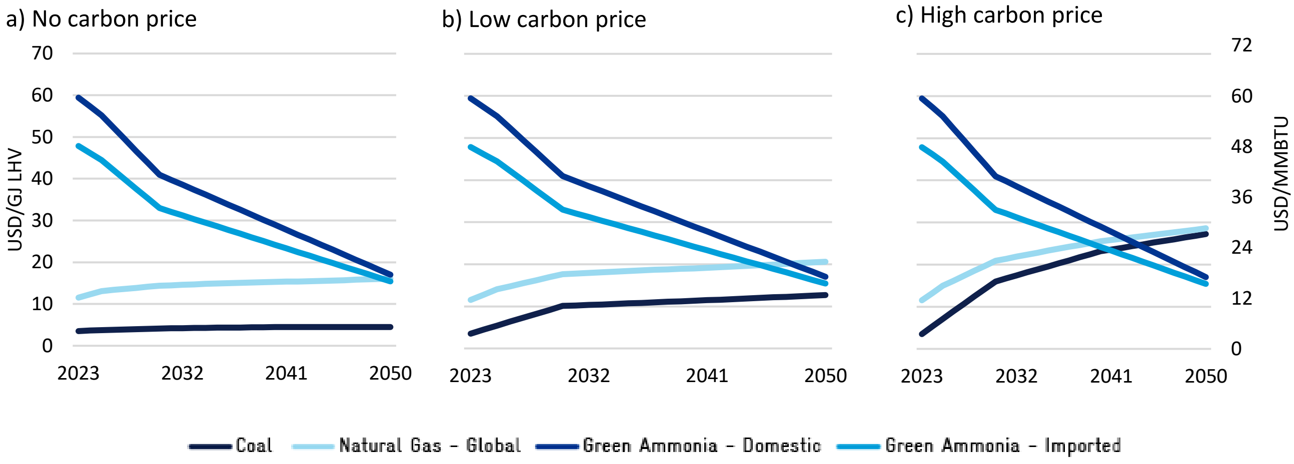

Figure ES-3. Cost comparison of green ammonia for different carbon pricing scenarios

Reflecting on the assessed potential supply and demand, Thailand is likely to be a green ammonia importer up to 2030. It is unlikely that Thailand will transition towards a role as an exporter of ammonia as it will be cheaper for other countries to import ammonia from these exporting nations themselves. As the price of domestic and imported ammonia is close in 2050, Thailand could consider producing ammonia for its domestic needs and become self-sufficient in later years. However, this would likely be a gradual switch due to the intensive CAPEX investments required for building the ammonia import infrastructure in the first place.

Although Thailand is most likely to be positioned as a green ammonia importer in the short term, several opportunities exist, such as:

- **Value addition** – where Thailand can import green ammonia but convert this into urea domestically and become self-sufficient in terms of fertilizer production. Currently Thailand imports urea for its domestic demand at a large scale. However, these dynamics may change as a result of a transition towards green fertilizer. With Thailand's access to green CO_2 from biomass and its existing petrochemical industry, value addition is a likely opportunity pathway for Thailand to explore.
- **Hydrogen export** - Another primary opportunity for Thailand will be hydrogen export to neighbouring countries due to its cost competitiveness.

Going forward, Thailand could boost local fertilizer production, primarily driven by the imperative to decarbonize the supply chain, which would lead to an increased demand for ammonia in the country. This presents a promising opportunity for Thailand to meet its ammonia demand domestically from low-carbon sources. The selected approach will partly depend on the cost-effectiveness of domestic green ammonia production compared to importing from other countries such as Australia.

Potential risks from the technology, market, economic and policy perspective

Due to the novel nature of many of the planned new applications of ammonia, several risk factors are expected to arise. While safety issues are extensively discussed in Chapter 2 and are being addressed via appropriate regulation, there are several other areas where risks may appear to the role of ammonia in decarbonization which should be given appropriate consideration. These topics include but are not necessarily limited to technology, the market, economics and policy.

- **Technology** development may not happen at the expected pace, which can delay the use of new applications of green ammonia, especially in power generation. It is also possible that technological existing barriers such as NO_x emissions will not be overcome, rendering the technology unsuitable. When successfully developing new technologies, bottlenecks may arise that can prevent scaling at the intended pace.
- **Markets** for ammonia require matching of potential offtakers with potential producers. Long-term offtake agreements are necessary to finance 30-year project lifetimes, but costs are dropping rapidly, and current projects will be out-competed by newer projects on price in only a few years.
- **Economic** issues include the uncertainty in costs for green ammonia as well as the high overall cost compared to business as usual. Cost projections depend on learning-by-doing and economies of scale that may not be realized if current projects are not able to reach financial closure. Infrastructure investments required are high which countries may struggle to finance.
- **Policy** is needed to close cost gaps and introduce standardization. The focus of policy should be on the long-term decarbonization of the energy system but is often aimed at short time horizons instead.

INTRODUCTION

Thailand is undergoing a transition to low-carbon energy with the commitment to meet the long-term goal of carbon neutrality by 2050 and net zero GHG emissions by 2065. Hydrogen has a potential role to play in achieving the targets. Green ammonia is one of the promising derivatives of green hydrogen, which is obtained from hydrogen and nitrogen. Ammonia has been an essential commodity in Thailand and Southeast Asia.

The main objective of this study is to provide an assessment of the ammonia market in Thailand and Southeast Asia and the potential role of green ammonia in decarbonizing the power, industrial and transport sectors, as well as challenges in developing the green ammonia market.

The study consists of the following key areas:

- Section 1: Overview of the current and future ammonia market globally, including demand and supply; production processes; value chains from production, synthesis, transport, storage and end-use
- Section 2: Policy and regulatory frameworks of green ammonia that are being implemented around the world, including policy roadmaps, targets, funding for R&D and industrial strategies
- Section 3: Cost structure of green ammonia and cost comparison between imported green ammonia and domestic production of green ammonia and hydrogen
- Section 4: Overview of standards and certification schemes for green ammonia, both new standards under development and applicable standards based on green hydrogen
- Section 5: Current market situation for ammonia demand and usage in Thailand including internal trade flows within SEA
- Section 6: Projected future market situation in Thailand and SEA regarding green ammonia supply chains and demand forecasting
- Section 7: Risks and considerations for the development of large-scale green ammonia markets
- Section 8: Topics of research and ongoing pilot projects related to green ammonia production and end-use

1 OVERVIEW OF CURRENT AND FUTURE AMMONIA MARKET – GLOBAL PERSPECTIVE

The ammonia industry plays a vital role in modern society, driven by the need for increased food production and diverse industrial applications. Ammonia (NH_3), a colourless gas, was harnessed through the ground-breaking Haber-Bosch (HB) process in the early 20th century (1900s), enabling the conversion of atmospheric nitrogen into a usable form on an industrial scale. The process was named after its two primary inventors, Fritz Haber and Carl Bosch, both of whom received Nobel Prizes for their contributions.

Before the Haber-Bosch process, ammonia was mainly obtained through natural sources, such as from decomposing organic matter or as a by-product of various industrial processes. However, these sources could not meet the increasing demand for ammonia required for agricultural fertilizers and other applications.

The breakthrough came in 1909 when Fritz Haber, a German chemist, successfully demonstrated the synthesis of ammonia from nitrogen and hydrogen gases. He accomplished this by using high pressure and a catalyst, enabling the nitrogen gas (N_2) from the air to react with hydrogen gas (H_2) to form ammonia (NH_3).

Haber's process was industrially scaled up by Carl Bosch, an engineer and chemist at BASF (Badische Anilin und Soda Fabrik), a German chemical company. Bosch collaborated with Haber to optimize the process and develop the necessary high-pressure equipment for large-scale production. By 1913, BASF had built the first ammonia plant based on the Haber-Bosch process, and it went into operation the following year.

The significance of the Haber-Bosch process cannot be overstated. It not only paved the way for the large-scale production of ammonia but also revolutionized agriculture by making it possible to synthesize nitrogen-based fertilizers. This, in turn, dramatically increased crop yields and helped to address food shortages around the world.

The ammonia industry continued to grow throughout the 20th century, with improvements in process efficiency, advances in catalyst technology, and additional applications for ammonia. Today, ammonia is a vital chemical in various industries and its production has a substantial impact on global agriculture and food production.

While the Haber-Bosch process has been immensely successful and is a success story of industrial development, it is energy-intensive and mostly relies on the production of hydrogen from natural gas or other fossil fuels. In recent years, there has been an increased interest in exploring more sustainable methods of ammonia production. This includes utilizing renewable energy sources and developing novel catalysts to mitigate the environmental impact of this essential chemical. Additionally, there is a focus on leveraging ammonia as a hydrogen carrier for clean energy solutions.

From its origins as a solution to agricultural challenges to its current role in advancing sustainable practices, the ammonia industry remains a pivotal player in shaping our modern world.

1.1 Summary of ammonia value chains

To analyze the status quo of Ammonia, it is essential to provide a common picture of the available technology categories and their functions. This can be effectively achieved by constructing a value chain framework which outlines the multiple steps that can be taken between the production and consumption of ammonia. The ammonia value chain is typically composed of a series of key stages:

- Production of chemical inputs – Typically involves exploration, extraction, and processing of natural gas or coal, or the production of renewable hydrogen through electrolysis using renewable electricity.

- Ammonia synthesis – Production of ammonia through the Haber-Bosch process, which involves combining hydrogen and nitrogen in the presence of a catalyst.
- Transport – Can be transported through different means, by road, train, trucks, ships and pipeline. Usually transported in its liquid form, which requires specialized equipment and handling procedures to ensure safety and security.
- Storage – Usually stored in large tanks or spheres at production sites and terminals.
- End-use – Ammonia is used in a wide range of applications, either on existing uses or potential future use cases. Most of the ammonia produced is consumed on-site as a feedstock for downstream processes.

1.2 Current ammonia value chain

1.2.1 Production of chemical inputs for ammonia synthesis

1.2.1.1 Hydrogen

Green hydrogen is produced through the electrolysis of water using renewable electricity, including from solar, wind and hydroelectric power. The production of green hydrogen is considered to be carbon-free, as it does not produce any greenhouse gas emissions. Blue hydrogen is produced from natural gas using various forms of technology with the combination of Carbon Capture and Storage (CCS) technology, such as Steam Methane Reforming (SMR) or Autothermal Reforming (ATR). Blue hydrogen can be produced using a variety of feedstocks, including natural gas, biogas, and biomass. The production of blue hydrogen with CCS is considered to be a low-carbon option, as it can reduce greenhouse gas emissions by up to 90%. Grey hydrogen is produced from natural gas using SMR and ATR without the use of CCS technology. Grey hydrogen is the most common form of hydrogen produced today, and it produces significant greenhouse gas emissions, prompting many countries to consider cleaner options such as blue or green hydrogen.

1.2.1.2 Nitrogen

Air separation is the process of separating the components of air, which include nitrogen, oxygen, and other gases. This process can be done using a variety of methods, including cryogenic distillation, pressure swing adsorption (PSA), and membrane separation. In the context of ammonia production, air separation is typically done using cryogenic distillation, which involves cooling the air to very low temperatures to liquefy the nitrogen and other components. The nitrogen is then separated from the other components using distillation columns, with the separated nitrogen used as a feedstock for the Haber-Bosch process, which combines it with hydrogen to produce ammonia. The air separation unit (ASU) is a critical component of the ammonia production process, as it provides the nitrogen feedstock required for ammonia synthesis. The ASU can also be a significant source of energy consumption and greenhouse gas emissions, depending on the method used for air separation.

1.2.2 Ammonia Synthesis

Ammonia synthesis is commonly used as a term to describe the production of ammonia through the process of combining nitrogen and hydrogen. The most common method for ammonia synthesis is the Haber-Bosch process, which was developed in the early 20th century and is still used today. The Haber-Bosch process involves the reaction of nitrogen and hydrogen in the presence of a catalyst, typically iron or ruthenium, at high temperatures and pressures. The reaction is exothermic, meaning that it releases heat, and it is typically carried out in multiple stages to improve the efficiency of the process. The ammonia produced is then separated from the unreacted nitrogen and hydrogen using distillation or other separation methods. The Haber-Bosch process is highly optimized and has a high energy efficiency, with natural gas-based ammonia production processes achieving energy efficiencies of 60-70%. However, this process also has significant environmental impacts, including greenhouse gas emissions from the production of hydrogen by the steam methane reforming process and the use of fossil fuels as a feedstock (refer to **Error! Reference source not found.** in Chapter 4.2).

In the evolving energy landscape, the electrification of the Haber Bosch process could pave the way for a carbon-free future in ammonia production, by using renewable energy sources and replacing the CO_2-intensive methane-fed process with hydrogen obtained from water splitting. This electrical-driven technology promises to curtail CO_2 emissions (refer to Chapter 4.2 for further information) while also heightening the energy efficiency of the ammonia synthesis loop by 50%, when disregarding the energy lost in the hydrogen production (Figure 1-1 and Figure 1-2). This decrease in energy losses can be attributed to:

(i) Electrolysis units producing pressurized hydrogen offset gas compression energy

(ii) Purity of hydrogen and nitrogen eliminates the need for purging, and

(iii) More efficient electric motors power compressors instead of steam turbines.

Further advancements are needed in water-splitting efficiency, alternative ammonia separation techniques, and catalyst development. Also, the successful implementation of this electrical-driven technology will depend on adapting to renewable energy's intermittent nature through small-scale, cost-effective, agile processes. Utilizing modular hydrogen production via electrolysis alongside low-pressure ammonia will reduce energy and capital costs significantly.

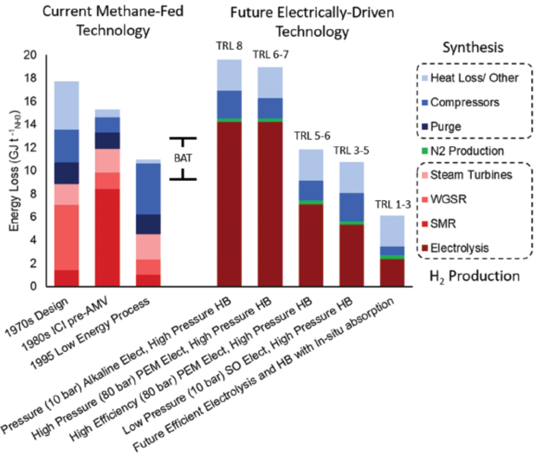

Figure 1-1. Comparison of methane-fed and electrified Haber-Bosch process energy losses[2]

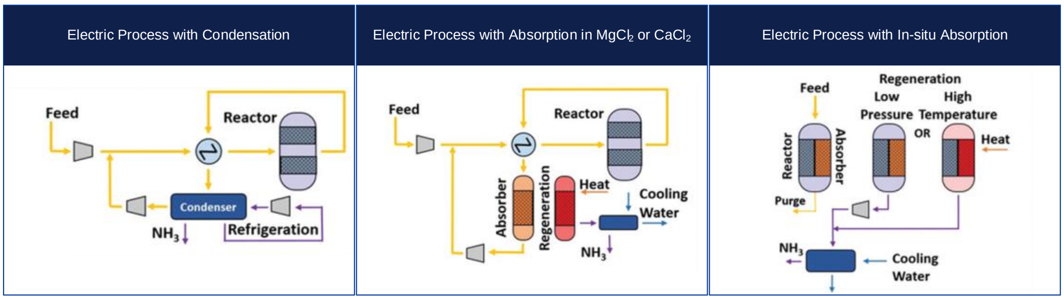

Figure 1-2. Different electrically driven HB synthesis loop configurations[3]

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[2] Smith et al. (2020): Current and future role of Haber-Bosch ammonia in a carbon-free energy landscape

[3] Smith et al. (2020): Current and future role of Haber-Bosch ammonia in a carbon-free energy landscape

There are also a variety of other novel ammonia production technologies being researched, including electrochemical and photochemical processes, plasma-based processes, chemical looping approaches, homogeneous synthesis, biological processes, and ammonia purification from animal waste or wastewater. However, these technologies have not yet been fully commercialized, and the Haber-Bosch process is expected to remain the dominant technology for ammonia synthesis in the coming decades.

Table 1-1. Summary of renewable ammonia production technologies[4]

Ammonia production technologies	TRL
Electric HB with alkaline electrolysis	8-9
Electric HB with high-pressure PEM electrolysis	6-7
Electric HB with SO electrolysis	3-5
Electrochemical	1-3
Electric low-pressure HB with absorption	4-5
Electric low-pressure HB with *in-situ* absorption	1-3
Non-thermal plasma	1-3
Photocatalytic	1-3
Metallocomplexes	1-3
Biological	1-3

1.2.3 Transport

Ammonia can be transported through several established methods, including ships, pipelines, and trucks, which are chosen based on distance and ammonia volume. The IRENA Innovation Outlook Ammonia (2022)[5] predicts a surge in demand due to emerging markets like hydrogen carriers, shipping, and power generation fuels. This growth could lead to a total of 354 million tonnes of ammonia transported by 2050. Accommodating this demand requires significant infrastructure expansion, resulting in a notable 10-15 times increase in the demand for transport infrastructure. Thus, robust infrastructure is crucial for effective ammonia transportation. While existing commercial transport infrastructure can manage shipments up to 25-30 million tonnes, it falls short of what is needed for the projected new markets.

IRENA's report identifies shipping as the primary mode of ammonia transport, accounting for around 18-20 million tonnes annually. Approximately 170 operational ships are equipped for ammonia transport, with 40 dedicated exclusively to this purpose. To support the envisioned 300 million tonnes of ammonia transport by 2050, approximately 235 vessels, each with an ammonia capacity of 50 kton, will be necessary, assuming bi-weekly voyages. This will entail either constructing new ammonia-specific vessels or repurposing LPG transport vessels approximately every two months until 2050.

Pipeline transport is another viable option for ammonia. Both natural gas and liquid pipelines can be repurposed for this purpose. In the United States, about 1.5 million tonnes of ammonia are transported annually through 3,220 kilometres of mild carbon-steel pipelines spanning seven states. Similarly, in the Russian Federation, a 2,424-kilometre pipeline conveys ammonia from Tolyatti to Odessa. While pipelines are also common for short distances in Europe, where they span 1-12 kilometres within industrial zones, trains are the primary mode of ammonia transportation in this region.

Lastly, truck transport is reserved for short distances or remote areas where other methods are impractical. However, it generally proves costlier and less efficient for larger ammonia volumes.

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[4] Smith et al. (2020): Current and future role of Haber-Bosch ammonia in a carbon-free energy landscape

[5] IRENA Innovation Outlook – Renewable Ammonia (2022).

The anticipated surge in demand for ammonia, driven by its emerging applications in various industries, is poised to reform its transport landscape. Foremost among these advancements is the vision of ammonia emerging as a prominent maritime fuel, propelling the shipping industry towards greater sustainability. This shift holds the potential to propel shipping into a leading role within ammonia transport, thereby reshaping worldwide transportation dynamics. This underscores the imperative for enhanced, environmentally conscious shipping technologies, and the establishment of dedicated supply chains and infrastructure. While maritime transport takes centre stage, it is important to recognize that ammonia's diverse applications will continue to necessitate a multi-pronged approach to its transportation. The use of pipelines will persist but will be particularly for domestic distribution and will most likely be limited to industrial or port areas due to the safety risk associated with ammonia toxicity. As such, the imminent increase in demand for ammonia will have an impact on the means of transportation, with shipping at the forefront of this transformation.

1.2.4 Storage

Another critical component of the ammonia value chain is the storage of ammonia, which can be further broken down into the use of large-scale storage and small-scale storage. Ammonia is typically stored in large tanks or vessels, which can be located at production facilities, ports, or other locations along the supply chain.

Ammonia, a gas under standard conditions, can be transformed into a liquid by either pressurization, resembling the method used for liquefied petroleum gas (LPG), or through refrigeration, similar to the liquefied natural gas (LNG) process. Pressurized storage poses higher risks due to greater energy release and the potential for a BLEVE (boiling liquid expanding vapor explosion), making it a more expensive option. Conversely, refrigerated storage, commonly employed for bulk storage, is safer and therefore preferred for large-scale operations due to its reduced risk profile.

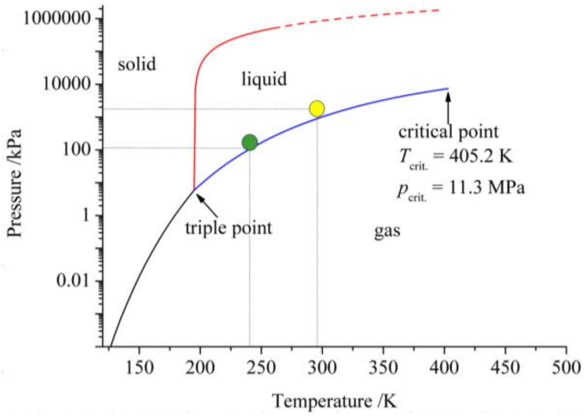

Figure 1-3. Phase diagram of Ammonia (NH_3)[6]

When considering large-scale storage, ammonia is commonly liquefied using refrigeration at -33°C and atmospheric pressure (refer to green dot in Figure 1-3). The most substantial ammonia storage tanks can accommodate as much as 50 kton of ammonia. These storage facilities are typically situated at ports in proximity to ammonia production sites, and they can possess a total ammonia storage capacity of up to 150 kton, distributed across multiple tanks. According to DNV's "Transition in Transport" report, onshore storage generally involves pressurization for quantities below 5 kton of ammonia while larger storage units employ cooling techniques alongside a reliquefication plant for liquefaction. There is currently no dedicated bunkering infrastructure for ammonia. However, as ammonia is a commonly traded product, there are 215 terminals for local storage in connection with ports, as outlined in DNV's report. It is expected that all ammonia terminals could be used as a reload terminal for an ammonia bunker vessel or barge, with no or limited modifications to the terminal. Loading and unloading from terminals to ammonia-carrying ships is currently handled safely with proper specialized training due to the safety issues with ammonia, and safety is believed to be improved by using a bunkering ship as an intermediate

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[6] Richter et al (2014), Chemistry of Ammonothermal Synthesis

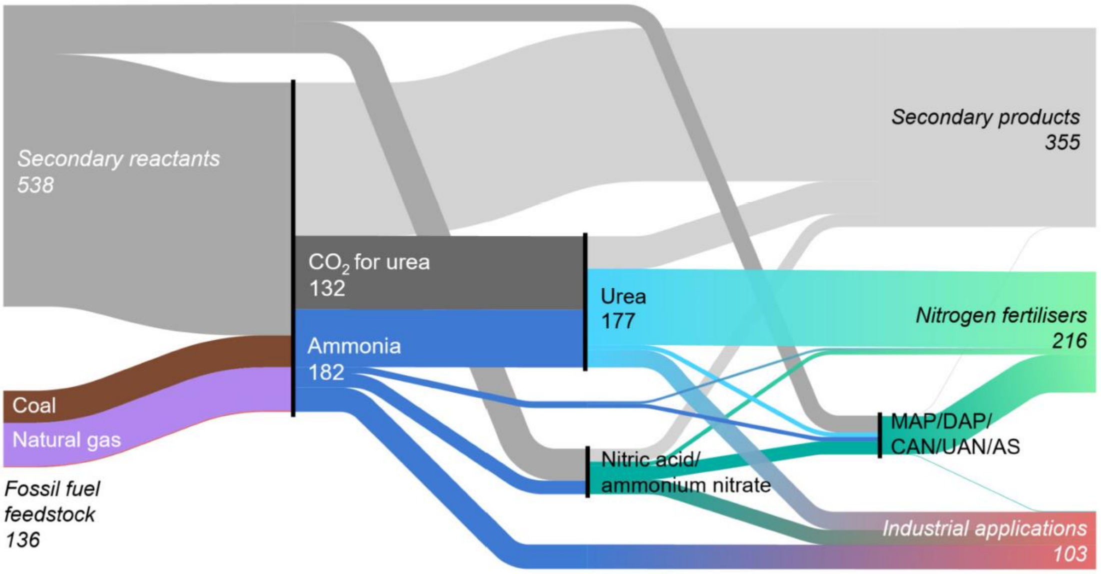
between the terminal and the ship using ammonia as fuel.

In terms of small-scale storage, ammonia is liquefied by pressure, stored at ambient temperature of around 16-18 bar (refer to yellow dot in Figure 1-3). This form of storage is commonly applied in refrigeration, air conditioning, and heat pump systems, with a typical storage capacity ranging from a few hundred kilograms to several tonnes of ammonia. However, the storage of ammonia comes with various safety and environmental challenges such as the potential risks of leaks, spills, explosions, and the likelihood of ammonia reacting with other chemicals or materials. Therefore, implementing best practices for storage and handling procedures are critical to ensure the safe and efficient transport and use of ammonia.

1.2.5 End-use

Ammonia (NH_3) is a chemical produced on a global scale, finding extensive use in various industries including fertilizer production, explosives, plastics, and pharmaceuticals. Ammonia plays a pivotal role as a vital component in fertilizer production, constituting roughly 70% of the current global ammonia consumption. Additionally, ammonia acts as a feedstock for the synthesis of various other chemicals, which are further explained in section 1.2.5.2.

Figure 1-4 showcases the current main routes through which ammonia is transformed into valuable products that find application in multiple industries.



IEA, 2021.

Figure 1-4. Current Primary Pathways for Ammonia Conversion into End-Use Products[7]

1.2.5.1 Fertilizers

Ammonia is currently used as a feedstock for fertilizers such as urea, ammonium nitrate, and diammonium phosphate, which are essential for

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[7] IEA (2021), Ammonia Technology Roadmap

enhancing crop yields and increasing food production. With the rising in global population and the need for escalated food production, the demand for fertilizers is expected to continue to increase.

Mineral fertilizers, also known as mined and chemical fertilizers, are sourced from geological resources like phosphate rock, other ores, and nutrient-rich brines. Additionally, for nitrogen, they can be synthesized from atmospheric sources.

These mineral fertilizers often undergo manufacturing processes to concentrate the nutrient elements or transform them into forms that are readily accessible to plants. However, in some cases, they can be used directly, such as when phosphate rock is applied directly to the soil or reacted with acids to produce various phosphorus fertilizers. The chart in Figure 1-5 illustrates the main pathways to produce mineral fertilizers based on *Fertilizers Europe*.

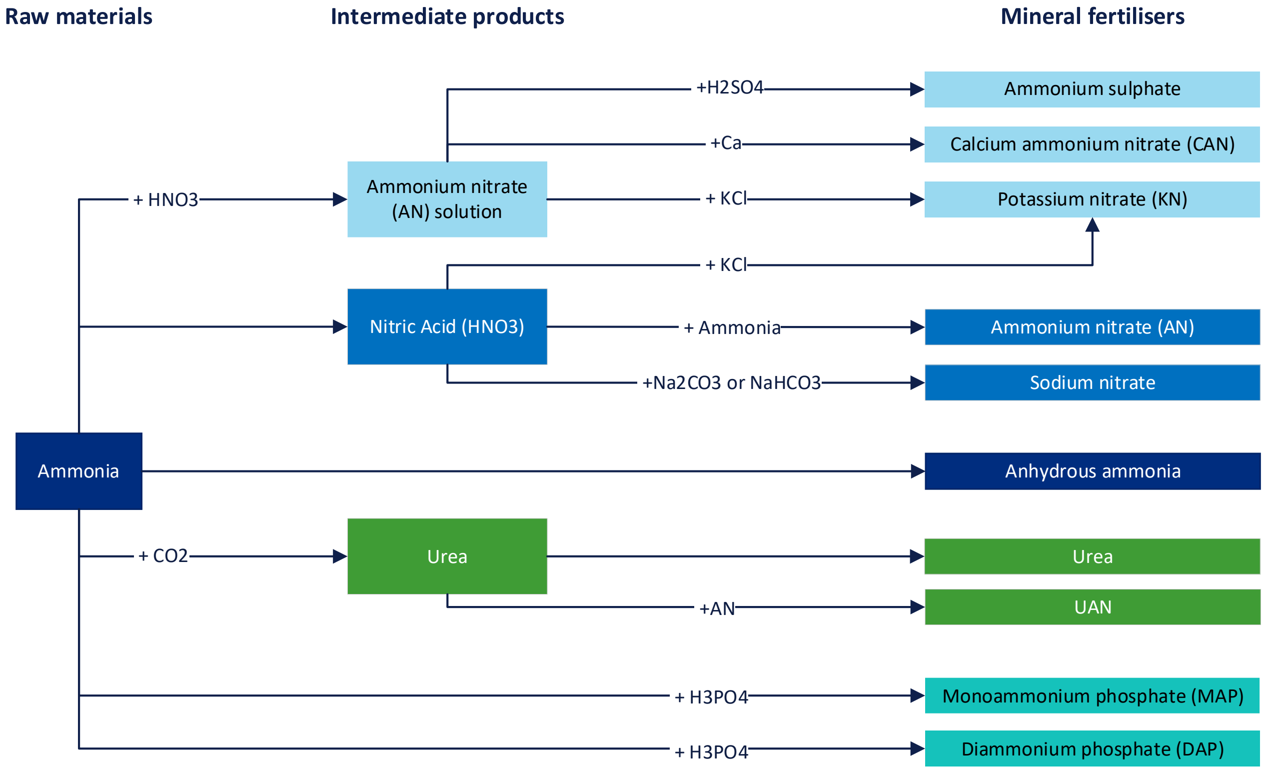

Figure 1-5. Current pathways for mineral fertilizers production from ammonia

Mineral fertilizers can be classified into three main groups: nitrate-based, phosphorus-based, and potassium-based fertilizers.

- **Nitrogen-based fertilizers** are the most commonly used straight fertilizers. Ammonia serves as the fundamental precursor for all mineral nitrogen fertilizers, constituting nearly 70% of the overall ammonia demand, including the downstream utilization of its various derivatives. Ammonia is a crucial component in the production of nitric acid, which is subsequently combined to create nitrate fertilizers like ammonium nitrate (AN). Additionally, ammonia can be mixed with liquid carbon dioxide to form urea. These two products, urea and ammonium nitrate, can further be blended with water to produce a UAN (urea ammonium nitrate) solution. Other nitrogen fertilizers include ammonium sulphate, ammonium sulphate nitrate, calcium ammonium nitrate (CAN), sodium nitrate, Chilean nitrate, and anhydrous ammonia.
- **Phosphorus-based fertilizers** are derived from mined ores, primarily phosphate rock. This rock undergoes a treatment process with sulphuric acid to yield phosphoric acid, which is further concentrated or combined with ammonia to create a variety of phosphate (P_2O_5) fertilizers. Among the commonly used phosphate fertilizers are single superphosphate (SSP), triple superphosphate (TSP), monoammonium phosphate (MAP), diammonium phosphate (DAP), and ammonium polyphosphate liquid.
- **Potassium-based fertilizers** originate from potash, specifically potassium chloride, which is obtained through mining. Potassium is found in various fertilizer formulations that either exclusively contain potassium or combine it with two or more nutrients. These formulations include Potassium chloride (KCl), Potassium sulphate (K_2SO_4) or sulphate of potash (SOP), and Potassium nitrate (KNO_3), commonly referred to as KN.

The following pie charts present a comprehensive overview of the global consumption of these three types of fertilizers for the year 2020, based on data from the IFA 2022 report.

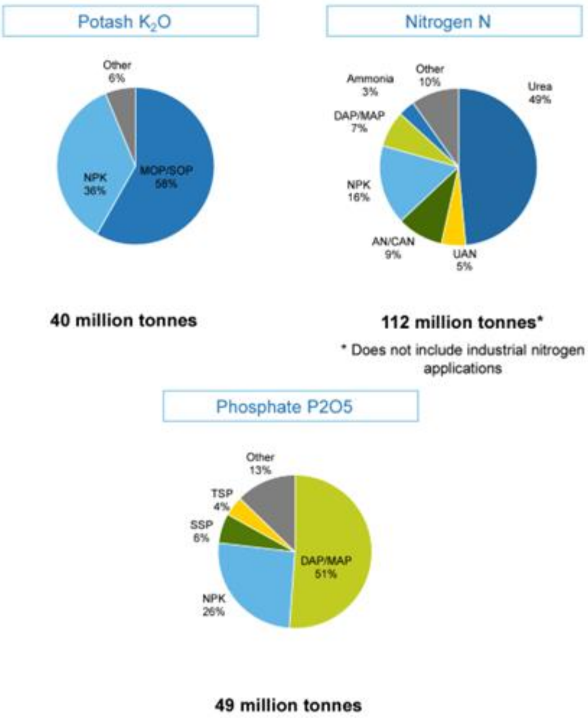

Figure 1-6. Current global consumption of fertilizers (2020)[8]

Analyzing the aforementioned diagrams reveals that the primary types of ammonia-derived fertilizers consumed on a global scale are urea, DAP/MAP, and AN/CAN.

Urea:

Urea ($CO(NH_2)_2$) is a widely used chemical derived from the combination of ammonia and CO_2, used particularly in the agricultural sector, where it accounts for approximately 80% of total production. Its popularity stems from its high solid nitrogen content, containing about 46% N, and its cost-effectiveness. Urea is commonly marketed in its prilled form, which makes it easy to handle

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[8] https://www.yara.com/siteassets/investors/057-reports-and-presentations/other/2022/fertilizer-industry-handbook-2022-with-notes.pdf/

and apply. Through chemical and bacterial processes, urea is converted into the ammonium and nitrate forms, which are readily available to plants for uptake and utilization.

Apart from its predominant use in agriculture, urea also finds applications in other domains. For instance, it is used in flue gas conditioning to reduce NO_x levels in selective catalytic reduction systems (SCR). It is also utilized as a raw material in the plastics, resins, and adhesives industries. The versatility and effectiveness of urea make it a valuable resource in various sectors.

When urea is applied as a top-dressing in agricultural practices, there are certain considerations to keep in mind. Urea has the potential to undergo transformation in the soil, converting into ammonium carbonate. This transformation can cause a temporary increase in local pH levels, which may have detrimental effects on plants or soil microorganisms. Moreover, in warm weather conditions, if urea is left uncovered on the soil surface, there is a potential for nitrogen losses. Urea can undergo hydrolysis if it is applied as a top-dressing without proper incorporation, leading to the volatilization of ammonia from chalk, limestone, or light sandy soils. However, when urea is properly incorporated into the soil through washing or cultivation, it is as effective as any other nitrogen fertilizer.

The efficiency of urea application is maximized in soils with sufficient moisture, as it facilitates the rapid dissolution of gaseous ammonia. If urea is top-dressed on the soil surface and followed closely by heavy rainfall, the urea will be washed into the soil, reducing the potential loss. In dry conditions during the peak of summer, it may be more advantageous to use ammonium nitrate instead.

According to the European Council (EC No. 1272/2008) and the UN transport regulations, urea products are not considered hazardous materials. However, they do carry potential risks as they can release ammonia when exposed to high temperatures. It is crucial to avoid mixing urea with other chemicals, especially Nitric acid, as this combination can be particularly dangerous.

Ammonium nitrate:

Ammonium nitrate (NH_4NO_3) is another key intermediate product of ammonia, and a widely used fertilizer that contains between 33 and 34% nitrogen (N). It involves the combination of ammonia with nitric acid. The unique composition of ammonium nitrate, with its half nitrate $(NO_3)^-$ and half ammonium $(NH_4)^+$ components, provides readily available nitrogen to plants. This characteristic makes ammonium nitrate a popular choice for top-dressing in cropping situations where additional nitrogen is required. Additionally, ammonium nitrate serves as the fundamental building block for all inorganic nitrate fertilizers.

Ammonium nitrate is typically marketed in a special prilled or granular form that resists moisture absorption. This characteristic helps maintain its quality and effectiveness during storage and application.

Ammonium nitrate offers an advantage over urea in terms of its application method. It can be safely applied to the soil surface without causing significant nitrogen losses to the atmosphere, except in calcareous soils where this risk is greater. In such soils with higher pH levels, there's a possibility of ammonium converting into ammonia gas and escaping into the air.

However, when comparing ammonium nitrate to urea, its main drawback lies in safety and transportability. Ammonium nitrate is classified as hazardous due to its oxidizing properties, which could lead to accidents or unintended detonations. This mandates strict safety precautions during its transportation, storage, and handling. On the contrary, urea is a safer choice with simpler handling, making it the preferred option for solid-form fertilizers in most scenarios. Its safety benefits and high nitrogen content have made urea the top choice among solid nitrogen fertilizers. Nevertheless, ammonium nitrate remains favoured for some specific agricultural uses due to its ability to reduce nitrogen loss and its effectiveness in certain soil conditions.

Ammonium nitrate has other downsides, which include:

- It deteriorates over time, especially in humid environments, due to hygroscopic properties.
- It demands careful attention during storage and transportation due to its explosive nature. While not officially classified as an explosive or flammable substance, it can pose a significant explosive risk under specific circumstances. As an oxidizer, it contains compounds rich in oxygen that can accelerate fires or explosions. However, for a reaction to occur, ammonium nitrate requires another element, such as fire or heat, to trigger it.
- Its storage and use are now highly regulated due to safety concerns, leading to restricted sales.

Ammonium phosphate (DAP and MAP):

Ammonium phosphate fertilizer ($(NH_4)_3PO_4$) contains nitrogen and phosphorus, typically produced through the neutralization reaction of ammonia and phosphoric acid. This type of fertilizer is widely recognized for its effectiveness, as it is applied to nearly all soils and crops due to its high concentration of active ingredients and reduced hygroscopicity. Ammonium phosphate fertilizers include:

- Slurry monoammonium phosphate (MAP),
- Diammonium phosphate (DAP)
- industrial MAP
- water soluble MAP
- water soluble ammonium polyphosphate (APP)
- others

Ammonium phosphate plants crucially rely on nearby mines to ensure a supply of phosphate rock and on nearby smelters or mining operations for the availability of sulphur dioxide, which is essential for sulphuric acid production. The phosphate rock serves as the primary source of phosphorus needed to produce phosphoric acid, a key raw material of this fertilizer, while sulphuric acid acts as a key reagent in the manufacturing process. The proximity of the mines provides the necessary raw materials, forming the backbone of the production process, and their close proximity allows for efficient transportation, reducing costs and ensuring an uninterrupted supply.

Current emission challenges and future insights:

Mineral fertilizers in the agri-food sector contribute to greenhouse gas emissions through mining, manufacturing, and on-farm use. In 2019, the production of mineral fertilizer accounted for around 0.8% of global greenhouse gas emissions, primarily due to fossil fuel usage and processes like nitrification and denitrification. Nitrous oxide (N_2O), a potent greenhouse gas, is released during these processes, especially from fertilizer use rather than from production, and contributes to ozone depletion. Nitrous oxide emissions can also occur indirectly through volatilization, redeposition, leaching, and runoff of nitrogen compounds.

The following bar chart shows a range of emission factors for different fertilizer products, taking into account the current process technology (without CCS) and application practices.

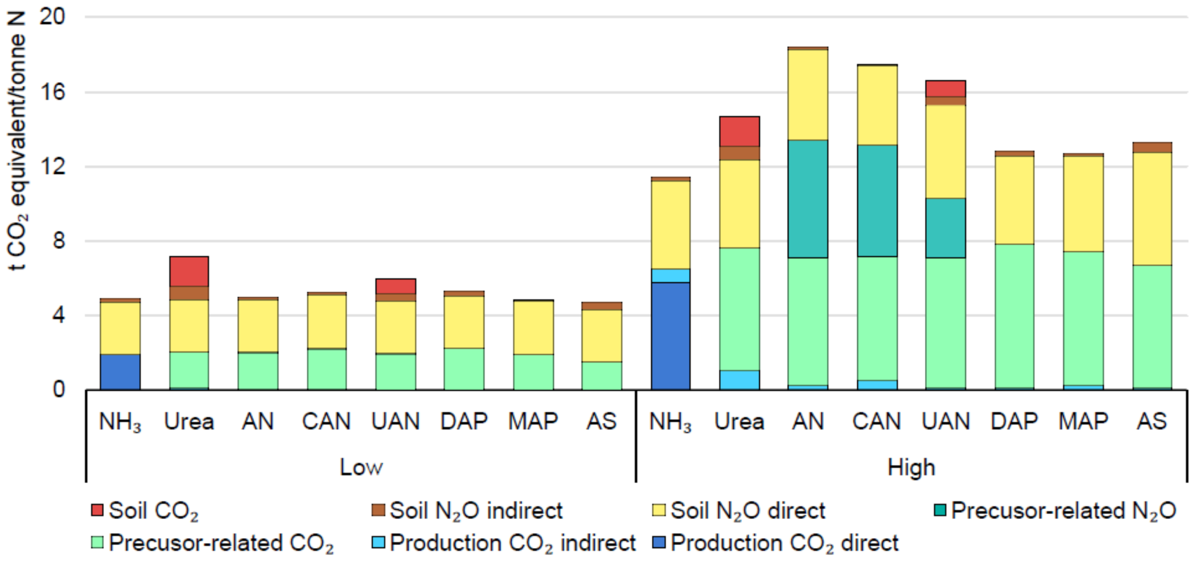

Figure 1-7. Current range of emission factors by fertilizer product[9]

Note: NH_3 = ammonia; AN = ammonium nitrate; CAN = calcium ammonium nitrate; UAN = urea ammonium nitrate; DAP = diammonium phosphate; MAP = monoammonium phosphate; AS = ammonium sulphate; N_2O = nitrous oxide. The real emission factors for nitrogen fertilizers in a given instance are highly uncertain; ranges are shown here using standard emission factors and are illustrative. For the direct CO_2 emission intensity of ammonia production, low and high values are based on a range of energy intensities and feedstocks: natural gas-based steam methane reforming with gross natural gas consumption of 28 GJ/t NH_3 (low), and coal gasification with gross coal consumption of 45 GJ/t NH_3 (high). Indirect CO_2 emissions from ammonia production include emissions from electricity generation with emission intensities of 6 g CO_2/kWh (low) and 933 g CO_2/kWh (high). All these emissions refer only to productions without CCS.

Nitric acid (HNO_3) serves as a crucial precursor for the manufacturing of specific fertilizers, including ammonium nitrate, calcium ammonium nitrate, and urea ammonium nitrate. This process, which involves the reaction between ammonia and oxygen, accounts for approximately 75-80% of nitric acid usage. Notably, nitric acid is a significant source of N_2O emissions in fertilizer production. While technologies to mitigate nitrous oxide emissions from industrial facilities are available, more than half of total N_2O emissions result from fertilizer application.

As emissions from fertilizer production decrease in the future, the focus on fertilizer utilization emissions and the choice of fertilizers will become increasingly crucial in reducing the overall greenhouse gas impact associated with fertilizers. In sustainable future scenarios, ammonium nitrate and calcium ammonium nitrate are anticipated to play a more prominent role due to their capacity to minimize GHG emissions, with low to zero CO_2 emissions during application. This transition could be pivotal in achieving net-zero emissions by decarbonizing ammonia feedstock when these fertilizers are employed.

In-field emissions are specifically associated with urea-based fertilizers. Urea, along with its derivative urea ammonium nitrate, is a carbon-containing fertilizer ($CO(NH_2)_2$) produced through the synthesis of ammonia and CO_2. When applied to the soil, interacting with water and urease enzymes, the carbon dioxide fixed within the urea molecule during manufacturing is released through hydrolysis. These emissions are inherent to urea's chemical composition, resulting in approximately 40% higher greenhouse gas emissions during usage compared to ammonium nitrate.

Given urea's high solubility in water and its decomposition into original compounds at the end of its life cycle, the utilization of fossil fuel-based CO_2 sources in the production process would undoubtedly undermine its "green" credentials.

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[9] IEA (2021), Ammonia Technology Roadmap

Therefore, it is essential that the CO_2 input comes from non-fossil fuel sources to ensure a carbon-neutral and environmentally friendly pathway. Presently, CO_2 primarily originates from fossil fuels, amplifying the overall CO_2 emissions linked to fertilizer usage. However, a shift towards non-fossil fuel sources like direct air capture (DAC), biogenic sources (biomass), or renewable methane would enable carbon-neutral CO_2 release in the future, thereby not adding to the total emissions.

As a result, ammonium nitrate (AN) and calcium ammonium nitrate (CAN) could emerge as more prominent players in the fertilizer landscape, primarily due to their ability to mitigate greenhouse gas emissions. Yet, the intricate regulatory complexities surrounding the shipping of AN/CAN, attributed to their heightened risk profile, could present obstacles to the potential expansion of their utilization.

Foreseeing that the overall demand for ammonia will remain stable within the fertilizer sector, the decision between ammonia-based products—whether AN or urea—is likely to be primarily influenced by the availability of economically viable CO_2 sources. Achieving a complete displacement of urea as the primary nitrogen fertilizer is a complex endeavour, potentially due to safety apprehensions related to ammonium nitrate, encompassing explosion hazards and the ensuing regulations for transportation. In the long run, the demand for nitrogen is projected to remain consistent, excluding the nutrient uptake by plants within the actual soil.

Lastly, it is plausible to predict that specific regions will choose to import ammonia and bolster local fertilizer production, either by prioritizing local AN to address transportation challenges associated with hazardous materials or by locally manufacturing urea through the utilization of biomass resources. The intricate interplay among environmental, economic, and regulatory factors will ultimately define the trajectory of nitrogen-based fertilizers.

1.2.5.2 Other current applications

Apart from its role in the fertilizer industry, ammonia has a range of industrial applications. It plays a vital role in the production of plastics like polyurethane and nylon, as well as synthetic fibres such as nylon and rayon. Ammonia's versatile nature extends to other chemical manufacturing processes as well. Refrigeration has been a long-standing use of ammonia, dating back to the 1850s. Even today, it remains a preferred choice for industrial refrigeration systems used in food processing and cold storage. Furthermore, ammonia serves as a cleaning agent and can be used as a fuel for internal combustion engines.

1. **Chemical industry**: Ammonia is a fundamental building block for the production of numerous chemicals, such as nitric acid, ammonium nitrate, and various organic nitrogen compounds. These chemicals serve as raw materials for the manufacturing of plastics, pharmaceuticals, explosives and cleaning agents.
    a. **acrylonitrile**: used in the manufacture of acrylic and modacrylic fibres for use in clothing and textiles. Acrylic fibres are also used as a precursor in the production of carbon fibre. It is used in the production of plastics and resins such as acrylonitrile-butadiene-styrene (ABS), styrene-acrylonitrile (SAN) and nitrile rubber for fuel hoses and O-ring seals.
    b. **Caprolactam**: mostly used in the production of filament and synthetic fibres, especially Nylon-6, small amount used in the manufacturing of plastic, coatings, and as a chemical intermediate.
2. **Refrigeration and air conditioning**: Ammonia has excellent thermodynamic properties, making it an efficient refrigerant in industrial cooling systems. It is used in large-scale refrigeration applications, such as in food processing and cold storage facilities. Ammonia is also a relatively eco-friendly refrigerant with zero ozone depletion potential and low global warming potential, making it an attractive alternative to some other synthetic refrigerants.
3. **Cleaning agents**: Ammonia-based cleaning products, such as ammonia solution or

"ammonia water," are widely used for household and industrial cleaning purposes. They are effective in removing grease, grime, and stains from various surfaces.

4. **Water treatment**: Ammonia plays a vital role in water treatment processes, particularly in wastewater treatment plants. It is used to control water pH, remove contaminants, and convert harmful pollutants into less toxic substances through processes like nitrification and denitrification.
5. **Pharmaceuticals**: Ammonia and its derivatives are utilized in pharmaceutical manufacturing for various purposes, including pH adjustment, as a reagent in chemical synthesis, and in certain drug formulations.
   a. **Methionine**: finds utility in diverse industrial uses, ranging from the manufacturing of feed and food additives to serving as a fundamental component for medical supplies and pharmaceuticals.
6. **Explosives and propellants**: Ammonia is a key ingredient in the production of explosives and propellants, such as nitrogen-based explosives (e.g. high explosives such as trinitrotoluene 'TNT') and propellants for rockets and munitions. Such production processes and industries are typically highly geopolitically strategic as they typically support military applications for these products.

1.3 Future ammonia value chain developments

Ammonia also presents several promising future applications that can contribute to the transition towards a low-carbon economy. Firstly, it can serve as a hydrogen carrier, enabling the storage and transportation of hydrogen, which can be utilized as a clean fuel or as a feedstock for various industrial processes. This application is particularly valuable as it addresses the challenges associated with hydrogen's storage and distribution (ammonia has significantly higher volumetric energy density compared to hydrogen[10], as well as favourable storage and transportation characteristics[11]). Secondly, ammonia can be employed as a maritime fuel, offering a greener alternative for ships, and assisting in reducing emissions within the shipping industry.

Given the significant environmental impact of maritime transportation, this usage has the potential to contribute to overall emission reduction efforts. The DNV Transition in Transport document also discusses the potential of ammonia as a zero-emission fuel but highlights that the engine technologies for ammonia are not yet mature and commercially available. There are however significant development efforts being made to get these engines to the market moving forward.

Furthermore, ammonia can function as a stationary fuel, powering electricity generation in stationary applications like fuel cells or gas turbines. This application provides an avenue for cleaner energy production, which can help in decarbonizing the power sector. Additionally, renewable ammonia produced from renewable electricity sources such as wind and solar power, holds promise in decarbonizing existing ammonia markets, including the chemical and fertilizer industries. By replacing fossil fuels with renewable ammonia, these industries can significantly reduce their carbon footprint and contribute to sustainable practices.

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[10] Galusnyak et al. (2023): Environmental impact assessment of green ammonia coupled with urea and ammonium nitrate production

[11] Galusnyak et al. (2023): Environmental impact assessment of green ammonia coupled with urea and ammonium nitrate production

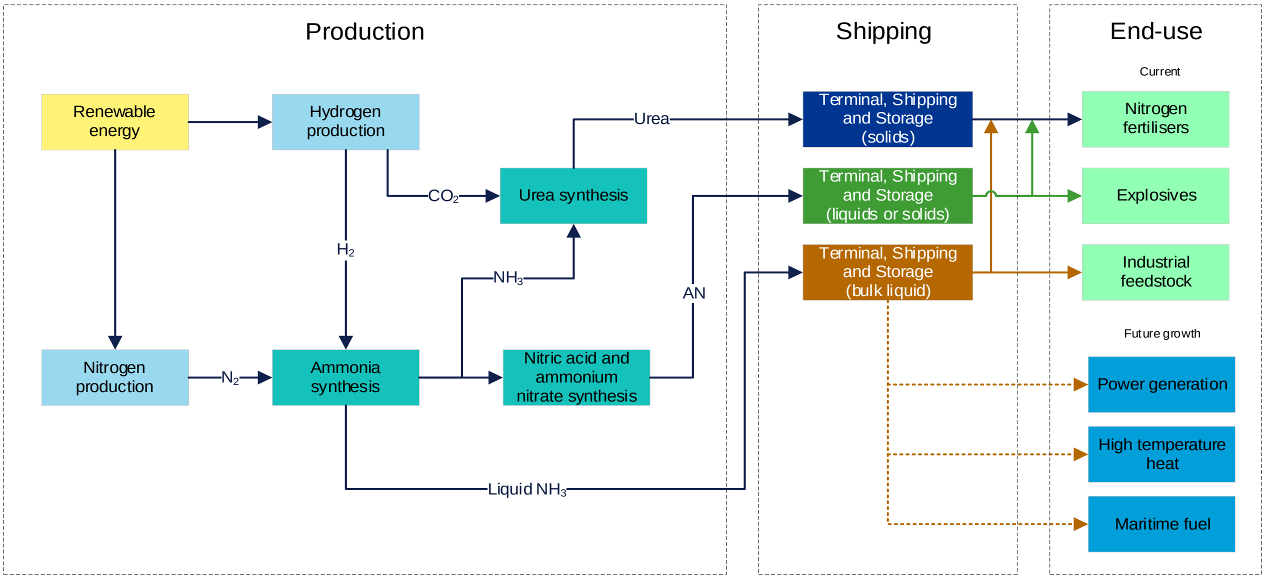

Figure 1-8. Current and Future Ammonia Value Chain

1.3.1 Green urea synthesis

In the context of forthcoming advancements, urea will continue to hold a significant role as a primary fertilizer, complemented by a gradual shift towards the production of green urea utilizing carbon-neutral CO_2 sources either from biomass, renewable methane, or direct air carbon capture (DAC). The pace of this transition may depend on the implementation of supportive measures and the establishment of effective regulatory mechanisms, such as carbon taxes, by governments and investors. These measures will be crucial to ensure the availability of cost-effective and accessible CO_2 for downstream storage and utilization pathways.

Each path of carbon-neutral CO_2 sourcing carries its own advantages and disadvantages (Table 1-2). As these technologies progress towards maturity, selecting the most suitable technology will primarily be influenced by the reliability, consistency of resources, and economic considerations.

Table 1-2. A comparison between different common carbon-neutral CO_2 feedstocks[12]

Carbon-neutral CO_2 feedstock	Pros	Cons
Biomass	- Biomass gasification has the lowest net carbon footprint. - H_2 from biomass gasification can directly contribute to green ammonia synthesis.	- Biomass quantity and quality highly affected by water resources and climate conditions. - Economics highly affected by locality and quantity of raw materials. - Relatively lower in energy density and H_2 yield. - Conversion efficiency highly related to moisture, energy, and mineral content. - High transport/storage costs.
Renewable Methane	- Compatible with existing energy infrastructure. - Wastes fermentation is a mature technology option. - Landfill biochemical conversion to biogas is the most economical option. - Opportunity to use existing SMR infrastructure to convert biogas to clean H_2 and CO_2 by-product.	- Biomass gasification-methanation and power-to-methane routes are costly. - Biogas produced from anaerobic digesters or landfills contains 35–70% CH_4 only. - H_2 production from renewable methane is relatively higher in cost. - Biogas resources are randomly distributed and often have limited capacity. - Resource inconsistency may limit the use of existing SMR infrastructure. - Dispersed H_2 and CO_2 production opportunities for small-scale urea production might lead to higher production costs due to limited scale.
DAC	- Rapidly emerging as a key climate change mitigation technology. - Occupies less land area, consumes less water, and highly scalable and flexible technology. - High-concentration CO_2 product that may not need further purification for end-users. - Integration with downstream processes can lower shared infrastructure cost and carbon footprint of long-distance CO_2 transport.	- Relatively new technologies with low Technology Readiness Level (TRL). - Excessive energy demand for DAC plants. - Levelized cost of CO_2 product from DAC is 2.5–3 times higher than point-source carbon capture. - DAC's sustainability may be compromised if sorbent regeneration energy comes from non-renewable sources. - Erecting large-scale DAC systems optimized for both CO_2 storage and utilization purposes may be more economically viable than multiple small-scale systems.

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[12] Milani et al (2022), Green pathways for urea synthesis: A review from Australia's perspective

Creating a green approach to urea production entails the responsible utilization of natural resources and efficient process integration to optimize the entire production line's performance.

While urea synthesis itself is relatively energy-efficient due to the initial exothermic ammonium carbamate formation, maintaining balanced heat exchange through an advanced Heat Exchange Network (HEN) can offset the slightly endothermic urea synthesis process. However, energy-intensive processes in ammonia synthesis like Air Separation Unit (ASU) and Steam Methane Reforming (SMR) require substantial energy. To reduce this carbon footprint, renewable energy input or excess green hydrogen through hydrogen fuel cells can be utilized. By making the Haber-Bosch process exothermic, the energy demand of SMR can be eliminated, redirecting this energy for water electrolysis and regenerating carbon capture sorbents. Further improving the green nature of the urea synthesis involves integrating a carbon-neutral CO_2 source, making urea synthesis a truly "green" process.

Although carbon-neutral CO_2 routes have cost-related opportunities and challenges, the trajectory of urea prices and market demand can balance the cost of green urea production. Maximizing the utilization of cost-effective renewable resources poses a challenge that can be tackled through intelligent energy networks (IENs). These networks play a pivotal role in efficient energy management, encompassing supply and demand coordination, proper interconnections, storage systems, efficiency enhancements, and waste heat integration.

Table 1-3. Example visualization of the commercial availability of different value chain components

Value chain	Year	Conversion	Shipping	Reconversion	End-use
Ammonia	2025	🟩	🟨	🟨	🟨
	2030	🟩	🟩	🟨	🟨
	2035	🟩	🟩	🟩	🟩
	2040	🟩	🟩	🟩	🟩

Employing a smart technology selector can intelligently allocate energy to different technology blocks based on resource availability and usage patterns. Effective management of micro-units and optimization of the energy management system (EMS) are crucial for reducing energy demands and costs associated with green urea technology.

Moving forward, the primary focus should remain on process integration, optimization, and innovative approaches for advancing the green urea initiative. Comparative techno-economic and life cycle analyses must assess scalability, costs, and long-term trade potential.

1.4 Ammonia demand and supply

While ammonia is a key feedstock in various industrial processes globally, it is not always produced domestically. Instead, it is a globally traded commodity, with large volumes of production coming from regions with access to large volumes of natural gas such as the Middle East and Russia and a significant amount of demand coming from regions dependent on agriculture such as North America and Asia. This section will provide an overview of historic demand and supply, combined with an outlook of the expected developments towards 2050.

Within the comprehensive examination of ammonia demand and supply, a crucial aspect is the analysis of its diverse applications across various industries. This analysis entails a closer look at the specific sectors that contribute significantly to ammonia utilization. The graph below offers valuable insights into the distribution of ammonia's usage across industries from the year 2000 to 2020, notably underlining the prominence of urea production within this context. Such an exploration aids in understanding the intricate interplay between ammonia demand, supply, and its application landscape.

1.4.1 Ammonia demand

IRENA's Innovation Outlook Ammonia notes that market demand for ammonia is around 183 Mt (Figure 1-10) where ammonia is primarily used as a fertilizer, which accounts for around 80% of global ammonia consumption, while the remaining 20% are used for industrial chemicals, refrigerants, and fuel. The Asia-Pacific region accounts for more than half of the world's ammonia consumption, mainly for agricultural activities. The largest consumers of ammonia-based fertilizer are China and India, followed by the United States, Brazil, and Russia. China is the largest consumer and producer of ammonia in the world, accounting for around 40% of global production and consumption. India is the second-largest consumer of ammonia-based fertilizer, with around 30% of global consumption. The United States is the largest consumer of ammonia-based fertilizer outside of Asia, with around 10% of global consumption.

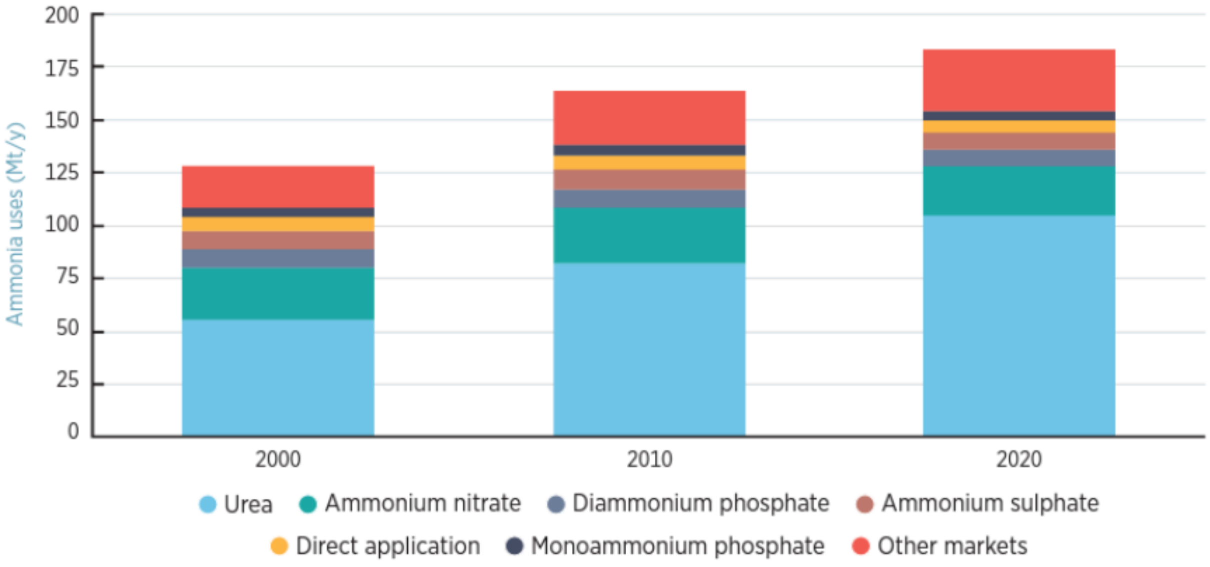

Figure 1-9. Distribution of ammonia's usage across industries for the years 2000, 2010 and 2020.

Note: Direct application refers to the use of ammonia as fertilizer. Other markets include the textile industry, the explosives and mining industry, pharmaceuticals production, refrigeration, plastics manufacturing, waste treatment and air treatment, such as nitrogen oxide (NOX) abatement. IRENA's Innovation Outlook Ammonia (2022).[13]

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[13] IRENA Innovation Outlook – Renewable Ammonia (2022).

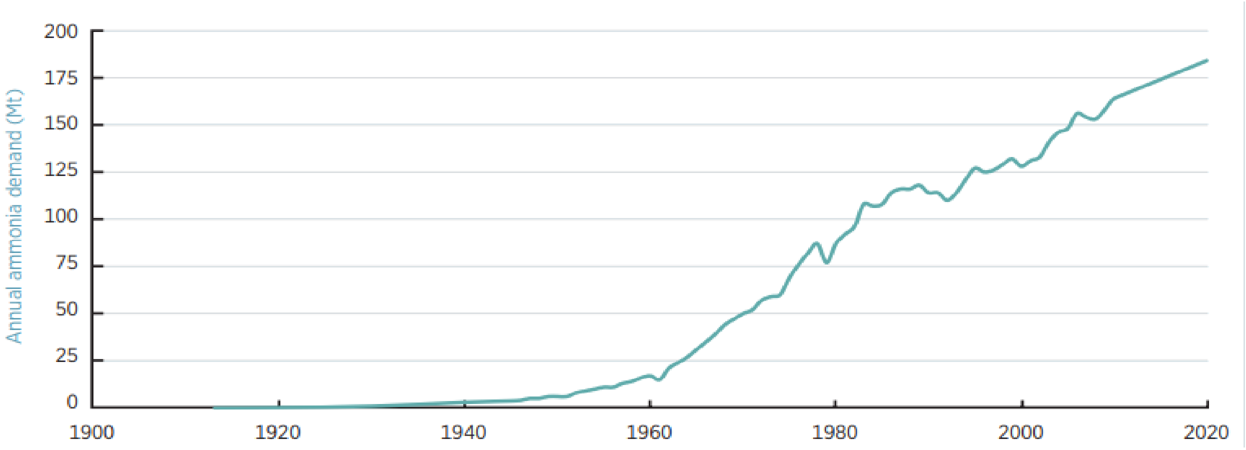
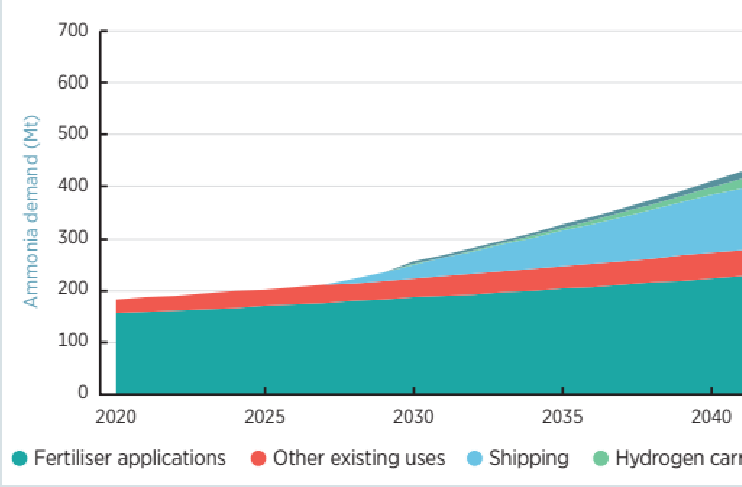


Figure 1-10. Ammonia demand trend[14]

Under the 1.5°C Scenario, which assumes a more ambitious set of policies and measures to limit global warming to 1.5°C above pre-industrial levels, the global demand for ammonia is projected to increase to 223 Mt by 2030 and 333 Mt by 2050, representing an increase of around 58%, where the primary drivers of market growth are anticipated to be the maritime sector and international trade of ammonia as a hydrogen carrier. By 2050, the maritime sector is expected to contribute to a new demand of 197 Mt, while the international trade of ammonia as a hydrogen carrier is projected to generate a new demand of 127 Mt, illustrated in Figure 1-11. The increase of global demand in the coming years is expected to be also supported by population growth, urbanization, and increasing demand for food, particularly in developing countries.



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[14] IRENA Innovation Outlook – Renewable Ammonia (2022).

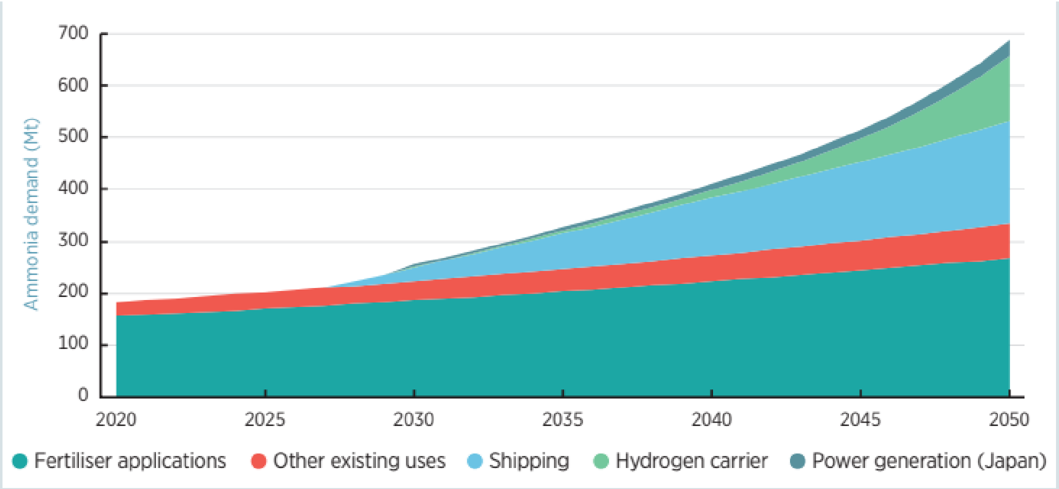

Figure 1-11. Ammonia demand outlook based on 1.5°C scenario[15].

1.4.2 Ammonia production

Ammonia plays a vital role in both the fertilizer and chemical industries, primarily serving as a key component in the production of fertilizers like urea and ammonium nitrate. According to the IRENA's report[16], the annual production of ammonia stands at approximately 183 Mt. It is important to note that the most of this production, nearly 100%, relies on fossil fuel sources. Specifically, natural gas accounts for 72% of the production, while coal, naphtha, and heavy fuel oil collectively contribute 22% to the production of ammonia. Cleaner sources of ammonia such as renewable ammonia were produced on a commercial scale around 100 years ago, but the quantity produced is still negligible. With pressures towards decarbonization, there will be an increase in industrial production towards renewable ammonia. The same report also notes that Asia has more than half of the global ammonia production capacity, with China, India, and Indonesia being the largest producers. Other significant producers of ammonia include Russia, the United States, and Ukraine.

According to projections by IRENA, if the transition to renewable ammonia production aligns with the Paris Agreement's objective of limiting global temperature rise to 1.5 degrees Celsius (°C) by 2050, it would result in a significantly expanded ammonia market. The estimated market size would reach 688 Mt (Figure 1-12), nearly four times larger than the current market. This growth would be achieved through the decarbonization of ammonia production, with 566 Mt coming from new renewable ammonia production facilitated by renewable hydrogen and renewable power. Additionally, fossil-based ammonia production combined with carbon capture and storage (CCS) would complement the renewable production methods. The global ammonia production capacity is also expected to increase in the coming years, driven by new production facilities in the Middle East, North Africa, and the United States.

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[15] IRENA Innovation Outlook – Renewable Ammonia (2022).

[16] IRENA Innovation Outlook – Renewable Ammonia (2022).

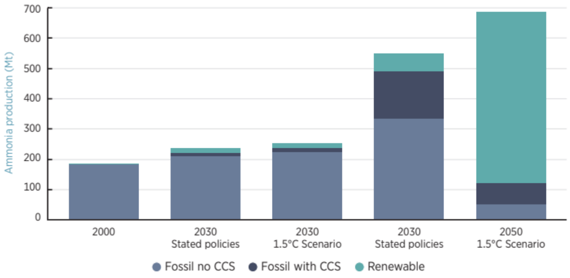

Figure 1-12. Ammonia production outlook by source[17]

The production and import of ammonia are influenced by various factors, such as feedstock availability, energy costs, and demand, leading to different approaches in different countries. In the United States, ammonia production is predominantly domestic, concentrated in the Gulf Coast region due to abundant and inexpensive natural gas. On the other hand, Japan heavily relies on ammonia imports as it has limited domestic resources. According to the Innovation Outlook Ammonia report by IRENA, Japan plans to import low-carbon fossil-based ammonia in the short term and transition to renewable ammonia imports beyond 2030. The country has already started importing blue fossil-based ammonia from Saudi Arabia and expects increased ammonia imports for power generation in the future. These examples demonstrate the variations in production and import strategies based on specific country circumstances.

The decision to import either urea or ammonia for urea production is influenced by several factors, including feedstock availability, energy costs, and transportation expenses. Urea, a widely used nitrogen fertilizer, is produced by combining ammonia with carbon dioxide. Countries with access to low-cost ammonia and carbon dioxide feedstocks may choose domestic urea production. However, some countries may lack such resources or the necessary infrastructure and technology for domestic production, making it more cost-effective to import either ammonia or urea based on production and transportation costs. For instance, countries rich in natural gas reserves, like the United States, may choose to produce ammonia domestically and export it to other countries, where it can be converted into urea. Conversely, countries with limited natural gas resources, such as Japan, may import ammonia or urea to fulfil their nitrogen fertilizer requirements. In summary, the decision to import urea or ammonia depends on factors such as feedstock availability, energy costs, transportation expenses, and the presence of infrastructure and technology for local production.

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[17] IRENA Innovation Outlook – Renewable Ammonia (2022).

2 OVERVIEW OF POLICY AND REGULATORY FRAMEWORK OF GREEN AMMONIA – GLOBAL PERSPECTIVE

2.1 Overview of green ammonia – Global perspective

Governments and regulators are developing policy, regulations and standards to support green ammonia. These are important for supporting existing ammonia producers to achieve emissions reductions as well as for incentivizing new, green ammonia projects. In this section, an overview will be provided of the broad spectrum of rules and regulations that are in place today to support ammonia in existing use cases, most of which are in the industrial sector, as well as providing insight into gaps that exist related to new use cases. A view will also be provided on policies aimed at unlocking these new use cases for ammonia, though due to their nascent nature, concrete policies are still relatively limited and rarely move beyond stated intents and longer-term targets.

Due to its toxic nature, ammonia transport, storage and usage are subject to strict rules and regulations. Exact requirements are dependent on the jurisdiction(s) and uses, for example, whether ammonia is being transported by ship or rail, therefore here we present typical regulatory requirements. Several nations, particularly the major ammonia-producing countries, have progressed in developing advanced policies and regulations for applications related to green ammonia, particularly in the context of emerging uses and sustainability objectives. Most of the existing regulations are applicable to the broader industrial category of dangerous goods but some elements particularly target fertilizers and ammonia.

The role that ammonia is expected to play in countries differs significantly and is highly dependent on factors like geography but is also subject to choices made by individual countries with regard to their long-term vision. For example, South Korea and Japan are actively pursuing ammonia for power generation via co-firing with coal but with an ambition to move towards 100% pure ammonia-fired power plants in the future. This is both because of their dependence on imports of hydrogen via derivatives, which means that using ammonia directly is the cheapest option, and because this is seen as an opportunity to develop domestic industries, with Japanese companies especially leading the way in ammonia-fired turbines. European countries like Germany and the Netherlands have also made ammonia a cornerstone of decarbonization via the Green Hydrogen Strategy encompassing green ammonia utilization, though for them ammonia is primarily a hydrogen carrier that can be cracked back into hydrogen to be fed into the national or European hydrogen pipeline networks that are under development and can be mixed with direct hydrogen production from, for example, offshore wind. Countries like Singapore are keeping their options open, looking at both direct ammonia-fired power generation and in the future cracking ammonia back into hydrogen for decarbonization of both power generation and industry. Simultaneously Singapore is actively trying to retain its position as an international marine bunkering hub by developing pilots for ammonia refueling of ships, while countries like Norway are focused on developing the ships themselves. Countries like Australia see ammonia as the primary export product on the path to becoming a hydrogen superpower and are heavily focused on supporting green ammonia production projects via programmes such as Hydrogen Headstart, while the US is providing a broader stimulus for all low-carbon fuels (blue or green) via the Inflation Reduction Act (IRA).

Across nations, the development of global policies and regulatory frameworks for ammonia as a new bulk commodity is actively underway, reflecting a shared commitment to its potential as a sustainable energy carrier. Germany, Japan, Australia, the Netherlands, the United States, Norway, South Korea, the United Kingdom, and Singapore are at the forefront of this effort. These countries contribute significantly to international dialogues on safe ammonia transport and storage regulations, emphasizing stringent safety measures. Moreover, they explore ammonia's potential as a clean fuel for cracking and power generation, particularly in regions with dense populations. Singapore, with its expertise in maritime and logistics, plays a pivotal role in shaping discussions on safe ammonia transport and storage globally, while its commitment to exploring ammonia's applications aligns with global efforts to foster sustainable industries. The active involvement of these nations in international collaborations and forums strengthens the development of comprehensive, universally applicable regulations for ammonia's multifaceted uses. A good example of this collaborative effort includes Singapore's role in ammonia bunkering and ammonia-fired power generation, showcasing the shared emphasis on safety and sustainability in ammonia applications near population centres.

Developing Policies and Regulatory Framework for Green Ammonia

The development of policies and regulatory frameworks for green ammonia represents a pivotal global endeavour to harness the potential of this sustainable energy carrier. Green ammonia, produced from renewable energy sources and often touted as a key player in the transition to a low-carbon economy, demands comprehensive regulations that encompass safety, environmental considerations, and innovative applications. Countries worldwide are actively participating in shaping the regulatory landscape for green ammonia. International collaboration plays a key role in reaching the goals of reducing emissions. A number of countries formed a global coalition to launch the Industrial Deep Decarbonization Initiative (IDDI) to stimulate demand for low-carbon industrial material. The IDDI, which is co-led by the UK and India, works to standardize carbon assessments, establish ambitious public and private sector procurement targets, incentivize investment into low-carbon product development, and design industry guidelines. There are also international efforts to address nitrogen pollution at the international level that could improve the efficiency of nutrient use. Several United Nations multilateral environmental agreements are relevant to nitrogen, including the Paris Agreement, the Convention on Biological Diversity and the Convention on Long-range Transboundary Air Pollution.

Safety and Environmental Considerations

One of the primary motivations behind the establishment of robust regulations for green ammonia is its intrinsic properties. Green ammonia, while a promising carrier for clean energy, possesses characteristics such as toxicity, corrosiveness, and flammability, necessitating stringent safety measures. In this section, we delve into how nations are addressing safety and environmental considerations in the context of green ammonia production, transport, and usage. International collaborations and standards for the safe handling of green ammonia are also explored.

Transport and Storage Regulations

The transport and storage of green ammonia require specific guidelines and standards due to its unique properties. Countries such as Germany, Japan, and the United States actively contribute to international dialogues on safe ammonia transport and storage. This section of regulations examines the design considerations for ammonia storage vessels, transport procedures, and emergency response protocols. It highlights the importance of international cooperation in establishing rules that ensure the secure movement and containment of green ammonia.

Ammonia as a Fuel and Proximity to Population Centres

Green ammonia's versatility extends beyond its role as an energy carrier; it is increasingly explored as a fuel for applications like cracking and power generation. As these applications often occur in proximity to population centres, regulations must strike a balance between harnessing the potential of green ammonia and safeguarding communities. We investigate how nations like Australia and Singapore actively participate in discussions related to green ammonia's use as a future fuel and its implications for environmental sustainability in densely populated areas.

The global community needs to emphasize the collaborative global effort to develop policies and regulatory frameworks for green ammonia. It underscores the significance of addressing safety, environmental, and operational aspects while fostering innovation in ammonia applications. The active participation of nations in shaping these regulations reflects the shared commitment to harnessing green ammonia's potential as a sustainable energy carrier and a driver of the transition to a low-carbon future.

2.2 Introduction to the chemical properties and classification of ammonia

Ammonia is 82% nitrogen and 18% hydrogen. Anhydrous ammonia is an irritant, non-flammable liquified gas that is colourless and pungent in odour. Potential hazards stemming from the use of ammonia include:

- **Flammability** - Ammonia is not considered to be highly flammable compared to other fuels like liquid hydrogen and LNG due to a narrow range of flammable mixture concentration (lower to upper explosive limit: 16-25% of ammonia) and the higher ignition energy (8 mJ). Although the fire and explosion risk is not ignorable, the threat of toxicity is of significantly higher concern as this becomes an issue at much smaller concentrations than the flammable range.
- **Toxicity** - Human exposure to ammonia can be via inhalation, ingestion or by direct contact. Its pungent characteristics are typically detectable at very small volumes (5 ppm), allowing for swift action thereafter. Concentrations of the gas at 300 ppm are considered immediately harmful to life or health, with 2,500 to 4,500 ppm concentrations being fatal within 30 minutes, and 10,000 ppm leading to visible skin damage. Ammonia can impact the environment through soil acidification, direct toxic damage to plant leaves and by altering the susceptibility of plants to climatic conditions such as frost or drought[18]. Susceptibility to pathogens may also be altered. Ammonia pollution favours species that have adapted to nitrogen uptake and can rapidly change environments. Non-human animal species may also be affected, by changing food sources and habitats as well as direct toxicity. Ammonia is lighter than air in its gaseous phase, though when ammonia is released, it absorbs moisture from the air to form a dense and visible white cloud that is heavier than air, making it harder to disperse the toxic cloud.
- **Corrosiveness** - Ammonia storage, piping, valves and other fittings are made of steel as ammonia is corrosive to cast iron, copper, brass or copper alloys as well as galvanized metals.

Despite hazard risk, its production and use are considered routine with over a century of widespread industry use and knowledge.

2.3 Safety & environmental considerations for all ammonia infrastructure

Ensuring safety and environmental protection is of paramount importance when it comes to ammonia infrastructure in Thailand. As ammonia gains recognition as a versatile energy carrier and a solution for emissions reduction, upholding the highest safety standards is imperative. In order to achieve this, local, national, and international regulations and standards should be adhered to when addressing safety fundamentals.

At the local level, Thailand's regulatory framework plays a crucial role in ensuring the safe deployment, operation, and maintenance of ammonia infrastructure. Local regulations provide

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[18] Susan Guthrie et al. (2018) The impact of ammonia emissions from agriculture on biodiversity: An evidence synthesis Rand: Cambridge, UK

a foundation for safety protocols that must be meticulously followed during the design, construction, and operation phases of ammonia facilities. These regulations dictate aspects such as site selection, hazard assessments, emergency response plans, and worker training. By aligning with local guidelines, stakeholders contribute to the protection of surrounding communities and the environment, minimizing potential risks associated with ammonia handling and storage.

National regulations in Thailand provide a broader context for safety and environmental considerations, encompassing various aspects of ammonia infrastructure across the country. National standards may address issues such as design codes, materials selection, transportation requirements, and emissions monitoring. In Thailand, relevant safety regulations include the Factory Act (1992)[19], which contains provisions on engagement in a factory business, supervision of the factory, and penalties; the Safety, Health and Environment Act (2011)[20] and the Industry Product Standards Act (No. 7) (2015)[21]. Compliance with these standards ensures that ammonia projects are developed and executed with uniform safety measures, enhancing public confidence and regulatory oversight. Moreover, national regulations play a crucial role in promoting consistency and harmonization among different ammonia infrastructure projects, facilitating effective risk management and mitigation.

On an international scale, aligning with established safety and environmental standards is vital for maintaining Thailand's standing in the global energy landscape. As ammonia markets become increasingly interconnected, adhering to international norms ensures that Thai ammonia infrastructure is compatible with global supply chains and industry best practices. Organizations such as the International Code Council (ICC)[22], the International Maritime Organization (IMO)[23], and the United Nations Economic Commission for Europe (UNECE) [24] develop guidelines and protocols that shape the safe transport, storage, and utilization of ammonia worldwide. By incorporating these international benchmarks into local practices, stakeholders contribute to a safer and more sustainable ammonia industry that transcends geographical boundaries.

Thailand's safety and environmental considerations for ammonia infrastructure must align with international best practices, drawing from established guidelines set forth by organizations such as the American Institute of Chemical Engineers (AIChE), the International Institute of Ammonia Refrigeration (IIAR), and the International Organization for Standardization (ISO). These organizations provide comprehensive frameworks for assessing and managing risks associated with ammonia, offering insights into process safety, risk communication, and emergency preparedness.

2.3.1 Evaluating and managing risks

Risk assessment and management are fundamental pillars in ensuring the safety and environmental integrity of ammonia infrastructure in Thailand. The process of risk assessment involves identifying potential hazards and evaluating their likelihood and consequences. In the context of ammonia infrastructure, this encompasses a wide spectrum of factors, including ammonia leakage, fire, explosion, toxic release, and environmental impact. By conducting thorough hazard assessments, stakeholders can develop a comprehensive understanding of potential vulnerabilities and establish protocols to minimize their occurrence.

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[19] Factory Act, B.E.2535 (1992). Unofficial Translation. http://web.krisdika.go.th/data/outsitedata/outsite21/file/FACTORY_ACT,_B.E.2535_(1992).pdf Accessed in November 2023

[20] Occupational Safety, Health, and Environment Act, B.E. 2554 (2011). Unofficial Translation. http://web.krisdika.go.th/data/outsitedata/outsite21/file/OCCUPATIONAL_SAFETY,_HEALTH,_AND_ENVIRONMENT_ACT,B.E._2554.pdf Accessed in November 2023

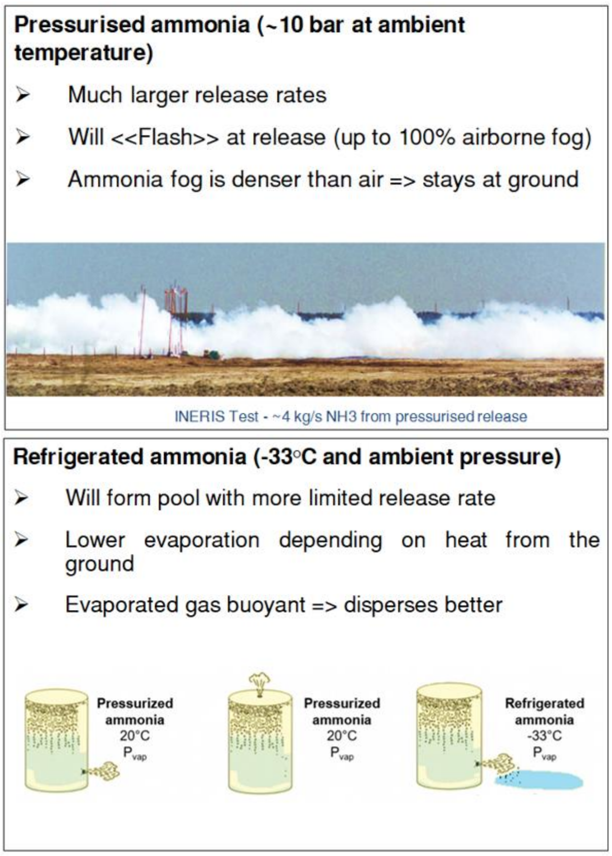
[21] Industry Product Standards Act (No. 7) (2015). Unofficial Translation. http://web.krisdika.go.th/data/document/ext809/809939_0001.pdf Accessed in November 2023

[22] American Institute of Chemical Engineers (AIChE). https://www.aiche.org/

[23] International Institute of Ammonia Refrigeration (IIAR). https://www.iiar.org/

[24] International Organization for Standardization (ISO). https://www.iso.org/home.html

For instance, storage of pressurized ammonia has different associated risks when compared to refrigerated ammonia at ambient pressure. See example below:



Pressurised ammonia (~10 bar at ambient temperature)

- Much larger release rates
- Will <<Flash>> at release (up to 100% airborne fog)
- Ammonia fog is denser than air => stays at ground

INERIS Test - ~4 kg/s NH3 from pressurised release

Refrigerated ammonia (-33°C and ambient pressure)

- Will form pool with more limited release rate
- Lower evaporation depending on heat from the ground
- Evaporated gas buoyant => disperses better

Figure 2-1. An example of associated risks of ammonia. Source: Gexcon

Therefore, effective risk management strategies are essential for translating risk assessments into actionable measures that prevent, mitigate, or respond to potential incidents. These strategies involve the implementation of engineering controls, safety protocols, emergency response plans, and continuous monitoring to prevent, detect, mitigate and respond to potential accidental scenarios. Considerations include:

- Engineering controls (advanced leak detection systems, redundant safety mechanisms, ventilation systems)
- Routine inspections, maintenance, and corrosion prevention measures to contribute to the longevity and integrity of storage facilities, reducing the risk of leaks and accidents.
- Procedural protocols designed to mitigate identified risks.
- Equipping workers with personal protective equipment (PPE) such as respiratory protection, goggles, gloves, and protective clothing. PPE acts as a vital barrier against potential exposure and is a non-negotiable element when working with or around ammonia. Regular training on the correct usage and maintenance of PPE ensures its effectiveness and underscores its importance in safeguarding personnel.
- Training programmes to ensure that workers are well-versed in ammonia's properties, risks, and safe handling practices, empowering them to make informed decisions and respond effectively to unexpected situations.
- Emergency response plans: Regular drills and simulations bolster preparedness, enabling workers to respond confidently and efficiently to potential emergencies, thereby minimizing risks and preventing escalation.
- Zoning classification as a vital aspect of risk assessment, forming a critical component of safety and environmental considerations for all ammonia infrastructure in Thailand. By categorizing different areas within ammonia facilities into high, intermediate, and low-risk zones, stakeholders can tailor safety measures and protocols to effectively address the varying levels of potential hazards associated with each zone.
    - High-Risk Zones: Areas with high potential for hazardous incidents, such as storage facilities and processing units. Rigorous safety measures include engineering controls, leak detection, safety mechanisms, and PPE. Specialized training equips personnel for high-risk zones.
    - Intermediate-Risk Zones: Moderate likelihood of incidents, involving transition areas. Combining engineering controls and administrative protocols, these zones include ventilation systems, equipment inspections, and worker training.

    - Low-Risk Zones: Minimal potential for incidents, including administrative offices and walkways. Safety measures like safety awareness programmes and evacuation routes prevent unforeseen incidents.

The collaboration between stakeholders, including government agencies, industry players, and local communities, is vital for effective risk assessment and management. Transparent communication of potential risks, emergency response plans, and mitigation measures foster a shared understanding of the risks involved and enhance community preparedness. Regular training, drills, and public awareness campaigns play a pivotal role in ensuring that all stakeholders are well-informed and capable of responding to potential emergencies effectively.

2.3.2 Security measures, and community engagement: building trust

Security measures and community engagement are intertwined pillars in ensuring safety and environmental protection within ammonia infrastructure. Security measures encompass a range of protocols designed to prevent unauthorized access, mitigate potential threats, and safeguard ammonia infrastructure from intentional harm. These measures include controlled access zones, surveillance systems, intrusion detection, and cybersecurity protocols. Given the potential hazards associated with ammonia, stringent security measures are vital to prevent deliberate acts that could result in accidents, breaches, or harm to the community.

Engaging with local communities is equally crucial for building trust, sharing information, and enhancing preparedness. Open and transparent communication about ammonia infrastructure's safety protocols, potential risks, and emergency response plans fosters a sense of collaboration and shared responsibility. Community engagement initiatives, such as public meetings, workshops, and educational campaigns, empower residents to understand the benefits and risks of ammonia infrastructure, enabling them to make informed decisions and take appropriate precautions.

Government agencies, industry stakeholders, and community representatives must collaborate to develop comprehensive security and engagement strategies. Community input and feedback play a vital role in shaping safety protocols, emergency response plans, and risk communication strategies that resonate with local contexts and concerns. By involving community members in decision-making processes, stakeholders can tailor safety measures to address specific needs and ensure that emergency procedures are well-understood and effectively implemented.

Thailand can draw inspiration from international best practices in security and community engagement, adapting successful models from countries that have robust ammonia industries. Countries with well-established ammonia sectors often prioritize community involvement and employ comprehensive security systems to prevent and respond to potential threats. Thailand can leverage these experiences to develop a holistic approach that combines advanced security technology with community empowerment, ultimately enhancing overall safety and preparedness.

2.4 Design considerations for ammonia storage vessels & transport vessels

Designing ammonia storage vessels and transport vessels such as ship tanks and rail cars involves a careful balance between safety, efficiency, and environmental considerations due to the hazardous nature of ammonia. Ammonia is a toxic, flammable, and highly reactive gas that requires specialized equipment and engineering to ensure safe storage and transportation. Some key design considerations for both ammonia storage and transport vessels include:

- **Material Selection:** Selecting appropriate materials for vessel construction is crucial to ensure compatibility with ammonia. Materials such as carbon steel, stainless steel, and some types of non-corrosive alloys are commonly used. These materials should be resistant to ammonia corrosion, and their mechanical properties should remain stable at both low and high temperatures.

- **Pressure and Temperature:** Ammonia is typically stored and transported as a refrigerated liquid (-33°C), liquid under pressure at ambient temperature or as a compressed gas. Designing vessels to withstand the pressure and temperature conditions is essential to prevent leaks, ruptures, or structural failures. The pressure and temperature ratings should consider both normal operating conditions and potential emergency scenarios. Conventionally pressurized ammonia storage tanks are designed for 20 bar with a maximum allowed working pressure of 17 bar. Because ammonia is stored under pressure, the vessels are manufactured from thick steel plate and typically have a high cost per unit of storage. Large volumes of ammonia can be stored at atmospheric pressure in refrigerated insulated storage tanks operated at around -33°C. The tanks are typically of a double or full containment design where both the inner and outer tank shell are designed for the hydrostatic pressures and cold temperatures required for ammonia storage. Engineering features typically include an air gap or foundation slab heaters to prevent foundation damage through 'frost heave'. Where ammonia is stored as a refrigerated liquid, it can be transported to distant markets through fully refrigerated Very Large Gas Carriers (VLGCs). Refrigerated ammonia cannot be loaded into pressurized ammonia storage tanks without being first warmed since generally pressurized storage tanks are not constructed from low temperature steel suited to operate at this temperature.
- **Safety Systems:** Storage and transport vessels should be equipped with safety systems, including relief valves, pressure and temperature monitoring, emergency shutdown systems, and fire suppression systems. These systems help prevent overpressure, overtemperature, and other hazardous situations that could lead to accidents.
- **Ventilation and Leak Detection:** Effective ventilation and leak detection systems are crucial to ensure that any accidental ammonia release is detected early and controlled. Ammonia sensors should be strategically placed to monitor for leaks and trigger alarms or automatic shutdowns if ammonia levels exceed safe limits.
- **Insulation:** For ammonia transport vessels, insulation is vital to maintain the desired temperature and prevent the gas from vaporizing during transit. Proper insulation can help minimize pressure changes and reduce the risk of leaks or ruptures caused by thermal expansion.
- **Corrosion Protection**: Ammonia is corrosive, so proper protective coatings and corrosion-resistant materials should be used to prevent degradation of the vessel's structural integrity over time.
- **Loading and Unloading Systems:** Designing efficient loading and unloading systems is essential for minimizing handling risks. These systems should be designed to prevent spills, leaks, and exposure of workers to ammonia. Automated systems can help reduce human error during loading and unloading processes.
- **Structural Integrity:** The vessel's structural integrity is of utmost importance. Rigorous engineering analyses, including finite element analysis and stress testing, should be conducted to ensure that the vessel can withstand the stresses it will experience during operation, including transportation vibrations and thermal cycling.
- **Transportation Considerations:** Transport vessels, such as ship tanks and rail cars, need to be designed to withstand the mechanical forces encountered during transportation. The design should account for factors like vibration, impact, and stability to prevent accidents or damage to the vessel.

- **Regulatory Compliance**: Designs must adhere to local, national, and international regulations and standards that govern the storage and transportation of hazardous materials, such as ammonia. Compliance with regulations ensures that vessels meet safety requirements and minimize risks to human health and the environment.
- **Emergency Response Plans:** In the event of a leak, spill, or accident, vessels should be designed with emergency response plans in mind. This includes easy access for emergency personnel, proper signage, and well-defined procedures for containment, evacuation, and mitigation of potential hazards.

3 COST STRUCTURE OF GREEN AMMONIA VALUE CHAIN – GLOBAL PERSPECTIVE

In the previous sections, an overview of the present and future market, as well as relevant policy and regulatory landscape in the ammonia market were explained. Moving forward, this chapter focuses on examining the cost structure of ammonia. The cost of ammonia is usually represented as Levelized Cost of Ammonia (LCOA) in USD/kg-NH_3. The LCOA is comprised of different cost elements required to produce and procure ammonia before using it - which are hydrogen production, conversion to ammonia, export terminal, transport/shipping, and the import terminal.

The cost structure analysis will be carried out by calculating the estimated landed cost of ammonia under different value chains that are applicable for Thailand. Two distinctive value chain scenarios that are chosen and will be compared are:

- Domestic production – East Thailand

  Thailand is comprised of seven regions: Metropolitan Bangkok, Central-north (referred to as Central in this report), Central-east (referred to as East), Central-west (referred to as West), North, Northeast, and South. A prior study conducted by DNV has highlighted the Eastern region's significant potential for hydrogen production, both from renewables (wind and solar) and gas with electricity grid and gas network infrastructure. Furthermore, this region shows promising hydrogen demand potential in various sectors, including power, industry, and transport. Additionally, the Eastern region benefits from robust infrastructure, including well-established electricity grids, gas networks, and major seaports. Therefore, the Eastern region has been chosen for further cost calculation in this chapter as the domestic production case scenario.

- Imported Ammonia – Australia

  Australia is one of the likely large-scale exporters in the Asia-Pacific region due to its abundant renewable resources. Australia has announced over 100 green hydrogen/ammonia projects, with a production capacity of up to 22,808 ktpa by 2030, some targeting export markets, particularly in Asia. This production capacity translates into an electrolyser capacity of 185 GW, with 3,672 ktpa expected by 2025 as progress continues. The biggest project announced is the Western Green Energy Hydrogen Plan project, with a 3,500 ktpa and 28 GW electrolyser capacity. In addition, compared to other potential global exporters (i.e. Oman, Saudi, United Arab Emirates, Chile, Canada, Mauritius, South Africa, the United States), importing from Australia to Thailand would be the shortest and therefore preferred.

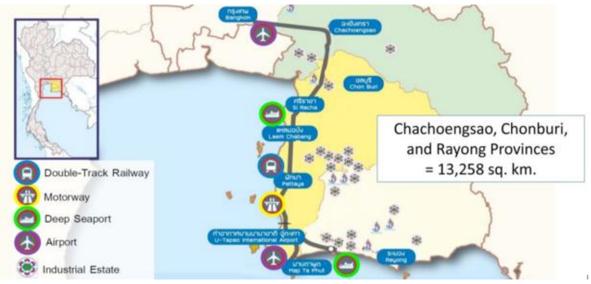


Figure 3-1. Thailand's eastern region industrial estate showing the main infrastructure

3.1 LCOA in Thailand and Australia

To obtain the estimated landed cost of ammonia, DNV used an LCOA calculation in-house model which optimizes the sizing and mix of renewable resources such as wind and solar in combination with flexible sizing of battery energy storage systems (BESS) and intermediate hydrogen storage, with the objective to minimize the overall LCOA.

The input to the model consists of:

- Technological and financial parameters such as plant parameters, conversion efficiencies, equipment costs
- Hourly renewable profiles in the case of wind and solar energy resources.
- The areas in the vicinity of Rayong and Laem Chabang port in East Thailand and the port in Geraldton in Western Australia (WA) were selected as the ammonia production sites in each country due to their favourable renewables resource and proximity to a port.
- The hourly wind and solar profiles of these two locations with the time horizon of one year were obtained. In the case of Geraldton in WA, the profiles were obtained using the Renewables Ninja software tool which generates these profiles based on weather data from global reanalysis models and satellite observations. The renewable generation profiles for East Thailand were provided by EGAT.

The model minimizes the net present value of the plant over its lifetime based on a target production capacity of 1 mtpa of ammonia as well as constraints on renewables availability and plant operation to obtain the optimal sizes of the energy resource (wind and solar farm), production facility (hydrogen production and Haber-Bosch synthesis) and storage technology providing flexibility (BESS and hydrogen storage). The LCOA for production in Australia and Thailand are differentiated by their respective renewables profile, technology costs and estimated discount rates.

A summary of the main parameters used for Thailand and Australia is listed in Table 3-1, while the full list of parameters is provided in the Appendix. The main costs drivers such as the renewable energy resources and electrolyser for hydrogen production are much higher than the cost of the ammonia synthesis plant and they have thus been included.

Table 3-1. Main input parameters used in LCOA modelling

Country / Scenario	AUS 2030	THA 2030	AUS 2050	THA 2050
Solar Farm CAPEX (USD/kW)	779	717	347	319
Wind Farm CAPEX (USD/kW)	1385	1274	1104	1016
BESS CAPEX (USD/kWh)	194	179	110	101
Electrolyser CAPEX (USD/kW)	442	407	136	125
Electrolyser stack efficiency (kWh/kg-H_2)	55	55	50	50
Hydrogen storage cost (USD/kg)	800	736	500	460
Ammonia synthesis cost (USD/kg)	0.63	0.58	0.50	0.46
Ammonia storage cost (USD/kg)	0.80	0.74	0.60	0.55
Air separation unit cost (USD/kg)	0.20	0.18	0.13	0.12
Discount rate	10%	12%	7%	9%

Other key assumptions for the calculation include:

- The costs are obtained from CSIRO Generation Cost[25] which contains estimated CAPEX based on projects in Australia. Thailand costs were then adapted using a location factor of 0.92 with respect to Australia due to its cheaper material and labour costs. (Australia location factor = 1)
    - A lower discount rate was applied to Australia in both the 2030 and 2050 cases as compared to Thailand, as Australia has a lower risk of investment due to its more favourable government policies for renewables development in the country.
    - As for the performance of the electrolyser, an efficiency gain of -5 kWh/kg-H_2 for the stack is projected for 2050 compared to 2030.
    - For import scenarios from Australia, the shipping and terminal costs were added to obtain the overall estimated landed cost. The shipping and terminal costs were calculated with an in-house model, taking into account distance (nautical miles (nm)), manoeuvring, expected annual transport volume, terminal (including storage) capacities and financial parameters.

The aim of the comparison is to demonstrate if domestic production in Thailand is more economical compared to production in Australia plus shipping cost for importing ammonia into Thailand. One of the key drivers is whether the more favourable capacity factor of solar and wind generation in Australia outweighs the cost required to ship the ammonia to Thailand.

The breakdown of the LCOA is shown in Figure 3-2. The LCOA consists of the total CAPEX and OPEX of each component throughout the lifetime of the plant divided by the total ammonia production discounted to the present. The cost of replacement of certain equipment such as the BESS has also been included since its lifetime is not as long as the other components such as solar panels and wind turbines. The hydrogen storage cost includes the storage tank as well as compressors.

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[25] Graham, P., Hayward, J., Foster J. and Havas, L. 2022, GenCost 2022-23: Consultation draft, CSIRO, Australia https://publications.csiro.au/rpr/download?pid=csiro:EP2022-5511&dsid=DS1

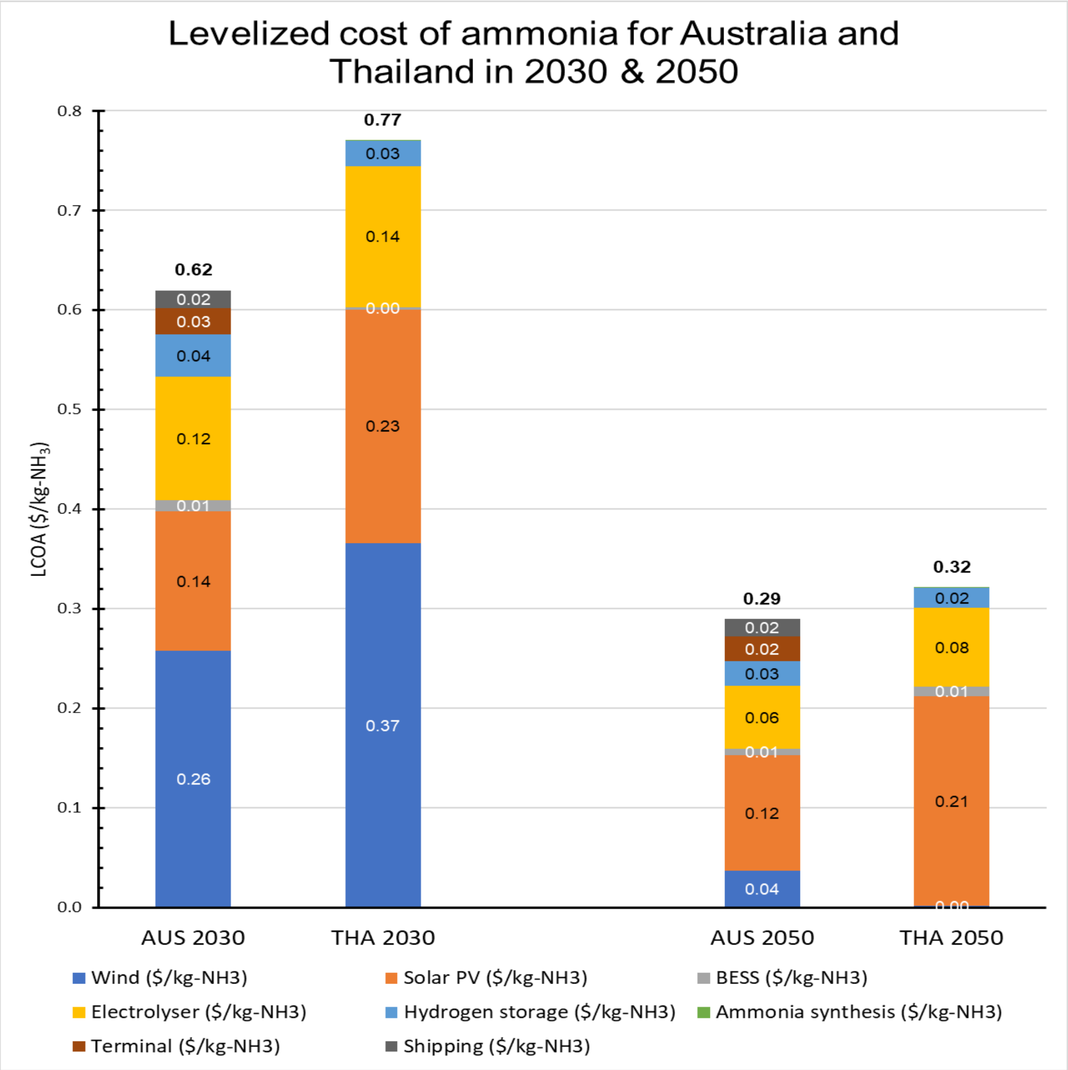

Figure 3-2. Levelized cost of ammonia in Thailand and Australia, 2030 and 2050

In 2030, the production and shipping cost of ammonia from Australia to Thailand is \$0.62/kg-NH$_3$, which is cheaper than the cost for local production in Thailand (\$0.77/kg-NH$_3$). Therefore the case of importing from Australia is competitive as the additional costs required for building the import and export terminals as well as shipping from Australia amounts to an increase of only \$0.05/kg-NH$_3$. The ammonia synthesis cost portion of the LCOA is small (< \$0.01/kg-NH$_3$) in comparison with the others, especially for 2050, and as such it is not visible in the bar chart.

The cost contribution of renewables portion towards the overall LCOA is 40 – 60% higher in Thailand as compared to Australia. The main reason is that larger wind and solar farms are needed in Thailand to obtain a similar quantity of energy compared to Australia. In Table 3-2, although the wind farm size in Thailand is 2.26 GW as compared to 1.66 GW in Australia for the 2030 case, they are both producing around the same amount of energy per year (~7 TWh). This is due to the higher capacity factor of 48% for the wind farm in Australia compared to 31% in Thailand. The same is the case for solar, whereby the capacity factor is 31% in Australia and 21% in Thailand.

The gap in production and import cost is significantly reduced for 2050, where Australia is priced at \$0.29/kg-NH$_3$ and Thailand at \$0.32/kg-

NH_3, bringing the Australia cost much closer to the Thailand case. This is because the difference in cost for all components between Australia and Thailand is smaller but the capacity factor is kept the same. The capacity factor is not expected to change significantly over the years as the same sites are used as comparison for both wind and solar. It could be argued that technological improvements could potentially change this, but this will not significantly impact the comparative results as both countries will have the same improvements by 2050.

The following similar trends are exhibited for both Australia and Thailand when comparing between 2030 and 2050:

- The renewable and electrolyser remain the two biggest cost drivers for both 2030 and 2050. The ammonia synthesis components, which consist of the air separation unit and Haber-Bosch reactor are almost negligible relative to the other components. The cost for the Haber-Bosch reactor also includes the costs required for auxiliary components such as the compressors required for the recycle stream.
- The proportion of solar PV and wind in Thailand decreases from a roughly 50:50 margin in 2030 to being almost entirely dominated by solar PV in 2050. Australia retains around 10% of its share of renewables from wind. One possible reason is the assumption on the solar PV price – the decrease in price is more than 50% for 2050, while for wind the projected decrease in price is around 20%. An optimization run was performed for the case where the solar PV price had a 25% decrease in 2050 instead of 50%. The LCOA amounted to \$0.43/kg-NH_3 with a 1.4 GW wind farm and 3.3 GW solar farm.

Table 3-2. Capacity of wind, solar, electrolyser and hydrogen storage in AUS (Geraldton) and THA (East Thailand)

Component	AUS 2030	THA 2030	AUS 2050	THA 2050
Wind	1.66 GW (51%)	2.26 GW (46%)	0.35 GW (10%)	0 GW (0%)
Solar PV	1.62 GW (49%)	2.61 GW (54%)	3.22 GW (90%)	5.5 GW (100%)
BESS	424 MWh	88 MWh	511 MWh	667 MWh
Electrolyser	1.68 GW	1.95 GW	2.46 GW	3.44 GW
Hydrogen Storage	395 tons	166 tons	420 tons	242 tons

Table 3-3. Cost components of different technologies in Australia and Thailand, 2030 and 2050

Component	AUS 2030	THA 2030	AUS 2050	THA 2050
Wind CAPEX (mil USD)	2,300	2900	383	0
Wind OPEX (mil USD/yr)	28	38	6	0
Solar CAPEX (mil USD)	1,266	1900	1120	1800
Solar OPEX (mil USD/yr)	13	21	26	45
BESS CAPEX (mil USD)	82	16	56	68
BESS OPEX (mil USD/yr)	1	0.3	0.8	1.8
Electrolyser CAPEX (mil USD)	741	795	335	431
Electrolyser OPEX (mil USD/yr)	19	20	8	11
Hydrogen storage CAPEX (mil USD)	567	200	210	181
Hydrogen storage OPEX (mil USD/yr)	3	1	2	1
NH_3 synthesis CAPEX (mil USD)	0.88	0.60	0.46	0.10
NH_3 synthesis OPEX (mil USD/yr)	0.002	0.002	0.002	0.002
Jetty & import terminal cost (mil USD)	50	-	50	-
Shipping CAPEX (mil USD)	75.5	-	60	-
Shipping OPEX (mil USD/yr)	12.4	-	10	-

In the case of 2030, the balancing technologies (BESS and hydrogen storage) is higher in Australia at 424 MWh compared to Thailand at 88 MWh. The optimizer selects the required sizes based on a least-cost approach. In Australia's case a larger BESS size leads to less wind and solar generation capacity being required, which minimizes the overall costs. The excess energy is stored at a period with low energy production. The lower capacity factor of wind and solar in Thailand on the other hand requires a larger solar and wind capacity to meet the energy requirement.

Higher BESS capacity is required in Australia due to the variability of wind generation profile as compared to Thailand as shown in Figure 3-3.

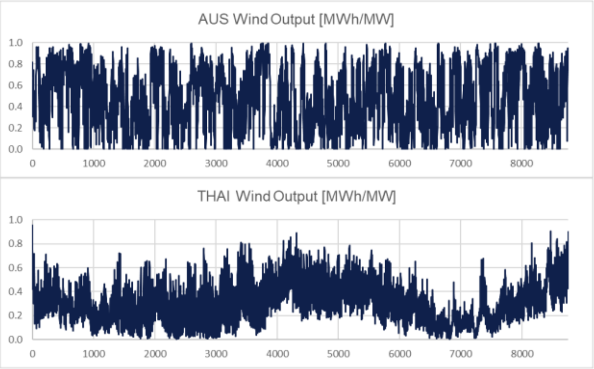

Figure 3-3. Hourly wind profiles for Australia and Thailand

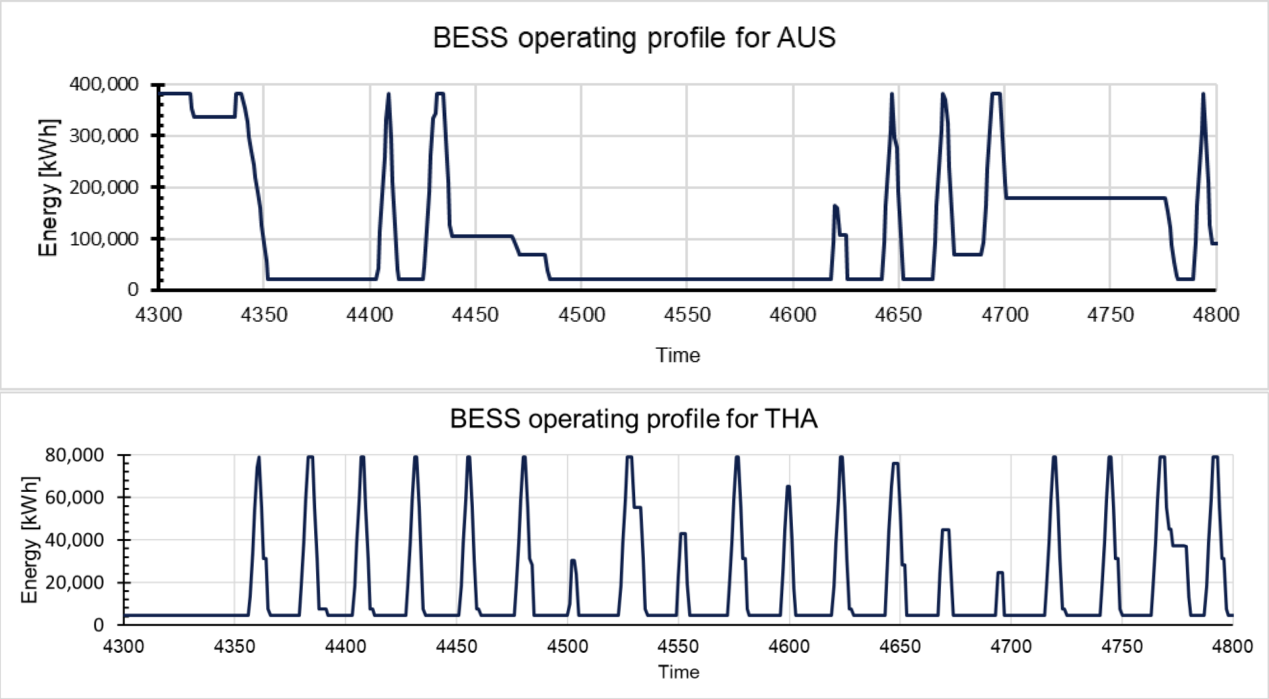

Figure 3-4. BESS operating profile over a 3-week period for Australia and Thailand

Based on the BESS state of charge profile throughout the year, BESS in Australia has fewer charge-discharge cycles compared to Thailand. **Error! Reference source not found.** shows a snapshot of the BESS operating profile for a three-week period, whereby the BESS in Australia shows a less consistent charge / discharge pattern. The longer periods in which the state of charge of the BESS is flat reflect that sufficient energy is produced by the wind and solar to be fed to the electrolyser. The BESS in Thailand on the other hand is used for daily storage whereby there is typically one full charge / discharge cycle per day to compensate for any excess / deficiency in energy.

The scenario is different for 2050, whereby there is no wind farm selected by the optimizer in Thailand due to its higher costs. The BESS in Thailand is thus larger than in Australia as a larger capacity is required to store excess energy during the day to operate the electrolyser during the night period.

The hydrogen storage is in the region of hundreds of tons for both Australia and Thailand. Similar to the BESS case, the hydrogen storage is larger in Australia compared to Thailand. The need for constant production of ammonia (minimum turndown of 40%) requires that sufficient quantity of hydrogen is stored in order to ensure a continuous supply. This strict requirement thus translates to a larger hydrogen storage. In practice, the amount of storage can be reduced by allowing for several stoppages of ammonia production throughout the year.

3.2 Comparison between Australia and Thailand for hydrogen production

A further case study was conducted to compare the case for domestic hydrogen production in Thailand with the production in Australia combined with conversion to ammonia as an energy carrier and a further cracking of ammonia back to hydrogen once in Thailand. Ammonia as an energy carrier is currently the most likely option despite the large inefficiencies of cracking ammonia back to hydrogen due to its commercial viability and mature supply chain compared to other modes of carrier such as liquefied hydrogen and liquid organic hydrogen carriers (LOHC).

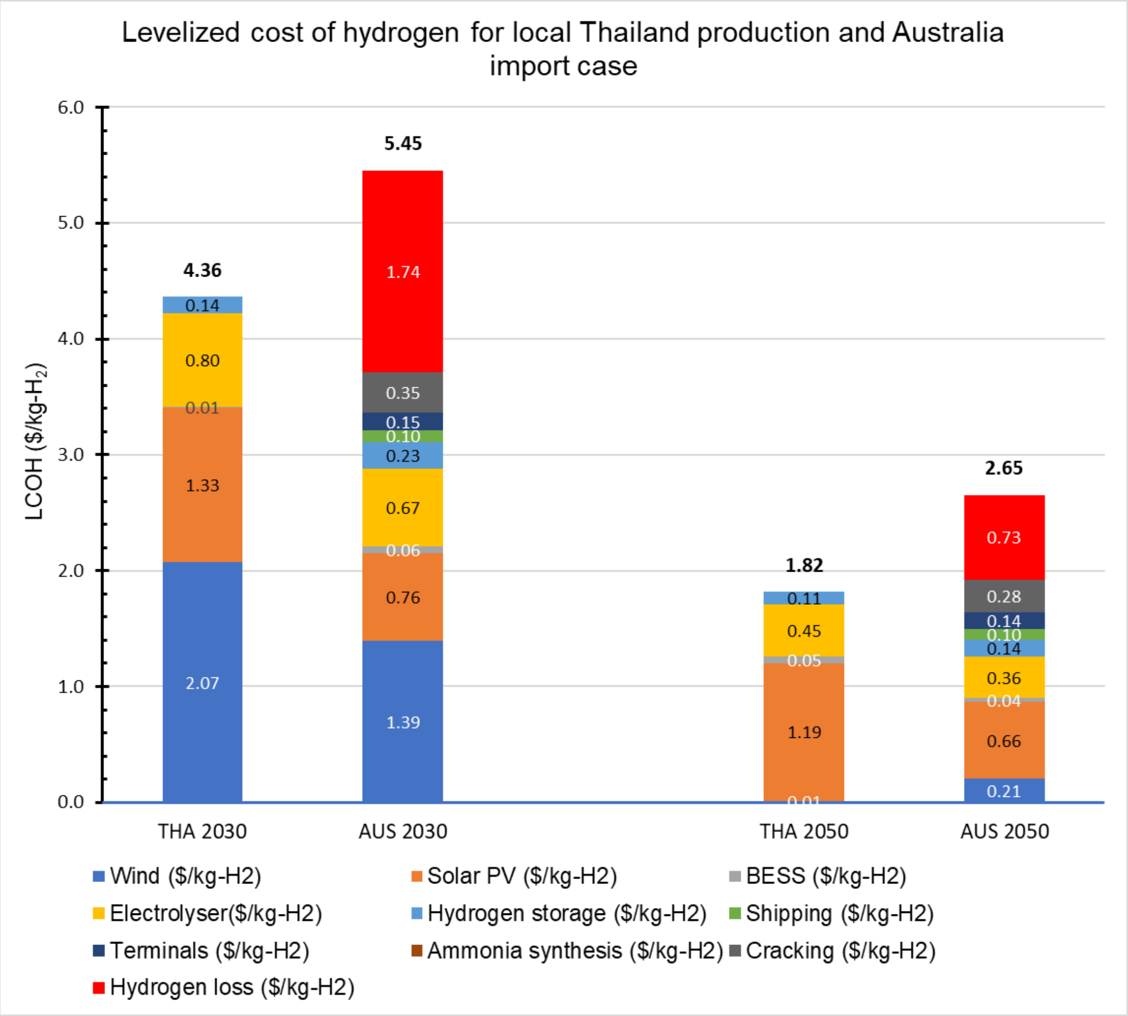

Figure 3-5. LCOH for production in Thailand and import from Australia

The LCOH shows the difference in cost between the two scenarios for a production of 176.5 ktpa of hydrogen (Figure 3-5). According to the mass balance, 1 mtpa of ammonia can be cracked to produce a theoretical maximum of 176.5 ktpa of hydrogen. However, due to losses in the hydrogen recovery process post-cracking, 1.43 mtpa ammonia is required instead to obtain that same amount of hydrogen. The losses in the case of Australia (shown in red) arise from the cracking process (including hydrogen recovery) of ammonia back to hydrogen. A hydrogen recovery rate of 70% was assumed. Without this cost, the hydrogen production cost alone is cheaper in Australia ($3.11/kg) compared to Thailand ($4.36/kg).

With the cracking inefficiencies as well as shipping and terminal costs included, the Australia cost rises to $5.45/kg compared to local green hydrogen production in Thailand at $4.36/kg for 2030. The difference in LCOH between Thailand and Australia in 2050 is smaller compared to 2030 but the economics still favours Thailand. The option of using ammonia as a hydrogen carrier, and then re-cracking it back to hydrogen upon landing is thus not economically favourable compared to domestic production. For this reason, current research efforts have focused on utilizing ammonia directly in applications such as power generation, as a fuel for direct firing, for instance, to avoid the inefficient cracking process.

Comparison of the LCOA and LCOH results suggests that different strategies are required depending on the end-product and year. For the case of green ammonia in 2030, it is more economical for Thailand to import ammonia from Australia rather than produce it domestically due to cheaper renewable resources in Australia. Over the long run however, Thailand should gradually shift towards domestically produced green ammonia due to the small difference in cost in 2050 and greater security of supply though this may prove challenging once committed to imports due to sunk costs of infrastructure such as import terminals. It may however be viable to service increasing demand using domestically produced ammonia based on the potential growth in the chemical and fertilizer industries that utilize urea in Thailand which would require a larger supply of ammonia feedstock. The same growth in urea demand in Australia would also mean greater domestic competition for ammonia, increasing the risk of insufficient supply for export. If supply becomes scarcer, Thailand could potentially play a role as a regional exporter if it produces its own ammonia, though from an economic standpoint, it does not look like it can compete with imports from other regions.

In the case of green hydrogen, it would make much more sense to produce domestically in Thailand due to the large losses associated with cracking the ammonia (hydrogen carrier) back to hydrogen. Thailand will likely adopt green hydrogen-firing in power generation and other industries in the future due to its higher technological readiness level (TRL) as compared to ammonia-firing. Although ammonia is cheap to transport and carbon free when combusted, it is less flammable and requires a higher ignition temperature compared to other fuels. Natural gas power plants can adopt hydrogen blending as a temporary measure and transition when turbines become 100% hydrogen-ready, whilst this blending has proven to be more challenging with ammonia in coal-fired power plants. The existence of centralized hydrogen storage in ammonia can also ensure a stable and continuous supply of hydrogen. As such, it would be worthwhile for Thailand to ensure that it has capabilities for domestic hydrogen production.

It is possible for Thailand to adopt ammonia blending with coal as a temporary decarbonization measure, but as the cost of domestic hydrogen production is lower than the cost of imported ammonia per unit of energy, the adoption of 100% ammonia blending or extending the lifetime of coal-fired power plants is not economically sensible. The consideration of 100% ammonia-fired power generation is primarily suitable for countries that are fully dependent on imports and cannot produce cost-effective hydrogen domestically, such as Japan, South Korea and Singapore. The option of importing ammonia should therefore not lead to Thailand deviating from its plans to phase out coal-fired power generation.

To delve deeper into these scenarios that are end-use and demand-dependent, a more thorough study is conducted in Chapter 6, where a deep dive into opportunities for green ammonia in Thailand across the power, industry, and transportation sectors with a traffic light analysis is conducted. A cost parity analysis is also performed to identify when green ammonia will be more cost competitive compared to BAU fuels/feedstock. From these results, the potential uptake and respective timeline can be estimated.

4 STANDARDS, CERTIFICATION AND ENVIRONMENTAL BENEFITS INCLUDING LCA OF GREEN AMMONIA – GLOBAL PERSPECTIVE

4.1 Introduction

There are numerous standards in existence or under development relating to low-carbon hydrogen. All seek to establish rules – some mandatory and some voluntary – relating to safety, performance or sustainability (including emissions) or combinations of these areas. Hydrogen as well as ammonia can be produced in many different ways – ranging from fossil fuels (with and without carbon capture and storage) to bioenergy, dedicated renewable electricity, and grid-connected electricity, each with different emission levels. Emissions in the production of hydrogen may also differ depending on the region of the world where, for example, different extraction of input feedstock have different approaches or efficiencies. Consequently, the greenhouse gas emissions associated with different production methods can vary significantly, based on the design and operation of green hydrogen production facilities and the overall value chains. Hydrogen standards determine particular sets of characteristics required of the hydrogen, with certification schemes supporting tracking of claims made and verification that may be made.

Certification schemes, on the other hand, are systems comprising various bodies, functions, and relationships that collaboratively establish conditions to be met. In the context of hydrogen, these conditions could be related to emissions footprint or other sustainability criteria. When these conditions are met, certificates are issued, containing details about the origin and attributes of the hydrogen. Schemes typically establish governance processes, verification expectations, and a tracking mechanism from issuance to retirement of the certificates. These certification schemes may incorporate hydrogen and potentially ammonia standards as a means of setting expectations for compliance. Adherence to standards and certification scheme rules may support claims that hydrogen is green, renewable or low carbon. Incentives may be contingent upon meeting certain standards.

However, currently there are no existing certification schemes specifically designed for ammonia, as most of them are still in the early stages of development and discussion. To the extent that there are standards, currently they originate from existing hydrogen certifications (i.e. GH2 Green Hydrogen Standard), where emissions intensity production thresholds that determine eligibility apply for both low-carbon and renewable hydrogen and ammonia as a derivative product. While this is a limitation, reference to hydrogen emissions intensity and sustainability standards and certification schemes offer an input to ammonia and a reference point on how rules may develop around the world.

In this chapter, ammonia standards and certification are explored in further detail through several sections:

- An overview of the challenge and the role of hydrogen standards and certification of attribution claims.
- A look at the different criteria emerging in standards and certification schemes around the world for green hydrogen and ammonia.
- Identification of certification schemes or taxonomy suitable for the Thailand context and expectations for their introduction, including considerations for treating the carbon emissions during seaborne trade.
- A high-level life cycle assessment (LCA) of green ammonia production under varying scenarios, especially on comparing domestic production vs. import pathway.

4.2 The role of hydrogen standards and certification of attribution claims

4.2.1 Hydrogen

The significance of attribution claims, particularly concerning emissions in hydrogen production, lies in the fact that not all hydrogen is low carbon. The provenance of hydrogen as well as ammonia production pathways can lead to varying degrees of greenhouse gas emissions (GHG) reduction, and some methods may even increase emissions compared to traditional fossil-based alternatives like coal, oil, or natural gas. Addressing this challenge is essential for meeting national emissions reduction goals and fulfilling international commitments like those outlined in the Paris Climate Agreement. To tackle this issue, standards, certificates, and certification schemes are employed to identify different attributes, allowing for appropriate rewards and incentives to be allocated accordingly. This becomes especially crucial when directing funding towards lower carbon technologies rather than others.

As shown in Figure 4-1, there are varying hydrogen production pathways each with different GHG emissions, which subsequently would impact the GHG emissions of the resulting ammonia produced from that hydrogen. These differences highlight the critical role played by standards in defining what qualifies as eligible. Based on DNV's Energy Transition Outlook[26], it can be seen from the chart that both high- and low-emission scenarios for each production pathway are comparable to one another and to the global average emissions from conventional fossil fuel as indicated by the red dotted lines. Notably, yellow hydrogen (hydrogen produced from grid electricity) exhibits the most significant disparity between high and low values, reflecting the differences worldwide, where certain electricity networks heavily rely on renewables while others still predominantly depend on fossil fuels.

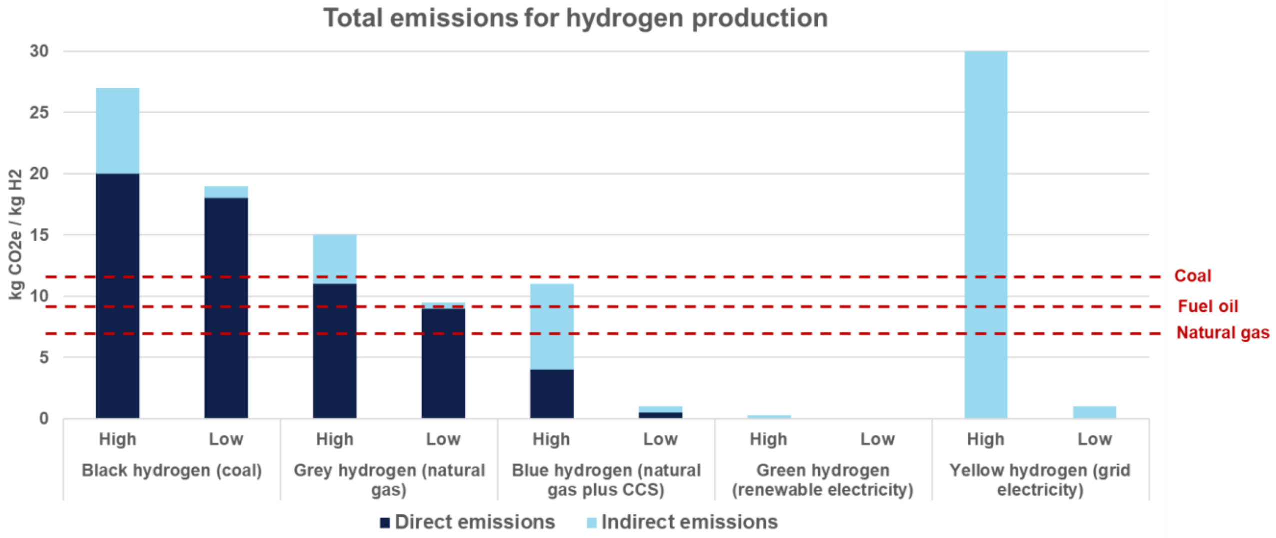

Figure 4-1. Direct and indirect emissions from different hydrogen production pathways (Source data: DNV Energy Transition Outlook)

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[26] DNV Energy Transition Outlook 2022

4.2.2 Ammonia

As ammonia is a hydrogen derivative, the main emissions are related to hydrogen production (which was touched upon in the previous sub-section), with added emissions associated with the ammonia production itself. The main technology used for ammonia production is the Haber-Bosch process. As mentioned in the overview chapter, the Haber-Bosch process, developed in the early 20th century, remains the predominant method for ammonia synthesis even to this day. The main difference from a process perspective between the conventional ammonia production pathway compared to lower carbon ammonia production pathways would be in the hydrogen production.

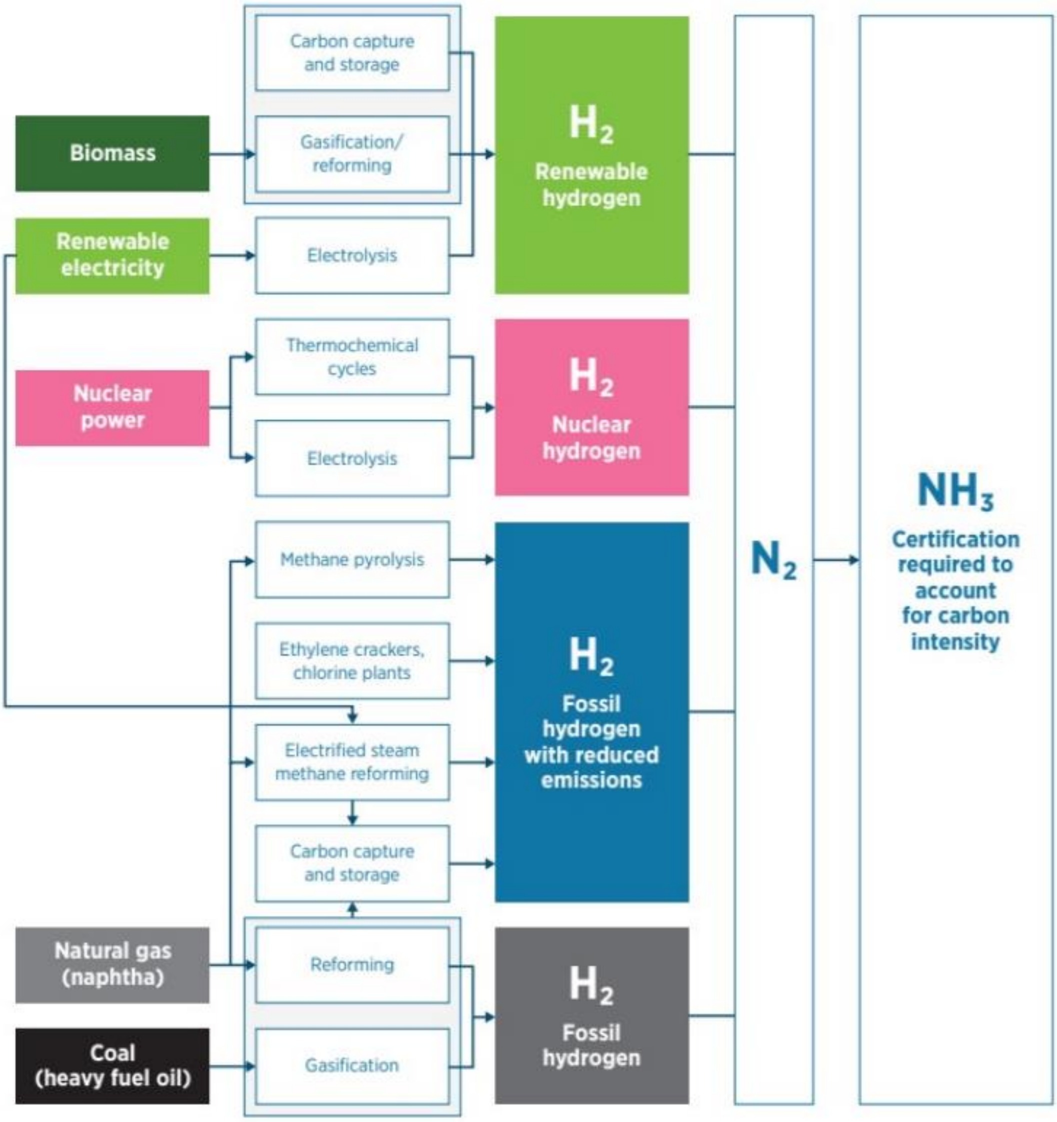

Figure 4-2. Different ammonia production pathways (Ammonia Energy Association, 2022)[27]

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[27] AEA Certification Initiative – Ammonia Energy Association

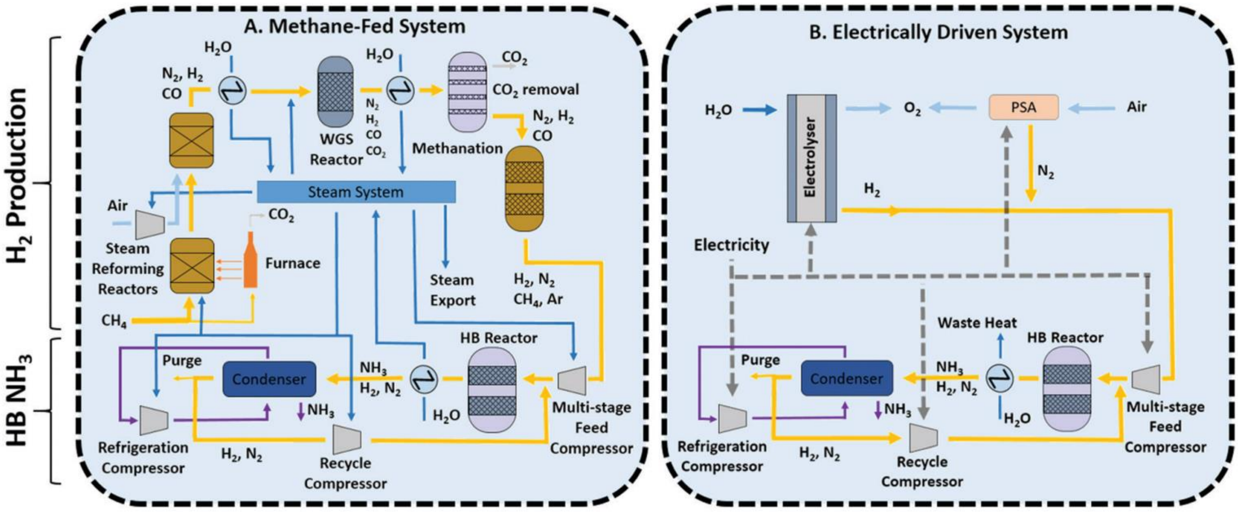

Figure 4-3. Schematic diagram of A. methane-fed system (conventional) and B. electrically driven system Haber Bosch process (Source: Current and future role of Haber-Bosch ammonia in a carbon-free energy landscape, 2020)[28]

The two most distinctive production pathways are a conventional methane-fed system or an electrically driven system where hydrogen is produced via electrolysis (**Error! Reference source not found.**). The electrically driven system GHG emissions would mainly depend on the electricity grid emission used. Therefore, if electricity from fossil fuels is used for producing hydrogen from water electrolysis, it would result in a higher life cycle GHG emissions compared to the natural gas steam methane reforming pathway.

For the electrically driven system, emissions are primarily related to the electricity supply source. The latest GH2 standard published in early 2023 lists the emission factors that should be applied for electrolysis, with the expectation that the same standards would be applied to green ammonia production. Emissions are expected to come mainly from electricity consumption, followed by fugitive emissions, and refrigerant emissions. Process units that contribute to these emissions would be the air separation unit, syngas compression, Haber Bosch process, and cooling shown in **Error! Reference source not found.**.

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[28] Smith, C., Hill, A. K., & Torrente-Murciano, L. (2020). Current and future role of Haber-Bosch ammonia in a carbon-free energy landscape. *Energy & Environmental Science*, *13*(2), 331-344.

Table 4-1. GHG emissions summary for green ammonia according to GH2 standard (GH2, 2023)[29]

Process unit/stage	Key emissions sources	Other emissions sources
Air separation unit	• Electricity consumption for relevant units	
Syngas compression	• Electricity consumption for relevant units • Fugitive emissions	
Haber-Bosch (HB)	• Electricity consumption for relevant units • Fugitive emissions	
Cooling	• Electricity consumption for relevant units	HFC (or other refrigerant) emissions

The environmental impact of ammonia production is therefore influenced by several key factors, particularly the energy usage in the production process. This energy consumption depends on how nitrogen and hydrogen are sourced, with methods like cryogenic distillation or pressure swing adsorption for nitrogen and various techniques for hydrogen production such as low-temperature electrolysis, high-temperature electrolysis, and by-product utilization. If electricity is sourced via electricity network as opposed to dedicated generation, then the emissions grid factor of the electricity used, along with potential emissions from leakage and refrigerant usage, plays a role in the overall environmental footprint of ammonia production. For example, a study by Bicer & Dincer [30] as seen in Table 4-2 calculates greenhouse gas emissions (including scope 3 upstream emissions) for different electricity sources used.

Table 4-2 GHG emissions of green ammonia with varying energy sources (Bicer & Dincer)

Electricity source	GHG footprint [kg CO_2-eq/kg NH_3]
Hydropower	0.38
Nuclear	0.84
Biomass	0.85
Municipal-waste based	0.34

The calculation shows varying emissions results of 0.38 kg CO_2-eq, 0.84 kg CO_2-eq, 0.85 kg CO_2-eq, and 0.34 kg CO_2-eq per kg/kg NH_3 for hydropower, nuclear, biomass, and municipal waste-based methods respectively.

In summary, hydrogen standards and certification schemes are important to reduce uncertainty in the different emissions or other sustainability imperatives in different production pathways (or for more a comprehensive system boundary that encompasses production, transport and use).

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[29] GH2 Standard 2023 – The Global Standard for Green Hydrogen and Green Hydrogen Derivatives including Green Ammonia

[30] Bicer, Y., & Dincer, I. (2017). Life cycle assessment of nuclear-based hydrogen and ammonia production options: A comparative evaluation. *International Journal of Hydrogen Energy, 42*(33), 21559-21570.

4.3 Emerging hydrogen and ammonia certification schemes around the world

No ammonia certification schemes currently exist, as most are still in the stages of discussion and formulation. To circumvent this issue, an approximation can be derived using the certification scheme that currently exists for hydrogen. This is done by multiplying a factor which quantifies the amount of hydrogen that can be extracted from 1 kg of ammonia. While for hydrogen certification schemes,

Table **4-3** shows various certifications (both voluntary and mandatory) at national and global level that are already emerging to define and promote low-carbon and renewable hydrogen.

Table 4-3. Examples of voluntary and mandatory hydrogen standards and certification schemes

Public regulatory schemes		Private voluntary schemes	
🇪🇺	REDII EU Taxonomy for Sustainable Activities	🌐	Global Green Hydrogen Standard ISCC Plus
🇬🇧	Low Carbon Hydrogen Standard Renewable Transport Fuel Obligation	🇪🇺	CertifHy TÜV SÜD / TÜV Rhineland
🇯🇵	Aichi Prefecture Certification Scheme	🇯🇵	Clean Fuel Ammonia Association
🇺🇸	Low Carbon Fuel Standard Clean Hydrogen Production Standard	🇬🇧	Green Gas Certification Scheme (biomethane)
		🇨🇳	China Hydrogen Alliance Standard

These standards are designed to provide information on the emissions footprint of the hydrogen value chain – from production, transportation to end use. Certification will be necessary to encourage the adoption of hydrogen for decarbonization efforts and to facilitate the implementation of carbon border adjustment measures. Amongst these standards, the Green Hydrogen Organization (GH2) Green Hydrogen Standard, Smart Energy Council Zero Carbon Certification Scheme, and CertifHy from TÜV SÜD / TÜV Rhineland extends its certification to ammonia as well.

Criteria imposed by these certification schemes differ in scope, encompassing diverse emissions thresholds and accounting approaches. As a consequence of the multiplicity of schemes, the same labels such as 'clean hydrogen' or 'green hydrogen' may encompass different characteristics or attributes under various certification frameworks.

Among the most impacting differences between standards is the emissions intensity required for eligible pathways as shown in Figure 4-4. Another critical issue and point of differentiation between standards relates to the requirements on additionality - new renewable electricity generation - including when and where that is generated in relation to the hydrogen. As well as emissions and electricity provenance, there may also be requirements relating to water and a more encompassing set of environmental, social and governance imperatives.

The Ammonia Energy Association (AEA) is currently developing a certification scheme for ammonia to be operational by 2024. Other schemes or iterations of this scheme are expected as the industry matures. The scheme aims to provide a globally harmonized framework for the accounting, reporting, and verification of the carbon intensity of ammonia in an absolute value (tCO_2e/tNH_3). The main goal of the certification scheme is to certify the absolute well-to-gate emissions, which include scopes 1, 2, and upstream 3 emissions. Additionally, there is an option for optional certification of Well-to-Tank or Well-to-Wheel/Wake emissions.

The AEA proposes this minimum boundary of Well-to-Gate certification with the possibility of expanding the boundaries as needed. This approach ensures the development of a certification system that is suitable for multiple customer types, such as producers, traders, retailers, and end-users, operating in different and potentially conflicting sectors or jurisdictions. The certification scheme adopts the definitions of GHG emissions scope according to WRI/WBCSD GHG protocol definitions for scope 1, 2, and 3 emissions. Key methodological references for this certification are listed in Table 4-4.

Table 4-4. Key methodological references for AEA's Ammonia Certification (under development)

References
• 2006 IPCC guidelines for national greenhouse gas inventories • IFI TWG – AHG-003 International Financial Institutions Guideline for a Harmonized Approach to Greenhouse Gas Accounting, v0.2.0 INTERIM, June 2021
Standards
• ISO 14064-1:2018 Greenhouse gases — Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals • ISO 14064-2:2019 Greenhouse gases — Part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements • ISO 14064-3:2019 Greenhouse gases — Part 3: Specification with guidance for the verification and validation of greenhouse gas statements

- ISO 14066:2011 Greenhouse gases — Competence requirements for greenhouse gas validation teams and verification teams
- ISO 14067:2018 Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification
- ISO/CD 14083 Greenhouse gases — Quantification and reporting of greenhouse gas emissions arising from operations of transport chains
- ISO 19694-1:2021 Stationary source emissions — Determination of greenhouse gas emissions in energy-intensive industries — Part 1: General aspects ISO 20951:2019 Soil Quality — Guidance on methods for measuring greenhouse gases (CO_2, N_2O, CH_4) and ammonia (NH_3) fluxes between soils and the atmosphere
- ISO/TR 27912:2016 Carbon dioxide capture — Carbon dioxide capture systems, technologies and processes
- ISO/TR 27915:2017 Carbon dioxide capture, transportation and geological storage — Quantification and verification

In addition to new ammonia standards, there are also hydrogen standards being adapted to provide initial guidance on the ammonia production step. It is advisable to maintain a close watch as to how this area develops. For instance, the Green Hydrogen Organization announced in early 2023 that the new updated Green Hydrogen Standard[31] emissions threshold for green ammonia would be 0.3 kg CO_2/kg NH_3. (in addition to the 1kg CO_2/kg emission threshold the Standard has for green hydrogen production). The Standard itself is in the process of being reviewed, with version 2.0 expected to be launched late 2023. Another standard currently being developed is the ISO/WD 19870 on "Methodology for determining the greenhouse gas emissions associated with the production, conditioning and transport of hydrogen". This is using work developed by the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) and is a work within the ISO TC 197/SC 1/WG 1 - which aims to standardize the GHG calculation methodology.[32]

It is possible that standards in development and those coming present more rigorous rules relating to renewable energy generation and stronger environmental, social and governance requirements. Existing rules may also be tightened.

Alignment with the European Union Renewable Energy Directive and its Delegated Acts presents the lowest risk option for Thailand and would ensure that hydrogen and green ammonia produced and used to manufacture low carbon products destined for European markets would not be penalized under the EU's Carbon Border Adjustment Mechanism. With this set of rules presenting the most rigorous hydrogen standard in operation today, compliance here would likely mean compliance with other standards in other jurisdictions. In light of there being few standards relating to ammonia, consideration of the Green Hydrogen Organization's ammonia standard is recommended at this time.

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[31] GH2 Standard 2023 – The Global Standard for Green Hydrogen and Green Hydrogen Derivatives including Green Ammonia

[32] ISO/DTS 19870 - Hydrogen technologies — Methodology for determining the greenhouse gas emissions associated with the production, conditioning and transport of hydrogen to consumption gate

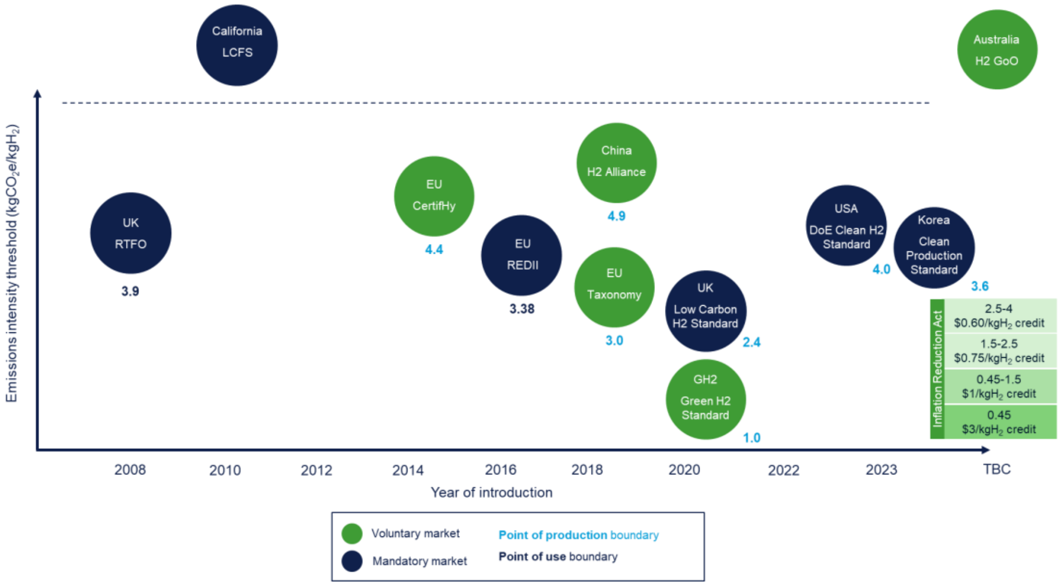

Figure 4-4. Timeline of voluntary and mandatory emissions standards (Source: IRENA, DNV)[33]

Taxonomies can help ensure capital flows into clean energy projects and technologies, away from unabated or emissions-intensive fossil fuel activity. There are many taxonomies in place or in the design stage around the world, see Figure 4-5. Within taxonomies, colour systems are often employed to distinguish economic activities or products to be recognized for their environmental compliance (typically green activities) or for being on the pathway to compliance (amber activities). Other systems include designation of different activities as net zero compliant or as energy transition activity. While there is no obligation on companies to be taxonomy aligned, many finance market participants looking for green and sustainable investments will rely on it and momentum is expected to build over time.

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[33] Notes: California Low Carbon Fuel Scheme and the Australian Guarantee of Origin certificate do not have specific emission intensity thresholds and so cannot be plotted on the Y axis. EU = European Union; GH2 = Green Hydrogen Organisation; H2 GoO = Hydrogen Guarantee of Origin; LCFS = Low Carbon Fuel Standard; RED II = Renewable Energy Directive II; RTFO = Renewable Transport Fuel Obligation; TBA = To be announced; USA DOE = US Department of Energy.

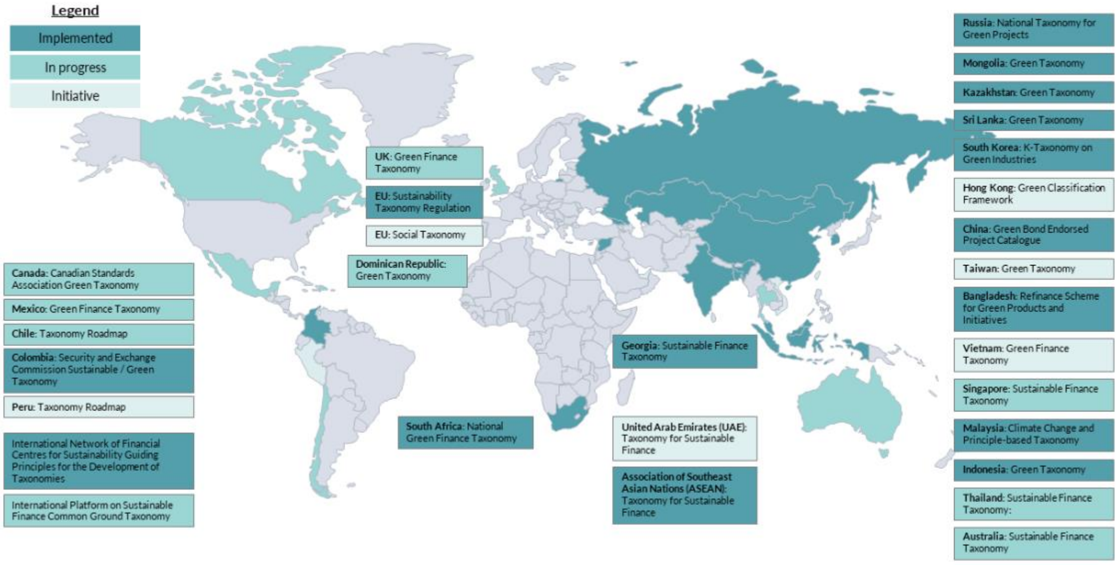

Figure 4-5. Overview of green taxonomies and their various stage of development (Source: EcoFact)

4.4 In-depth study of certification schemes and taxonomies emerging or in place in key markets

This section examines the hydrogen emissions and sustainability standards and certification schemes in key markets, focusing on the European Union, Australia, and the United States of America (USA). Consideration is first given to European Union (EU) policy relating to hydrogen provenance standards and certification. This is done for the reference point it provides for countries where rules are incomplete, rather than constituting an export market with which to ensure alignment. International, non-jurisdictional developments are also considered to inform the discussion. Australia is also considered as it would be the most likely green hydrogen and ammonia exporter to Thailand.

4.4.1 European Union

Table 4-5. EU hydrogen requirements

Standard	Applicability	Emissions	Electricity
RED II (Delegated Acts)	Renewable hydrogen only	Below 28.2 g CO_2e/MJ (equivalent to 3.4 tonnes CO_2e per tonne H_2). Point of use, so include the transport of hydrogen, and derivative processing	Additionality: From 2028, new and unsubsidized renewable generation required must be installed no more than 3 years before the electrolyser starts operation. The relationship can be via direct line or PPA. No additionality requirement if bidding zone has more than 90% renewables Temporal matching: Until 2030 hydrogen must be produced within the same month as electricity generation. After 2030, must be matched to within the hour. If the bidding zone has more than 90% renewables, no temporal matching required Geographic matching: Grid-connected electrolysers must be in the same bidding zone as the RE asset or in an interconnected bidding zone if the day-ahead market price in the interconnected zone is equal or higher

EU Taxonomy for Sustainable Activities	All low carbon hydrogen production methods	3 tonnes CO_2e per tonne H_2 (equivalent to 25 g CO_2e/MJ) Point of use	No additionality requirement No temporal correlation specified

The different European Union standards of the Renewable Energy Directive (RED II) and EU Taxonomy relate to different policy areas and have different objectives. The former relates to renewable energy while the latter is a classification system to support financial decision-making, determining what is a sustainable economic activity. RED II provides the basis for eligibility under the European Union's renewable energy targets. Grey hydrogen is produced in the EU already, but this is not eligible under the RED and so does not count towards the renewable energy target. The EU Taxonomy Regulation designates different types of financial investments as sustainable or not. It is intended to provide policymakers, companies, and investors with definitions for different activities, signalling which economic activities are sustainable as a means of supporting the flow of money to that which is more sustainable. The policy schemes should align in terms of hydrogen. For example, green hydrogen produced from additional renewables in the EU could be expected to meet the RED II requirements (falling below the emissions thresholds and meeting the requirements of the RED II Delegated Acts) and would meet the technical criteria of the EU Taxonomy relating to electrolysed hydrogen, also falling below this directive's emission thresholds.

The EU’s REPowerEU plan targets a 45% renewable energy share by 2030. As part of the RePowerEU package of May 2022, the bloc has a target of 10 million tonnes of green hydrogen production within the EU in 2030, together with 10 million tonnes of green hydrogen imports. This boosts their hydrogen strategy targets of 6GW electrolyser capacity by 2024 and 40GW by 2030. There are also targets and a policy aimed at specific sectors including for renewable fuels of non-biological origin (RFNBO) by 2030 of 75% for industry and 5% for transport. Hydrogen must meet the RED II standard for it to be counted towards the 20 million tonnes of hydrogen target the bloc has.

The RED II determines eligible hydrogen as that below 28.2 g CO_2e/MJ (equivalent to 3.38 tCO_2e/tH_2). The definition of renewable hydrogen was arrived at in February 2023 after considerable negotiation. As set out in Table 4-5, the Delegated Acts set requirements for additional renewable electricity generation, including when and where that is generated in relation to the hydrogen. These requirements must be adhered to for hydrogen produced in the EU to meet its target and any that is imported.

After 2041, industrial CO_2 sources will not be considered as avoided in the production of renewable fuels of non-biological origin (RFNBOs) with this date coming forward to 2036 in the case of CO_2 arising from the production of electricity. Encouraged CO_2 sources (and those eligible after 2041) are CO_2 captured from direct air capture, from biogenic (sustainability compliant) or geological sources (releasing naturally) or captured from the combustion of RFNBOs or Recycled Carbon Fuels (RCFs). Industrial CO_2 point sources will no longer be eligible inputs for e-fuels from 1 January 2036 when the CO_2 source is from the combustion of non-sustainable fuels for production of electricity, and up until 1 January 2041 in other cases for CO_2 arising from combustion of fuels for electricity generation. Direct air capture CO_2 or that from biogenic or geological sources are intended to be the only eligible route after 2041.

A methodology for determining greenhouse gas savings from renewable liquid and gaseous transport fuels of non-biological origin and from recycled carbon fuels has been established as part of RED II[34]. The methodology has requirements for each processing step (emissions from supply of inputs, from processing, from transport and distribution, from combustion of the fuel in its end-use). Emissions from the manufacture of machinery and equipment are not to be taken into account. If at any point in the supply chain a fuel is a mix of RNFBO, Recycled Carbon Fuels (RCF) and other fuels, all fuel types are deemed to have a singular emissions saving. This figure is arrived at as follows:

$Savings = (E_F - E) / E_F$

Where:

E = the total emissions from the use of renewable liquid and gaseous transport fuel of non-biological origin or recycled carbon fuel

E_F = total emissions from the fossil fuel comparator of 94 g CO_2eq/MJ.

The exception to this is in the case of co-processing where renewable liquid and gaseous transport fuels of non-biological origin and recycled carbon fuels are only partially replacing a conventional input in a process. In this instance, greenhouse gas emissions intensity is calculated on a proportional basis of the energetic value of the different inputs. An example of this exception is where renewable hydrogen is used in a refinery to remove impurities during hydro treating processes where the use of the hydrogen is not adding to the heating value of the fuels. RED II establishes that only the share of intermediate product that is used for the production of conventional transport fuels will be considered.

Pending recognition by the European Commission, CertifHy will be an EU Voluntary Scheme for the purposes of certification of hydrogen as RFNBO, compliant with RED II and the RED II Delegated Acts requirements. The certification process is set out below.

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[34] European Commission Delegated Regulation (EU) 2023/1185 'Annex to the Commission Delegated Regulation supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a minimum threshold for greenhouse gas emissions savings of recycled carbon fuels and by specifying a methodology for assessing greenhouse gas emissions savings from renewable liquid and gaseous transport fuels of non-biological origin and from recycled carbon fuels'. Available at: https://energy.ec.europa.eu/system/files/2023-02/C_2023_1086_1_EN_annexe_acte_autonome_part1_v4.pdf (accessed September 2023).

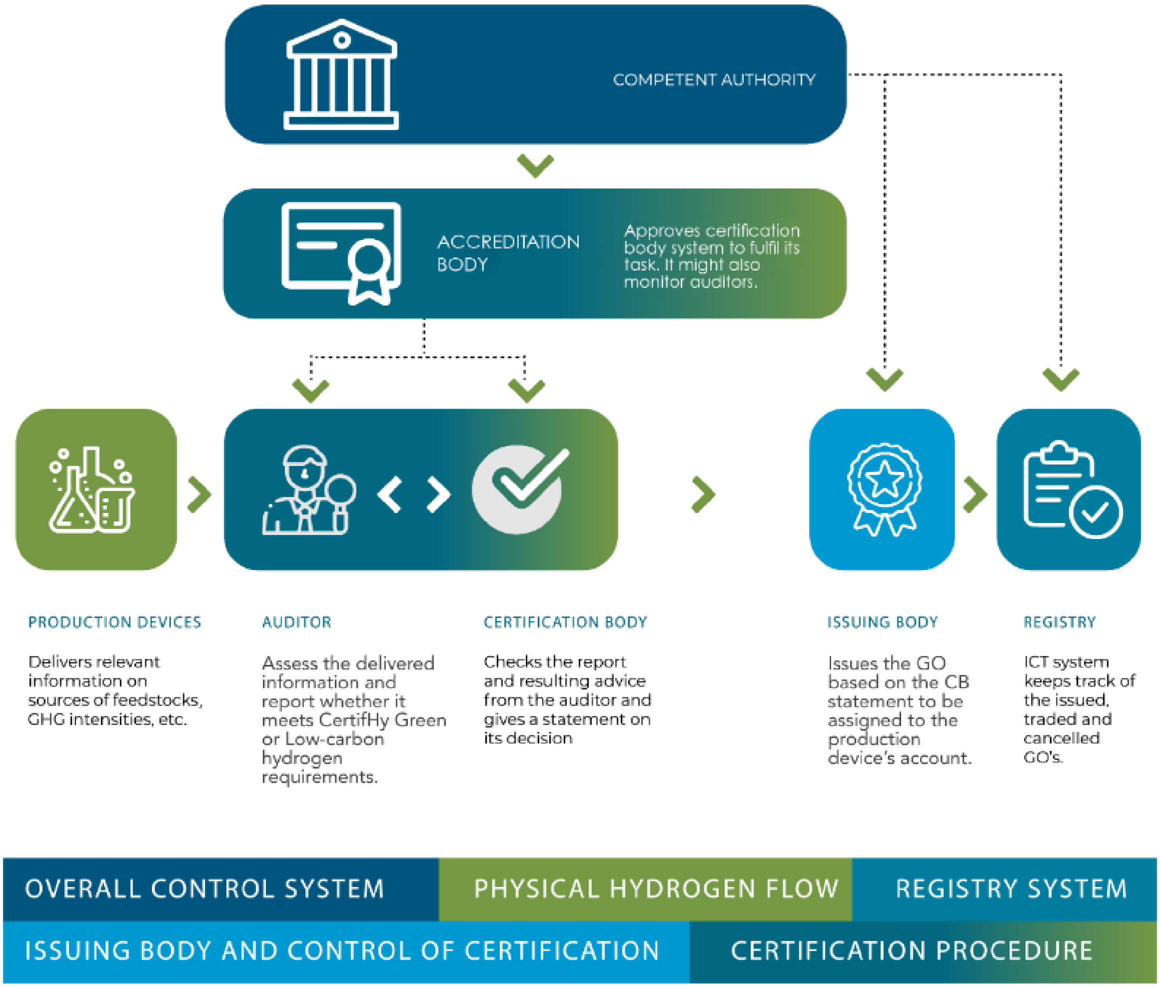

Figure 4-6. Certify certification process

The European Union currently has the most detailed sustainable finance taxonomy. Entering into force in 2020, Regulation (EU) 2020/852 'the Taxonomy Regulation' establishes the basis for the EU taxonomy by setting out the overarching conditions that an economic activity must meet to qualify as environmentally sustainable. It is the cornerstone of the EU Sustainable Finance Action Plan and will inform forthcoming regulatory initiatives including the EU Green Bond Standard and the EU Ecolabel for retail investment funds. The Taxonomy Regulation establishes six environmental objectives:

- Climate change mitigation
- Climate change adaptation
- The sustainable use and protection of water and marine resources
- The transition to a circular economy
- Pollution prevention and control, and
- The protection and restoration of biodiversity and ecosystems

Under the Taxonomy Regulation, the European Commission was required to define technical screening criteria for each environmental objective through delegated acts. The Commission Delegated Regulation (EU) 2021/2139 of June 2021 includes technical criteria relating to the manufacture of hydrogen. Here mitigation measures are eligible under the taxonomy provided that they meet the emissions thresholds of 3 tCO_2e/t H_2.

The EU taxonomy also requires a 'Do No Significant Harm' assessment to be undertaken. In addressing hydrogen concerns, attention must be given to climate change adaptation, sustainable use and protection of water and marine resources, pollution prevention and control (adhering to best available techniques for chlor-alkali production, common wastewater and waste gas treatment/management systems, or the refining of oil and gas). Requirements relating to the protection and restoration of biodiversity and ecosystems must also be adhered to. There are no requirements relating to renewable electricity usage. There is no temporal or spatial correlation required.

Separate technical screening criteria exist for manufacture of anhydrous ammonia, storage of hydrogen and transmission and distribution networks for renewable and low-carbon gases. Hydrogen is part of many other specified activities. CO_2 storage may also be eligible where this would otherwise be emitted from the manufacturing process if captured for the purpose of underground storage.

4.4.2 Australia

In 2022 Australia legislated a 43% reduction in greenhouse gas emissions by 2030 (relative to 2005 levels) and for net zero emissions by 2050. Australia has no specific targets for hydrogen production and no standard against which hydrogen is deemed eligible or not, low carbon or not, in respect of any targets. Two certificate schemes are being developed to attribute claims relating to hydrogen production and its supply chain to help ensure accountability. These two schemes are the Guarantee of Origin certificate and the Zero Carbon Certification Scheme.

Guarantee of Origin certificate

This certificate is being designed by the federal Commonwealth Government's Department of Climate Change, Energy, the Environment and Water (initiated by the former Department of Industry, Science, Energy and Resources) to be administered by the Clean Energy Regulator.

The certificate is currently in a trial phase, expected to continue until the end of 2023, with 28 pilot projects currently involved. Further industry consultation will take place over the coming years to inform final scheme design, legislation, with implementation then to follow in 2024-2025.

The latest proposals are to create 'Product Guarantee of Origin certificates' which will cover hydrogen as well as other low emission commodities. Certificates will indicate the emissions of hydrogen and allow for other details to be included such as water sources and their sustainability. The certificates are technology agnostic and will support green and blue hydrogen production routes. The system boundary is cradled to user. As illustrated in Figure 4-7 this encompasses raw material supply, transport, production, product transport and use. The International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) methodology is to be adhered to.

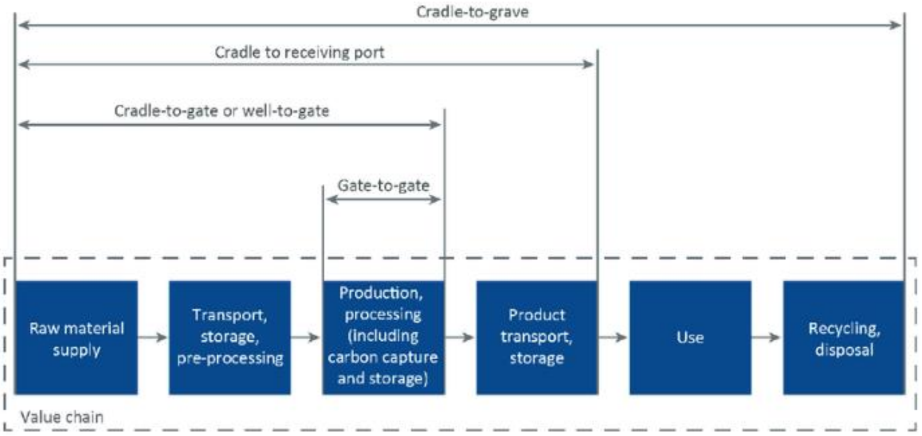

Figure 4-7. Hydrogen system boundaries[35]

Zero Carbon Certification Scheme

This alternative scheme is being designed and administered by industry bodies Smart Energy Council and Hydrogen Australia. The trial phase is underway with the first project receiving formal certification in February 2022 and subsequent trials now taking place. The scheme covers hydrogen produced from renewable energy only (including electrolysis using grid supplied electricity with a renewables PPA). The system boundary is cradle to gate. The embedded carbon of derivatives such as renewable ammonia and renewable metals will be covered. As well as a certificate, a certification body and registry will be created allowing for trading nationally and internationally.

An Australian sustainable finance taxonomy is in development, being led by the Australian Sustainable Finance Institute (ASFI). Building on work done on sustainable finance taxonomies internationally, including by the EU, the Common Ground Taxonomy (which compares EU and China taxonomies and can act as a reference point for others being developed), Japan and in Singapore, work in Australia is underway to determine what a sustainable finance taxonomy should look like to ensure international credibility and interoperability while reflecting the Australian economy and context. The ASFI has formed a SteerCo made up of key financial market stakeholders, government and regulators who will provide strategic direction and oversight of the taxonomy project. Members include IFM Investors, Commonwealth Bank, NAB, IAG, and Clean Energy Finance Corporation. Development is taking place in stages with Phase 1 focused on key framework design elements for an Australian sustainable finance taxonomy. Deliverables include:

- A scoping paper of international taxonomies, released October 2022, which analyzed Australia's economic and environmental context, key international taxonomies, and implications for taxonomy development in Australia
- A recommendations paper on the key design elements for an Australian taxonomy, published March 2023, and
- Analysis and case studies to inform the methodology for integrating transition activities in an Australian taxonomy.

Phase 2 commences in July 2023 and will encompass the development of taxonomy screening criteria for at least 3 priority sectors. The required technical work on data requirements, methodology for incorporating transitional activities, minimum social safeguards and a 'Do No Significant Harm' framework will be developed. This phase of work will be co-funded by the Commonwealth Government. As of early-May 2023 the priority sectors have not yet been identified.

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[35] W. Cheng and S. Lee 'How Green Are the National Hydrogen Strategies?' 2022 *Sustainability* 14(3):1930

Table 4-6. USA hydrogen requirements

Standard	Applicability	Emissions	Electricity
US Clean Hydrogen Production Standard	All low carbon hydrogen production methods	Lifecycle greenhouse gas emissions of 4.0 kg CO_2e/kg H_2 (credit is greater where hydrogen is lower carbon).	Electricity requirements still to be determined, expected by Q3 2023.

4.4.3 USA

The United States of America has a target to reduce greenhouse gas emissions by 50-52% by 2030 (relative to 2005 levels) and has considerable policies in place relating to hydrogen to help achieve this. Published in June 2023, the US National Clean Hydrogen Strategy and Roadmap establishes three strategies to achieve its national decarbonization goals. These are to target strategic, high-impact uses of clean hydrogen, reduce the cost of clean hydrogen and to focus on regional networks[36]. The Inflation Reduction Act 2022 (IRA) is at the centre of the policy being implemented to support the development of hydrogen with changes to the Unites States Internal Revenue Code creating a ten-year tax credit for hydrogen production as well as enabling 'direct pay', meaning that tax liability is not required to receive a refund from the Inland Revenue Service – in effect making this a production incentive.

The Clean Hydrogen Production Standard (CHPS) adopts a cradle to gate system boundary within which lifecycle greenhouse gas emissions must equal or be less than 4.0 $kgCO_2e/kgH_2$[37]. As such, this includes upstream processes such as electricity generation, fugitive emissions, and downstream processes associated with ensuring that CO_2 produced is durably sequestered. CHPS is not a regulatory standard and the Department of Energy (DOE) may not require future funded activities to achieve the standard. However, hydrogen hubs funded under the IRA will need to "demonstrably aid achievement" of the CHPS by mitigating emissions across the supply chain and the DOE has indicated that it will prioritize applicants to the H2Hubs that do so. It is also possible that future Department of Energy funding is limited to projects where the CHPS is being met.

While no national taxonomy is known to be in development in the USA, there are growing calls for its consideration. The USA Commodity Futures Trading Commission (CFTC) Climate-Related Market Risk Subcommittee of the Market Risk Advisory Committee released a report in September 2020 titled 'Managing Climate Risk in the US Financial System'[38]. Among many other recommendations, the subcommittee called for the development of a classification system or taxonomy to support risk management.

4.4.4 International, non-jurisdictional developments

Selected organizations are proposing voluntary standards to accelerate the production, transport and utilization of hydrogen. These are not geographically constrained and may provide a suitable option for organizations operating in countries where there are no applicable standards or certification systems.

With its Green Hydrogen Standard, the Green Hydrogen Organization has one of the lowest emissions thresholds with a limit of 1.0 kg CO_2e

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[36] U.S. Department of Energy (2023) 'US National Clean Hydrogen Strategy and Roadmap' available at: https://www.hydrogen.energy.gov/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf (accessed June 2023)

[37] U.S. Department of Energy 'US Department of Energy Clean Hydrogen Production Standard (CHPS) Guidance' available at https://www.hydrogen.energy.gov/pdfs/clean-hydrogen-production-standard-guidance.pdf (accessed June 2023)

[38] Commodity Futures Trading Commission (2020) 'Managing Climate Risk in the US Financial System' https://www.cftc.gov/sites/default/files/2020-09/9-9-20%20Report%20of%20the%20Subcommittee%20on%20Climate-Related%20Market%20Risk%20-%20Managing%20Climate%20Risk%20in%20the%20U.S.%20Financial%20System%20for%20posting.pdf (accessed April 2023)

per kg of H_2. This is taken as an average over a 12-month period.

Table 4-7. International hydrogen requirements

Standard	Applicability	Emissions	Electricity
Green Hydrogen Standard	Renewable hydrogen only	- Limit of 1.0 kg CO_2e/kg H_2 taken as an average of a 12-month period – measured at point of production. - Pressure of 3 MPa assumed – emissions from compressing up to this level are included within the threshold. - Option to account for ammonia conversion emissions as appropriate. - Plans to expand standard to include H_2 transport and storage, and conversion into other derivatives besides ammonia.	- At least 95% of the electricity in a given year must be from renewable sources, either directly connected or purchased via the grid. Overall emissions threshold must not be exceeded. - For grid electricity, proof of renewability must be provided with a PPA and, where available, guarantee of origin certificates.
	Green Ammonia Definition	- Limit of 0.3 kg CO_2/kg NH_3 as an average over a 12-month period. - Expected reported emissions are energy usage associated with the storage, conversion and delivery of H_2 and its derivatives.	Green ammonia is ammonia produced using green hydrogen (as defined above) with 100% or near 100% renewable energy with close to zero greenhouse gas emissions.

4.5 Certification schemes or taxonomy suitable for the Thailand context

Thailand has a goal of carbon neutrality by 2050 and net-zero GHG emissions by 2065. There are no specific targets for hydrogen production or use but the state and industry in the country appears to be supportive of the fuel as part of the energy transition. As of early August 2023, Thailand does not have a hydrogen or ammonia standard or certification scheme (published or known to be in development). For electricity generation to support green hydrogen production and ammonia conversion, Thailand does not presently have a mandated carbon trading market but voluntary offset schemes such as the International Renewable Energy Certificate Standard can be employed within the country. In the absence of clear rules specific to Thailand, developers may look to follow the European Union's RED II requirements in the first instance as this reduces the risk of emerging rules in the country being more stringent than what the project has been designed around. Doing so would be in adherence with the current Technical Screening Criteria of the ASEAN Taxonomy for Sustainable Finance.

Thailand is an ASEAN Member State (AMS) and proponent of the ASEAN Taxonomy for Sustainable Finance. It is recommended that any development of hydrogen standards align with the ASEAN Taxonomy, this being a guide designed to support a just transition towards sustainable finance among AMS. The taxonomy provides a classification system of sustainable activities and assets across ASEAN. It is based on four environmental objectives: Climate Change Mitigation, Climate Change Adaptation, Protection of Healthy Ecosystems and Biodiversity, and Resource Resilience and the Transition to a Circular Economy. ASEAN Taxonomy Version 2 centres on the classification of Activities and hydrogen and ammonia are in the scope within the in-development Technical Screening Criteria. Technical Screening Criteria (TSC) classify Activities based on their contributions to environmental objectives using quantitative, qualitative, or nature of Activity-based criteria. An Activity takes place when resources such as capital, goods, labour, manufacturing techniques or intermediary products are combined to produce specific goods or services. An Activity is not the same as the facilities used to conduct the Activity. Annex 1 to the ASEAN Taxonomy for Sustainable Finance Version 2, updated as at 9 June 2023[39], includes Technical Screening Criteria guidance on what can be classified as 'Tier 1, Green' under environmental objective 1: Climate Change Mitigation. Activity in this class should be consistent with limiting global temperature rise to no more than 1.5°C. As a qualitative threshold, the current guidance notes typical thresholds of 28 g CO_2e/MJ. This would establish a hydrogen emissions threshold for the ASEAN taxonomy similar to the EU RED II level of 28.2 g CO_2e/MJ (equates to 3.38 g CO_2e/kg H_2).

In the coming years, organizations and international bodies may look to address gaps in transportation of hydrogen. Thailand may require adherence to this growing body of rules. International shipping as well as other transportation parts of the hydrogen value chain are less developed in terms of certification. All certification systems espouse interoperability yet how this will work in practice is untested. Difficulties should be anticipated, especially where multiple schemes are interacting across borders and in international waters. In the absence of specific rules on the certification of transportation of hydrogen or a derivative product, project proponents should seek to secure comprehensive data on emissions which can be used to substantiate attribute claims. One means of meeting these may be the carbon intensity measures of the International Maritime Organization. From 1 January 2023, it has been mandatory for all ships to calculate their attained Energy Efficiency Existing Ship Index (EEXI) to measure their energy efficiency and to begin to

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[39] https://asean.org/wp-content/uploads/2023/03/ASEAN-Taxonomy-Version-2.pdf

collect data sufficient for the reporting of annual operational carbon intensity indicator (CII) and CII rating.

Processes or systems introduced may come with specific requirements as is the case with standards and certification systems focused on production such as guarantee of origin. Consideration of attribute claims should include the following elements:

Table 4-8. Attribute claims and applicable standards

Value chain part	Attribute claims	Applicable standards
Transport	• Chain of custody of feedstock claims • Chain of custody of emissions from hydrogen production • Emission associated with transport of hydrogen • Sustainable Development Goal impacts	• ISO 14064-1 • ISO 22095 (Chain of custody) • ISO 14040 and 14044 (Life cycle assessment)

4.6 Quantifying the value chain

Having an overview of emerging hydrogen and ammonia certifications, a high-level life cycle assessment (LCA) for applicable ammonia value chains in Thailand can be conducted. By doing so, it can be determined whether these value chains meet the specified thresholds of various certification schemes or not. The value chain is comprised of three segments – production, shipping, and ammonia processing. The following value chain scenarios are analyzed at the end of the chapter:

- **Thailand domestic production** – domestic green ammonia production in East Thailand, where there are sufficient renewables resources and infrastructure.
- **Import from Australia** – importing green ammonia from Geraldton, Western Australia. The Oakajaee port is chosen as the importing port due to its location (distance-wise to Southeast Asia) and the state's renewable resources. The Western Australia government has set out Oakajee port as its main exporting port, making use of Western Australia's good wind (7.50 – 8.75 m/s speeds, capacity factor up to 50%) and solar (GHI of 2,000 – 2,200 kWh/m^2) resources and upcoming renewables projects. The scenario will assume the imported ammonia will be received in Thailand's Rayong port, which was identified as a major port close to industrial areas in the Central East region of Thailand.

4.6.1 Production

Table 4-9 presents an overview of the values considered for ammonia production. The system boundary encompasses scope 1, scope 2, and partial scope 3 emissions. Scope 1 refers to direct greenhouse gas (GHG) emissions from the production pathway. Scope 2 refers to emissions related to electricity generation, as well as steam purchased for consumption and heating/cooling. Scope 3 refers to other indirect GHG emissions not covered in Scope 2. To be consistent with the IPHE methodology, partial scope 3 is considered, which includes upstream emissions arising from raw materials extraction and processing, such as natural gas production and transport for steam methane reforming (SMR).

To account for variations in emission intensity estimations, both a 'high' (H), 'median' (M), and 'low' (L) bound are provided to indicate the uncertainty range for a specific ammonia production pathway. In practice, the actual emission intensity varies due to different factors like countries, production practices, and efforts to mitigate emissions.

Table 4-9. Overview of typical carbon intensity values[40]

Point of production	Technology	kg CO_2e/kg NH_3-eq*			
		L	M	H	Source
Grey NH_3	SMR + WGS (natural gas)	1.77	2.12	2.65	IEA
Blue NH_3	SMR with 75% CCS capture rate (natural gas)	0.62	1.16	1.59	IEA
	SMR with 94% CCS capture rate (natural gas)	0.25	0.69	1.16	IEA
Green NH_3	Electrolysis using renewable electricity	-	0.03	0.04	DNV estimated values based on required energy for ammonia production

**Conversion factor used: 5.67 kg NH_3/ kg H_2, refrigerant, leakage not included in the figures.*

The table above shows three different grades of production (grey, blue, green) of ammonia. Grey ammonia production is a conventional methane-fed system, which is a similar process to hydrogen production from natural gas. Once the hydrogen is obtained via SMR and the water gas shift reaction, it is reacted with nitrogen gas using a metal catalyst under high temperature and pressure via the Haber-Bosch process. The difference in emission intensity of producing grey hydrogen and grey ammonia are small since around 90% of carbon emissions for ammonia production originate from the production of hydrogen.[41]

For blue ammonia, CCS is used to capture the CO_2 emission produced from the SMR process. For 75% CCS capture rate, this is done by capturing the feedstock CO2 that was separated from the syngas produced via SMR. If additional CO_2 produced from natural gas-fired steam boilers are captured, the overall capture rate is increased to 94% and the emissions intensity reduces as well.

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[40] https://www.iea.org/reports/towards-hydrogen-definitions-based-on-their-emissions-intensity

[41] 'Ammonia: zero-carbon fertilizer, fuel and energy store', The Royal Society

Table 4-10. Green ammonia emission values (including vs excluding upstream emissions) with varying renewable sources

Green NH_3 Process	$gCO_2e/kgNH_3$-eq (including upstream emissions)		
	Renewable sources		
	Solar	Wind	Solar 60% Wind 40% (energy basis)
H_2 Production			
Electrolysis	**478.18**	**135.28**	**341.02**
NH_3 production			
N_2 (Air Separation)	6.79	1.92	4.84
Electricity for HB process	16.47	4.66	11.75
Sub-total NH_3 production	**23.26**	**6.58**	**16.59**
TOTAL	**501.44**	**141.86**	**357.61**

Green NH_3 Process	g CO_2e/kg NH_3-eq (excluding upstream emissions)		
	Renewable sources		
	Solar	Wind	Solar 60% Wind 40% (energy basis)
H_2 Production			
Electrolysis	**33.47**	**20.29**	**28.20**
NH_3 production			
N_2 (Air Separation)	0.48	0.29	0.40
Electricity for HB process	1.15	0.70	0.97
Sub-total NH_3 production	**1.63**	**0.99**	**0.97**
TOTAL	**35.10**	**21.28**	**29.17**

**Conversion factor used: 5.67 kg NH_3/ kg H_2, refrigerant, leakage not included in the figures.*

Table 4-10 shows the estimated GHG values (including vs. excluding upstream emissions) with varying renewable resources based on energy required. The associated upstream emissions are related to the infrastructure of the renewables plant. The GHG emission values for green ammonia in the table are calculated based on the amount of electricity required for each process with different sources of renewables. The different renewable electricity emission factor results in different overall emissions, with solar used as a high case.

For green ammonia, the associated emissions in addition to the green hydrogen production would come from the following processes, tied to the energy requirements involved.

- **Air Separation Unit:** This initial phase segregates air into its elemental constituents—nitrogen, oxygen, and argon—employing cryogenic distillation or pressure swing adsorption. The resultant nitrogen is harnessed for ammonia synthesis, while oxygen and argon are marketed as by-products. The energy necessity for separating one standard cubic meter of pure N_2 at 8 bar pressure spans from 0.15 to 0.25 kWh.
- **Syngas Compression:** This stage compresses natural gas and steam to create syngas, a blend of hydrogen and carbon monoxide. The ensuing purification rids the syngas of carbon dioxide and other impurities. The extracted hydrogen is integral to ammonia synthesis, whereas carbon dioxide is either discharged or captured for alternate uses.
- **Haber-Bosch Process:** This crucial step unites nitrogen and hydrogen within a reactor at high temperature (400-500°C) and pressure (150-300 bar), yielding ammonia catalyzed by iron-based catalysts. Separation from unreacted gases occurs through condensation. The electricity needed by the Haber-Bosch loop ranges from 0.324 kWh/kg NH_3 to 0.65 kWh/kg NH_3, with a calculation using Aspen yielding 0.44 kWh/kg NH_3.
- **Cooling:** The concluding phase involves refrigeration or heat exchange to transition ammonia to a liquid state, suitable for storage or transport via pipelines or vessels.

As shown in Table 4-10, there is a difference between the total emissions depending on whether upstream emissions are included or excluded. As of 2023, most standards and certifications for hydrogen such as RED II and GH2 exclude the upstream emissions. However, AEA's certification scheme planning aims to have cradle to gate (well to gate) which include scopes 1, 2, and potentially upstream 3 emissions to be mandatory for ammonia production. Therefore, upcoming certifications have to be monitored to ensure the produced green ammonia is compliant with the carbon threshold.

4.6.2 Shipping

The scope 1 and 3 emissions of ammonia shipping were calculated based on the following variables:

- Size of vessels
- Type of fuel
- Distance travelled

Results from this analysis have been compiled in a model filled with data sourced from IEA reports, European Commission reports, published scientific papers and the expertise of the DNV Maritime department. The main summary is indicated in Table 4-11.

Table 4-11. Overview of the estimated carbon intensities for shipping H_2 or NH_3 from Geraldton, Australia – Rayong, Thailand (resulting from a calculation model built by DNV)

	Emission intensities [g CO_2e/kg NH_3]									
Scope	HFO		LNG		MeOH		MGO		NH_3	
	L	H	L	H	L	H	L	H	L	H
Scope 1	41.04	74.01	32.86	59.27	33.19	59.87	33.83	61.01	3.98	7.18
Scope 3	8.60	15.52	7.88	14.21	21.89	39.48	8.92	16.09	24.16	43.58
Scope 1 + 3	**49.64**	**89.53**	**40.74**	**73.48**	**55.08**	**99.34**	**42.75**	**77.10**	**28.14**	**50.76**

Note: the scope 3 impact of ammonia used as a shipping fuel considered an average footprint for production of blue ammonia. **This footprint will be reduced to zero if green ammonia is used**, providing an even bigger advantage for the use of ammonia over conventional fuels or LNG from a carbon footprint point of view.

The ships considered are laden and ballast vessels that have sizes of 20,500 m^3 and 65,000 m^3 respectively. The values reflect the lower and upper limit for typical cargo ships used for fuel transport. Ballast is included due to the return trip of the ship with empty vessels. Overall, the energy used for laden journey, ballast journey, hotel, manoeuvring and ammonia reliquification (of boiled-off ammonia during transportation) are accounted for in the calculation model. The lower values in the above table are associated with the larger vessel, while higher values are associated with a smaller vessel.

4.6.3 Processing

The carbon footprint of ammonia processing such as import terminals and storage facilities also contributes to the product footprint. Depending on storage needs, it may be necessary to liquefy ammonia to prevent losses due to boiling off. The energy-intensive liquefaction process has the potential to contribute to greenhouse gas emissions, especially when conventional energy sources are utilized. However, this impact can be negligible when renewable and green electricity sources are used for the liquefaction process.

4.6.4 Analysis

The different threshold values from various standards can serve as a guideline to determine when to focus investments or efforts in different parts of the value chain. Currently, the most rigorous standard would be the EU RED II, which sets a threshold of 3.38 kg CO_2e/kg H_2 at the point of use boundary, which limits possible pathways for production, transport, and processing. Extending this to ammonia, it would be equivalent to a threshold of 0.6 kg CO_2/kg NH_3 (stoichiometric translation from the 3.38 kg). Next to RED II, the GH2 standard sets a threshold of 1.0 kg CO_2/kg H_2 for the H_2 production (equivalent to 0.1765 kg CO_2/kg NH_3 excluding upstream emissions) and additional emissions threshold for the ammonia production as much as 0.3 kg CO_2/kg NH_3. This is being drafted and is expected to be announced late 2023.

In the short term, the focus of decarbonization would be on the cradle to gate boundary before eventually moving towards a cradle to grave system boundary in the long term. This aligns with AEA's certification scheme planning, where they aim to have cradle to gate (well to gate) which include scopes 1, 2, and potentially upstream scope 3 emissions to be mandatory for ammonia production. Since upstream emissions were previously excluded in the carbon threshold of other studies, it is important to be aware and to continuously monitor any changes.

In the context of Thailand, ammonia can either be produced locally or imported from other perspective countries such as Australia. Based on the quantified GHG emissions of each value chain from the previous sections, the overall/total GHG emissions are added up for both cases, which are the following:

- **Thailand domestic production** – domestic green ammonia production in East Thailand, where there are sufficient renewables resources and infrastructure.

- **Import from Australia** – exporting green ammonia from Geraldton, Western Australia, also known for good renewables resources and aims to be a hydrogen exporter with a good proximity distance to the Southeast Asia region.

Table 4-12. Estimated GHG footprint (excluding upstream emissions)

Point of production	Technology		kg CO_2e/kg NH_3-eq					
		Value Chain	Domestic Production			Export (from Australia, WA)		
			L	M	H	L	M	H
Grey NH_3	SMR + WGS (natural gas)	Production	1.765	2.118	2.648	1.765	2.118	2.648
		Shipping	-			-	0.061	0.099
		Total	**1.765**	**2.118**	**2.648**	**1.765**	**2.179**	**2.747**
Blue NH_3	SMR with 75% CCS (natural gas)	Production	0.618	1.165	1.589	0.618	1.165	1.589
		Shipping				-	0.061	0.099
		Total	**0.618**	**1.165**	**1.589**	**0.618**	**1.226**	**1.688**
	SMR with 94% CCS (natural gas)	Production	0.247	0.688	1.165	0.247	0.688	1.165
		Shipping				-	0.061	0.099
		Total	**0.247**	**0.688**	**1.165**	**0.247**	**0.749**	**1.264**
Green NH_3	Electrolysis using renewable electricity	Production - H_2 production	-	0.028	0.033	-	0.028	0.033
		Production - H_2 to NH_3 production		0.001	0.002	-	0.001	0.002
		Shipping				-	0.061	0.099
		Total	**-**	**0.029**	**0.035**	**-**	**0.090**	**0.134**

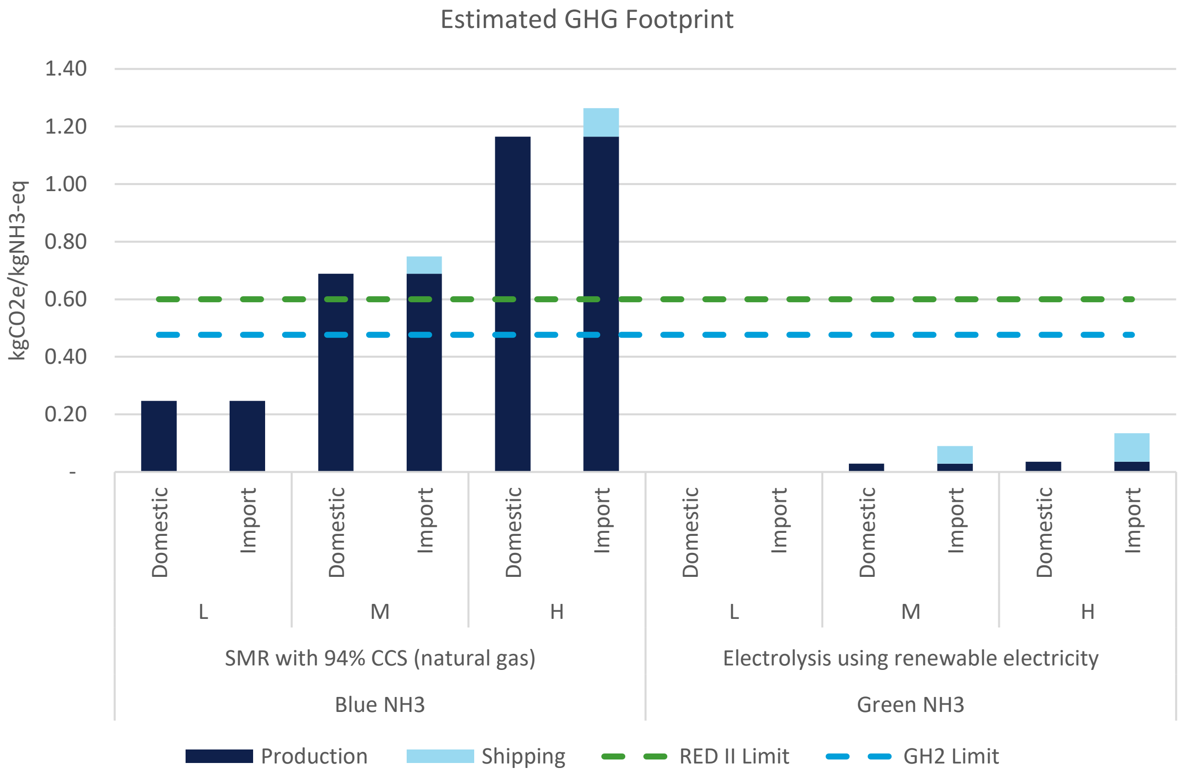

Figure 4-8. Estimated GHG footprint of blue and green ammonia for domestic production and import case scenarios

Based on these calculated values, it can be noted that all green ammonia, as well as blue ammonia with high capture rate at a lower range value will be able to meet the current most rigorous threshold (RED II limit, assuming the limit is extended to derivatives processing). Therefore, it can be concluded that both domestic production and imported green ammonia would have sufficiently low GHG emissions to meet the requirements. However, by producing domestically, the carbon emissions related to transport can be saved, which is as much as 28.14 – 99.34 $gCO_2e/kgNH_3$-eq depending on the vessel sizes and type of fuel is used. As the carbon threshold would be able to be met, the next considerations for future decisions would be cost competitiveness.

Since standards and certifications for green ammonia are still emerging, it is important to be aware of upcoming certifications and whether there would be differences in scope and boundaries of the carbon accounting (i.e. whether scope 3 upstream emissions would be included or not). Following that, it has to be checked whether imported ammonia would still be compliant with the emerging ammonia standards such as GH2 or AEA as it may no longer be the case.

As previously discussed, the process of decarbonizing the ammonia value chain is expected to unfold gradually. Currently, achieving a 94% capture rate is not commercially viable yet, and the utilization of ammonia as a viable commercial marine fuel is not feasible yet. Given these circumstances, the priority should be in decarbonizing the production of hydrogen and green ammonia by leveraging renewable energy resources.

5 CURRENT AMMONIA MARKET & STATUS QUO IN SEA & THAILAND

In recent years, the ammonia market in Thailand has witnessed remarkable growth, extending its influence across the wider Southeast Asian (SEA) region. This expansion can be attributed to a confluence of factors, ranging from heightened industrial demand to its diverse applications in agriculture.

As discussed in Section 1, ammonia assumes a pivotal role across an extensive spectrum of sectors, a trend that resonates throughout Southeast Asia. The ammonia market in this area demonstrates a dynamic nature, propelled by a diverse range of industrial applications and intricate interregional trade dynamics. This intricate interplay of trade flows reinforces ammonia's status as an important commodity. Likewise, within the context of Thailand, the demand for ammonia encompasses a wide array of industries, spanning agriculture, fertilizers, petrochemicals, and industrial chemicals. This demand strategically extends across diverse geographical regions where agricultural activities, manufacturing processes, and chemical production centres thrive.

Given its versatility and multifaceted applications, ammonia assumes a central role within the industrial framework of SEA and Thailand. Therefore, attaining insights into the dynamics of the ammonia market and its current state within these regions is imperative for a comprehensive understanding of their industrial and economic landscapes.

5.1 Ammonia market in Thailand

The core of Thailand's ammonia demand centres around its indispensable role as a fundamental component in fertilizer manufacturing. Given the pivotal significance of the agricultural sector to the nation's economy, this demand is substantial. Beyond its agricultural application, ammonia is also integral to the production of various chemicals, thereby contributing significantly to the country's industrial expansion. Regarding ammonia production, some localized facilities for ammonia synthesis already exist in Thailand but are insufficient to meet its entire demand.

In the realm of the ammonia market, Thailand's position is distinctly that of an importing nation, a fact evident from the consistently positive net import values presented in Table 5-1. The substantial disparity between imports and exports underscores the nation's current reliance on external sources to fulfil its demand for ammonia-related products.

Table 5-1. Current Exports and Imports for Ammonia-derived products for Thailand

THAILAND			
Ammonia-derived products	Quantity (in kilotonnes)		
	Imports	Exports	Net Imports
Anhydrous ammonia	438	-1	**437**
Ammonium sulphate	0	-152	**-152**
Ammonium nitrate	33	-23	**10**
DAP	8	0	**8**
Other fertilizers, mineral or chemical containing nitrates and phosphates	0	-21	**-21**
Urea	2,213	-189	**2,024**
Other fertilizers, mineral or chemical, than ammonium sulphate	5	-18	**-13**
MAP and mixture thereof with DAP	10	-15	**-5**
Nitric acid; sulphonitric acids	0	-4	**-4**
Others**	7	-1	**6**
TOTAL	**2,714**	**-424**	**2,290**

Source: (World Bank Trade Database, 2021)

Note * Net imports were calculated as the value of an imported product minus the quantity of that product exported.

** Others: Ammonia in aqueous solution; sodium nitrate; other nitrogenous fertilizers, minerals or chemicals than ammonium sulphate; ammonium nitrate with calcium carbonate or other inorganics.

Urea and Anhydrous Ammonia stand as the pivotal constituents of Thailand's ammonia imports. The significance of urea imports lies in its critical use as a fertilizer in the country, addressing nitrogen-deficient soils resulting from prevalent agricultural practices. Furthermore, the import of Anhydrous Ammonia addresses the demand for this commodity both as a direct fertilizer and as a raw material for producing various other fertilizers, including ammonium sulphate, MAP, DAP, and Nitric Acid. It also plays a pivotal role as an intermediary in numerous industrial applications.

Looking ahead, Thailand could boost local fertilizer production, primarily driven by the imperative to decarbonize the supply chain, which would lead to an increased demand for ammonia in the country. This presents a promising opportunity for Thailand to meet its ammonia demand domestically from low-carbon sources. The selected approach will partly depend on determining the cost-effectiveness between local green ammonia production and importing it.

The data in

Table 5-1. clearly illustrate that the demand for Urea (2,024 kilotonnes) in Thailand vastly outpaces that of AN (10 kilotonnes), as evident from the Net Imports values. This significant disparity suggests a reasonable anticipation that, while there is potential for AN (Ammonium Nitrate) to gain traction as a favoured solution for achieving zero carbon emissions, urea is still expected to maintain its role as the primary fertilizer consumed in Thailand.

Strategies for enhancing local fertilizer production could involve establishing domestic Ammonium Nitrate (AN) production to overcome transportation challenges (due to its oxidant hazards) or harnessing the country's abundant biomass resources to locally manufacture urea. External factors such as increasing shipping costs and international geopolitical tensions may also help to boost the Thailand-made green fertilizers production provided that well-planned government incentive programmes are active in-place.

In a scenario where all current imports of ammonia anhydrous and urea (Figure 5-1) are replaced with local production and applying a conversion factor of 1,000 kg of Urea being 597 kg of NH_3 equivalent, Thailand has the potential to establish a market for producing approximately 1,759 kilotonnes of green ammonia annually. Out of this total, around 1,321 kilotonnes of green ammonia, in combination with 1,707 kilotonnes of carbon-neutral CO_2, could be utilized for urea synthesis. According to Krungsri Research[42], this current potential market is expected to grow by 2.0-3.0% annually from 2023 to 2025, driven by the increase in domestic demand for fertilizers.

5.1.1 Ammonia equivalent (kg NH_3/kg Urea)

Taking into account the molar masses of ammonia (17.03 g/mol), carbon dioxide (44.01 g/mol), and urea (60.06 g/mol), in an ideal scenario where all the ammonia and carbon dioxide is converted into urea and water, the calculation indicates the need for 567 kg of ammonia and 733 kg of CO_2 to produce 1 tonne of urea. Now, considering a 95% mass efficiency observed in industrial urea synthesis, the quantities required for each component can be determined, as depicted in Figure 5-1.

Note *These values were calculated based on an industrial urea production mass efficiency of 95%.

Figure 5-1. Urea synthesis from ammonia and carbon dioxide

5.1.2 Fertilizer landscape in Thailand

The Thai fertilizer industry follows a downstream approach, heavily relying on imports from foreign producers. These imports can be classified into two primary categories[43]:

- **Straight fertilizers** accounted for about 66.1% of fertilizer imports in 2021, encompassing nitrogen-based products (48.6% of imports) sourced from Saudi Arabia, Malaysia, China, Oman, and Qatar; phosphorus products (0.1% of imports) from Egypt and China; and potassium (17.4% of imports) obtained from Canada, Belarus, Israel and Germany.

  To meet local demands, fertilizer manufacturers import straight fertilizers and mix them with fillers to the required quantities and proportions, producing **mixed fertilizers** that contain at least two major nutrients. While most of this production serves the domestic market, around 5% is exported again, with neighbouring countries like Cambodia, Lao PDR, Myanmar, and Vietnam being the primary recipients. Nevertheless, domestic production remains limited, primarily focusing on ammonia and ammonium sulphate, with an annual output of approximately 800,000 tonnes in Thailand.
- The remaining 33.9% of fertilizer imports consist of **finished or semi-finished compound fertilizers**, ready for distribution to wholesalers and retailers.

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[42] Industry Outlook 2023-2025: Chemical Fertilizer: Industry forecast for the chemical fertilizer sector in Thailand.

[43] Industry Outlook 2023-2025: Chemical Fertilizer: Industry forecast for the chemical fertilizer sector in Thailand.

These fertilizers mainly originate from China, Russia, Norway, and South Korea

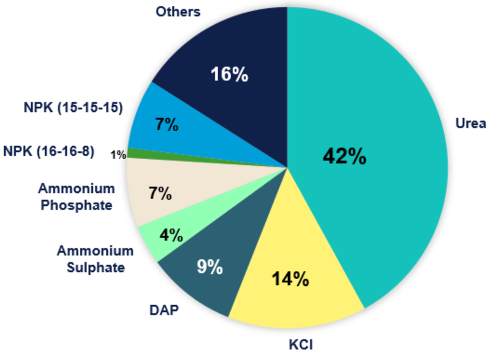
In Thailand, agriculture relies heavily on a select group of commonly used fertilizers, catering to the diverse needs of crops such as rice, fruits, and others. These fertilizers can be categorized into two main groups:

(i) **Straight and compound fertilizers**: The commonly used ones include urea (46-0-0), ammonium sulphate (21-0-0), potassium chloride (0-0-60), and diammonium phosphate (18-46-0)*.

(ii) **Mixed fertilizers**: Among the popular choices are 16-20-0, 15-15-15, 16-16-8, and 13-13-21 mixes*.

*The numbers in brackets refer to the percentage of nitrogen, phosphorus, and potassium in the fertilizer (N, P, K).

These eight types of fertilizers hold significant importance in Thailand's agricultural landscape, constituting more than 90% of the domestic fertilizer consumption and over 80% of imports (Figure 5-2). Such a wide-ranging applicability across various crops has contributed to their prevalence in the country's farming practices.



Source: Office of Agricultural Economics (OAE)

Figure 5-2. Share of Chemical Fertilizers Imported to Thailand[44]

Between 2019 and 2021, the largest share of fertilizers in Thailand was utilized for rice cultivation, representing 41% of all chemical fertilizers used during that period. This substantial demand for rice fertilization can be attributed to the extensive cultivation of over 70 million rai (11.2 million hectares) of land dedicated to rice farming in the country. Following rice, other significant crops included rubber with 28%, oil palm 12%, sugarcane 7%, maize 7% and cassava with 5%. Interestingly, when considering the quantity of fertilizers applied per unit, oil palm and rubber emerge as the most heavily fertilized crops, followed by sugarcane, off-season rice, maize, cassava, and first season/rainy-season rice. These findings highlight the importance of specific crops in driving fertilizer demand and underscore the direct impact that changes in the cultivation area of commercial crops can have on the overall demand for fertilizers in Thailand.

The domestic demand for fertilizer in Thailand is influenced significantly by two main factors. Firstly, the total area under cultivation plays a pivotal role, with rice and rubber accounting for more than 60% of the country's farmland. The cultivation of crops, such as sugarcane and oil palm, also contributes to this demand. These crops, due to their extensive presence, have a substantial impact on the overall fertilizer requirements.

Secondly, climatic conditions and access to water and irrigation systems also play a crucial role in determining fertilizer demand. Regions with favourable conditions and adequate water resources often witness higher agricultural productivity, which in turn leads to increased fertilizer usage.

Fertilizer production:

In the context of ammonium nitrate in Thailand, the primary ammonium nitrate production facility is operated by Thai Nitrate Co. Ltd. Located in Rayong, this factory boasts a production capacity of 70,000 tons per year, catering to both export markets and domestic consumption. Additionally, there are nine licensed factories in Thailand that employ ammonium nitrate as a key ingredient in their production processes. These facilities are

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[44] Industry Outlook 2023-2025: Chemical Fertilizer: Industry forecast for the chemical fertilizer sector in Thailand.

engaged in the manufacturing of various products, such as matches, explosives, and fireworks, contributing to a diverse range of industries in the country.

Regarding urea production, as of 2023, Thailand boasts an annual production capacity of 2.16 million tonnes per year, as indicated in Figure 5-5.

5.1.3 Ammonia production in Thailand

Outlined in its National Energy Plan, Thailand has announced its commitment to achieving carbon neutrality by 2050 and attaining net-zero status by 2065. To realize these ambitious objectives, the country is anticipated to enhance collaborative efforts with Japan in the realm of decarbonization technologies, encompassing hydrogen and ammonia.

While there are currently no registered ammonia plants in Thailand, recent years have witnessed efforts to reverse this situation. In late 2022, a novel consortium consisting of Japanese and Thai entities, including Mitsui OSK Lines, Mitsubishi, and Chiyoda along with the Electricity Generating Authority of Thailand (EGAT) signed a Memorandum of Understanding (MoU) with the intention of establishing a clean hydrogen and ammonia value chain, with production based on renewable energy generation in the southern region of Thailand. Through this MoU, the coalition will undertake a feasibility study aimed at decarbonizing Thailand's energy sector, likely through the utilization of hydrogen and ammonia as fuels for power generation.

Notably, Thailand is already advancing two initiatives in this domain. Firstly, there is an ongoing feasibility study led by Mitsubishi Heavy Industries in cooperation with BLCP Power Limited (BLCP), a Thai Independent Power Producer, to implement ammonia co-firing at BLCP's Map Ta Phut coal-fired power plant in Thailand. Map Ta Phut, which commenced operations in 2006-2007, boasts a generating capacity of 1,434 MW. Additionally, there exists an agreement between GE and IHI to develop gas turbines powered entirely by ammonia. GE-manufactured turbines constitute 30% of Thailand's current installed generating capacity.

Furthermore, a significant development is the official launch of the Asia Zero Emissions Community (AZEC). This collaborative effort includes countries such as Australia, Brunei, Cambodia, Indonesia, Japan, Laos, Malaysia, the Philippines, Singapore, Thailand, and Vietnam. The purpose of AZEC is to collectively expedite the transition to sustainable energy practices within the Asian region. As part of this initiative, specific collaborations have been identified, including enhancing fuel ammonia production in partnership with Malaysia, the Philippines, and Indonesia, fostering renewable ammonia production alongside the Republic of Laos, and engaging in broader cooperation related to hydrogen and ammonia with Singapore and Australia.

Also, in November 2022, ACWA Power joined forces with the Thai government to collaborate on a sizable initiative aimed at establishing a substantial green hydrogen and green ammonia facility within Thailand. The proposed renewables-powered plant is projected to possess a capacity enabling the production of 225,000 tonnes per year of green hydrogen, equivalent to 1.2 million tonnes per year of green ammonia. The output generated will be utilized for both domestic energy consumption and exports.

5.2 Ammonia landscape in Southeast Asia

Expanding the viewpoint to encompass the broader Southeast Asian context, ammonia stands out as a crucial element that underpins a multitude of industrial pursuits across the region. Like Thailand, the demand for ammonia in the Southeast Asian region is primarily propelled by fertilizer production and utilization.

According to the data presented in Table 5-2, anhydrous ammonia and urea stand out as the most significant products being exported in the region. Indonesia takes the lead as the largest exporter, followed by Malaysia, Thailand, Vietnam, and Singapore in sequential order. Regarding the remaining nations within the Southeast Asian (SEA) region, they primarily operate as net importers of ammonia-related products as of 2021. Contrastingly, ammonium sulphate emerges as the primary product imported within the SEA region, particularly by Vietnam, Indonesia, and Malaysia.

Interregional trade flows occupy a pivotal role in shaping the ammonia market within Southeast Asia. Nations with surplus ammonia production actively partake in cross-border trade to meet the diverse demands of neighbouring countries. This intricate web of trade routes highlights both the interconnectedness of the region and the intrinsic importance of ammonia as a pivotal commodity and urea as a key fertilizer.

Table 5-2. Current Exports and Imports for Ammonia-derived products for the SEA region (World Bank Trade Database, 2021)

SEA Region			
Ammonia-derived product	Quantity (in kilotonnes)		
	Imports	Exports	Net Imports*
Anhydrous ammonia	653	-2,309	**-1,656**
Ammonium sulphate	3,651	-217	**3,434**
Ammonium nitrate	188	-139	**49**
DAP	827	-154	**673**
Other fertilizers, mineral or chemical containing nitrates and phosphates	82	-166	**-84**
Urea	4,110	-4,688	**-578**
Other fertilizers, mineral or chemical than ammonium sulphate	225	-30	**195**
MAP and mixture thereof with DAP	152	-26	**126**
Nitric acid; sulphonitric acids	230	-12	**218**
Others*	179	-7	**172**
TOTAL	**10,297**	**-7,748**	**2,549**

* Net imports were calculated as the value of an imported product minus the quantity of that product exported.

** Others: Ammonia in aqueous solution; sodium nitrate; other nitrogenous fertilizers, minerals or chemicals than ammonium sulphate; ammonium nitrate with calcium carbonate or other inorganic non-fertilizing substances mixtures thereof; double salts and mixtures of calcium nitrate and ammonium nitrate.

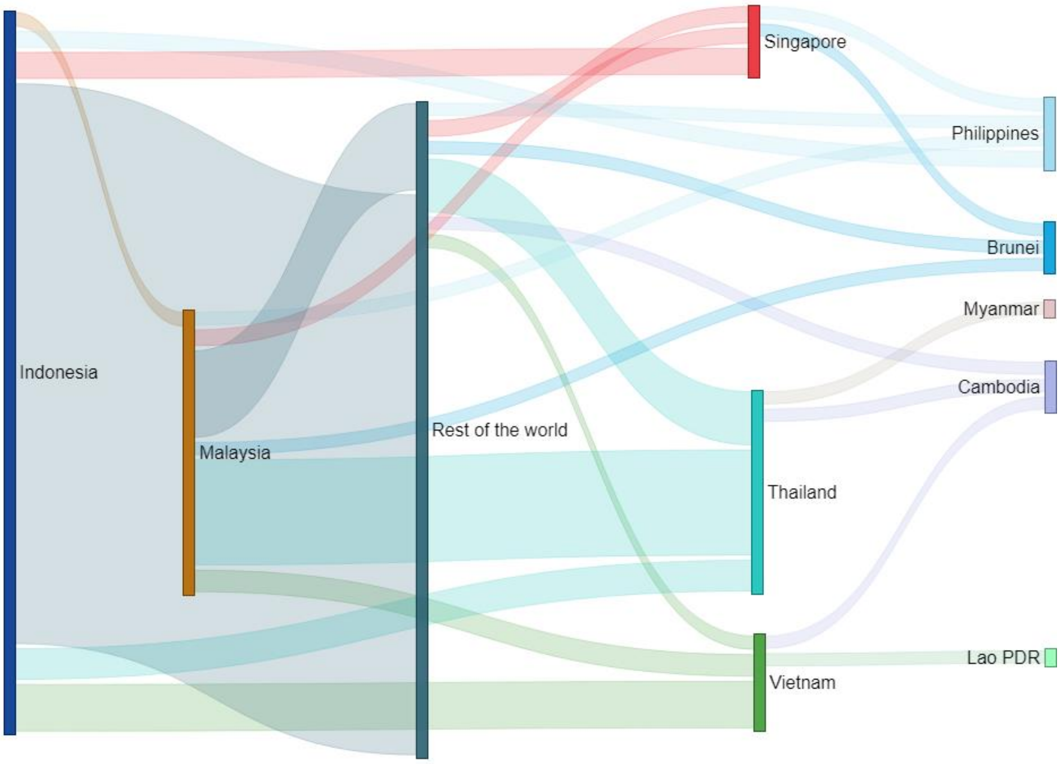

Figure 5-3. Trade Flows of Anhydrous Ammonia within the SEA region and the rest of the world

In the context of Anhydrous Ammonia, as illustrated in Figure 5-4, Indonesia holds the lead in exports of Anhydrous Ammonia. However, most of these exports go to other parts of the world, with only 11% of its exports, totalling 205.3 ktpa, directed towards the Southeast Asia region. Malaysia, on the other hand, is the primary exporter to the SEA region, with 297.9 ktpa. Thailand is the largest importer, bringing in 438.5 ktpa of ammonia to the country, followed by Vietnam and Singapore, which import 134 ktpa and 38.6 ktpa respectively. For the remaining countries, their ammonia imports are less than 12 ktpa.

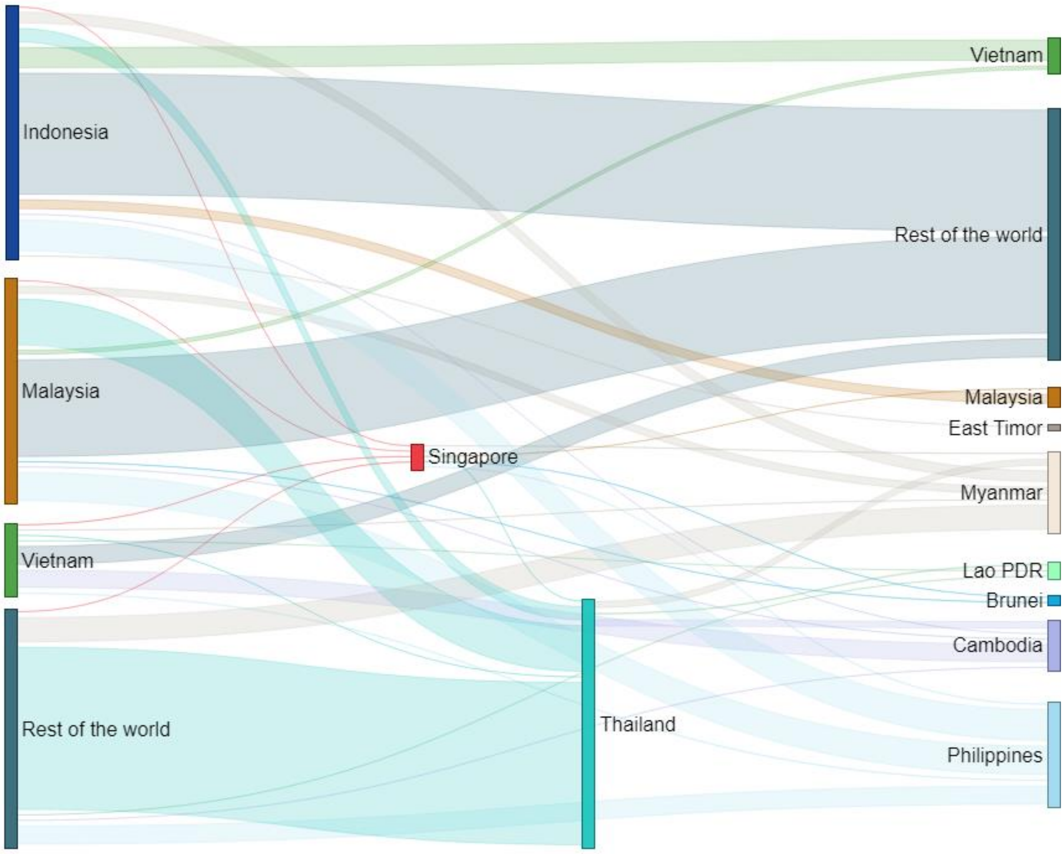

Figure 5-4. Trade Flows of Urea within the SEA region and the rest of the world

In the urea market, as depicted in Figure 5-4, Indonesia and Malaysia emerge as the largest exporters, with nearly half of their exports directed towards the SEA region. Malaysia's exports to SEA total 936.2 kilotonnes, while Indonesia's stand at 837.1 kilotonnes. Thailand remains the primary importer, yet only 27% of its imports come from the SEA region. Among neighbouring countries, Philippines sources the most urea imports from the SEA region, amounting to around 623 ktpa (807 kilotonnes when considering other parts of the world). This is followed by Myanmar and Cambodia, which import 357 and 205 kilotonnes of urea per year, respectively. For the remaining countries, their urea imports are less than 16 kilotonnes per year.

According to data from GlobalData (Table 5-3), refer to Appendix A for further information, Indonesia leads the Southeast Asian region in terms of the number of ammonia plants, with 17 operational plants. These facilities collectively contribute to the country's exports, resulting in an annual ammonia production of approximately 8.3 million tonnes. Following Indonesia, Malaysia emerges as the next significant local ammonia producer with four active plants, producing in total around 2.1 million tonnes of ammonia per year. Among the other countries in the region that operate ammonia plants are Vietnam and Myanmar, each with four plants. Vietnam's annual production stands at 1.4 million tonnes, while Myanmar contributes 0.3 million tonnes annually. Lastly, Brunei has recently launched an ammonia plant, accounting for approximately 0.8 million tonnes of ammonia production annually, all of which is fully converted into urea.

The majority of these plants utilize steam methane reforming processes, relying on natural gas as the primary feedstock. However, two plants located in Vietnam produce ammonia through coal gasification processes.

Table 5-3. Existing Ammonia plants in the SEA region (source: GlobalData)

Ammonia Plants in the SEA region			
Country	**Number of active plants**	**Main Processes**	**Total Capacity [mtpa] (2021)**
Indonesia	17	Steam Methane Reforming	8.33
Malaysia	4	Steam Methane Reforming	2.07
Vietnam	4	Steam Methane Reforming or Coal Gasification Process	1.41
Myanmar	4	N/A	0.31
Brunei	1	Steam Methane Reforming	0.77

The only countries with local urea production in the SEA region are Indonesia, Vietnam, Thailand, Philippines, and Singapore, based on the data from GlobalData. As of 2023, Indonesia produces the largest amount, with 6.06 million tonnes of urea, followed by Vietnam with 2.46 million tonnes, Thailand with 2.16 million tonnes, and the Philippines with 0.91 million tonnes. Finally, Singapore contributes a smaller amount, producing 0.01 million tonnes of urea per year (Figure 5-5). Also, the forecasts shown in the graph indicate a projected increase in urea production capacities of approximately 10-13% by 2030.

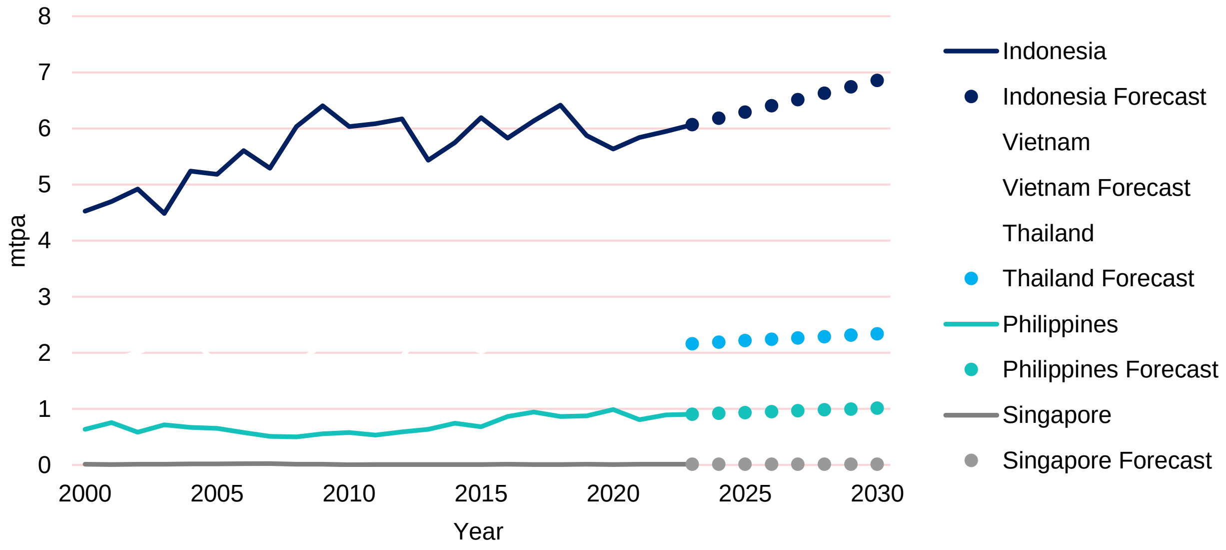

Figure 5-5. Urea Production for different countries in the SEA region and their forecast (source: GlobalData)

6 FUTURE GREEN AMMONIA MARKET IN SEA & THAILAND

6.1 Potential supply chain of green ammonia in Thailand & SEA

The future green ammonia market is likely to be transformed globally, as the current natural-gas feedstock dominated production of ammonia (grey ammonia) is augmented and displaced by green ammonia production. The primary driver for this transition will be the availability of competitive renewable energy, but a secondary consideration will also be the availability of biomass energy and/or sustainable sources of carbon. This therefore paints a potential future picture where large, centralized ammonia production assets located near to low-cost natural gas sources slowly lose market share to locations where ultimately the lowest levelized cost of renewable electricity will provide the cheapest form of green ammonia.

However, the ammonia market is closely tied to the fertilizer market globally, and the majority of the global ammonia supply is used for the production of urea – a safe and easily transported bulk solid commodity and useful carrier of nitrogen – considered more suitable for direct fertilizer end-use compared to liquid ammonia. Traditionally, urea production plants are adjacent and complementary to ammonia production plants: the magnitude of ammonia vs urea production is driven by economic factors and market preferences. If, for example, the price of urea is significantly greater than the price of ammonia, there would be an incentive to convert the excess ammonia into urea using the recovered CO_2 from the steam methane reforming (hydrogen production) processes, subject to the limiting availability of CO_2 recovered upstream. In converse situations, where the urea price is low and ammonia price is high, the urea production can be scaled back and ammonia can be sold without further conversion, subject to plant operating constraints. However, this typically also means that CO_2 emitted by ammonia production is released to the atmosphere without further value-adding (conversion to urea). Therefore, the size of the traditional urea plant is often constrained by the projected urea demand and the capacity of the upstream ammonia facility.

However, when transitioning to a green supply chain, the co-location of urea synthesis with green ammonia production is not quite as straightforward. Hydrogen is the primary building block for ammonia, which in turn is used as a feedstock for urea production. In the process of making green ammonia and urea, green hydrogen will be the most sought-after commodity since it requires the most energy input in order to synthesize, and it dominates the total production cost of these derivatives. This favours production of hydrogen and therefore ammonia in locations with abundant low-cost renewable availability. A green pathway for urea synthesis however requires a carbon-neutral pathway for the CO_2 feedstock needed to make urea. The main source for such carbon-neutral CO_2 is either via biomass combustion/ gasification, renewable methane, or via direct capture of CO_2 from the atmosphere known as Direct Air Capture (DAC). The consistency, reliability, purity, and cost of this CO_2 feedstock are important factors influencing the whole value chain of green urea synthesis and are often categorized as location-specific parameters. This means that the ideal location for urea synthesis is in locations with abundant access to such clean CO_2 sources, which in early years will likely come from gasification of biomass.

The above discussions showcase that the transformation of the ammonia production sector from grey to green will likely not follow the same template of co-located production. While at face value, the supply chain seems to require only low-cost, green electricity, the production of the main derivative in urea necessitates the sourcing of sustainable biomass and/or carbon sources as well, which may not be available in the same location. Furthermore, biomass is notoriously difficult and costly to transport – arguably more so than hydrogen transport – due to the strong need to process biomass locally with careful consideration of local dynamics (feedstock availability variability, seasonal variability, impurities and general lack of homogeneity). This could generally mean that biomass availability, to a large extent, could become the most decisive factor when it comes to selecting ideal locations for green urea production.

As the agricultural industries within the Southeast Asia region and Thailand are strongly leaning towards more sustainable pathways, it might be an opportunity for Thailand to innovate new business models for green urea production facilities. Although opportunities also exist for ammonia production to synergize with the urea production, Thailand is unlikely to be able develop its own ammonia production in a cost competitive manner since imported green ammonia is expected to be cheaper than domestically produced green ammonia even towards 2050 (refer to Chapter 3).

Thailand has interesting synergies with this potential new supply chain in that it is currently the largest consumer of urea in the Southeast Asia region, but also one of the few countries in the region with a combination of potential for green urea production from its biomass availability. Thailand also has a strong reputation for industrial hubs, and existing heavy industries including chemicals and petrochemicals means local expertise and engineering would be well-suited to further development in green urea production. Other global and regional factors such as increasing shipping costs, increasing scrutiny on supply chain resilience, and international geopolitical tensions may also help to boost the possibility that Thailand can pivot from a net importer of urea and ammonia into being self-sufficient for urea, and even potentially being a net exporter. This translates into several pathways in the future for Thailand:

a) Continue being a net importer of ammonia and urea, with some green urea production domestically ('pessimistic' pathway)

b) Develop domestic urea production facilities and become self-sufficient for domestic green urea (in a 'base' pathway)

c) Further develop domestic urea production facilities and become a net exporter of green urea within the region (in the 'optimistic' pathway)

In this sense, urea could potentially become an anchor point for Thailand to pivot existing ammonia trade around; transforming from a net importer of grey urea and grey ammonia towards increasing local green production assets, underpinned by a strong local agricultural market demand for urea. This could simultaneously enable the development of new local industries and jobs, while simultaneously providing decarbonization benefits – subject to government policy and incentives to help bridge the initial green premiums and cost gaps of 'green' ammonia/urea compared to existing 'grey' comparators.

Other demand-side drivers for green ammonia in Thailand will include the use of maritime fuel, co-firing in coal-fired power stations, and importing ammonia as a hydrogen carrier or for direct use in electrical power generation. For these end-use cases, uncertainty in the demand growth trajectory is much greater and subject to many regional and global dynamics, and heavily reliant on certain technologies dominating or developing quickly. In the case of ammonia as a maritime fuel, for example, a significant majority of ocean-going vessels bunker fuel in Singapore, and this fuel supply dynamic in a green-ammonia dominated fuel supply chain may be unlikely to shift in future – the lowest-cost source of ammonia will tend to be aggregated in a logical centralized bunkering location such as Singapore.

When it comes to power generation from ammonia or hydrogen cracked from ammonia, this will be a highly costly route for power generation due to the inherent efficiency losses and technology development still required – likely constraining these options to countries which have a willingness to pay this premium due to limited natural renewable energy resources, such as Singapore and Japan.

The final use case of ammonia, co-firing with coal-fired power stations, could have some synergies in terms of stimulating early demand for ammonia production or imports to Thailand. However, where infrastructure must be built to cater to this pathway, the case for investment could be tenuous: depending on the expected lifetime of coal-fired generation assets, the path for co-firing may be short lived and risky.

In short, the potential ammonia value chain in Thailand is poised to be transformed mainly by virtue of the unique dynamic of Thailand being a large consumer of urea and ammonia, as well as a natural and biomass-resource rich nation, combined with existing large-scale industrial, manufacturing and petrochemical hubs which can be built upon and leveraged. Further transformation due to the scaling of new end-uses of ammonia, such as power generation and maritime fuel, remain highly likely on a regional and global level, but not necessarily to the benefit of Thailand. This will be outlined further in the remainder of this chapter.

6.2 Potential Demand for green ammonia in Thailand

6.2.1 Approach – Quantifying the potential green ammonia demand

To quantify the potential demand for green ammonia in Thailand, an analysis of sectoral end-use cases where green ammonia could play a role in decarbonization was first performed. This analysis was done using a traffic light system with the colors indicating the potential of green ammonia to replace the business as usual (BAU) fuel/feedstock in each sub-sector. The criterion used for each color is outlined in Table 6-1.

The traffic light analysis has been conducted across the power, industry, and transport sectors. While the focus of the study is on direct ammonia use, a category was also added to the demand forecast to account for the potential role of ammonia as an energy carrier capable of meeting Thailand's hydrogen demand.

The results of the traffic light analysis were combined with the expected total demand per sector to estimate the expected future green ammonia demand. This was done using a lower and upper bound, where the lower bound is formed by sectors where ammonia demand is guaranteed (green) and the difference to the upper bound consisting of the demand where ammonia could play a role depending on circumstances such as policy and economics (yellow). After quantifying the potential demand, a comparative cost analysis will be performed to provide insights into a potential market driven transition in the yellow sectors, in combination with potential policy mechanisms that can be utilized to stimulate the role of hydrogen in said sectors.

The energy demand values are quantified for the power and industry sector using data from external studies. The power sector demand is based on the CASE study's energy consumption values (MWh) in 2019. For industry, it is based on the World Bank Trade Database (2021), which is also presented in Chapter 5. For the industry demand, ammonia equivalent conversion from Urea based on molar masses was used (refer to Figure 6-1). Estimated amount of ammonia required for cracking into hydrogen is based on

Table 6-1. Traffic light framework to estimate future ammonia intake in Thailand

Current fuels/ feedstock	Possible role for green ammonia	
BAU fuels/ feedstock	Green ammonia is the only pathway to decarbonization	🟩
	Green ammonia an option, but faces competition from other routes to decarbonization	🟨
	Green ammonia is not expected to play a (significant) role in decarbonization	🟥

the GIZ report ‘Knowledge series on market development for Green Hydrogen and Power-to-X in Thailand’. Available data on transportation demand is limited to domestic demand, which is not the primary use case for ammonia as a fuel. This section will therefore be addressed qualitatively only.

6.2.1.1 Ammonia equivalent (kg NH_3/kg Urea)

Taking into account the molar masses of ammonia (17.03 g/mol), carbon dioxide (44.01 g/mol), and urea (60.06 g/mol), in an ideal scenario where all the ammonia and carbon dioxide is converted into urea and water, the calculation indicates the need for 567 kg of ammonia and 733 kg of CO_2 to produce 1 tonne of urea. Now, considering a 95% mass efficiency observed in industrial urea synthesis, the quantities required for each component can be determined, as depicted in Figure 6-1 below.

Figure 6-1. Urea synthesis from ammonia and carbon dioxide

*These values were calculated based on an industrial urea production mass efficiency of 95%.

6.2.2 Future green ammonia use cases

The traffic light framework is adopted on a sectoral level, split into role (fuel or feedstock) and use case for the power generation, industry, and transport sectors in addition to ammonia as energy carrier. Based on the type of industry and their individual processes, types of demand and fuel utilization, different decarbonization pathways can emerge with green ammonia as one of the potential pathways. It is however imperative to consider what green ammonia would compete with to find the optimal pathway for each sector and type of demand. Before considering the unique aspects of each sector and identifying the potential role of green ammonia, some general observations can already be made:

- Demand for electricity should always be met via electricity as this is the most efficient pathway.

- Applications where cracking of ammonia is required to produce hydrogen will have additional efficiency losses and therefore could be less competitive in the long-term depending on the cost of both commodities. For example, cracking of ammonia to produce hydrogen for a combined cycle gas turbine may need to compete with direct combustion of ammonia in gas turbines. In accordance with the results in Chapter 3, hydrogen produced in Thailand is an economically more attractive route for power generation than imported ammonia. As a result, for Thailand the role of ammonia in power generation should therefore remain limited to existing power plants, but this consideration will be different for other countries.

- Ammonia combustion as a fuel for maritime uses will naturally be limited to ship types and journeys where it makes most economic sense. For example, ships which already transport cargoes such as bulk gases (ammonia being one such cargo) or bulk iron ore carriers which sail from locations that are also producing green ammonia at large scale/low cost. Similarly, the refuelling (bunkering) of these ships will happen where this is the most economic. As a result of this, the presence of ammonia-fired ships in Thailand will not necessarily lead to a demand for ammonia bunkering in Thailand.

- Applications where ammonia is required (as a chemical feedstock) are largely without any real competition: this is mostly the fertilizer and explosives industries, where ammonia is a key feedstock and this is not going to change or alternative pathways found.

Table 6-2 summarizes the traffic light analysis conducted across the sectors and use cases, which will be further elaborated per sector in the subsequent sub-sections.

Table 6-2. Potential role of green ammonia on power, industry, transport sector, and as an energy carrier

Sector	Role	Current (BAU)	Role for green ammonia	Comment
Power generation	Fuel	Coal	🟩	• Co-firing ammonia is possible in existing coal- fired power plants. Blending rates up to 20% should be feasible by 2030. However, coal will not likely be used for power generation by 2050 in Thailand.
		Gas	🟥	• Green ammonia would not play a direct role in gas/oil replacement unless cracked into green hydrogen.
		Oil	🟥	
Industry	Feedstock	Grey Ammonia	🟩	• Green ammonia is the only decarbonization pathway for grey ammonia feedstock.
	Fuel	Electricity	🟥	• No replacement of electricity demand with green ammonia is expected.
		Coal	🟥	• Other alternatives (biomass, hydrogen, electrification) would be preferred according to each BAU compared to ammonia, which is only likely to be used for niche use-case (i.e. ammonia cracking sites).
		Gas	🟥	
		Oil	🟥	
Transport	Fuel	Electricity	🟥	• Other alternatives (electrification, biofuels, hybrid) would be preferred according to each BAU compared to ammonia, which is only likely to be used for niche use-case (i.e. farming/agriculture)
		Gasoline	🟥	
		Diesel	🟥	
		CNG	🟥	
		LPG	🟥	
		Marine Fuel (Commodity)	🟩	• Ammonia is the most likely candidate, though there is expected competition with drop-in fuels such as renewable diesel
		Marine Fuel (Container)	🟨	• E-methanol, green methane and LNG are preferred for their suitability as a drop-in fuel. Ammonia might play a role but the demand will be considerably low.
		Marine Fuel (Passenger ships)	🟨	• Smaller vessels are headed towards electrification, while larger vessels are leaning towards methanol. Ammonia might play a role but the demand will be considerably lower.
		Aviation Fuel (short haul)	🟥	• Hybrid electrification is preferred
		Aviation Fuel (long haul)	🟥	• A mix of sustainable aviation fuels (SAFs) and hydrogen is preferred
Energy Carrier	Cracking into H_2	Various	🟨	• Cracking into hydrogen is a suitable route • Will be in competition with domestic hydrogen production and other carriers

🟥	Green ammonia will not play a role for decarbonization	🟨	Green ammonia is an option, but face competition from other routes to decarbonization	🟩	Green ammonia is the only pathway to decarbonization

6.2.2.1 Power sector

Table 6-3. Potential role of green ammonia on power sector

Sector	Role	Current (BAU)	Role for green ammonia	Comment
Power generation	Fuel	Coal	🟩	• Co-firing ammonia is possible in existing coal- fired power plants. Blending rates up to 20% should be feasible by 2030. However, coal will not likely be used for power generation by 2050 in Thailand.
		Gas/oil	🟥	• Green ammonia would not play a direct role in gas/oil replacement unless cracked into green hydrogen.

In the power sector, green ammonia can play a role in decarbonizing existing coal-fired power plants. Co-firing of ammonia with a blending rate up to 20% should be technically feasible by 2030. However, green ammonia is not a suitable fuel to replace natural gas in existing power plants due to technology limitations, and significant capital investment in repowering would be required in order to facilitate direct ammonia firing.

Due to the favourable LCOH of hydrogen produced in Thailand over the LCOA of imported ammonia, the use of ammonia for new power plants is not economically viable. Hence the role of ammonia in power generation will be limited to existing power plants only. Thailand is planning to phase out its coal-fired power generation by 2050 and the cost difference between ammonia and hydrogen shows that there is no economic case for the continued or extended use of coal because of the opportunity to utilize ammonia, and instead Thailand should continue to phase out its coal-fired power plants in favour of gas-fired generators that can switch to hydrogen.

From a technical perspective, ammonia can be co-fired with coal in the near future. However, there are several limitations to its potential based on current technology. The expectation is that initially the maximum blending rate will be limited to around 20%, though research is ongoing to increase this towards 50% ahead of development of 100% pure ammonia-fired power generation, however the viability will be highly dependent on the coal power station age and technology. This will also limit the decarbonization potential of the implementation of co-firing. From an economic perspective, there is a significant cost difference between coal and green ammonia which means that while co-firing is technically possible, it is not economically favourable towards 2050 even in case of higher carbon taxes. Policy support will be required to close the cost gap, though this will require significant policy supporting tools such as high carbon taxes, or incentives.

The existing coal-fired generation capacity in Thailand is around 6 GW (both domestic and imports under IPP scheme), representing around 12% of the country's total installed capacity. Around half of domestic coal generation capacity (2.2 GW) is from EGAT's Mae Moh power plant which uses lignite, located in the Northern part of Thailand where there are no existing gas pipelines. Other domestic coal-fired power plants are owned and operated by private power producers using imported bituminous coal, which are located in the eastern region. This poses logistic challenges for the implementation of both ammonia and hydrogen fired power generation in existing power plants. Moreover, upon comparing coal co-firing with ammonia against hydrogen blending in gas-fired power plants, it is less favourable as burning gas provides more operational flexibility which aligns better with the need for balancing capability in a high renewables power grid. As Thailand's generation mix is currently dominated by gas, accounting for round 60% of total electricity generation, more focus should be placed on replacing natural gas with hydrogen for power generation. Thailand is currently already planning to run a pilot project at an existing gas-fired power plant regarding hydrogen blending.

Therefore, it is unlikely that Thailand will gain a lot of benefit from co-firing with ammonia to decarbonize the sector.

In the broader SEA and Asia Pacific (APAC) region, there are other countries that could benefit more from co-firing ammonia or including 100% pure ammonia combustion in their decarbonization plans. Utilization of ammonia in decarbonization of power generation is a potentially suitable pathway for:

1) Countries that cannot produce hydrogen domestically at a price that is competitive with imported ammonia; or

2) Countries that plan to continue using coal-fired powered plants in a longer term.

Several countries in the region will not be able to produce cost-efficient hydrogen domestically, which can either be the result of a lack of space (e.g. Singapore, Japan, South Korea), lack of access to other renewables than solar and/or relatively poor renewable resource quality. As a result, these countries will be dependent on imports of green molecules to meet their domestic dispatchable power demand which can come via hydrogen or any of its derivatives.

Hydrogen produced at low cost by neighbouring countries and transported by pipeline is the route that is the most efficient if available, but for countries that are looking to import via shipping routes like Japan and South Korea, the direct combustion of ammonia will likely be a more cost-effective route than cracking the ammonia back into hydrogen ahead of combustion. This need drives the technology development of ammonia firing in such countries. Notable progress is shown by Japan, where the main turbine manufacturers there (MHI, IHI) are continuously developing ammonia firing turbines.

Additionally, ammonia is a suitable candidate for (partial) decarbonization of existing coal-fired power plants in countries that have no plans to phase out these plants, such as Indonesia. Utilizing green ammonia can reduce the emissions produced by these plants and in the long-run potentially fully replace the coal with retrofits of the existing equipment, which is more cost-effective for power plant owners than replacing the entire plant in order to enable hydrogen firing.

6.2.2.2 Industry sector

Table 6-4. Potential role of green ammonia on industry sector

Sector	Role	Current (BAU)	Role for green ammonia	Comment
Industry	Feedstock	Grey Ammonia	🟩	- Green ammonia is the only decarbonization pathway for grey ammonia feedstock.
	Fuel	Electricity	🟥	- No replacement of electricity demand with green ammonia is expected.
		Coal	🟥	- Biomass is a cost-competitive competitor. Ammonia is usually the last choice, after electrification and hydrogen.
				- There are potential niche use-cases (i.e. ammonia cracking sites) for coal replacement but the demand can be negligible
		Gas	🟥	- High-heat: Hydrogen is the preferred choice for high-heat, with competition from biomass depending on scalability of site and resources availability.
		Oil	🟥	- Low-heat: Electrification via heat pumps or resistive heating is considered to be the preferred route.

Green ammonia is expected to play a role for decarbonization in the industry only as a feedstock. Replacement of fuels with ammonia is not expected as there are other more suitable alternatives available. Electricity demand should always be replaced with the use of renewables, while the ideal replacement for coal, gas, or oil depends on the industry's heat temperature required. However, due to its chemical properties, ammonia is not a preferred alternative for any temperature range. For low temperatures, electrification with heat pump is more efficient and cost-effective. For high temperatures, there will be competition with hydrogen, biomass and biofuels depending on the scale of the site and biomass resources available. Due to the nature of processes, some industries such as machinery and transportation equipment could even potentially be electrified (e.g. melting and casting metals). Ammonia does not burn at a high temperature and struggles with sustained combustion, making it more complicated and less effective for high temperature heat when compared to combustion of hydrogen. Hydrogen also has the advantage that it can act as a drop-in fuel in gas-fired boilers, which can save on investment costs. Green ammonia can be preferred to replace coal for heat generation but only for niche applications such as at ammonia cracking sites, where it is practical to use ammonia since it's already available on site. However, the demand is small and therefore is negligible.

Thailand currently imports its ammonia – mostly in the form of anhydrous ammonia and urea, where most of it is used as a direct fertilizer or intermediary product of a fertilizer. Towards 2050, the ammonia market within Thailand might develop into varying pathways as explained in 6.1. The first 'pessimistic' pathway is that Thailand continues as it is, being an ammonia and urea importer in the region. While for the 'optimistic' pathway, Thailand can boost its local urea and fertilizer production with imported green ammonia, creating value addition and afterwards export the fertilizer or other derived products. This study assumes the 'optimistic' pathway will be the most likely pathway as it allows decarbonization more efficiently. In addition, by doing so Thailand has an advantage to leverage synergies from its industrial clustering and biomass availability to produce urea. This will be addressed further in section 6.3.

The same applies to other countries within the region, where green ammonia can primarily be used to decarbonize the current industrial feedstock demand. However, similar to Thailand, these countries may struggle to produce green ammonia in a cost-effective manner compared to imported ammonia. There may be opportunities for them to produce green urea, with the limiting factor being the availability of biomass and renewable resources. Most countries in the ASEAN region possess abundant biomass resources due to their agriculture-centric economies and extensive forest reserve, estimated at > 500 million tonnes per year[45]. The biomass resources generally come from fuelwood, wood residues, rice husk, rice straw, sugarcane residues, oil palm residues, and coconut residues. Amongst the countries in the region, Vietnam has the biggest biomass resources potential, supported by its wind resources, followed by Indonesia, Malaysia, Cambodia, Myanmar, and Laos. Therefore, these countries are expected to have capabilities to produce green urea for their own demand or potentially for export within the region or between regions. Other countries in the region do not have access to sufficient biomass feedstock and/or sustainable sources of carbon and will remain dependent on imports for ammonia and urea. It should however be noted that urea production will compete for biomass resources with potential other low-carbon fuels such as biofuel and sustainable aviation fuel. The capability of countries to therefore pursue urea production depends on the availability of biomass overall as well as on the other forms of competition locally.

However, outside of Thailand none of these countries have experience with value adding of chemicals or have the infrastructure in place to facilitate this, which would mean they need to make significant investments to internalize these supply chains. Malaysia and Indonesia are large-scale producers and exporters of ammonia and may want to consider moving into the green production and export market, but current production is based on natural gas and it is highly uncertain if they will be able to compete with imports from other regions when transitioning to a green ammonia supply chain. They do, however, have a competitive advantage against countries with no experience in this field if they can utilize existing supply chains and training partners.

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[45] Resources | Free Full-Text | Biomass Energy: An Overview of Biomass Sources, Energy Potential, and Management in Southeast Asian Countries (mdpi.com)

6.2.2.3 Transport sector

Table 6-5. Potential role of green ammonia on transport sector

Sector	Role	Current (BAU)	Role for green ammonia	Comment
Transport	Fuel	Electricity	🟥	- Electrification is the preferred route for almost all land-based transport
		Gasoline	🟥	
		Diesel	🟥	- Niche application of hydrogen in long-distance travel. But electrification and biofuels still preferred
		CNG	🟥	- Internal combustion engines running on ammonia, but only the farming and agricultural sector presents itself as a potential use-case.
		LPG	🟥	- Hybrid and electrification measures are preferred
		Marine Fuel (Commodity)	🟩	- Ammonia is promising but there is expected competition with drop-in fuels such as renewable diesels
		Marine Fuel (Container)	🟨	- E-methanol, green methane and LNG are preferred for their suitability as a drop-in fuel. Ammonia might play a role but the demand will be considerably low.
		Marine Fuel (Passenger ships)	🟨	- Smaller vessels are headed towards electrification, while larger vessels are leaning towards methanol. Ammonia might play a role but the demand will be considerably low.
		Aviation Fuel (short haul)	🟥	- Hybrid electrification is preferred
		Aviation Fuel (long haul)	🟥	- A mix of sustainable aviation fuels (SAFs) and hydrogen is preferred

Looking across varying modes of transport, green ammonia is expected to play a role as marine fuel for commodity shipping, with a potential role in container and passenger shipping as well. In the commodity shipping sector, ammonia is promising as a direct fuel in large ship reciprocating engines such as bulk iron ore carriers, large gas carriers and other similar vessels. While ammonia is considered to be the front-runner for this segment, competition is expected with other drop-in fuels such as renewable diesel and green LNG. These fuels will likely be more expensive than green ammonia to produce but have the advantage of being usable in existing ships without the need for retrofit and refurbishment which is a costly exercise for ammonia. Newer ships can be designed around the use of ammonia from the start, making this less of a concern.

For container ships, e-methanol, green methane and green LNG are preferred compared to ammonia as conversion of existing ships to methanol-ready ships is easier compared to ammonia, making it an option that can help extend the lifetime of the existing fleet. Ammonia, however, has lower costs per energy content compared to methanol, and does not have the challenge of tailpipe CO_2 emissions or sustainable sourcing of carbon in the production value chain. Therefore, it is expected there will be demand for ammonia, but competing with various alternatives on a cost, region-specific and ship class-specific basis.

Due to toxicity, the safety risk of ammonia is higher than with other alternatives and is a key consideration when it comes to fuel choice. For passenger ships, ammonia demand is also considered to support decarbonization, but due to safety concerns, other alternatives could be preferred even if the cost of the fuel is higher per unit of energy. Generally, smaller vessels will likely be electrified (particularly inner-harbour and river craft) while large ocean-going vessels could be powered by a myriad of options including methanol, ammonia, renewable diesel, renewable LNG/LPG and biodiesel.

Ammonia is not expected to play a role for other transport modes such as land or aviation transport. For land transport modes, electrification would be the preferred route for almost all land-based transport, especially passenger cars as it is the most efficient. There would be some niche applications such as long-distance travel for heavy vehicles in which hydrogen would be preferred, but direct combustion of ammonia is not considered in this segment. Ammonia might be used to replace CNG or LPG in certain internal combustion engines where ammonia is already readily available due to existing synergies, but this will generally only be applicable to agricultural sectors in which anhydrous ammonia is already used for fertilizers – therefore making this use case negligible in terms of demand.

For aviation, ammonia will not play a role, as electrification and direct use of hydrogen or sustainable aviation fuels will be more competitive and lower risk routes. Hybrid electrification is preferred for short haul aircraft, while for long haul aircraft, sustainable aviation fuels (SAFs) will dominate with potentially some direct use of hydrogen. In the long term, post 2050, electrification of medium and long-haul aircraft could become real possibilities depending mainly on battery technology innovation.

It is expected that the demand for green ammonia for marine fuel replacement will increase significantly in the region, particularly at bunkering facilities used for international shipping. However, the likelihood of Thailand transitioning to a bunkering hub is limited. This is primarily due to the strategic position of Singapore within the region. Singapore has been actively setting goals and developing implementation plans to continue as the primary bunkering hub in Southeast Asia, making it a preferred stop for ships traversing the area. Given that Singapore is strategically located along the major shipping routes leading to and from Thailand, it is likely that vessels will choose to refuel there on their way to Thailand, rather than at Thai bunkering facilities. As a result, while the demand for green ammonia as a marine fuel is expected to rise, Thailand's growth in bunkering facilities may not be as significant as Singapore's due to its likely continued dominant position as the region's primary bunkering hub.

6.2.2.4 Energy carrier: cracking into Hydrogen

Table 6-6. Potential role of green ammonia as an energy carrier

Sector	Role	Current (BAU)	Role for green ammonia	Comment
Energy Carrier	Cracking into H_2	Various	🟨	• Cracking into hydrogen • Competition with domestic hydrogen production and other carriers

In addition to use cases in the power, industry, and transport sector, green ammonia itself is an energy carrier that can be cracked into green hydrogen for varying use cases. The varying use cases of green hydrogen have been elaborated in a previous study "Knowledge series on market development for Green Hydrogen and Power-to-X in Thailand". It is likely green ammonia will play a role to be cracked into green hydrogen only if imported green ammonia costs can compete with domestic hydrogen production and other carriers (i.e. liquefied hydrogen). Thailand has good renewables resources (both solar and wind), as well as centralized storage for hydrogen using existing salt caverns. This results in cost competitive domestic hydrogen (refer to Chapter 3.2) even towards 2050, resulting in the market leaning towards domestically produced hydrogen rather than importing green ammonia and afterwards cracking it into hydrogen. Therefore, it is not expected that green ammonia will play a significant role in meeting the demand for hydrogen in Thailand as long as sufficient domestic hydrogen production will be developed.

Other countries however, with high cost or limited renewables, will be dependent on imports to meet their green hydrogen demand. Within the APAC region, the main examples are Hong Kong, Taiwan, Japan, Korea, and Singapore with limited renewables resources but even within SEA where renewable resources are readily available, hydrogen imports are being considered. Importing a hydrogen derivative would be the main pathway to meet future green hydrogen demand, where ammonia is currently seen as the front-runner due to its low cost and existing supply chains which provide synergies with ammonia used for feedstock demand. However, competition will exist with hydrogen supplied from neighbouring countries by pipeline or the import of other hydrogen derivatives such as liquid hydrogen or LOHC.

6.2.3 Timeline of green ammonia transition

As outlined in the previous sub-section, green ammonia is likely to play a role in the decarbonization of Thailand's industrial sector and as marine fuel replacement. However, whether this transition takes place and when it would happen depends on several factors such as the economic viability of the introduction of green ammonia or the applicable policy climate. This section will aim to give insights into the first and provide a forecast of the anticipated demand for ammonia based on expected price developments. In this analysis, a cost comparison will be provided of green ammonia against the fossil alternatives for each sector and role (power as fuel, industry as feedstock, transport as marine fuel, energy carrier).

If the cost gap is not seen to be closing quickly enough, then policies aiming to close this cost gap may be required such as carbon taxes or incentive mechanisms. For this study, carbon taxation has been considered to highlight the influence of policy mechanisms on the cost competitiveness of green ammonia. Due to ongoing discussions regarding the implementation of a carbon tax in Thailand and the impact this may have on the cost analysis, three different carbon tax scenarios have been utilized:

- No carbon tax
- Low carbon price, based on current EU pledge: 65 USD/t in 2030, 75 USD/t in 2040 and 90 USD/t in 2050
- High carbon price, based on IEA scenario for Net Zero Advanced Economies: 130 USD/t in 2030, 205 USD/t in 2040 and 250 USD/t in 2050

Interpolation was used to cover intermediate years, assuming a linear increase between anchor points. The cost forecast for fossil fuels has been based on CASE data. Grey ammonia cost baseline was based on average 2021 and ammonia prices in Thailand for WITS world bank (wits.worldbank.org) and escalated based on increasing natural gas prices from CASE. The cost for green hydrogen and ammonia are based on DNV's analysis from the Chapter 3 report.

6.2.3.1 Ammonia as power generation fuel

The cost comparison of green ammonia against different fossil alternatives can be found in Figure 6-2. Without any carbon tax, there is a distinct cost gap between the pricing of coal and green ammonia until 2050. In this context, coal emerges as the most economical choice per energy unit, with domestic green ammonia the most expensive. However, the introduction of a carbon tax alters this dynamic significantly, particularly in a scenario featuring a high level of carbon taxation. Under these circumstances, ammonia will become a lowest-cost option instead of coal by 2050.

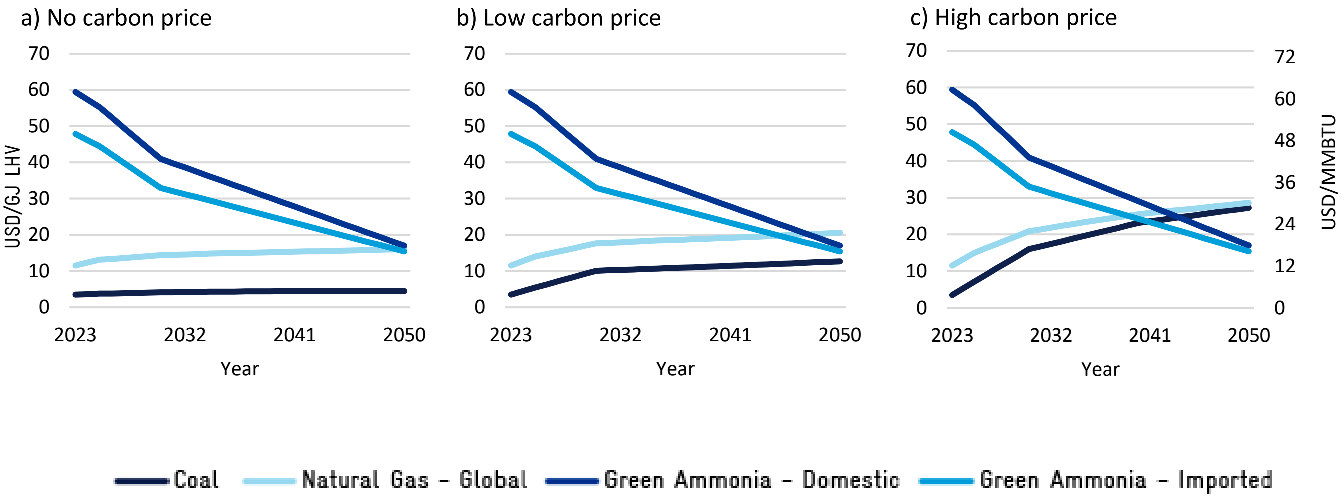

Figure 6-2. Cost comparison for green ammonia as fuel; a) no carbon tax b) low carbon price c) high carbon price

The cost competitiveness of green ammonia can be noted to be largely dependent on the carbon tax utilized. Only in the high carbon tax scenario is green ammonia able to reach parity with gas and coal, both between 2040-2045. As Thailand has no intention of utilizing its coal power plants in the long run, along with limitations mentioned in the analysis previously, co-firing will likely not be economically viable before coal plants are expected to be phased out.

6.2.3.2 Ammonia as feedstock

Transitioning to green ammonia from grey ammonia as industrial feedstock is expected to reach cost parity faster. As can be seen in the cost comparison in Figure 6-3, by 2030 both imported and domestic green ammonia will likely be cheaper than grey ammonia without the introduction of any carbon tax, which means that a carbon tax is not required for this transition. This is the result of natural cost declines in green hydrogen and subsequently ammonia, and cost increases in the natural gas required to produce grey hydrogen, which is used to make grey ammonia via the Haber-Bosch process. The main constraint will likely be the access to sufficient ammonia supply by this point, in addition to the availability of the required infrastructure for shipping and transport.

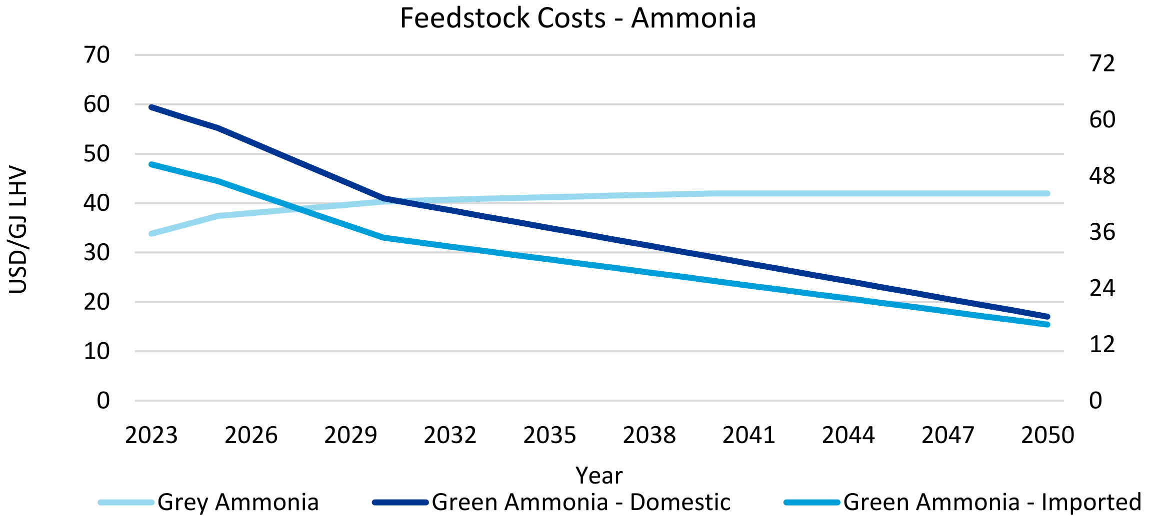

Figure 6-3. Cost comparison for green ammonia as feedstock

Compared to imported ammonia, domestic ammonia will require longer to reach cost parity but this is still expected to occur around 2030. The cost differences between the domestic and imported green ammonia are expected to gradually be decreased towards 2050. However, imported green ammonia (from Australia) is expected to remain cheaper due to its higher quality renewables and relatively low shipping costs. It is therefore expected to remain beneficial to import green ammonia.

6.2.3.3 Ammonia as marine fuel

Hydrogen-based fuels, including green ammonia, have the potential to be used in both international freight and domestic passenger transport, depending on the type of ships involved. In this section, we compared the costs of liquid hydrogen, green ammonia, and green methanol with the business-as-usual (BAU) fuels (Figure 6-4). In the maritime sector in Thailand, the primary fuels used include MGO, LSMGO, VLSFO, and IFO380. Among these, we chose MGO as a comparison fuel because it is one of the most commonly used. While LSMGO could have been an alternative, the price difference between the two fuels is limited. Although there is a shift towards using LNG as a potential shipping fuel due to its lower carbon emissions compared to existing fuels, we did not include it in the cost comparison. This is because LNG is seen as a transitional solution rather than a long-term decarbonized fuel. Additionally, LNG ship engines need to effectively manage the release of natural gas like methane, which is a potent greenhouse gas, and this can offset the greenhouse gas benefits of using LNG over MGO as a fuel.

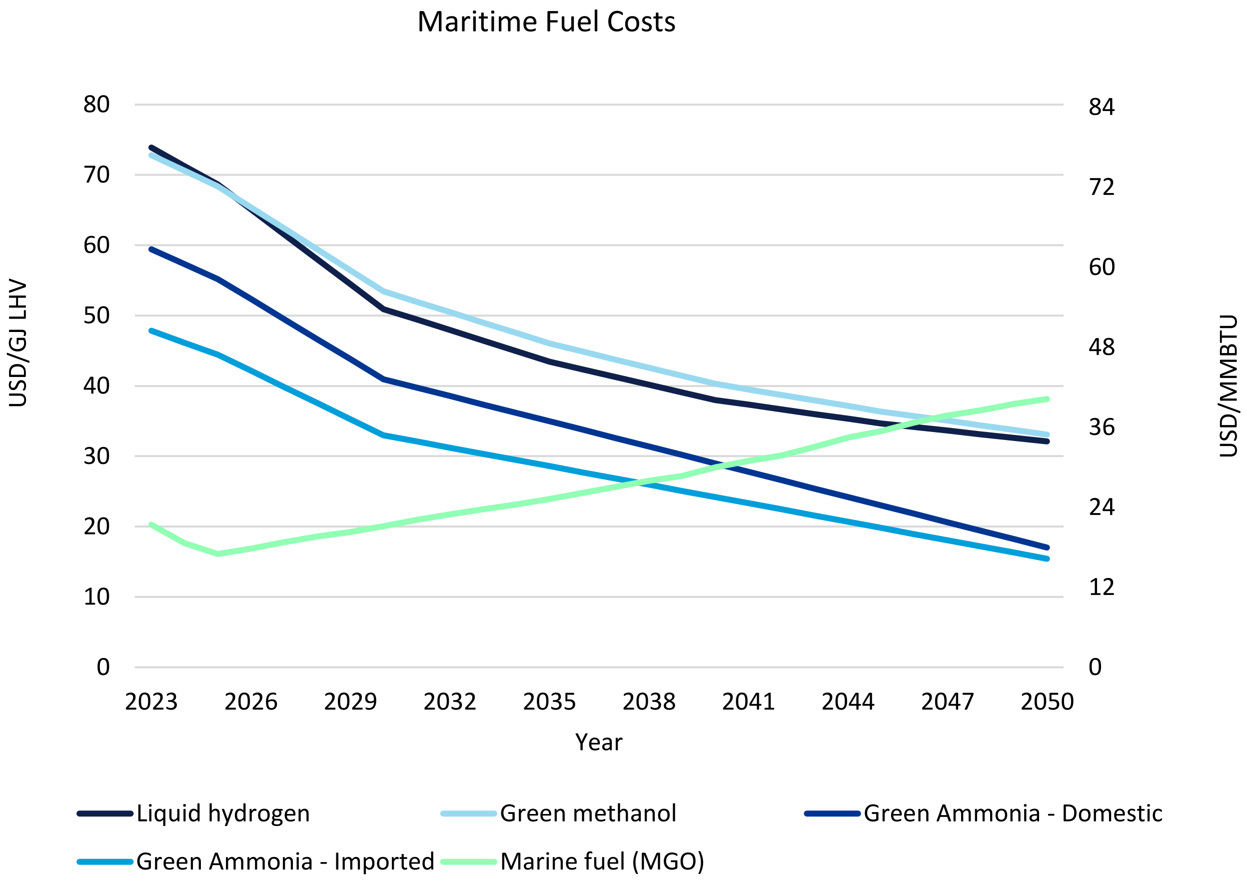

Figure 6-4. Cost comparison for green ammonia as marine fuel

Both imported and domestic green ammonia are expected to reach cost parity with MGO in 2038 – 2041, with imported ammonia reaching cost parity earlier. Among all the decarbonized fuels, green ammonia stands out with the lowest production costs. As a result, the market push is most likely to move towards ammonia in the maritime sector. However, ammonia has drawbacks compared to other options. Ammonia-powered engines produce exhaust gases containing unburned ammonia, nitrogen oxides, and nitrous oxide, raising Health, Safety & Environmental (HSE) concerns regarding toxicity and corrosiveness. This has led to a recent preference for methanol in new ship orders, especially in container shipping, as converting existing ships to methanol-ready vessels is more feasible than with ammonia, thus prolonging their service life. This is reflected by the current order book for methanol-fuelled ships, which is 20 times the amount (gross tonnage) of currently operational ones. Previously methanol-fuelled ships were used only for methanol trade, but this trend is shifting towards container shipping as well.[46] However, it should be noted that most of the ships which can use alternative fuels can also operate on fuel oils in dual-fuel solutions. The alternative fuel may be derived from fossil energy sources, which emphasizes the need for requirements that address greenhouse gas emissions from well-to-wake.

Regarding liquid hydrogen, while it shares a similar cost with methanol, it faces challenges due to its low energy density and issues with boil-off gas. It competes effectively with methanol for short distance ships (i.e. ferries and other small, short distance vessels) but faces competition from

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[46] DNV Maritime Forecast to 2050 (2023)

electrified vessels. However, for longer journeys or larger ships, liquid hydrogen is not practical due to the limitations in liquid hydrogen volumetric energy density.

Overall, based on cost comparisons, it is anticipated that cost parity for shipping fuels in Thailand will likely not be achieved until around 2040 for green ammonia and the late 2040s for methanol and liquid hydrogen. The cost of ammonia can continuously go down due to learning rates of hydrogen, while green methanol costs are additionally constrained by renewable CO_2 costs, making it more expensive in the long run. On the other hand, cost of MGO is primarily driven by the underlying oil price, with slower price increases leading to later than expected cost parity.

6.2.4 Potential future market size for green ammonia

To project the future demand for green ammonia, the traffic light analysis and cost comparison are combined. The assumption used is that the transition to a cleaner energy solution (such as green ammonia) will naturally occur once it becomes cost-competitive with the fossil fuels it aims to replace. Hence, the potential demand for ammonia in a given year will be made up of the volume of demand in each sector where cost parity between ammonia and what it aims to replace has been reached. However, for use cases labelled as 'yellow,' green ammonia will still face competition from other possible decarbonization methods, creating an upper and lower limit to this potential demand. The traffic light analysis therefore serves as a guideline on which demand will be included in the upper or lower limit:

- **Green**: Guaranteed transition towards green ammonia, included in the lower bound and upper bound for green ammonia demand.
- **Yellow**: Green ammonia will be in competition with other decarbonization routes, included only in the upper bound – this makes the difference between the lower and upper bound the uncertain demand based on how green ammonia performs in such competition.
- **Red**: No role for green ammonia, thus not included in the lower or upper bounds.

The demand for power generation is derived based on the CASE study, while the industrial demand is made up of data from Chapter 5 of this report (feedstock) and the previous 'Knowledge series on market development for Green Hydrogen and Power-to-X in Thailand' (energy carrier) study in which the CASE study was also the main underlying data source. Due to data for the maritime sector being limited to domestic demand where green ammonia will not play a role, the analysis is limited to the qualitative assessment provided previously.

Table 6-7: Upper and lower bounds for green ammonia demand under different carbon price scenarios

Unit: Mton NH_3		No Carbon Price					
Year	Role for Green Ammonia	2030		2040		2050	
Use cases		L	H	L	H	L	H
Power generation - Fuel	🟩	-	-	-	-	-	-
Industry - Feedstock	🟩	2.40	2.40	3.10	3.10	4.00	4.00
Energy Carrier - Cracking into H_2	🟨	-	-	-	3.89	-	8.10
TOTAL		**2.40**	**2.40**	**3.10**	**6.99**	**4.00**	**12.10**
Unit: Mton NH_3		Low Carbon Price					
Year		2030		2040		2050	
Use cases		L	H	L	H	L	H
Power generation - Fuel	🟩	-	-	-	-	-	-
Industry - Feedstock	🟩	2.40	2.40	3.10	3.10	4.00	4.00
Energy Carrier - Cracking into H_2	🟨	-	-	-	3.89	-	8.10
TOTAL		**2.40**	**2.40**	**3.10**	**6.99**	**4.00**	**12.10**
Unit: Mton NH_3		High Carbon Price					
Year		2030		2040		2050	
Use cases		L	H	L	H	L	H
Power generation - Fuel	🟩	-	-	-	-	-	-
Industry - Feedstock	🟩	2.40	2.40	3.10	3.10	4.00	4.00
Energy Carrier - Cracking into H_2	🟨	-	-	-	5.85	-	39.71
TOTAL		**2.40**	**2.40**	**3.10**	**8.95**	**4.00**	**43.71**

When combining the traffic light with the cost analysis insight, the expected timing and potential demand from the transition to green ammonia can be obtained. This is done under the assumption that the regulatory and policy framework put in place would ensure no additional cost would have to be borne by the consumer compared to the current situation. As the fuel costs are highly dependent on the introduction of a carbon tax, this market-based uptake forecast was performed for all three carbon tax scenarios and is showcased in Figure 6-5.

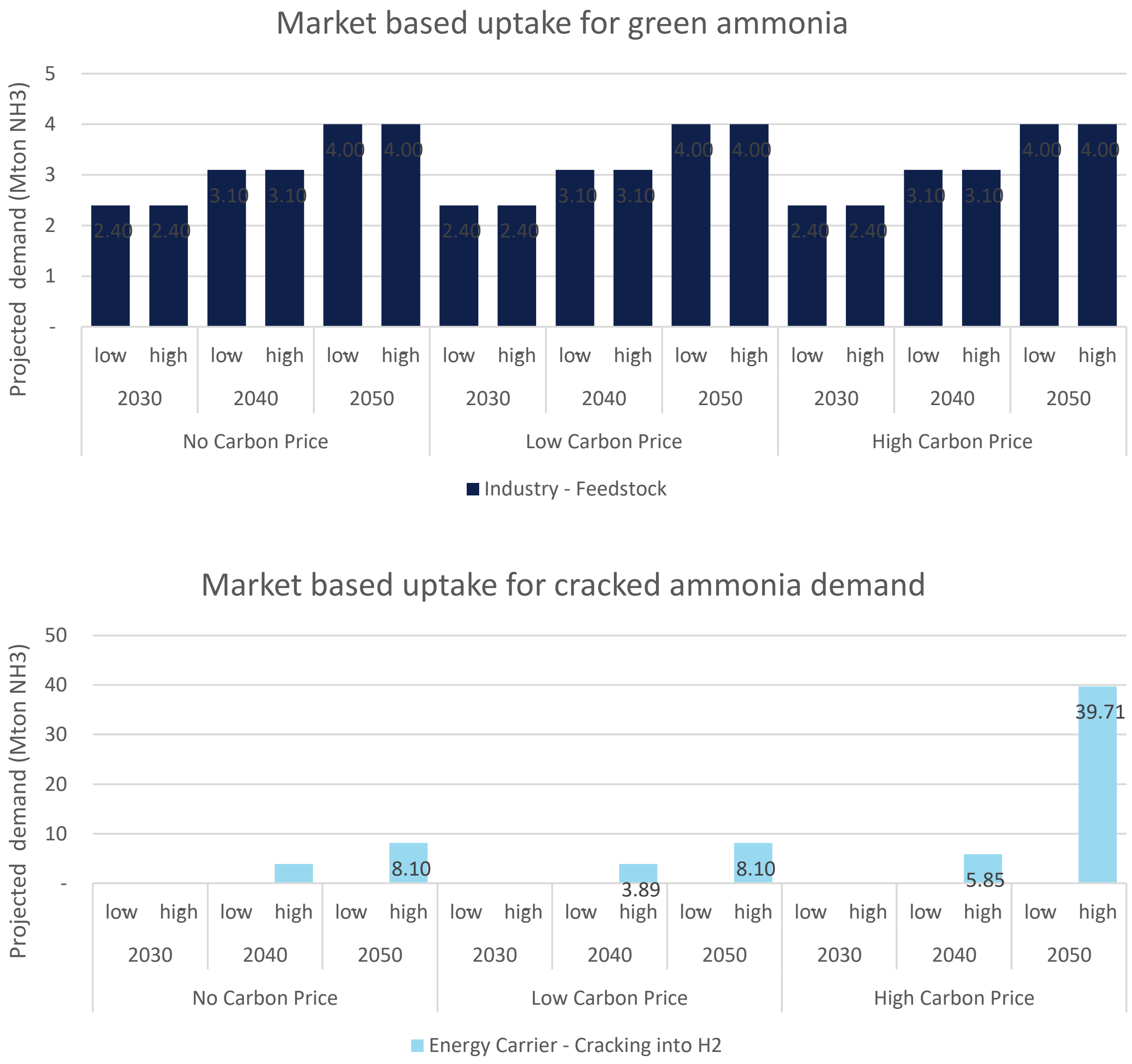

Figure 6-5. Market based uptake of green ammonia and cracked ammonia demand (no carbon tax, low carbon tax, and high carbon tax)

The demand is primarily from industry feedstock, followed by energy carrier for cracking into hydrogen. This aligns with the previous analysis, where green ammonia generally is expected to play a role for decarbonization of power generation (co-firing ammonia), industry feedstock, and marine fuel. For Thailand's context, looking at each use cases, it can be concluded that:

- **Ammonia co-firing in coal-fired power plants for power generation** – no expected demand for co-firing ammonia in Thailand. Although cost parity is reached 2040 onwards for co-firing ammonia, coal will be fully phased out around this time in Thailand and as such there is no assumed demand for ammonia co-firing.
- **Industry feedstock** – The green ammonia market is estimated to come from industrial feedstock, up to 2.40 Mt in 2030, 3.1 Mt in 2040, and 4.00 Mt in 2050. The market is estimated as the same across all carbon price scenarios as cost parity is reached right before 2030 already even without any carbon tax introduction. This demand is estimated under the assumption that Thailand imports green ammonia and afterwards produces its own urea for domestic use. If Thailand chooses to import urea directly, the demand would be lower, and if they choose to export urea, the demand would be higher.
- **Marine fuel** – the demand for ammonia as marine fuel is not reflected quantitatively in the figures above due to limited data availability or international freights from Thailand. However, it should be noted that ammonia has significant potential to contribute to decarbonization efforts in the shipping industry, particularly if there is increased initial availability in key regions. In addition to cost drivers, having first movers such as shipowners initiating projects within the sector will drive the demand in the region.

  Ammonia is one of the carbon-neutral fuels expected to dominate the 2050 energy mix globally, along with bio-MGO, bio-LNG, e-MGO, e-ammonia and blue ammonia, and bio-methanol. The DNV maritime forecast (2022) estimates that the maximum share of (carbon-neutral) ammonia by is 65% to achieve decarbonization by 2050 in the maritime sector (Figure 6-6).

Range of (carbon-neutral) ammonia fuel uptake over time

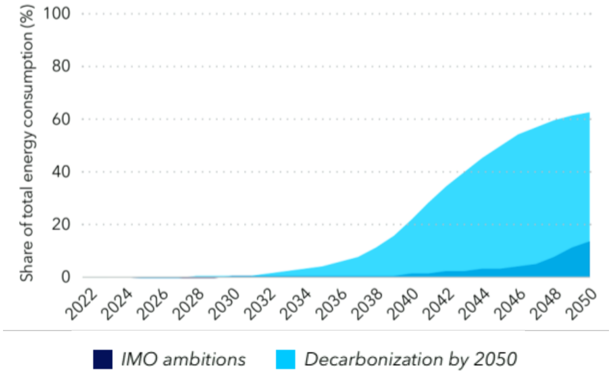

Figure 6-6. Share of ammonia fuel uptake across varying decarbonization scenarios (DNV Maritime Forecast, 2022) [47]

- **Energy carrier to crack into hydrogen** – as Thailand has cheaper domestic green hydrogen production, importing green ammonia as an energy carrier and cracking it into green hydrogen is not preferrable. Therefore, the range of demand for cracked ammonia goes from 0 to 39.71 Mtonnes of NH_3 in 2050 under a high carbon price scenario, which is its maximum potential demand in which all required green hydrogen is assumed obtained from green ammonia. Though as noted from a cost perspective, this demand is expected to be limited for Thailand due to the potential for cost-competitive domestic hydrogen production.

Overall, it can be observed that there is no difference in the market-based uptake between the no carbon and low carbon price scenario as the demand is mostly dominated by industrial

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[47] DNV Maritime Forecast to 2050 (2022)

feedstock which will reach cost parity without carbon taxation.

Based on the analysis, it can be concluded that in Thailand, green ammonia will mainly be used for decarbonization in existing use cases like industry feedstock. In a broader Southeast Asian context, new use cases can be decarbonized by green ammonia when applicable. This applies especially for countries with limited access to renewable energy resources. Such a scenario would apply where hydrogen production from renewables can be cost-extensive, and therefore importing green ammonia offers an alternative decarbonization solution, or alternatively in countries aiming to be a bunkering hub, where ammonia demand would be higher as it has the potential to be used as an alternative to MGO.

6.3 Opportunities for Thailand as an exporter / importer / self sufficient

As outlined in Chapter 5, Thailand is currently a large-scale importer of ammonia. Most of this ammonia is used for its domestic market, but Thailand also acts as a local distribution hub for some of the imported ammonia by sending it on to Cambodia and Myanmar. Based on the cost comparison in Chapter 3, it was noted that Thailand will likely not be able to produce ammonia domestically at a cost-competitive rate compared to imported ammonia until around 2050, which means that it is unlikely that Thailand will transition towards a role as exporter for ammonia as it will be cheaper for other countries to import ammonia from these exporting nations themselves (though part of it may continue to flow through Thailand). As the price of domestic and imported ammonia is close in 2050, Thailand could consider producing ammonia for its domestic need and become self-sufficient in later years, but this may be difficult to achieve once Thailand has committed to ammonia imports and has built all the requisite infrastructure, as it will need to build a different set of domestic infrastructure while accepting sunk costs in existing infrastructure and requiring significant investments (as well as policy support) to achieve domestic production at scale. A more likely route would be to continue to serve a large portion of demand via imports and only seek to meet demand growth beyond a certain year with domestic production, which can grow over time and in the long-term perhaps replace imported ammonia.

A more likely route for Thailand is that of value addition. Currently Thailand imports urea for its domestic demand at a large scale, but as outlined in previous sections this could change as a result of a transition towards green fertilizer due to Thailand's access to green CO_2 from biomass and opportunity for Thailand to import ammonia but convert this into urea domestically and become self-sufficient in terms of fertilizer production. This will require Thailand to leverage its existing petrochemical industry and experience with value-addition in an effective manner, but it does have some inherent advantages such as industrial clusters with existing heavy industry, geopolitical stability and investment credit rating with low investment risk that could make it an attractive area to invest in. This could potentially open up opportunities for Thailand to import additional ammonia for conversion into urea and export said urea to neighbouring countries.

The primary export opportunity for Thailand will however lie in the hydrogen it produces. The analysis in Chapter 3 has shown that domestically produced hydrogen has a sizable cost gap with imported ammonia that is cracked back into hydrogen; this offers an opportunity for Thailand to meet (part) of this regional demand for hydrogen via pipelines. How competitive this is will primarily depend on the distance and how the transport cost by pipeline offset the cost difference between Thailand's hydrogen production and cracked imported ammonia.

7 RISK FACTORS AND OTHER CONSIDERATONS

Due to the novel nature of many of the planned new applications of ammonia, several risk factors are expected to arise. While safety issues have been extensively discussed in Chapter 2 and are being addressed via appropriate regulation, there are several other areas where risks may appear to the role of ammonia in decarbonization which should be given appropriate consideration. These topics include, but are not necessarily limited to, technology, the market, economics and policy.

7.1 Technology

New applications of ammonia require the development of new technologies, with none of the expected key use cases (maritime fuel, power generation and cracking into hydrogen) being available commercially yet. Potential technical risks therefore include:

- Technology development does not happen as fast as expected, causing a delay in when ammonia can start contributing to decarbonization of the energy sector. This is primarily a risk for ammonia-fired power generation, which is still at a low technology readiness level, but can also affect ammonia cracking or ammonia as maritime fuel as neither are operating at scale yet.

- Technology challenges for ammonia cannot be solved or cannot be solved in a cost-effective manner. Besides its inherent corrosive and toxic nature, ammonia suffers from a low flame speed and high NO_x emissions when combusted. This will require new designs for ammonia combusting equipment, which is especially challenging for power generation turbines even in comparison to maritime engines. It is possible that these challenges, such as emissions that cannot reasonably be resolved, will inflate the cost of the solution or have a negative effect on performance in such a manner that the technology becomes unviable.

- Green ammonia projects require new and more complicated supply chains compared to fossil fuels, combining renewables, electrical infrastructure and bulk energy transport by land or sea. In combination with its rapid expected growth pace, this means that the supply chain is more prone to bottlenecks and disruptions. Examples of such disruptions are already visible in the supply of electrolysers, which can have a lead time of several years. Additionally, the Inflation Reduction Act in the US has caused a run on electrical infrastructure which is looking to cause a potential additional bottleneck in the near future. Other potential supply chain issues can be found in the maritime sector, where the lead time for new ships capable of transporting ammonia at large scale (compared to current ammonia trade) will take several years to build due to backlogs which can cause a constraint in the speed of scaling up the ammonia trading market.

7.2 Market

In order for ammonia to play a significant role in decarbonization of energy systems globally, a large-scale global market will need to develop, facilitating international trade between countries with high renewable resource potential at low cost and countries with limited or high-cost renewables. While green hydrogen and ammonia have received a lot of interest in recent years, development of both supply and demand have remained limited. This is the result of a combination of different risks that will have to be addressed:

- The key issue is that most planned green ammonia production projects are still struggling to find offtakers that are willing to provide the security that production projects need in order to make their investments. As it stands, the price of green ammonia and green hydrogen are still significantly higher than the price of their grey counterparts as well as the direct use of fossil fuels. This means that offtakers have to be willing to accept a significant price premium, which many do not appear to be willing to accept. Currently there is an absence of mechanisms to stimulate the development of early demand, which creates a lot of uncertainty for investors.

- While there may be companies willing to commit to a higher price for several years, this will be insufficient for investment in production to take place. The lifetime of production projects is expected to be around 30 years, during which the investment will have to be recovered. This requires long-term commitments from offtakers, which is considered a significant first mover risk as projects that will be developed a few years later will benefit from technology development and economies of scale which will rapidly drive down costs. This means that production from the first few projects will no longer be economically competitive within a few years of commissioning.
- As production projects require long-term commitments to recoup investments, there is no incentive to move towards a spot market for green ammonia akin to fossil fuel markets, which would connect multiple buyers and sellers and can increase security of supply (reduced dependence on single source), increase market liquidity and flexibility while reducing costs for consumers. The reason for this is that older projects will not be able to compete with newer projects in a competitive market and will get priced out quickly. This means that trade of green ammonia will likely remain point-to-point for the foreseeable future, connecting single buyers with single suppliers. A result of this is that the buyer will have to take on the majority of the risk associated with the variability of supply, where the supply of ammonia can differ from season to season as well as from year to year. This variability risk means that production projects also may have to be oversized to ensure sufficient production even in poor renewable resource seasons or years, increasing costs, as well as requiring significant investments in storage infrastructure.

7.3 Economic

One of the key challenges with the energy transition is the cost, both in terms of the overall investment required and the viability of individual projects. As a result, there is an overall risk of hesitancy within the market to invest and a preference to wait. Specific risks related to economics include:

- The actual cost of green ammonia produced at scale is still uncertain, as no large projects are currently operational. New projects therefore heavily depend on feasibility studies, cost estimates and yield projections that may not be representative of actual operations. These uncertainties can reduce the bankability of individual projects and require lenders or investors to be willing to take on significant risks.
- Cost projections for future projects tend to rely heavily on expected cost declines resulting from learning-by-doing and economies of scale. However, with a limited number of projects actually reaching final investment decision (FID) so far, it is possible that the rate of cost development will be slower than projected. This could affect the speed of transition going forward.
- Ammonia supply chains are very capital intensive. This applies to individual production or end-use projects, but even more so to the infrastructure required to facilitate a large-scale transition such as ships, import and export facilities and national pipeline networks. This will require a massive injection of capital, which many countries will not be able to provide domestically. As a result, countries in Southeast Asia will likely be heavily dependent on foreign direct investment to enable a transition towards green ammonia.

7.4 Policy

While in the long-term, it is expected that green ammonia will be cost competitive, it requires scale and experience to achieve the required cost reductions. This means that in early stages of development, there will tend to be a low willingness to invest from the market, requiring policy support. However, policies are not yet aligned globally, with different countries moving at their own pace and with their own focus, which can hinder the adoption of green ammonia. Policy risks include:

- Cost gaps between green ammonia and grey ammonia or fossil fuels are still large, requiring a high willingness to pay for the increased sustainability, support on the demand and/or supply side or significant penalties to emitters to close said cost gap. Currently there is a lack of large-scale supporting mechanisms that have managed to effectively unlock investment, with only the Inflation Reduction Act in the US an apparent success. Other markets are moving ahead with their own schemes such as Hydrogen Headstart in Australia, but doubts have been raised regarding their effectiveness as these schemes may not align with the needs of the market through implementing requirements such as a minimum volume of domestic offtake or local content requirements which can reduce their ability to close cost gaps.
- There is a lack of standardization across the ammonia and hydrogen supply chain. The lack of standardization in certification schemes has already been outlined in Chapter 4 but extends beyond the topic of classification of low carbon. For example, increased levels of standardization will also be required in equipment, safety, performance standards and quality of product. On a macro-level, there is no alignment yet between countries about the role of ammonia and hydrogen in the energy transition, with countries focusing on their own domestic interests which could lead to time and capital being expended on inferior technologies and even lock-ins if countries are unwilling to change pathways.
- In many countries, policy is being developed or considered to target the viability of individual projects on the supply or demand side. However, this is a very short-term focus area. In order for the energy transition to be successful, countries will need to put additional emphasis on the longer term. They will need to consider what is required on a system level for the end goal of decarbonization in 2050 and work backwards from there, facilitating developments that serve broader interests such as import/export and transport infrastructure. Governments will need to provide a clear long-term picture and provide certainties while de-risking these large-scale investments. Infrastructure should be developed for the expected final demand, rather than based on individual initial projects. This means that infrastructure will be underutilized in early years, requiring tariff structures that do not punish early adopters by letting them carry the full cost in this period but rather designing a low-risk long-term tariff structure that does not punish investors and keeps cost equal to users. Stability of policy and long-term vision is required for this, with the short-term focus of individual governments that have to bear early investment, with limited returns being a major risk.

8 R&D AND PILOT PROJECTS

8.1 Introduction

R&D and pilots are useful tools to transition technology from an early-stage innovation to commercially viable technology. In this Chapter, we will provide an overview of technologies for the ammonia industry which includes those that are ready to be deployed and those that are still under development and still need to overcome innovation hurdles before they can become commercially available in the market. An overview will be created of where in the development cycle the different technologies are. The main near-zero-emission technologies in ammonia production, including example projects, will be provided including the deployment status and levels of technology readiness. In the first section, an overview will be provided of the key areas of focus in R&D presently, before diving deeper into the current status.

8.1.1 Dynamic renewable ammonia production

One of the key issues with ammonia production is its lack of flexibility, which makes for a poor pairing with renewables without some form of storage. The dynamic approach to ammonia production using renewable resources entails the direct integration of clean energy generated by wind turbines and solar panels into the ammonia plant, aiming for a more cost-effective solution than the inclusion of a battery or hydrogen storage system. Presently, these technologies, often referred to as Power-to-Ammonia, are in the early stages of design and conceptual development. Across the globe, several pilot plants have taken the initiative to showcase the feasibility of green ammonia production from wind and solar sources, validating the concept, refining production processes, and collecting crucial data to facilitate future scaling-up efforts.

8.1.2 Co-firing and combustion

For the power sector, co-firing thermal power plants with hydrogen and ammonia has taken place recently in large-scale test projects as these are viewed as an additional technical option to decarbonize the sector. This option has been considered in many countries in Southeast Asia, including Thailand and Indonesia, due to the large and young thermal power fleet. Additionally, 100% ammonia use as a fuel in gas turbines is a developing field, with several turbine manufacturers developing ammonia-fuel based solutions and pilot projects.

8.1.3 Maritime fuel combustion and handling

Ammonia is gaining prominence as a carbon-neutral marine fuel, looking to play a pivotal role in decarbonizing the shipping industry and addressing environmental concerns arising from stringent emission regulations and sustainability goals.

8.1.4 Combustion for high temperature heat

DNV will address the multifaceted landscape of ammonia as a fuel source, emphasizing its role in decarbonizing high-temperature energy applications, particularly in furnaces. The discussion will cover the numerous benefits of utilizing ammonia as a fuel, while also addressing the complexities associated with ammonia combustion.

8.1.5 Cracking

For ammonia as an energy / hydrogen carrier, the catalytic ‘cracking’ of ammonia to yield hydrogen and nitrogen gas is a key process which requires large amounts of energy input and large-scale facilities to optimize cost. While many pilot projects are underway and the underlying technologies (process equipment and catalysts) are proven, the large-scale use of ammonia cracking to produce hydrogen remains an emerging industry, and even the major ammonia industry EPC and technology companies do not yet have experience in commissioning and operation of large-scale plants.

8.2 Status of research and development

8.2.1 Technology readiness evaluation criteria

The Technology Readiness Level (TRL) index stands as a globally accepted benchmarking tool used to monitor advancement and aid in the evolution of a particular technology throughout its initial stages, starting from theoretical research (TRL1) to comprehensive system demonstration under anticipated conditions (TRL9).

Figure 8-1 provides visual illustrations of the TRLs and Commercial Readiness Indexes (CRIs). The figure demonstrates that the CRI initiates when the technology reaches a stage where research validates its feasibility in the field (TRL 2). The CRI continuum extends until the technology or application is commercially deployed and becomes a bankable asset class.

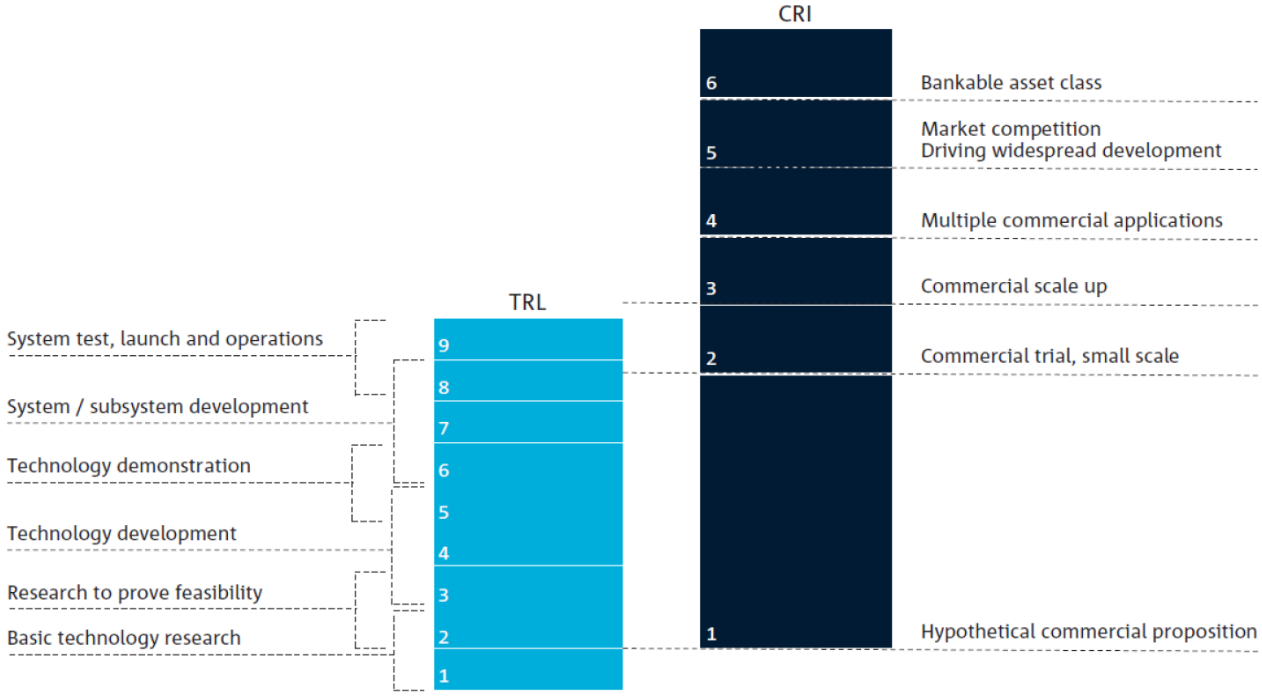

Figure 8-1. TRL and CRI scheme for qualification of technology readiness[48]**.**

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[48] ARENA, Technology Readiness Levels for Renewable Energy Sectors (2014).

The table 8-1 summarizes the Technical Readiness Level (TRL) scale applied in the assessment of technologies relevant to hydrogen value chains. Both the current and the expected change in state of development are provided.

Technologies falling between TRL 1 to TRL 7 are deemed 'hypothetical commercial propositions'. Typically, when technologies reach TRL 8-9, they transition to a 'commercial trial' scale, allowing for the application of the Commercial Readiness Index (CRI) up to CRI 6. This effectively reflects the 'bankability' of the commercialized technologies.

The table serves as guidance, offering an estimated timeline for commercialization/development based on the TRL ranking. However, it is important to note that this is indicative and represents technologies that successfully achieve full commercialization. Some technologies may encounter insurmountable obstacles that hinder their further progress and commercialization.

8.2.2 Dynamic renewable ammonia production

Dynamic renewable ammonia production offers a promising solution for tackling the technical challenges associated with storing renewable energy efficiently. This approach converts excess wind or solar energy into more durable forms, addressing the need for effective renewable energy storage. Additionally, it can help mitigate common challenges encountered in traditional ammonia production processes. It will also reduce reliance on non-renewable resources and decreased greenhouse gas emissions.

Renewable ammonia production utilizes renewable hydrogen, derived through water electrolysis powered by renewable electricity sources. The resulting hydrogen is then converted into ammonia, with the necessary nitrogen extracted from the air.

To classify the produced ammonia as renewable, it is essential that all feedstocks and energy sources used in its production come from renewable origins, such as biomass, solar, wind, hydro, and geothermal energy sources.

Table 8-1. Technology development timeline guidance

TRL	Description	Remaining development time
TRL 1	Basic principles observed	10-15 years
TRL 2	Technology concept formulated	8-12 years
TRL 3	Experimental "Proof of concept" basic technology experimentally demonstrated	6 years
TRL 4	Technology validated in lab	5 years
TRL 5	Technology validated in relevant environment	4 years
TRL 6	Technology demonstrated in relevant environment	3 years
TRL 7	System prototype demonstration in operation environment	2 years
TRL 8	(Pre)-production of series production qualified and tested in operational environment	1 year
TRL 9	Serial production and further development, commercially available-review commercial readiness indicator	

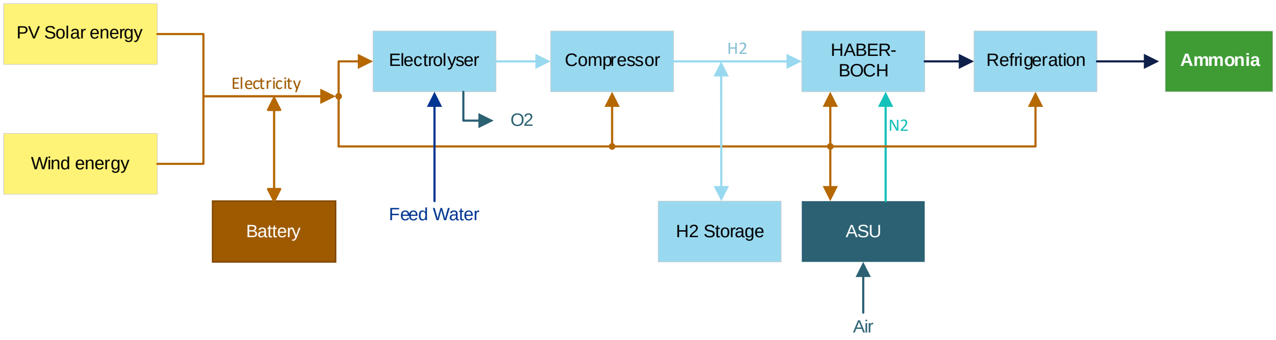

Figure 8-2. Schematic of major components considered in the off-grid green ammonia production model[49]

However, dynamic renewable green ammonia production faces multifaceted challenges, including the need for system flexibility to manage fluctuations in renewable energy sources like solar and wind power. These fluctuations can lead to operational disruptions and affect the Levelized Cost of Ammonia (LCOA). This novel approach links ammonia synthesis to input electric power through hydrogen (H_2) and nitrogen (N_2) generation and storage, introducing complexities that require innovative solutions. Additionally, site-specific energy profiles have varying effects on the viability of the green ammonia (g NH_3) concept, necessitating tailored strategies and designs.

The primary challenge in ammonia production revolves around minimizing load fluctuations within the ammonia synthesis loop. Continuous hydrogen, nitrogen, and process electricity supply is essential due to the challenging conditions within the ammonia synthesis reactor. Traditional synthesis loops are designed for stable operation throughout a plant's lifespan. Some technology licensor solutions offer operational flexibility down to 10% of capacity, with potential operation at 0% capacity supported by electricity and hydrogen storage. However, efficiency at low production capacities may be lower than under ideal conditions. Various components, such as compressors, pumps, and chiller units, could be optimized for steady-state operation, with a conventional turndown limited to 40% and a dynamic ramp rate of 20% per hour. Alkaline electrolysers are required to operate within a range of 10% to 40% minimum load to prevent gas impurities in hydrogen and oxygen streams, with safety systems activating at 1% to 2% hydrogen contamination in the oxygen stream.

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[49] Wang et al (2023): Optimising renewable generation configurations of off-grid green ammonia production systems considering Haber-Bosch flexibility

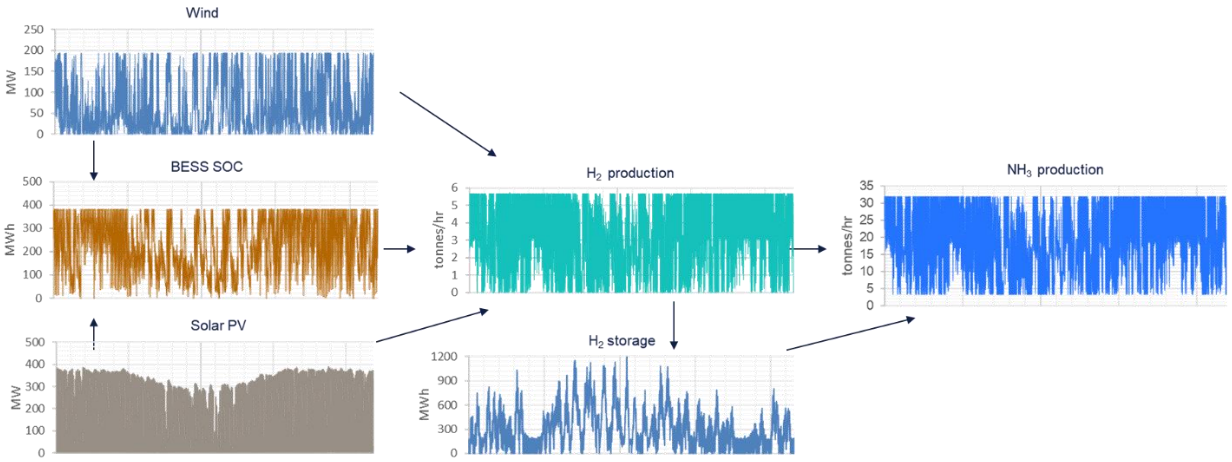

Figure 8-3. Fluctuation in renewable energy sources over a one-year period

Matching variable electricity supply with electrolysis and hydrogen production presents a significant challenge. Among available electrolyser technologies, proton exchange membrane (PEM) electrolysers offer the highest operational flexibility and turndown capability. While PEM electrolysers are more expensive than alkaline electrolysers (AE), AE systems also possess operational flexibility, albeit with a higher minimum load requirement. Some AE models can be placed in a warm standby state, and periodic stack shutdowns are possible without significant catalyst degradation. The modularity of electrolyser stacks plays a crucial role in achieving system-wide dynamic operation, enabling actions such as shutting down a bank of stacks during winter months to optimize utilization during low solar conditions[50].

Another key challenge associated with green ammonia production includes the need for competitive renewable electricity prices, the impact of intermittent generation on production consistency, high capital expenditures for electrolysis facilities, uncertainty regarding market pricing and incentives, and the consideration of passing on costs to consumers. Navigating these challenges requires a strategic approach addressing technological, economic, and regulatory aspects.

Designing a flexible and optimized system is crucial for achieving competitive green ammonia production costs. Systems relying solely on a single-generation source and possessing inflexible hydrogen-based (HB) components tend to have higher costs. Flexible HB systems, especially when incorporating wind and solar PV sources, reduce the reliance on wind deployment and contribute to cost reduction. Systems with a significant solar PV component typically require battery energy storage systems (BESS) for night-time operation. Flexible HB systems, while moderately reducing the need for BESS, still require it to balance alkaline electrolysis for hydrogen production and the Air Separation Unit-Hydrogen-Based (ASU-HB) system for ammonia production during night-time hours. Hybrid wind-solar PV generation systems can substantially reduce the Levelized Cost of Ammonia (LCOA) by enhancing capacity factors and reducing the need for renewable energy capacity, curtailment, and storage. The flexibility of the HB system, even with a partially relaxed minimum operational load requirement, enables large-scale ammonia production. A balanced wind

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[50] Wang et al (2023): Optimising renewable generation configurations of off-grid green ammonia production systems considering Haber-Bosch flexibility

and solar PV configuration could further reduce the LCOA.

Finally, the transition from grey ammonia production to green ammonia production is promising but faces substantial challenges, including the need for investment, expertise, integration of renewable energy sources, and optimization of production processes. The intermittent nature of wind and solar energy poses technical and commercial challenges, requiring innovative energy storage and integration solutions. Efficient energy storage and demand-side management strategies are essential to address energy generation variability.

Despite these challenges, the industry is forging ahead with pioneering pilot plants, such as the Yara Pilbara Renewable Hydrogen Project and the Fukushima Wind Power-to-Ammonia initiative, which are demonstrating the viability of green ammonia production. Furthermore, key players like Topsoe, Casale, KBR, and ThyssenKrupp are in the design and concept phase, highlighting the industry's commitment to innovation. Chinese companies are also developing their own facilities, with Envision's green ammonia plant in Inner Mongolia potentially becoming the world's first commercial-scale dynamic green ammonia facility in 2024. These developments mark a significant step towards a sustainable future for ammonia production.

Table 8-2. Dynamic green ammonia technology readiness

End-use technologies and systems	Current TRL	2030	2035	2040
Dynamic Renewable Ammonia production	5-6	8-9	9	

8.2.3 Gas turbine power generation

Hydrogen possesses the capacity to serve as a clean and adaptable fuel for gas turbines, offering the capability to deliver on-demand power to bolster renewable energy resources. Nonetheless, numerous obstacles need to be surmounted to enable the extensive adoption of hydrogen in gas turbines.

One of the main challenges is the combustion characteristics of hydrogen. Hydrogen has a higher flame speed and a wider flammability range than natural gas, which can lead to increased combustion instability and the risk of flashback. This can result in increased emissions of pollutants such as NO_x. Moreover, hydrogen exhibits a reduced energy density compared to natural gas, necessitating the storage and transportation of larger volumes of hydrogen to achieve an equivalent energy output.

In response to these obstacles, ongoing research aims to create gas turbine combustion systems capable of efficient and secure operation with hydrogen. This encompasses the utilization of cutting-edge fuel injection mechanisms, innovative combustion chamber configurations, and refined control systems, all geared towards enhancing combustion stability and minimizing emissions. Furthermore, advancements in hydrogen storage and transportation technologies are imperative to establish hydrogen as a feasible fuel source for gas turbines.

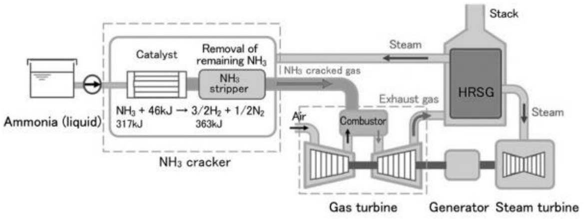

Figure 8-4. Concept of ammonia decomposition gas turbine cycle[51]

Currently, there are only a few gas turbines that have been specifically designed or modified for the combustion of 100% ammonia fuel. Here are some examples of companies and projects related to ammonia-fuelled gas turbines, along with their corresponding power capacities:

- Chalmers University of Technology: Researchers at Chalmers University in Sweden have modified a Siemens SGT-400 industrial gas turbine to run on 100% ammonia. The modified turbine has a power output capacity of 400 kW.
- Gas Turbine Research Establishment (GTRE): GTRE, an Indian government-owned laboratory, has designed and developed an experimental gas turbine that can operate on 100% ammonia. The turbine has a power output capacity of 100 kW.
- Mitsubishi Power is in the process of developing a 40 MW-class gas turbine, with a specific focus on enabling 100% ammonia combustion. The project, called "Green Ammonia Demonstrator", aims to achieve operation on commercial-grade systems and commercialization of ammonia-fuelled gas turbines by the mid-2020s. Currently, the project is actively conducting combustion validation testing.
- In September 2022, Mitsubishi Power's parent company, Mitsubishi Heavy Industries (MHI), entered into an agreement with the Indonesian research institution Institut Teknologi Bandung (ITB) for collaborative research focused on the advancement of an ammonia-fired gas turbine, with the ultimate goal of demonstrating its capabilities on an H-25 gas turbine (Figure 8-5). Subsequently, MHI partnered with Keppel New Energy, an energy solutions company based in Singapore, to conduct a feasibility study regarding the establishment of a power plant fuelled entirely by ammonia, located at a site in Singapore. In August 2022, MHI and JERA announced their joint exploration into the potential development of a 100% ammonia-fired combined cycle plant on Jurong Island in Singapore.

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[51] Development of Hydrogen/Ammonia Firing Gas Turbine for Decarbonized Society

- GE Gas Turbine and IHI Corporation agreed early this year to develop a technology roadmap to convert existing GE gas turbine models to run on up to 100% ammonia by 2030. A "retrofittable" ammonia combustion system will be developed for three utility-scale GE models: the 6F.03 (88 MW), 7F (201 – 239 MW) and 9F (288 MW) gas turbines, with additional models to be explored should the trials be successful (Figure 8-6).
- IHI Corp. achieved noteworthy progress by successfully testing mono-firing of liquid ammonia in a new combustor integrated into a 2-MW class IM270 gas turbine. These tests yielded a greenhouse gas reduction rate exceeding 99%, even with ammonia fuel ratios between 70% and 100%. This achievement is significant as liquid ammonia's inherent low flammability makes combustion challenging. IHI Corp. aims to further reduce nitrous oxide (N_2O) emissions, enhance operational aspects, assess long-term durability, and work towards realizing a practical 100% liquid ammonia combustion gas turbine by 2025.

Figure 8-5. H-25 series gas turbine

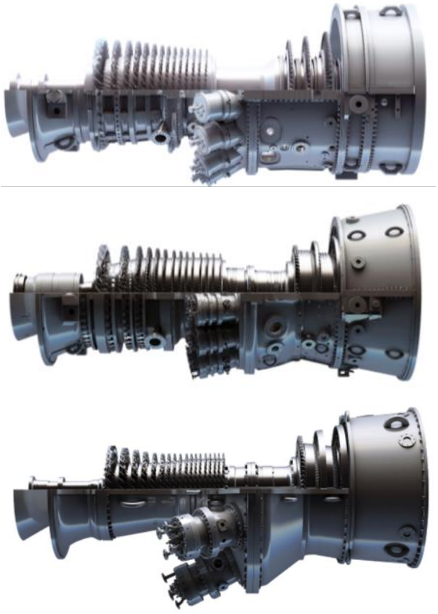

Figure 8-6. From top to bottom: the 6F.03, 7F and 9F GE gas turbine models of GE Gas Power.

There are several technical challenges associated with using ammonia as a fuel in gas turbines. These include issues related to combustion instability, increased nitrogen oxide (NO_x) emissions, and the potential for fouling of components.

The commercial readiness of ammonia-fuelled gas turbines for large-scale power generation will depend on various factors, including the pace of technological advancements, the availability of ammonia as a fuel, and the policy and regulatory environment. While some demonstration projects are underway, it may take until the 2030s before ammonia-fuelled gas turbines are commercially viable for large-scale power generation.

Table 8-3. Gas turbine power generation technology readiness

End-use technologies and systems	Current TRL	2030	2035	2040
Direct use of ammonia in gas turbines (aeroderivative)	5-6	8-9	9	
Direct use of ammonia in gas turbines (large-scale)	3-5	6-7	7-8	9

8.2.4 Fuel for reciprocating engines

Ammonia is gaining traction as a promising marine fuel to tackle shipping's environmental impact. This move is driven by regulations demanding emission reductions and sustainability improvements in the industry. Ammonia offers several advantages as a marine fuel, particularly when derived from renewable sources. Its combustion leads to lower carbon content in the fuel, resulting in reduced CO and CO_2 emissions. However, the higher hydrogen atom content in ammonia (3), compared to hydrogen molecules (2), can lead to increased emissions of HC and NO_x, which can be mitigated through the utilization of Selective Catalytic Reduction (SCR). Also, the absence of sulphur content in ammonia prevents the emission of sulphur dioxide during combustion, setting it apart from conventional maritime fuel.

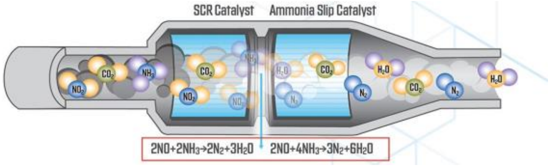

Figure 8-7. Selective Catalytic Reduction technology[52]

Ammonia also offers advantages in storage compared to hydrogen. Despite its lower energy content per ton, its higher density translates to a reduced storage volume requirement for equivalent energy. Consequently, the cost of storage per energy unit is notably lower than that of hydrogen, battery-stored electricity, or LNG. However, it necessitates more space than other fuels like MGO and LPG. This can have implications for cargo capacity and transportation costs, potentially requiring larger storage tanks, more frequent refuelling, or the potential adoption of dual-fuel approaches[53].

However, ammonia also presents challenges. Its toxicity, limited experience as a combustion engine fuel, and relatively low energy utilization rate demand thorough analysis to ensure both safe and efficient implementation. The impact on the aquatic environment must also be considered, as ammonia can be harmful to marine life. However, the risks of using ammonia as a fuel appear to be low due to factors such as rapid evaporation after spillage (due to considerable disparity between ammonia's normal saturation temperature and water temperature) and the small ratio of fuel to surrounding water.

The choice of ship fuel significantly impacts safety measures, varying across different fuel types. In the case of ammonia, its toxicity, flammability, and low-temperature storage requirements necessitate tailored safety protocols. Despite its toxicity, ammonia's combustion properties are comparable to LNG, and its strong odour enables easy detection even at low concentrations (17 ppm). It is reactive but stable, soluble in water, and its potential for hazardous particle formation is of greater concern in polluted urban areas. Ammonia's refrigeration storage temperature (-33°C) mitigates certain risks, such as cryogenic burns, distinguishing it from LNG or liquid hydrogen[54].

Addressing the issue of ammonia toxicity in enclosed spaces is a paramount concern when

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[52] Selective Catalytic Reduction (SCR)

[53] Machaj et al (2022): Ammonia as a potential marine fuel: A review

[54] Machaj et al (2022): Ammonia as a potential marine fuel: A review

adopting it as a marine fuel. Ammonia's inherent toxicity can pose risks in confined areas with limited ventilation, potentially leading to delayed leak detection, increased exposure and potential health hazards for crew members. Ensuring crew readiness through training, equipping ships with effective monitoring systems, and emphasizing meticulous system design to prevent leaks are crucial steps in managing this challenge. Warranting personnel safety during ammonia spills and emergency equipment for work in gas filled space are paramount in the maritime industry, involving measures like water spray systems, emergency showers and eye wash stations, and compartment sealing. Preventing routine ammonia release and addressing various risks, such as pipe ruptures, exposure during maintenance, and valve malfunctions, requires context-specific mitigation strategies based on ship characteristics and activities[55].

Another aspect of ammonia to consider is its corrosiveness to materials like copper and zinc which mandates careful material selection. Dissolved oxygen in liquid ammonia elevates stress corrosion risk, underlining the importance of air purging before filling systems. While stress corrosion can be mitigated by adding water and maintaining lower transportation temperatures, meticulous design, like post-weld stress relief for tanks, further reduces its probability[56].

For storing ammonia as a propulsion fuel, pressurized tanks at ambient temperatures are the primary choice due to their reliability. While options like semi-refrigerated or refrigerated tanks are feasible, they introduce complexities related to temperature control and require backup systems for reliability. Pressurized tank storage is a simpler and more dependable solution[57].

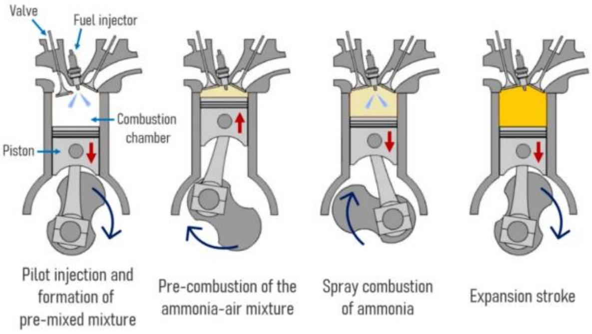

Figure 8-8. Ammonia as fuel for internal combustion engine[58]

Research on spark-ignited and compression-ignited engines has yielded positive results (Figure 8-8). Theoretically, ammonia can be utilized in diesel engines in single or dual fuel modes. However, employing ammonia in the dual-mode concept reduces Brake Thermal Efficiency (BTE) due to its slow flame speed, which becomes more pronounced with higher concentrations. As the flame weakens, the auto-ignition temperature rises, impacting thermal efficiency. Ammonia exhibits resistance to autoignition temperatures across various engine loads[59].

Applying insights from LPG experience, similar strategies can be used to handle ammonia, especially in its liquid form. Yet, adapting diesel engines for ammonia's unique properties requires redesign and solutions to mitigate NO$_X$ emissions. Ammonia's high octane rating allows for elevated compression ratios without knocking, and its lower stoichiometric air-fuel ratio permits increased ammonia introduction to compensate for lower energy content. However, this can lead to challenges such as unburnt ammonia and ammonia slip due to its narrow flammability range and slower flame speed.

In the foreseeable future, internal combustion engines are poised to maintain an important position, driven by factors including cost-effectiveness, power density, load response, and durability. Among these engines, two-stroke diesel

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[55] DNV, Ammonia as a Marine Fuel, 2020.

[56] DNV, Ammonia as a Marine Fuel, 2020.

[57] DNV, Ammonia as a Marine Fuel, 2020.

[58] Ammonia as an energy vector: Current and future prospects for low-carbon fuel applications in internal combustion engines. https://bicef-nh3.netlify.app/

[59] S. Manigandan et al (2023): Hydrogen and ammonia as a primary fuel – A critical review of production technologies, diesel engine applications, and challenges.

variants are particularly prominent for powering large ships due to their spacious combustion chambers and extended operational periods at low RPMs. MAN Energy Solutions (MAN ES) is leading the way with dual-fuel engine development, including ammonia compatibility. They anticipate ammonia-ready engines within five years, along with retrofit packages for existing models. MAN ES's innovation extends to low-pressure fuel injection for reduced costs and weight but also overall simplified engine system[60].

Wärtsilä Corporation is actively investing in research and development to enhance the adaptability of four-stroke engines, with a specific focus on incorporating carbon-free fuels like ammonia. The tests use ammonia fuel at either gaseous low pressure (Otto cycle) or liquid high pressure (Diesel cycle), both requiring pilot fuel. This ongoing effort includes specialized technologies for marine vessels, currently in developmental stages. Advanced platforms like the W31 exemplify modularity, enabling potential adaptations for ammonia usage. This flexibility extends to diesel, dual-fuel, and spark-ignited platforms. The decision to proceed with a commercial product will depend on market interest.

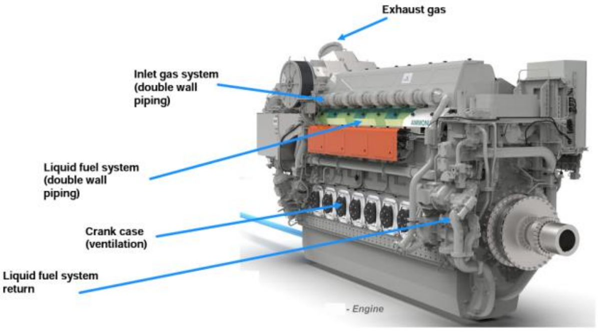

Figure 8-9. Wärtsilä's four-stroke multi-fuel marine engine[61]

Solid oxide fuel cells (SOFC) are gaining traction in the market because of their capacity to efficiently transform fuels like ammonia, LNG, methanol, and hydrogen into electricity. This technology offers the prospect of achieving higher energy efficiency when compared to internal combustion engines. In addition to the potential efficiency gains, fuel cells offer a range of other advantages, including decreased noise levels, reduced maintenance requirements, a modular and adaptable design, and enhanced efficiency during part-load operation. Intensive research efforts are currently for Solid Oxide Fuel Cells-H (proton-conducting electrolyte) and Solid Oxide Fuel Cells -O (oxide ion-conducting electrolyte) models, with the latter being more widely adopted, although there are still no commercially-available fuel cells. The utilization of hydrogen stored in ammonia presents two potential paths for electricity generation: direct conversion through Solid Oxide Fuel Cells (SOFCs) or employing ammonia cracking before utilizing SOFCs. Overcoming challenges related to SOFC degradation rates and system heat integration remains crucial. Addressing load change challenges could involve integrating batteries; however, while established guidelines for battery-powered ships provide insights for hybrid systems, combining SOFCs with batteries introduces complexities in spatial and weight management due to the larger size and weight of SOFC systems compared to conventional diesel engines. Additionally, evolving regulatory requirements for ship-based fuel cell energy production further contribute to the complexity. These intricacies underline the ongoing investigation into the feasibility of ammonia fuelled SOFCs and emphasize the need for further research[62].

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[60] DNV, Ammonia as a Marine Fuel, 2020.

[61] AEA Webinar – Marine Ammonia Engine Safety

[62] Machaj et al (2022): Ammonia as a potential marine fuel: A review

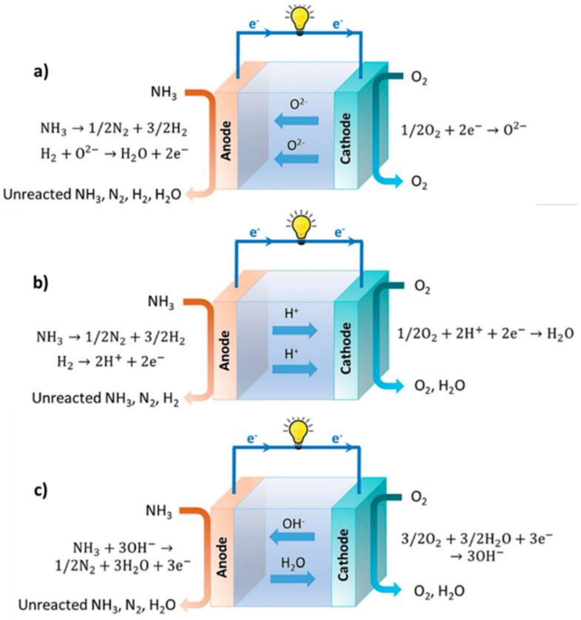

Figure 8-10. Schematic representation of: (a) oxygen direct fuel cell ammonia-fed (SOFC-O); (b) proton direct fuel cell ammonia-fed (SOFC-H) and (c) alkaline ammonia-fed fuel cells (AMFCs)[63]

The ShipFC54 project aims to showcase the viability of ammonia-fuelled Solid Oxide Fuel Cells for enabling long-range, zero-emission journeys on larger ships. In this initiative, the Viking Energy offshore vessel, owned by Eidesvik, will undergo retrofitting by late 2023, equipping it with a 2-megawatt (MW) ammonia fuel cell. The project's goal is to demonstrate the vessel's capability to operate solely on ammonia for up to 3,000 hours annually. Furthermore, the project seeks to validate that a large fuel cell can reliably and safely serve as the primary source of electric power for the ship's onboard systems. In parallel efforts, a consortium led by Shell is set to test a 600-kilowatt (kW) SOFC auxiliary power unit on an LNG carrier in 2025, with the goal of assessing its decarbonization potential, scalability for shipping propulsion, and fostering wider acceptance of fuel cell technology within the industry. Additionally, cruise ship operators like MSC Cruises are exploring the integration of SOFCs with natural gas and hydrogen as part of their commitment to cleaner, more sustainable operations in the maritime sector[64].

Table 8-4. Fuel for reciprocating engines technology readiness

End-use technologies and systems	Current TRL	2030	2035	2040
Direct use of ammonia in two stroke engines	5-6	8-9	9	
Direct use of ammonia in four stroke engines	5-6	8-9	9	
Direct use of ammonia in SOFC	5-6	6-7	7-8	9

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[63] Current Research on Green Ammonia (NH3) as a Potential Vector Energy for Power Storage and Engine Fuels: A Review

[64] DNV. Energy Transition Outlook 2023, Maritime Forecast to 2050

8.2.5 Co-firing in coal power stations

Co-firing ammonia with coal in coal-fired power plants has gained attention for its potential to reduce greenhouse gas emissions. This involves injecting ammonia into the coal combustion process, which can effectively reduce CO_2 emissions for a given power output.

Ammonia co-firing offers several advantages for existing coal-fired power plants. It can reduce greenhouse gas emissions, enhance fuel flexibility, and even create a potential market for renewable ammonia production. However, it is essential to note that the impact on plant efficiency will depend on the specific technology of the coal power station.

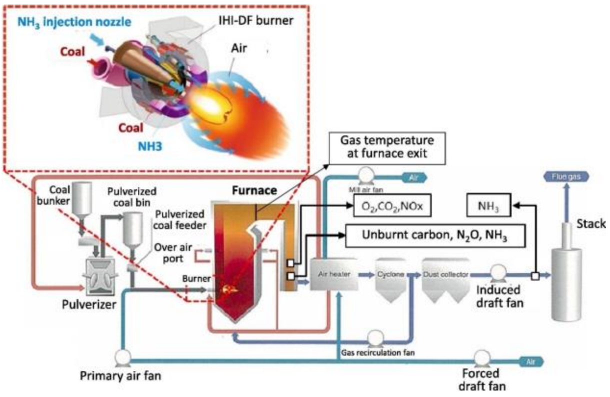

Figure 8-11. Main flow diagram of Ammonia-coal co-firing facility[65]

One challenge[66] associated with ammonia co-firing is the potential for increased NO_x emissions due to ammonia's higher nitrogen content compared to coal. To address this, selective non-catalytic reduction (SNCR) systems and other emission control technologies can be employed. Research indicates that NO_x emissions increase notably only when the NH_3 ratio reaches 30%, and effective control measures can enable co-firing NH_3 up to 25%. It is important to balance NO_x reduction with unburnt carbon levels, requiring careful combustion controls for economically efficient operation.

The compatibility of coal-fired boilers with ammonia co-firing should also be evaluated. Research suggests that the air requirement for the boiler remains stable across different NH_3 ratios, indicating that primary and secondary air fans typically do not need modifications for NH_3 co-firing. However, adjustments may be necessary for the primary air required by mills, such as implementing a bypass system to accommodate NH_3 substitution for coal.

Maintaining the right flue gas temperature at the furnace outlet is crucial for boiler safety. Some studies indicate that as the NH_3 ratio increases, there is a decrease in furnace heat load due to changes in flame characteristics. While this affects radiation and adiabatic flame temperature, the flue gas temperatures at the furnace outlet remain stable, mitigating the risk of overheating and slag accumulation on heating surfaces.

Flue gas speed and temperature alterations can affect tube wall temperatures and potentially lead to tube overheating. Research suggests that co-firing NH_3 up to 50% is unlikely to cause tube overheating, as indicated by stable steam temperatures and minimal changes in heat transfer coefficients for superheaters.

Low-temperature corrosion concerns in air preheaters can also be influenced by NH_3 co-firing, particularly due to changes in acid dew points and metal temperatures. While the impact is minimal at 100% boiler load, anti-corrosion measures may be needed at lower loads.

Implementing NH_3 co-firing in different ratios requires modifications to burners, NH_3 feeding systems, and primary air pipes, which come with associated costs. Running costs vary with NH_3 ratios, with ammonia's higher cost compared to coal posing an economic challenge. To address this, reducing NH_3 prices through green hydrogen production or other methods could enhance economic viability. Additionally, a higher CO_2 tax

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[65] Zhang et al (2020): Numerical investigation on ammonia co-firing in a pulverized coal combustion facility: Effect of ammonia co-firing ratio

[66] Wang et al (2022): Effect of ammonia co-firing on heat transfer, safety, and economy of coal-fired boilers.

can further incentivize NH_3 co-firing as a cleaner energy option.

While ammonia co-firing is feasible in various blend ratios, higher ratios need careful consideration due to potential NO_x emissions. While small-scale pilot projects have shown promise, addressing reliability, efficiency, and cost-effectiveness challenges is essential for scaling up ammonia co-firing in coal-fired power plants.

Table 8-5. Co-firing in coal power stations: technology readiness

End-use technologies and systems	Current TRL	2030	2035	2040
Co-firing of ammonia in coal fired power plants	5	6-7	7-8	9

8.2.6 Combustion for high temperature heat

Ammonia, a carbon-free fuel, is attracting significant attention due to its potential to meet high-temperature energy needs, particularly in applications like furnaces. Its adoption is driven by several advantages, including ease of storage and transport, compressibility, lower operational costs for liquefaction, well-established production methods and infrastructure, and the ability to enable carbon-free combustion. As nations worldwide transition towards cleaner and more sustainable energy sources, ammonia has emerged as a versatile contender. Ammonia's role in high-temperature applications, such as in furnaces and power plants, presents a potential opportunity for contributing to carbon neutrality.

However, ammonia combustion presents certain challenges that hinder its widespread adoption. Research[67] has shown that ammonia exhibits weaker combustion reactivity compared to traditional fuels like hydrogen or methane. This is characterized by a lower laminar burning velocity and extended ignition delay times. These characteristics can lead to combustion instability, limiting its adoption as a fuel source. Additionally, ammonia combustion is associated with flame instability due to erratic combustion behavior and significant emissions of nitrogen oxides (NO_x) and unburned ammonia, further complicating its use.

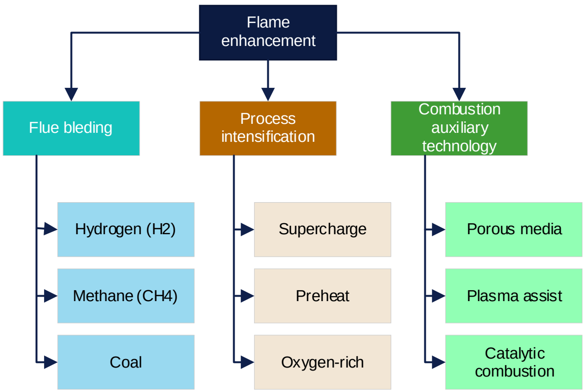

Figure 8-12. Parameters for ammonia combustion enhancement[68]

To mitigate these limitations and enhance ammonia combustion characteristics, researchers are exploring the synergistic potential of ammonia and other fuels such as hydrogen, methane, methanol, or even coal (Figure 8-12). This approach can enhance combustion stability, increase the burning velocity, and reduce ignition delay time. The ammonia-hydrogen blend, in particular, has garnered attention for its ability to improve reactivity, promote ammonia ignition, reduce ignition temperature, and make the combustion process more efficient. Blending with coal in power generation, though in its early stages, is an area of interest for its potential in reducing CO_2 emissions and NO_x through selective non-catalytic reduction (SNCR) reactions. However, this field requires more comprehensive exploration, including challenges in accurately modelling ammonia combustion, optimizing system configurations, and managing the storage of blended fuels.

Research explores emission characteristics and technologies like burner optimization and injection strategies. Achieving a specific equivalence ratio can minimize both total NO_x and unburned

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[67] Duan et al. (2023): Research progress of ammonia combustion toward low carbon energy

[68] Figure based on data from Duan et al. (2023): Research progress of ammonia combustion toward low carbon energy

ammonia emissions, underscoring the importance of micro-rich combustion in effective ammonia utilization. However, research in this area is in its early stages and requires comprehensive testing under diverse conditions.

Despite ongoing research, there is still much to learn about ammonia combustion, especially in turbulent flames, which are widely used in industrial applications.

Studying laminar flames helps understand primary radical species and combustion properties. Ammonia flames, while visually similar to hydrocarbon flames, exhibit differences in the mechanisms responsible for their appearance (Figure 8-13). Laminar burning velocity is a crucial parameter for laminar flames, and ammonia's relatively low value distinguishes it from other fuels. Various methods, including fuel blending, temperature elevation, and oxygen content increase, can enhance ammonia's burning velocity. The presence of carbon monoxide can impact ammonia's burning velocity, but its effect varies with concentration. Research in this area continues to refine our understanding.

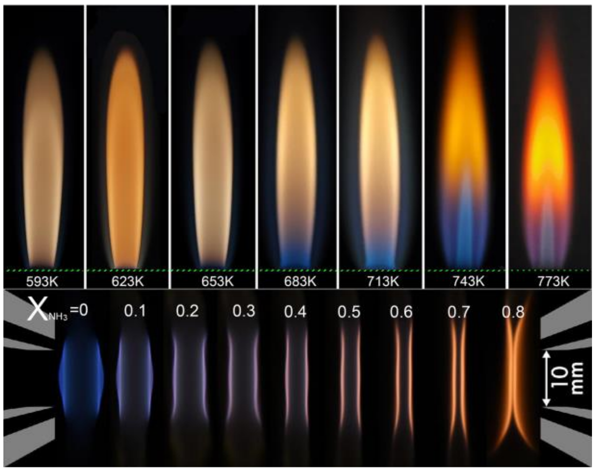

Figure 8-13. Ammonia flame images at different preheating temperatures (top photo) and Ammonia dual flame images at different ammonia fuel fractions (bottom photo)[69]

Temperature, pressure, and oxygen enrichment variations significantly influence ammonia combustion (Figure 8-12)., affecting heat and mass transfer, laminar burning velocity, and emissions, particularly NO_x. Higher temperatures and pressures can improve combustion characteristics and stability, but they also require the use of suitable materials in combustors. Oxygen enrichment can substantially enhance combustion efficiency but also increases NO_x production. Consequently, optimizing combustion parameters for specific applications becomes essential.

In addition to addressing combustion challenges, researchers are investigating combustion auxiliary technologies (Figure 8-12). These include porous media burners, plasma-assisted combustion, and catalytic combustion, which have the potential to control emissions and stabilize combustion. These technologies require further research for practical application.

Ammonia has emerged as a promising carbon-free fuel, but challenges in combustion characteristics and emissions persist. Research, especially in fuel blending and combustion intensification technologies, is crucial for its widespread adoption and a cleaner energy future. Further investigation into production, safety, economics, and application will be essential to address various aspects of ammonia's role in decarbonization efforts.

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[69] Duan et al. (2023): Research progress of ammonia combustion toward low carbon energy

Table 8-6. Combustion for high temperature heat: technology readiness

End-use technologies and systems	Current TRL	2030	2035	2040
Ammonia combustion for high temperature heat	4	5-6	6-7	8-9

8.2.7 Re-conversion to hydrogen (cracking)

As of 2023, the process of turning ammonia back into hydrogen (and nitrogen) is much less mature than the rest of the ammonia value chain. The general process involves the catalytic decomposition of ammonia at 500-900°C, to form a mixture of hydrogen (75%) and nitrogen (25%) which requires purification if high-purity hydrogen is required. In short, the ammonia cracking process is not particularly complex, and is an established industrial process technology; however, the process has to date not required scaling to the huge, industrial volumes being proposed for the future trade of hydrogen and ammonia. This is because in the past, cracking of ammonia to hydrogen has been a small-scale niche business area, to produce hydrogen on-site for industrial uses where ammonia is available as a feedstock.

The process is endothermic and is favoured at high temperatures and low pressures. These conditions lead to potential inefficiencies and costs, as the need to input heat to the process typically requires combustion. Industrial scale cracker designs generally rely on OEM experience with steam methane reformer (SMR) hydrogen plants, which operate at similar temperatures and pressures using very similar nickel-based catalysts. That said, direct electric heating ('e-cracker') is being developed, however they remain at a low TRL for industrial scale applications and scaling up of the e-cracker designs may not occur until post 2030.

Generally, nickel catalyzed crackers based upon incumbent SMR technology, heated by burning the product hydrogen are likely to the technology of choice for most major suppliers. There is currently technology in the market to perform ammonia cracking, but these are generally small scale and inefficient as a result. However, these systems are generally electrically heated crackers for the steel or nuclear industry, where efficiency is not the key consideration.

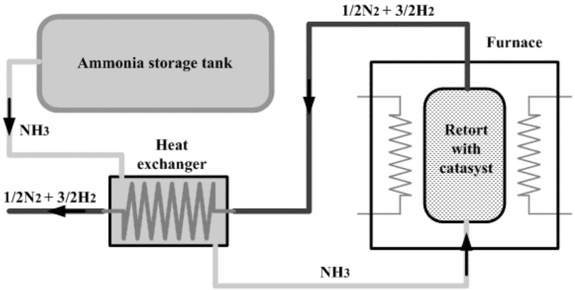

Figure 8-14. Ammonia cracker

As of 2023, technology providers (such as Air Liquide, Casale, Topsoe, KBR and Johnson Matthey) are taking notice of the large demand for ammonia as an energy carrier and are soon expected to provide larger scale cracking systems for use in major ammonia import terminals. These plant designs are expected to build upon existing industrial scale SMR plant designs and know-how the respective OEMs bring from their experience in existing hydrogen and ammonia industries.

Newer systems with novel designs or catalysts are under development at much lower TRL but are not expected to make a large impact in the next few years. Generally, the full cracking of ammonia and subsequent separation of hydrogen from nitrogen as an energy vector needs to be compared to other energy carriers as well as partial cracking or direct use of ammonia in power production. High temperature processes such as ammonia cracking will tend to have favourable economics for larger-scale (centralized) processes, which favours process scale, heat integration and efficiency. However, smaller-scale cracking plants may be able to be integrated with sources of waste heat, such as a combined cycle gas turbine. This type of heat integration is likely, however, to present increased cost to ensure sufficient system flexibility, and may have reduced efficiency which must be traded off with the centralized alternative.

8.2.7.1 Ammonia technology readiness summary

Table 8-7. Ammonia technology readiness summary

Ammonia value chain technologies and systems	Current TRL	2030	2035	2040
Industrial scale ammonia cracking to produce high purity hydrogen, electrified furnace (e-cracker)	5-7	7-8	9	
Industrial scale ammonia cracking to produce high purity hydrogen, SMR reformer-type design	8	9		
Cracking of hydrogen into ammonia (decentralized) coupled with gas turbines	3-5	6-7	7-8	9

APPENDIX A

A.1 Ammonia Plants in the SEA region

Table 0-1: List of ammonia plants in the SEA region (Source: GlobalData)

							Capacity (mtpa)
Country	**Plant Name**	**Operator**	**Start Year**	**Process**	**Technology**	**Key Feedstock**	**2021**
Indonesia	PT Pupuk Kaltim Bontang Ammonia Plant 5	PT Pupuk Kalimantan Timur	2015	Steam Methane Reforming	KBR Ammonia Technology	Natural Gas	0.83
	PT Panca Amara Utama Luwuk Ammonia Plant	PT Panca Amara Utama	2018	Steam Methane Reforming	KBR Ammonia Technology	Natural Gas	0.70
	PT Petrokimia Gresik Ammonia Plant 2	PT Petrokimia Gresik	2018	Steam Methane Reforming	KBR Ammonia Technology	Natural Gas	0.66
	PT Pupuk Kaltim Bontang Ammonia Plant 6	PT Pupuk Kalimantan Timur	2000	Steam Methane Reforming	Haldor Topsoe Ammonia Technology	Natural Gas	0.66
	PT Pupuk Sriwidjaja Palembang Ammonia Plant 5	PT Pupuk Sriwidjaja	2016	Steam Methane Reforming	KBR Ammonia Technology	Natural Gas	0.66
	PT Pupuk Kaltim Bontang Ammonia Plant 2	PT Pupuk Kalimantan Timur	1984	Steam Methane Reforming	KBR Ammonia Technology	Natural Gas	0.60
	PT Kaltim Parna Bontang Ammonia Plant	PT Kaltim Parna Industri	2002	Steam Methane Reforming	Haldor Topsoe Ammonia Technology	Natural Gas	0.50
	PT Pupuk Sriwidjaja Palembang Ammonia Plant 1	PT Pupuk Sriwidjaja Palembang	1994	Steam Methane Reforming	KBR Ammonia Technology	Natural Gas	0.45
	PT Petrokimia Gresik Ammonia Plant 1	PT Petrokimia Gresik	1994	Steam Methane Reforming	KBR Ammonia Technology	Natural Gas	0.45
	PT Pupuk Iskandar Muda Lhokseumawe Ammonia Plant 2	PT Pupuk Iskandar Muda	2005	Steam Methane Reforming	KBR Ammonia Technology	Natural Gas	0.40
	PT Pupuk Sriwidjaja Palembang Ammonia Plant 3	PT Pupuk Sriwidjaja Palembang	1976	Steam Methane Reforming	KBR Ammonia Technology	Natural Gas	0.40
	PT Pupuk Sriwidjaja Palembang Ammonia Plant 4	PT Pupuk Sriwidjaja Palembang	1977	Steam Methane Reforming	KBR Ammonia Technology	Natural Gas	0.40
	PT Pupuk Kaltim Bontang Ammonia Plant 3	PT Pupuk Kalimantan Timur	1989	Steam Methane Reforming	Haldor Topsoe Ammonia Technology	Natural Gas	0.33
	PT Pupuk Kaltim Bontang ammonia Plant 4	PT Pupuk Kalimantan Timur	2004	Steam Methane Reforming	Haldor Topsoe Ammonia Technology	Natural Gas	0.33
	PT Pupuk Kujang Cikampek Ammonia Plant 1	PT Pupuk Kujang	1978	Steam Methane Reforming	KBR Ammonia Technology	Natural Gas	0.33
	PT Pupuk Kujang Cikampek Ammonia Plant 2	PT Pupuk Kujang	2006	Steam Methane Reforming	KBR Ammonia Technology	Natural Gas	0.33
	PT Pupuk Iskandar Muda Lhokseumawe Ammonia Plant 1	PT Pupuk Iskandar Muda	1985	Steam Methane Reforming	KBR Ammonia Technology	Natural Gas	0.33
	Total ammonia production in Indonesia						**8.33**
Malaysia	PETRONAS Chemicals Fertilizer Sabah Sipitang Ammonia Plant 1	PETRONAS Chemicals Fertilizer Sabah Sdn Bhd	2017	Steam Methane Reforming	KBR Ammonia Technology	Natural Gas	0.74

	PETRONAS Ammonia Kerteh Ammonia Plant	PETRONAS Ammonia Sdn Bhd	2001	Steam Methane Reforming	KBR Ammonia Technology	Natural Gas	0.45
	Asean Bintulu Fertilizer Bintulu Ammonia Plant	Asean Bintulu Fertilizer Sdn Bhd	1985	Steam Methane Reforming	ThyssenKrupp Uhde Ammonia Technology	Natural Gas	0.45
	PETRONAS Fertilizer (Kedah) Gurun Ammonia Plant	Petronas Chemical Fertilizer (Kedah) Sdn Bhd	1999	Ammonia/Methanol Co-Production Process	KBR Ammonia Technology	Natural Gas	0.44
	Total ammonia production in Malaysia						**2.07**
Vietnam	Petrovietnam Fertilizers & Chemicals Phu My Ammonia Plant	PetroVietnam Fertilizer and Chemicals Corp	2004	Steam Methane Reforming	Haldor Topsoe Ammonia Technology	Natural Gas	0.54
	Petrovietnam Fertilizers & Chemicals Khanh Tan Ammonia Plant	PetroVietnam Fertilizer and Chemicals Corp	2012	Steam Methane Reforming	Haldor Topsoe Ammonia Technology	Natural Gas	0.47
	Habac Nitrogenous Fertilizer and Chemical Company Bac Giang Ammonia Plant 2	Ha Bac Nitrogenous Fertilizer & Chemicals JSC	2015	Coal Gasification Process	Haldor Topsoe Ammonia Technology	Coal	0.30
	Habac Nitrogenous Fertilizer and Chemical Company Bac Giang Ammonia Plant 1	Ha Bac Nitrogenous Fertilizer & Chemicals JSC	1976	Coal Gasification Process	Casale/Haldor Ammonia Technology	Coal	0.10
	Total ammonia production in Vietnam						**1.41**
Myanmar	Myanma Petrochemical Enterprise Myaungdaga Ammonia Plant	Myanma Petrochemical Enterprise	2010	N/A	N/A	Natural Gas	0.11
	Myanma Petrochemical Enterprise Kangyidaunt Ammonia Plant	Myanma Petrochemical Enterprise	2011	N/A	N/A	Natural Gas	0.11
	Myanma Petrochemical Enterprise Sale Ammonia Plant 2	Myanma Petrochemical Enterprise	n/a	N/A	N/A	Natural Gas	0.06
	Myanma Petrochemical Enterprise Sale Ammonia Plant 1	Myanma Petrochemical Enterprise	1970	N/A	N/A	Natural Gas	0.04
	Total ammonia production in Myanmar						0.31
Brunei	Brunei Fertilizer Industries Brunei Ammonia Plant	Brunei Fertilizer Industries Sdn Bhd	2022	Steam Methane Reforming	ThyssenKrupp Uhde Ammonia Technology	Natural Gas	0,77 (2022)
	Total ammonia production in Brunei						**0.77**

A.2 Ammonia cracking technology OEMs

Many of the ammonia cracking technology providers are also involved in ammonia synthesis, or other aspects of ammonia production and handling.

Table 0-2: Ammonia cracking technology OEMs

Supplier	Country	Type	Scale	Comment
CSIRO	Australia	Catalytic membrane	Small	Limited info available
Fortescue Future Industries	Australia	Catalytic Membrane	Small	Limited info available
Air Liquide	France	Reformer	Large	Limited info available
Topsoe	Denmark	Reformer	Large	Manufacturer of catalyst and cracker / technology licensor
WS Reformer	Germany	Reformer	Small	Small scale combustion technology company -
thyssenkrupp (tkIS)	Germany	Reformer	Large	EPC and technology licensor. Partnership with Johnson Matthey
Ammonigy	Germany	Reformer	Small	Aiming for transportation applications, including Deutsche Bahn
MVS engineering	India	Reformer	Small	Gas processing technology company
Labh group	India	Reformer	Small	Gas processing technology company
SamGas	India	Reformer	Small	Gas processing technology company
Nitrotech Engineers	India	Reformer	Small	Gas processing technology company
Gencell energy	Israel	Reformer	Small	Developing cracker tech to support fuel cell business
Linde	Germany	Reformer	Large	Multinational chemical company – limited info available
Proton Ventures	Netherlands	Reformer	Large	Studies on ammonia cracking. Not responding after multiple requests
Duiker Combustion	Netherlands	Reformer	Large	Combustion technology company
H2site	Spain	Catalytic Membrane	Small	Small scale catalytic membrane development
Helbio (metacon)	Sweden	Reformer	Small	Focus on maritime. Not responding after multiple requests
Casale	Switzerland	Reformer	Large	EPC and technology licensor. Non-exclusive partnership with Clariant Catalysts. Major player in ammonia synthesis technologies.
Johnson Matthey	UK	Reformer	Large	Manufacturer of catalyst and cracker
James Hogg	UK	Reformer	Small	Small scale manufacturer - limited info available
KBR	UK	Reformer	Large	EPC and technology licensor. Non-exclusive partnership with Clariant Catalysts
Air Products	USA	Reformer	Large	Multinational gas supplier – limited info available
Amogy	USA	Reformer	Small	Small scale manufacturer - limited info available
Starfire	USA	Reformer	Small	Works across the ammonia value chain

A.3 Assumptions for potential future market size of green ammonia

Fuel prices

Historical and expected fuel and electricity prices for the power, industry and transport sectors were adopted from various sources, such as EPPO, World Bank Commodity Prices, IEA forecasts. The key inputs are presented in the table below.

Table 0-3: Fuel prices

Commodity	Unit	2023	2025	2030	2035	2040	2045	2050	Source
Natural Gas – Thailand	USD/GJ LHV	11.53	13.12	14.37	14.91	15.27	15.63	16.08	EPPO
Coal – Thailand	USD/GJ LHV	3.50	3.75	4.16	4.32	4.48	4.48	4.48	EPPO
Natural Gas – Global	USD/GJ LHV	11.53	13.12	14.37	14.91	15.27	15.63	16.08	World Bank Commodity and IEA Price Forecasts
Coal – Global	USD/GJ LHV	3.50	3.75	4.16	4.32	4.48	4.48	4.48	World Bank Commodity and IEA Price Forecasts
Grey Ammonia	USD/tonnes	635.86	703.33	758.22	775.38	789.10	789.10	789.10	Thailand Ammonia; anhydrous imports by country | 2021 | Data (worldbank.org)
	USD GJ/LHV	33.82	37.41	40.33	41.24	41.97	41.97	41.97	Converted to USD GJ/LHV
Green Ammonia – Domestic	USD/kg NH_3			0.77				0.32	Chapter 3 of the study
	USD/GJ LHV	59.43	55.20	40.96	34.97	28.99	23.01	17.02	Converted to USD GJ/LHV
Green Ammonia – Imported	USD/kg NH_3			0.62				0.29	Chapter 3 of the study
	USD/GJ LHV	47.85	44.44	32.98	28.59	24.20	19.81	15.43	Converted to USD GJ/LHV
Green Hydrogen – Domestic	USD/kg H_2	6.33	5.88	4.36	3.73	3.09	2.46	1.82	Chapter 3 of the study
	USD GJ/LHV	52.74	48.98	36.35	31.05	25.76	20.47	15.17	Converted to USD GJ/LHV
Liquid hydrogen	USD/GJ LHV	73.90	68.63	50.93	43.47	37.99	34.67	32.11	World Bank Commodity Price Forecasts
Green methanol	USD/GJ LHV	72.81	68.37	53.45	46.04	40.29	36.37	33.08	World Bank Commodity Price Forecasts
Marine fuel (MGO)	USD/GJ LHV	20.27	16.10	20.07	23.90	28.41	33.57	38.14	World Bank Commodity Price Forecasts

Energy demand data

Historic and forecasted demand data for the power, transport, and industry sector was obtained from the CASE study as the basis for analysis in this report[70]. Specifically, for the industry sector, it was assumed that the fuel share and energy consumption share per sector to the total consumption would remain constant. The fuel share derived is shown in the following table.

Table 0-4: Energy demand and fuel share per sector based on CASE Study

Sector	Fuel	Fuel share	High heat demand (TWh)	Low heat demand (TWh)	Total (TWh)
Chemical and Petrochemical	Coal	3%	0.61	0.59	1.20
	Oil	15%	2.28	3.81	6.09
	Gas	52%	7.19	14.00	21.19
	Biomass	5%	0.81	1.17	1.98
	Electricity	25%	4.08	6.03	10.11
Chemical and Petrochemical Total	**-**	**100%**	**14.96**	**25.60**	**40.56**
Iron and Steel	Coal	2%	0.30	0.02	0.32
	Oil	22%	2.58	0.28	2.85
	Gas	34%	4.04	0.51	4.55
	Biomass	0%	0.02	0.00	0.02
	Electricity	41%	5.01	0.48	5.49
Iron and Steel Total	**-**	**100%**	**11.96**	**1.28**	**13.24**
Machinery	Coal	0%	-	-	-
	Oil	17%	0.14	1.40	1.55
	Gas	19%	0.15	1.65	1.80
	Biomass	0%	-	-	-
	Electricity	64%	0.63	5.37	6.00
Machinery Total	**-**	**100%**	**0.92**	**8.43**	**9.35**
Non-metallic minerals	Coal	67%	56.79	4.81	61.59
	Oil	7%	5.77	0.84	6.61
	Gas	14%	11.43	1.93	13.36
	Biomass	4%	3.04	0.38	3.42
	Electricity	8%	6.62	0.85	7.47
Non-metallic minerals Total	**-**	**100%**	**83.65**	**8.81**	**92.46**
Others (Manufacturing of vehicles)	Coal	0%	0.02	0.11	0.13
	Oil	80%	2.86	30.38	33.24
	Gas	16%	0.49	6.00	6.48
	Biomass	0%	0.02	0.18	0.20
	Electricity	4%	0.15	1.40	1.55
Other Total	**-**	**100%**	**3.53**	**38.08**	**41.61**

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[70] https://www.agora-energiewende.de/en/publications/towards-a-collective-vision-of-thai-energy-transition/

Carbon prices

Due to ongoing discussions regarding the implementation of a carbon tax in Thailand and the impact this may have on the cost analysis, three different carbon tax scenarios have been utilized:

- No carbon tax
- Low carbon price, based on current EU pledge: 65 USD/t in 2030, 75 USD/t in 2040 and 90 USD/t in 2050.
- High carbon price, based on IEA scenario for Net Zero Advanced Economies: 130 USD/t in 2030, 205 USD/t in 2040 and 250 USD/t in 2050.

Interpolation was used to cover intermediate years, assuming a linear increase between anchor points.

The carbon prices used can be found in the following Table 0-5.

Table 0-5: Carbon prices

Year		2020	2025	2030	2035	2040	2045	2050
Low carbon price (USD/t)	Based on current EU pledge	0.00	18.57	65.00	70.00	75.00	82.50	90.00
High carbon price (USD/t)	Net Zero Advanced Economies	0.00	37.14	130.00	167.50	205.00	227.50	250.00

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