# THE EUROPEAN AMMONIA INDUSTRY
# GREY, GREEN OR GONE?

Master thesis submitted to Delft University of Technology in partial fulfilment of the requirements for the degree of

**Master of Science**
in **Complex Systems Engineering and Management**

by

Maarten Henrik van Muijen
Student number: 4275632

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|---|---|
| Chairperson & First Supervisor: | Prof. Dr. K. Blok<br>Engineering Systems and Services |
| Second Supervisor: | Dr. ir. Z. Roosenboom-Kwee<br>Values, Technology and Innovation |

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# PREFACE

Before you lie the final version of my graduation thesis for the fulfilment of the Master's program of Complex Systems Engineering and Management. Writing the preface at the end seems rather simple but the process that that led to the construction of this report was long and challenging for various reasons. Luckily, I had support from a lot of people whom I would like to thank.

First of all I want to express my sincere gratitude and appreciation to my graduation committee. I want to thank Kornelis for his guidance throughout my thesis and his constructive feedback during our sessions. I am thankful for your patience and encouraging me to be more pragmatic, as well as asking for help when needed. I would also like to thank Zenlin Roosenboom-Kwee for her role as second supervisor. I'm grateful for Zenlin taking over the role as second supervisor; thank you for your comments and understanding.

I also want to thank the industry experts for taking the time and providing information and knowledge that was invaluable to the research. It broadened my knowledge concerning the ammonia production process, the technologies and the complexities regarding transitioning towards a more sustainable industry.

Then I would like to thank my girlfriend, parents, sister, old roommates, friends and family for their unconditional support and for providing distraction when required. Due to the COVID-19 pandemic, the circumstances have not been optimal but your kind words, messages, online meetings and cards kept me motivated throughout the process.

This marks the end of my wonderful journey in Delft, which started years ago at the Faculty of Technology, Policy and Management. I feel privileged to have been able to learn and develop myself in many aspects at TU Delft, surrounded by inspiring staff, students and friends.

From a young age, I have been pursuing new experiences, and this remains my drive to this day. It pleases me that this thesis allowed me to explore an entirely new and complex industry of which I was uninformed. The importance of an innovative and competitive European chemical industry can not be unseen and I regard it as one of the cornerstones for a sustainable and resilient future. I would be delighted if this research could contribute in any way to the transition of the ammonia industry.

*Maarten van Muijen*
*Amsterdam, December 2023*

# EXECUTIVE SUMMARY

Ammonia is one of the most energy and emission-intensive chemicals in Europe. Carbon emissions are inevitable due to fossil fuel-based hydrogen production. Hydrogen, crucial for ammonia production, heavily relies on natural gas, making the industry susceptible to fluctuations in gas prices.

Energy efficiency or demand-side measures are necessary but are not sufficient to meet the ambitious climate targets of the European Union. Europe's ammonia industry faces a critical juncture as it seeks to decarbonize while remaining competitive globally amid regulatory pressures. Achieving sustainable production methods is essential. This thesis delves into the critical issue of cost-effective decarbonization within the European ammonia industry. The central research question of this study is:

*How can the European ammonia industry effectively transition towards sustainable and economically viable decarbonization?*

This research investigates the pathway to sustainable and economically feasible decarbonization of the European ammonia industry through a comprehensive approach. Firstly, a comprehensive literature review and expert interviews elucidate technological opportunities for decarbonization. Secondly, a detailed LCOA analysis compares the costs and carbon intensity of cleaner production methods against the conventional Haber-Bosch process. Finally, the competitive landscape is assessed by analyzing LCOA data from both EU and non-EU countries, supplemented by expert insights.

This approach aims to provide a nuanced understanding of the challenges and opportunities associated with transitioning the ammonia industry toward sustainability. This study offers a fresh perspective on sustainable and economically viable decarbonization pathways by integrating comprehensive literature reviews, expert interviews, and detailed LCOA analyses. This study pioneers a comparative examination, contrasting LCOA between European and non-EU countries. Through this lens, the intricate trade dynamics and industrial policy implications unveil strategic considerations shaping Europe's future ammonia production landscape.

Key to the scientific contribution is integrating carbon costs into the levelized costs of products and analyzing the CBAM effects on European versus non-European production. This pioneering approach extends beyond ammonia and fertilizers to encompass industries such as iron, steel, aluminium, hydrogen, and cement, offering a comprehensive framework for addressing the broader challenges of decarbonization across sectors.

The findings of the study highlight the economic benefits of ATR with CCS. It is the most financially feasible option, followed closely by other CCS alternatives for SMR and methane pyrolysis. In comparison, biobased alternatives and electrolyzers are currently less cost-competitive. However, in the future, electrolyzers could be a more viable option and compete with CCS alternatives, but this would depend on the reduction of capital costs and

lower electricity prices. Assuming the current natural gas price in Europe and an electricity price of 40 €/MW, alkaline and PEM electrolyzers would be in the same price range as CCS alternatives. On the other hand, if electricity prices were to drop to less than 20 €/MWh, the improved electrolyzers could compete with foreign ammonia producers. This information sheds light on the comparative economics of various decarbonization paths, making a significant contribution to the field.

The adoption of cleaner technologies in non-European countries is being influenced by the CBAM, which is a key factor shaping the current landscape. This mechanism significantly influences the adoption of CCS options, particularly in countries outside Europe. The study highlights a shift in the globally preferred decarbonization options, with ATR with CCS and methane pyrolysis emerging as economically attractive choices in regions such as Algeria, Canada, Australia, and Saudi Arabia. CBAM fosters a reduction in carbon-intensive practices worldwide, making cleaner technologies more competitive and encouraging the adoption of sustainable ammonia production processes outside of Europe.

Algeria, Canada and Saudi Arabia are well-positioned to supply Europe with ammonia. For European ammonia producers, relocating to a production environment with lower energy costs and exporting ammonia to Europe becomes a strategic consideration. Previously, staying in Europe might have been the preferred choice. Policymakers should be mindful that CBAM positively mitigates carbon emissions outside Europe. However, if energy prices continue to be considerably higher than those outside Europe, certain vital industries like ammonia production may move to other regions, which could pose a challenge to Europe's self-sufficiency. Overdependence on other countries could become a geopolitical weapon. The ammonia industry is crucial to the European food system. The absence of this industry could have significant implications for food security. Policymakers need to address the potential relocation of essential industries such as ammonia production with due diligence.

This research is a comprehensive guide for decision-makers in the ammonia industry, providing insights into sustainable and economically viable decarbonization pathways. It offers a strong foundation for future efforts and emphasizes the need for a collaborative commitment to substantial change. The study aims to guide the ammonia industry towards a future characterized by sustainability and economic viability, offering a roadmap for navigating the complex landscape of decarbonization options.

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# ACRONYMS

| | | |
|---|---|---|
| **AACE International** | Association for the Advancement of Cost Estimating International | 24 |
| **AEM** | Anion Exchange Membrane | 35 |
| **ASU** | Air Separation Unit | 37 |
| **ATR** | Autothermal Reforming | 11 |
| **BAT** | Best Available Techniques | 4 |
| **BECCS** | Bioenergy with Carbon Capture and Storage | 41 |
| **BoP** | Balance of Plant | 42 |
| **CAC** | Cost of Avoided Carbon | 4 |
| **CBAM** | Carbon Border Adjustment Mechanism | 4 |
| **CCS** | Carbon Capture and Storage | 15 |
| **CCU** | Carbon Capture and Utilization | 12 |
| **CEFIC** | European Chemical Industry Council | 2 |
| **CEPCI** | Chemical Engineering Plant Cost Index | 24 |
| **CI** | Carbon Intensity | 22 |
| **EPC** | Engineering, Procurement, and Construction | ix |
| **EU ETS** | EU emissions trading system | 2 |
| **GHG** | Greenhouse gas | 1 |
| **IEA** | International Energy Agency | 15 |
| **IFA** | International Fertilizer Association | 3 |
| **LCOA** | Levelized Cost of Ammonia | 7 |
| **LOHC** | liquid organic hydrogen carriers | 10 |
| **MACCs** | Marginal abatement cost curves | 17 |
| **NASA** | National Aeronautics and Space Administration | 19 |
| **NPV** | Net Present Value | 84 |
| **PEM** | Proton-Exchange-Membrane | 33 |
| **POX** | Partial Oxidation | 11 |
| **SEC** | Specific Energy Consumption | 3 |
| **SMR** | Steam Methane Reforming | 6 |
| **SOEC** | Solid Oxide Electrolyzer Cell | 33 |
| **TRL** | Technology Readiness Level | 19 |
| **UNFCCC** | United Nations Framework Convention on Climate Change | 2 |

# 1 INTRODUCTION

## 1.1 PROBLEM DEFINITION

### 1.1.1 The Urgency to Decarbonize Ammonia Production

The European Union is an instigator in tackling climate change and a forerunner in climate policy. It presented the Green Deal on the 11th of December 2019, which is aligned with the EU's commitment to global climate action. The Green Deal includes transforming towards a climate-neutral Europe in 2050 (European Commission, 2019c). This means that there are net-zero greenhouse gas (Greenhouse gas (GHG)) emissions. The European industry plays a vital role in achieving this goal, 25% of the GHG emissions in Europe stem from the industry (United Nations, 2020a).

The chemical industry is the largest final energy consumer and industrial consumer of natural gas in Europe (Pisca, 2017). The chemical industry is energy-intensive due to its reliance on energy inputs for raw materials as well as for fuel and power. Globally 58% of the total energy input of the chemical industry was consumed as feedstock in 2014 (IEA, 2017). Due to the consumption of energy input as feedstock, the total emitted greenhouse gases during production are lower compared to other industries.

The production of ammonia, methanol and high-value chemicals such as ethylene, propylene, benzene, toluene and xylenes are the most energy-intensive in absolute terms. On a global scale, these products resembled around 50% of the total process-related energy demand for the chemical industry in 2010 (IEA et al., 2013). The corresponding emissions from these processes accounted for 55% of the emissions of the global chemical industry in the same year.

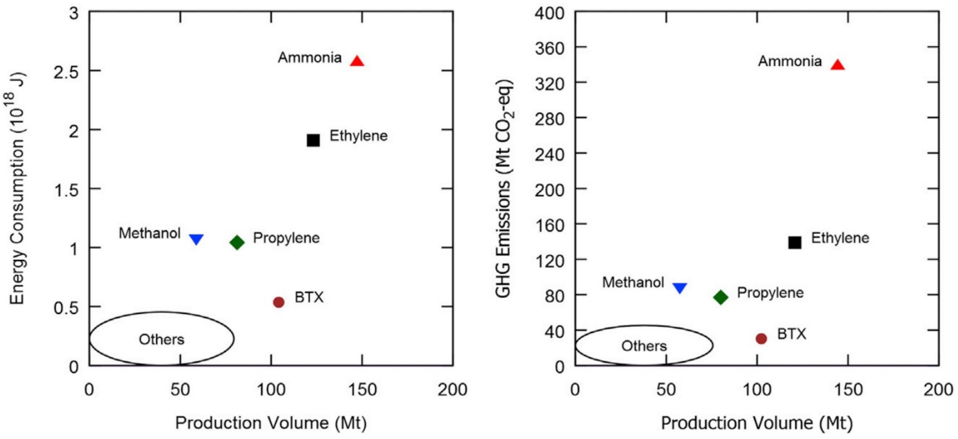

**Figure 1.1:** Global energy consumption and GHG emissions of large-volume products in 2010. Retrieved from (Schiffer and Manthiram, 2017, pg. 2)

Due to the complexities of carbon accounting for high-value chemicals, the EU emissions trading system (EU ETS) provides limited visibility into European emissions related to these substances. Verified emissions from high-value chemicals like ethylene, propylene, and aromatics are grouped together under the category of bulk chemicals. As illustrated in Table 1.1, the predominant portion of emissions from the chemical industry within the EU ETS stems from bulk chemical production, with ammonia production and the combined production of hydrogen and synthesis gas following closely behind.

In 2019 ammonia amounted to 27% of the total verified emissions of the EU ETS for production within the chemical industry (European Environment Agency, 2020). Hydrogen and synthesis gas are predominantly used to produce ammonia and methanol, which accounted for 12% of the verified emissions (Bozzano and Manenti, 2016). The Greenhouse Gas Inventory Data of the United Nations Framework Convention on Climate Change (UNFCCC) confirms that the majority of GHG emissions in the European chemical industry originate from the production of ammonia and bulk chemicals such as ethylene and its derivatives.

| Production of | Share of EU ETS verified emissions | Number of installations |
|---|---|---|
| Carbon black | 2% | 18 |
| Nitric acid | 5% | 36 |
| Adipic acid | 0% | 3 |
| Glyoxal and glyoxylic acid | 0% | 1 |
| Ammonia | 27% | 30 |
| Bulk chemicals | 48% | 458 |
| Hydrogen and synthesis gas | 12% | 47 |
| Soda ash and sodium bicarbonate | 6% | 14 |

Table 1.1: Share of emissions and number of installations per type of EU ETS activity in 2019. Retrieved from (European Environment Agency, 2020)

### 1.1.2 Energy Efficiency is not Enough

Large quantities of hydrogen are needed for ammonia production, for which natural gas is used as energy and feedstock supply. The price of natural gas can, therefore, have a significant effect on the operating costs. The cost component of natural gas for ammonia production can be as high as 80% of the operating expenses (Egenhofer et al., 2014).

Ammonia is a globally traded commodity, meaning regions with cheaper natural resources have a competitive advantage. The European ammonia industry has had strong financial incentives to reduce its energy use to compete with producers from Russia, the Middle East and Trinidad and Tobago. In the last 30 years, the ammonia industry has built up experience and knowledge in reducing energy consumption with innovative solutions (ICCA, 2017). Also, according to the European Chemical Industry Council (CEFIC), there have been major efforts to reduce the environmental impact of the production of goods.

European ammonia plants are regarded as the most energy-efficient and least polluting facilities globally (Pattabathula and Richardson, 2016). Between 1990 and 2018, the UNFCCC recorded a 29.4% decline in GHG emissions for the European ammonia industry (UNFCCC, 2020). Due to the lack of production data on ammonia, it is unclear whether this reduction in emissions stems from improved energy efficiency or lower consumption. However, the data from Eurostat and UNFCCC show in Figure 1.2 that ammonia production and the corresponding emissions have been stable over the last decade. According to (UNFCCC, 2020), $CO_2$ is the only GHG that is emitted in the process of ammonia production. This means that in recent years, the carbon intensity of ammonia production has remained unchanged. A report from CEFIC and Ecofys (2013) confirms the stagnating reduction in energy efficiency.

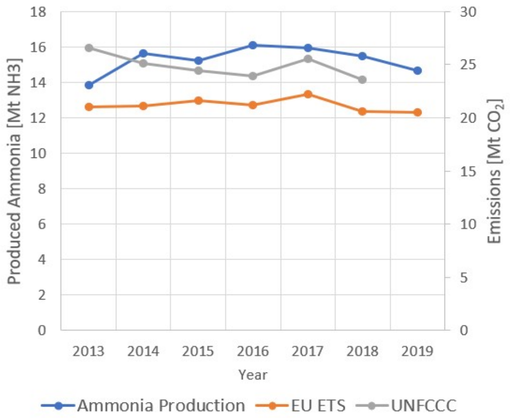

**Figure 1.2:** The ammonia production [Mt $NH_3$] and corresponding emissions [Mt $CO_2$] according to EU ETS and UNFCCC of EU27 + UK. Retrieved from (Eurostat, 2019; UNFCCC, 2020)

The demand for nitrogen-based fertilizers predominantly determines the demand for ammonia. The IEA (2018) projects that the ammonia demand in Europe will remain stable till 2030, after which it will reduce slightly. Fertilizers Europe is the association for most fertilizer manufacturers in the European Union, and they also expect a steady ammonia demand till 2030. Besides the demand for ammonia, the International Fertilizer Association (IFA) also expects that the ammonia production capacity will not increase nor decrease in the coming 5 years (IFA, 2020). The rigid carbon intensity of ammonia as well as its demand, is a reason for concern. The current production process of ammonia is similar at every European plant, by steam reforming of natural gas. Obviously, there are discrepancies between the ammonia plants. This leads to a divergence in the required energy input, referred to as Specific Energy Consumption (SEC). Despite the efforts of ammonia producers, a reduction of SEC will not lead to deep decarbonization of the industry. The average SEC of ammonia plants in Europe was 37.5 GJ/t$NH_3$ in 2006, resulting in 2.10 t$CO_2$/t$NH_3$ (IPCC, 2006). Nowadays, the modernized ammonia plants in Europe emit around 1.7 t$CO_2$/t$NH_3$, based on the SEC of 30.2 GJ/t$NH_3$.

According to CEFIC (2013) a new build ammonia plant would emit 1.6 $tCO_2/tNH_3$, based on the Best Available Techniques (BAT), with 28 $GJ/tNH_3$ (EIPPCB, 2007). Supposedly if ammonia is produced with the theoretical minimum required energy of 21.2 $GJ/tNH_3$ for the current production process, then it would still omit 1.2 $tCO_2/tNH_3$. Carbon emissions are inevitable due to fossil fuel-based hydrogen production. Energy efficiency or demand-side measures are necessary but are not sufficient to meet the ambitious climate targets of the European Union.

## 1.2 RESEARCH PROBLEM

Fertilizers Europe acknowledges the need to decarbonize, while it is believed that the costs are too high to remain globally competitive (Fertilizers Europe, 2020). The research problem concerns the costs of making ammonia production more sustainable. According to the report of CEFIC and Ecofys (2013), the investment costs for the capture, compression, transport and storage of $CO_2$ for existing and new ammonia plants range between 120 and 320 €/ton of annually captured $CO_2$ in 2020. The production of green ammonia is only foreseen as an option for 2030 or later. However, the Cost of Avoided Carbon (CAC) for an ammonia plant in Germany and Poland was calculated to respectively 33.1 and 29.2 (Irlam, 2017).[1] This issue requires a comprehensive analysis and understanding of the factors influencing the cost variations in sustainable ammonia production methods. Addressing this problem is crucial for identifying cost-effective strategies and technologies that can drive the widespread adoption of sustainable ammonia production practices.

Firm policy and governmental guidance are imperative to steer and effectively support green fertilizer production. Policy frameworks and funding of low-carbon technologies have to be designed in a way that does not affect the competitiveness of the European industry in a global context. This is burdened with internalizing the negative environmental externalities, which could affect competitiveness at the macroeconomic level. Europe embraced the pioneering role in sustainable transformation but should show leadership and put the word by deed.

The EU ETS is regarded as a valuable tool for reducing the GHG emissions cost-effectively, but for the ammonia industry, it has not led to proven progress. On average, in the last five years, the ammonia industry received free allowances for 82% of their verified emissions under the EU ETS (European Environment Agency, 2020). When European ammonia manufacturers are exposed to high energy and climate policy costs, it could lead to an uneven playing field with carbon leakage and relocation of European manufacturers beyond European borders as a result (CEFIC and Ecofys, 2013).

In the third quarter of 2020, the European Commission revealed its long-term strategy for the European chemical industry (European Commission, 2020). The Carbon Border Adjustment Mechanism (CBAM) will be introduced in 2023 to prevent the deteriorating effect on the global competit-

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[1] For an ammonia plant with a nameplate capacity of 403 kt/year, operating for 7400 hours a year and a capture rate of pure 0.57 t CO2/tNH3 due to the vicinity of an urea plant.

iveness of the European manufacturing industries, including the fertilizer industry. It is a tool to price imported products' carbon intensity into the European Union.

Other objectives of the European Commission involve, for example, creating markets for climate-neutral and circular economy products (European Commission, 2019b). That would have an enormous impact on the current value chains of the fertilizer industry. Such factors and uncertainties influence the strategic considerations and investment planning of established ammonia producers that have to deal with depreciation or sunk costs of their brownfield installations. However, the decision to not invest, to invest less or wait to invest in low-carbon technologies can lead to a negative competitive position (Seto et al., 2016).

The European Commission presented the "Fit for 55 Package" in 2021, which aims to align EU climate and energy legislation with the EU's objective to reduce greenhouse gas emissions by at least 55% by 2030 and to achieve climate neutrality by 2050. The proposals include ambitious hydrogen targets for 2030, which encompass the installation of 40GW of hydrogen electrolysis capacity and the production of 10 million tonnes of renewable hydrogen (European Commission, 2021). These targets signify the EU's commitment to scaling up hydrogen technologies and fostering the production and utilization of renewable hydrogen as a vital element in achieving a sustainable and decarbonized energy system.

The transformation towards a low-carbon ammonia industry is shaped, among others, by the political framework, the technological feasibility of decarbonization options and their cost-effectiveness. The trajectory in the direction of a sustainable ammonia industry is not linear, there are multiple potential pathways which know countless traps. The short- and long-term costs and risks have to be balanced. The pathways of the IPCC (2014) show that passivity concerning mitigation efforts now will lead to unequal higher costs in the future. The mitigation costs can increase up to 44% in the medium- and long term if additional mitigation measures are delayed until 2030.

Fay et al. (2015) emphasize that immediate decarbonization efforts are more cost-effective since delayed actions create lock-ins due to investments in emitting industrial installations with long lifetimes. The lead time for implementing the new technologies may exceed ten years for deep decarbonization of the ammonia industry. Which decarbonization options for producing ammonia are the most cost-effective is uncertain. The final report of the High-level Panel of the European Decarbonisation Pathways Initiative acknowledges that uncertainty concerning the cost-effectiveness of decarbonization options for the European chemical industry (European Commission, 2018).

There are three main knowledge gaps in the ammonia production decarbonization research. First, existing research predominantly focuses on incremental improvements in energy efficiency within the ammonia production process. While valuable, this approach fails to address the urgent need for deep decarbonization.

Secondly, there is a knowledge gap due to the assumption that producing clean hydrogen and ammonia is a distant goal. Focusing solely on long-term strategic visions of clean hydrogen and ammonia production limits practical short- and medium-term decarbonization solutions. However, political commitment to reduce carbon emissions and shift away from the use of fossil fuels, combined with technological advancements, have made cleaner hydrogen and ammonia production more economically viable. This shift is mainly explored for hydrogen production and less for ammonia production. The impact of this shift on the standard Steam Methane Reforming (SMR) Haber-Bosch process is uncertain.

Thirdly, the existing techno-economic assessments of decarbonization options for the ammonia industry exhibit a limited scope. These assessments typically focus on single processes within specific geographical areas, hindering comprehensive comparisons of decarbonization options on a broader European scale. This narrow approach restricts the ability to conduct thorough evaluations across different European regions.

## 1.3 RESEARCH OBJECTIVE

Innovation sparkles the technological breakthroughs necessary to reduce emissions from the chemical industry and is essential to staying competitive in the global ammonia market. Technological progress is reliant on investments. The European Commission, therefore, wishes to make Europe the best place to invest in breakthrough technologies (European Commission, 2019a).

From 2021 onward, the Innovation Fund will be available for investments in the next generation of low-carbon technologies for energy-intensive industries. Considering the European targets and the need for far-reaching measures, investment in low-carbon technologies for the ammonia industry is paramount. Policy-makers and corporate leaders are challenged to find solutions that cultivate sustainable growth. This study will guide these parties to implement abatement options for the European ammonia industry.

The study aims to review the potential of various decarbonization options and their costs under boundary conditions, which can break down economic barriers and foster discussions and investment strategies for policy-makers and corporate stakeholders. Furthermore, based on this study, national governments or the European Commission can allocate R&D subsidies or fiscal incentives. These economic mechanisms can be implemented in the long-term strategy of the European Commission for the European chemical industry.

This study could catalyse the following steps within the cost-effective decarbonization pathways for the European ammonia industry. These next steps refer to the investment and uptake of the decarbonization options that can impact the future of the European ammonia industry.

## 1.4 RESEARCH QUESTIONS

This research focuses on the decarbonization options of the European ammonia industry that can be deployed now or are expected to be commercially available within the coming ten years. The main research question of this research is formulated as follows:

> *How can the European ammonia industry effectively transition towards sustainable and economically viable decarbonization*

Due to the extensive nature of the leading research question, it is divided into three comprehensible sub questions. The first sub question is related to the first knowledge gap. To address this gap, this research will explore the technological opportunities for achieving deep decarbonization within the ammonia industry. The objective is to investigate innovative technologies beyond incremental energy efficiency improvements to discover transformative paths towards sustainable production methods.

This research will compare the costs per ton of ammonia and the intensity of carbon emissions of cleaner plant configurations to the standard SMR Haber-Bosch process. By evaluating these alternatives' economic viability and environmental impact, the goal is to identify feasible pathways for immediate decarbonization efforts, thus addressing the second knowledge gap.

To overcome the third knowledge gap, this research expands its scope to encompass a European-focused assessment of short-term deep decarbonization options for the ammonia industry. By considering the broader European context and evaluating the competitive position of European producers relative to global counterparts, the aim is to provide a holistic understanding of the implications of sustainable ammonia production in Europe. In addressing the uncertainty surrounding how sustainable ammonia production will impact the price and competitiveness of European producers compared to their foreign counterparts, sub question 3 delves into the extent to which the cost and carbon intensity of sustainable production in Europe affect the competitive position of European producers relative to global counterparts. This research seeks to assess the implications of sustainable transformation on European competitiveness through a comparative analysis of the Levelized Cost of Ammonia (LCOA) of European and non-EU countries. Answering the main research question by accumulating the answers to the sub questions is possible. The following three sub questions support the research question of this study:

1. What are the technological opportunities for deep decarbonization of the ammonia industry?

2. How do the costs per ton of ammonia and carbon emissions intensity of cleaner ammonia plant configurations compare to the standard SMR Haber-Bosch process?

3. To what extent does the cost and carbon intensity of sustainable ammonia production in Europe affect the competitive position of European ammonia producers relative to global counterparts?

## 1.5 THESIS STRUCTURE

The research design outline is depicted in Figure 1.3. Chapter 1 serves as an introduction to the challenges of decarbonization of the European ammonia industry. How this research is positioned within the existing scientific literature is described in Chapter 2, in which key concepts of this thesis are also specified. This chapter will also explain the researcher's choices while considering the methodology of the sub questions. The following chapter outlines the technological possibilities for deep decarbonization of the ammonia chemical industry. The feasible cost-effectiveness assessments, including the cost-effectiveness of sustainable ammonia production, will be discussed for global competitors and sensitivity analysis is defined in Chapter 4. In Chapter 5, the limitations and contribution of this thesis to scientific literature are discussed. The conclusion can be found in Chapter 6. The thesis is mainly conducted in 2021, during COVID-19 and before the Russia-Ukraine war. These events extensively impact the prices and the import and export of ammonia and natural gas. These effects are mentioned in various chapters of this study.

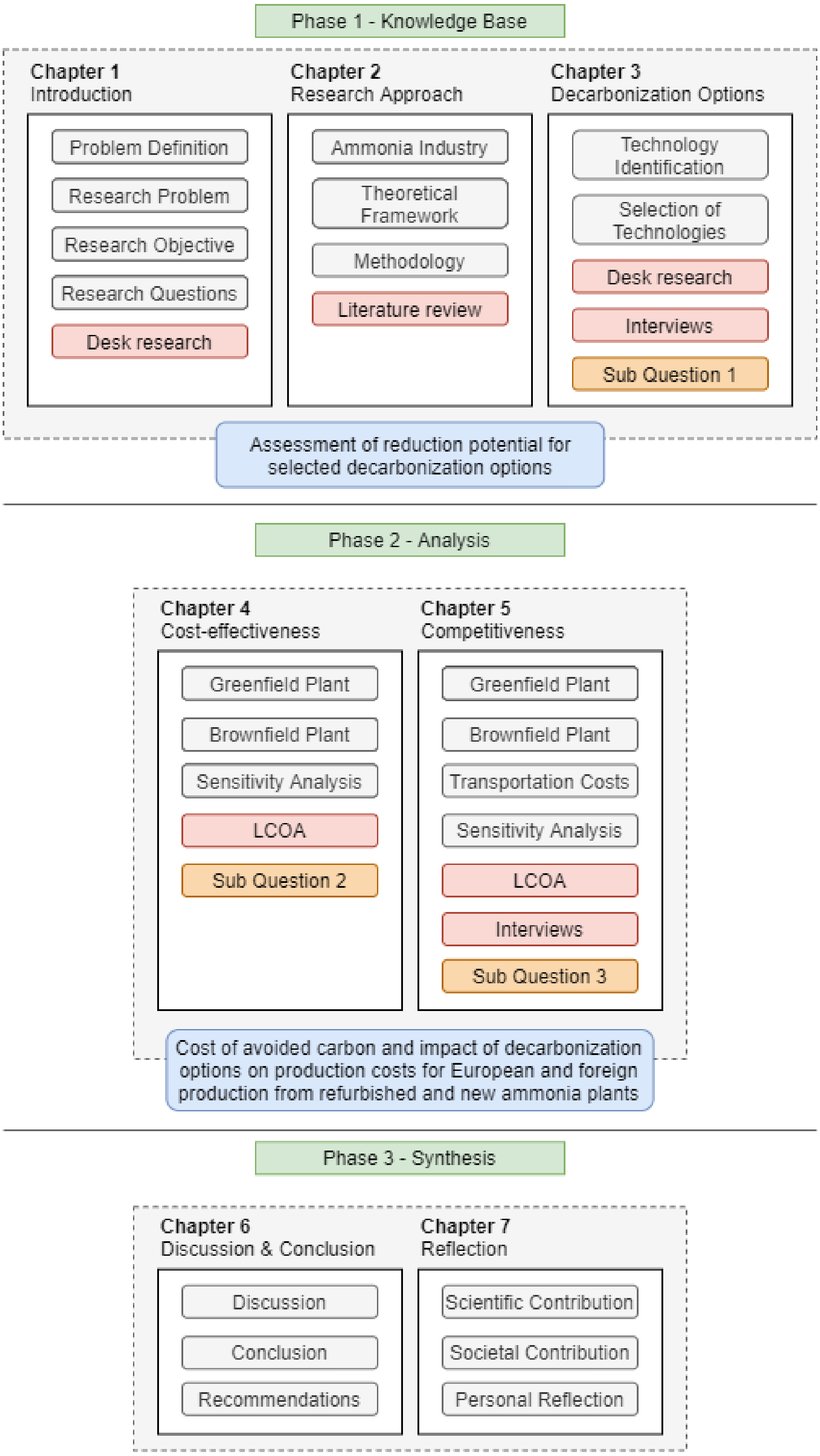

**Figure 1.3:** Research flow diagram

# 2 BACKGROUND AND RESEARCH APPROACH

The theoretical framework forms the scientific justification of this research. After the formulation of the problem definition and the research questions in Chapter 1, the main concepts, theories and models will be discussed on which this study builds. First, a description of the ammonia production process and its industry will be discussed in section 2.1. Second, the relevant concepts of the problem definition and the existing literature regarding the decarbonization of the ammonia industry will be described in section 2.2. Third, the methodological approach to address novel ammonia production processes' costs and emission reduction potential will be discussed in section 2.3.

## 2.1 BACKGROUND OF THE AMMONIA INDUSTRY

This section provides a knowledge base regarding the applications and production of ammonia. It also briefly describes the European ammonia industry.

### 2.1.1 The Applications

Ammonia is a vital industrial chemical with various applications. Ammonia is mainly used to produce fertilizers which are necessary for crop cultivation. Moreover, the chemical produces other chemicals, such as fibres and plastics. Ammonia is used in mining, metallurgy, pulp and paper, and the pharmaceutical industry. The synthetic chemical can also function as a detergent or refrigerant and can be used to produce explosives.

Ammonia is one of the most economical energy vectors for hydrogen (Gomez et al., 2020; MacFarlane et al., 2020). This is mainly due to its high volumetric energy density compared to compressed or liquefied hydrogen and liquid organic hydrogen carriers (LOHC) (Giddey et al., 2017). Renewable energy storage is gaining traction in scientific literature as one of the future applications of green ammonia (Bargiacchi et al., 2019). Besides energy storage, green ammonia is also considered a clean alternative for marine fuels (Katikaneni et al., 2014; Palys and Daoutidis, 2020).

### 2.1.2 The Production

The chemical formula of ammonia is $NH_3$. It is produced through the Haber-Bosch process where hydrogen $H_2$ and nitrogen $N_2$ form ammonia according to the reaction:

$$N_2 + 3\,H_2 \rightleftharpoons 2\,NH_3 \tag{2.1}$$

Around the world, the Haber-Bosch process takes place in large-scale centralized production plants. Nitrogen can be obtained from the air, which is not energy- and emission-intensive. In Europe, hydrogen is produced with natural gas as feedstock through SMR. Another process to produce hydrogen is Partial Oxidation (POX), where heavy fuel oil is used as a hydrocarbon. According to Ecofys et al. (2009) there are two ammonia plants in Europe where this process is incorporated. The plant of Amoniaco de Portugal is located in Barreiro, Portugal and the Yara plant in Brunsbüttel, Germany. The ammonia plant in Portugal was shut down in 2009, and the Yara plant was revamped in 2013, enabling the plant to run on natural gas. Additionally, Autothermal Reforming (ATR) is an alternative for SMR. It combines the reactions of partial oxidation and steam reforming in a single reactor.

According to Egenhofer et al. (2014) natural gas is used as feedstock for the whole ammonia production in Europe. Similarly, natural gas is predominantly used as a hydrocarbon in other parts of the world, but LPG, naphtha or coal can also be utilized. Specifically, coal gasification is used in China to produce hydrogen. The production and preparation of high-purity hydrogen is the primary source of pollution in the ammonia production process. The term grey ammonia is applied to the current SMR Haber-Bosch process. When the emitted carbon dioxide from the production process is captured and stored, the ammonia is called blue ammonia. If ammonia is produced through a carbon-free process, it is labelled green ammonia. There are numerous ammonia production designs possible. The block diagram in Figure 2.1 is a simplified example of the SMR Haber-Bosch process.

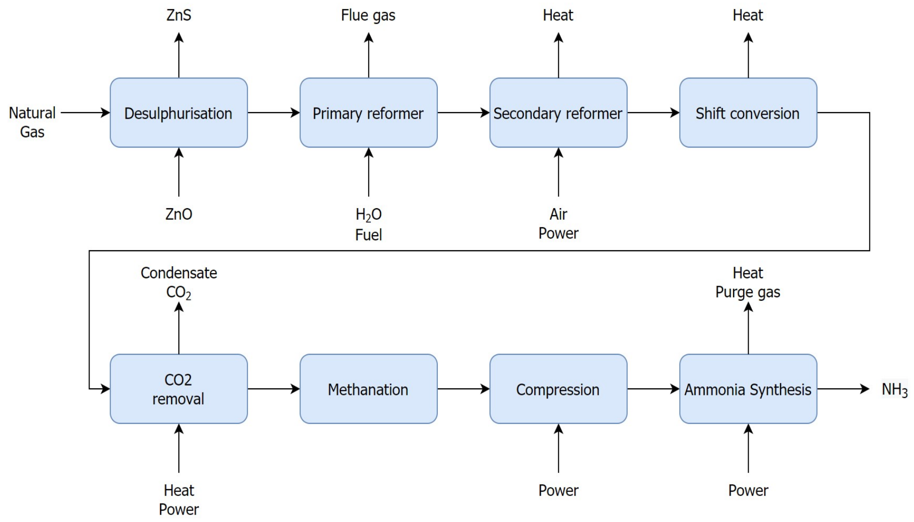

**Figure 2.1:** A block diagram of the ammonia production process. Retrieved from (EIPPCB, 2007, pg. 39).

The reforming section is highly endothermic, requiring a lot of heat (Pattabathula and Richardson, 2016). The combustion of natural gas supplies this heat. The flue gas from the combustion has a low concentration of $CO_2$

and accounts for 30% of the $CO_2$ emissions from $NH_3$ production (ISPT, 2017).

The remaining 70% of the $CO_2$ emissions stem from the process itself. Impurities such as CO and $CO_2$ arise in the reforming section. They poison the catalyst for ammonia synthesis and, therefore, have to be removed. To achieve a high-purity hydrogen gas stream, CO is converted into $CO_2$ because it is easier to remove from the process. The conversion takes place in the shift conversion, after which the $CO_2$ is removed using chemical or physical absorption techniques (EIPPCB, 2007). Subsequently, the high-purity stream of $CO_2$ is utilized to produce urea (Batool and Wetzels, 2019). Hence Carbon Capture and Utilization (CCU) is already applied within the fertilizer industry. Alternative applications of high purity $CO_2$ are manufacturing methanol and carbonated drinks.

### 2.1.3 The Industry

The exact ammonia production capacity in Europe is indecipherable due to suppressed or outdated data and confidential information. Statistics from Eurostat, IFA, Fertilizers Europe or manufacturers are aggregated or incomplete, complicating the assignment of production capacity per individual ammonia plant. Databases from independent business intelligence providers such as ICIS and Argus are also not freely accessible. With the use of publicly available information, it is estimated that there are around 40 ammonia production sites throughout Europe with a total production capacity of 20 million tonnes of ammonia per year (Batool and Wetzels, 2019; Egenhofer et al., 2014; Fertilizers Europe). This includes six mothballed ammonia plants in Romania, which are expected to reopen in 2021 (Banila, 2020). A list of the nameplate capacity per country and the involved companies can be found in Appendix B.

The map displayed in Figure 2.2 shows the locations of ammonia plants in Europe. Among the European countries, Germany, Poland, and the Netherlands have the highest installed ammonia production capacity, which accounts for approximately 45% of the total production capacity (Ecofys et al., 2009; Egenhofer et al., 2014). However, the study does not concentrate on any specific European country. Instead, it examines a typical European ammonia plant to provide insights that can be applied to other European countries with similar production environments and conditions. This approach allows for a comprehensive analysis of decarbonization alternatives and their wider implications across the European region, beyond particular national contexts.

Figure 2.2: A map of the European ammonia plants.

The production site of Yara in Sluiskil, the Netherlands, is the largest in Europe. The site contains three ammonia plants, each with a production capacity ranging between 450 and 730 thousand tonnes per year. The combined production capacity is 1.8 million tonnes of ammonia per year (Batool and Wetzels, 2019).

In 2019 14.7 million tonnes of ammonia were produced, which did not cover the total European demand for ammonia (Eurostat, 2019). 3 million tonnes of ammonia were imported in the same year, mainly from Russia, Algeria, Trinidad & Tobage and Ukraine (United Nations, 2020b). 70% of the imported ammonia came from Russia and Algeria. It is noteworthy that the same countries are also leading exporters of natural gas to Europe (Eurostat, 2019). 0.6 million tonnes of ammonia were exported in 2019. The total European demand for ammonia in 2019 was, therefore, 17.1 million tonnes.

## 2.2 THEORETICAL BACKGROUND

This section provides a knowledge base regarding decarbonization, the type of decarbonization options, and the solutions that are predominantly mentioned within energy-intensive industries, such as ammonia. The last subsection will describe the theoretical concepts for this research.

### 2.2.1 Broader Context of Decarbonization

Sustainable development is a core concept for the cost-effective decarbonization of the chemical industry. It entails the development "that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987, pg. 16). According to Perez (2009), sustainability has technological, social and economic aspects. The goals for reducing GHG emissions can be achieved with technical, economic and behavioural changes.

The decarbonization of the ammonia industry is part of a more considerable structural change in the industrial sectors of Europe. The European ammonia industry is a subsystem within the extending systems of the European chemical industries and the global fertilizer industry. With transformation, the change of fundamental attributes of the European ammonia industry towards a low-carbon industry is implied. The ongoing system transformation towards a low-carbon industry requires components of the old systems to be replaced or substituted. The transformation of the ammonia industry is more than reducing emissions and is underpinned by the 12 principles of green chemistry. Green or sustainable chemistry is defined as "the design, development and implementation of chemical products and processes that reduce or eliminate the use and generation of hazardous substances" (Anastas and Eghbali, 2010, pg. 301).

### 2.2.2 Categorization of Decarbonization Options

In this report, decarbonization refers to reducing $CO_2$ emissions emitted during processes or due to the consumption of fossil-based carbon in fuels or feedstock. The exhaust of other GHG emissions during the production of ammonia is negligible and thus disregarded in this research.

A decarbonization option is a measure such as a specific technology that reduces the $CO_2$ emissions. Different decarbonization categories exist for energy-intensive industries from the supply and demand sides. There are options such as fuel and feedstock substitution, energy efficiency or substitution within the process design and carbon capture and storage or utilization. Moreover, the residual energy of processes could be used, or an enhanced product design could reduce the use or be substituted with a product with a smaller $CO_2$ footprint.

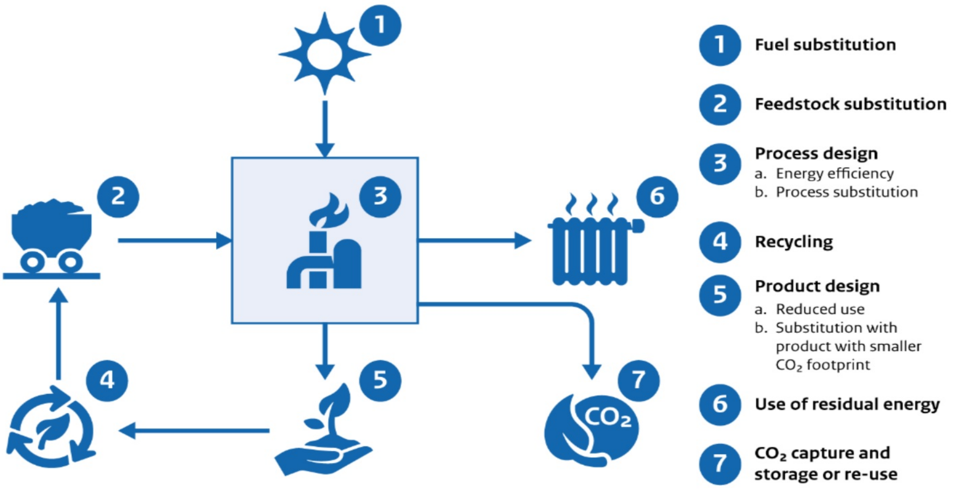

Figure 2.3: Categories of decarbonization options. Retrieved from (Advani and van Dril, 2020, pg. 27).

This research will focus on the cost-effectiveness of technical options within the industry, which is restricted by the production side and site of the industry. This includes fuel and feedstock substitution, Carbon Capture and Storage (CCS) and CCU. Behavioural changes such as shifts in dietary patterns, decreased food waste or improved utilization of nitrogen-based fertilizers could result in lower demand for ammonia (van Grinsven et al., 2020). This research follows the stable ammonia outlook of Europe from the International Energy Agency (IEA) and IFA. Behavioural changes that would result in lower demand for ammonia and thus $CO_2$ emissions from its production are out of the scope of this study and will not be considered.

As discussed in 1.1.2, energy efficiency for the current ammonia plant configurations will not lead to deep decarbonization even when produced at the theoretical minimum of required energy. However, the researcher acknowledges the opportunities and necessity for short-term energy efficiency and demand-side decarbonization options for the ammonia industry.

### 2.2.3 Decarbonization of Energy-Intensive Industries

The variation in the scientific literature regarding decarbonization options lies in particular with the scope of industrial sectors. Besides the ammonia industry, other energy-intensive industries, such as cement and refining, are challenged with the same decarbonization problem (European Commission, 2019b). There is no straightforward solution to this multi-headed and complex matter. However, technical options can be applied in various energy-intensive industries. For energy-intensive industries, the following cross-cutting low-carbon solutions are mentioned predominantly and repeatedly in scientific literature (De Pee et al., 2018; Wyns et al., 2018):

- Electrification of heat and processes
- Use of low-$CO_2$ hydrogen
- Use of biomass

- CCS and CCU

Decarbonization options relevant to the energy-intensive and hard-to-abate industries can also be important for the ammonia industry. Due to the dependency on hydrogen, low-carbon or green hydrogen for ammonia production are regarded as no-regret moves in the short- and medium-term (Fuel Cells and Hydrogen 2 Joint Undertaking, 2019). The international attention and uptake of low-carbon and green hydrogen projects will likely shape the ammonia industry's transformation. The ambitious plans of the European Commission included 40 GW of renewable hydrogen electrolysers in Europe and an additional 40 GW in neighbouring countries by 2030 for export to Europe (European Commission, 2019c).

### 2.2.4 Scientific Approaches towards Cost-effective Decarbonization

This subsection sets out the main concepts for the costs of reducing $CO_2$ emissions. Neoclassical economics are hereby fundamental. It is assumed that consumers and companies act rationally and maximize their utility and, respectively, their profits. Furthermore, markets are believed to be the preeminent mechanism for allocating goods and services effectively. In line with the neoclassical approach, costs are paramount within microeconomics. This translates to reducing $CO_2$ emissions for the lowest prices.

Externalities are positive or negative external effects on a third party that are not accounted for by the party who creates these effects. $CO_2$ emissions from ammonia production are a negative externality which can be regarded as a market failure following the neoclassical theory. The allocation of costs and benefits is distorted as the societal costs or damage caused by pollution are not passed on to the product user. Pigou (1920) argued that negative externalities such as $CO_2$ emissions ought to be internalized in the product's price by exemplifying a carbon tax. A practical problem that environmental economists struggle with is that it is impossible to measure the exact costs of pollution. There is a broad range of estimations concerning the social costs of carbon (Tol, 2019; Wang et al., 2019). Environmental cost-benefit analysis is an addition to the conventional cost-benefit analysis as it monetizes the social costs of pollution (Hoogmartens, 2019).

The LCOA is a techno-economic analysis that is a suitable approach to evaluate the costs and emission reduction potential of novel ammonia production processes. It can be regarded as an analogy from the established analysis that focuses on the levelized costs of energy or hydrogen. The method allows for comparing various technologies based on their costs and benefits but can also be used to assess a single technology. The number of studies that use the LCOA approach is limited, a list can be found in Appendix C.1. The variation in assumptions and production circumstances does not allow European ammonia manufacturers to adequately grasp the impact of sustainable ammonia production on the production costs of ammonia.

The production costs are useful to compare novel and sustainable ammonia production options to the current SMR Haber-Bosch process. The cost of $CO_2$ avoided is a useful addition to compare the costs of $CO_2$ reduction among various production processes. The cost of $CO_2$ avoided is commonly used within Marginal abatement cost curves (MACCs), a method which can help to determine which abatement options to implement and in which order (Vogt-Schilb and Hallegatte, 2014). According to Harmsen et al. (2019) MACCs is regarded as a useful tool for policymakers and corporations to achieve emissions reduction cost-effectively. However, this analysis method is unsuited for this study since it emphasises incremental decarbonization improvements rather than completely new production processes.

## 2.3 RESEARCH APPROACH

This section will outline the research approach for the study and describe the research methods and activities for each sub question. At the end of this section, you will find a research flow diagram in Figure 1.3. In Section 2.2.4, it was discovered that various modifications can be made to examine the cost-effectiveness of decarbonization options. This section will discuss how to appropriately address methodological considerations to achieve the research objectives and any potential limitations. The main research question for this study is stated as follows:

*How can the European ammonia industry effectively transition towards sustainable and economically viable decarbonization?*

Three sub questions support the research question of this study. To answer the main research question, it is essential to gain insight into the options that allow for deep decarbonization with sub question 1. After the selection, the remaining decarbonization options will be assessed based on their costs and carbon intensity with sub question 2. The impact and relations between the production factors on the production costs of ammonia will be explored. Afterwards, the process will be repeated for countries outside Europe with favourable production conditions. The competitiveness and risks of foreign and sustainable ammonia production will be explored in sub question 3. The method and output of the three sub questions will be discussed accordingly.

### 2.3.1 Sub question 1

*What are the technological opportunities for deep decarbonization of the ammonia industry?*

#### *Literature Research*

The first question is designed to identify the available deep decarbonization options for the ammonia production process. The technology scanning will be conducted through literature research and expert interviews. In the following paragraphs, the systematic approach of the literature research is provided by its search strategy, the keywords used, and the study selection. The method regarding the expert interviews is clarified afterwards.

**SEARCH STRATEGY** Data will be collected by conducting a literature review. However, a multi-faceted approach is proposed for technology identification to identify all technologies that may apply to a more sustainable ammonia production process. From the desk research, several decarbonization options are mentioned in the literature. Besides scientific publications and books, other sources of information will be used due to the practical field of study. Private companies such as ammonia producers and technology providers also invest significantly in the research and development of new technologies. Professional sources and conference proceedings will be used to discover the latest trends and technologies in the field. The online websites from news magazines such as Chemical & Engineering News and The Chemical Engineer are used to keep up with the newly announced ammonia projects worldwide. Furthermore, the Ammonia Energy Association website will be consulted for the same reason.

The researcher will attend webinars from the Ammonia Energy Association, Argus Fertilizers, Aurora Energy Research, Center for Strategic and International Studies, the European Committee of Regions, the International Association for Energy Economics, IEA and TNO. Besides insightful information regarding the economics of hydrogen and ammonia production, transportation, and their value chains, these webinars were used to build a network to approach experts for the interviews following the literature research.

**KEY WORDS** As explained in section 2.1.1, ammonia is a widely used chemical. In addition to synthetic ammonia production, the gas is a polluting emission. Ammonia is interwoven with agriculture, the nitrogen is used for fertilizers, but it is also released from livestock manure (van Grinsven et al., 2020). $NH_3$ emissions form fine particles when they react with acidic compounds, which can harm human health (Sommer et al., 2019). Furthermore, $NH_3$ emissions lead to eutrophication and acid deposition, translating into a detriment for water quality and loss of biodiversity (Giannakis et al., 2019). Due to the versatile occurrence of ammonia in modern society and academic literature, keywords must be selected carefully. Irrelevant articles focusing on ammonia co-firing in coal plants or $NH_3$ emission reduction will be disregarded.

Scopus was used as a search engine for scientific literature for technology identification. Ammonia and hydrogen resulted in 240.000 and 1.4 million documents on Scopus respectively. Hence, it is essential to be as precise as possible with the keywords to narrow down the set of results. Boolean operators AND, OR, and NOT trim the relevant output. AND was used to connect different categories of keywords. OR was used for other words of the same keyword categories. NOT was used to exclude irrelevant ammonia occurrences.

The keywords for the literature research correspond with the research focus, the ammonia process and the cost of new technologies. Section 2.1.2 demonstrates that the preparation of hydrogen for the Haber-Bosch process is the sole emission-intensive process and is, therefore, the focus for the decarbonization options. The division between categories and keywords can be found in Table 2.1.

| Category | Key words |
|---|---|
| Ammonia | Ammonia, Haber-Bosch, NH3, fertilizer, hydrogen, nitrogen |
| Renewable | Renewable, green, sustainable, decarbonized, clean, low-carbon, abated, mitigated |
| Cost | Cost, techno-economic, LCOA, levelized |
| Technology | Technology, option, lever, process, state-of-the-art, CCS, end-of-pipe, electrolysis, biomass gasification, methane pyrolysis |

**Table 2.1:** Key words

**SELECTION OF DECARBONIZATION OPTIONS** Studies or documents describing the chemical industry's decarbonization options contain time-sensitive information. It is plausible that the analysed decarbonization options are no longer relevant, so it is necessary to use up-to-date information. Furthermore, it is probable that new low-carbon technologies have emerged or that technology costs have been reduced.

Additional information about the technology would be related to its potential in reducing GHG emissions, the Technology Readiness Level (TRL) and cost data. TRL is a classification developed by the National Aeronautics and Space Administration (NASA) to indicate the degree of development of a technology. TRL 1 stands for technology at the beginning of development or discovery, whereas TRL 9 means that the technology is technically and commercially ready. TRL 7 till 9 are recognized as pre-commercialization phase (Kral et al., 2021). Technology development does not stop atTRL 9 but remains commercially competitive. The European Commission uses a similar approach to classify technologies for the Horizon 2020 EU Research and Innovation programme (Bruno et al., 2019). The IEA uses a more elaborated TRL scale by adding two more levels to indicate the integration of the technology in the existing energy systems (IEA, 2020a).

2030 is the time frame for this study by, the possibility of assessing the current technologies' development, deployment and costs. Increasing uncertainty is inherent to a more extended period. Technologies with a TRL of 4 or lower still being developed in a laboratory, are not likely to be deployed on a large scale within the upcoming decade. The same goes for technologies with TRL of 5 and 6 and their pilot experiments. Within the chemical industry, it can take years between an investment decision to implement and operate a new technology (Bazzanella and Ausfelder, 2017). A longer time frame would include disruptive or immature technologies with a low TRL for which the monetary value and reduction potential are merely speculative (Thomassen et al., 2019). This could negate the credibility of the cost-effectiveness of the decarbonization options with a more intelligible deployment trajectory. By addressing the economic and technical feasibility of decarbonization options, corporate stakeholders can compare sustainable alternatives knowing that sustainability will be assimilated into future investment strategies.

There are set criteria that the scientific article must comply with to include the decarbonization option. These criteria are:

- Language: only English sources are considered.

- Publication date: the articles should not be older than 10 years.
- Technical information: the articles should include details about the material flow and processes.
- Cost information: the articles should include reliable cost information about the equipment used.

Only English sources are considered for consistency and accessibility. Recent uptake in awareness concerning decarbonization and the development of green hydrogen has had a non-linear impact on cost data. Therefore, it was decided to exclude articles with a publication date exceeding ten years. Preferably, the cost information from scientific articles should not be older than five years to stay up-to-date with the latest information. Technologies from scientific papers are included if the article is specifically about the material flow of the process, this includes the input and output flows. The equipment used, including sizing, capital, and operational expenditures, should also be mentioned. This ensures a thorough understanding of the technology. There are also set criteria for what the decarbonization options must comply with. These criteria are:

- TRL: at least 7 in 2020 or a TRL of 9 by 2030.
- $CO_2$ reduction: offer minimum $CO_2$ reduction of 50% in comparison to the current SMR process.
- Cost information: availability of multiple sources of cost information for the equipment.

With a TRL of 7 and higher or a TRL of 9 in 2030, the current or expected commercial availability within the coming ten years is ensured. As described in 2.2.2, energy efficiency for the current ammonia plant configurations will not lead to deep decarbonization even when produced at the theoretical minimum of required energy. Therefore, the 50% $CO_2$ emissions reduction criterion is set. The availability of diverse sources of cost information for the equipment used in the decarbonization options is necessary to ensure a comprehensive analysis of the cost-effectiveness and economic viability of the technology. Regulatory coverage and public acceptability are not considered exclusion criteria for decarbonization options. In the following paragraphs, the method of the expert interviews is clarified.

### *Expert Interviews*

The literature research aimed to identify the decarbonization options for the ammonia industry and establish a broad understanding of the technologies. Subsequently, semi-structured interviews are conducted to achieve two objectives:

1. To ensure the inclusion of the main decarbonization options.
2. To explore technical and economic details, insights and perspectives regarding the decarbonization options.

**SEMI-STRUCTURED INTERVIEWS** The details provided by industry experts will enhance the comprehensiveness and quality of the data regarding the decarbonization options. The researcher opted for semi-structured interviews since structured interviews with planned questions would not allow asking newly devised questions during the interview, which would hinder the data collection. Semi-structured interviews are suitable for this research phase since they will enable the interviewer to ask in-depth questions based on the previously imposed information (Bogner et al., 2009). The semi-structured interview gives it a more flexible and personalised approach which is required due to the heterogeneous background of the industry experts.

The choice for semi-structured interviews instead of unstructured interviews is based on the need to ask the industry experts the same questions. These are the questions regarding the decarbonization options, their technological viability, limitations and influence on the ammonia production process. The prepared questions for the interviewees can be found in Appendix D.1.2. The prepared questions are partially tailored to the experience and knowledge of the industry expert.

The subjective nature of interviews and the potential bias in the industry expert selection are regarded as limitations of semi-structured interviews. Moreover, the experts' perspectives do not represent the entire industry. An attempt was made to mitigate the limitations of this method by selecting a diverse group of industry experts. However, the researcher acknowledges that the expert selection was dependent on the responses to emails and messages sent.

**INDUSTRY EXPERT SELECTION** The researcher sought to select a mix of interviewees, including representatives of ammonia producers, technology providers, research and technology organisations, and academic researchers. An overview of the selected interviewees and their affiliations can be found in Table D.1.

The desk research led to an overview of ammonia producers, technology providers, research institutions and industry associations, consultancy and advisory firms. Online webinars allowed for networking with industry experts, after which the researcher approached them by email or LinkedIn.

The ten largest European ammonia producers by nameplate capacity were contacted, the list can be found in B.1.1. Representatives from Yara Norway, and Borealis Austria were the only ammonia producers who agreed to an interview. BASF declined the request due to the present workload and the lack of personnel resources. The remaining ammonia producers did not respond to the request and ignored repeated calls. From the EPC companies, representatives from ThyssenKrupp Australia, G.I. Dynamics, and GIDARA Energy agreed to an interview. The publication of Batool and Wetzels (2019) provides an insightful synopsis of decarbonization options for the Dutch fertilizer industry, including the ammonia production process. Both authors from PBL and TNO agreed to an interview, as well as another academic researcher from TU Delft, which was mentioned in the literature review.

**OUTPUT** The interviews with industry experts will lead to the validation of the list of decarbonization options deemed as technologically realistic deep decarbonization options for the ammonia industry that can be deployed now or within ten years. However, decarbonization options may be missing from the literature review and expert interviews, but the information was collected to the author's best knowledge. The combined literature research methodology and expert interviews allowed the researcher to gain a deeper and more nuanced understanding of the technological landscape in the ammonia industry. The synthesis ensures a reliable assessment of the decarbonization options, providing a solid foundation for further analysis.

### 2.3.2 Sub question 2

*How do the costs per ton of ammonia and carbon emissions intensity of cleaner ammonia plant configurations compare to the standard SMR Haber-Bosch process*

#### *Techno-Economic Analysis*

The selected decarbonization options from sub question 1 will be assessed based on their costs and emissions reduction. The energy and carbon prices currently do not allow for a cost-competitive production of blue and green ammonia in Europe. The fundamental issue of this sub question is to determine under which conditions the alternative technologies can achieve cost parity and deployment. The three key performance indicators which allow for a fruitful comparison of the ammonia plant configurations are:

1. Levelized Cost of Ammonia (LCOA) [€/t $NH_3$]
2. Carbon Intensity (CI) [t $CO_2$/t $NH_3$]
3. CAC [€/t $CO_2$ avoided]

The LCOA approach was chosen to evaluate the cost-effectiveness of the decarbonization options. The costs associated with more sustainable alternatives consist of various elements and deviate from main cost components such as capital expenditures and the costs for operation and maintenance. Furthermore, the technological performance of the decarbonization options is compared to the current process after which it is monetized. This encompasses the benefits of lower costs for raw materials, electricity or steam, for example.

The geographical scope of Europe restricts the scope of the cost-effectiveness analysis and $CO_2$ since other GHG are negligible. The private cost perspective is adopted, and the $CO_2$ costs will also be included. The analysis will focus on technical abatement options and assume 2022 prices and the annual production capacity of 440 kt ammonia per facility based on Egenhofer et al. (2014). The scale and learning effects per decarbonization options will be described while disregarding rebound and feedback effects. Interdependencies between decarbonization options will be assessed.

The LCOA approach has limitations, including a wide range of estimations and a lack of data regarding the initial investment and energy consumption for every ammonia plant in Europe. Additionally, heterogeneity among national political support for specific decarbonization options such as CCS and different circumstances for the availability and price of renewable electricity pose challenges.

**LEVELIZED COST OF AMMONIA** As described in 2.2.4, the LCOA is a suitable method to evaluate the costs and emission reduction potential of novel ammonia production processes, and it can be calculated as follows:

$$LCOA = \frac{\alpha * I + O + F + C}{A} \tag{2.2}$$

Where:

$\alpha$ = Capital recovery factor
$I$ = Initial investment
$O$ = Annual costs for operation and maintenance
$F$ = Annual fuel costs
$C$ = Annual costs for $CO_2$
$A$ = Annual ammonia production

The variables from the LCOA will be explained in detail in subsequent order.

**CAPITAL RECOVERY FACTOR** The capital recovery factor can be calculated as follows:

$$\alpha = \frac{r}{1-(1+r)^{-n}} \tag{2.3}$$

Where:

$r$ = Discount rate
$n$ = Lifetime of project

According to Jouini et al. (2010) the discount rate is a substantial factor for a cost-benefit analysis, and its selection can significantly impact the economic viability of a project. A non-exhaustive list of techno-economic studies of green ammonia production is shown in Table C.1. In these publications, the discount rate varies between 4% and 12%. In this analysis, a constant discount rate of 8% is assumed, considered standard within the chemical industry and used by IEA (2021a). The sensitivity analysis will discuss the effect of a lower and higher discount rate. Furthermore, an average lifetime of 25 years is assumed, based on IEA (2021a). The average lifetime can be prolonged substantially through maintenance, but plants usually need extensive refurbishing after 25 years.

**INITIAL INVESTMENT** Within chemical engineering, the detail of the initial investment estimation of a plant depends on the project's development stage (Peters et al., 2003). Knowing the initial investment is impossible at an early stage of developing a new process plant. However, it is possible to estimate these costs. Preliminary cost estimates can be used for the decision-making process between alternatives. It gives an approximate idea of the probable cost of a plant. It is helpful at this conceptual stage of process design when a comparison between alternative process routes is made. This thesis follows the "class 5 estimate" according to the Association for the Advancement of Cost Estimating International (AACE International), which corresponds with Class 5 from Green and Southard (2019). The other types of cost estimations can be found in Appendix C.2.

It should be clarified that only battery limits are considered, and grassroots estimates are not included, which aligns with the Class 5 estimate classification. Major site development, infrastructure, and other elements associated with a grassroots project are excluded from the initial investment estimates.

Accurate data is crucial for making informed decisions in engineering design and cost estimation. However, the availability of comprehensive data on initial investment costs in the ammonia industry can be limited. To estimate the initial investment, an approach combines the scale laws and cost indexes, which allows for a quick assessment of the economic feasibility of a design concept (Sinnott and Towler, 2019).

Scale laws, derived from fundamental principles and empirical observations, allow for the estimation of various parameters and costs associated with scaling up or down processes, equipment, and systems. By applying scale laws to existing data or prototypes, it is possible to extrapolate the costs and capacity characteristics of larger-scale production units as follows:

$$C = C_{ref}\left(\frac{P}{P_{ref}}\right)^{R} \tag{2.4}$$

Where:

$$\begin{aligned} C &= \text{Cost of equipment} \\ C_{ref} &= \text{(Known) cost of equipment with capacity } P_{ref} \\ P &= \text{Capacity of equipment} \\ P_{ref} &= \text{Capacity of equipment for which the cost } C_{ref} \text{ is known} \\ R &= \text{Constant scale factor} \end{aligned}$$

If the constant scale factor is not provided by Sinnott and Towler (2019), 0.6 is used, commonly called the "six-tenths rule".

Cost indexes, such as the widely recognized Chemical Engineering Plant Cost Index (CEPCI), can adjust costs based on market conditions, inflation, and technological advancements over time. By utilizing cost indexes, it is possible to update and refine preliminary cost estimates to align them with the current economic landscape.

$$Cost_B = Cost_A\left(\frac{Index_B}{Index_A}\right) \tag{2.5}$$

Where:

$$\begin{aligned} C_A &= \text{Cost of equipment in year A} \\ C_B &= \text{Cost of equipment in year B} \\ Index_A &= \text{Cost index of year A} \\ Index_B &= \text{Cost index of year B} \end{aligned}$$

CEPCI is widely preferred over other cost indexes, such as the Marshall and Swift Cost Indexes and Nelson-Farrar Indexes, for preliminary investment estimations. This preference arises for several reasons, including the discontinuation of the Marshall and Swift Cost Indexes and the specialized focus of the Nelson-Farrar Indexes on the petrochemical industry. The yearly average of the dollar-euro exchange rate from the European Central Bank is utilized to convert dollars to euros. Furthermore, when conducting calculations using the CEPCI, the base year of 2022 is used. An overview of the CEPCI index can be found in Appendix C.3.

Utilizing these methods compensates for limited data availability in the ammonia industry and offers a practical solution during the early stages of project development. However, it is essential to recognize the limitations inherent to this method. These include simplified assumptions, lack of industry-specific data and project-specific factors such as site location, regulatory requirements, and environmental considerations. This should be carefully considered and taken into account while interpreting the results.

**OPERATION AND MAINTENANCE** In addition to the challenges of estimating the initial investment, it is essential to acknowledge that operational expenditure data is often even more limited and challenging to obtain. The availability of comprehensive and reliable data for ammonia plants can be scarce, making it a significant challenge to estimate ongoing operational costs accurately. Factors such as labour and maintenance cost variations can significantly influence this, and obtaining precise data on these factors is challenging. Similarly, with the presented studies in C.1, the costs for operation and maintenance will be estimated based on their initial investment and TRL. 5% of the initial investment is used for decarbonization options with a TRL of 7 in 2020, and 3% for the options with a TRL of 8 and above in 2020.

**FUEL COSTS** The input of required energy depends on the decarbonization option. It could be natural gas, biomethane, electricity, or a combination of these inputs. The decision is made to include the latest available data on natural gas, electricity and carbon prices instead of the limitation of not using the latest research papers. The current geopolitical situation, especially the Ukraine-Russia war, has significant implications for the energy landscape of Europe. The reliability and affordability of natural gas come into question. Energy market dynamics translate this to higher and more volatile gas prices. For example, in 2020, some countries had a natural gas price excluding taxes and levies as low as 2.6 - 4.6 €/GJ. In 2022, that range would be 18 - 36 €/GJ for the largest bandwidth under non-household consumers (Eurostat, 2023b). Outdated data could lead to inaccurate conclusions. Recent prices for commodities allow for a more realistic cost-effectiveness assessment for decarbonization options. Data from Eurostat (2023a) is also used for electricity prices. Similarly, as with the natural gas prices, the unweighted average price of countries with ammonia producers is used. The energy requirement of every production process will be stated in GJ/t$NH_3$. The price range of biomethane in Europe is between 5 - 28 €/GJ, according to IEA (2020b). However, the supply of biomethane at low cost is minimal, the average price is around 20 €/GJ.

**CARBON COSTS** An extra addition to the formula is incorporating carbon costs, which are often neglected in the literature. It is an essential variable which allows for a fruitful comparison of CI and CAC between different decarbonization options. It can also be considered a vital pressure point from a political perspective. Legislation, such as a $CO_2$ tax, could severely impact carbon costs and thus the LCOA. For carbon costs, it is essential to distinguish between $CO_2$ emissions that are emitted and costs for $CO_2$ emissions that are captured. Large amounts of $CO_2$ are most efficiently transported either by pipelines or by ship. Before transportation, the $CO_2$ needs to be purified and compressed or liquefied. The costs for transportation of $CO_2$ depend on the volumes, distance and possibilities to use existing infrastructure. For CCS options, the costs of transport and storage of captured $CO_2$ are assumed on 20 €/t $CO_2$, based on Irlam (2017).

The pricing dynamics of emissions allowances within the EU ETS have changed radically in recent years. In 2020, the trading range for emissions allowances spanned from 15 to 35 euros per metric ton of $CO_2$. However, by 2022, the pricing landscape has shifted substantially, with the price range surging to 60-100 euros per metric ton of $CO_2$ (EMBER, 2023). These developments reflect the significant disruptions and geopolitical uncertainties that have unfolded, leading to a notable impact on the market valuation of emissions allowances within the EU ETS.

For this study, the analysis will be conducted using incremental values of 50 euros per metric ton of $CO_2$. Specifically, the selected increments will be 0, 50, 100, 150, and 200 euros per metric ton of $CO_2$. These specific increments provide a systematic approach to examine and evaluate the potential impacts and cost implications associated with varying levels of carbon pricing within the context of the study. By considering these distinct intervals, a comprehensive understanding of the financial and economic implications of different carbon pricing scenarios can be gained, facilitating informed decision-making and policy analysis.

**ANNUAL AMMONIA PRODUCTION** As stated before by Fertilizers Europe, it is unlikely that there will be newly built ammonia capacity in the next 5 to 10 years. According to IEA (2021a), the average age of ammonia plants in Europe is between 7 and 17 years. The annual production capacity of 440 kt ammonia per facility is assumed because it is the median production capacity according to Egenhofer et al. (2014). This represents the midpoint of the production capacity range. This approach helps to account for the average or typical scale of ammonia production facilities, providing a reasonable baseline for analysis purposes. It's important to acknowledge that larger production plant capacity can be achieved by either a single train or multiple parallel trains, such as the Yara plant, as described in 2.1.3.

**CARBON INTENSITY** The formula for CI follows the IPCC Guidelines for National Greenhouse Gas Inventories for Industrial Processes and Product use (IPCC, 2006, pg. 12):

$$E_{CO_2} = A * FR * CCF * COF * \frac{44}{12} - R_{CO_2} \tag{2.6}$$

Where:

$E_{CO_2}$ = emissions of $CO_2$
$A$ = ammonia production
$FR$ = fuel requirement per unit of output, GJ/tonne ammonia produced
$CCF$ = carbon content factor of the fuel, kg C/GJ
$COF$ = carbon oxidation factor of the fuel, fraction
$R_{CO_2}$ = $CO_2$ recovered for downstream use

Recovered $CO_2$ is a well-established CCU process in the ammonia industry for producing urea. The carbon intensity is derived from the previous formula by dividing the emissions of $CO_2$ by the total ammonia production. The $CO_2$ emissions per ton of produced ammonia are then the outcome:

$$\mathrm{CI} = \frac{\mathrm{E}_{CO_2}}{\mathrm{A}} \tag{2.7}$$

**COST OF AVOIDED CARBON** The analysis does not include positive externalities that stem from the possible reduced amount of $CO_2$ such as health benefits to society and improved biodiversity or enhanced soil quality. A social cost-benefit analysis could monetize these welfare effects for governmental bodies and thus contribute to the decision-making process but that is not in the scope of this thesis. Based on the LCOA and CI the CAC can be calculated as follows:

$$\mathrm{CAC} = \frac{\mathrm{LCOA}_{\text{Decarbonization Option}} - \mathrm{LCOA}_{\text{Reference}}}{\mathrm{CI}_{\text{Reference}} - \mathrm{CI}_{\text{Decarbonization Option}}} \tag{2.8}$$

This means that a decarbonization option with a negative CAC suggests that the decarbonization option is not cost-effective. Low CAC indicates that the decarbonization option is cost-effective. The cost per unit of emissions reduction is comparatively lower, suggesting that the measure is financially efficient in reducing $CO_2$ emissions. This result implies that the investment required to achieve emission reductions is relatively reasonable and justifiable. A high CAC indicates that the carbon reduction measure is relatively expensive, suggesting that the decarbonization option may have limited cost-effectiveness. It could imply that alternative strategies or decarbonization options that offer a more favourable cost-benefit ratio should be explored to achieve the desired carbon reduction targets.

**OUTPUT** All analyses will be carried out in Excel 2019. The calculated output of the LCOA, CI and CAC provide valuable information regarding the cost-effectiveness of the decarbonization options. Interpreting the results allows decision-makers to assess the cost-effectiveness of different carbon reduction strategies and make informed decisions about the most viable and economically efficient pathways to mitigate carbon emissions in the ammonia industry.

### 2.3.3 Sub question 3

*To what extent does the cost and carbon intensity of sustainable ammonia production in Europe affect the competitive position of European ammonia producers relative to global counterparts?*

#### *Techno-Economic Analysis Non-European Producers*

The implications of sustainable ammonia production for the competitiveness of European producers on a global playing field have become a significant concern, particularly in the wake of recent geopolitical events and the urgent need for decarbonization. The COVID-19 pandemic and the Ukraine-Russia war have profoundly impacted the geopolitical landscape in Europe, leading to a reassessment of energy and resource dependencies. Besides the ethical concerns, the unreliability of Russia as a business partner, coupled with the changing dynamics of natural gas and ammonia exports, has prompted Europe to seek self-dependence and prioritize green recovery. While Europe holds a strong position in sustainable hydrogen demand and technological advancements, the production circumstances for green or blue hydrogen and ammonia outside Europe appear more favourable due to lower prices for green electricity or natural gas. Importing blue and green ammonia from non-EU countries is likely to remain happening and could foster the maturity of the low-carbon hydrogen and ammonia market. This sub question explores the cost-effectiveness of sustainable ammonia production outside of Europe and its implications.

**COUNTRY SELECTION** In the "Fit for 55 Package", the European Commission intends to facilitate the import of hydrogen and ammonia into Europe, recognizing the significance of international collaboration and diversified hydrogen sources in advancing the EU's decarbonization objectives. There are a lot of countries which could be potential hydrogen and ammonia suppliers. Therefore, a selection must be made to limit the analysis to all potential countries.

Several key factors were carefully considered when selecting countries for inclusion in this study to ensure a comprehensive analysis of potential non-EU ammonia producers. These factors encompass:

- Maturity of ammonia industry
- Export potential
- Feasibility of low-carbon or green hydrogen potential

The maturity of the ammonia industry in a given country is a criterion, as it indicates the readiness and capability for sustained production. Countries with established ammonia industries or concrete plans for commissioning new plants within the next five years were prioritized for inclusion. This criterion ensures the analysis remains relevant and accounts for existing or imminent production capacity.

Export potential emerged as another crucial factor, reflecting the likelihood of ammonia production being directed towards international markets rather than solely catering to domestic demand. Nations with significant export capabilities are favoured, as they present opportunities for increased trade and collaboration within the global market for ammonia.

Countries such as Russia, Trinidad Tobago, Saudi Arabia, Algeria, Australia and Canada, known for their mature ammonia industries and global export capabilities, were initially considered. However, Russia and Trinidad Tobago were excluded due to geopolitical concerns and a lack of possibilities for CCS infrastructure. China, the US and India have mature ammonia industries but cannot be considered ammonia exporters (United Nations, 2020b).

As indicated by IRENA (2022), the potential for low-carbon or green hydrogen production also played a pivotal role in the selection process. Countries possessing favourable conditions for renewable energy resources, such as high solar irradiation or wind capacity factors, and opportunities for CCS or low-cost biomethane, were deemed conducive to sustainable ammonia production. These factors align with the broader objective of promoting environmentally friendly and economically viable decarbonization strategies.

Given their favourable renewable energy resources, projected hydrogen prices indicated by sources like IRENA, pointed towards countries such as China, Chile, Australia, and Colombia as potential candidates for cost-competitive ammonia production. Chile, in particular, stood out due to its robust governmental commitment and ideal conditions for green ammonia production, driven by initiatives like the National Hydrogen Strategy.

Furthermore, the existence of Memoranda of Understanding (MoUs) between European countries like the Netherlands and Germany with potential supplier nations like Australia, Canada, Chile, and Saudi Arabia underscored the willingness to collaborate on sustainable ammonia initiatives.

The consideration of these three factors collectively guided the selection of countries for inclusion in the study. While numerous countries possess varying degrees of relevance to the production and export of ammonia, the analysis focused on those that exhibited the most promising combination of industry maturity, export potential, and conducive conditions for low-carbon hydrogen production. The selection process ultimately included Algeria, Australia, Canada, Chile, and Saudi Arabia. These countries were chosen based on their alignment with the specified criteria and their potential to offer valuable insights into the dynamics of sustainable ammonia production on a global scale.

**TRANSPORTATION COSTS** The cost analysis of ammonia transportation contributes to a better understanding of non-EU producers' overall feasibility and competitiveness in the European market. The methodology is similar to sub question 2, as described in 2.3.2, and is used to assess the cost-effectiveness of non-EU ammonia producers. Compared to European ammonia producers, the calculations for the LCOA of non-European ammonia producers primarily differ in terms of additional transportation costs. Ammonia transportation is a well-established and fully commercialized practice, unlike the transportation of hydrogen (Giddey et al., 2017). Compared to compressed hydrogen, liquefied hydrogen, and LOHC, ammonia has a higher volumetric energy density (Roos, 2021). Moreover, it is easier to store and transport. Therefore ammonia is a promising energy vector for the future (Navas-Anguita et al., 2020).

The choice of transportation means for ammonia depends on the country of production. Options may include transport by vessel, pipeline, truck or rail transportation. The suitability of each method varies depending on factors such as quantity, distance, infrastructure availability, logistical considerations, and cost-effectiveness. Due to the large amounts of ammonia, truck and rail transportation are excluded from the analysis.

Argus Media Group, the company behind Argus Ammonia, is a market intelligence provider and publishes the monthly ammonia freight rates on its website. The freight rates from common routes, such as from Ras Al-Khair (Saudi Arabia), Anzwer (Algeria) or Point Lisas (Trinidad & Tobago) to Antwerp or Rotterdam, are provided and will be used to assess the transportation costs (Argus Media Group, 2021). If Argus does not provide shipping routes, the Shiptraffic website calculates the shipping routes' distances. With this, the port of Rotterdam is used as the destination port to calculate the distances for marine transport. According to IEA (2021b), maritime transport costs estimates for ammonia are between 40 and 60 dollars per ton $NH_3$ for a shipping distance of 10000 km, and between 60 and 80 dollars per ton $NH_3$ for a shipping distance of 20000 km. However, shipping prices increased rapidly in the last few years. 100 dollars per ton $NH_3$ for a shipping distance of 10000 km has become common.

Algeria and Saudi Arabia are the only countries among the selected countries capable of supplying ammonia to Europe through a pipeline, considering their geographical position. Notably, ammonia pipelines, such as the longest spanning 2,470 kilometres from Tolyatti, Russia, to Odessa, Ukraine (IEA, 2021a), are already operational. Also, in the fertilizer industry in the United States, ammonia pipelines are common practice (Papavinasam, 2014). It is worth mentioning that there are existing natural gas pipelines connecting Algeria to Spain and Italy, indicating a well-established infrastructure for energy transport in the region. However, ammonia transport by pipeline between North Africa or the Middle East and Europe is not considered economically viable and, therefore, not considered a means of transport for ammonia. A hydrogen pipeline appears to be a more viable option in the future, but that is out of the scope of this study.

### *Expert Interviews*

Similar to the method for sub question 1, semi-structured interviews will be conducted with industry experts to gather qualitative insight into the challenges, opportunities, and implications of EU versus non-EU ammonia production. Understanding these implications provides valuable insights into European ammonia producers' global prospects and challenges. For the selected interviewers and examples of prepared questions, see Appendix D.1.4 and D.2.

**OUTPUT** From a system perspective, the implications of EU production versus non-EU ammonia production are multifaceted and encompass various industrial, economic, and policy aspects. The comparison between ammonia production within the EU and production in non-EU regions raises questions about the competitiveness and prospects of European ammonia producers. These insights and opinions will be gathered using semi-structured interviews with industry experts.

Industrial implications arise concerning the technological advancements and production efficiency of ammonia plants. Non-EU countries may have access to lower-cost energy sources, such as natural gas, which can impact their production costs and potentially make them more competitive. Additionally, differences in regulations and environmental standards between the EU and non-EU countries may affect the sustainability and carbon footprint of ammonia production processes.

Economically, cost structures and market dynamics play a significant role. Non-EU ammonia producers may benefit from lower labour costs, fewer regulatory burdens, and potentially lower $CO_2$ prices. These factors can influence the overall cost competitiveness of their ammonia products in international markets, including Europe. Market conditions, demand-supply dynamics, and trade agreements also affect the market share and profitability of EU and non-EU ammonia producers.

Policy implications revolve around the EU's sustainability and decarbonization objectives. The EU's climate measures and policies, such as the EU ETS, CBAM and the Renewable Energy Directive, set targets for reducing greenhouse gas emissions and increasing the share of renewable energy sources. These policies impact the cost structure and competitiveness of EU ammonia producers. Moreover, the EU's ambition to establish a circular economy and transition to low-carbon technologies may shape the long-term viability of ammonia production within Europe.

## 2.4 CONCLUSION

Concluding on the methodology employed in this thesis, a comprehensive approach was adopted to investigate the technological opportunities for deep decarbonization of the European ammonia industry. The analysis encompassed multiple ammonia plant configurations and incorporated techno-economic evaluations to assess the economic attractiveness of cleaner ammonia production processes. Furthermore, the implications of sustainable ammonia production on the competitiveness of European producers within the global market were explored.

Quantitative and qualitative methods are employed to achieve the research objectives. Techno-economic analysis in the form of the LCOA provided valuable insights into the economic feasibility of cleaner ammonia plant configurations. The use of cost indexes, scale laws, and estimation methodologies for the costs of operational expenditures allowed for a more robust assessment of initial investment and operating costs. Additionally, semi-structured interviews with industry experts provided valuable perspectives on the implications and challenges associated with sustainable ammonia production.

However, it is essential to acknowledge the limitations of this study. The accuracy and reliability of the findings are subject to the availability and quality of data, which can be limited, especially concerning capital and operational expenditures data. Assumptions made during the techno-economic analysis and estimation processes may introduce uncertainties. Moreover, the study focused on a specific time frame and may not account for all future developments or changing market conditions. These limitations highlight the need for further research, ongoing data collection, data transparency, and collaboration with industry stakeholders to enhance the accuracy and applicability of the findings.

In conclusion, the methodology employed in this thesis provided valuable insights into the technological opportunities, economic viability, and competitiveness of sustainable ammonia production in Europe. By considering multiple plant configurations and conducting comprehensive techno-economic analyses, the study contributes to understanding how the European ammonia industry can decarbonize cost-effectively. Nevertheless, future research should continue to address data limitations, refine methodologies, and account for evolving market dynamics to support informed decision-making and foster the transition towards a sustainable and competitive European ammonia sector. These findings serve as a foundation for the subsequent chapter, where a detailed evaluation of decarbonization options will be conducted.

# 3 DECARBONIZATION OPTIONS

This chapter addresses sub question 1 by exploring the technological decarbonization options available for the European ammonia industry. The analysis is based on an extensive literature review and interviews with industry experts as described in section 2.3.1. The chapter begins with the identified decarbonization options from the literature and their selection for techno-economic analysis. Subsequently, the selected decarbonization options are described, followed by a discussion of the limitations associated with each technology.

## 3.1 DECARBONIZATION OPTIONS FROM LITERATURE

A comprehensive analysis has identified several decarbonization options as promising solutions. Table 3.1 presents an extensive list of decarbonization options for primarily hydrogen production, considering the close relationship between hydrogen and ammonia production. It is important to note that some options in the list mainly focus on hydrogen production, and their TRL is related to that aspect rather than ammonia production. However, it is assumed that decarbonization options for hydrogen production can be combined, utilized or integrated into ammonia production processes.

Specific options have been excluded to ensure a focused selection of decarbonization options. Options for small-scale ammonia or hydrogen production, such as transparent baggie systems utilizing microorganisms and photocatalytic systems, are excluded from the analysis. According to Mr Rebreyend from TU Delft, these technologies won't be deployable on a commercial scale within the next decade. Decarbonization options, like water splitting using seawater, have not been considered separate decarbonization options in this chapter. Instead, they are grouped under existing electrolyzer technologies such as alkaline, Proton-Exchange-Membrane (PEM), and Solid Oxide Electrolyzer Cell (SOEC) electrolyzers, which are already recognized as viable options for hydrogen production.

| **Technology** | **TRL** |
|---|---|
| SMR CCS - Partial capture | 9 [b] |
| SMR CCS - High capture rate | 5 [b] |
| ATR CCS - Single reformer | 5 [b] |
| ATR CCS - Gas Heated Reformer | 5 [b] |
| Sorption Enhanced SMR | 4 [b] |
| Tri-reforming | 5 [a] |
| POX CCS | 6 [b] |
| Coal Gasification CCS - Partial capture | 9 [b] |
| Coal Gasification CCS - High capture rate | 5 [b] |
| Alkaline electrolysis | 9 [b] |
| Polymer electrolyte membrane electrolysis | 9 [b] |
| Solid oxide electrolyzer cell | 7 [b] |
| Anion exchange membrane electrolysis | 6 [b] |
| Nuclear thermolysis | 3 [b] |
| Biomass waste gasification | 6 [b] |
| Biomass waste gasification CCS | 5 [b] |
| Biomass waste pyrolysis | 6 [b] |
| Biomass anaerobic digestion | 9 [b] |
| Biomass anaerobic digestion CCS | 8 [b] |
| Methane pyrolysis - Thermal decomposition | 3-4 [bc] |
| Methane pyrolysis - Catalytic decomposition | 4-6 [bc] |
| Methane pyrolysis - Plasma decomposition | 6-8 [bc] |
| Direct bio-photolysis | 3-4 [d] |
| Indirect bio-photolysis | 3-4 [d] |
| Photolytic $N_2$ splitting | 3-4 [e] |
| Photo-electrochemical systems | 4 [f] |
| Photo-fermentation | 3-5 [d] |

**Table 3.1:** Decarbonization options in scientific literature

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[a] Walden, 2022
[b] IEA, 2022a
[c] Schneider et al., 2020
[d] Faber et al., 2019
[e] Rebreyend and De Bruin, 2015
[f] Frowijn and van Sark, 2021

Multiple technologies are excluded from the analysis when the criteria for decarbonization options, as described in 2.3.1, are followed. By excluding options with lower TRL and those focused on small-scale production, the chapter ensures a more focused evaluation of decarbonization options that are closer to being deployed at a larger scale. This approach allows for a more pragmatic assessment of options that can contribute significantly to the decarbonization of ammonia production while considering their technological readiness and potential for large-scale implementation.

Consultation with Rob Stevens from Yara Norway and Karan Bagga from ThyssenKrupp-Uhde led to the ex- and inclusion of several decarbonization options. Coal gasification with CCS and POX with CCS are excluded. The decision to exclude coal gasification is based on the understanding that it is primarily of interest to China. After consulting with Mr Stevens and Mr Bagga it was determined that coal gasification is not a prominent option for ammonia production in Europe. Consequently, it was deemed unnecessary to include POX as its initial investment, fuel requirement, and $CO_2$ emissions are higher than SMR. It is noteworthy that industry experts assert that no new ammonia plants in Europe will adopt this technology. Contrarily, it is decided to include the high capture rate and single reformer CCS options for respectively SMR and ATR. This decision was informed by consultation with Ms Batool and Mr Wetzels from PBL and TNO, respectively, indicating these technologies' viability and maturity in 2030. The gas heated reformer CCS option for ATR is excluded due to a lack of economic data.

The reason for including biomass digestion is the proposed RePowerEU plan that aims to produce 35 bcm of biomethane within the EU by 2030. This will replace 10% of the European gas demand. Biomass digestion is a production process for biomethane. Biomethane can replace natural gas for reforming production pathways since it has the same chemical composition as natural gas (IEA, 2020b). This study assumes an average input price of 55 €/MWh for biomethane, not the initial investment for producing biomethane. The availability and stable supply of biomethane is, however, a constraint. After consultation with Robert Schelsinger and Markus Aichinger from Borealis Austria, it is also decided to include biomass gasification as a decarbonization option. Although the TRL is below the threshold of 7, industry experts suggest that the development of this technology will evolve rapidly.

The increasing demand for hydrogen in Europe, coupled with the ongoing energy crisis, has triggered a surge in the development of electrolyzer technologies. This does not only go for the matured alkaline electrolyzer but also the relatively new types of electrolyzers such as PEM, SOEC and Anion Exchange Membrane (AEM). This intensified interest and investment in electrolyzer research and innovation leads to an increasing TRL for these technologies.

AEM electrolysis represents a hybrid technology that combines the cost-effectiveness of alkaline electrolyzers with the flexibility, high power density, and high gas purity associated with PEM electrolyzers. Therefore, AEM electrolysis offers a promising solution for efficient and sustainable hydrogen production. Despite the rapid development of this type of electrolyzer, it is not included in the analysis due to the lack of financial data. The description of the technologies will be simplified for the remaining part of the study. The final list of decarbonization options is listed below, after which they will be described in the next section.

- SMR CCS - Partial capture
- SMR CCS - High capture rate
- ATR CCS - Single reformer
- Biomass gasification
- Biomass anaerobic digestion
- Alkaline electrolysis
- PEM electrolysis
- SOEC electrolysis
- Methane pyrolysis

## 3.2 SELECTED DECARBONIZATION OPTIONS

This section explains the selected decarbonization options for the European ammonia industry. It is assumed that decarbonization options are globally available for the ammonia industry, although there could be potential variations between European and non-European contexts. Policy frameworks, resource availability, and industrial infrastructure can significantly influence the feasibility and adoption of specific decarbonization options in different regions. However, the study did not delve deeper into analyzing these regional differences. Instead, it focused on identifying a broad range of decarbonization technologies and assessing their potential applicability within the European context. The options such as the CCS options and different electrolyzers can be grouped into clusters based on their similarities. The working principles of the options are focused on the hydrogen production process and will be discussed accordingly.

### 3.2.1 CCS

#### *SMR CCS - Partial capture*

In this CCS option, the $CO_2$ capture occurs in the hydrogen production process after the shift conversion. State-of-the-art chemical absorption technology known as MDEA is used (Bui et al., 2018). The shifted syngas are directed to the flash drum, where the vapour is utilized as additional fuel for the steam reformers. The rich solvent from the flash drum is further processed in a heat exchanger and heated by incoming lean solvent from the stripper's reboiler. The heated rich solvent is then fed into the top of the stripper column.

In the stripper column, the rich solvent flows down and is stripped of its $CO_2$ by the vapour generated from the stripper's reboiler, primarily consisting of steam. The stripper's reboiler is heated by low-pressure steam from the back-pressure steam turbine of the cogeneration plant. The condensed vapour from the reboiler is sent back to the hydrogen plant's boiler feed water system (Collodi et al., 2017).

The overhead gas from the stripper column is condensed in the stripper's condenser, and the collected steam is returned as reflux to the stripper column. The $CO_2$-rich gas from the stripper's condenser is then directed to the $CO_2$ compression and dehydration unit for further processing. This process efficiently captures $CO_2$ from the shifted syngas, contributing to a 55% decrease in $CO_2$ emissions.

#### *SMR CCS - High capture rate*

In this CCS option, the $CO_2$ is captured from the flue gas in the hydrogen production process and utilizes chemical absorption with MEA as the solvent. The flue gas from the SMR is cooled, desulphurized, and washed in a series of units, including a gas-gas heater, quench scrubber, absorber, and water wash column. The rich MEA solvent is regenerated in the stripping column with the help of reboilers heated by low-pressure steam, and the $CO_2$-rich gas is sent for compression and dehydration.

In a split flow configuration, the rich amine is split into two streams, one fed to the stripper column and the other processed through the flash column. The recovered CO2-rich gas is then directed to the $CO_2$ compression and dehydration unit. Additionally, a portion of the lean amine is withdrawn periodically to remove heat-stable salts through a reclaimer process. The low-pressure steam is also used to re-boil the lean amine, with the condensate sent back to the hydrogen plant's deaerator. This process captures $CO_2$ from the flue gas, contributing to a 90% decrease in $CO_2$ emissions (Collodi et al., 2017).

### *ATR CCS - Single reformer*

ATR is an emerging reactor design for clean hydrogen production that combines partial oxidation and steam reforming to convert natural gas into syngas. Figure 3.1 shows the conventional ATR process without CCS. The decarbonization option has a $CO_2$ removal after the shift conversion (Schneider et al., 2020). In that case, ATR achieves approximately 95% of the $CO_2$ for efficient capture. The process operates at harsher conditions than SMR, with higher temperatures and pressures, reducing coking and allowing for more waste-heat recovery. ATR eliminates the need for external heating, resulting in no flue gas emissions, simplifying the carbon capture process. While ATR offers advantages in $CO_2$ capture, it also has disadvantages.

Large-scale blue hydrogen production requires multiple reactor trains and a cryogenic Air Separation Unit (ASU) to supply oxygen, increasing capital and operational costs (Oni et al., 2022). However, it's important to note that the ASU provides oxygen for the ATR process and nitrogen for the Haber-Bosch synthesis. The carbon dioxide is captured from the syngas using an activated MDEA solvent, operating similarly to the process described for the SMR CCS partial capture option.

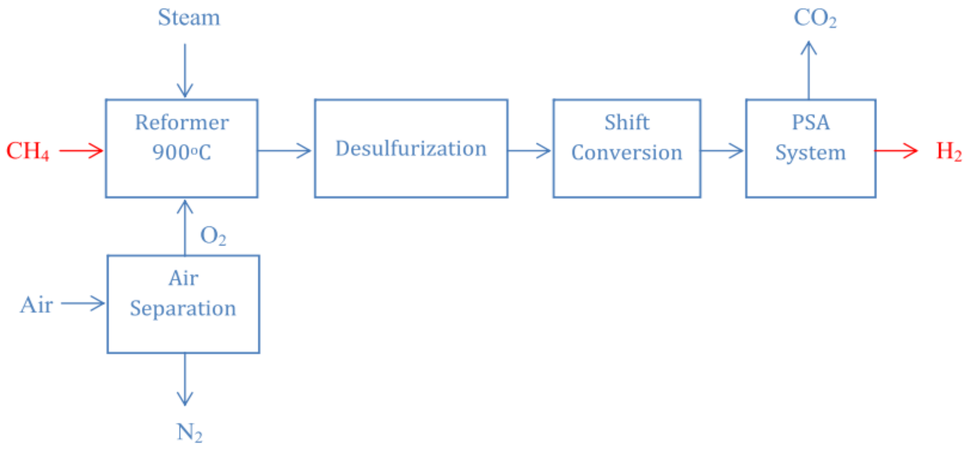

**Figure 3.1:** ATR flow diagram. Retrieved from Nikolaidis and Poullikkas, 2017, pg. 601

### 3.2.2 Electrolyzers

Electrolysis of water is an established and well-known method for hydrogen production. The reaction is endothermic, meaning that it requires energy input. In this study, the energy input is provided by renewable electricity. Therefore, the associated $CO_2$ emissions from these processes are regarded as zero.

An electrolyzer consists of a cathode and an anode immersed in an electrolyte. When an electrical current is applied, the water molecules split into hydrogen and oxygen gas. The hydrogen gas is produced at the cathode, while the oxygen gas is produced at the anode. An overview of the electrolyzers is depicted in Figure 3.2. The overall reaction for the three types of electrolyzer is as follows:

$$2\,H_2O \longrightarrow 2\,H_2 + O_2 \tag{3.1}$$

#### *Alkaline electrolysis*

Alkaline electrolysis is a well-established technology for hydrogen production. The process involves the electrolysis of water using an alkaline electrolyte, typically potassium hydroxide (KOH), as the conductive medium. The electrolyzer comprises an anode and a cathode, separated by a porous membrane. When an electric current is passed through the electrolyte, water molecules at the anode are oxidized, releasing oxygen gas. At the same time, hydrogen ions ($H^+$) are reduced at the cathode, producing high-purity hydrogen. $OH^-$ is the charge carrier. The operating temperature is usually between 60°C and 80°C, while the operating pressure is less than 30 bar (Shiva Kumar and Himabindu, 2019). Alkaline electrolyzers are known for their high efficiency, reliability, and long operational lifespan (Nayak-Luke et al., 2021). The alkaline electrolyzers have a stack lifetime of 60,000 to 90,000 hours (Schmidt et al., 2017). The reaction for the anode and cathode are as follows:

$$2\,OH^- \longrightarrow \frac{1}{2}O_2 + H_2O + 2\,e^- \tag{3.2}$$

$$H_2O + 2\,e^- \longrightarrow H_2 + 2\,OH^- \tag{3.3}$$

#### *PEM electrolysis*

PEM electrolysis operates similarly to alkaline electrolysis but uses a solid polymer electrolyte membrane. The membrane selectively allows the transport of protons ($H^+$). The electrolyzer comprises a proton-conducting membrane sandwiched between an anode and a cathode. Water is supplied to the anode, and an electric current is applied, causing water molecules to split into oxygen at the anode and protons at the membrane. The protons then migrate through the membrane to the cathode, combining with electrons from the external circuit to form hydrogen gas. $H^+$ is the charge carrier. The operating temperature is usually between 50°C and 80°C, while the operating pressure is less than 200 bar (IEA, 2021b). PEM electrolyzers have a stack lifetime of 40,000 to 80,000 hours (Schmidt et al., 2017). PEM electrolysis offers several advantages, including high energy efficiency, rapid response to load changes, and a compact system design. The reaction for the anode and cathode are as follows:

$$2\,H_2O \longrightarrow \frac{1}{2}O_2 + 2\,H^+ + 2\,e^- \tag{3.4}$$

$$2\,H^+ + 2\,e^- \longrightarrow H_2 \tag{3.5}$$

### *SOEC electrolysis*

In this study, solid oxide electrolysis cells are used for electrolysis. SOEC technology enables the conversion of steam into hydrogen and oxygen at high temperatures, utilizing a solid oxide ceramic electrolyte. This distinction is important as SOECs are designed explicitly for electrolysis, unlike solid oxide fuel cells, which produce electricity and heat from fuel sources such as methane or hydrogen.

The electrolyzer comprises a dense ceramic electrolyte sandwiched between a porous anode and a cathode. At high temperatures of over 800°C, steam molecules dissociate into oxygen ions ($O_2^-$) at the cathode and protons ($H^+$) at the anode. The oxygen ions migrate through the electrolyte and combine with protons at the cathode to form oxygen gas. At the same time, electrons flow through an external circuit to the anode, which reacts with hydrogen ions to generate hydrogen gas. $O^{2-}$ is the charge carrier. The operating temperature is usually between 650°C and 1000°C, while the operating pressure is less than 25 bar (Schmidt et al., 2017). This type of electrolyzer's stack lifetime is lower than the other types, between 10,000 and 40,000 hours. SOEC offer the advantage of operating at high temperatures, allowing for the utilization of waste heat or renewable thermal energy sources, which can significantly improve overall system efficiency. The reaction for the anode and cathode are as follows:

$$O^{2-} \longrightarrow \frac{1}{2}O_2 + 2\,e^- \tag{3.6}$$

$$H_2O + 2\,e^- \longrightarrow H_2 + O^{2-} \tag{3.7}$$

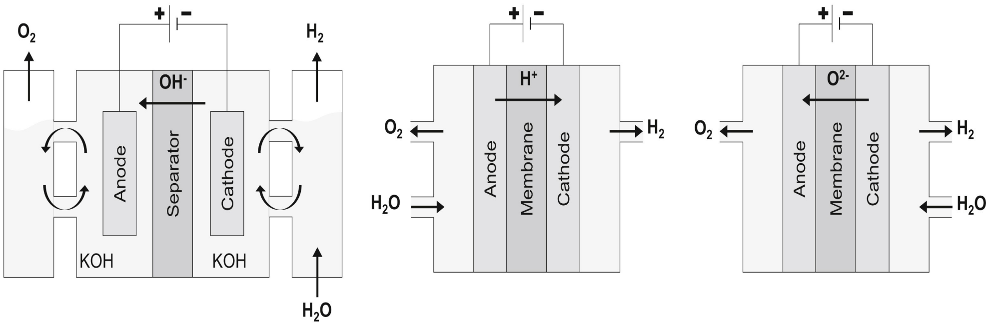

**Figure 3.2:** Conceptual designs of 3 types of water electrolysers (Schmidt et al., 2017, pg. 30471)

### 3.2.3 Methane pyrolysis

#### *Plasma decomposition*

This technology can be regarded as an emerging technology, which developments are following up rather quickly. According to IEA (2022a), the TRL for plasma decomposition methane pyrolysis was raised from 6 in 2020 to 8 in 2022. The process originates from the production of carbon black but can also be leveraged for hydrogen production without $CO_2$ emissions. Hydrogen from methane pyrolysis is often called turquoise hydrogen instead of blue, green or grey hydrogen. Currently, a large-scale plant is being built in the US. The plant from Monolith Materials will be operational in 2023 or 2024 and will use plasma decomposition, powered by renewable electricity, to produce 290kt of ammonia annually (Bhaskar et al., 2021; IEA, 2022a).

Plasma is generated while natural gas flows in the reactor. The plasma heats the reactor to over 1000°C (Oni et al., 2022). In the centre of the reactor, methane is split into hydrogen gas and solid carbon. The gas rises to the top of the reactor while the carbon is left on the bottom as a solid granulate (Schneider et al., 2020). The reaction equation for methane pyrolysis is:

$$CH_4 \rightleftharpoons 2\,H_2 + C \tag{3.8}$$

### 3.2.4 Biomass

#### *Biomass anaerobic digestion*

Anaerobic digestion, followed by biogas upgrading, is the dominant process for biomethane production (Molino et al., 2016). This versatile process accepts various feedstocks, such as sewage sludge or biowaste, which are digested by microorganisms in an oxygen-free environment within a biogas plant. Initially, biogas was mainly used for on-site power and heat generation, but many facilities now focus on upgrading biogas to biomethane for diverse applications.

Biogas typically contains varying proportions of methane, carbon dioxide, and trace amounts of other gases. Upgrading biogas to biomethane involves the removal of impurities, primarily $CO_2$, to increase the methane concentration and achieve a product that meets the required natural gas specifications. Commonly used separation methods are water scrubbing and membrane separation.

With water scrubbing, biogas is passed through a water-filled column. This technique leverages the physical properties of gas dissolution in water. The $CO_2$ is absorbed by the water due to the higher solubility compared to methane, leaving behind a higher methane content. Another approach is membrane separation, in which specialized membranes are used. These allow smaller methane molecules to pass through, while larger $CO_2$ molecules are separated (Molino et al., 2016).

Both water scrubbing and membrane separation methods produce a stream of purified biomethane, which has the same chemical composition as natural gas. Biomethane produced in this manner is considered a renewable and sustainable energy source, often called renewable natural gas (Lepage et al., 2021). The biomethane could be used in the SMR and ATR decarbonization options, further reducing carbon emissions. Biomethane is regarded as an input variable for the LCOA analysis, similar to natural gas and electricity. Therefore the initial investment for a biogas plant upgrading to biomethane is disregarded. The carbon emissions from biomethane are regarded as zero, due to its biogenic nature.

### *Biomass gasification*

Biomass gasification is a thermochemical process that converts biomass into syngas. The process involves several key steps: biomass drying, pyrolysis, and gasification (Gilbert et al., 2014). The drying of biomass is required to improve the efficiency of the gasifier. During pyrolysis, the biomass is heated in a controlled atmosphere with limited oxygen, enabling thermal decomposition (Molino et al., 2016). The oxygen comes from an ASU, which is also required for the nitrogen production for the Haber-Bosch process (Sánchez et al., 2019). The output of pyrolysis is char and tar, which react with oxygen or steam in the gasifier to create a mixture of gases. There are various types of gasifiers, the fixed-bed and fluidized-bed gasifiers are most commonly used. Afterwards, the syngas is cleaned from impurities, purifying the hydrogen output. The use of bio-energy such as biomethane combined with CCS is also known as Bioenergy with Carbon Capture and Storage (BECCS) and is considered a net negative emission technology (Consoli, 2019). The deployment of BECCS is, however, slow. Using biomass gasification with CCS can result in negative $CO_2$ emissions while also allowing for the production of urea from biogenic $CO_2$ (Shahbaz et al., 2021). Also for this process, the carbon emissions are regarded as zero due to its biogenic nature.

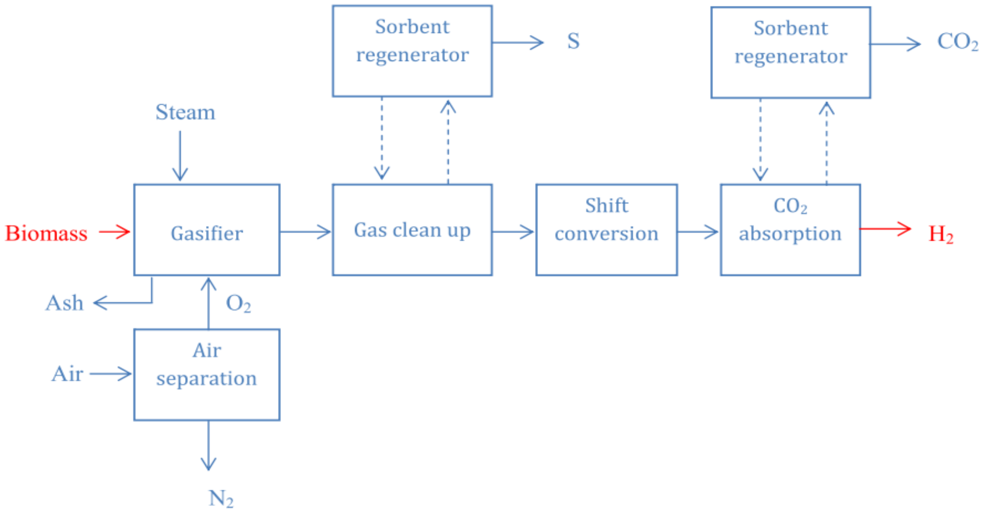

**Figure 3.3:** Biomass gasification flow diagram. Retrieved from Nikolaidis and Poullikkas, 2017, pg. 603

## 3.3 INPUT LCOA ANALYSIS

### 3.3.1 Initial Investment

It is essential to discuss the input parameters, especially the initial investment, before going into the results of the LCOA analysis. The initial investment varies significantly depending on the selected decarbonization option. Every ammonia plant configuration consists of a reactor for the Haber-Bosch synthesis loop, an ASU, Balance of Plant (BoP) and storage for liquid ammonia at -33°C with a capacity of 45 kt. BoP entails process utilities, water treatment, pumps and heat exchangers. There are different required sizes for equipment for every configuration, which are considered for the initial investment cost for every decarbonization option. The costs for the reference plant with the SMR Haber-Bosch process are provided in Table E.2, based on Papadias et al. (2021).

| **Cost component** | **Costs in M€** |
|---|---|
| Reforming section | 167 |
| Haber-Bosch synthesis loop | 235 |
| ASU | 54 |
| BoP | 57 |
| Storage | 48 |
| **Total** | **561** |

**Table 3.2:** Initial investment for a conventional ammonia plant

These capital cost components are not included in Table 3.3. This table provides an overview of the main differences regarding cost components for the initial investment for every decarbonization option.

| **Decarbonization option** | **Cost components** |
|---|---|
| SMR CCS - Partial capture | Reforming section and carbon capture plant |
| SMR CCS - High capture rate | Reforming section and carbon capture plant |
| ATR CCS - Single reformer | Reforming section and carbon capture plant |
| Alkaline electrolysis | Electrolyzer stacks |
| PEM electrolysis | Electrolyzer stacks |
| Solid oxide electrolysis | Electrolyzer stacks |
| Methane pyrolysis | Plasma generation and pyrolysis reactor |
| Biomass gasification | Pyrolysis section and gasifier |
| Biomass anaerobic digestion | N.A.[a] |

**Table 3.3:** Main cost components of the initial investment

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[a] The price of biomethane will be used to calculate the LCOA using the conventional SMR production process.

### 3.3.2 Input parameters

The same calculation for the levelized costs of ammonia is applied for every production process. The input parameters are shown in Table 3.6. It is important to state that with the current prices for natural gas and electricity, the production conditions for European ammonia producers are undeniably dreadful. Before the pandemic and the Russia-Ukraine war, the prices for large industrial consumers were approximately 5 €/GJ for natural gas and 50 €/MWh for electricity. Still, they stand at 25 €/GJ and 170 €/MWh, respectively (Eurostat, 2023a). Due to the volatility regarding energy prices, a wide range will be used for the input parameters. In cases of high natural gas prices, ammonia production is reduced. It is decided to set a base case to prevent using the extremes in recent years. The base case energy prices for natural gas and electricity are set at 12 €/GJ and 60 €/MWh. Compared to the current electricity price, the relatively low price is based on the assumption that the electricity stems from renewable energy, similar to the electrolyzers, available for 40% of the year. Besides the energy prices, the initial investment costs increased tremendously in the same period. According to the CEPCI index, the costs in 2022 are 37% higher compared to 2020. The following chapter will elaborate on the results for the LCOA. Still, an example is provided first to showcase the remarkable impact of rapid price changes between 2020 and 2022.

| Parameter | Value |
|---|---|
| Nameplate capacity | 440 kt/year |
| Capacity factor | 90% |
| Discount rate | 8% |
| Natural gas price | 12 €/GJ |
| Electricity price | 60 €/MWh |
| Biomethane price | 20 €/GJ |
| Biomass price | 75 €/dry tonne |
| $CO_2$ price EU ETS | 100 €/t $CO_2$ |
| $CO_2$ transport and storage cost | 20 €/t $CO_2$ |

**Table 3.4:** General input parameters

The comparison of the conventional SMR Haber-Bosch cost price for ammonia between 2020 and 2022 highlights the remarkable impact of rapid price changes during this period. In 2020, when the prices for natural gas, electricity, $CO_2$ and initial investment were lower, respectively, 6 €/GJ, 60 €/MWh and 25 €/t $CO_2$. In that case the LCOA for SMR was 382 €/t $NH_3$. However, with the escalated prices in 2022, the LCOA for the same process increased to 932 €/t $NH_3$. This drastic change shows how the volatile energy prices and investment costs affect the LCOA. The perceived ranges of LCOA of the decarbonization options as compared to the conventional SMR Haber-Bosch process from two years ago are no longer valid. This demonstrates the complexity of decision-making for decarbonization pathways from a cost-effectiveness perspective. With a comprehensive understanding of the decarbonization options, its input parameters and the cost dynamics, the interpretation of the results regarding the LCOA of greenfield plants can start.

### 3.3.3 Input parameters non-European production

Not all the listed decarbonization options are relevant for the selected foreign countries. According to IEA (2023), no CCS projects are planned or in operation in Chile. Furthermore, Chile is an importer of natural gas. Therefore, the CCS options and methane pyrolysis are not considered for Chile. Similarly, the potential biomass supply is limited in Algeria and Saudi Arabia (IEA, 2020b). Therefore the use of biomass and biomethane in these countries is not deemed realistic, the options will be excluded from these countries. An overview of the decarbonization options per country is included in Appendix E. The initial investment and capacity hours are the same for the European ammonia producers.

| Parameter | Country | Value |
|---|---|---|
| Natural gas price | Algeria | 3 €/GJ |
| | Australia | 10 €/GJ |
| | Canada | 3 €/GJ |
| | Saudi Arabia | 2 €/GJ |
| Electricity price | Algeria | 45 €/MWh |
| | Australia | 40 €/MWh |
| | Canada | 40 €/MWh |
| | Chile | 30 €/MWh |
| | Saudi Arabia | 45 €/MWh |
| Biomethane price | Australia | 15 €/GJ |
| | Canada | 10 €/GJ |
| | Chile | 25 €/GJ |
| Biomass price | Australia | 60 €/dry tonne |
| | Canada | 50 €/dry tonne |
| | Chile | 70 €/dry tonne |
| $CO_2$ price | Canada | 35 €/t $CO_2$ |
| | Chile | 5 €/t $CO_2$ |
| $CO_2$ transport and storage cost | Algeria | 20 €/t $CO_2$ |
| | Australia | 20 €/t $CO_2$ |
| | Canada | 20 €/t $CO_2$ |
| | Saudi Arabia | 20 €/t $CO_2$ |

**Table 3.5:** General input parameters

| Country | Port | Costs in € per t $NH_3$ |
|---|---|---|
| Algeria | Arzew | 40 |
| Australia | Hedland | 148 |
| Canada | Hawkesbury | 67 |
| Chile | Mejillones | 111 |
| Saudi Arabia | Ras Al-Khair | 100 |

**Table 3.6:** Transportation costs to the Port of Rotterdam

The transportation costs are interpolated using Argus ammonia prices from 2022 Argus Ammonia (2023). Two main standardized shipping options for international trade are free on board, and cost and freight. It is used to clarify and transfer the responsibilities of the buyer and seller. Compared to free on board shipping, cost and freight shipping entails that the seller is responsible for delivering the ammonia to the destination port instead of the port of origin. The costs are based on medium gas carriers, which carry 25300 tons of ammonia (Argus Ammonia, 2023).

## 3.4 LIMITATION OF THE SELECTED TECHNOLOGIES

An essential aspect of the analysis is the examination of potential limitations related to the selected decarbonization options. By scrutinizing these limitations, a more nuanced understanding can be gained regarding the feasibility and effectiveness of each option within the context of ammonia production. In this section, we delve into the various constraints and challenges associated with each decarbonization option, shedding light on factors that might impact their practical implementation and overall viability.

Long lead times are expected for CCS projects, the deployment time would take at least seven years according to EBN and Gasunie (2017). Unlike the deployment of BECCS, there are operational CCS projects within the fertilizer industry (Doyle, 2020). There are five operational CCS facilities for producing ammonia (Global CCS Institute, 2020). All of these projects are located in the United States or Canada.

Deploying large-scale CCS projects in Europe has been challenging due to insufficient financial and regulatory incentives and public acceptance (IOGP, 2019). In Europe, two commercial CCS facilities operate in Norway with a maximum capture capacity between 0.7 and 1 million tonnes of carbon dioxide per year. Eleven CCS facilities are in development across the United Kingdom, Norway, the Netherlands and Ireland (Global CCS Institute, 2020). The maximum capture capacity of these projects ranges between 0.4 and 6 million tonnes of carbon dioxide per year.

Since 2019, the altered London Protocol has allowed the international shipment of $CO_2$, which stimulates the uptake of large-scale CCS projects such as in the North Sea. According to IOGP (2019), storage capacity is not a constraint in Europe, and it estimates that the storage capacity in Europe amounts to 300 Gt $CO_2$. Considering the restrictions in certain European Member States Terlouw et al. (2019) estimates 134 Gt $CO_2$ of storage capacity in Europe.

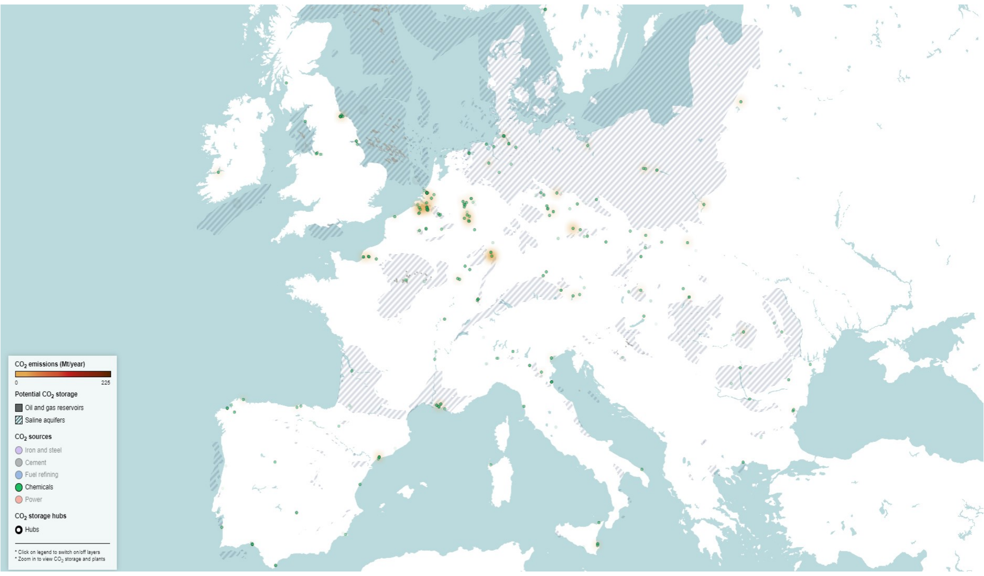

**Figure 3.4:** Map of $CO_2$ sources and potential geological storage in Europe (IEA, 2020c, pg. 136)

For sustainable gains of electrification, the availability of low-carbon energy is essential. Switching to green hydrogen from electrolysis of water powered by renewable energy resources would require extensive capacity expansion of renewable energy generation. In 2019, 830 TWh was generated from renewable energy sources in Europe (Eurostat, 2020). Based on the total energy demand of 12.5 MWh per ton of ammonia and the European ammonia demand of 17.1 Mt, the hypothetical electrification of ammonia production would require around 214 TWh (Bazzanella and Ausfelder, 2017), more than a quarter of all generated renewable electricity. Besides the spatial issue, it would also take between 8 and 12 years to build the required capacity and infrastructure for the electrification necessary to produce enough green hydrogen for the European ammonia sector (Scholten et al., 2021).

The availability issue is also valid for using biomethane, of which the current availability is minimal (Rissman et al., 2020). Biomethane could replace natural gas as feedstock and fuel for ammonia production due to the similar chemical composition (IEA, 2020b). However, here also, the availability of biomethane globally and in Europe forms an obstacle. Globally, biomethane represents 0.1% of the current natural gas demand (IEA, 2020b). Costs of biomethane hindered the uptake, but with the rise of natural gas prices, the prospects for biomethane are becoming more favourable.

Individual technologies for the process are available (TRL 7-8), but complete system integration must be demonstrated commercially. The key challenges are procuring low-cost electricity from renewable sources in areas where production will take place, reducing costs, raising electrolysis technology's efficiency, and integrating economical buffer storage or flexibility in the synthesis step to accommodate variable electricity input.

## 3.5 CONCLUSION

Chapter 3 provides an in-depth exploration of various decarbonization options, focusing on selecting options that demonstrate strong potential for $CO_2$ reduction and have achieved a sufficiently high TRL. Through comprehensive literature research and semi-structured interviews with industry experts, several decarbonization options have been identified as promising solutions. The basic principles for each selected option are carefully explained.

However, it is essential to acknowledge the limitations associated with these decarbonization options. Some options are not fully commercialized yet, requiring significant advancements in technology and scalability. Challenges related to stability, efficiency, cost-effectiveness and using abundant and non-toxic materials must be overcome to achieve widespread adoption. Moreover, certain options have limited applicability due to specific requirements, such as resource availability.

To address these limitations, the chapter emphasizes the need for continued research and development efforts. Technological breakthroughs in material science, process and system engineering are crucial for improving the efficiency, stability, and overall performance of these decarbonization options. Additionally, knowledge transfer across different sectors and collaboration among researchers, industry stakeholders, and policymakers is essential to accelerate progress and drive the transition to a low-carbon ammonia industry.

In conclusion, Chapter 3 provides a comprehensive overview of decarbonization options with a focus on $CO_2$ reduction potential and TRL levels. While these options promise to reduce greenhouse gas emissions, their successful implementation requires further advancements and overcoming specific challenges. By addressing the limitations and fostering innovation, these decarbonization options can play a vital role in achieving a sustainable and climate-friendly ammonia industry.

# 4 COST-EFFECTIVENESS OF DECARBONIZATION OPTIONS

This chapter aims to assess the economic viability of the technological decarbonization options for the European ammonia industry, described in 3. The analysis can provide valuable insights for choosing the most cost-effective decarbonization pathway. First, the results for European ammonia production will be discussed, after which ammonia production outside Europe will be presented. At the end of this chapter, the sensitivity analysis is described.

## 4.1 LCOA OF EUROPEAN AMMONIA PRODUCTION

The results of the LCOA-analysis are shown as stacked columns in Figure 4.1, the overall table of the LCOA, CI and CAC is depicted below in Table 4.1. From all the decarbonization options, the CCS option for ATR allows for the lowest cost for ammonia production, shortly followed by the other CCS options for SMR. ATR holds a slight advantage over SMR with a high capture rate in energy efficiency and carbon capture. As discussed in 3.2, there are no flue gases emitted in the ATR process. All the $CO_2$ is in the syngas stream, allowing for easier and thus cheaper carbon capture than the SMR high capture rate CCS process. High capture rates result in higher initial investment, operational expenditures and amplified energy costs compared to the partial capture method. Notably, the carbon costs for partial carbon capture are nearly twice as high as for high carbon capture options. Consequently, it is interesting to explore the production conditions where full carbon capture becomes a more cost-effective alternative than SMR with a partial capture rate. From the decarbonization options that use natural gas, methane pyrolysis is the least cost-effective for ammonia production at present. The initial investment is, however, particularly low, indicating that with a stable carbon price and lower natural gas prices, it might compete with the aforementioned production processes.

The electrolyzers are not cost-competitive with the CCS options under these conditions. Not only are the initial investments two and a half to six times higher than the CCS options, also the costs for electricity are twice as high as compared to the costs for natural gas. It is expected that the components for the initial investment, such as the electrolyzer costs, stack lifetime, number of operating hours and efficiency, will improve in the coming years. However, under these conditions, green ammonia production is not economically viable. From the electrolyzer options, alkaline is the most cost-effective decarbonization option, followed by PEM. The higher energy efficiency of PEM and SOEC are negated by shorter stack lifetimes and higher electrolyzer costs, leading to immense initial investments.

The biomass options are not cost-competitive under these conditions. As expected, the results of using biomethane compared to natural gas are related to the energy prices since the initial investment is the same. The difference is slightly reduced by the lack of carbon costs for using biomethane, due to the biogenic carbon. Biomass gasification stands out with its relatively low fuel and feedstock costs, whereas the initial investment and operational expenditures shoulder a substantial portion.

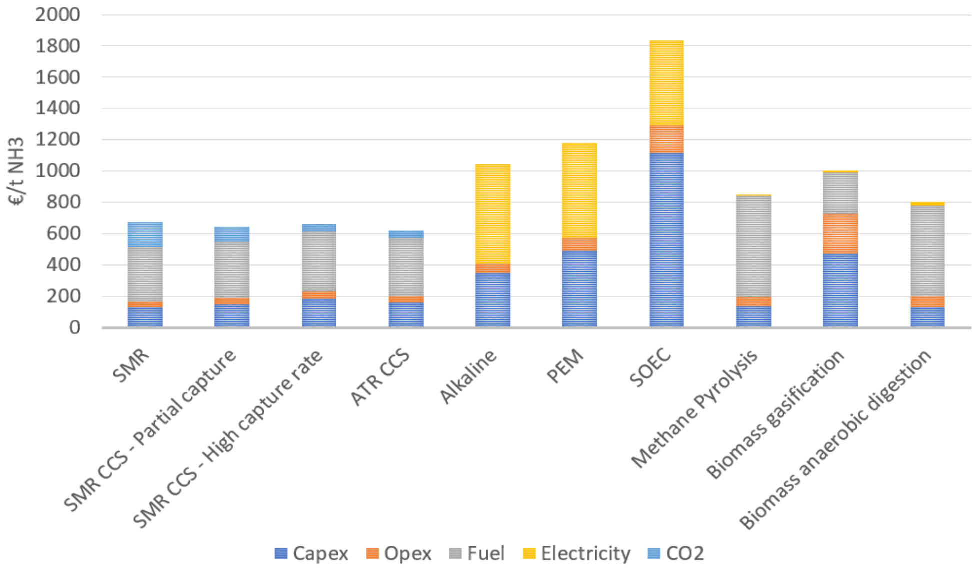

**Figure 4.1:** LCOA results

The costs of avoided carbon are calculated with the LCOA per production pathway in combination with the carbon intensity. Due to the use of renewable energy sources for the electrolyzer options and the emission factor for biomass pathways considered zero, the only options which emit $CO_2$ are the CCS options. The CAC provide insight into the cost-effectiveness of the decarbonization options to reduce $CO_2$ emissions. The negative CAC from the CCS options indicate that these options are economically beneficial due to the carbon costs. Under these conditions, the costs of producing ammonia are lower than the conventional SMR Haber-Bosch process while simultaneously reducing carbon emissions

Similarly to the LCOA, the ATR CCS option is the most cost-effective, followed by partial and high rates of carbon capture. The remaining decarbonization options suggest higher costs than the reference scenario. The use of biomethane and biomass, as well as methane pyrolysis, is deemed more cost-effective than the electrolyzer options in this case. Solely fixating on the CAC is not advised, several factors need to be considered. For example, partial capture for SMR is more cost-effective than a high capture rate. However, higher capture rates will lead to lower carbon emissions, which seem more desirable in the long term. Further analysis is required to evaluate the trade-offs between the reduced $CO_2$ emissions and the associated financial implications.

| **Decarbonization option** | **LCOA [€/t $NH_3$]** | **Carbon Intensity [$CO_2$t/t $NH_3$]** | **Cost of Avoided Carbon [€/t $CO_2$]** |
|---|---|---|---|
| SMR CCS - Partial capture | 647 | 0.76 | -36 |
| SMR CCS - High capture rate | 666 | 0.18 | -8 |
| ATR CCS - Single reformer | 620 | 0.09 | -38 |
| Alkaline electrolysis | 1045 | 0 | 226 |
| PEM electrolysis | 1179 | 0 | 309 |
| Solid oxide electrolysis | 1836 | 0 | 713 |
| Methane pyrolysis | 850 | 0 | 106 |
| Biomass gasification | 1004 | 0 | 201 |
| Biomass anaerobic digestion | 802 | 0 | 77 |

**Table 4.1:** Overview of LCOA, CI and CAC per decarbonization option

## 4.2 LCOA OF NON-EUROPEAN AMMONIA PRODUCTION

This section focuses on the results of non-European ammonia production. The detailed overviews of cost components for the LCOA analysis for every country are provided in Appendix E.1.2. The appendix provides a granular view of the selected countries' cost breakdown and specific decarbonization pathways. This section presents the key results from the analysis in Figures 4.2 and 4.3. The figures show the LCOA and CAC of the selected non-European countries, with Europe and the standard SMR Haber-Bosch production process added as a reference. Details can be found in Tables E.5 and E.6 in the appendix.

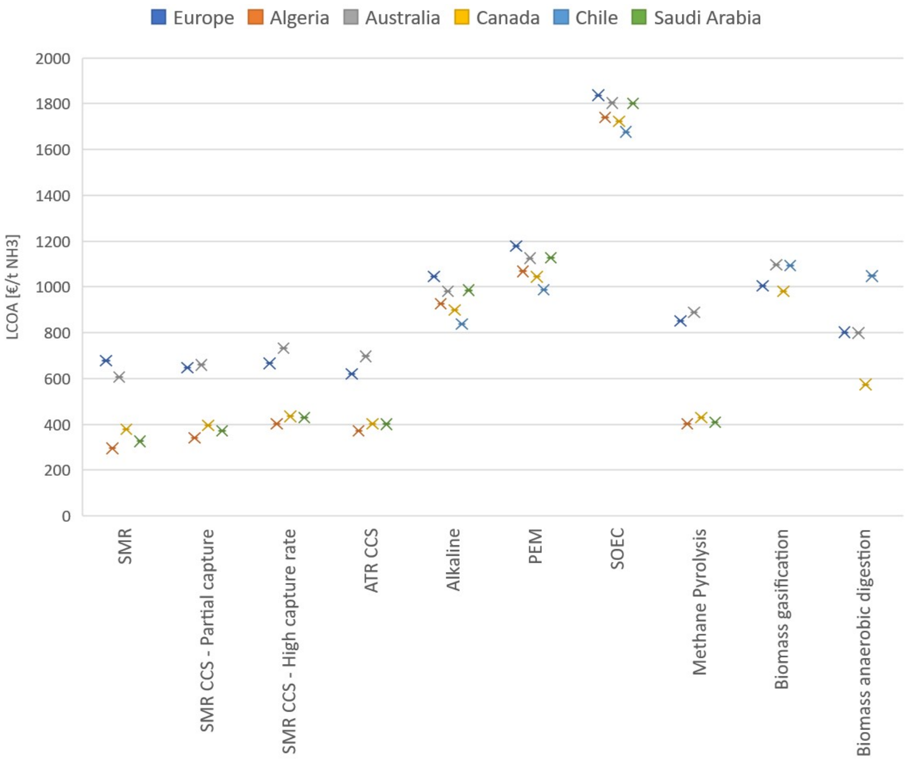

**Figure 4.2:** Overview of LCOA per decarbonization option and country

Except for Europe, the standard SMR Haber-Bosch production process is the lowest cost option for all countries. Regarding the decarbonization options, for all the countries that included the CCS options, partial capture SMR is the lowest cost production option, followed by ATR with CCS. Whereas the production costs in Europe for the CCS options are more favourable than methane pyrolysis, that is not the case for the other countries. In Algeria, the prices are similar, whereas, in Canada and Saudi Arabia, the levelized costs of ammonia from methane pyrolysis are lower than from SMR with high capture CCS. The main reasons for this are the lower levelized costs for the initial investment and $CO_2$ that make up for the higher costs for natural gas compared to the most expensive CCS option.

Similarly to Europe, ammonia from SOEC electrolysis results in the highest levelized costs for all the countries. The electrolyzer options are not cost-competitive with CCS options. The ratio between the lowest LCOA from any natural gas and electricity-based option widens abroad. In non-European countries, the relative cost differential between the lowest cost CCS option and the electrolyzer option is more pronounced. The selected countries are characterized by abundant access to natural gas resources. Blue ammonia is a logical option to monetize these resources and, thus, might lead to resistance towards green ammonia production methods. Notably, the ratio between the lowest cost CCS and electrolyzer option is the smallest in Australia. That is not the only remarkable result of Australia from the LCOA analysis. Although the production environment in Australia is quite different from Europe, with the relatively high transportation costs, the LCOA for all the decarbonization options are close to the European LCOA. It can be concluded that ammonia import from Australia to Europe is highly unlikely under these production conditions.

Besides the decarbonization options from Australia and the biomass options from Chile, all the other decarbonization options are cheaper abroad than if ammonia were to be produced in Europe. This is not a surprise since the initial investment and operational expenditures are constant for every option. The differences in costs are related to the lower energy costs, for which the countries were selected. Additionally, the carbon costs in these countries are lower, some countries have a low carbon tax or don't participate in any form of carbon emission trading scheme. The additional transportation costs reduce the overall difference in LCOA between European and non-European countries but cannot compensate for the lower energy and carbon costs.

The regional variation in LCOA clarifies the unique position of Algeria from a cost perspective for natural gas-based decarbonization options. The low natural gas price, in combination with the lowest transportation costs due to the proximity to Europe, enables Algeria to produce and ship ammonia at the lowest costs. Saudi Arabia follows shortly, but the higher transportation costs mitigate the advantages of the lowest natural gas prices. Similarly, Chile stands out for the lowest LCOA for the electrolyzer options and Canada regarding the biomass options.

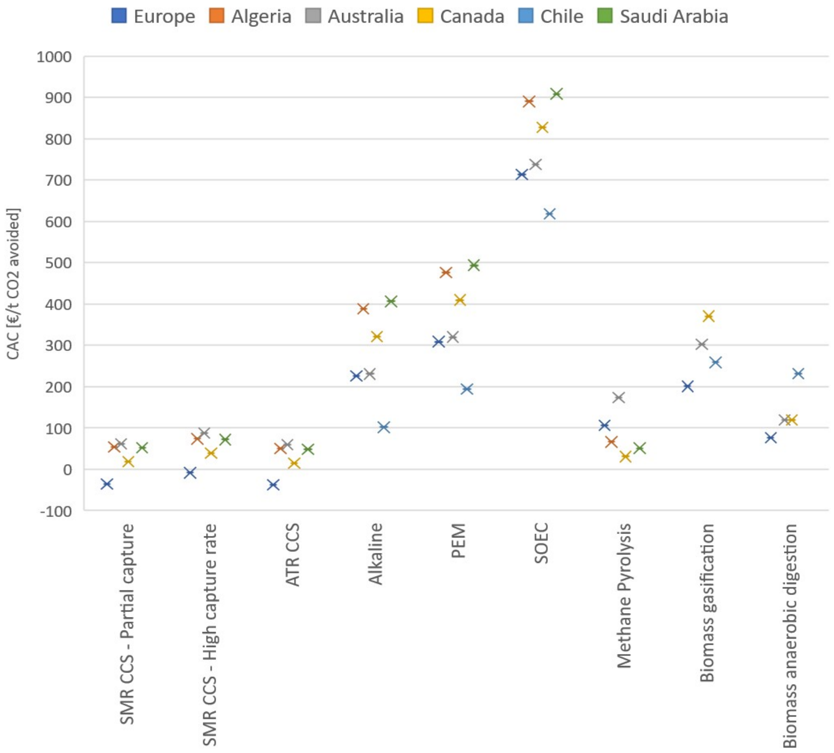

**Figure 4.3**: Overview of CAC per decarbonization option and country

Having explored the economic feasibility of decarbonization options in non-European countries, it's time to delve into their cost-effectiveness. The ATR CCS consistently emerges as the most economically efficient option across all the selected countries. However, the differences in CAC with partial capture SMR CCS are limited. Of all the decarbonization options, SOEC electrolyzers are consistently the least cost-effective option for all regions, similar to Europe.

In Algeria, Canada and Saudi Arabia, the countries with inexpensive natural gas, the cost-effectiveness of methane pyrolysis surpasses that of high capture rate SMR CCS. The cost-effectiveness of biomass anaerobic digestion compared to electrolyzer options is generally superior across various countries, except for Chile. The pattern also does not hold in the European context. Since there is no reference available for Chile, the European standard SMR Haber-Bosch process is used for the CAC calculation for Chile.

Negative CAC as in Europe are not present in the selected countries. Regarding cost-effectiveness, investments in decarbonization options in Canada yield the highest results in terms of $CO_2$ reduction for the natural gas-based decarbonization options. The same investment in these options in Chile would result in less value for your money, but here, the cost-effectiveness of electrolyzer options is superior compared to other countries.

## 4.3 SENSITIVITY ANALYSIS

There are a lot of input parameters that influence the results of the LCOA analysis. Usually, this section aims to understand the sensitivity of these assumed parameters better. Instead of exploring every input parameter, pivotal factors that significantly influence the economic viability and cost-effectiveness of decarbonization options are selected. This approach addresses key questions that enhance understanding of the practical implications of decarbonization pathways.

### 4.3.1 Cost parity of electrolyzers in 2030

The first topic of the sensitivity analysis revolves around the economic viability of the electrolyzer options in 2030. The key factors, such as electricity prices and stack costs on the LCOA, will be explored. Under the current production conditions, the electrolyzers are not economically viable. The goal is to examine under which conditions the electrolyzer options can reach cost-parity with the other decarbonization options, and assess how realistic that is.

The results, as displayed in Figure 4.1, show that the annualized initial investment, operational expenditures and electricity are the three cost components for the LCOA for the electrolyzer options. Table 4.2 shows the cost components of the LCOA for electrolyzer options expressed in percentages. Currently, the electrolyzer types with a higher efficiency are more expensive. The higher efficiency rates result in lower levelized costs for electricity to produce ammonia. This means that a reduction in electricity prices has the largest impact on alkaline electrolysers in LCOA since it requires more electricity. The key parameters influencing the initial investment for electrolysers are improved lifetime of electrolyzer stacks, higher capacity factors or reduced stack costs. In a proportionate reduction of initial investment for the electrolyzers, the LCOA of SOEC electrolyzers yields the highest gains.

| Cost component | Alkaline | PEM | SOEC |
|---|---|---|---|
| Capex | 34% | 42% | 61% |
| Opex | 5% | 7% | 10% |
| Electricity | 61% | 51% | 29% |

**Table 4.2:** Percentages of levelized cost components for electrolyzer options

Although the deployment of electrolyzers is gaining traction, in terms of LCOA, the decarbonization options are not economically viable yet. From a financial perspective, the conventional Haber-Bosch SMR process or CCS options are preferred. However, the capital costs of electrolyzers are expected to decrease due to learning by doing and economies of scale. Estimating the costs for electrolyzer stacks is difficult, especially if it's about the future. How much or how fast the costs for the stacks will drop is uncertain. According to IEA (2022c), the electrolyzer stacks have a learning rate of 18%, whereas the learning rate of the other components of the electrolyzer lies between 7% and 13%.

The future electrolyzer costs for alkaline and PEM electrolyzers have been forecast by IEA (2022c) for 2030, with the price dropping to 440$/kW for alkaline and 500$/kW for PEM electrolyzers. This is a reduction in electrolyzer costs of roughly 70%, the same decline in costs is assumed for SOEC electrolyzers.

Electrolyzers are not the only decarbonization options, of which it is expected that the initial investment will reduce in the coming years. According to IEA (2019), the capital expenditures of CCS options will slightly reduce. In the analysis, the costs for biomass anaerobic digestion remain stable till 2030. For hydrogen production, the initial investment costs for CCS and electrolyzers in 2030 are expected to drop 19% and 22% according to IEA (2019). The cost reduction for electrolyzers is not the same as previously mentioned, for this study, the most contemporary costs from the IEA will be used. Incorporating the initial investment costs for hydrogen production into the overall investment costs for the ammonia plant leads to an overall smaller cost reduction. This information allows for a prospective examination of the LCOA of decarbonization options in 2030, which is in the temporal scope of the study.

In section E.2 of Appendix E, the assumptions related to the reduced initial investment as a result of improved technical abilities of the decarbonization options are listed. The initial investment for the electrolyzers with the combined assumptions in 2030 drops 50%, 60% and 75% for alkaline, PEM and SOEC electrolyzers. However, the price reductions of LCOA of the decarbonization options are 20%, 29% and 53%. When simultaneously using the reduced electricity demand for hydrogen production in the LCOA analysis, in 2030, the electrolyzers with the reduced initial investment are still not within range of the CCS options. The 19% decline for initial investment costs for CCS options result in a reduced LCOA of 2% till 6%. The overview of the LCOA and CAC of the decarbonization options with revised initial investment costs can be found in Table 4.3.

| Decarbonization option | LCOA [€/t $NH_3$] | CAC [€/t $CO_2$] |
|---|---|---|
| SMR CCS - Partial capture | 610 | -78 |
| SMR CCS - High capture rate | 625 | -37 |
| ATR CCS - Single reformer | 607 | -46 |
| Alkaline electrolysis | 820 | 88 |
| PEM electrolysis | 805 | 79 |
| Solid oxide electrolysis | 822 | 89 |
| Methane pyrolysis | 850 | 106 |
| Biomass gasification | 1004 | 201 |
| Biomass anaerobic digestion | 802 | 77 |

**Table 4.3:** Overview of LCOA and CAC per decarbonization option for 2030 in Europe

The remaining input variables that could enhance the economic viability of the electrolyzer options compared to the CCS options are the price for electricity, natural gas and $CO_2$. The carbon price has a minor effect on the LCOA of CCS options, as most $CO_2$ is captured. For 2030, under base case conditions, the $CO_2$ price must be over 2600 €/t $CO_2$ for electrolyzers to undercut the LCOA of ATR CCS. Therefore, it is decided to focus on the natural gas and electricity price as main variables. For Europe, the natural gas price range of 6 €/GJ to 12 €/GJ is considered. For electricity, the range is set between 20 €/MWh and 90 €/MWh. The results are shown in Figure 4.4. If the gas price remains 12 €/GJ, the electricity price must drop below 40 €/MWh for electrolyzers to become economically viable. Similarly, if natural gas is 8 €/GJ, the electricity price needs to drop below 25 €/MWh for alkaline and PEM electrolyzers to have a lower LCOA. On the low range of natural gas, 6 €/GJ, alkaline and PEM electrolyzers require an electricity price of 20 €/MWh or lower to be economically beneficial.

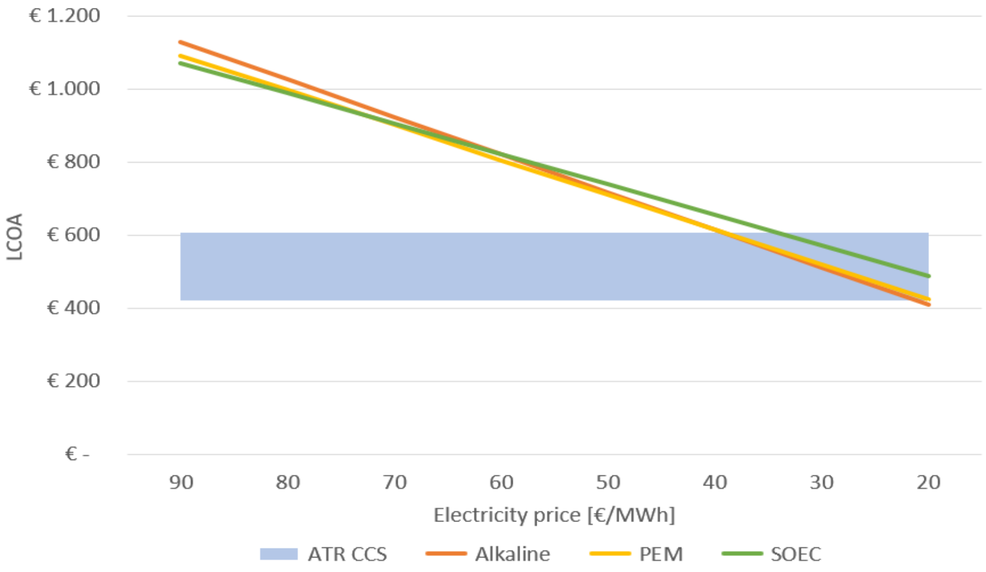

**Figure 4.4:** LCOA comparison of electrolyzers and ATR CCS

Figure 4.4 also shows that alkaline results in the electrolysers' lowest LCOA if the electricity prices are below 30 €/MWh. If the electricity prices range between 30 €/MWh and 70 €/MWh, PEM electrolyzers have the lowest LCOA, although not cost-competitive with the natural gas-based decarbonization options. SOEC electrolyzers are the best electrolyzer alternative for higher electricity prices. The findings should be interpreted with caution due to some inherent uncertainty in the cost estimations, which may impact the robustness and significance of the results.

### 4.3.2 The impact of CBAM

The second topic of the sensitivity analysis revolves around the impact of the CBAM. CBAM is a policy measure proposed by the European Union to address the issue of carbon leakage. This phenomenon occurs when companies move their production to countries with lower carbon prices or weaker environmental regulations to reduce carbon costs. Under CBAM, companies that import goods into the EU must pay a carbon border adjustment on the carbon emission associated with producing those goods. The carbon border adjustment would be based on the carbon intensity of the ammonia as well as the difference in carbon price in the EU and the carbon price in the country of origin. In this case, all parameters are similar as displayed in Table 3.6, only a uniform $CO_2$ price of 100 €/t $CO_2$ is used. The results are shown in Figure 4.5. The details can be found in Table E.7 in the appendix.

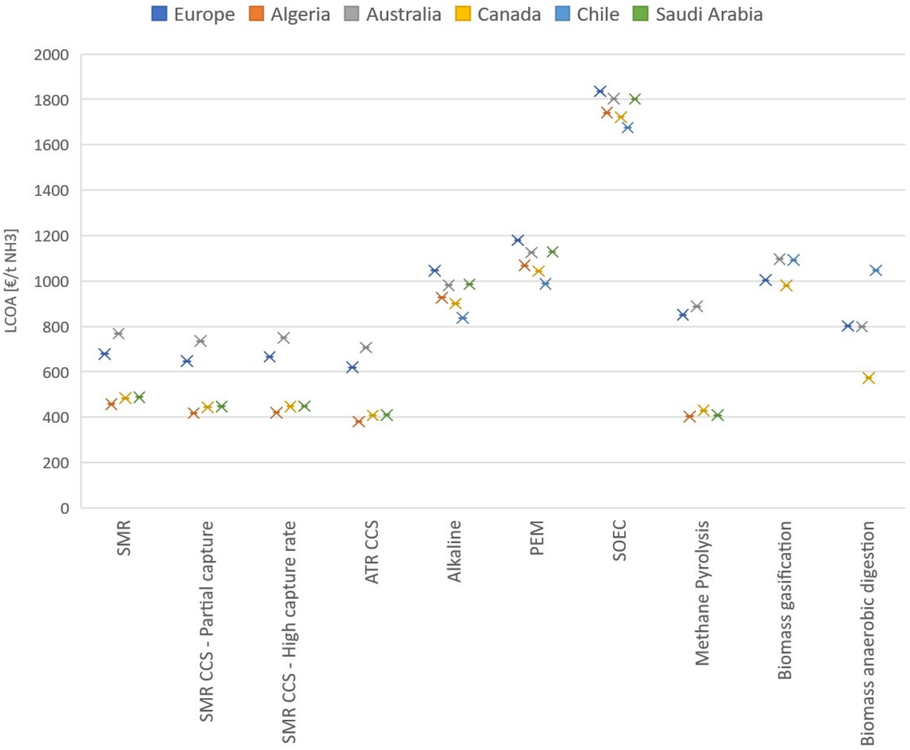

**Figure 4.5:** Overview of LCOA per decarbonization option and country with CBAM

Without the CBAM, the standard SMR Haber-Bosch process was the lowest-cost option for ammonia production in non-European countries, after which SMR CCS with partial capture was the decarbonization option with the lowest LCOA. The implementation of a uniform carbon price results in a shift towards ATR with CCS and methane pyrolysis as the lowest-cost option. ATR with CCS emerges as the most economically attractive option in Algeria, Australia and Canada, whereas methane pyrolysis is slightly cheaper than ATR with CCS in Saudi Arabia. This demonstrates the efficacy of CBAM in the adoption of low-carbon ammonia production processes outside of Europe.

The threshold points where the adoption of decarbonization options becomes economically viable differs per country. In Algeria and Canada, ATR with CCS is the lowest cost option if the carbon price exceeds 50 €/t $CO_2$. This applies to Australia at 60 €/t $CO_2$. In Saudi Arabia, ATR with CCS undercuts the price of the standard SMR Haber-Bosch process if the carbon price exceeds 48 €/t $CO_2$. However, above 85 €/t $CO_2$ methane pyrolysis is the lowest-cost option. For all regions, there is not a carbon price that allows SMR CCS with partial capture to undercut both the standard SMR Haber-Bosch process as well as ATR with CCS.

Examining the cost-effectiveness of the decarbonization options, CBAM encourages the adoption of cleaner technologies, especially CCS options and methane pyrolysis. Under previous circumstances, none of the decarbonization options would result in a negative CAC. However, in the new scenario, CCS options and methane pyrolysis show enhanced cost-effectiveness compared to the standard SMR Haber-Bosch production process in Algeria, Canada and Saudi Arabia. Due to Canada's current carbon pricing, the reduction in CAC is more pronounced in Algeria and Saudi Arabia. Additionally, these countries have a more substantial negative CAC, indicating that investments in these regions yield greater carbon cost reduction than European ammonia producers.

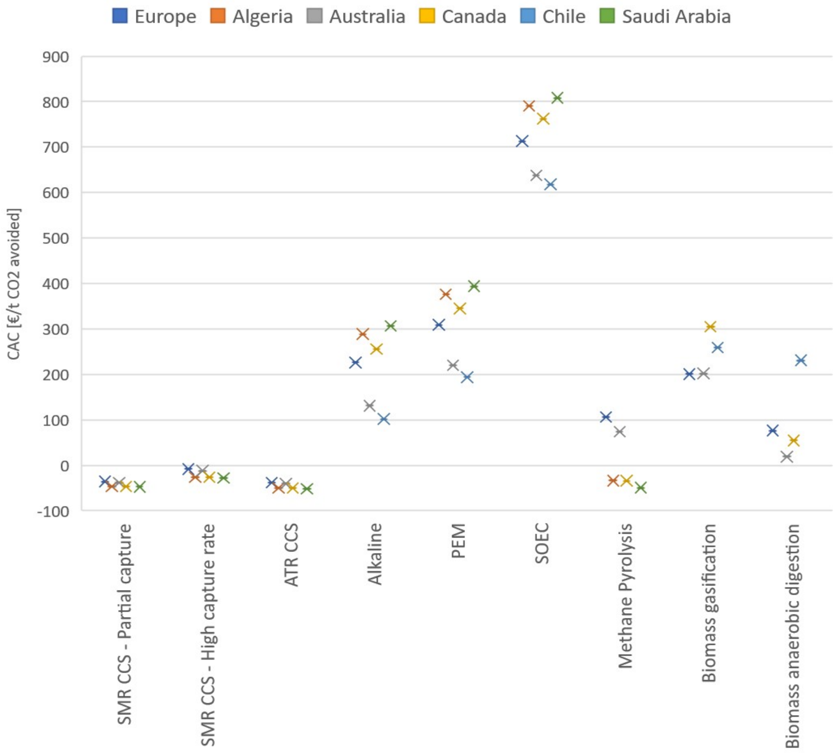

**Figure 4.6:** Overview of CAC per decarbonization option and country with CBAM

In Algeria and Canada, the carbon price must exceed 353 and 350 €/t $CO_2$ for methane pyrolysis to be the country's lowest-cost option. In Australia, biomass anaerobic digestion is the lowest-cost option with a carbon price of 1170 €/t $CO_2$. The effect of CBAM on the position of electrolyzer options is negligible. The standard SMR Haber-Bosch and CCS options become more expensive with higher $CO_2$ prices, but there is not a situation in which electrolyzers are more economically viable than methane pyrolysis or the biomass options. Chile is the only exception here since no natural gas-based options exist.

Regarding global competitiveness, Algeria remains the lowest-cost producer of ammonia. Without CBAM, Saudi Arabia would be the second best option from a financial perspective, followed by Canada. After introducing a uniform carbon price, ammonia from Canada is slightly cheaper than from Saudi Arabia. Whereas Algeria and Saudi Arabia held positions of lowest-cost producers, the introduction of CBAM opens the doors for Canada to export blue ammonia to Europe. This could alternate the trade dynamics, as there would be more suitable suppliers to fulfil the European ammonia demand. Due to the rise of LCOA after the CBAM implementation, the price differences between European and non-European are decreasing. However, a higher uniform carbon price would only increase the absolute and not the relative prices.

Although the CBAM benefits Europe's global competitiveness, Europe's position on a global playing field is tied to natural gas prices. Under the current parameters, the natural gas price in Europe should drop below 5.2 €/GJ in order to undercut the lowest LCOA of Canada and Saudi Arabia. In order to compete with Algeria, the natural gas price must drop below

4.3 €/GJ. These prices seem highly unlikely in the current volatile energy markets.

## 4.4 CONCLUSION

This chapter conducts a comprehensive analysis to answer the sub questions related to the economic viability and competitiveness of decarbonization options in the European ammonia industry. To assess its impact on a global playing field, the non-European context was also used to examine the LCOA and CAC of Algeria, Australia, Canada, Chile and Saudi Arabia. Additionally, a sensitivity analysis explored the potential economic viability of electrolyzer options and assessed the impact of the CBAM.

For European ammonia production, the analysis revealed that ATR with CCS emerged as the most economically attractive, closely followed by other CCS options for SMR. On the other hand, SOEC electrolyzers consistently demonstrated higher LCOA and were less cost-competitive. The same results were derived from the LCOA analysis for non-European countries. In the future, electrolyzers could compete with CCS options, but this heavily depends on capital cost reductions and lower electricity prices. Assuming the current natural gas price in Europe and an electricity price of 40 €/MW puts alkaline and PEM electrolyzers in the same price range as CCS options. With less than 20 €/MWh electricity prices, the improved electrolyzers could compete with foreign ammonia producers.

The impact of CBAM is profound, as it stimulates the adoption of cleaner technologies in non-European countries, especially CCS options. Algeria, Canada, Australia, and Saudi Arabia witnessed a shift in the lowest-cost decarbonization option, with ATR with CCS and methane pyrolysis emerging as economically attractive choices. CBAM facilitated a reduction in carbon-intensive practices globally, positioning cleaner technologies as more competitive and encouraging the adoption of sustainable ammonia production processes outside of Europe. Regarding global competitiveness, CBAM improves Europe's position but underscores the significant influence of natural gas prices. To compete with countries like Algeria, Canada and Saudi Arabia, Europe would need natural gas prices to drop substantially, which presents a considerable challenge in the current energy market dynamics.

In summary, this chapter provides a nuanced understanding of the economic and environmental implications of various decarbonization options, offering valuable insights for decision-makers in the ammonia industry and policymakers as they navigate the path toward sustainable and economically viable production.

# 5 DISCUSSION

In the previous chapters the decarbonization options for European ammonia production are explored by assessing costs, cost-effectiveness, and global ramifications. Beyond addressing initial research questions, the study encompasses economic, environmental, and policy perspectives. The discussion delves into result interpretation, literature comparison, theoretical implications, and significance for industry and policymakers. It also outlines future research directions, emphasizing the intertwined role of technology and regulations in shaping the European ammonia industry's future.

## 5.1 REFLECTION ON THE RESULTS

### 5.1.1 Methodological limitations

Starting with an exploration of the limitations of the study, the chosen parameters deserve close examination due to their potential influence on the results, especially in the LCOA analysis. The selected plant size of 440 kt with a capacity rate of 90% may not align with all industry scenarios. Variations in plan size and operating hours could impact the cost considerations. While larger plants generally benefit from economies of scale, it's plausible that foreign countries build larger and potentially more economically attractive ammonia plants than those in Europe.

This study focuses on the LCOA without delving into the profitability metrics such as return on investment or discounted cash flow analysis. The LCOA results are tailored for decision-making between decarbonization options in a feasibility study rather than facilitating a comprehensive evaluation of economic viability or as a basis for final investment decisions.

The exclusion of waste or by-products in the analysis is acknowledged as another methodological limitation. $CO_2$ or solid carbon derived from the methane pyrolysis process has inherent financial value, which is not accounted for in the LCOA analysis. Additionally, it should be noted that in the event of widespread implementation of CCS and methane pyrolysis at scale, the economic value of $CO_2$ and solid carbon may be constrained and may even create waste issues. These limitations constrain the economic and cost-effectiveness assessment, as these by-products may alter the economic viability of decarbonization options. Including the financial value of waste or by-products, such as $CO_2$ or solid carbon, in the LCOA analysis would provide a more accurate assessment of the economic feasibility of decarbonization options.

Another limitation relates to the lack of industrial cost data. Collecting accurate and comprehensive data on the cost components of an ammonia plant has proven to be a challenge. Another limitation stems from the assumption that all ammonia plants in Europe operate with the same efficiency and that non-European countries operate with the same efficiency. Moreover, all countries consider the initial investment and operating expenses uniform.

Focusing solely on greenfield plants for ammonia production in Europe, while pragmatic for theoretical analysis, diverges from the current trend favouring retrofitting. Given the unlikelihood of new ammonia plants for fertilizers in Europe, this limits the practical relevance of the study, especially considering the economic advantages of retrofitting. However, emerging sectors like maritime fuel and hydrogen carriers offer growth opportunities for the European ammonia market. This underscores the importance of acknowledging the evolving landscape where new greenfield plants could meet demand in these emerging sectors.

Assessing decarbonization options for the ammonia industry is difficult due to the complexity caused by the volatile nature of natural gas and electricity prices. These factors introduce uncertainty that can significantly impact cost-effectiveness. This uncertainty is exacerbated by macro-level geopolitical considerations, such as the war between Russia and Ukraine, which have changed the landscape for European ammonia producers. The relevance of cheap natural gas or ammonia from Russia may evolve in the coming years. These factors are complex and subject to rapid change, creating an element of unpredictability.

The study assumes that the decarbonization options can seamlessly be implemented while it involves untested integration of new technologies. The standard SMR Haber-Bosch process has improved over the last decades. The integration of the decarbonization options has not been fully tested on a commercial scale for all decarbonization options. Practical challenges or unforeseen complications in implementation might alter the economic viability. PEM electrolyzers are suitable for ramping up, but this poses challenges for alkaline electrolyzers, for example. Collaborating with technology providers to validate the economic viability on a commercial scale could address this limitation.

The CCS options emerge as economically favourable, but generalizing $CO_2$ transport and storage costs across Europe oversimplifies the regional variations and the maturity of large-scale implementation. Localized differences in regulatory frameworks and public acceptance could significantly alter these costs. Assuming consistent CCS support in Europe overlooks the diversity in regulatory landscapes. Controversies and varying acceptance levels could impede the uniform implementation of CCS. Detailed assessments of support mechanisms, regulatory frameworks, and public acceptance levels could address this limitation.

Lastly, the study neglects using $CO_2$ for urea production. Although it is out of the scope for this study, it is a significant aspect given the current demand for ammonia in the fertilizer industry. In the case of green ammonia, this leads to a need for alternative $CO_2$ production. In the case of blue ammonia, the $CO_2$ used for urea production is released in a later stadium, impacting the potential environmental benefits.

### 5.1.2 Interpretation of the results

Based on the results, ATR with CCS emerges as the most economically viable decarbonization option for ammonia production in Europe. This finding holds not only in terms of economic viability but also in cost-effectiveness for mitigating carbon emissions. For non-European ammonia producers, ATR with CCS is the most cost-effective decarbonization option, although the standard SMR Haber-Bosch production process remains the lowest-cost alternative. The introduction of the CBAM is a crucial factor that positions ATR with CCS as most economically viable option for non-European ammonia producers. Without CBAM or a domestic carbon price, non-European ammonia suppliers such as Algeria, Canada and Saudi Arabia do not have a financial incentive to reduce the $CO_2$ emissions of the ammonia production process.

The study suggests a future trend toward the extended use of CCS in ammonia production, but there is also a notable potential for methane pyrolysis. Despite being less discussed during the interviews, its potential inclusion in the discussion around blue or green hydrogen and ammonia is crucial. Solid carbon's financial value may position ammonia from methane pyrolysis as a competitive option against CCS alternatives if included.

Although electrolyzers are currently not cost-competitive, projections for 2030 indicate potential competition. However, this depends on improved efficiency rates, stack lifetime, reduced capital costs, and especially lower electricity prices. Biomass gasification and the use of biomethane are currently not interesting for ammonia producers due to the high costs. Also the complexity of biomass supply and infrastructure might hinder the development of these decarbonization options. It is essential to continue investing in electrolyzers and not prioritize CCS over other decarbonization options. Overemphasizing CCS could lead to investments becoming locked in and Europe becoming more reliant on natural gas prices. This approach could jeopardise European ammonia production in a scenario with consistently high natural gas prices.

The LCOA of the standard SMR Haber-Bosch production process highlights the turbulent situation in the European ammonia industry. Pre-2020, an average market price of 350 €/t NH3 was considered, but current conditions differ significantly. The study results would have been remarkably different if conducted before 2020. Factors such as the rise in natural gas prices, technology readiness levels, and politics play a significant role. Although the relative position amongst decarbonization options in Europe could have been the same, the level of superiority of ATR with CCS is becoming less stringent. The economic viability of decarbonization options change and the dynamics between European and non-European ammonia producers shift. With current natural gas prices, it becomes more cost-effective to import ammonia. While Europe used to import 20% of its ammonia demand, this proportion is expected to increase in the coming years.

While the study indicates that Algeria is well-positioned to supply Europe with ammonia due to geographical proximity and lower transportation costs, Canada and Saudi Arabia could also be viable suppliers. However, the likelihood of importing ammonia from Australia is low due to high transportation costs. Importing green ammonia from Chile is also highly unlikely due to the high LCOA, although this could change rapidly in the coming decade. The study suggests that importing from Algeria, Canada, and Saudi Arabia is probable, with ATR with CCS being the likely production method. However, methane pyrolysis and SMR with CCS may also be a viable option due to small differences in LCOA between the alternatives.

For European ammonia producers, relocating to a production environment with lower energy costs and later exporting ammonia to Europe becomes a strategic consideration. Previously, staying in Europe might have been the preferred choice. Policymakers should be mindful that CBAM positively mitigates carbon emissions outside Europe. If structural natural gas prices remain elevated compared to non-European ammonia producers, the short-to-medium-term outlook for the European ammonia industry appears bleak. Lowering the capital costs of electrolyzers and harnessing abundant, low-cost renewable energy could shift the landscape for European ammonia producers. When energy prices remain significantly higher than outside Europe, essential industries like ammonia production might relocate, posing a challenge to a self-sufficient Europe. Dependency can be turned into a geopolitical weapon. The European food system is heavily dependent on ammonia. The absence of an ammonia and fertilizer industry could have far-reaching consequences for food security. Policymakers must carefully address the challenges associated with the potential relocation of essential industries such as the ammonia industry.

### 5.1.3 Comparison with existing literature

This study adopted a comprehensive approach to assess decarbonization options, focusing on the LCOA as a key metric. This approach aligns with previous studies that also used LCOA as a crucial indicator for economic viability. The report of IEA (2021a) is unique, depicting the LCOA of various ammonia production processes. This study shares similarities with the IEA's approach, examining multiple ammonia production processes.

An important addition this study provides is the inclusion of Europe and various countries outside of Europe, offering a nuanced analysis considering each country's specific production environments and conditions. This provides a more detailed understanding of the factors influencing the LCOA in different regions. This granularity allows for a more tailored assessment of the economic, environmental and policy implications from a European perspective, offering valuable insights for strategic decision-making and policy formulation at national and international levels. Specifically, the study delves deeper into trade dynamics, exploring the industrial policy implications for the future of Europe by comparing LCOA between EU and non-EU countries. This comparative approach sheds light on the potential impact on the European ammonia production landscape, highlighting similarities and differences in strategic considerations.

An overview of the LCOA can be found in Figure 5.1. Notably, IEA (2021a) appoints methane pyrolysis as the lowest-cost option, closely trailed by the standard SMR Haber-Bosch and ATR with CCS. This corresponds with the observations in this study, showing that the differences in LCOA between methane pyrolysis as well as ATR and SMR with CCS are marginal. Due to the large range of sensitivity for the various production processes, there is no clear preferred decarbonization option.

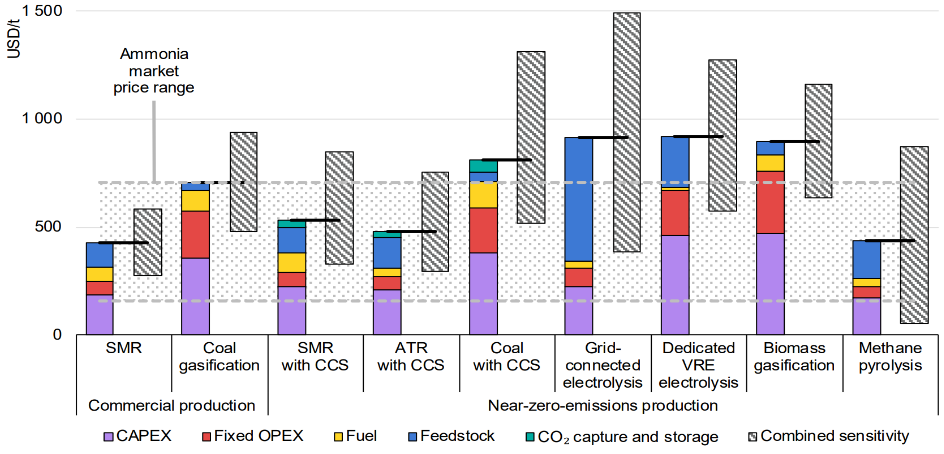

**Figure 5.1:** LCOA in 2020. Retrieved from IEA, 2021a, pg. 40

The prices mentioned in IEA (2021a) are slightly lower compared to this study. However, the cost ratio between the natural gas-based options compared to electrolysis and biomass gasification remains consistent. Furthermore, the ratio between capital expenditures, operational expenditures, and fuel and feedstock costs concur with this study.

Table C.1 in Appendix C illustrates the extensive range disparities in LCOA for decarbonization options. Notably SOEC options are often overlooked, and studies focusing on methane pyrolysis are focused on levelized costs of hydrogen, not on ammonia, hindering direct comparisons.

The LCOA of alkaline and PEM electrolysis in this study fall within the price ranges as calculated by Eichhammer et al. (2019), Sánchez and Martín (2018) and Morgan et al. (2017). The price ranges for alkaline electrolysis as stated by Armijo and Philibert (2020) is not attainable in Chile due to the use of higher electricity prices in this study. The use of lower LCOA extends to the work of Bazzanella and Ausfelder (2017), where LCOA for electrolysis at different energy price levels are 30% to 100% lower compared to this study. Here the capital expenditures per ton ammonia are half compared to this study. The studies of Nosherwani and Neto (2021) and Sánchez et al. (2019) are the only studies where the LCOA is higher than is this study, for PEM electrolysis and biomass digestion. The inconsistency underscores the sensitivity of the LCOA to varying input parameters.

Irlam (2017) states that the cost of avoided carbon for an ammonia plant with CCS in Germany and Poland ranges between 29 - 33 \$/t $CO_2$. Due to the rising EU ETS price, the cost of avoided carbon lowered and turned negative in this study for Europe. Without the carbon costs included in the LCOA analysis, the CAC for Europe would range between 62 - 92 €/t $CO_2$ for CCS which does not correspond with the findings of Irlam (2017).

## 5.2 IMPLICATIONS OF RESULTS

### 5.2.1 Theoretical implications

The results of this study hold several theoretical implications that contribute to the understanding of the economic and environmental dynamics within the context of the decarbonization of ammonia. The study integrates theoretical foundations such as LCOA, the CAC and neoclassical economics. Collectively, these frameworks contribute to the theoretical implications of the study's results, providing a comprehensive lens through which the complexities within the ammonia production industry can be interpreted.

Within the theoretical framework of neoclassical economics, the study provides insights into the rational decision-making of ammonia producers, policymakers or investors. The consideration of utility and profit maximization aligns with the expected strategic decisions, offering theoretical depth to understanding economic incentives guiding the involved parties.

A theoretical development recognizes the necessity of quantifying and integrating externalities, such as carbon emissions, into the analysis. This study contributes to the theoretical understanding of internalizing externalities and advancing discussions on the true costs of sustainable ammonia production. The study highlights the importance of ongoing methodological refinement, data transparency, and collaboration with industry stakeholders. These theoretical considerations underscore the dynamic nature of the ammonia production landscape and emphasize the need for adaptive methodologies that can evolve with emerging data and industry developments.

The study delves into the complexities of deep decarbonization within the ammonia industry, providing theoretical insights into the challenges and opportunities related to transitioning towards a more sustainable industry. The focus on multiple plant configurations and techno-economic analyses contributes to understanding the possible decarbonization pathways. Furthermore, the theoretical implications extend to the regional focus on Europe and potential ammonia suppliers outside Europe. This approach allows for a comprehensive analysis of the challenges and opportunities of transitioning towards a sustainable ammonia industry in Europe in a global context.

### 5.2.2 Future research directions

This section builds upon the insights and gaps gained during the various stages of this research. These recommendations serve as a compass, directing future research towards a transformative and sustainable future for the European ammonia industry.

Future research should consider conducting economic evaluations for each European ammonia plant. This would allow for fine-tuning of the economic details specific to each plant's unique parameters and context. Such tailored economic evaluations would offer a more nuanced and precise perspective, considering the diverse operational scenarios across the European industry.

Besides the detailed LCOA analysis for every European ammonia plant, the analysis should incorporate waste and by-products into the techno-economic analysis for each ammonia production pathway. In addition to a profound economic evaluation, it embraces circular practices.

An option towards a more holistic approach would be a life cycle analysis for every single ammonia production process. This would include the meticulous examination of methane emissions from natural gas production and a detailed assessment of the environmental impact of the materials used in electrolyzers. This way, a more thorough understanding of the environmental footprint of each production process can be achieved.

Long-term scenario analysis should assess the long-term implications of chosen decarbonization pathways or potential lock-ins of CCS. Additionally, it should account for technological advancements, policy changes, and evolving market dynamics. By embracing a long-term perspective, research can provide robust insights to guide sustained industry transformation.

Exploring policy implications and regulatory considerations linked to decarbonization options would be another possibility for future research. This involves evaluating the influence of existing and potential future policies such as the CBAM and the European Innovation Fund and environmental and industrial policy measures from, for example, the USA and China. This would contribute to aligning European industry practices with evolving regulatory frameworks in a global context.

Understanding the societal dynamics and perspectives around decarbonization options is critical. Future research should delve into the public perception and social acceptance of various decarbonization options. This involves investigating citizen backing, societal concerns, and the role of costs in shaping perceptions. By acknowledging and addressing these factors, research contributes to successfully implementing sustainable practices that align with societal expectations.

In conclusion, these recommendations collectively pave the way for future research endeavours prioritising economic precision, environmental consciousness, and a profound understanding of the economic, societal, and regulatory dimensions shaping the European ammonia industry's transformative journey.

# 6 CONCLUSION

The role of ammonia within the European chemical industry is of paramount importance. Notably, ammonia stands out as one of Europe's most energy and emission-intensive chemicals. Even under the hypothetical scenario of producing ammonia with the theoretical minimum required energy for the current SMR Haber-Bosch production process, it would still result in emissions of 1.2 $tCO_2/tNH_3$. This unavoidable carbon footprint is attributed to fossil fuel-based hydrogen production. While energy efficiency and demand-side measures are imperative, they fall short of meeting the ambitious climate targets set by the European Union. Despite being recognized as the most energy-efficient and least polluting facilities globally, European ammonia plants underline that energy efficiency alone is insufficient.

This research focuses on the deep decarbonization options of the European ammonia industry that can be deployed now or are expected to be commercially available within the coming ten years. The main research question of this research is formulated as follows:

*How can the European ammonia industry effectively transition towards sustainable and economically viable decarbonization*

Key findings reveal that CCS for ATR emerges as the most economically attractive, closely followed by other CCS options for SMR and methane pyrolysis. In contrast, electrolyzers, especially SOEC, prove less cost-competitive under prevailing conditions. In the future, electrolyzers could compete with CCS options, but this heavily depends on capital cost reductions and lower electricity prices. Assuming the current natural gas price in Europe and an electricity price of 40 €/MW puts alkaline and PEM electrolyzers in the same price range as CCS options. With electricity prices of less than 20 €/MWh, the improved electrolyzers could compete with foreign ammonia producers.

The impact of CBAM is profound, as it stimulates the adoption of cleaner technologies in non-European countries, especially CCS options. Algeria, Canada, Australia, and Saudi Arabia witnessed a shift in the lowest-cost decarbonization option, with ATR with CCS and methane pyrolysis emerging as economically attractive choices. CBAM facilitated a reduction in carbon-intensive practices globally, positioning cleaner technologies as more competitive and encouraging the adoption of sustainable ammonia production processes outside of Europe. Regarding global competitiveness, CBAM improves Europe's position but underscores the significant influence of natural gas prices. To compete with countries like Algeria, Canada and Saudi Arabia, Europe would need natural gas prices to drop substantially, which presents a considerable challenge in the current energy market dynamics.

The implications of this study span theoretical, economic, and environmental dimensions. The study integrates neoclassical economic principles, considers externalities, and grapples with complexities in deep decarbonization, contributing to theoretical advancements. Acknowledging limitations, such as the oversimplification of a European greenfield ammonia plant and the sole focus on LCOA, enhances transparency in result interpretation.

The recommendations for future research include tailoring economic evaluations for individual European ammonia plants, incorporating waste and by-products, conducting comprehensive life cycle analyses, and exploring long-term scenarios aligned with the overarching goal of refining and expanding current knowledge.

This research serves as a compass, guiding decision-makers in the ammonia industry towards a sustainable and economically viable future. By navigating through the complexities of decarbonization options, considering global competitiveness, and addressing theoretical and practical nuances, the study provides a robust foundation for future endeavours. The journey towards sustainable ammonia production demands continual exploration, adaptation, and a collaborative commitment to transformative change.

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# A APPENDIX A

## A.1 BACKGROUND INFORMATION ON DECARBONIZATION

### A.1.1 Obstacles to Decarbonization

How the ammonia industry can decarbonize in a cost-effective way does not pave the way for direct implementation. The research, development and demonstration of new low-carbon technologies are associated with high costs. Financial restrictions such as a negative net present value, a long pay-back time or the lack of access to capital and funding could hinder the uptake of innovative technologies (WSP Parsons Brinckerhoff and DNV GL, 2015).

Although the economic aspects are considered decisive, there are various non-economic reasons why incumbent ammonia companies may refrain from deploying low-carbon technologies. The lack of public acceptance and support could hinder the deployment of CCS, for example. Blok and Nieuwlaar (2017) mention knowledge and organisational barriers, split incentives and bounded rationality as reasons for the inability to adopt energy-efficient measures. Knowledge barriers refer to the awareness and expertise of companies regarding decarbonization options and technologies. A company may be unfamiliar with innovative low-carbon technologies and their reliability, how to implement them or how they will affect their operating production plants.

Organisational barriers involve the complexity of decision-making of investments in large companies. It is conceivable that the person who requests the deployment of low-carbon technologies is not responsible for the investment decisions and has limited power. Furthermore, it is possible that sustainability or decarbonization issues are not embedded in the strategy or identity of the company. Split incentives and the disproportional allocation of costs and benefits of investing in decarbonization options defy competitiveness in the ammonia industry. Bounded rationality concerns the internal competition for resources and funding.

Besides barriers, there can also be various explanations for the delay of climate action. The postponement of climate action is categorized by Lamb et al. (2020) into four discourses, of which the redirecting of responsibility and the push for non-transformative solutions are the most applicable to describe a delay in the decarbonization of the chemical industry. Redirecting responsibility refers to whataboutism and the free rider excuse. The free rider excuse refers to the disproportional allocation of costs and benefits. Only collective climate action will prevent taking advantage of the effort of other countries. The push for non-transformative solutions stems from the perception that disruptive change is unnecessary. The idea that fossil fuels are used more efficiently and are part of the solution towards a low-carbon future hampers the development of cleaner alternatives. Technological optimism is the belief that future technologies will drastically reduce the GHG emissions, which also stalls the uptake of low-carbon technologies.

### A.1.2 $CO_2$ Emission Reduction Potential

The potential of a decarbonization measure depends on the category of potential that is applied. The following six categories of potential are distinguished by Blok and Nieuwlaar (2017):

- Theoretical potential
- Technical potential
- Economic potential
- Profitable potential
- Market potential
- Policy-enhanced market potential

The potential could, for instance, be dedicated to improving energy efficiency or reducing energy use. For this thesis, the potential of a decarbonization measure refers to lowering the first, second and third scope of $CO_2$ emissions.

The combined contribution of the various decarbonization options results in the total $CO_2$ reduction of the European ammonia industry while considering the potential competition between decarbonization options. The theoretical potential refers to the possible $CO_2$ reduction that is only constricted by the physical limits. The technical potential includes practical constraints such as the replacement rate of existing installations and the future deployment of novel technologies. The economic and profitable potential relates to the $CO_2$ reduction potential of options with a positive Net Present Value (NPV) from a social or business perspective. With this, the time value of money is included. The market potential builds further on the profitable potential by incorporating the non-economic obstacles to decarbonization described in section A.1.1. The market potential can be influenced, for example, by policy measures of the European Commission. The $CO_2$ reduction potential that is stimulated by these policy measures is called the policy-enhanced market potential.

# B APPENDIX B

## B.1 BACKGROUND INFORMATION ON THE AMMONIA INDUSTRY

### B.1.1 Ammonia capacity per country

This table uses data from Batool and Wetzels (2019); Egenhofer et al. (2014); Fertilizers Europe.

| Country | Number of plants | Capacity [kt/year] | Share of installed capacity [%] | Companies |
|---|---|---|---|---|
| Germany | 5 | 3260 | 16% | BASF, Ineos, BP, SKW Stickstoffwerke Piesteritz, Yara |
| Poland | 5 | 2700 | 14% | Anwil, Grupa Azoty S.A. |
| Netherlands | 2 | 2600 | 13% | OCI Nitrogen, Yara |
| Romania | 5 | 2000 | 10% | Azochim, Azomures, InterAgro, Nitramonia |
| France | 4 | 1330 | 7% | Borealis, Yara |
| United Kingdom | 3 | 1170 | 6% | CF Fertilisers, Yara |
| Lithuania | 1 | 1120 | 6% | Achema |
| Belgium | 2 | 1060 | 5% | BASF, Yara |
| Bulgaria | 2 | 650 | 3% | Agropolychim, Neochim |
| Spain | 2 | 600 | 3% | Fertiberia |
| Italy | 1 | 600 | 3% | Yara |
| Slovakia | 1 | 580 | 3% | Duslo |
| Austria | 1 | 485 | 2% | Borealis |
| Croatia | 1 | 450 | 2% | Petrokemija Plc |
| Norway | 1 | 400 | 2% | Yara |
| Hungary | 1 | 380 | 2% | Nitrogénművek Zrt. |
| Czech Republic | 1 | 350 | 2% | Lovochemie |
| Greece | 1 | 165 | 1% | Phosphoric Fertilizer Industry |
| Estonia | 1 | 100 | 1% | Nitrofert |

**Table B.1:** Ammonia capacity per country

## B.2 AMMONIA SUPPLY CHAIN

| **Category** | **Companies** |
|---|---|
| Ammonia producers | Achema, Anwil, BASF, Borealis, CF Fertilisers, Fertiberia, SKW Stickstoffwerke Piesteritz, Yara |
| Hydrogen technology providers | Air Liquide, Haldor Topsoe, Hydrogenics, ITM, Linde, NEL, Siemens, Thyssenkrupp |
| EPC companies | Bechtel, Casale SA, Fluor, KBR, McDermott International, Saipem, Technip Energies, Worley |

**Table B.2:** Non-exhaustive list of ammonia producers, hydrogen technology providers and EPC contractors

# C

# APPENDIX C

## C.1 BACKGROUND LITERATURE ON THE AMMONIA INDUSTRY

This section provides an overview of the ammonia industry, specifically focusing on the different production options for hydrogen, a key component in ammonia production. It explores various methods, such as alkaline electrolysers, PEM electrolysers, biomass gasification, and biomass digestion, with the intention of understanding the existing research and development efforts in decarbonizing the ammonia production process.

### C.1.1 Researched LCOA in scientific literature

The provided table offers a non-exhaustive list of LCOA for various decarbonization options, focusing on ammonia production processes. The LCOA studies explore different production methods, such as alkaline electrolysers, PEM electrolysers, biomass gasification, and biomass digestion, conducted in various locations and years by different authors.

| Production Process | $NH_3$ Production [a] | Location | LCOA | Year | Authors |
|---|---|---|---|---|---|
| Alkaline electrolysers [b] | 744 | Morocco | 676 - 1093 | 2017 | Eichhammer et al. (2019) |
| Alkaline electrolysers [c] | 110 | Spain | 900 - 1370 | 2012 | Sánchez and Martín (2018) |
| Alkaline electrolysers [c] | 110 | Germany | 917 | 2018 | Nosherwani and Neto (2021) |
| Alkaline electrolysers [c] | 110 | USA | 1083 | 2010 | Morgan et al. (2017) |
| Alkaline electrolysers [d] | 35 | Chile | 404 - 423 | 2020 | Armijo and Philibert (2020) |
| Alkaline electrolysers [d] | 35 | Argentina | 443 - 500 | 2020 | Armijo and Philibert (2020) |
| Alkaline electrolysers [c] | 2 - 6.8 | - | 729 - 1718 | 2011 | Tuna et al. (2014) |
| PEM electrolysers [c] | 110 | Germany | 1323 | 2018 | Nosherwani and Neto (2021) |
| PEM electrolysers [d] | 83.2 | Scotland | 665 | - | Nayak-Luke and Bañares-Alcántara (2 |
| PEM electrolysers [b] | 20 | Netherlands | 510 - 1400 | - | ISPT (2017) |
| Biomass gasification | 255.5 - 310.3 | - | 400 - 700 | - | Sánchez et al. (2019) |
| Biomass gasification | 28.7 | - | 486 - 964 | 2011 | Tuna et al. (2014) |
| Biomass digestion | 54.8 | - | 900 - 1250 | - | Sánchez et al. (2019) |
| Biomass digestion | 3.730 - 7.480 | - | 739 - 1650 | 2011 | Tuna et al. (2014) |

**Table C.1:** Non-exhaustive list of LCOA in scientific literature

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[a] in kt/year
[b] Using non-specified renewable energy
[c] Using wind energy
[d] Using solar and wind energy

### C.1.2 Technology Identification Process

The overview provided by Nikolaidis and Poullikkas (2017) offers a comprehensive analysis of different hydrogen production pathways. It delves into the various methods and technologies used for hydrogen production, making it a valuable resource for understanding the diverse landscape of hydrogen production processes.

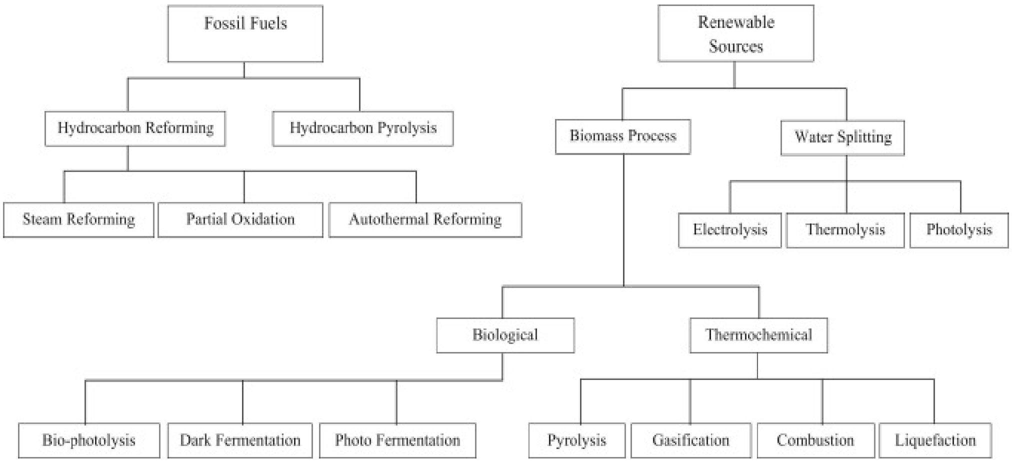

**Figure C.1:** Hydrogen production processes. Retrieved from Nikolaidis and Poullikkas, 2017, pg. 599

### C.1.3 Capital Cost Estimation

| Estimate Class | Maturity Level of Project | End usage | Methodology | Expected Accuracy Range |
|---|---|---|---|---|
| Class 1 | 65% to 100% | Check estimate or bid | Detailed unit cost with detailed take-off | L: -20% to -50%<br>H: +3% to +15% |
| Class 2 | 30% to 75% | Control or bid | Detailed unit cost with forced detailed take-off | L: -20% to -50%<br>H: +5% to +20% |
| Class 3 | 10% to 40% | Budget, authorization, or control | Semi-detailed unit costs with assembly level line items | L: -20% to -50%<br>H: +10% to +30% |
| Class 4 | 1% to 15% | Study or feasibility | Equipment factored or parametric models | L: -20% to -50%<br>H: +20% to +50% |
| Class 5 | 0% to 2% | Concept screening | Capacity factored, parametric models, judgement, or analogy | L: -20% to -50%<br>H: +30% to +100% |

**Table C.2:** AACE Cost Estimation Classes. Retrieved from Bredehoeft et al., 2020, pg. 5.

For the initial investment estimations, the CEPCI index is used; the table can be found below.

| Year | Index |
|---|---|
| 2010 | 551 |
| 2011 | 586 |
| 2012 | 585 |
| 2013 | 567 |
| 2014 | 576 |
| 2015 | 557 |
| 2016 | 542 |
| 2017 | 567,5 |
| 2018 | 603,1 |
| 2019 | 607,5 |
| 2020 | 596,2 |
| 2021 | 708,8 |
| 2022 | 816 |

**Table C.3:** CEPCI Index. Retrieved from Maxwell (2020).

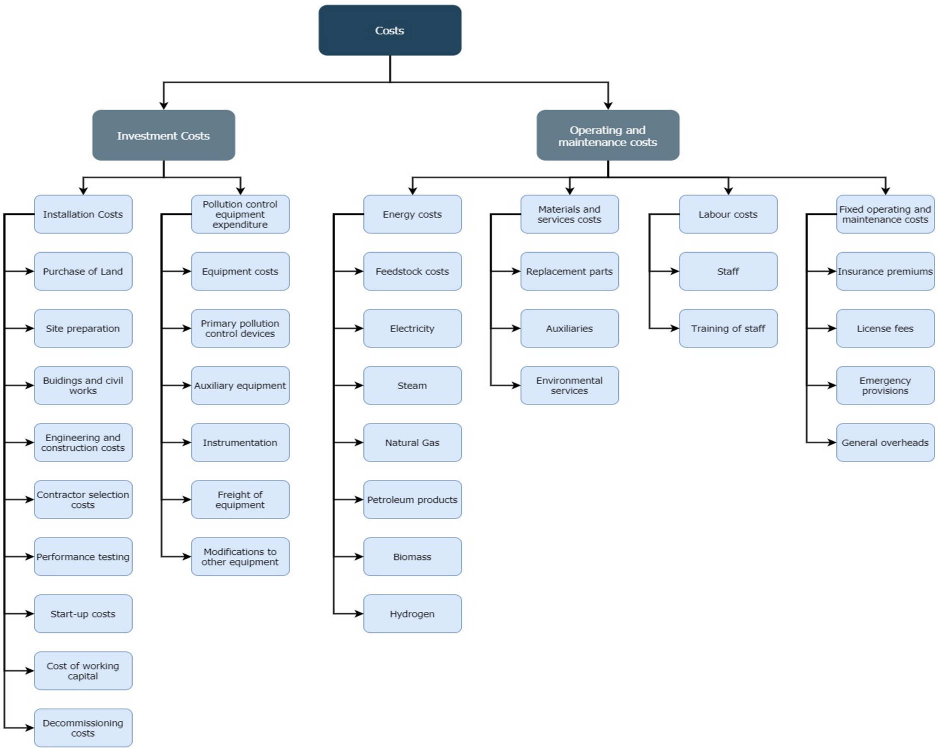

**Figure C.2:** Overview of cost components

# D APPENDIX D

## D.1 EXPERT INTERVIEWS

### D.1.1 Interview Process

The 10 largest ammonia producers by nameplate capacity were contacted, which can be found in B.1.1. Representatives based in Norway and Austria, respectively Yara and Borealis, were the only companies that agreed to an interview. BASF declined the request due to the present workload and the lack of personnel resources. The remaining ammonia producers did not respond to the request and ignored repeated calls. From the EPC companies, Thyssenkrupp agreed to an interview. The publication of Batool and Wetzels (2019) provides an insightful synopsis of decarbonization options for the Dutch fertilizer industry, including the ammonia production process. Both authors agreed to an interview as well as another academic researcher, which was mentioned in the literature review. Representatives from OCI Nitrogen, Yara, BASF, Fertibria, CF, Grupa Azoty, Agropolychim, and Duslo were contacted. The companies did not respond or did not have the personnel resources to comply to request an interview.

### D.1.2 Questions for semi-structured interview 1

- How do you see the role of green hydrogen in decarbonizing ammonia production?
- What are the most promising technological pathways for achieving carbon-neutral or low-carbon ammonia production?
- How do you assess the commercial viability of these decarbonization technologies?
- Are there any specific technical or operational challenges associated with retrofitting existing ammonia plants for decarbonization?
- What are the primary considerations for selecting the most suitable decarbonization technology for an ammonia production facility?
- What are the potential risks and uncertainties associated with adopting decarbonization technologies in the ammonia industry?
- How do you assess the readiness of the market and infrastructure for the widespread adoption of decarbonized ammonia?

- How do you see the role of public awareness and stakeholder engagement's role in driving the ammonia industry's decarbonization agenda?
- How do you envision the future of the European ammonia industry in a decarbonized world?
- What is your vision on CCS in Europe
- What is your vision on a hydrogen backbone in Europe?

### D.1.3 Interviewees Sub Question 1

| Name | Organizational Affiliation | Position |
|---|---|---|
| Rob Stevens | Yara Norway | VP |
| Robert Schlesinger | Borealis Austria | Technology Scout |
| Markus Aichinger | Borealis Austria | Product Manager Fertilizer |
| Karan Bagga | ThyssenKrupp-Uhde Australia | CTO |
| Wouter Wetzels | TNO | Researcher |
| Masooma Batool | PBL | Researcher |
| Christophe Rebreyend | TU Delft | Researcher |
| Chris van der Zande | GIDARA Energy | VP Innovation and Business Strategy |
| Dennis Chafiâ | G.I. Dynamics | Business Development Manager |

Table D.1: Interviewees sub question 1

### D.1.4 Questions for second round semi-structured interviews

These questions provide a starting point for exploring the implications of sustainable ammonia production for European producers, and the insights gathered from industry experts will contribute to a comprehensive understanding of the subject matter.

- What are the potential implications of decarbonization on the competitiveness of European ammonia producers in the global market?
- What are the potential implications of decarbonization options for the cost and competitiveness of ammonia producers in the global market?
- Can you discuss any potential socioeconomic or employment implications of adopting decarbonization options in the ammonia industry?
- Are there any specific certification or verification processes for carbon-neutral or low-carbon ammonia that can support market acceptance and differentiation?
- How do you perceive the impact of sustainable ammonia production outside of Europe on the competitiveness of European producers?
- What are the main advantages and disadvantages of partnering with countries like Chile, Morocco, and Australia for ammonia production?

- How do the Levelized Cost of Ammonia and Carbon Intensity of ammonia production in these countries compare to European production?
- How do you assess the readiness of the market and infrastructure for the widespread adoption of decarbonization options in the ammonia industry?
- Are there any specific policies or regulations that could incentivize or accelerate the deployment of decarbonization technologies in the ammonia industry?
- How might the transportation of ammonia from non-European countries impact the overall cost and competitiveness of European producers?
- In your opinion, what role do geopolitical considerations play in shaping the European ammonia industry's competitiveness?
- How important is it for Europe to reduce dependency on traditional ammonia suppliers and focus on self-dependence and green recovery?
- What potential synergies or collaborative opportunities can arise from European and non-European partnerships in sustainable ammonia production?
- From your perspective, what are the major implications, risks, or benefits for European producers in embracing sustainable ammonia production outside of Europe?

### D.1.5 Interviewees Sub Question 3

| Name | Organizational Affiliation | Position |
|---|---|---|
| Rob Stevens | Yara Norway | VP |
| Robert Schlesinger | Borealis Austria | Technology Scout |
| Karan Bagga | ThyssenKrupp-Uhde Australia | CTO |
| Willem Frens | TNO, BA2C Europe | Researcher and Director |
| Martijn de Graaff | TNO | Director Voltachem |
| Felipe van de Kerkhof | Aurora Energy Research Berlin | Researcher |
| Zachary Edelen | Aurora Energy Research Berlin | Researcher |
| Coby van der Linde | CIEP | Director |
| Pier Stapersma | CIEP | Senior Researcher |

**Table D.2:** Interviewees sub question 3

# E APPENDIX E

## E.1 LCOA ANALYSIS

### E.1.1 Initial investment

In Table E.2, the initial investment costs used per decarbonization option in the LCOA analysis are displayed. Each option is accompanied by a comprehensive list of sources consulted during the estimation process of the respective initial investment. This repository of sources not only substantiates the accuracy and rigour of the investment estimations but also underscores the scholarly foundation upon which the analysis of decarbonization options is built.

As described in the section 2.3.2, the equation for scale laws was used for an ammonia plant with 440 kt production capacity based on Egenhofer et al. (2014). Furthermore, when conducting calculations using the CEPCI, the base year of 2022 is used. An overview of the CEPCI index can be found in Appendix C.3. The yearly average of the dollar-euro exchange rate from the European Central Bank is utilized to convert dollars to euros.

| **Decarbonization option** | **Costs in M€** | **Sensitivity range** | **Sources** |
|---|---|---|---|
| SMR CCS - Partial capture | 645 | 16% | Arnaiz del Pozo and Cloete (2022)<br>Cloete et al. (2021)<br>Oni et al. (2022)<br>Collodi et al. (2017)<br>Liu et al. (2020)<br>Kyriakou et al. (2020)<br>Power et al. (2018) |
| SMR CCS - High capture rate | 782 | 22% | Arnaiz del Pozo and Cloete (2022)<br>Cloete et al. (2021)<br>Oni et al. (2022)<br>Collodi et al. (2017)<br>Parkinson et al. (2018)<br>Walden (2022) |
| ATR CCS - Single reformer | 687 | 24% | Cloete et al. (2021)<br>Ausfelder et al. (2022)<br>Arnaiz del Pozo and Cloete (2022)<br>Chaubey et al. (2013)<br>Noelker (2012) |
| Methane pyrolysis | 583 | 43% | Oni et al. (2022)<br>Schneider et al. (2020)<br>Parkinson et al. (2018)<br>Bhaskar et al. (2021)<br>Leal Pérez et al. (2021)<br>Sánchez-Bastardo et al. (2020)<br>Timmerberg et al. (2020)<br>Patlolla et al. (2023) |

**Table E.1:** Initial investment part 1

| Decarbonization option | Costs in M€ | Sensitivity range | Sources |
|---|---|---|---|
| Alkaline electrolysis | 1487 | 31% | Bodner et al. (2015)<br>Yao et al. (2017)<br>Rashid et al. (2015)<br>Buttler and Spliethoff (2018)<br>Smolinka et al. (2015)<br>Pinsky et al. (2020)<br>Roos (2021)<br>Fasihi and Breyer (2020)<br>Bazzanella and Ausfelder (2017) |
| PEM electrolysis | 2091 | 37% | Shiva Kumar and Himabindu (2019)<br>Smolinka et al. (2015)<br>Shiva Kumar and Himabindu (2019)<br>Rashid et al. (2015)<br>Taner et al. (2019)<br>Bazzanella and Ausfelder (2017) |
| Solid oxide electrolysis | 4716 | 42% | IEA (2022b)<br>Smolinka et al. (2015)<br>Rashid et al. (2015)<br>Pinsky et al. (2020)<br>Bazzanella and Ausfelder (2017)<br>Batool and Wetzels (2019) |
| Biomass gasification | 1189 | 28% | Sánchez et al. (2019)<br>Lepage et al. (2021)<br>Shahbaz et al. (2021)<br>Molino et al. (2016) |
| Biomass anaerobic digestion | 561 | N.A. [a] | |

**Table E.2:** Initial investment part 2

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[a] The price of biomethane will be used to calculate the LCOA using the conventional SMR production process.

Table E.3 showcases assumptions of the electrolyzers related to the operating parameters and initial investment costs. The costs are presented here since the stack costs and lifetime impact the initial investment, whereas the electricity demand is related to the levelized electricity costs for the electrolyzers.

| Cost component | Alkaline | PEM | SOEC |
|---|---|---|---|
| Electricity demand [kWh/kg $H_2$] | 50 | 47 | 41 |
| Stack costs [€/kW] | 900 | 1200 | 2500 |
| Stack lifetime [hours] | 80,000 | 60,000 | 40,000 |

**Table E.3:** Additional assumptions for electrolyzers

The costs for the stack replacement for the electrolyzers after its lifetime are assumed at 60% of the initial investment and depending on the capacity factor. In the base case, a capacity factor of 40% of the operating hours is assumed for enough available renewable energy to supply the electrolyzers.

### E.1.2 LCOA of non-European ammonia production

| Decarbonization option | Included | Excluded |
|---|---|---|
| CCS options | Algeria<br>Australia<br>Canada<br>Saudi Arabia | Chile |
| Electrolyzer options | Algeria<br>Australia<br>Canada<br>Chile<br>Saudi Arabia | |
| Methane pyrolysis | Algeria<br>Australia<br>Canada<br>Saudi Arabia | Chile |
| Biomass options | Australia<br>Canada<br>Chile | Algeria<br>Saudi Arabia |

**Table E.4:** Decarbonization options for non-European countries

### *LCOA results of non-European ammonia production*

### *Algeria*

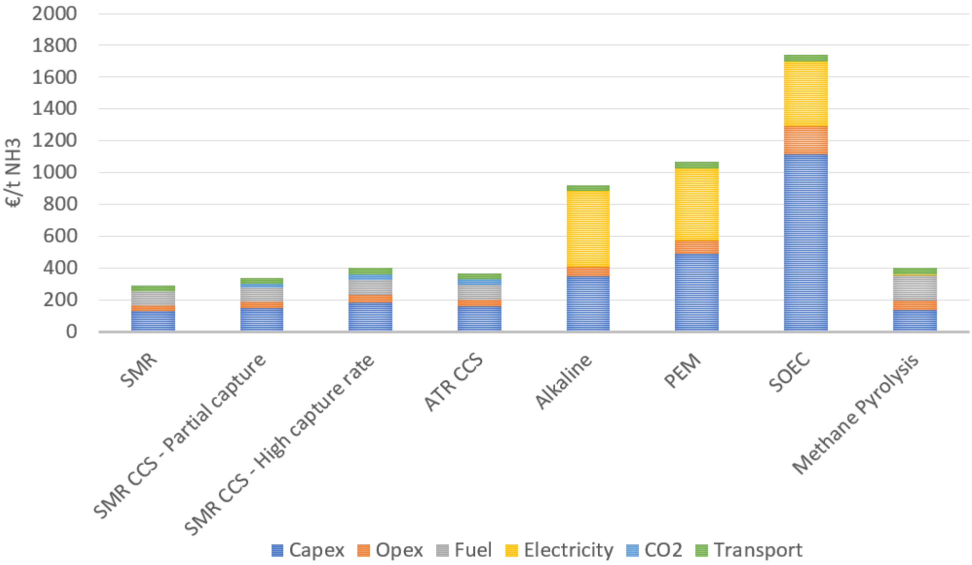

**Figure E.1:** LCOA results for Algeria

### *Australia*

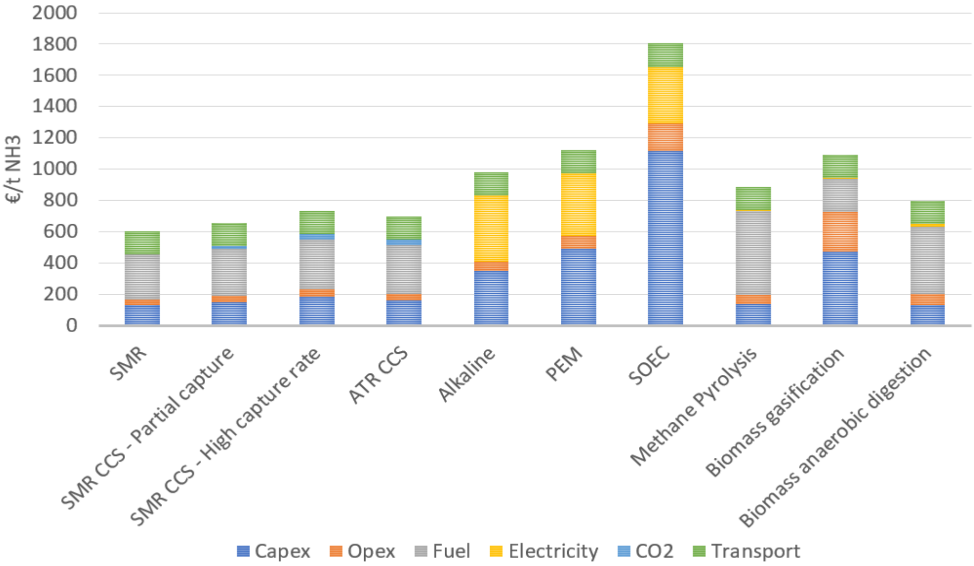

**Figure E.2:** LCOA results for Australia

### *Canada*

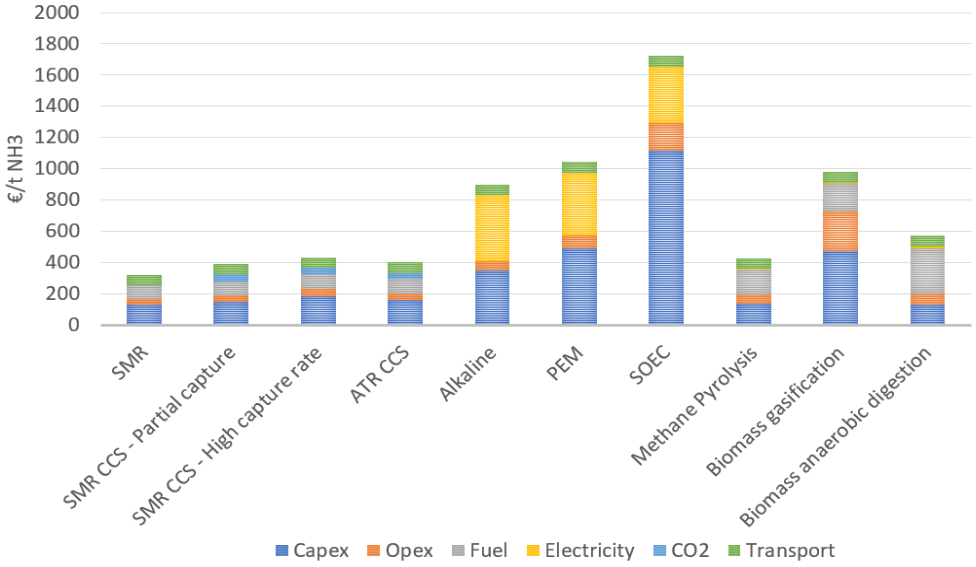

Figure E.3: LCOA results for Canada

### *Chile*

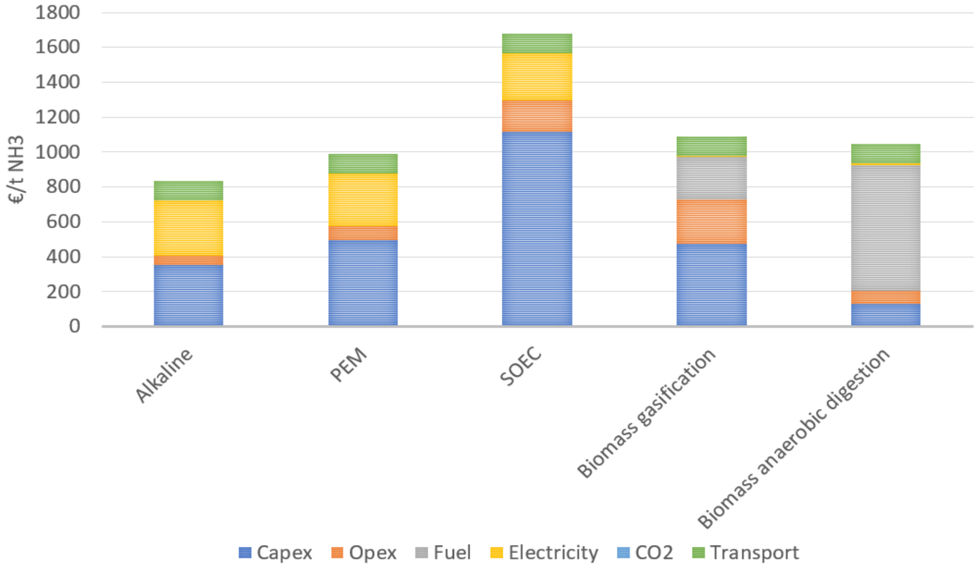

Figure E.4: LCOA results for Chile

### *Saudi Arabia*

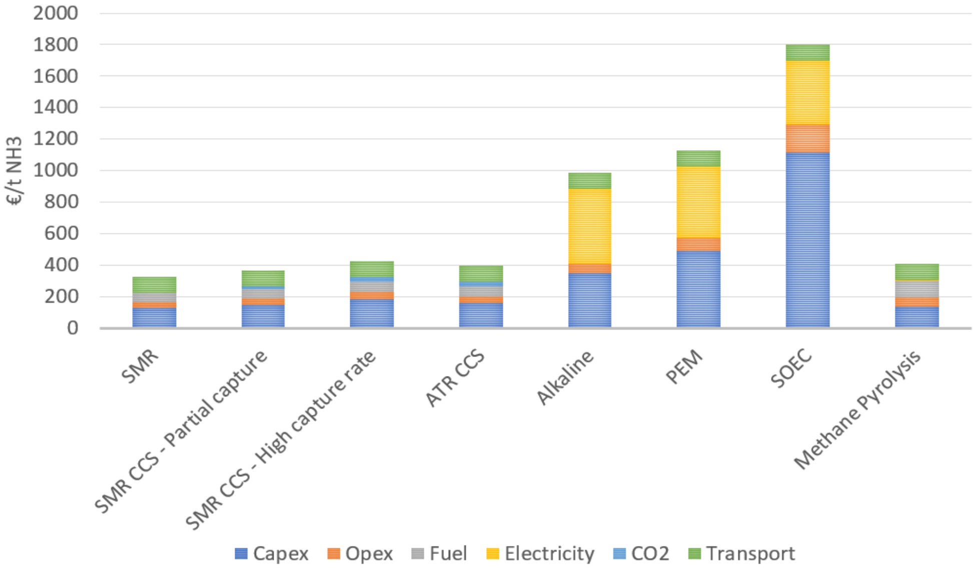

**Figure E.5:** LCOA results for Saudi Arabia

Table E.5 provides a comparative LCOA for each decarbonization option and country.

| **Decarbonization option** | Europe | Algeria | Australia | Canada | Chile | Saudi Arabia |
|---|---|---|---|---|---|---|
| SMR reference | 678 | 295 | 606 | 379 | N.A. | 326 |
| SMR CCS Partial capture | 647 | 342 | 659 | 395 | N.A. | 372 |
| SMR CCS High capture rate | 666 | 402 | 733 | 435 | N.A. | 430 |
| ATR CCS Single reformer | 620 | 372 | 697 | 402 | N.A. | 401 |
| Alkaline electrolysis | 1045 | 926 | 981 | 900 | 837 | 986 |
| PEM electrolysis | 1179 | 1068 | 1125 | 1044 | 987 | 1128 |
| SOEC electrolysis | 1836 | 1741 | 1803 | 1722 | 1676 | 1801 |
| Methane pyrolysis | 851 | 403 | 888 | 429 | N.A. | 409 |
| Biomass gasification | 1004 | N.A. | 1096 | 980 | 1092 | N.A. |
| Biomass anaerobic digestion | 802 | N.A. | 799 | 573 | 1047 | N.A. |

**Table E.5:** Overview of LCOA per decarbonization option

Table E.6 provides a comparative CAC for each decarbonization option and country.

| **Decarbonization option** | Europe | Algeria | Australia | Canada | Chile | Saudi Arabia |
|---|---|---|---|---|---|---|
| SMR CCS<br>Partial capture | -36 | 54 | 62 | 19 | N.A. | 53 |
| SMR CCS<br>High capture rate | -8 | 74 | 88 | 39 | N.A. | 72 |
| ATR CCS<br>Single reformer | -38 | 50 | 59 | 15 | N.A. | 49 |
| Alkaline electrolysis | 226 | 388 | 231 | 321 | 102 | 406 |
| PEM electrolysis | 309 | 476 | 320 | 410 | 194 | 492 |
| SOEC electrolysis | 713 | 890 | 738 | 827 | 618 | 908 |
| Methane pyrolysis | 106 | 66 | 174 | 31 | N.A. | 51 |
| Biomass gasification | 201 | N.A. | 302 | 370 | 259 | N.A. |
| Biomass anaerobic digestion | 77 | N.A. | 119 | 120 | 231 | N.A. |

**Table E.6:** Overview of CAC per decarbonization option

Table E.7 provides a comparative LCOA for each decarbonization option and country with CBAM.

| **Decarbonization option** | Europe | Algeria | Australia | Canada | Chile | Saudi Arabia |
|---|---|---|---|---|---|---|
| SMR reference | 678 | 457 | 768 | 484 | N.A. | 488 |
| SMR CCS<br>Partial capture | 647 | 417 | 735 | 444 | N.A. | 447 |
| SMR CCS<br>High capture rate | 666 | 420 | 750 | 447 | N.A. | 448 |
| ATR CCS<br>Single reformer | 620 | 381 | 706 | 408 | N.A. | 410 |
| Alkaline electrolysis | 1045 | 926 | 981 | 900 | 837 | 986 |
| PEM electrolysis | 1179 | 1068 | 1125 | 1044 | 987 | 1128 |
| SOEC electrolysis | 1836 | 1741 | 1803 | 1722 | 1676 | 1801 |
| Methane pyrolysis | 851 | 403 | 888 | 429 | N.A. | 409 |
| Biomass gasification | 1004 | N.A. | 1096 | 980 | 1092 | N.A. |
| Biomass anaerobic digestion | 802 | N.A. | 799 | 573 | 1047 | N.A. |

**Table E.7:** Overview of LCOA per decarbonization option with CBAM

Table E.8 provides a comparative CAC for each decarbonization option and country with CBAM.

| **Decarbonization option** | Europe | Algeria | Australia | Canada | Chile | Saudi Arabia |
|---|---|---|---|---|---|---|
| SMR CCS<br>Partial capture | -36 | -46 | -38 | -46 | N.A. | -47 |
| SMR CCS<br>High capture rate | -8 | -26 | -12 | -26 | N.A. | -28 |
| ATR CCS<br>Single reformer | -38 | -50 | -41 | -50 | N.A. | -51 |
| Alkaline electrolysis | 226 | 288 | 131 | 256 | 102 | 306 |
| PEM electrolysis | 309 | 376 | 220 | 345 | 194 | 394 |
| SOEC electrolysis | 713 | 790 | 638 | 762 | 618 | 808 |
| Methane pyrolysis | 106 | -34 | 74 | -34 | N.A. | -49 |
| Biomass gasification | 201 | N.A. | 202 | 305 | 259 | N.A. |
| Biomass anaerobic digestion | 77 | N.A. | 19 | 55 | 231 | N.A. |

**Table E.8:** Overview of CAC per decarbonization option with CBAM

## E.2 SENSITIVITY ANALYSIS

The objective of the first part of the sensitivity analysis is to examine under which conditions the electrolyzers become cost-compatible with the CCS options. The various costs and operating parameters of electrolysis-based ammonia plants, such as the stack costs and lifetime, are expected to improve till 2030. Similarly, the initial investment costs for CCS options are also expected to drop in the same period. It is interesting to examine the impact of these changes on the LCOA and CAC of the decarbonization options.

| **Cost component** | **Alkaline** | **PEM** | **SOEC** |
|---|---|---|---|
| Electricity demand [kWh/kg $H_2$] | 48 | 44 | 37 |
| Stack costs [€/kW] | 420 | 475 | 715 |
| Stack lifetime [hours] | 100,000 | 80,000 | 60,000 |

**Table E.9:** Additional assumptions for electrolyzers in 2030

| **Cost component** | **Alkaline** | **PEM** | **SOEC** |
|---|---|---|---|
| Stack costs reduction | -16% | -25% | -47% |
| Stack lifetime improvement | -4% | -7% | -17% |
| Capacity factor improvement | -4% | -4% | -6% |
| Combination | -20% | -29% | -53% |

**Table E.10:** Impact of electrolyzer assumptions on the LCOA in 2030