Cost competitiveness of blue and green ammonia in future energy markets

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Abstract

Low-carbon ammonia can be produced at relevant scales through the conventional Haber-Bosch process paired with carbon capture and sequestration (blue ammonia) or by using a renewable-driven Haber-Bosch process with hydrogen sourced from water electrolysis (green ammonia). The feasibility of each technology depends on the cost and availability of methane, green electricity, and the existence of carbon markets. To assess the feasibility of green and blue ammonia, we developed a detailed process model for each system and examined the energy, cost, and emissions associated with each system. We also assessed integration with the grid and intermittent operation from variable renewable energy resources on site. Our results suggest that an effective carbon tax of 50 USD/t_{CO_2} would make blue ammonia feasible. However, for green ammonia to be a viable alternative to gray ammonia in all scenarios, the required carbon tax would be between 100 USD/t_{CO_2} and 200 USD/t_{CO_2}. Furthermore, we find that green ammonia is only the preferred alternative over blue ammonia with advanced projections for renewable electricity and electrolysis technologies and with high natural gas price projections. Finally, we discuss the integration of emerging ammonia production routes with the grid and variable renewable power systems and their social impacts in future deployments.

Introduction

In the past decade, efforts to mitigate global CO_2 emissions have focused primarily on decarbonizing the electric power and transportation sectors.[1,2] Despite progress in these areas, the industrial and chemical sectors have proven difficult to decarbonize, with both combustion and process emissions, high-cost equipment with long service lifetimes, and competitive international markets for industrial products.[3] Between 2008 and 2018, CO_2 emissions from the power sector decreased by 26%, while CO_2 emissions from the industrial sector decreased by 9%.[4] Within the US industrial sector, chemical manufacturing remains the most energy and carbon-intensive.[5,6]

With global CO_2 emissions reaching a new record high of 37.4 billion tonnes in 2023,[7] emerging decarbonization strategies in the chemical industry often involve electrifying processes that have previously been based on fossil fuels.[8,9] The electrification of these processes directs the emissions to the energy production sector, which can rapidly decarbonize through the introduction of renewable energy.[10] A chemical that will play a pivotal role in the decarbonization of the energy, industry, and potentially transportation sectors is ammonia.[11–13] Approximately 175 million metric tons of ammonia are produced per year, emitting approximately 500 million tons of CO_2.[14–17] By 2050, emissions related to ammonia production could reach over 800 million metric tons of CO_2 yearly without major transformations to the ammonia production process.[18]

The Haber-Bosch process for the production of ammonia, an essential component for the fertilizer and food industries, contributes approximately 1 to 2% of anthropogenic CO_2 emissions, emitting between 1.5 and 1.7 tons of CO_2 per ton of ammonia produced.[19–22] This process currently relies on natural gas as the primary feedstock. The dependence on natural gas in the Haber-Bosch process means that the cost of ammonia production is highly dependent on the costs and markets of natural gas, with the average global price of ammonia fluctuating between 400 USD/t_{NH3} and 1,600 USD/t_{NH3} between 2022 and

2023 due to volatility in natural gas prices.[23]

The decarbonization of the Haber-Bosch process can be performed by using carbon capture coupled with the methane-fed Haber-Bosch process (blue ammonia) or by using hydrogen produced from electrolysis and fully electrifying the Haber-Bosch process (green ammonia).[24] Many experts consider blue and green ammonia as feasible alternatives to conventional gray ammonia production.[24–28] Research suggests that blue ammonia can reach costs between 200 USD/t_{NH_3} and 400 USD/t_{NH_3} and green ammonia can reach costs between 400 USD/t_{NH_3} and 800 USD/t_{NH_3}.[24,26] However, successful implementation of these technologies also requires further decarbonization of the electric grid by reducing the cost of renewable energy and carbon capture technologies. As such, projections for the electricity and natural gas markets should be studied in parallel with the deployment of blue and green ammonia to build robust infrastructure for different natural gas and electricity markets.

Several have investigated the technoeconomic performance of blue and green ammonia production. Each investigation varies in scope and complexity in the source of renewable energy, the level of interconnection with the grid, energy storage, and spatial variability. Some examinations compare the costs of ammonia production from blue and green ammonia without considering operation flexibility.[24] Other investigations focus on optimizing the integration of green ammonia with renewable energy sources.[29–32] However, studies are needed to compare the costs of gray, blue, and green ammonia in different technology, market, and policy scenarios. These studies must take into account intermittent energy profiles, geospatial resource availability, and policy considerations to accurately predict optimal locations and deployment strategies for decarbonizing ammonia production in the United States.

Here, we aim to improve our understanding of the competitiveness between blue and green ammonia in different technological, market, and policy scenarios. In order to find the most cost-effective route for decarbonizing ammonia production, this study seeks to

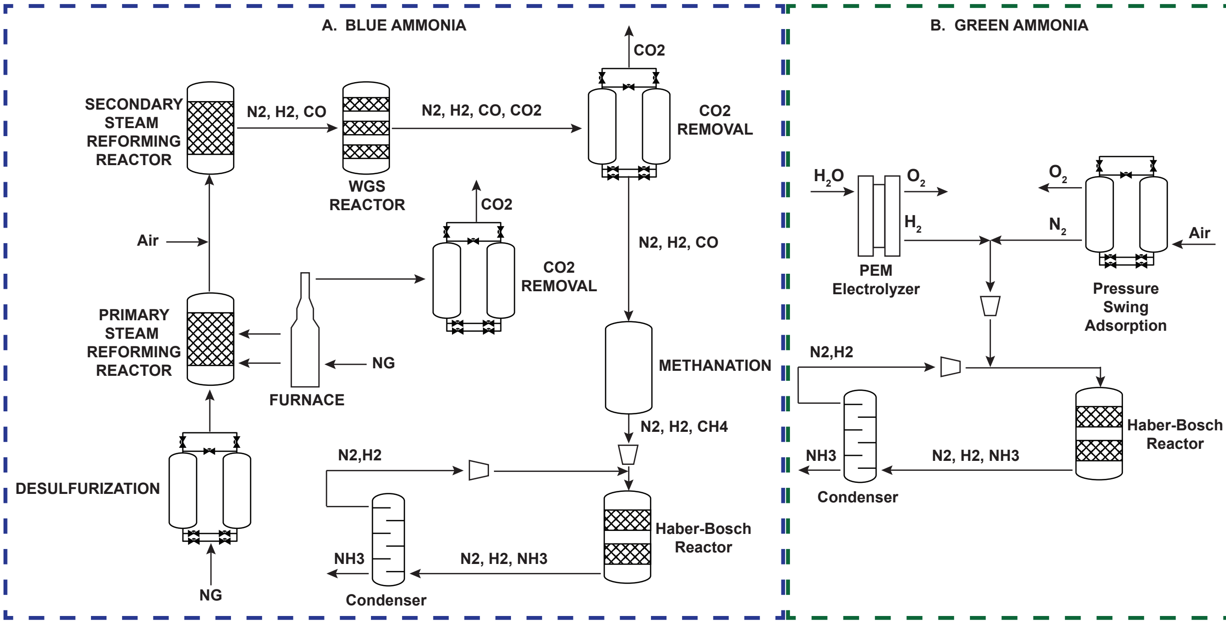

Figure 1: System diagram for blue ammonia production (a) and green ammonia production (b).

determine the appropriate circumstances under which blue and green ammonia should be utilized. In addition, we explore the necessary technological advancements, developments in the electricity and natural gas markets, and the implementation of policies essential to promote the adoption of blue and green ammonia. The fundamental information problem with respect to industrial site-specific emissions led us to employ a carbon tax as the policy instrument for our analysis. This market-based approach motivates companies to address emission reductions by internalizing the social cost of carbon into the market price of files, increasing fossil fuel costs, and rewarding investments in renewables. We also highlight how to strategically promote these sustainable ammonia production methods to contribute to global decarbonization efforts.

Process Description

Ammonia can be produced through the Haber-Bosch process through different pathways depending on the hydrogen sources and CO_2 emission intensity. The route in which hydrogen is produced from natural gas through the steam methane reforming process (SMR) is classified as gray ammonia if no CO_2 capture is implemented or blue ammonia if CO_2 capture is implemented (Figure 1a). The route in which hydrogen is produced from water electrolysis using renewable electricity is defined as green ammonia (Figure 1b). The energy consumption, energy cost, and emissions of gray, blue, and green have been the subject of limited comparative analysis.

Ammonia production

The ammonia production process requires high temperatures and pressures (Figure 1a-b). Higher temperatures favor higher reaction rates, and higher pressures are required to shift the equilibrium towards the forward reaction. Generally, the Haber-Bosch process takes place over four catalyst beds with cooling between the beds. The outlet streams from each reaction are used to heat the nitrogen and hydrogen streams that enter the first reactor while maintaining the product streams at a low enough temperature to maintain a reasonable equilibrium constant. The reaction is exothermic and can be represented by the equation:

$$N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$$

However, this reaction is reversible, and achieving a high yield of ammonia necessitates the continuous removal of ammonia from the reaction mixture as it forms. The ammonia produced is condensed out of the gas stream by cooling, while unreacted nitrogen and hydrogen are recirculated back into the reactor for improved efficiency and yield.

Gray and Blue Ammonia

Hydrogen Production from steam methane reforming

The steam methane reforming (SMR) process takes in a feed of natural gas, steam, and air to produce purified hydrogen and nitrogen streams using the steam methane reforming and water gas shift reactions (Figure 1a). Commonly, the natural gas stream comes contaminated with sulfur compounds that are detrimental to the catalyst performance in subsequent steps. As such, sulfur compounds are removed through catalytic hydrogenation, turning sulfur compounds into hydrogen sulfide, and the subsequent adsorption on zinc oxide beds. The sulfur-free natural gas then goes through the steam-methane reforming reactions. The primary reforming reaction in which CH4 and steam are converted into CO and H2. The primary reforming reaction is endothermic, as such, it needs an external heat source from a furnace. The secondary reforming reaction in which CH4 and air are converted into CO and H2. This reaction is adiabatic but it necessitates higher temperatures. The second reforming reaction also removes oxygen from the air feed. Then, the N2, H2, and CO streams go into a catalytic water-gas shift reaction that converts CO and H2O into CO2 and H2. A bulk of the CO2 is removed to avoid contamination of the Haber-Bosch catalyst. Finally, the remaining CO2 and CO are removed by converting them into methane using a methanation reaction.

Green Ammonia

Hydrogen Production from water electrolysis for green ammonia

Water electrolysis is the electrochemical process of using an electric current to split water into hydrogen and oxygen gases (Figure 1b). Multiple technologies can be used for water electrolysis. However, the three main ones are alkaline water electrolysis (AWE), proton exchange membrane water electrolysis (PEMWE), and solid oxide electrolyzer cell

(SOEC). We use PEMWE in our models due to projected improvements, cost reduction, and durability. During electrolysis in a PEMWE water is oxidized in the anode, producing O2 and protons (H+). The protons (H+) cross the proton exchange membrane (PEM) from the anode to the cathode to be reduced in the cathode to hydrogen gas. The electrolysis process is endothermic, requiring significant electrical energy.

Nitrogen production from PSA

The pressure swing adsorption (PSA) process purifies air to produce nitrogen (Figure 1b). Initially, this air is compressed and purified to remove impurities that could impair the performance of the PSA process, such as water vapor. Then, the oxygen is removed from the air using carbon molecular sieves (CMS). Under high pressure, oxygen molecules are adsorbed onto the surface of the adsorbent, allowing nitrogen molecules to pass through the vessel as the product gas. Upon reaching the adsorption capacity limit for oxygen, the vessel's pressure is decreased, and oxygen desorbs from the CMS. The PSA process employs several vessels, with each vessel undergoing adsorption and regeneration phases in opposite phases. This configuration allows for the continuous production of nitrogen, with one or more vessels in the adsorption phase while others are being regenerated.

Results

Future Scenario Analysis

The potential cost of each technology depends on the maturity and development of PEM water electrolysis, electricity markets, natural gas markets, and carbon taxes. As such, if the proposed technologies are to be deployed in the next several decades, it is important to consider the possible energy markets and determine the best technology for each scenario.

Cost projections of gray and blue ammonia

Understanding the future trajectory of natural gas markets is essential for assessing the economic viability of gray and blue ammonia (Figure 2). Fluctuations in natural gas prices, driven by factors such as supply-demand dynamics, geopolitical tensions, and advances in extraction technologies, can significantly impact the competitiveness of gray and blue ammonia. Here, we study the cost of gray and blue under three different scenarios of the natural gas market.

In the case of low natural gas prices, the levelized cost of gray ammonia ranges from 120 USD/t_{NH_3} to 135 USD/t_{NH_3} in 2050 (Figure 2a) and the levelized cost of blue ammonia ranges from 130 USD/t_{NH_3} to 180 USD/t_{NH_3} in 2050 (Figure 2b). In the case of baseline natural gas prices, the levelized cost of gray ammonia ranges from 190 USD/t_{NH_3} to 210 USD/t_{NH_3} in 2050 (Figure 2a) and the levelized cost of blue ammonia ranges from 220 USD/t_{NH_3} to 260 USD/t_{NH_3} in 2050 (Figure 2b). Finally, in the case of high natural gas prices, the levelized cost of gray ammonia ranges from 300 USD/t_{NH_3} to 350 USD/t_{NH_3} in 2050 (Figure 2a) and the levelized cost of blue ammonia ranges from 340 USD/t_{NH_3} to 400 USD/t_{NH_3} in 2050 (Figure 2b). Our results show that depending on the natural gas price scenario, the ammonia production cost could increase by nearly three times in 2050 between the low and high natural gas scenarios.

Coupling carbon capture and sequestration with the methane-fed Haber-Bosch process (blue ammonia) is an effective strategy that can reduce the emissions tied to ammonia production by over 70%.The energy-associated emissions for gray ammonia (Figure 2c) remain around an average of 1.7 metric tons of CO_2 per ton of ammonia between 2030 and 2050. Additionally, the energy-associated emissions for blue ammonia (Figure 2c) remain around an average of 0.5 metric tons of CO_2 per ton of ammonia between 2030 and 2050. This demonstrates the environmental burden associated with gray ammonia and the effectiveness of blue ammonia in significantly reducing the carbon intensity of ammonia manufacturing.

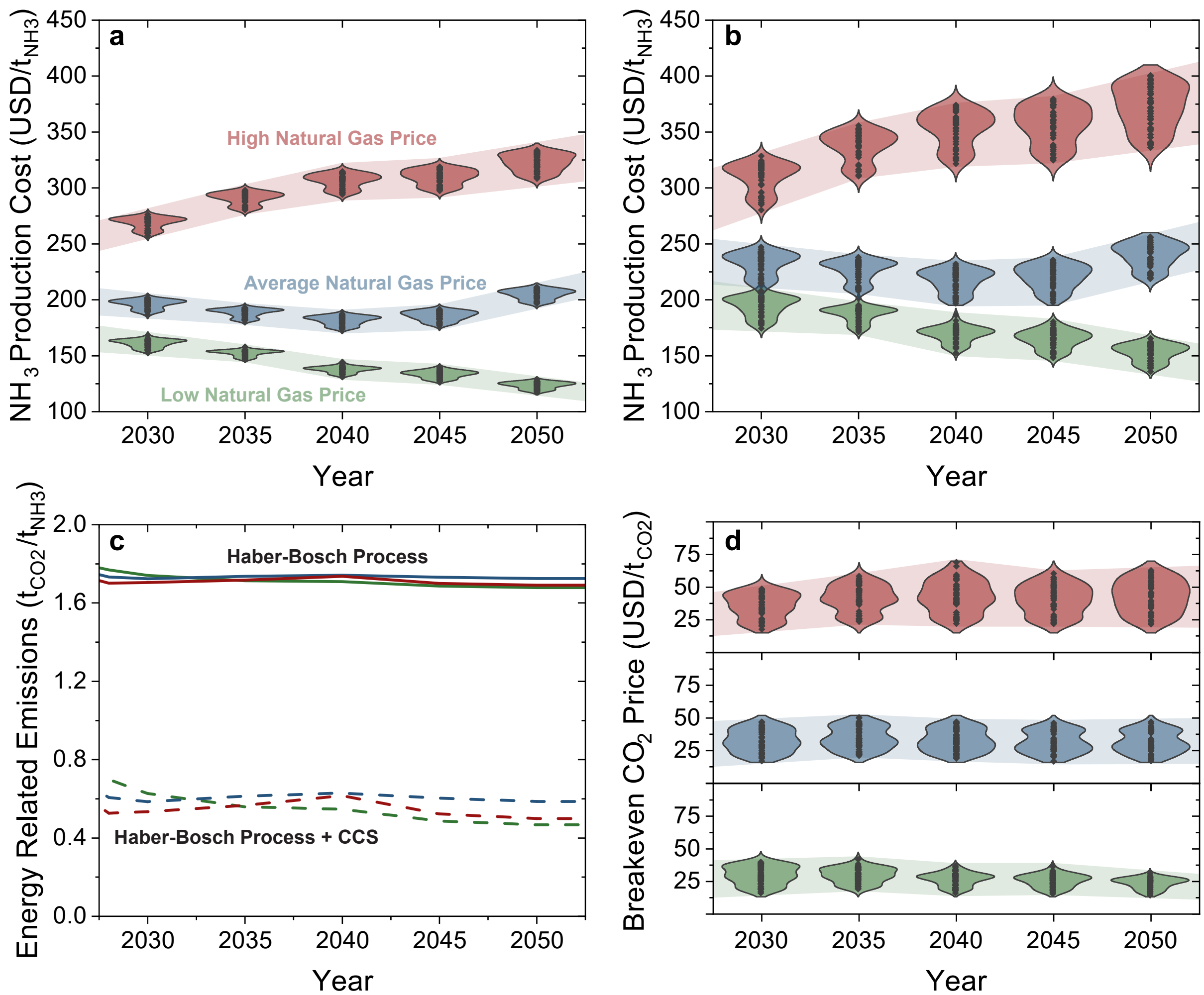

Figure 2: Ammonia production cost for brown ammonia (a) and blue ammonia (b), energy-associated emissions for brown and blue ammonia (c), and the break-even carbon tax for blue ammonia (d) under different natural gas market scenarios.

To compete with gray ammonia, blue ammonia will require policy support in the form of carbon taxing/incentives. Due to the lower levelized costs of gray ammonia, blue ammonia needs carbon taxes between 25 USD/t_{CO_2} and 50 USD/t_{CO_2} to bridge the gap between gray and blue ammonia (Figure 2d). Therefore, the future development of blue ammonia will necessitate the implementation of policy instruments and regulations that address these competitiveness gaps. Modeling the integration of gray and blue ammonia with the anticipated natural gas and electricity markets will inform future directions in projects and policies for decarbonizing ammonia production, like the deployment of appropriate carbon taxing to drive decarbonization.

In parallel, the evolving landscape of electricity markets introduces complexity to this analysis. As renewable electricity continues to get cheaper, the cost competitiveness of electrification in chemical manufacturing relative to natural gas becomes an important factor to consider. The potential for electrification of the ammonia production process, utilizing renewable energy sources for electrolysis and subsequent Haber-Bosch synthesis (green ammonia), presents an alternative pathway that could mitigate both cost and emissions concerns.

Cost projections of green ammonia

Insights into the future trends of pricing and carbon intensity in the electricity grid are crucial for evaluating the economic feasibility of green ammonia (Figure 3). Factors such as the availability and cost of renewable energy sources, regulatory policies, advancements in energy storage technologies, and the balance between supply and demand in electricity markets play a pivotal role in shaping the cost-effectiveness and emissions of ammonia production via electrification.

By connecting future electrified Haber-Bosch facilities directly with the developing electric grid infrastructure, these systems offer stability and reliability, ensuring a consistent power supply for ammonia synthesis. However, the economic viability and emission intensity of grid-connected green ammonia hinges upon several key factors – the cost reduction and market penetration of renewable energy production technologies, the development of water electrolysis technologies, and the availability of policies for carbon pricing.

An analysis of three renewable energy development scenarios for electricity production (Figure 3) evaluates the effect of projected grid prices and emissions on the average ammonia production costs and emissions in the United States for systems that are directly connected to the grid and operate continuously regardless of the electricity market price and emissions. This means that these systems are continuously producing am-

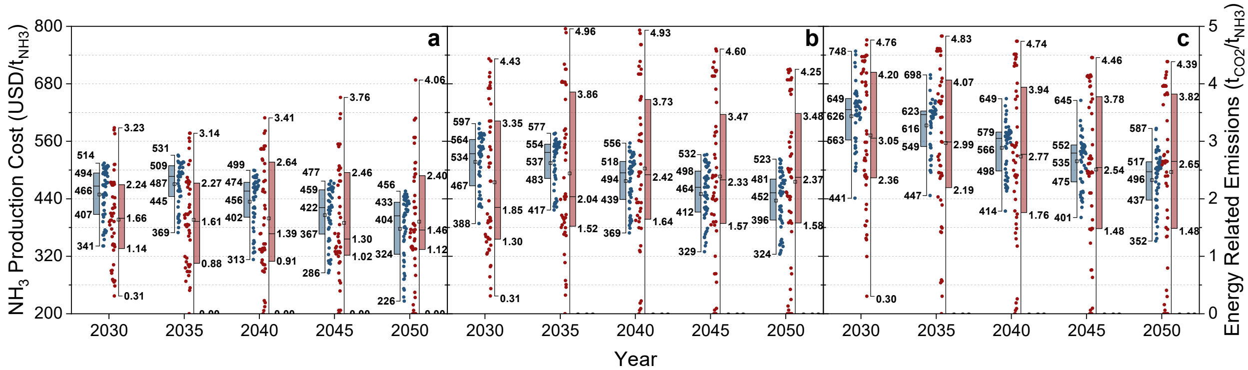

Figure 3: Cost and emissions for green ammonia under different connected to the grid with 100% capacity factor and low renewable energy cost grid scenario (a), baseline grid scenario (b), and high renewable energy cost grid scenario (c).

monia and consuming electricity all year round. In theory, these systems are ideal for maximizing ammonia production and minimizing capital costs per unit of ammonia produced. However, the electricity prices and emissions in the grid change throughout the year – especially in grids that have a high penetration of renewables – due to fluctuations in demand, fuel costs, and the availability of renewable energy sources. In periods of high demand, more electricity is needed, often requiring the use of additional, sometimes less efficient and more polluting, power plants (peaker plants), which can increase prices and emissions. Conversely, during periods with high renewable energy production and lower loads, the increased supply of clean energy can reduce both prices and emissions. Seasonal changes also affect the mix of energy sources used for power generation, further contributing to these fluctuations.

In the case of low renewable energy prices – which assumes the Annual Technology Baseline advanced projections for renewable energy – the levelized cost of green ammonia in 2050 ranges from 226 USD/t$_{NH_3}$ to 456 USD/t$_{NH_3}$ depending on the location (Figure 3a). In the case of average renewable energy prices – which assumes the Annual Technology Baseline moderate projections for renewable energy – the levelized cost of green ammonia in 2050 ranges from 324 USD/t$_{NH_3}$ to 523 USD/t$_{NH_3}$ depending on the location (Figure 3b). In the case of high renewable energy prices – which assumes the

Annual Technology Baseline conservative projections for renewable energy – the levelized cost of green ammonia in 2050 ranges from 352 USD/t$_{NH_3}$ to 587 USD/t$_{NH_3}$ depending on the location (Figure 3c). The cheapest five locations for green ammonia continuously operating from the grid are North Dakota, Colorado, Wyoming, New Mexico, and Kansas.

Green ammonia operating continuously connected to the grid has higher emissions than blue ammonia in most locations. For all renewable energy development scenarios by 2050, only eight states can produce green ammonia with energy-associated emissions under 0.5 t_{CO_2}/t_{NH_3} (equivalent emissions to blue ammonia). The states able to achieve low-emissions green ammonia when directly coupled to the grid are California, New York, Oregon, Washington, Rhode Island, Virginia, North Carolina, and New Mexico. It is important to note that the locations capable of producing low-emission green ammonia operating continuously connected to the grid often face the challenge of high production costs. Despite their environmental advantages, the economic viability of green ammonia production remains a significant hurdle in many of the states that are otherwise well-positioned to lead in its sustainable manufacture.

Our results suggest that without substantial improvements in operational flexibility, the electrified Haber-Bosch process may not offer the anticipated environmental benefits. A possible avenue for reducing the costs and emissions of the electrified Haber-Bosch process connected to the grid is to operate at a lower capacity factor when the electricity is cheaper and has lower emissions or to add on-site renewable energy capacity to supplement the grid electricity when the electricity prices and emissions are higher. However, the current catalyst and separations used for the Haber-Bosch loop necessitate low flexibility and long ramp-up and ramp-down times. As such, we have analyzed the deployment of two options 1) continuous operation coupled with flexible hydrogen electrolyzers with hydrogen storage (Figure 4) and 2) continuous operation with additional on-site renewable energy capacity (Figure 5).

We evaluate the operation of a continuous electrified Haber-Bosch process coupled with a flexible hydrogen electrolyzer and hydrogen storage connected to the grid (Figure 4) and we evaluate the effect of the hydrogen electrolyzer capacity factor on the average ammonia production costs and emissions in the United States.

In the case of low renewable energy prices, the average levelized cost of green ammonia in 2050 is 320 USD/t$_{NH_3}$ for a hydrogen electrolyzer operating at an 80% capacity factor (Figure 4a), 465 USD/t$_{NH_3}$ for a hydrogen electrolyzer operating at a 50% capacity factor (Figure 4d), and 880 USD/t$_{NH_3}$ for a hydrogen electrolyzer operating at a 20% capacity factor (Figure 4g). In the case of average renewable energy prices, the average levelized cost of green ammonia in 2050 is 400 USD/t$_{NH_3}$ for a hydrogen electrolyzer operating at an 80% capacity factor (Figure 4a), 540 USD/t$_{NH_3}$ for a hydrogen electrolyzer operating at a 50% capacity factor (Figure 4d), and 910 USD/t$_{NH_3}$ for a hydrogen electrolyzer operating at a 20% capacity factor (Figure 4g). In the case of high renewable energy prices, the average levelized cost of green ammonia in 2050 is 400 USD/t$_{NH_3}$ for a hydrogen electrolyzer operating at an 80% capacity factor (Figure 4a), 530 USD/t$_{NH_3}$ for a hydrogen electrolyzer operating at a 50% capacity factor (Figure 4d), and 840 USD/t$_{NH_3}$ for a hydrogen electrolyzer operating at a 20% capacity factor (Figure 4g).

In the case of low renewable energy prices, the average energy-associated emissions in 2050 are 1.2 t_{CO_2}/t_{NH_3} for a hydrogen electrolyzer operating at an 80% capacity factor (Figure 4a), 0.8 t_{CO_2}/t_{NH_3} for a hydrogen electrolyzer operating at a 50% capacity factor (Figure 4d), and 0.5 t_{CO_2}/t_{NH_3} for a hydrogen electrolyzer operating at a 20% capacity factor (Figure 4g). In the case of average renewable energy prices, the average energy-associated emissions in 2050 are 1.9 t_{CO_2}/t_{NH_3} for a hydrogen electrolyzer operating at an 80% capacity factor (Figure 4a), 1.5 t_{CO_2}/t_{NH_3} for a hydrogen electrolyzer operating at a 50% capacity factor (Figure 4d), and 1.1 t_{CO_2}/t_{NH_3} for a hydrogen electrolyzer operating at a 20% capacity factor (Figure 4g). In the case of high renewable energy prices, the average energy-associated emissions in 2050 are 2.1 t_{CO_2}/t_{NH_3} for a hydrogen electrolyzer operating at an 80% capacity factor (Figure 4a), 1.2 t_{CO_2}/t_{NH_3} for a hydrogen electrolyzer

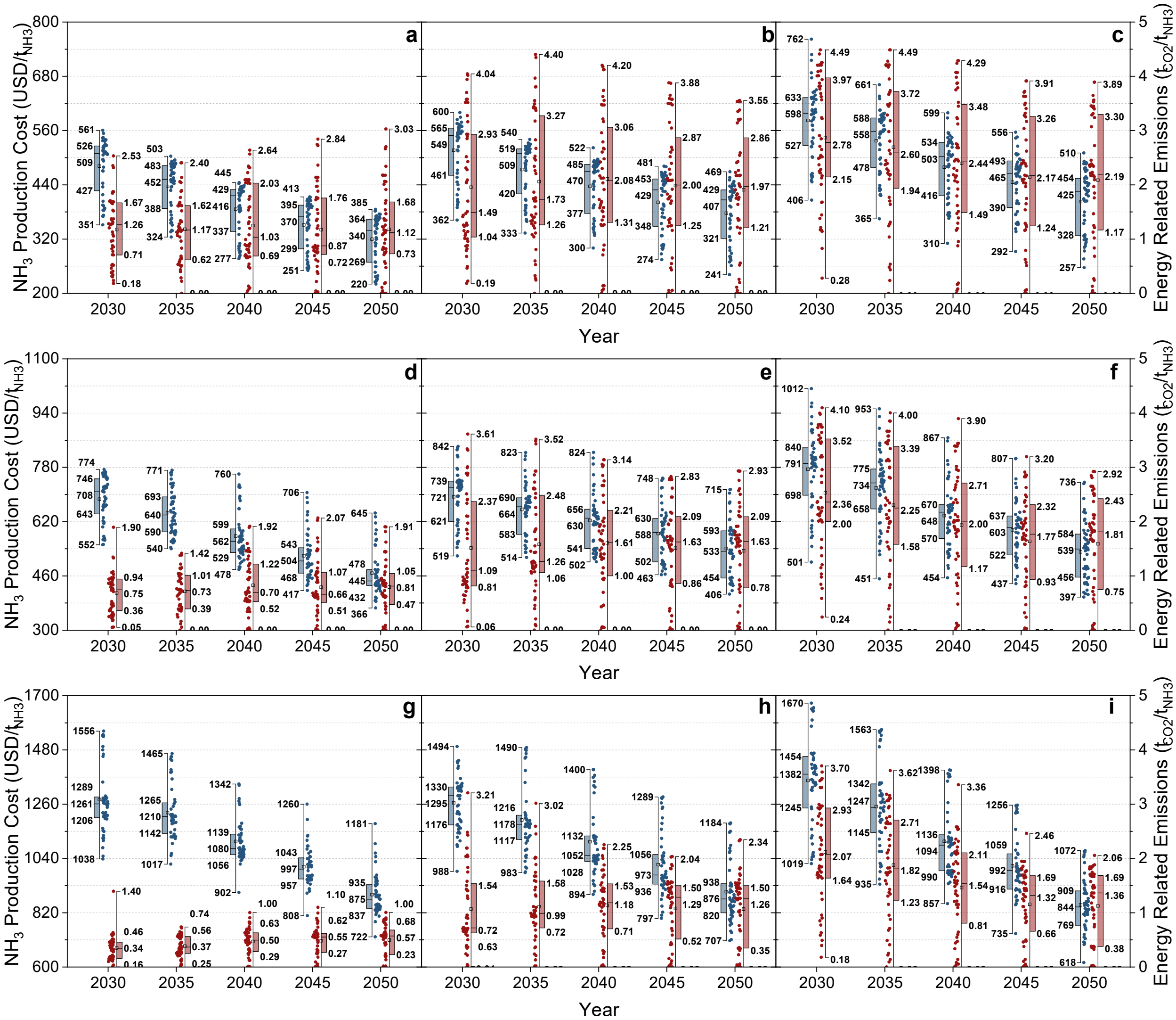

Figure 4: Cost and emissions for an inflexible electrified Haber-Bosch under different connected to the grid with 80% capacity factor and low renewable energy cost grid scenario (a), baseline grid scenario (b), and high renewable energy cost grid scenario (c). Cost and emissions for an inflexible electrified Haber-Bosch under different connected to the grid with 50% capacity factor and low renewable energy cost grid scenario (d), baseline grid scenario (e), and high renewable energy cost grid scenario (f). Cost and emissions for an inflexible electrified Haber-Bosch under different connected to the grid with 20% capacity factor and low renewable energy cost grid scenario (g), baseline grid scenario (h), and high renewable energy cost grid scenario (i). Assumed hydrogen storage cost of 50 USD/kg.

operating at a 50% capacity factor (Figure 4d), and 1.2 t_{CO_2}/t_{NH_3} for a hydrogen electrolyzer operating at a 20% capacity factor (Figure 4g).

Our results indicate a clear trend: as the capacity factor of the system decreases, the energy-associated emissions significantly diminish while the cost of green ammonia increases. This is an important consideration, as it suggests a potential trade-off between operating costs and emissions reduction. In all renewable energy cost grid scenarios, operating a hydrogen electrolyzer at lower capacity factors resulted in lower emissions but higher ammonia production costs, which is attributed primarily to the costs associated with hydrogen storage. Our results suggest that decreasing the cost of hydrogen storage to capital costs under 50 USD/kg_{H_2} is essential for these systems to be viable. Without reducing the hydrogen storage cost, reducing the emissions from the electrified Haber-Bosch process directly coupled with the grid would result in ammonia production costs in the thousands of dollars per ton. However, if hydrogen storage costs are reduced through the deployment of new technologies or by using geological storage, the levelized cost of green ammonia can reach values under 700 USD/t_{NH_3} and emissions close to 0.2 t_{CO_2}/t_{NH_3}. However, the use of geological hydrogen storage would limit the location where green ammonia production can be implemented. Finally, there is a significant spread in costs between the states that have successfully implemented renewable electricity production on a large scale and states that have failed to implement renewable electricity production on a large scale, indicating that certain geographical areas could achieve substantial environmental benefits from the implementation of these systems.

Our analysis of various operational scenarios and renewable energy development pathways reveals a complex interplay between cost, emissions, and operational flexibility that will shape the viability of these systems. While continuous operation under current technologies presents challenges in terms of emissions and cost, particularly in scenarios with higher renewable energy costs, the exploration of flexible operational strategies offers a pathway to reduce emissions and potentially manage costs more effectively. The deployment of technologies enabling operational flexibility in Haber-Bosch systems through the integration of flexible hydrogen electrolyzers with hydrogen storage emerges as a

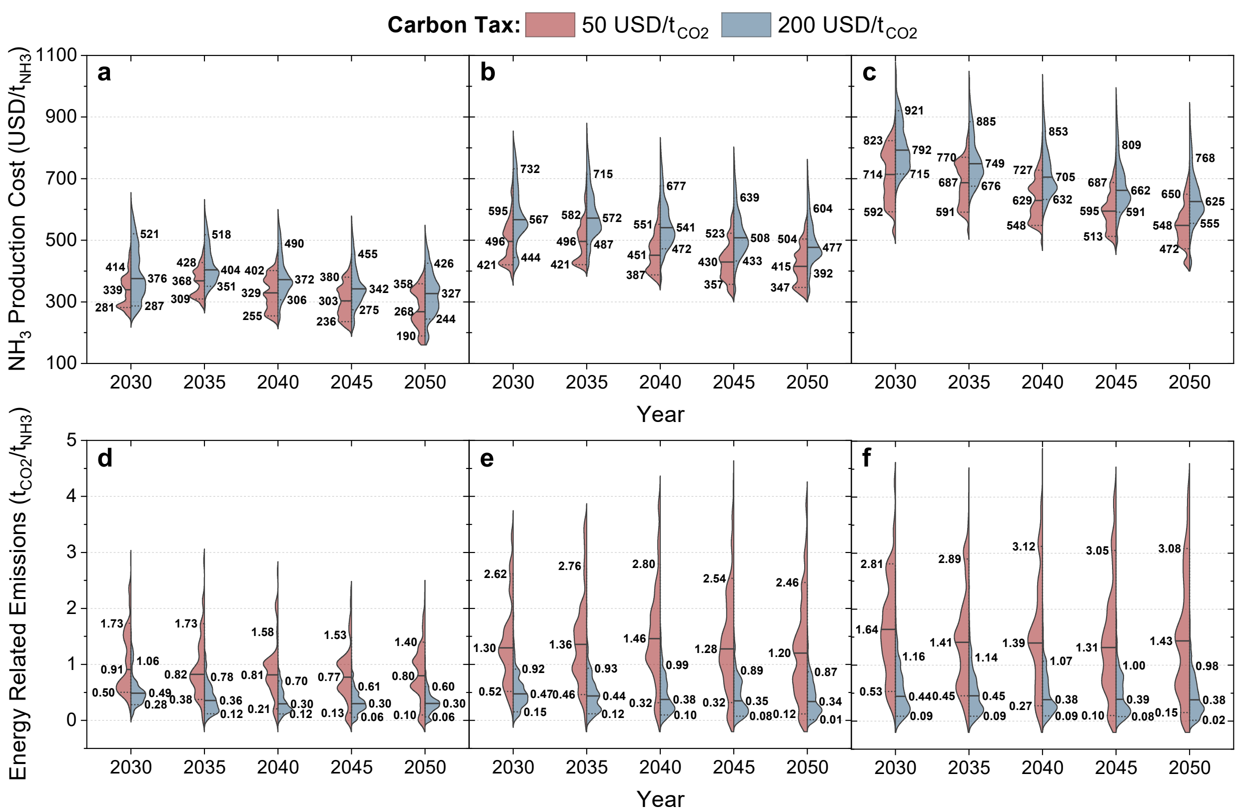

Figure 5: Production cost for an electrified Haber-Bosch coupled with the grid with additional on-site renewable energy generation under low renewable energy cost grid scenario (a), baseline grid scenario (b), and high renewable energy cost grid scenario (c). Energy-associated emissions for an electrified Haber-Bosch coupled with the grid with additional on-site renewable energy generation under low renewable energy cost grid scenario (d), baseline grid scenario (e), and high renewable energy cost grid scenario (f).

critical factor in aligning ammonia production with the objectives of a low-carbon economy. Our findings underscore the importance of advancing technological innovation and reducing the costs associated with hydrogen storage to make low-emission ammonia production economically feasible. Additionally, the variability in potential costs and emissions across different states highlights the need for approaches that consider the spatial distribution of costs like the one applied in this paper.

An alternative approach that can help reduce the emissions and costs of grid-connected systems while still offering a stable supply of ammonia is the addition of on-site variable renewable electricity capacity supplemented by grid electricity when needed (Figure 5).

We consider three renewable energy development scenarios for electricity production and projections of grid prices and emissions (Figure 5). Then, we optimize the sizing of the on-site renewable energy production systems for different carbon taxes to reduce costs and emissions. An increase in the carbon tax leads to increased on-site renewable capacity, leading to lower energy-associated emissions and higher costs.

A transition from a carbon tax of 50 USD/t$_{CO_2}$ to a carbon tax of 200 USD/t$_{CO_2}$ leads to an increase in the median green ammonia production costs with onsite renewable capacity. In the case of low renewable energy prices, the median production cost of green ammonia in 2050 is 268 USD/t$_{NH_3}$ for a carbon tax of 50 USD/t$_{CO_2}$ and 327 USD/t$_{NH_3}$ for a carbon tax of 200 USD/t$_{CO_2}$ (Figure 5a). In the case of average renewable energy prices, the median production cost of green ammonia in 2050 is 415 USD/t$_{NH_3}$ for a carbon tax of 50 USD/t$_{CO_2}$ and 477 USD/t$_{NH_3}$ for a carbon tax of 200 USD/t$_{CO_2}$ (Figure 5b). In the case of high renewable energy prices, the median production cost of green ammonia in 2050 is 548 USD/t$_{NH_3}$ for a carbon tax of 50 USD/t$_{CO_2}$ and 625 USD/t$_{NH_3}$ for a carbon tax of 200 USD/t$_{CO_2}$ (Figure 5c).

A transition from a carbon tax of 50 USD/t$_{CO_2}$ to a carbon tax of 200 USD/t$_{CO_2}$ leads to a reduction in the median green ammonia energy-associated emissions of around 70%. In the case of low renewable energy prices, the median energy-associated emissions for green ammonia in 2050 are 0.8 t$_{CO_2}$/t$_{NH_3}$ for a carbon tax of 50 USD/t$_{CO_2}$ and 0.3 t$_{CO_2}$/t$_{NH_3}$ for a carbon tax of 200 USD/t$_{CO_2}$ (Figure 5d). In the case of average renewable energy prices, the median energy-associated emissions for green ammonia in 2050 are 1.2 t$_{CO_2}$/t$_{NH_3}$ for a carbon tax of 50 USD/t$_{CO_2}$ and 0.34 t$_{CO_2}$/t$_{NH_3}$ for a carbon tax of 200 USD/t$_{CO_2}$ (Figure 5e). In the case of high renewable energy prices, the median energy-associated emissions for green ammonia in 2050 are 1.43 t$_{CO_2}$/t$_{NH_3}$ for a carbon tax of 50 USD/t$_{CO_2}$ and 0.38 t$_{CO_2}$/t$_{NH_3}$ for a carbon tax of 200 USD/t$_{CO_2}$ (Figure 5f).

Our analysis highlights the pivotal role of integrating on-site renewable energy sources with grid electricity in achieving a more sustainable and economically viable production of green ammonia. Additionally, higher carbon taxes incentivize the expansion of on-site renewable energy capacity, which, while marginally increasing production costs, significantly lowers energy-associated emissions of green ammonia.

Technology comparison, deployment, and policy considerations

The interplay between policy mechanisms, such as carbon taxation, and technological advancements is essential to understanding the deployment of future technologies for the decarbonization of the ammonia production industry.

In the low natural gas price scenario, blue ammonia stands out as the most economically viable option, provided there is a carbon tax in place to narrow the cost differential with gray ammonia. This pricing dynamic assumes that a financial mechanism, specifically a carbon tax, is applied to make up for the cost discrepancies between blue and gray ammonia, with the former incorporating carbon capture and storage technologies to reduce its environmental impact.

Under scenarios of sustained low natural gas prices, green ammonia, despite its environmentally friendly production process that involves zero carbon emissions, fails to rival blue ammonia in terms of cost competitiveness. This situation underscores the challenge green ammonia faces in becoming a cost-effective alternative under current economic conditions.

The advantage of blue ammonia in terms of cost-efficiency is heavily contingent upon the carbon tax staying above a threshold of 50 USD per ton of CO2. This detail underscores the significant role that policy measures, such as carbon pricing, play in shaping the competitive landscape of ammonia production. It highlights how, through strategic fiscal policies, the adoption of cleaner energy alternatives can be economically incentivized, ensuring that blue ammonia remains an attractive option for stakeholders looking to minimize their carbon footprint without incurring prohibitive costs.

In the reference natural gas scenario, blue ammonia is the most competitive option until 2045. In 2050 only 15% of locations for green ammonia in the most progressive

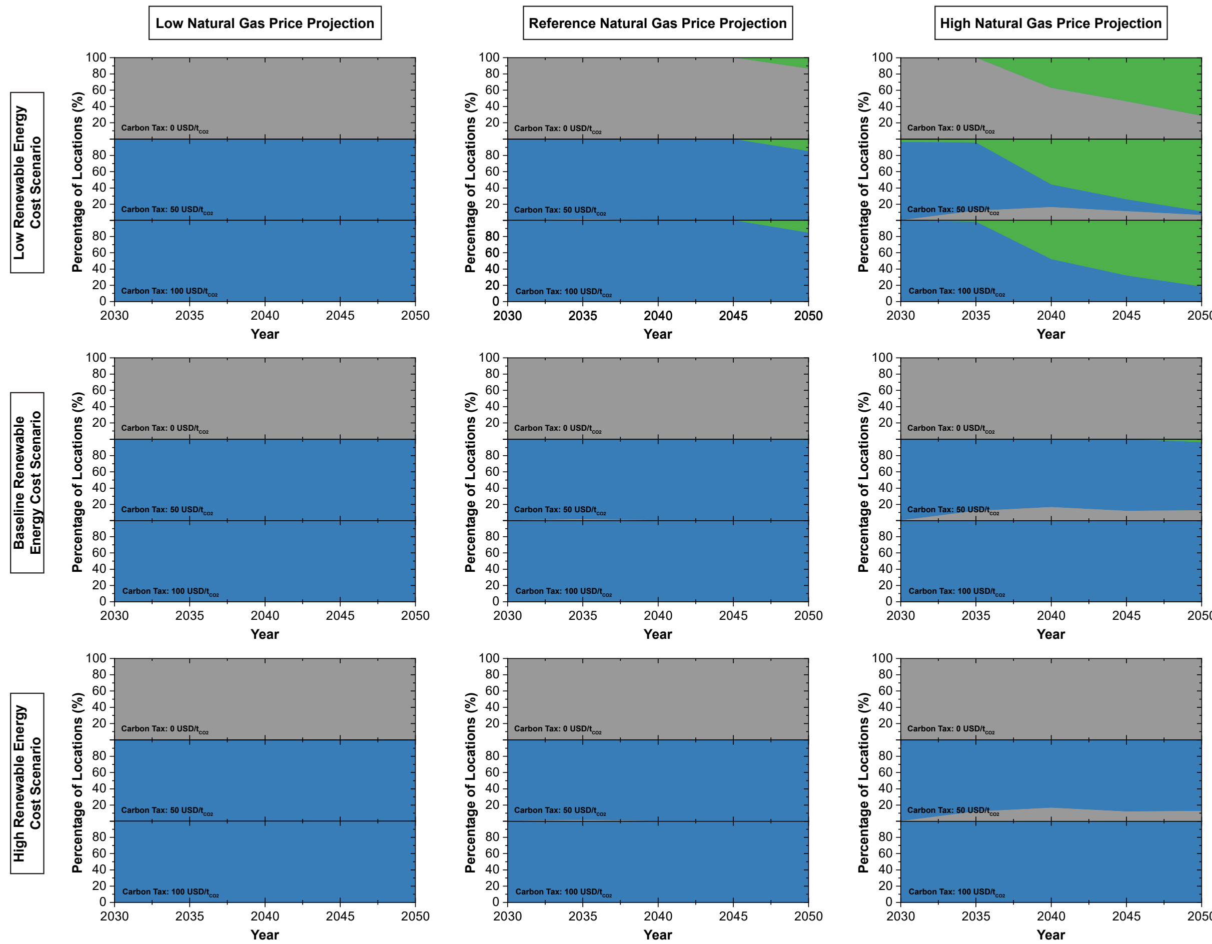

Figure 6: Ammonia price projections for gray, blue, and green ammonia under different technology development, market, and policy scenarios.

scenario are the most cost-effective option.

A carbon tax serves as a critical tool to incentivize decarbonization. At a carbon tax of 50 USD/t_{CO_2}, the economic landscape begins to tilt slightly, making blue and gray ammonia's cost almost equivalent. This highlights the sensitivity of ammonia production costs to policy interventions, indicating that even modest carbon pricing can influence the competitive balance between different production pathways.

As the carbon tax escalates to 50 USD/t_{CO_2} and then to 100 USD/t_{CO_2}, the dynamics between gray and green ammonia undergo noticeable changes. There is an increase in locations where green ammonia becomes more cost-effective than gray ammonia, underlying the potential of aggressive carbon pricing to catalyze a transition towards green ammonia production over gray ammonia production. By 2050, with a carbon tax of 200 USD/t_{CO_2}, green ammonia's competitiveness in most locations suggests a tipping point where renewable energy integration within industrial processes could become the preferred method over gray ammonia.

On the other hand, as the carbon tax escalates to 100 USD/t_{CO_2} and then to 200 USD/t_{CO_2}, the dynamics between blue and green ammonia undergo marginal changes. Despite this, a noticeable shift begins to materialize. By 2045, only the best locations for green ammonia in the most progressive scenario are more cost-effective than blue and gray ammonia, marking a pivotal moment in the industry's evolution. By 2050, around 15% of the locations for green ammonia emerge as the most cost-effective option, highlighting a significant transition towards electrification in the ammonia production industry. This trend underscores the increasing viability and competitiveness of green ammonia, especially in regions with abundant renewable energy resources, as a crucial component in the global shift towards decarbonization.

For high natural gas prices, green ammonia emerges as a more viable competitor to blue ammonia exclusively under the most progressive scenarios and in certain locations. By 2040, between 40% and 50% of the locations result in competitive green ammonia. Finally, by 2050, between 70% and 90% of the locations result in competitive green ammonia.

The gradual shift towards green ammonia underscores a broader transition within the energy landscape in the United States, heavily influenced by technological advancements, regulatory changes, and evolving market dynamics. The initial slow uptake of green ammonia is attributed to the uncertainty and early stage of development of relevant technologies and the need for substantial infrastructure investments. However, as renewable energy sources and water electrolysis become more abundant and cost-effective the scale tips in favor of green ammonia. Furthermore, the geographical variability in competitiveness underscores the impact of resource availability in determining the feasibility of green versus blue ammonia.

Under the most optimistic scenario, if natural gas prices rise while the costs of renewable energy sources and water electrolysis fall, electrification can play a pivotal role in the transition towards a low-carbon economy. This transition is particularly significant in sectors notoriously difficult to decarbonize, such as agriculture.

Discussion

The economic viability of gray, blue, and green ammonia depends on the costs of PEM electrolysis, renewable electricity, natural gas, and CO_2. Our analysis identifies two possible pathways for the decarbonization of ammonia production, contingent upon evolving market dynamics for natural gas and renewable energy resources.

1) Blue ammonia is the most cost-effective alternative for the low and reference natural gas scenarios, regardless of the state of development of renewable electricity and green ammonia. For blue ammonia to remain the most cost-competitive option, further improvements in the capture rate, cost, and scale of CCS are necessary. Achieving higher capture rates will ensure more carbon emissions are sequestered, enhancing the environmental benefits of blue ammonia over gray ammonia. Additionally, reducing the costs associated with CCS technologies will make blue ammonia production more economically viable, encouraging broader industry adoption. Furthermore, to bridge the cost gap with gray ammonia and promote a more competitive landscape for blue ammonia, the introduction of a carbon tax near 50 USD per ton is essential. This carbon tax would make blue ammonia more competitive and incentivize the reduction of greenhouse gas emissions across the board, fostering a more competitive market and accelerating the transition towards cleaner energy solutions.

2) Green ammonia is the most cost-competitive alternative for the high-price natural gas scenario and advanced projections for the cost of renewable electricity and water

electrolysis. In this context, green ammonia becomes the leading cost-competitive option after 2040, although only in specific locations. This pathway requires a significant decrease in renewable electricity and water electrolysis costs over the following decades; therefore, potentially positioning green ammonia as an economically feasible choice in strategically advantaged markets. Interestingly, under these conditions, green ammonia remains the most cost-competitive option regardless of the carbon tax. Our findings suggest that, given the high natural gas price scenario and advanced projections for the cost of renewable electricity and water electrolysis, the implementation of a carbon tax will no longer be necessary after 2040 to bridge the cost gap between green and gray ammonia. This outcome underscores the importance of continued technological advancements and cost reductions in renewable energy and electrolysis processes. In essence, green ammonia holds the potential to become the most economically viable solution in a future characterized by high natural gas prices and advanced renewable technologies, provided that these technological and economic conditions are met.

The competitiveness between green and blue ammonia is profoundly influenced by the structure of the energy markets in which production plants operate. This is particularly evident in the U.S., where there is a complex mix of regulated and deregulated electricity markets. In deregulated markets, the dynamics are notably favorable for green ammonia producers. These markets often provide opportunities for significant cost savings through on-site electricity generation. Producers can take advantage of more favorable rates for excess electricity sold back to the grid, which can lower the overall cost of production. This is largely due to market-driven pricing mechanisms that allow producers to benefit from peak electricity prices, thereby improving their economic viability.[33]

Conversely, in regulated markets, the scenario is less advantageous for on-site electricity generation. These markets typically offer less attractive buy-back rates for excess electricity, often basing these rates on the avoided cost rather than the higher market rates found in deregulated environments. This can diminish the economic incentives for green ammonia production, making blue ammonia, which relies on more conventional energy sources, comparatively more competitive.[33]

Our findings indicate that deregulated electricity markets play a crucial role in the adoption of green ammonia production (Figure S4). Shifting from regulated to deregulated markets reduces both ammonia production costs and energy-related emissions, leading to lower overall levelized costs of ammonia. This transition is particularly effective when the costs of renewable electricity are low, as on-site electricity tends to be cheaper than the average grid electricity price.

Additionally, several other factors significantly impact the feasibility and competitiveness of on-site electricity generation for green ammonia production. The role of renewable energy sources is crucial; regions with abundant renewable resources can offer lower-cost and more sustainable electricity options, which are vital for green ammonia plants. Market design also plays a critical role. Well-designed markets that support renewable integration and provide clear signals for investment in clean technologies enhance the viability of green ammonia. Lastly, the behavior of electric utilities, including their willingness to support renewable projects and offer favorable terms for grid integration, can substantially influence the competitiveness of green ammonia production.[34,35]

Need for a carbon Tax

The current price competitiveness of blue and green ammonia underscores the importance of supportive regulatory frameworks, such as carbon pricing, for facilitating the transition to decarbonized and electrified chemical processes. These frameworks are crucial for enabling research and development, providing subsidies for renewable energy, and offering incentives for adopting emerging technologies. Supportive regulatory frameworks play a pivotal role in reducing the economic barriers associated with the adoption of green technologies. By implementing carbon pricing mechanisms, governments can create a financial disincentive for CO_2 emissions, thus making sustainable practices more economically attractive. Carbon pricing can take various forms, including carbon taxes or cap-and-trade systems, both designed to internalize the environmental costs of carbon emissions. This financial pressure encourages industries to innovate and adopt cleaner technologies, thereby reducing their carbon footprint.

Effective regulation ensures that laboratory-scale processes are scalable and economically viable at industrial levels, which is vital for heavy industries like ammonia production. Well-structured regulatory policies can significantly advance the research, development, and adoption of new technologies, thereby reducing production costs and enhancing cost competitiveness, as illustrated in recent studies.[36,37] For instance, subsidies for renewable energy sources, such as wind and solar power, can lower the input costs for green ammonia production, making it more competitive with traditional fossil fuel-based blue ammonia. Similarly, these frameworks have been shown to have a considerable impact on promoting long-term sustainable industrial practices.[38,39]

The success of carbon taxes in the context of ammonia production ultimately depends on their ability to make the costs associated with CO_2 emissions exceed those of adopting environmentally sustainable practices. For carbon taxes to be effective, they must be set at a level that creates a substantial economic burden for carbon emissions, thereby incentivizing industries to reduce their carbon output. This can lead to increased adoption of green and blue ammonia production methods, which, while initially more expensive, become more viable as carbon taxes raise the cost of gray ammonia production.

Furthermore, it is important to acknowledge the limitations of using carbon taxes, such as carbon leakage, where production could relocate to regions with more lenient emissions standards, resulting in a 'leakage' of between 5% and 40% of emissions.[40] Carbon leakage undermines the environmental benefits of carbon taxes, as it merely shifts emissions from one region to another without reducing the overall global carbon footprint. Approaches to limit leakages, such as emissions allowances to energy-intensive, trade-exposed industries and tax rebates based on a firm's output, exist, and policymakers should consider such approaches when considering carbon taxes. Tax rebates can be structured to reward firms that reduce their emissions intensity, thereby aligning economic incentives with environmental goals.[40] Additionally, international cooperation and harmonization of carbon pricing policies can help reduce the risk of carbon leakage by ensuring that firms face similar carbon costs across different regions.

Beyond the discussion of carbon taxes, putting a price on carbon can also be achieved through coupled and nested approaches such as corporate goal setting and participation in offset markets. Ammonia producers, for instance, can engage in corporate carbon target setting with the guidance of the Science Based Targets Initiative (SBTI). The SBTI assists firms in setting scientifically grounded goals to reduce emissions in alignment with the 2015 Paris Accord. These targets are tailored to each firm and monitored by the SBTI, which tracks and reports on progress. By participating in this voluntary program, companies can demonstrate their commitment to reducing carbon pollution and gain recognition for their efforts. The program effectively monetizes the reduction of carbon emissions, providing financial and reputational rewards for companies that meet their targets.[41]

In addition to setting corporate carbon targets, ammonia producers can participate in carbon offset markets and renewable energy credit (REC) markets. Engaging in these markets allows companies to create and trade carbon offsets and RECs, offering economic incentives to reduce their emissions.[42] This participation helps companies meet their emission reduction goals and supports the broader transition to renewable energy. By purchasing carbon offsets, companies can compensate for their emissions by funding projects that reduce or remove carbon from the atmosphere, such as reforestation or renewable energy projects. Similarly, RECs represent proof that a company has purchased a specific amount of renewable energy, further encouraging the shift toward sustainable energy sources.[41,43] These market-based approaches provide flexible, economically viable pathways for companies to achieve significant emissions reductions while contributing to global climate goals.

The interplay between supportive regulatory frameworks, effective carbon pricing mechanisms, and measures to prevent carbon leakage is essential for the successful transition to sustainable ammonia production. These elements work together to create an environment where green and blue ammonia can compete with gray ammonia on both economic and environmental fronts, paving the way for a more sustainable future in heavy industries.

Regional resource availability

The feasibility and economic viability of blue and green ammonia production are significantly influenced by the regional availability of natural resources, particularly natural gas and renewable energy sources. The geographical distribution of these resources affects both the cost and sustainability of ammonia production processes.

Natural gas, the primary feedstock for the traditional Haber-Bosch process, plays a crucial role in gray and blue ammonia production. Regions with abundant and inexpensive natural gas reserves can produce ammonia at lower costs, making gray and blue ammonia more competitive. For example, in areas such as the Gulf Coast of the United States, the Middle East, and Russia, natural gas prices are relatively low due to local abundance and established extraction infrastructure. These regions are well-positioned to capitalize on blue ammonia production, provided that carbon capture and sequestration (CCS) technologies are effectively integrated and supported by policy frameworks such as carbon taxes.

In contrast, the production of green ammonia relies heavily on the availability and cost of renewable energy sources, particularly wind and solar power, which drive the electrolysis of water to produce hydrogen. Regions with high renewable energy potential, such as the southwestern United States, parts of Europe, and Australia, can leverage their natural advantages to produce green ammonia cost-effectively. These areas benefit from abundant sunlight and wind, which can reduce the overall cost of electricity and, consequently, the cost of hydrogen production through electrolysis.

Water availability is another critical factor, especially for green ammonia production, which requires significant quantities of water for electrolysis. Regions with abundant freshwater supplies or access to seawater desalination facilities can support large-scale hydrogen production. Coastal regions with desalination infrastructure are particularly well-suited for green ammonia production, given their ability to secure a stable water supply.

Existing infrastructure for natural gas transportation and renewable energy integration also plays a significant role in determining the feasibility of blue and green ammonia production. Regions with well-developed natural gas pipelines, storage facilities, and renewable energy grids can more readily adopt these technologies. For instance, the European Union's extensive natural gas network and its commitment to expanding renewable energy capacity position it as a potential leader in both blue and green ammonia production.

Water electrolysis scaling

Scaling up Proton Exchange Membrane (PEM) hydrogen electrolysis to the levels required for large-scale green ammonia production presents several significant challenges. One of the primary technical barriers is the durability and longevity of PEM electrolyzers. These systems operate under highly acidic conditions, leading to corrosion and degradation of the cell materials over time. To make large-scale deployment feasible, it is crucial to develop more durable materials and improve the overall lifespan of electrolyzers. Advances in membrane technology and the development of more resilient catalysts are necessary to enhance the long-term performance and cost-effectiveness of these systems.

Economic factors also play a critical role in the scalability of green hydrogen production. The high capital costs associated with PEM electrolyzers, driven by expensive materials like platinum group metal catalysts, present a significant hurdle. Scaling up production to meet the demands of green ammonia will require substantial investments and economies of scale. Additionally, the operational costs, particularly the cost of electricity, are a major concern. For green hydrogen to be economically viable, it must be produced using low-cost renewable electricity, necessitating significant investments in renewable energy infrastructure.

Infrastructural challenges further complicate the scaling of green hydrogen. The current manufacturing capacity for PEM electrolyzers is insufficient to meet the projected demand for large-scale ammonia production. Expanding manufacturing facilities, developing robust supply chains, and ensuring the availability of raw materials are essential steps. Furthermore, integrating PEM electrolyzers with renewable energy sources requires advanced energy management systems to handle the variability of renewable power generation. Efficient energy storage solutions and smart grid technologies are critical to ensure a stable and continuous supply of electricity to the electrolyzers.

Overall, while the potential of green hydrogen as a sustainable energy source is significant, addressing these scaling limitations is essential to achieve the levels of production needed for widespread green ammonia production.

Green hydrogen competition and scarcity

The competition for green hydrogen across various industrial applications poses significant challenges to its scalability for green ammonia production. As sectors such as steel manufacturing, chemical production, and energy storage transition towards decarbonization, they increasingly vie for the limited supply of green hydrogen, potentially impacting its availability and affordability for ammonia synthesis.

The steel industry, one of the largest industrial emitters of carbon dioxide, could adopt green hydrogen to replace coal in iron ore reduction processes. This shift aims to significantly reduce carbon emissions, making green hydrogen a critical resource for the industry. Similarly, the chemical sector relies on green hydrogen for producing low-carbon chemicals and synthetic fuels. These applications are essential for achieving broader decarbonization goals, further intensifying the competition for green hydrogen.

Additionally, green hydrogen plays a pivotal role in the energy sector as a means of storing excess renewable energy and generating electricity during periods of low renewable output. Hydrogen fuel cells and hydrogen-powered turbines are integral to balancing grid supply and demand, contributing to the stability of renewable energy systems. However, the increasing adoption of green hydrogen for energy storage and power generation exacerbates supply constraints for industrial uses like ammonia synthesis.

Addressing these challenges requires strategic allocation and robust policy support. Governments and industry stakeholders must collaborate to prioritize hydrogen use based on sector-specific decarbonization potential and economic impact. Investments in renewable energy infrastructure and electrolysis technology are crucial to expanding green hydrogen production. Policies that incentivize hydrogen production, such as subsidies, tax credits, and research grants, along with establishing hydrogen trading markets and standards, can facilitate efficient distribution and ensure green hydrogen is directed to applications with the greatest environmental benefits.

In summary, the intense competition for green hydrogen across various industries presents significant hurdles for scaling its use in ammonia production. Strategic management, substantial infrastructure investments, and supportive policy frameworks are essential to ensuring an adequate and cost-effective supply of green hydrogen, enabling it to play a critical role in the transition to a low-carbon economy.

Methods

Techno-Economic Model

The cost of ammonia production, or the levelized cost of ammonia, is a function of the discounted sum of the annual costs over the discounted sum of the yearly ammonia produced throughout the lifetime of the project. The ammonia production cost (levelized cost of ammonia) can be calculated using equation 1.

$$LCOA_{NH3} = \frac{CapEx + \sum_{t=0}^{t=lifetime} \frac{OpEx_t}{(1+d)^t}}{\sum_{t=0}^{t=lifetime} \frac{NH3_t}{(1+d)^t}} \quad (1)$$

Where CapEx is the initial capital investment, OpEx is the yearly operation costs, d is the discount rate, t is the year, and NH3$_t$ is the yearly ammonia production.

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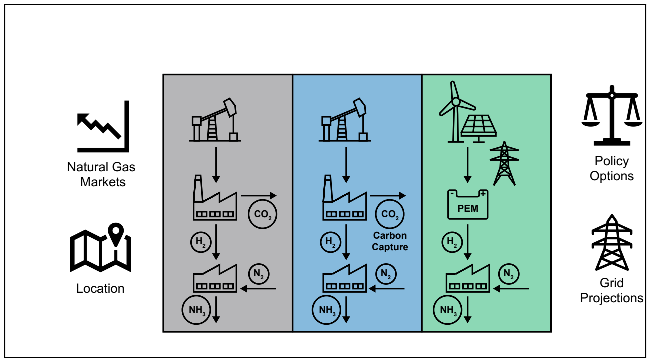
The authors declare no competing interests.

TOC Graphic



Natural Gas Markets
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