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LETTER

How are decarbonization policies in the US and Canada shaping low-carbon ammonia production strategies?

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Abstract

The US and Canada contribute to 11% (22 million tons (Mt) per year) of global ammonia production, with an additional 42 Mt of production capacity currently planned or under construction. The distinct decarbonization policies adopted by these two countries—namely production tax credits in the US and carbon taxes in Canada—lead to significantly different outcomes and implications for decarbonized ammonia production strategies. This study evaluates facility-specific production strategies for low-carbon ammonia, considering the decarbonization policies of both countries. We assess the most cost-effective strategy for low-carbon ammonia production at each facility, both with and without the influence of these policies. Our results indicate that Canada's carbon tax incentivizes the adoption of carbon capture and storage (CCS), while the US production tax credits promote the use of wind energy and biomass coupled with CCS, to produce hydrogen for ammonia synthesis. These findings highlight a dichotomy between the impacts of tax credits and carbon taxes: production tax credits facilitate the transition to low-carbon production methods, whereas carbon taxes incentivize existing facilities to upgrade with CCS technology. These insights underscore the effectiveness of tailored policy approaches and provide a comprehensive blueprint for other regions globally seeking to transition towards low-carbon ammonia production.

1. Introduction

The United States (US) and Canada have recently introduced policies to promote the decarbonization of their industries, with a strong emphasis on the production of low-carbon hydrogen [1–3]. In the US, the Inflation Reduction Act has been a key driver for low-carbon hydrogen production [4]. The Inflation Reduction Act includes the 45V and 45Q tax credits, which incentivize the production of low-carbon hydrogen and the implementation of carbon capture and storage (CCS) technologies, respectively [1, 3]. The 45V tax credit is designed to promote low-carbon hydrogen by providing up to US\$3 per kilogram for hydrogen (H_2) produced with a well-to-gate carbon intensity below 0.45 kg of carbon dioxide equivalent (CO_2e) per kg H_2 [3]. The term 'well-to-gate' refers to both direct emissions from the hydrogen production process and indirect emissions from upstream and midstream activities, such as the procurement and transport of fuels [5]. Instead, the 45Q tax credit offers US\$85 per metric ton of CO_2 (tCO_2) permanently sequestered with the capture and storage of CO_2 from carbon-intensive industrial activities, such as hydrogen production [6]. Similarly, in 2022, Canada introduced a hydrogen production tax credit offering up to 40% of investment costs for hydrogen produced with a well-to-gate carbon intensity below 0.7 kg CO_2e/kg H_2 [2]. Additionally, Canada also imposes a carbon tax on greenhouse gas emissions [7]. In 2024, the carbon tax is US\$58 per emitted tCO_2e, increasing by US\$11 every year until 2030 to US\$123/tCO_2e emitted [7].

In 2022, the US and Canada produced 11% of global ammonia (22 Mt NH_3), across 41 facilities[8]. Currently, 92% of the hydrogen used for ammonia production comes from steam methane reforming (SMR) of natural gas, while the remaining 8% is derived from coal gasification [9]. Approximately 90% of energy and carbon emissions from ammonia production are associated with hydrogen production during the Haber–Bosch process [9, 10]. The Haber–Bosch process combines hydrogen and nitrogen at high pressure and temperature to produce ammonia[9]. The development of low-carbon hydrogen policies, along with the introduction of policies offering financial incentives for low-carbon hydrogen production [1, 3], has resulted in a considerable increase in planned production capacity. Specifically, 30 facilities with a combined production capacity of 42 Mt of ammonia per year are planned in the US and Canada [11]. This positions the US and Canada as potential pioneers and major producers of low-carbon ammonia.

Previous work has analyzed different pathways to decarbonize ammonia production, including retrofitting current facilities with CCS, electrification via hydrogen production from water electrolysis, and biochemical processes that produce hydrogen from biomass [12–14]. Other research has estimated the production costs of ammonia from facilities powered by solar and wind electricity worldwide [15] and the potential for decarbonizing ammonia production by analyzing the technical feasibility and competitiveness of producing hydrogen from low-carbon electricity worldwide [16]. Based on a representative ammonia plant in Texas, the levelized cost of ammonia (LCOA)—which quantifies the average net present cost of ammonia production over the plant's lifetime—was assessed considering 45V and 45Q tax credits and CCS and electrification pathways for ammonia production [17]. Similarly, Ricks *et al* study production tax credits for low-carbon hydrogen in the US, focusing on grid-connected electrolysis systems [18]. Cheng *et al* focus on various clean hydrogen production technologies and synthetic liquid fuels by analyzing the impact of 45V and 45Q [19]. Other studies model decarbonization scenarios for the US ammonia production industry with multiple production pathways until 2050 [20]. Ueckerdt *et al* analyze the cost competitiveness of various production technologies for low-carbon hydrogen and their carbon emissions until 2050 [21]. Although these studies offer valuable insights, a more comprehensive evaluation that identifies the optimal decarbonization pathway for the ammonia industry in the US and Canada under the evolving policy landscape remains underexplored and requires further attention.

We aim to provide such a study by comparing various technological decarbonization pathways and assessing costs and emissions on a facility-by-facility basis, with consideration of the distinct decarbonization policies in the US and Canada. First, we quantify the carbon intensity and production volume of each ammonia facility in both countries. The 2022 ammonia production amount for each of the 41 facilities in the US and Canada is estimated based on a proprietary dataset of hydrogen producers [11] (supplementary dataset). Second, for each facility, we quantify the LCOA today and under potential decarbonization pathways. We assess the techno-economic feasibility of various decarbonization pathways, including CCS, biochemical processes that use biomass with and without CCS, and electrification using wind and solar [12, 13]. Finally, we determine the impact of decarbonization policies on the economic costs of each decarbonization pathway. Decarbonization policies considered are the 45V and 45Q tax credits in the US, and tax credit for low-carbon hydrogen and carbon tax in Canada. Results identify the most cost-effective strategy for low-carbon ammonia production in each facility with and without decarbonization policies. This study demonstrates how these policies influence ammonia decarbonization pathways and provides insights on cost-effective decarbonization strategies in the US, Canada and globally, offering valuable guidance for policymakers and industry stakeholders alike.

2. Results

2.1. Facility-specific carbon-intensity of ammonia

To ensure that our framework adheres to current regulations, we calculated the well-to-gate carbon intensity of ammonia for each facility (Methods: Carbon Intensity). This calculation encompasses (i) Scope 1 or direct emissions reported by each ammonia facility to the Environmental Protection Agency [22] and to the Canadian government [23], (ii) Scope 2 or indirect emissions from electricity use, and (iii) upstream emissions, from leakages in natural gas transportation—commonly referred to as partial Scope 3 [5]. We excluded embedded life cycle emissions, such as those from the production of materials for the construction of a facility, in line with existing regulatory frameworks in the US and Canada [2, 3, 5]. However, we discuss the impact of including these emissions in the section 'Cost-optimal decarbonization pathway'.

Figure 1 categorizes the US and Canadian ammonia production facilities based on their location, production volumes, and their corresponding carbon intensities in 2022. Figure 1(a) shows that three facilities located in North Dakota, Oklahoma, and Nebraska, collectively contributing to 8% of ammonia production in the US, rely on coal as their primary feedstock for ammonia production. These facilities exhibit carbon intensities exceeding 3.2 tCO_2/tNH_3—the minimum carbon intensity that coal-based ammonia production can achieve using

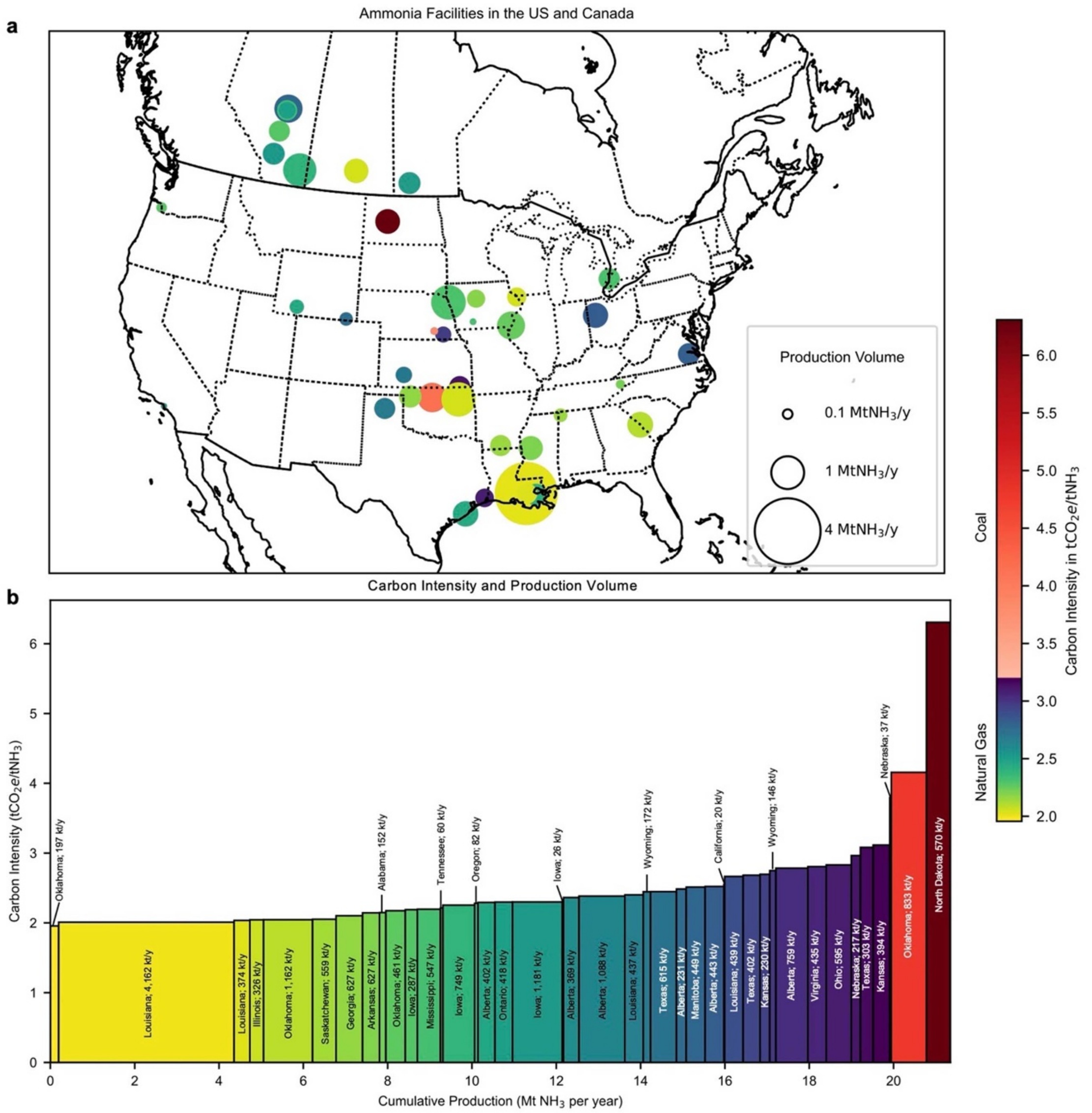

Figure 1. Carbon intensity and estimated production volume of ammonia facilities in the US and Canada. (a) Geographic overview of all ammonia production facilities. Each circle represents one facility and its annual ammonia production volume in $MtNH_3/y$. The color indicates the carbon intensity in tCO_2e/tNH_3. (b) Displays the carbon intensity for each facility, ranking facilities from highest to lowest carbon intensity along with their estimated production capacity in $MtNH_3/y$.

the best available technology [9]. Conversely, all other 38 facilities utilize natural gas as feedstock for ammonia production and have a carbon intensity between 1.96 and 3.07 tCO_2e/tNH_3 (figure 1(a)). Figure 1(b) ranks facilities in the US and Canada by carbon intensity, from highest to lowest, and includes their production volumes.

2.2. LCOA across various production pathways

We calculated the LCOA for each facility and decarbonization pathway by dividing the cumulative capital and operating expenses (CAPEX and OPEX) over a 30 year lifetime by the total amount of ammonia produced by each facility during that period. We assumed that each facility would maintain its 2022 annual ammonia production volume, regardless of the production pathway.

Figure 2(a) shows the business-as-usual (BAU) LCOA for each ammonia production facility. Here, BAU assumes that existing ammonia facilities maintain their operational practices and production techniques that are currently standard across the industry, based on 2022 ammonia production data. With a median production cost of US$236 per tNH_3, the BAU pathway serves as a benchmark. We considered state-specific natural gas prices for 2013–2023 showing how natural gas prices vary greatly between states, affecting LCOA (figure 2(a)). The facility with the lowest production cost, located in Saskatchewan, Canada, produces ammonia at US$178 per tNH_3 (figure 2(a)). In stark contrast, a facility in California

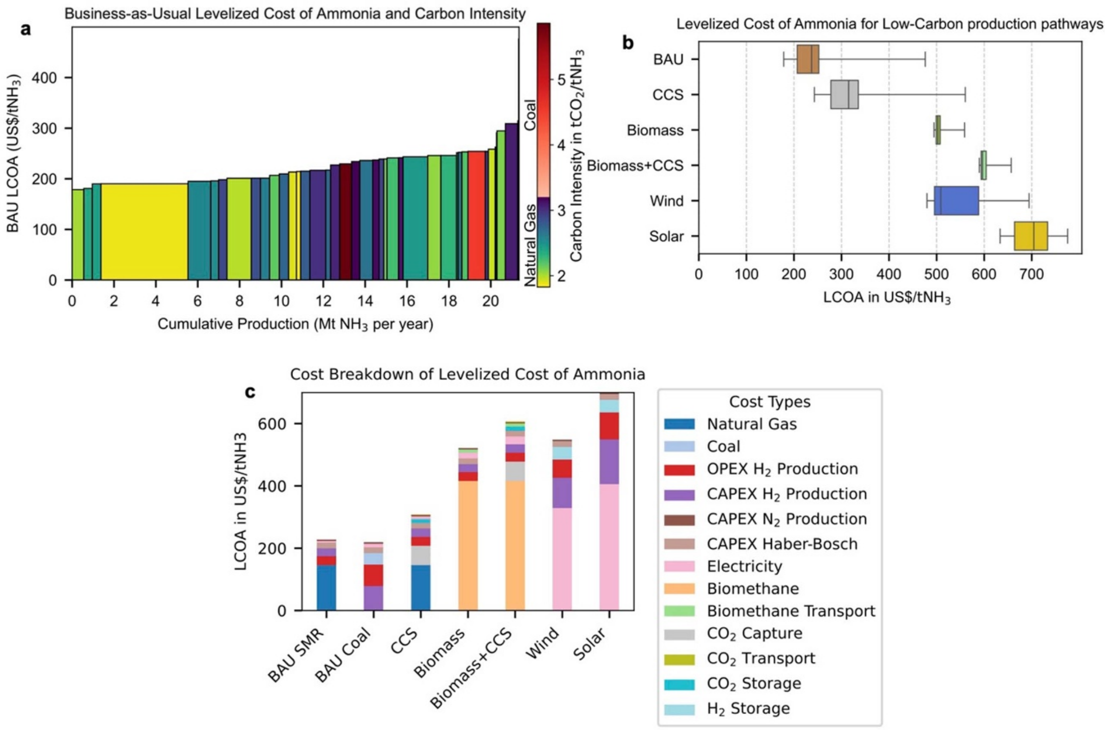

Figure 2. Levelized cost of ammonia (LCOA) across various production pathways. (a) LCOA in US dollars per metric ton of ammonia (US\$/tNH$_3$) over the cumulative production volume measured in million metric tons of ammonia per year (MtNH$_3$/y). The bars are color-coded to represent different carbon intensity levels in tons of CO$_2$ per ton of NH$_3$. The facilities are ranked from lowest LCOA to highest. (b) LCOA for each production pathway. Every box plot shows LCOA distribution among the 41 ammonia facilities considered in this study in the US and Canada. Box plots show the median, 25%, and 75% quartiles, and the minimum and maximum for each production pathway. (c) Comparative analysis of the average LCOA across all production pathways, with cost categorized into different components including feedstock, operation, capital expenses, transport and storage. Each color in the stacked bars represents a different cost component, providing a distinction of the cost structure associated with each ammonia production method. This figure does not include the impact of any decarbonization policies on LCOA.

registers the highest production cost of US\$476 per tNH$_3$, showcasing the wide variability in LCOA (figure 2(a)). California's LCOA can be attributed to high natural gas prices, which were ~80% higher than the average natural gas price in the US in 2013–2023 [24]. Louisiana and Texas had approximately 15% lower natural gas prices than the US average over the 2013–2023 period [24], resulting in ammonia with the lowest LCOA (figure 2(a)).

Figure 2(b) shows various pathways for ammonia production, comparing their LCOA to BAU. In the CCS pathway, costs increase by 33% compared to BAU, with a median cost of US\$315 per tNH$_3$ (figure 2(b)). The biomass pathway shows a substantial cost increase of 113% compared to BAU and 71% compared to CCS, with a median cost of US\$502 per tNH$_3$ (figure 2(b)). In particular, the cost of biomethane production from biomass significantly increases the LCOA (figure 2(c)). Combining biomass with CCS further increases costs by 19% compared to the biomass-only pathway (figure 2(b)). Our results align with the literature, as other studies found the production costs for biomass around US\$550 per tNH$_3$ [25] and between US\$430-US\$1418 per tNH$_3$ [26]. Wind-powered electrification varies in cost depending on regional wind resources, with a median cost of US\$508 per tNH$_3$ (figure 2(b)). Solar-powered electrification is the most expensive option, with a median cost of US\$704 per tNH$_3$, 197% higher than BAU (figure 2(b)). There is a broad range of LCOA due to factors like variable feedstock (natural gas, electricity and biomass) prices and diverse technological efficiencies that impact costs (figures 2(b) and (c)). Geographic location plays a significant role in the final LCOA, as regions differ in renewable resource availability and feedstock costs.

Figure 2(c) offers a breakdown of cost components for each production pathway. In most ammonia production pathways, the primary cost driver is the feedstock used for hydrogen production (figure 2(c)). However, BAU using coal has significantly lower feedstock costs but higher CAPEX and OPEX for hydrogen production (figure 2(c)). In the BAU with SMR pathway, natural gas accounts for 64% of costs, while in the CCS pathway, it contributes to 48% of costs (figure 2(c)). Biomethane costs are substantial in the biomass and biomass with CCS pathways, contributing to 80% and 69% of the total LCOA, respectively (figure 2(c)). Electricity accounts for 60% and 58% of the LCOA for wind and solar, respectively (figure 2(c)). In these pathways, where electricity powers hydrogen production via water electrolysis, costs differ due to variations in the capacity factors of wind and solar energy sources. The higher capacity factor of wind power compared to solar results in lower electricity costs, leading to an approximate total cost reduction of $151 per tNH_3 in the US and Canada when compared to solar-powered electrolysis (figure 2(c)).

2.3. Impact of policies on decarbonization costs

Based on 2013–2023 historical natural gas prices, the BAU scenario has the lowest LCOA, and it is the most cost-effective ammonia production pathway (figure 2(b)). However, the urgency to address climate change requires transformative measures in ammonia production [27]. To stay competitive in global markets, US and Canadian operators need to embrace low-carbon ammonia production strategies. This is paramount with importing regions like Europe enacting strict regulations on hydrogen and ammonia carbon intensity [28], setting a standard that industries must meet to maintain competitiveness. New legislation can function as a catalyst for this transformative shift in production methods.

Figure 3(a) shows LCOA under current US legislation. According to the 45V incentive, electrolytic pathways powered by wind and solar, and biomass with CCS qualify for the highest tax credit of US$3/$kgH_2$. Except for biomass, all low-carbon production pathways are more cost-effective than the BAU approach considering current tax credits (figure 3(a)). The CCS pathway shows a significant reduction in production costs, with a median cost of US$143/$tNH_3$, less than half of BAU production costs. Biomass alone is the most expensive option at US$397/$tNH_3$, whereas biomass + CCS, leveraging the full tax credit, costs US$73/$tNH_3$. Wind-based production has a negative LCOA at US$0.80/$tNH_3$ due to substantial tax credits under the 45V, while solar-based production has a median cost of US$150/$tNH_3$. Therefore, the 45V incentive greatly reduces costs for biomass + CCS and electrolysis (wind and solar) by 88%, 100%, and 79%, respectively (figure 3(a)). Both CCS and biomass + CCS pathways benefit from the 45V and 45Q incentives, with biomass + CCS receiving the most from the US$3/$kgH_2$ 45V tax credit, while CCS is more competitive with the 45Q, qualifying for a US$1/$kgH_2$ subsidy when capturing more than 95% of CO_2e emissions (figure 3(a)).

In addition to a tax credit, Canada has also introduced a carbon tax. Their emissions accounting includes Scope 1, Scope 2, and some Scope 3 emissions, such as those from transporting natural gas, but excludes Scope 3 emissions from technology manufacturing, resulting in zero emissions for solar and wind electrolysis. Figure 3(b) shows the impact of Canada's carbon tax policy on the LCOA for each production pathway, under three scenarios, namely with and without carbon taxes, and with Canadian tax credits for low-carbon hydrogen. The CCS pathway is cheaper than BAU in Canada, with a median LCOA of US$288/$tNH_3$ with carbon taxes and US$226/$tNH_3$ with tax credits, illustrating the impact carbon taxes and tax credits can have on decarbonization strategies. However, Canadian facilities receive significantly less tax credits compared to the US. The CCS pathway is 55% more expensive in Canada than in the US, and the cheapest electrification pathway in Canada (wind) is over four times more expensive than the most expensive pathway in the US (solar).

2.4. Cost-optimal decarbonization pathway

Policy interventions significantly reshape the landscape of cost-optimal decarbonization pathways in the US and Canada. Currently, decarbonization policies focus on well-to-gate emissions or partial Scope 3 emissions. However, future policies might encompass all emissions throughout the hydrogen and ammonia supply chains, including those from the manufacturing of machinery and materials (Scope 3 embedded technology emissions). Incorporating these full Scope 3 emissions substantially impacts the evaluation of wind and solar pathways, given the significant infrastructure required to power large-scale ammonia plants with renewables (supplementary table 1). Our results illustrate the cost-optimal ammonia production pathway without decarbonization policies (figure 4(a)); with decarbonization policies and partial Scope 3 emissions (figure 4(b)); and with decarbonization policies and full Scope 3 emissions, accounting for the entire life cycle emissions (figure 4(c)).

Figure 4(a) shows the cost-optimal scenario without any decarbonization policies. For all facilities in the US and Canada, BAU has the lowest overall cost. Among the decarbonized production pathway, CCS emerges as the most cost-effective option, except in California, where high natural gas prices make the biomass pathway the least expensive choice. Figure 4(b) shows the cost-optimal decarbonization route for facilities when accounting for the 45V and 45Q tax credits in the US and the tax credits in Canada for well-to-gate emissions. The analysis underlines two distinct outcomes shaped by the different policies. In the US, tax credits enable electrolytic hydrogen production from wind energy to be the most cost-competitive pathway for ammonia production. However, in regions with a higher wind energy cost, biomass with CCS becomes the most cost-competitive method. Conversely, Canada's tax credits make CCS technologies more cost-competitive.

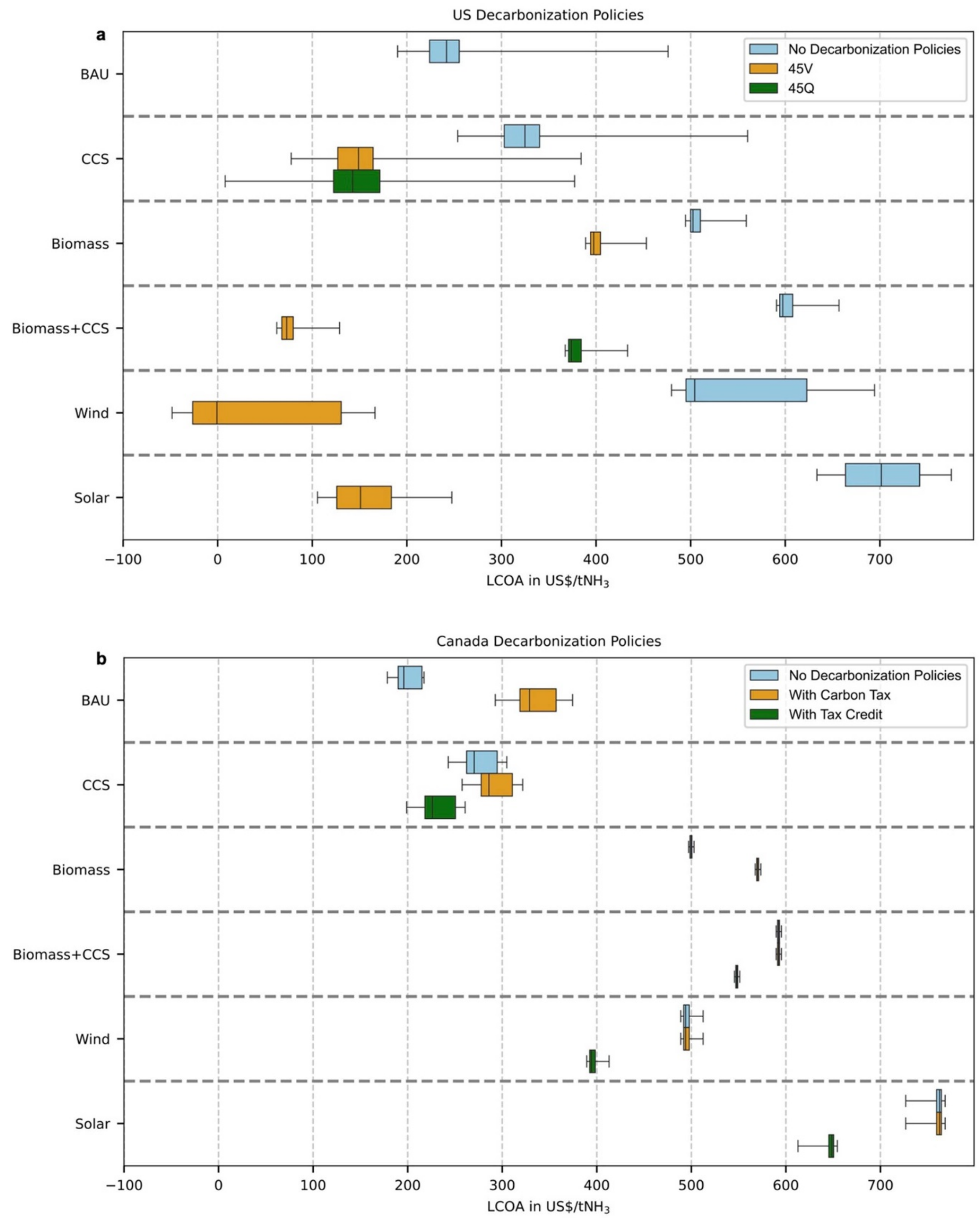

Figure 3. Levelized cost of ammonia (LCOA) with and without tax credit and carbon taxes. (a) LCOA for all ammonia production pathways with and without 45V and 45Q tax credits in the US. (b) LCOA with and without carbon taxes, and with tax credit for low-carbon hydrogen in Canada. All results are in United States dollars per ton of ammonia (US$/tNH$_3$). Every box plot shows LCOA distribution among the 41 ammonia facilities in the US and Canada. Box plots show the median, 25%, and 75% quartiles, and the minimum and maximum for each production pathway.

Canada's tax credits for low-carbon hydrogen are not as substantial as those in the US, leading to higher costs compared to hydrogen production with CCS. When full lifecycle emissions are factored in (figure 4(c)), biomass with CCS emerges as the pathway with the lowest LCOA across all facilities since it is the only pathway that qualifies for the 3$/kg H_2 tax credit (figure 4(c)). This regulatory change, however, would not alter the cost advantage of CCS in Canada, where it would remain the most economical option. For the US, figure 4(c) shows the importance of the scope of the emissions that is defined for tax credits. For sustainable, long-term decarbonization of ammonia production, lifecycle emissions should be

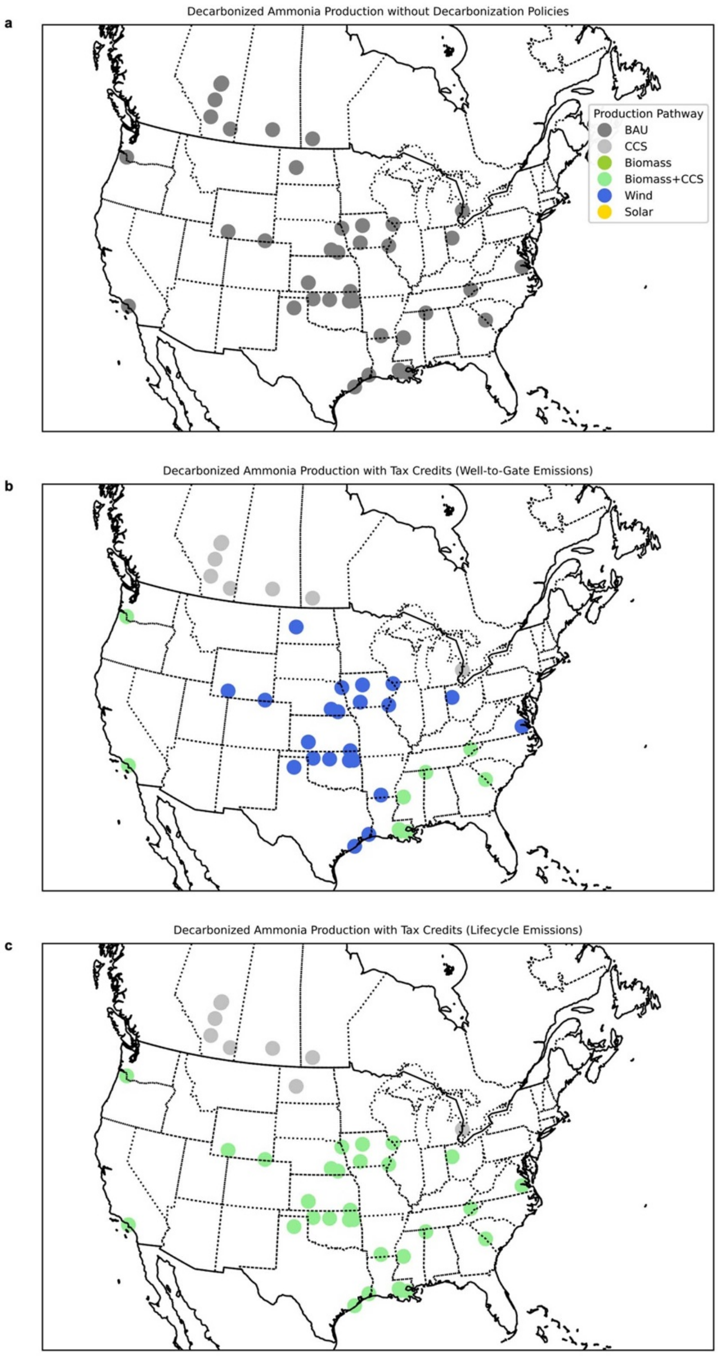

Figure 4. Cost-optimal low-carbon ammonia production pathway with and without carbon tax and tax credits in the US and Canada. (a) Visualization of cost-optimal decarbonized ammonia production pathways without decarbonization policies. (b) Geographical distribution of the cost-optimal decarbonized ammonia production pathways, illustrating the impact of tax credits and carbon tax in Canada and 45V and 45Q in the US accounting for partial Scope 3 emissions, as in the current legislation. (c) Map showing cost-optimal decarbonized ammonia production with tax credits and carbon tax factored into full lifecycle emissions, or Scope 3 emissions.

accounted for. However, including all Scope 3 emissions as a requirement for the tax credit would reduce the cost-competitiveness of low-carbon ammonia. Biomass + CCS is the only pathway that would qualify for the full credit; however, securing a sustainable, reliable, and affordable biomass feedstock in the quantities needed to replace current ammonia production at scale remains a significant challenge [29, 30].

3. Discussion

Ammonia-based nitrogen fertilizers are essential for feeding half of the global population, and their demand is expected to rise by 25% by 2050 due to population growth and increased food needs [9]. Ammonia's role as a zero-carbon fuel and hydrogen carrier is also driving its use in various industrial processes [9]. However, ammonia production in 2021 accounted for 1.3% of global greenhouse gas emissions and consumed 2% of global energy [9], with 90% of these emissions resulting from the energy-intensive hydrogen production for the Haber–Bosch process [10, 31]. This process, which combines hydrogen and nitrogen at high pressure and temperature to produce ammonia, relies heavily on fossil fuels. The industry's dependency on fossil-based hydrogen, long-distance transportation, and complex logistics has caused major disruption to the food supply chain [12]. Therefore, diversifying hydrogen production pathways for ammonia synthesis is a crucial strategy for decarbonization and reducing fossil fuel dependence [12].

We show that regulatory frameworks can significantly alter which ammonia decarbonization pathway is cost-optimal (figure 4). In a scenario without decarbonization policies, BAU has the lowest overall cost, while CCS emerges as the cheapest low-carbon option for almost all facilities (figure 4(a)). However, under the incentives provided by the Inflation Reduction Act tax credits, electrolytic hydrogen production from wind energy and biomass + CCS have the lowest LCOA in the US (figure 4(b)). In a scenario that accounts for full lifecycle emissions (figure 4(c)), wind does not qualify for a full 45V tax credit and biomass + CCS becomes the most economical pathway. In Canada, the prevailing carbon tax structure tends to favor the adoption of CCS. However, the production costs for Canadian ammonia producers are significantly higher compared to the US, threatening their ability to compete with US facilities (figures 3 and 4(b); supplementary dataset). This could lead to a potential shift in production locations to maintain cost competitiveness. The findings suggest a dichotomy between the impact of tax credits and carbon taxes, namely tax credits appear to support the transition to low-carbon production methods, while carbon taxes seem to encourage existing facilities to upgrade to CCS technology.

Upgrading ammonia plants with CCS offers cost-effectiveness and reduced water, land, and energy usage [12]. However, it does not fully eliminate greenhouse gas emissions. To achieve net-zero ammonia production, the use of negative emission technologies is necessary [12, 32]. Its reliance on fossil fuels and related supply chain shocks positions it as a potential transitional technology rather than a long-term solution [12]. Renewable-based water electrolysis eliminates natural gas dependency but requires large installations and faces higher costs compared to fossil-based production [33, 34]. Biochemical processes using sustainably sourced biomass can eliminate fossil fuel dependency and potentially achieve negative emissions when coupled with CCS [29]. However, challenges include costly biomass infrastructure, securing sustainable supply, and extensive land and water requirements [29, 30, 35]. The transformation of biomass to biomethane is a complex and resource-intensive process, and biomass transport is challenging [13]. We estimated that an average-sized ammonia facility would need approximately 12 300 MWh of biomethane for hydrogen production (supplementary dataset). Given that a liquefied natural gas transport truck has a capacity of 142 MWh [36], 86 daily truck deliveries are required to meet the biomethane demands of an ammonia plant.

Steady hydrogen supply, fluctuating energy generation from wind and solar, and land constraints are the key challenges for the wind and solar pathway [14]. An alternative to address the intermittent issue is to use grid electricity as a backup to maintain operations [37]. However, this can cause indirect Scope 2 emissions, which may reduce the tax credit if the electricity is not low-carbon. Hence, the tradeoff between ensuring continuous production and maintaining a low-carbon footprint should be carefully considered [38]. Another promising direction is the development of a more flexible Haber-Bosch process to better accommodate intermittent renewable energy by reducing ramp-up times and improving operational flexibility [39]. Although this can provide interesting benefits, and technology licensors claim that new generations of plants can have quick dynamics [40–42], current plants still require steady-state conditions in the Haber–Bosch loop [43]. Research is underway to explore alternative technologies to the traditional Haber–Bosch process for ammonia production [33]. These include electrochemical synthesis and plasma-activated processes, which utilize light instead of high temperature and pressure to convert nitrogen into ammonia [33]. Electricity-driven ammonia synthesis holds promise for low-carbon fertilizer distribution and reduced reliance on imports [33]. However, further optimization and scalability are necessary to assess their viability as a solution.

Given these challenges, no single technology or pathway emerges as the universal solution for every location and facility. As such, a variety of pathways will be necessary to realize a decarbonized ammonia industry. The International Energy Agency [9] states that low-carbon technologies like electrolyzer and CCS are required to meet the 2050 climate goal. To address these challenges and accelerate the commercial scalability of hydrogen technologies, the US government has introduced seven hydrogen hubs [44]. The six largest hydrogen hubs are close to at least one ammonia facility, potentially serving as hydrogen suppliers. Qualifying for 45V or 45Q, this could significantly reduce hydrogen prices and impact the ammonia market.

This study models the impact of decarbonization policies on ammonia production without incorporating the proposed hourly matching requirement for 45V eligibility, which has been proposed as an additional criterion for the tax credit [3]. Future studies should include this temporal matching in plant-by-plant decarbonization models, as it could enable facilities to effectively reduce emissions by using grid electricity that is matched with additional clean energy generation [18]. The insights can inform policymakers and industry stakeholders about cost-effective strategies for reducing greenhouse gas emissions.

4. Methods

This study leverages novel data on operative ammonia production facilities in the US and Canada [11]. This dataset contains industrial information about location, production capacity, and emissions of 41 ammonia producing facilities in the US and Canada. Mimicking the methods of Rosa and Gabrielli [12], the carbon intensity of 2022 ammonia production facilities was calculated and compared with five decarbonization pathways, including (i) CCS, (ii) biomass, (iii) biomass coupled with CCS, and electrolysis powered by (iv) wind, and (v) solar energy. For each pathway and facility, the study estimates LCOA with and without existing tax credits and carbon taxes. All input parameters used in the analysis are listed in supplementary table 2 and supplementary dataset.

4.1. Carbon intensity

For each facility, carbon intensity is calculated as the ratio of total annual CO_2e emissions to annual ammonia production, measured in tCO_2e/tNH_3. CO_2e represents a metric used to compare the emissions of various GHG based on their global warming potential relative to carbon dioxide [45]. The annual CO_2 emissions from US facilities are reported to the Environmental Protection Agency, as per regulatory requirements [22]. Likewise, Canadian facilities have to report their CO_2e emissions to the Canadian government [23].

A critical component in assessing the carbon intensity of these operations is the accurate estimation of the ammonia production volumes. Despite knowing the nominal capacities of these facilities, actual ammonia production is lower than production capacity. Notably, a capacity factor of 86% has been documented for US operations [8]. Additionally, the best available technology carbon intensity for the production of ammonia from coal and natural gas is known [9]. Utilizing these information, along with various production reports from operating companies [46–52], it is possible to estimate the carbon intensities of each facility (supplementary methods).

In the US, 92% of the feedstock used for ammonia production is derived from natural gas [53]. An ammonia production facility that utilizes natural gas (CH_4) as its primary feedstock, requires approximately 0.38 tCH_4/tNH_3 [9] with carbon emissions of 1.8 tCO_2/tNH_3 [9]. Most of these emissions are related to SMR to produce hydrogen, responsible for approximately 9.13 $kgCO_2/$ kgH_2 produced [54]. Using natural gas, ammonia synthesis consumes an average of 0.18 MWh of electricity per tNH_3 produced [9]. The consumption can be as low as 0.08 MWh per tNH_3 with SMR [9]. For coal-based ammonia production, the electricity usage averages 0.91 MWh per tNH_3 [9].

The production of ammonia via the Haber–Bosch synthesis process critically depends on a continuous supply of pure hydrogen and nitrogen to enable the formation of ammonia [10]. The predominant method of nitrogen production in large-scale plants is cryogenic distillation, accounting for more than 90% of the global supply [55]. Considering the density of nitrogen (N_2) at standard temperature (0 °C) and pressure (1 bar) as 1.23 kg m^{-3}, the electricity consumption amounts to 162 kWh per ton of N_2 produced [55, 56]. A contemporary, streamlined, natural gas-based, and highly efficient Haber–Bosch process utilizing methane requires 26 gigajoule (GJ) per tNH_3 produced [57].

Given that hydrogen production accounts for approximately 90% of both the energy use and emissions in ammonia [10, 31], this study consequently explores five decarbonization pathways for hydrogen production while maintaining the Haber–Bosch process for all ammonia production methods. A plant-specific analysis is conducted for each pathway to ascertain the most economic pathway to decarbonize ammonia under existing and proposed regulatory frameworks. Each pathway is scrutinized to determine its viability in the context of cost, resource efficiency, and capacity to meet decarbonization targets. All pathways are depicted in supplementary figure 1. CCS, biomass, and biomass with CCS utilize SMR for hydrogen generation. In contrast, the wind and solar pathways derive hydrogen through water electrolysis (supplementary figure 1).

4.2. Technological pathways for decarbonization

The LCOA is calculated for each facility and pathway. The LCOA estimates the long-term cost implications of adopting each decarbonization strategy. This metric can be a benchmark for decision-making processes, allowing for an informed evaluation of the economic viability of transitioning to low-carbon ammonia production.

The LCOA encompasses all capital expenditures required for various technologies involved in ammonia production, including electrolyzer, hydrogen storage, compressors, SMR, air separation unit (ASU) for nitrogen production, and the Haber–Bosch process. Since this study focuses on existing facilities, these technologies, except for renewable installations, electrolyzer, hydrogen storage, and compressors, are already in place and operational. Retrofitting existing facilities eliminates the need to construct new plants entirely. It is important to note that this study does not incorporate financial costs for capital expenditures (cost of capital or discount rate).

4.3. CCS pathway

The emissions for the CCS pathway were determined by using emissions data reported by the governments [22, 23], in addition to considering emissions from the production of merchant hydrogen and leakage of natural gas (supplementary methods). The natural gas leakage rate is assumed between 0.75% and 9.63% [58]. A geospatial analysis is employed to determine the CO_2 transport distance from each ammonia facility to the nearest CO_2 storage location. CO_2 storage location are from a dataset that determines potential CO_2 storage sites [59]. In scenarios where an ammonia facility is sited directly on top of a prospective CO_2 storage location, the transportation costs are nominally set to zero, considering the absence of transport requirements. Given the high volumes of CO_2 emissions produced by ammonia facilities, it is assumed that pipelines will serve as the primary modality for CO_2 transport to the storage sites. The associated transportation expenses of CO_2 by pipeline, encompassing both capital and operational expenditures, are between \$0.008 and \$0.029 per tCO_2 per km [60]. Given the high (>98%) [61] purity of CO_2 in ammonia production [62], CO_2 capture is cheaper than in other industries with lower CO_2 purity [63]. CO_2 capture costs are estimated to be between \$22 and \$32 per tCO_2 [64]. Storage expenses are an additional cost ranging from \$2 to \$12 per tCO_2 [65]. Therefore, for ammonia facilities, which are located directly above a potential storage location, the costs for CCS are therefore between \$24 and \$44 per tCO_2. The LCOA calculation includes merchant hydrogen costs. Based on the dataset [11] 12 facilities purchase a significant amount (>50%) of their hydrogen demand from external producers. This study assumes that merchant hydrogen has an additional 25% sales margin. In other production pathways, this study assumes that all hydrogen is produced onsite.

The LCOA in $\$/tNH_3$ without decarbonization policies for the CCS pathway is calculated by the following equation:

$$\mathrm{LCOA}_{\mathrm{CCS}} = \frac{1}{V_{\mathrm{NH3}}}\left(\sum_{k\in K}(\mathrm{CAPEX}_k+\mathrm{OPEX}_k)+\sum_{l\in L}(c_l d_l)\right) \tag{1}$$

$$\forall k\in K=\{\mathrm{SMR},\mathrm{ASU},\mathrm{HB},C,T_{\mathrm{CO2}},S_{\mathrm{CO2}}\},\quad \forall l\in L=\{f,m,e\}$$

where V_{NH3} is the annual ammonia production volume, CAPEX and OPEX are capital and operational expenditures, c is costs, d is the demand, SMR, ASU for nitrogen production, HB is the Haber–Bosch process, C is the CO_2 capture, T_{CO2} is the CO_2 transportation, S_{CO2} is the CO_2 storage, f is the feedstock for hydrogen production, m is the merchant hydrogen, and e is the total electricity for the ammonia production process. The detailed values for each plant and variables are shown in supplementary dataset and table 2.

4.4. Biomass pathways

This study assumes the conversion of waste biomass, such as livestock manure and crop residues, into biomethane through anaerobic digestion [29, 30, 66]. The reason for focusing on anaerobic digestion rather than gasification is that biomass gasification is typically too expensive, as it requires building new infrastructure. In contrast, biomethane can be used as a drop-in replacement for fossil natural gas [29], allowing existing steam methane reforming (SMR) infrastructure to be utilized for hydrogen production. This approach enables ammonia plants to maintain operations while transitioning to a renewable feedstock without the need for costly new units.

To produce one ton of ammonia, 0.176 tons of hydrogen are required [67]. The efficiency of the biomethane to hydrogen conversion is 0.29 kg of hydrogen per kg of biomethane[29]. Geospatial information of producible biomethane in the US and Canada was taken from a study that assessed biomethane potential from waste biomass [30]. To meet biomethane demand for each ammonia facility, we quantify the required biomethane by linking hydrogen consumption to biomethane yields, then calculate distances to biomethane sources until annual demand is satisfied. This analysis shows that US and Canadian ammonia facilities would require between 467 and 98 652 MWh of biomethane per day averaging at 12 297 MWh d^{-1}. The demand can be met through the potentially available biomethane. The distances from the ammonia facilities to the biomethane demand are between 26.5 and 291.6 km, with an average of 80.6 km. This study focuses on the potential of biomethane and does not analyze existing biomethane refinery plants. The predominant expenses in the biomethane pathway are attributed to the procurement of biomass, its conversion into biogas, and the subsequent upgrading into biomethane [30]. Collectively, these processes incur costs of \$41.3 to \$55.1 per MWh [68]. The biomass pathway still results in CO_2e emissions ranging from 1.2 to 8.6 kg CO_2e/kgH_2 [29]. These emissions are further increased by biomethane leaks and additional emissions generated during the transportation of biomethane from its source to the ammonia production facility (between 1.08 and 6.012 gCO_2e/kWh [69]). The Haber–Bosch process and the nitrogen air separation require 0.5–0.86 MWh/tNH_3 [10], which results in additional emissions.

Based on our geospatial analysis that match biomethane available [30] with each ammonia facility, we find that for each facility there is enough biomethane within a radius of 100 kilometers. Therefore, biomethane is assumed to be transported by truck, primarily due to the short transport distances. Transportation costs range from 0.00975$ to 0.018$ per cubic meter per kilometer [70]. The emissions associated with truck transport are estimated at 0.73 kg CO_2e/km [71].

Another pathway is biomass coupled with CCS, where CCS is adopted to capture CO_2 emissions from SMR during hydrogen production. Although CCS increases production costs, it offers the benefit of potentially reaching negative carbon emissions, as the CO_2 captured from biomethane is biogenic and originates from biological sources [72]. Producing hydrogen from biomethane with CCS can remove between 8.84 and 11.6 tCO_2e/tNH_3 [72]. This range underscores the potential for this pathway to not just reduce GHG emissions but to actively contribute to carbon dioxide removal. The LCOA in US$/$tNH_3$ for the biomass and biomass + CCS pathway can be calculated using the following equation:

$$\mathrm{LCOA}_{\mathrm{Biomass(Biomass\,+\,CCS)}} = \frac{1}{V_{\mathrm{NH3}}}\left(\sum_{k\in K}(\mathrm{CAPEX}_k + \mathrm{OPEX}_k) + \sum_{l\in L}(c_l d_l)\right) \tag{2}$$

$$\forall k \in K = \{T_{\mathrm{B}}, \mathrm{SMR}, \mathrm{ASU}, \mathrm{HB}(C, T_{\mathrm{CO2}}, S_{\mathrm{CO2}})\},\quad \forall l \in L = \{f, e\}$$

where T_{B} is the biomethane transportation cost.

4.5. Wind and solar energy pathways

Hydrogen can be produced using electrolyzers instead of SMR, powered by either grid electricity or renewable energy. Given the high energy requirements of ammonia synthesis and the current carbon intensity of the US energy grid (0.376 tCO_2/MWh) [73], using only grid electricity would increase the carbon footprint of ammonia production by 3.5 times compared to the BAU scenario. In Canada the grid greenhouse gas intensity is 0.137 tCO_2/MWh [74] so the electrolytic pathway would have 1.27 times higher emissions than BAU. Additionally, the significant energy demand makes the cost of electricity the primary expense in the electrification pathway. With an average electricity price of \$77.3 MWh^{-1} [75], the LCOA using only grid electricity would be US\$1,041.60 per ton of NH_3. For Canada with an average electricity price of US\$95.24 MWh^{-1} [76], the LCOA would be US\$1,181.49/tNH_3. Consequently, this study does not consider grid electricity alone as a viable path for decarbonizing ammonia production in the near term. To address these challenges, we propose that ammonia production facilities operate their own renewable wind or solar energy parks, leveraging renewable energy to reduce both the carbon footprint and overall production costs.

While the electrolysis process does not directly emit GHG emissions, there are indirect life cycle emissions from electricity production (supplementary methods and supplementary table 1). Solar energy has full life cycle GHG emissions estimated to be between 0.008 and 0.083 CO_2e/MWh, while wind energy has life cycle GHG emissions that range from 0.0078 to 0.016 CO_2e/MWh [77]. Producing one ton of ammonia via electrolysis requires between 8.6 and 10 MWh of energy [9, 10, 67], resulting in a carbon intensity of 0.07–0.83 tCO_2e/tNH_3 and 0.07–0.16 tCO_2e/tNH_3 for solar and wind, respectively.

The costs for solar and wind energy are based on the levelized cost of energy (LCOE) for wind and solar for each state [78] (see supplementary dataset). The LCOE provides a comprehensive measure of the average net present cost of electricity generation for a generating plant over its lifetime, incorporating capital costs, taxes, capacity factors, and operational costs.

The capital expenditure for an alkaline electrolyzer is assumed to be \$950 kW [79]. Additionally, the operational expenditures are estimated to be approximately 2% of the capital expenditures [80]. The installed capacity of electrolyzers is calculated based on the daily demand on hydrogen and the capacity factor for wind and solar.

Wind and solar dependency on weather conditions means that without wind or sunlight, power generation halts, which is problematic for continuous processes like the Haber–Bosch that require a steady hydrogen supply. To maintain continuous production in large-scale plants hydrogen storage is necessary. This study assumes that hydrogen is stored for one day to ensure constant ammonia production, and the associated costs account for an additional 6.6% of the LCOA on average (supplementary methods).

We use the average capacity factor for solar and wind energy in the US [81] to estimate the required amount of installed wind and solar energy. The average capacity factor of solar for the US is 24.4% while wind has a capacity factor of 35.9% in 2022 [81]. The LCOA for the wind and solar pathway is calculated as:

$$\mathrm{LCOA}_{\mathrm{Wind/Solar}} = \frac{1}{V_{\mathrm{NH3}}}\left(\sum_{k\in K}(\mathrm{CAPEX}_k + \mathrm{OPEX}_k) + \sum_{l\in L}(c_l d_l)\right) \tag{3}$$

$$\forall k \in K = \{R, \mathrm{ALK}, \mathrm{ASU}, \mathrm{HB}, S_{\mathrm{H2}}\}, \forall l \in L = \{f\}$$

where R is the renewable energy source, ALK is the electrolyzer, and S_{H2} is the hydrogen storage.

4.6. Modeling policies

The regulations for the 45V tax credit are still being finalized, with decisions on implementation currently in progress. The full subsidy 'three pillars'—additionality, hourly matching, and deliverability [82], with hourly matching being a particularly contentious point—are at the key areas of ongoing debate (supplementary methods). The mechanisms to claim 45V benefits, which include direct payments and tax credits [83, 84] provide significant financial incentives for ammonia production facilities. Direct payments towards low-carbon hydrogen production are estimated at $5.3 billion, with the total cost projected at $13.2 billion [85]. Following the approach of Ricks *et al* [18] and Mersch *et al* [17], this study models the regulation as a production credit (as of April 2024), thereby subtracting the tax credits from overall expenses to assess economic impact, though this may not fully reflect actual cash flow or pricing dynamics. Canadian dollar (C$) was converted into US$ using the exchange rate as of 0.72 in April 2024.

Data availability statement

Output datasets are available in the Supplementary Dataset of this study.

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions

LR conceived and designed the study. Y S, N B and L R collected data. Y S performed analysis and analyzed data with input from all authors. Y S, S M, and L R wrote the study.

Conflict of interest

The authors declare no conflict of interest.

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References

[1] U.S. Department of Energy 2023 Inflation reduction act and carbon management opportunities in Texas (available at: www.energy.gov/sites/default/files/2023-11/IRA%20and%20Carbon%20Management%20Opportunities%20in%20Texas%20Nov%2014%202023%20v2%20reduced%20file%20size.pdf)

[2] Government of Canada 2023 A made-in-Canada plan: affordable energy, good jobs, and a growing clean economy (available at: www.budget.canada.ca/2023/report-rapport/chap3-en.html)

[3] U.S. Department of Energy 2023 Clean hydrogen production tax credit (45V) resources (available at: www.energy.gov/articles/clean-hydrogen-production-tax-credit-45v-resources)

[4] 117th Congress 2022 H.R.5376—inflation reduction act of 2022 (available at: www.congress.gov/bill/117th-congress/house-bill/5376)

[5] International Energy Agency 2023 Towards hydrogen definitions based on their emissions intensity (available at: www.iea.org/reports/towards-hydrogen-definitions-based-on-their-emissions-intensity)

[6] Congressional Research Service 2023 The section 45Q tax credit for carbon sequestration (available at: https://sgp.fas.org/crs/misc/IF11455.pdf)

[7] Minister of Justice 2024 Greenhouse gas pollution pricing act (available at: https://laws-lois.justice.gc.ca/PDF/G-11.55.pdf)

[8] National Minerals Information Center 2023 U.S. geological survey mineral commodity summaries 2023 data release: U.S. geological survey data release (https://doi.org/10.5066/P9WCYUI6)

[9] International Energy Agency 2021 Ammonia technology roadmap (available at: www.iea.org/reports/ammonia-technology-roadmap)

[10] Smith C, Hill A K and Torrente-Murciano L 2020 Current and future role of Haber–Bosch ammonia in a carbon-free energy landscape *Energy Environ. Sci.* **13** 331–44

[11] SEP North American Hydrogen Market Model 2022-2024 ed © Copyright 2023 saoradh enterprise partners LLC

[12] Rosa L and Gabrielli P 2022 Energy and food security implications of transitioning synthetic nitrogen fertilizers to net-zero emissions *Environ. Res. Lett.* **18** 014008

[13] Gabrielli P, Rosa L, Gazzani M, Meys R, Bardow A, Mazzotti M and Sansavini G 2023 Net-zero emissions chemical industry in a world of limited resources *One Earth* **6** 682–704

[14] Mingolla S, Gabrielli P, Manzotti A, Robson M J, Rouwenhorst K, Ciucci F, Sansavini G, Klemun M M and Lu Z 2024 Effects of emissions caps on the costs and feasibility of low-carbon hydrogen in the European ammonia industry *Nat. Commun.* **15** 3753

[15] Fasihi M, Weiss R, Savolainen J and Breyer C 2021 Global potential of green ammonia based on hybrid PV-wind power plants *Appl. Energy* **294** 116170

[16] Nayak-Luke R M and Bañares-Alcántara R 2020 Techno-economic viability of islanded green ammonia as a carbon-free energy vector and as a substitute for conventional production *Energy Environ. Sci.* **13** 2957–66

[17] Mersch M, Sunny N, Dejan R, Ku A Y, Wilson G, O'Reilly S, Soloveichik G, Wyatt J and Mac Dowell N 2024 A comparative techno-economic assessment of blue, green, and hybrid ammonia production in the United States *Sustain. Energy Fuels* **8** 1495–508

[18] Ricks W, Xu Q and Jenkins J D 2023 Minimizing emissions from grid-based hydrogen production in the United States *Environ. Res. Lett.* **18** 014025

[19] Cheng F, Luo H, Jenkins J D and Larson E D 2023 Impacts of the inflation reduction act on the economics of clean hydrogen and synthetic liquid fuels *Environ. Sci. Technol.* **57** 15336–47

[20] Jabarivelisdeh B, Jin E, Christopher P and Masanet E 2024 Achieving net-zero US ammonia: technology and policy options and their emissions, investment, and cost tradeoffs *J. Cleaner Prod.* **469** 143144

[21] Ueckerdt F, Verpoort P C, Anantharaman R, Bauer C, Beck F, Longden T and Roussanaly S 2024 On the cost competitiveness of blue and green hydrogen *Joule* **8** 104–28

[22] U.S. Environmental Protection Agency Office of Atmospheric Protection 2023 Greenhouse gas reporting program (GHGRP) (available at: www.epa.gov/ghgreporting)

[23] Greenhouse Gas Reporting Program (GHGRP) 2023 Greenhouse gas reporting: facilities (available at: www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/facility-reporting.html)

[24] U.S. Energy Information Administration 2024 Natural gas prices (available at: www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PIN_DMcf_a.htm)

[25] Martín M and Sánchez A 2024 Biomass pathways to produce green ammonia and urea *Curr. Opin. Green Sustain. Chem.* **47** 100933

[26] Sánchez A, Martín M and Vega P 2019 Biomass based sustainable ammonia production: digestion vs gasification *ACS Sustain. Chem. Eng.* **7** 9995–10007

[27] Rosa L and Gabrielli P 2023 Achieving net-zero emissions in agriculture: a review *Environ. Res. Lett.* **18** 063002

[28] European Commission 2024 Renewable hydrogen (available at: https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen/renewable-hydrogen_en#:~:text=To%20ensure%20that%20the%20hydrogen,renewable%20hydrogen%20to%20the%20EU)

[29] Rosa L and Mazzotti M 2022 Potential for hydrogen production from sustainable biomass with carbon capture and storage *Renew. Sustain. Energy Rev.* **157** 112123

[30] Feng Y and Rosa L 2024 Global biomethane and carbon dioxide removal potential through anaerobic digestion of waste biomass *Environ. Res. Lett.* **19** 024024

[31] Innovation for Cool Earth Forum 2022 Low-carbon ammonia roadmap (available at: www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Low-Carbon_Ammonia.pdf)

[32] Terlouw T, Bauer C, Rosa L and Mazzotti M 2021 Life cycle assessment of carbon dioxide removal technologies: a critical review *Energy Environ. Sci.* **14** 1701–21

[33] Tonelli D *et al* 2024 Cost-competitive decentralized ammonia fertilizer production can increase food security *Nat. Food* **5** 469–79

[34] Tonelli D, Rosa L, Gabrielli P, Caldeira K, Parente A and Contino F 2023 Global land and water limits to electrolytic hydrogen production using wind and solar resources *Nat. Commun.* **14** 5532

[35] Beltran-Peña A, Rosa L and D'Odorico P 2020 Global food self-sufficiency in the 21st century under sustainable intensification of agriculture *Environ. Res. Lett.* **15** 095004

[36] Public Utilities Regulatory Authority 2024 What is LNG? (available at: https://portal.ct.gov/PURA/Gas-Pipeline-Safety/What-is-LNG.#:~:text=LNG%20Trucks&text=The%20trailers%20are%20approximately%2042,to%2013%2C000%20gallons%20of%20LNG)

[37] Salmon N and Bañares-Alcántara R 2021 Impact of grid connectivity on cost and location of green ammonia production: australia as a case study *Energy Environ. Sci.* **14** 6655–71

[38] Terlouw T *et al* 2024 Future hydrogen economies imply environmental trade-offs and a supply-demand mismatch *Nat. Commun.* **15** 7043

[39] Palys M J and Daoutidis P 2024 Renewable ammonia for islanded energy storage *Current Opinion in Green and Sustainable Chemistry* p 100946

[40] Rouwenhorst K 2023 Flexible ammonia synthesis: shifting the narrative around hydrogen storage (available at: https://ammoniaenergy.org/articles/flexible-ammonia-synthesis-shifting-the-narrative-around-hydrogen-storage/)

[41] Ostuni R, Bialkowski M and Corbetta M 2021 Dynamic analysis of casale green ammonia synthesis process (available at: https://ammoniaenergy.org/wp-content/uploads/2021/11/Casale-slides-AEA-21-published.pdf)

[42] ALFA LAVAL, H, HALDOR TOPSØE, VESTAS, SIEMENS GAMESA 2020 Ammonfuel—an industrial view of ammonia as a marine fuel (available at: https://hafnia.com/wp-content/uploads/2020/08/Ammonfuel-Report-an-industrial-view-of-ammonia-as-a-marine-fuel.pdf)

[43] Armijo J and Philibert C 2020 Flexible production of green hydrogen and ammonia from variable solar and wind energy: case study of Chile and Argentina *Int. J. Hydrog. Energy* **45** 1541–58

[44] Office of Clean Energy Demonstrations 2024 Regional clean hydrogen hubs selections for award negotiations (available at: www.energy.gov/oced/regional-clean-hydrogen-hubs-selections-award-negotiations)

[45] IPCC 2018 Annex I: glossary [Matthews, J.B.R. (ed.)] *Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* ed V Masson-Delmotte *et al* (Cambridge University Press) pp 541–62

[46] CVR Partners 2023 CVR partners reports fourth quarter and full-year 2022 results and announces a cash distribution of $10.50 (available at: https://investors.cvrpartners.com/node/10721/pdf)

[47] Incitec Pivot Limited 2022 IPL ANNUAL REPORT 2022 (available at: www.annualreports.com/HostedData/AnnualReports/PDF/LSE_INCH_2022.pdf)

[48] Mosaic Company 2020 The mosaic company (available at: https://s1.q4cdn.com/823038994/files/doc_presentations/2020/0228806e-b5af-c77f-21c0-9fafb1af6b8c.pdf)

[49] Nutrien 2023 Low-Carbon Fertilizer (available at: www.nutrien.com/sustainability/strategy/low-carbon-fertilizer)

[50] RMR Holdings 2023 Nebraska Nitrogen (available at: https://rmrholdings.com/nebraska-nitrogen/)

[51] Atchison J 2023 OCI Global: renewable ammonia in Texas (available at: www.ammoniaenergy.org/articles/oci-global-renewable-ammonia-in-texas/)

[52] Fertilizer Canada 2023 Ammonia production greenhouse gas emissions benchmarking (available at: https://fertilizercanada.ca/wp-content/uploads/2023/10/Nitrogen-Benchmarking-Report-Final.pdf)

[53] U.S. Energy Information Administration 2021 Natural gas weekly update (available at: www.eia.gov/naturalgas/weekly/archivenew_ngwu/2021/04_01/#:~:text=Ammonia%20is%20produced%20at%2032,million%20mt%2Fy%20in%202020)

[54] Sun P, Young B, Elgowainy A, Lu Z, Wang M, Morelli B and Hawkins T 2019 Criteria air pollutants and greenhouse gas emissions from hydrogen production in US steam methane reforming facilities *Environ. Sci. Technol.* **53** 7103–13

[55] Liu X, Elgowainy A and Wang M 2020 Life cycle energy use and greenhouse gas emissions of ammonia production from renewable resources and industrial by-products *Green Chem.* **22** 5751–61

[56] Belloni A 2008 *Industrial Gases Processing* (Wiley)

[57] Rouwenhorst K H R *et al* 2021 Future trends *Techno-Economic Challenges of Green Ammonia as an Energy Vector* (Elsevier) pp 303–19

[58] Sherwin E D *et al* 2024 US oil and gas system emissions from nearly one million aerial site measurements *Nature* **627** 328–34

[59] Paige Morkner, N. E. T. L.-U. S. D 2022 NATCARB viewer web map (available at: https://arcgis.netl.doe.gov/portal/apps/sites/#/edxspatial/maps/fef81b04ec7c404f8f69bbc2cb352928/explore)

[60] Becattini V, Gabrielli P, Antonini C, Campos J, Acquilino A, Sansavini G and Mazzotti M 2022 Carbon dioxide capture,

transport and storage supply chains: optimal economic and environmental performance of infrastructure rollout *Int. J. Greenhouse Gas Control* **117** 103635

[61] Han K, Ahn C K, Lee M S, Rhee C H, Kim J Y and Chun H D 2013 Current status and challenges of the ammonia-based CO_2 capture technologies toward commercialization *Int. J. Greenhouse Gas Control* **14** 270–81

[62] Porter R T *et al* 2016 Techno-economic assessment of CO_2 quality effect on its storage and transport: CO_2 QUEST: an overview of aims, objectives and main findings *Int. J. Greenhouse Gas Control* **54** 662–81

[63] Pereira R J L, Argyris P A and Spallina V 2020 A comparative study on clean ammonia production using chemical looping based technology *Appl. Energy* **280** 115874

[64] Moch J M, Xue W and Holdren J P 2022 Carbon capture, utilization, and storage: technologies and costs in the US context *Belfer Center for Science and International Affairs*

[65] Rubin E S, Davison J E and Herzog H J 2015 The cost of CO_2 capture and storage *Int. J. Greenhouse Gas Control* **40** 378–400

[66] Zhang X, Sabo R, Rosa L, Niazi H, Kyle P, Byun J S, Wang Y, Yan X, Gu B and Davidson E A 2024 Nitrogen management during decarbonization *Nat. Rev. Earth Environ.* **5** 717–31

[67] Pfromm P H 2017 Towards sustainable agriculture: fossil-free ammonia *J. Renew. Sustain. Energy* **9** 034702

[68] International Energy Agency 2020 Outlook for biogas and biomethane: prospects for organic growth (available at: www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth)

[69] Bakkaloglu S, Cooper J and Hawkes A 2022 Methane emissions along biomethane and biogas supply chains are underestimated *One Earth* **5** 724–36

[70] U.S. Department of Transportation 2019 Risk assessment of surface transport of liquid natural gas (available at: www.phmsa.dot.gov/sites/phmsa.dot.gov/files/docs/research-and-development/hazmat/reports/71651/fr2-phmsa-hmtrns16-oncall-20mar2019-v3.pdf)

[71] Speirs J *et al* 2020 Natural gas fuel and greenhouse gas emissions in trucks and ships *Prog. Energy* **2** 012002

[72] Antonini C, Treyer K, Streb A, van der Spek M, Bauer C and Mazzotti M 2020 Hydrogen production from natural gas and biomethane with carbon capture and storage–A techno-environmental analysis *Sustain. Energy Fuels* **4** 2967–86

[73] U.S. Energy Information Administration 2023 U.S. energy-related carbon dioxide emissions, 2022 (available at: www.eia.gov/environment/emissions/carbon/#:∼:text=Changes%20in%20electricity%20generation%20sources,2%20per%20GWh%20in%202022)

[74] Government of Canada 2023 Pre-publication: updated carbon intensities for Canadian grid electricity and excess electricity to grid processes (available at: www.canada.ca/en/environment-climate-change/services/managing-pollution/fuel-life-cycle-assessment-model/updated-carbon-intensity-electricity.html)

[75] U.S. Energy Information Administration 2024 Table 6.07.B. capacity factors for utility scale generators primarily using non-fossil fuels (available at: www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b)

[76] Statistics Canada 2024 Electric power selling price index, monthly (available at: www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1810020401)

[77] United Nations Economic Commission for Europe 2022 Carbon neutrality in the UNECE region: integrated life-cycle assessment of electricity sources (available at: https://unece.org/sites/default/files/2022-04/LCA_3_FINAL%20March%202022.pdf)

[78] National Renewable Energy Laboratory 2023 Levelized cost of energy, state and local planning for energy (available at: https://maps.nrel.gov/slope)

[79] International Energy Agency 2019 The future of hydrogen (available at: https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf)

[80] Saba S M, Müller M, Robinius M and Stolten D 2018 The investment costs of electrolysis–A comparison of cost studies from the past 30 years *Int. J. Hydrog. Energy* **43** 1209–23

[81] U.S. Energy Information Administration 2023 Electric power monthly (available at: www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b)

[82] U.S. Department of Energy 2023 Assessing lifecycle greenhouse gas emissions associated with electricity use for the section 45V clean hydrogen production tax credit (available at: www.energy.gov/sites/default/files/2023-12/Assessing_Lifecycle_Greenhouse_Gas_Emissions_Associated_with_Electricity_Use_for_the_Section_45V_Clean_Hydrogen_Production_Tax_Credit.pdf)

[83] The White House 2024 Direct pay through the inflation reduction act (available at: www.whitehouse.gov/cleanenergy/directpay/)

[84] U.S. Department of the Treasury 2024 U.S. department of the treasury, IRS release final rules on provisions to expand reach of clean energy tax credits through president biden's investing in america agenda (available at: https://home.treasury.gov/news/press-releases/jy2157)

[85] Congressional Research Service 2024 Tax credit transfers and direct payments in the inflation reduction act of 2022 (available at: https://crsreports.congress.gov/product/pdf/IF/IF12596)