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Ammonia's Dual Role in Decarbonizing Energy and Agriculture

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This article discusses the dual role of Low Carbon Intensity Ammonia (LCIA) in agriculture and energy, emphasizing its potential in advancing decarbonization efforts in both sectors. As a versatile energy carrier, LCIA can complement hydrogen in decarbonizing hard-to-abate energy sectors while also bringing low-carbon benefits to its existing agricultural and industrial uses. The food–energy–water (FEW) nexus presents a framework for integrating LCIA into both sectors to promote sustainable development.

Decarbonizing the energy sector is particularly urgent in light of global climate targets, but equally important is addressing emissions from agriculture, which account for a significant portion of global greenhouse gas (GHG) emissions. LCIA offers a solution to both sectors, as it can be used not only as a low-carbon fuel but also in its traditional role as a nitrogen-based fertilizer in agriculture. In this way, LCIA creates synergies between energy and agriculture, stimulates broader demand, supports the scaling up of hydrogen infrastructure, and promotes low-carbon technologies in both sectors.

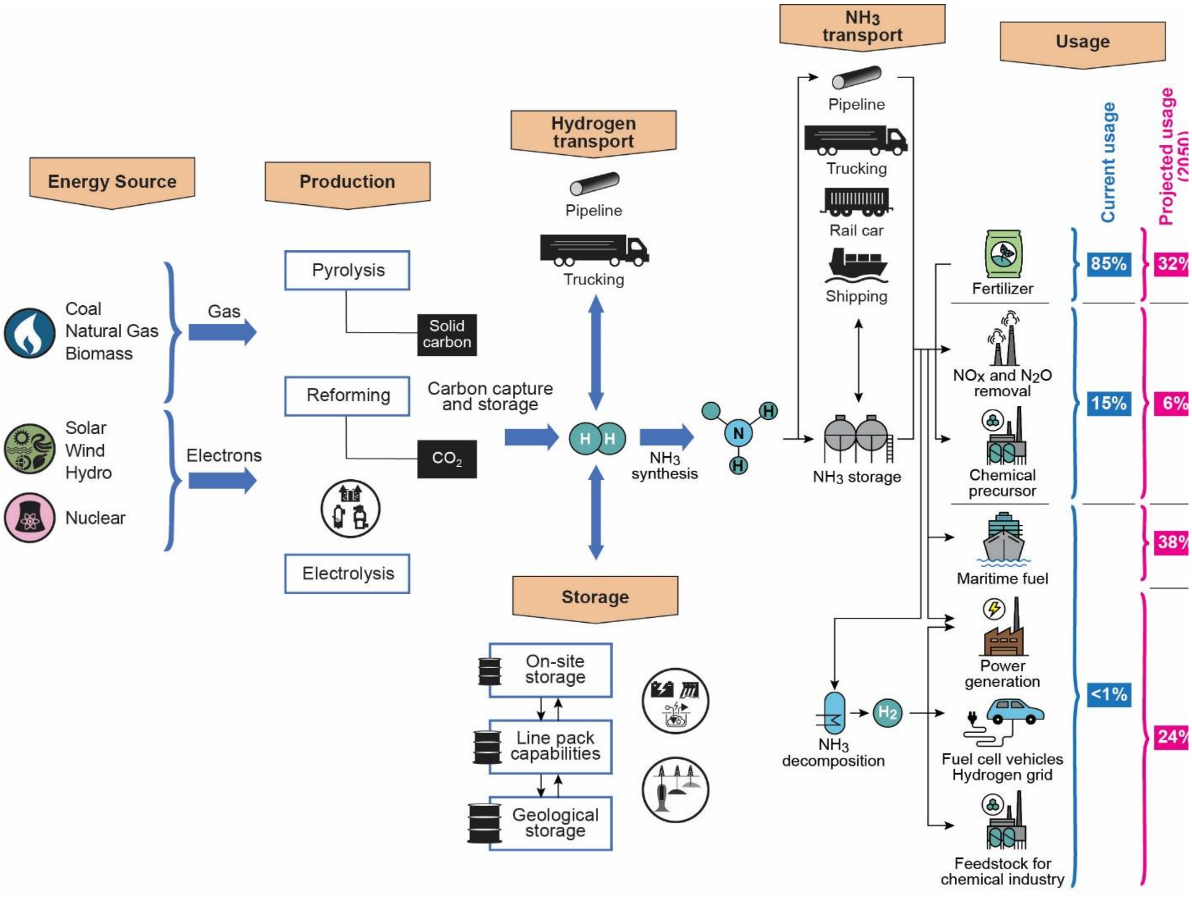
The Food-Energy-Water (FEW) Nexus

The food, energy, and water (FEW) nexus is at the heart of this transformative development, defined by the United Nations, as it highlights the critical roles of two sectors—agriculture and energy—in supporting human well-being and global economic prosperity. Examining this nexus through an economic lens reveals the elements interacting in multiple ways through either production or consumption relations. In a production system, water and energy serve as essential inputs in complex ways to produce food—the fuel of humanity. Recent studies have increasingly shifted attention to the environmental footprint of the system, especially its measurement and mitigation. Each element of the FEW nexus can involve greenhouse gases (GHG) emissions and environmental impacts throughout its life cycle. For example, water extraction, treatment, and distribution can be energy intensive and may result in considerable GHG emissions. One-quarter of the world's greenhouse gas emissions result from food and agriculture, including production, post-farm processing, packaging, and distribution. Meanwhile, modern agriculture also becomes more and more energy-intensive, from traditional machinery and fertilizers to future precision and smart agriculture technologies (Department of Energy, 2023a; FAO, 2000). Across sectors, the shift toward cleaner energy sources—such as renewable energy, bioenergy, and hydrogen—is key to meeting the targets set by the Paris Agreement, ratified by nearly 200 countries, which calls for limiting the long-term global temperature to 1.5° Celsius above preindustrial levels (United Nations, 2023, 2015). This transformation involves phasing out coal, increasing the share of renewable energy sources, and improving energy efficiency across all sectors. Additionally, solutions like carbon capture and storage (CCS) and sustainable low-carbon fuels (such as bioenergy and hydrogen) are essential.

LCIA as a Decarbonization Solution

Low Carbon Intensity Hydrogen (LCIH) produced from fossil fuels with CCS or renewable energy via electrolysis is considered a critical and versatile solution, which accounts for 8% of U.S. emissions reductions—primarily in hard-to-abate applications in the industrial, transportation, and power sectors—with a savings of 0.5%–1% of GDP compared to other abatement alternatives (National Petroleum Council, 2024). When it comes to agricultural applications, there are different pathways for integrating with a hydrogen economy. Some pathways would focus on decarbonizing fuel and energy for machinery systems. Other pathways could focus on innovating the use of chemicals and fertilizers while creating value-added components through the supply chain. Ammonia (NH_3), containing 17.8% hydrogen by weight and no carbon, plays a key role in addressing challenges and harnessing opportunities. Currently used mostly in agriculture and chemical industry, ammonia can store hydrogen through the

Figure 1. Low Carbon Intensity Hydrogen and Ammonia



synthesis of nitrogen and hydrogen under high pressure and temperature conditions. Low carbon intensity ammonia (LCIA), made from LCIH, on one hand, can be a multipurpose energy carrier. On the other hand, given its central role in the fertilizer industry, it can be a catalyst input in both decarbonizing the agricultural supply chain and creating new value chains (Wang et al., 2024).

Policy and Market Development

Recognizing the urgency of accelerating the decarbonization process, the Department of Energy (DOE) has introduced various policies and incentives. For instance, the 45V Hydrogen Production Tax Credit and the establishment of Regional Clean Hydrogen Hubs are designed to stimulate demand and support the development of hydrogen infrastructure. These policy impacts can be extended to LCIA, providing economic incentives to expand its use in both energy and agricultural sectors. Federal support and policy-driven subsidies are not unfamiliar to the agricultural sector. Integrating energy policy and agricultural policy seems to be a logical choice for bringing about an energy transition across sectors. At a practical level, positioning LCIA as a dual solution for both energy and agriculture can stimulate demand, support the scaling up of hydrogen infrastructure, and create synergies that benefit both sectors (Lin et al., 2024).

Technology and Value Chain

Figure 1 demonstrates the complete value of ammonia from production via hydrogen to end uses. Among many pathways, hydrogen can be produced, with greatly reduced from fossil fuels using reforming or nearly zero carbon intensity from gasification technologies with Carbon Capture and Storage (CCS) or through electrolysis from renewable electricity. These low carbon intensity production technologies significantly reduce carbon emissions compared to traditional processes like steam methane reforming (SMR) without CCS or coal gasification without CCS. The most common technology, SMR, reacts natural gas with steam to produce hydrogen and carbon dioxide. Autothermal reforming (ATR), which combines partial oxidation and steam reforming, offers flexibility in scaling hydrogen production and achieving higher carbon capture efficiency (Antonini et al., 2020). Integrating CCS with SMR or ATR reduces emissions and provides a cost-competitive option for producing LCIH, especially in regions with abundant natural gas.

Electrolysis splits water into hydrogen and oxygen using electricity. The main types of electrolysis technologies are alkaline (ALK), polymer electrolyte membrane (PEM), and solid oxide electrolyzer cell (SOEC) (Ansar et al., 2022). Alkaline electrolysis, using a liquid alkaline solution, is the most mature and cost-effective. PEM electrolysis uses a solid polymer membrane, also known as proton exchange membrane, offering higher efficiency and quicker response times, suitable for intermittent energy sources. SOEC electrolysis operates at high temperatures with a solid ceramic electrolyte, achieving above 90% efficiency by using both electricity and heat, though it is still early in commercialization. Powered by renewables, electrolysis offers zero direct emissions.

Scaling up electrolysis is challenging due to the intermittent nature of renewable energy and high costs. ATR and SMR require large-scale storage infrastructure and stable technical and legal support for storing CO2, addressing methane leakage in the natural gas supply chain. A balanced approach using both SMR and ATR with CCS and advancing electrolysis technologies ensures a steady and scalable hydrogen supply while transitioning to greener production methods.

Hydrogen produced through these methods can be synthesized with nitrogen to form ammonia at high pressure and temperatures with an iron catalyst, a process developed by Fritz Haber and Carl Bosch. Typical production systems yield 2,000–3,300 metric tons per day, equating to about 0.7–1.2 million metric tons annually. Ammonia produced from low-carbon-intensity hydrogen using CCS or renewables is known as blue or green ammonia (IRENA and AEA, 2022). There is also rising demand for smaller, decentralized ammonia production facilities near application areas to reduce transportation expenses and emissions, utilizing regional renewable energy resources.

Ammonia is key in producing various nitrogen-based fertilizers that enhance soil fertility. Urea, the most widely used ammonia-based fertilizer, contains about 46% nitrogen, the highest among solid nitrogenous fertilizers, making it highly efficient for delivering nitrogen to plants. It is available in solid granules; easy to store, transport, and apply; and highly soluble in water, allowing versatile application methods. Other nitrogenous fertilizers include ammonium nitrate and ammonium sulfate, produced by reacting ammonia with nitric or sulfuric acid, respectively. Major U.S. crops like corn, wheat, cotton, and rice require nitrogenous fertilizers for optimal growth.

Corn is one of the most nitrogen-intensive crops, and nitrogen fertilizer contributes approximately 40% of emissions in its production life cycle (U.S. Department of Agriculture, 2022). The U.S. Corn Belt—primarily Iowa, Illinois, Nebraska, and Minnesota—is known for intensive corn production for food and feedstock as well as for biofuels such as ethanol, making it a major demand region for synthetic nitrogen fertilizers. In 2021, the United States planted 93 million acres of corn, at a yield of 177 bushels per acre (U.S. Department of Agriculture, 2022). On average, each acre required 150 lb of nitrogen fertilizers. Ammonia can also be decomposed to release hydrogen, which can be used in various biofuel production processes. Ammonia has a high energy density and can store hydrogen more efficiently than traditional methods. Existing infrastructure for producing, storing, and transporting ammonia can be used for hydrogen distribution, reducing the need for new investments. Ongoing research aims to develop more efficient catalysts and processes for ammonia decomposition to hydrogen.

Markets

Currently, the global hydrogen market is 90 million metric tons supported mainly by refinery, chemicals, and heavy industries. The global hydrogen demand could range from 125 to 585 million metric tons by 2050. This wide range reflects hydrogen's significant potential as an energy carrier to decarbonize sectors like heavy industry, transportation, and power generation but also highlights the uncertainties in future demand (IEA, 2023a; McKinsey and Company, 2023). The United States currently produces and consumes about 10 million metric tons of hydrogen, mainly through the SMR process without carbon capture, and holds a significant portion of this fast-growing demand, supported by recent initiatives and projects by the federal government. The Department of Energy (DOE) has announced $750 million in funding for 52 projects aimed at reducing the cost of clean hydrogen and supporting its infrastructure, aiming to reduce clean hydrogen production costs to $1/kg by 2030 (Department of Energy, 2024; Higman and Zacarias, 2022). The U.S. hydrogen market is also shaped by the development of regional clean hydrogen hubs (H2Hubs) based on public-private partnerships, aiming to create diverse domestic clean energy pathways and support economic growth through job creation and technological advancements (Center for Houston's Future, 2023).

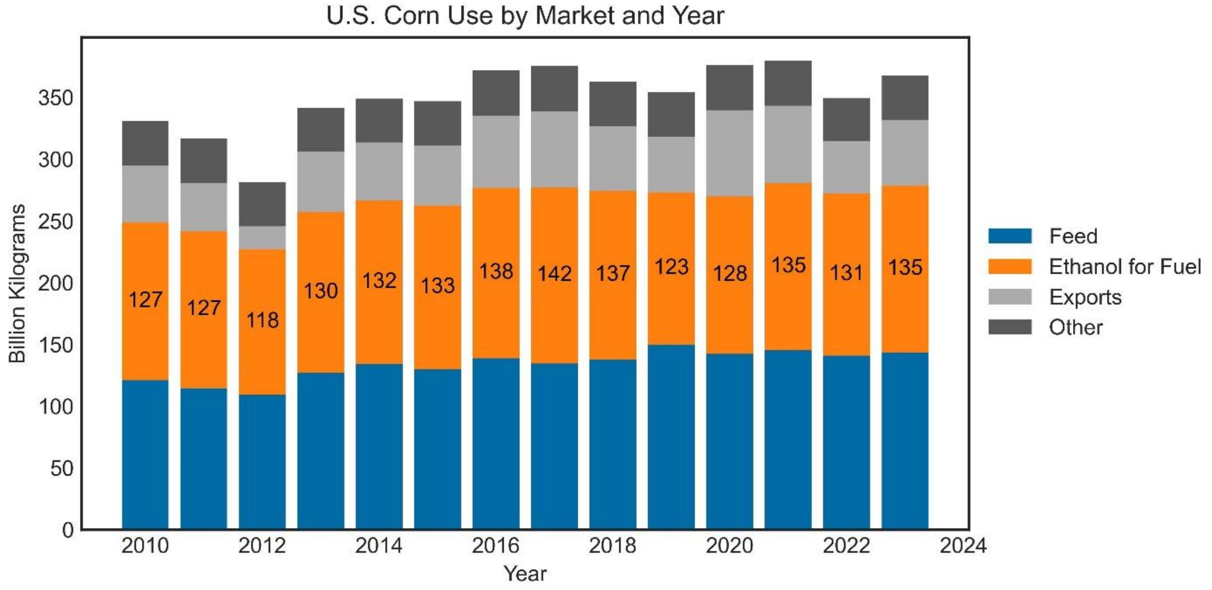
The ammonia market is a downstream market for hydrogen, now well-established for fertilizers and for some industrial applications. Global ammonia demand is expected to grow from 183 million metric tons in 2020 to 688 million metric tons in 2050, in a 1.5°C scenario, by 2050. Whereas the existing use sector presents incremental growth to 320 million metric tons by 2050, the emerging sectors present the most potential. By 2050, the maritime sector is expected to consume 197 million metric tons of ammonia as fuel, and ammonia imports as a hydrogen carrier are projected to reach 127 million metric tons. Additionally, power generation could demand 30 million metric tons of ammonia. In total, emerging uses are anticipated to reach more than 60% of the market by 2050, from nonexistent today (IRENA and AEA, 2022). Due to the cost hurdle of switching to low-carbon intensity alternatives, activating this vast potential in emerging applications requires additional momentum and supportive policies. The synergy between established and emerging sectors underscores the need for strategic investments to realize the full benefits of low-carbon-intensity ammonia (LCIA). Recent policy initiatives such as the European Union’s Green Deal and carbon-reduction targets are expected to boost the adoption of LCIA in Europe (Gatto et al., 2024; Gislam, 2021). In Asia, Japan’s Basic Hydrogen Strategy and South Korea’s Hydrogen Economy Roadmap highlight commitments to low carbon intensity hydrogen and ammonia, proposing substantial investments in infrastructure and technology incentives (Atchison, 2021; Heuser et al., 2019; IEA, 2023b).

The global market for ammonia-based fertilizers is substantial, reflecting their importance in ensuring food security for a growing population. Urea dominates this market, valued at over $129 billion in 2023, with a projected over 2% compounded annual growth rate (CAGR) in 2024–2032 driven by its widespread adoption and effectiveness as a fertilizer and animal feed. The global ammonium nitrate market, valued at approximately $19.1 billion in 2023, is expected to grow at a CAGR of 5.7% to reach $33 billion by 2032, driven by its dual application in agriculture as a nitrogen fertilizer and in the industrial sector for explosives. Similarly, the global ammonium sulfate market is projected to grow from $3.36 billion in 2024 to $5.04 billion by 2030, at a CAGR of 7.0% and is driven by its use as a nitrogen and sulfur fertilizer, essential for crop growth and soil fertility improvement. Ammonia-based fertilizers are integral to global agriculture, underpinned by robust production and consumption dynamics. Fluctuations in natural gas prices, which are a key input for ammonia production, can impact the cost and supply of these fertilizers. Additionally, geopolitical tensions and trade policies can influence the global distribution and availability of ammonia-based fertilizers and market dynamics.

Figure 2 provides a comprehensive breakdown of the key markets for corn from 2010 to 2024, focusing on major sectors such as feed, ethanol for fuel, exports, and other uses. One key observation is the steady yet slightly variable use of corn for ethanol production. From 2010 to 2020, ethanol consumption remained fairly constant, averaging around 5 billion bushels per year, with slight fluctuations reflecting changes in the economy and market dynamics. Since 2012, corn usage for ethanol has generally stayed above 5 billion bushels despite occasional decreases driven by economic challenges and shifts in fuel demand. These patterns are likely shaped by biofuel promotion policies, oil price volatility, and evolving market demands for ethanol both domestically and internationally.

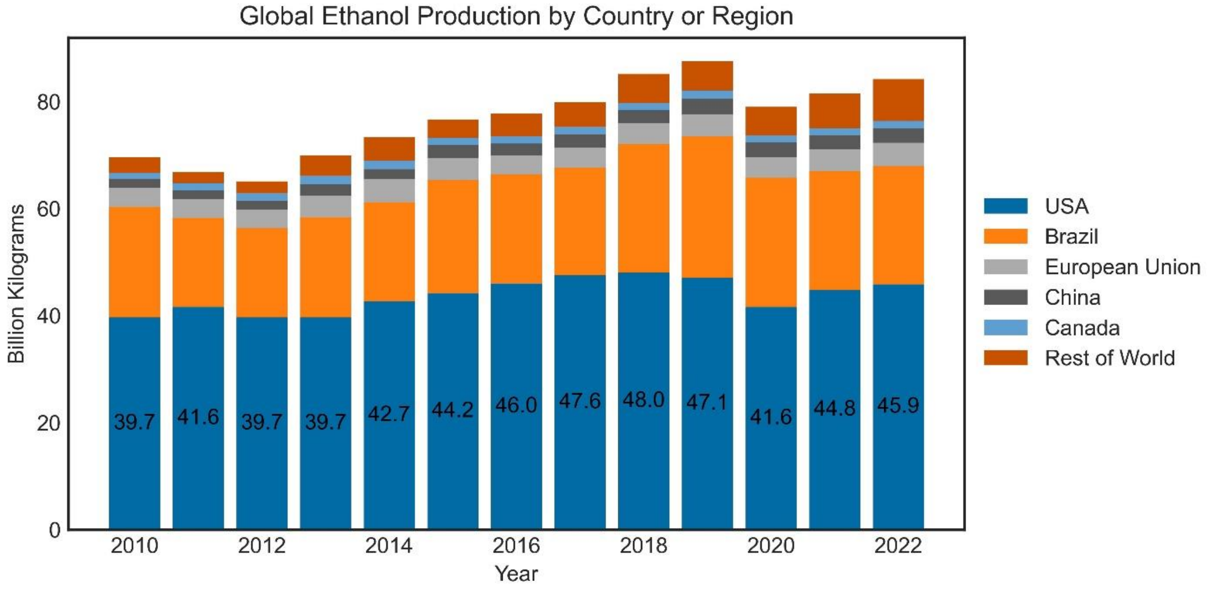
As of 2022, the United States remains the largest producer of ethanol globally, contributing the most to worldwide production (see Figure 3). U.S. ethanol output reached approximately 45.9 billion kilograms, showcasing a consistent trend over the years. Since 2010, the United States has maintained a dominant position in global ethanol production, with a steady increase from 39.7 billion kilograms in 2010 to over 47 billion kilograms by 2018, before slightly decreasing in 2020.

Figure 2: U.S. Corn Use by Market, 2010–2024



Source: U.S. Department of Agriculture (2024).

Figure 3: Global Ethanol Biofuel Production, 2010–2024



Source: U.S. Department of Agriculture (2022).

This stability reflects a more mature market, where ethanol has become a critical component of the national fuel supply, particularly as part of gasoline blends (commonly E10 or E15). Government policies, such as the Renewable Fuel Standard (RFS), have played a crucial role in maintaining demand, ensuring that ethanol remains a significant player in the nation's energy portfolio.

Geographically, ethanol production is highly concentrated in the Midwest, a region that accounts for over 95% of the nation's total ethanol output (U.S. Energy Information Administration, 2023). This dominance is closely tied to the Midwest's role as the heart of U.S. corn production, which supplies the majority of feedstock for ethanol plants. States like Iowa, Nebraska, and Illinois—with their vast agricultural resources and proximity to ethanol refining facilities—are strategic hubs for biofuel manufacturing. The co-location of corn production and ethanol refining minimizes transportation costs and maximizes efficiency, further solidifying the Midwest's leadership in U.S. ethanol production.

This regional concentration not only supports domestic fuel needs but also strengthens the U.S. position as a key player in the global biofuel market. Ethanol production in the United States has contributed to both energy security and the reduction of greenhouse gas emissions, positioning it as a sustainable alternative to fossil fuels while simultaneously bolstering the agricultural economy of the Midwest.

Costs and Impacts

The costs of Low-Carbon Intensity Hydrogen (LCIH) and Low-Carbon Intensity Ammonia (LCIA) vary greatly based on location, production methods, policy, and subsidies. Government incentives, such as tax credits, play a crucial role in reducing these costs and encouraging the adoption of low-carbon technologies. Two key tax credits in the United States that impact the cost of LCIH and LCIA are the 45V Hydrogen Production Tax Credit and the 45Q Carbon Capture and Storage (CCS) Tax Credit. The 45V Hydrogen Production Tax Credit was introduced under the Inflation Reduction Act (IRA) to incentivize the production of clean hydrogen. It provides a production tax credit of up to \$3.00/kg of clean hydrogen, depending on its life cycle greenhouse gas emissions (U.S. Department of the Treasury, 2023). Hydrogen with a very low carbon footprint, such as hydrogen produced using electrolysis powered by renewable energy, qualifies for the full credit. The 45Q Carbon Capture and Storage (CCS) Tax Credit provides incentives for capturing and storing carbon dioxide (CO_2) emissions from industrial sources, including those from ammonia production. The 45Q credit offers up to \$85/ton of CO_2 stored in geological formations and up to \$60/ton for CO_2 used for enhanced oil recovery (Jones and Marples, 2023). This credit is particularly important for industries like ammonia production, which is traditionally a high-carbon process. By integrating CCS into the production of ammonia, the 45Q tax credit can significantly reduce costs and improve the economic viability of low-carbon ammonia. For instance, hydrogen produced via ATR with 90% CCS costs about \$1.41/kg in the Permian Basin due to its abundant natural gas and renewable resources. This cost can drop by 40% with 45Q tax credit and offers a slightly better incentive for natural-gas-based production routes compared to 45V (Lin and Xu, 2024). Renewable hydrogen ranges from \$3.50/kg to \$8.00/kg but can decrease by \$2.12/kg with the 45V tax credit, depending on its life cycle carbon footprint. (Klerke et al., 2008). The levelized cost of ammonia using conventional natural gas without CCS is about $0.23/kg. With CCS, the cost rises to $0.37/kg, but this can be reduced to $0.29/kg with the 45Q tax credit (Lee et al., 2022). Renewable ammonia costs between $0.92/kg and $1.16/kg, potentially decreasing by $0.46/kg with the 45V tax credit.

Low-carbon intensity ammonia (LCIA) offers a notable potential to cut emissions. The current ammonia production technology generates around 0.5 gigatonnes of CO2-equivalent annually, accounting for 1% of global greenhouse gas emissions (The Royal Society, 2020). The carbon footprint of ammonia production processes is assessed using life cycle analysis, also known as life cycle assessment. It is a systematic method for evaluating the environmental impacts of a product, process, or service throughout its entire life cycle. Table 1 summarizes the life cycle analysis of ammonia production, corn production for biofuels, and ethanol production for U.S. gasoline blending, incorporating different pathways of ammonia production.

Conventional ammonia production using mainly natural gas emits 2.165 kg of CO_2 per kilogram of ammonia. Capturing CO_2 from the synthesis process reduces emissions by nearly 60%. Further capturing CO_2 from both production and energy combustion halves the remaining emissions. Using renewable hydrogen production for ammonia from electrolysis powered by renewable energy sources results in the lowest emissions, at 0.080 kg CO_2 per kilogram of ammonia.

Nitrogenous fertilizers are the largest emission source in corn cultivation for biofuels. Conventional ammonia used in corn production results in CO_2 emissions of 0.121 kg per kilogram of corn. Using LCIA can reduce emissions of corn production by up to 33%. Given that the United States produces 120–140 billion kg of corn annually for ethanol biofuels, LCIA in corn farming can further reduce ethanol production emissions by about 11%–15%, aiding in the decarbonization of ethanol blending in gasoline and supporting sustainability goals.

Incorporating low-carbon solutions into traditional value chains offers significant economic potential. The U.S. Department of Energy's H2@Scale initiative aims to enhance hydrogen production, transportation, storage, and utilization, projecting a two- to five-fold increase in hydrogen production (Miller, 2022; Ruth et al., 2020). This growth could double current solar or wind energy deployment, requiring substantial investments. H2@Scale anticipates creating up to 700,000 new jobs by 2030 in manufacturing, construction, and renewable energy sectors. Developing a robust hydrogen economy also demands advancements in infrastructure, further boosting employment and economic growth.

Recommendations and Looking Forward

As the market for LCIH and LCIA-based products emerges, it is critical to support further research, technology commercialization, and market development programs (including raising product awareness). There are at least two aspects to look forward to. First, LCIH and LCIA have broad applications for effective decarbonization in the agricultural sector, enabling low-

Table 1. Life Cycle Assessment

Roles of Different Ammonia Production Pathways in Life Cycle Emissions Target Year 2022			
Pathways	Ammonia (1 kg)	Corn (1 kg)	Ethanol (1 kg)
Conventional Ammonia (NG from shale and conventional recovery)	2.165 kg CO_2	0.121 kg CO_2	1.210 kg CO_2
NG-based Ammonia with Carbon Capture (Process CO_2 Only)	0.920 kg CO_2	0.098 kg CO_2	1.069 kg CO_2
NG-based Ammonia with Carbon Capture (Process and combustion CO_2)	0.487 kg CO_2	0.089 kg CO_2	1.051 kg CO_2
Green Ammonia (From Renewable Hydrogen)	0.080 kg CO_2	0.081 kg CO_2	1.034 kg CO_2
Total Corn Production for Ethanol Biofuel in U.S.	135 billion kg		
Total Ethanol Production in U.S.	45.9 billion kg		
Notes: Table 1 shows the emissions reported in the GREET 2023 (Department of Energy, 2023b) model of corn production. Results are from ammonia production, corn production for biofuel refineries, and ethanol produced for gasoline blending, all in the U.S.			

carbon solutions ranging from low-carbon fertilizers and biofuel production to food systems. Such transformations call for deeper collaborations between federal agencies. A recent White House memo exemplifies a collaboration between the USDA and the USDOE along this line (White House Office of Science and Technology Policy, 2023). Second, sustainable market growth for LCIH- and LCIA-based products relies on continuous investment in the upstream infrastructure and technology advancements, where public-private partnerships and industry-wide policy incentives could play a vital role. Currently, policy support focuses primarily on upstream stages, such as the 45V and 45Q tax credits for CCS and clean hydrogen production. However, similar support is needed for the downstream adoption of low-carbon solutions. This could include tax credits, product certification standards, labeling programs, or rebate programs for intermediate commodities like corn. A potentially efficient market mechanism is a voluntary carbon credit market, which aligns with USDA's efforts to facilitate participation in voluntary carbon markets (Bailey, 2024). Efficient facilitation of carbon credit transactions among upstream, middle, and downstream sectors can create effective synergies in decarbonizing both the energy and agricultural sectors. Given the pressing need for regional and global decarbonization, innovative policies are more necessary than ever.

LCIA's unique dual-role solution enhances the synergy between the energy and agriculture sectors, facilitating decarbonization and policy alignment to maximize impact. Collaboration among federal agencies, industry stakeholders, and community stakeholders—especially between the USDA and the USDOE—can unlock LCIA's full potential, driving economic growth, enhancing food security, and mitigating climate change impacts, thus fostering a sustainable and resilient global economy.

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