Ohio River Valley Institute

THE UNCERTAIN AMMONIA INDUSTRY, PRESENT & FUTURE

ZANE GUSTAFSON
ERIC DE PLACE
JULIA STONE

FEBRUARY 2025

Table of Contents

Executive Summary

This report explores the merits of the new ammonia economy and a massive buildout planned in the US, along with its underpinnings in hydrogen and carbon capture technologies. It focuses especially on ammonia projects in the Ohio River Valley region, where a developer has proposed building the world's single largest ammonia production facility.

Energy experts project that the existing ammonia market will swell by more than a quarter by 2050. Today, nearly nine tenths of the 185 million metric tons of ammonia produced globally is used as fertilizer, but in the future other industries may claim a greater share. There are risks associated with that growth because producing ammonia is very carbon intensive, with 2.35 metric tons of carbon dioxide emitted for each ton of ammonia made using conventional methods. Whether significant quantities of ammonia can be produced in cleaner ways—and at a competitive cost—remains to be seen.

The future of ammonia demand is highly uncertain. The projected scale of the new market for ammonia by 2050 varies by nearly an order of magnitude. When factoring in potential new uses of ammonia—as fuel for maritime vessels, power generation, or as a carrier for hydrogen transportation—forecasters argue that ammonia demand will grow by between 170 million metric tons and 900 million metric tons, if it materializes at all. The bullish future for ammonia demand would depend on the creation of new markets and the mass adoption of technologies that are, as of this writing, still nascent and dubious. To take just one example, this report finds that the adoption of ammonia as a maritime fuel—often heralded as a major new market for ammonia—is progressing slower than previous reports had projected.

There is some reason to think that ammonia production will scale up dramatically in the near future. This report documents a massive proposed ammonia buildout of at least 37 new production facilities in the US alone. If built and operated at their planned capacity, annual US ammonia production could increase by over 350%, from 18 million metric tons today to 80 million metric tons within a decade. One of these, the Adams Fork Energy "blue" ammonia project in Mingo County, West Virginia, would be the single largest ammonia production facility in the world, with an annual capacity of 13 million metric tons.

Almost 90% of anticipated new ammonia production capacity is for "blue" ammonia, which purports to capture and sequester up to 95% of carbon emissions. Yet this report finds that carbon capture and sequestration claims should be met with a healthy degree of skepticism. And if capture and sequestration does not work as advertised, these ammonia facilities could annually emit upwards of 129 million metric tons of carbon dioxide.

Finally, this report finds that "green" ammonia, which is produced entirely with zero-carbon electricity, accounts for 7.5% of proposed new ammonia production in the US. Although "green" ammonia may sound promising, it is energy intensive, requiring almost 10 Megawatt-hours (MWh) of electricity to make one metric ton of ammonia. Producing the planned 4.6 million metric tons of new "green" ammonia would therefore require 44 million MWh of electricity, nearly as much as the 52 million MWh of electricity produced in the entire state of West Virginia in 2023, and a potential added burden on the US electricity grid that is already straining to meet a range of new demands.

Introduction: A New Face for the Gas Industry

The story of industrial ammonia in Appalachia is rooted firmly in the story of another industry: fracking for natural gas. It is important to this story that Appalachia is home to two of the world's largest and most productive gas fields. Because, as it turns out, the driving force behind ammonia production in Appalachia is not consumer demand for ammonia, but rather the natural gas industry's relentless pursuit of new uses and new markets for natural gas.

Since the beginning of the fracking revolution, when new drilling and extraction techniques opened up vast reserves of oil and gas deep underground, Appalachia has emerged as the workhorse of US gas production. During the boom years from 2010 to 2019 gas production in the region grew by a staggering 36% per year.[1] Today, if it were its own country, the Appalachian basin would be the third-largest gas producer in the world, behind only Russia and the rest of the United States.[1F]

Churning out nearly 34 billion cubic feet of gas daily, the three major producing states in Appalachia (Ohio, Pennsylvania, and West Virginia) supply roughly four times more natural gas than the region consumes. Three-quarters of Appalachia's gas is shipped via pipeline to other regions for a variety of uses, including LNG exports, petrochemicals, and gas-fired power. And as fracking boomed in the region, so did pipeline construction. Between 2014 and 2020, pipeline capacity increased by 16.5 billion cubic feet per day (Bcf/d)—equivalent to three times the amount of gas used by the entire state of California or four times as much as New York state— designed primarily to move gas to the Midwest, Southeast, and Canada.[2]

Yet pipeline buildout from Appalachia slowed in recent years after several major projects stalled due to uncertain economics and in the face of opposition. These include the Atlantic Coast Pipeline and the Constitution Pipeline. The only major new pipeline out of the region, Mountain Valley Pipeline, was eventually placed into service in June 2024, but it was 6 years behind schedule and over $6 billion over budget.[2F] And in the absence of new pipelines to ship gas elsewhere, the gas industry found that it could not keep increasing production. During that same period, the Permian Basin and Haynesville fields surpassed Appalachia in output.

Leading natural gas producing company CEO Toby Rice of EQT told reporters in 2022 that natural gas pipeline capacity in the Appalachian basin had "hit the wall," and that investment in midstream takeaway capacity was needed before companies could increase production.[3] EQT executive David Khani specifically called out the need to build more LNG export terminals along the eastern seaboard to meet projected growth in global natural gas demand. Khani told reporters that "70% of incremental US LNG export growth will ultimately need to come from Appalachia."[4]

[1F] According to EIA, in 2021, natural gas production increased 2% and reached 118.8 billion cubic feet per day (Bcf/d) on a monthly basis in December 2021, the highest on record. Production in the Appalachian basin led this growth, accounting for nearly a third (31%) of all gas produced in the US. The Haynesville and Permian basins, important production areas that span Texas and eastern New Mexico, accounted for just 12% and 16% respectively of all gas production in 2021. Production across the rest of the US made up the remaining 41%. See https://www.eia.gov/todayinenergy/detail.php?id=49377.

[2F] The Mountain Valley Pipeline was first announced in 2014 and projected to be completed in 2018 with a budget of $3.5 billion. Following years of delays and costly regulatory battles, the MVP entered service in June 2024 at a cost of $9.67 billion. See Marcellus Drilling News, "Mountain Valley Pipeline's Final Cost Pegged at Nearly $10 Billion", December 3, 2024, https://marcellusdrilling.com/2024/12/mountain-valley-pipelines-final-cost-pegged-at-nearly-10-billion/#:~:text=According%20to%20a%20recent%20filing,build%20MVP%20was%20%249.67%20billion.

However, Appalachia cannot supply existing LNG export markets without a significant build out of LNG facilities along the eastern and mid-Atlantic seaboard, or an increase in pipeline takeaway capacity out of Appalachia to the southeast.

To boost profits, Appalachia's gas industry will continue to advocate for new gas pipeline capacity, while at the same time searching for new profitable uses of gas within the region. For a time, it looked as though a massive regionwide petrochemical buildout would absorb demand for much of that gas and its byproducts, but those schemes largely withered in the face of dubious economics. Meanwhile, the increasing urgency of reducing fossil fuel use to protect the climate was making investors more skeptical of the industry's long-term prospects.

Then, in a surprise turn of events, the Biden administration enacted new climate legislation that, perhaps inadvertently, cast a lifeline to the industry.

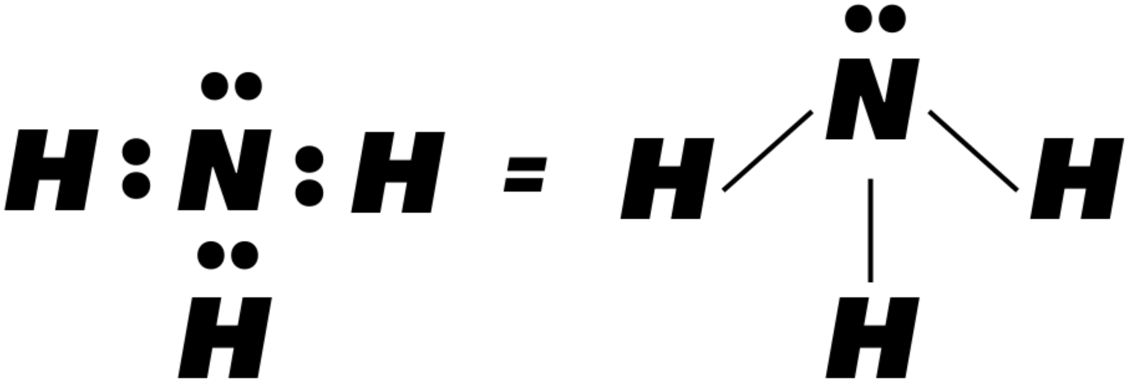
The Inflation Reduction Act of 2022 created unprecedented federal subsidies to scale up low-carbon energy technologies in the US, including for carbon capture and storage and certain kinds of hydrogen production. Because hydrogen in the US is made almost exclusively from natural gas, subsidizing hydrogen has the effect of subsidizing gas. And because ammonia in the US is made almost exclusively from a combination of hydrogen and natural gas, the new policies had the effect of subsidizing ammonia production too.

The result, then, was a sudden proliferation of new proposals to build ammonia facilities in the US—at least 37 by the most recent count—including one project in West Virginia that, if it were built, would be the single largest ammonia-making facility in the world. All of it would be subsidized by American taxpayers and all of it would be a boon to the gas industry, which would benefit from a suite of new buyers (the hydrogen and ammonia makers) for the gas it fracks in Appalachia and other basins. In other words, the Biden administration's climate legislation gave the gas industry a vested interest in carbon capture, hydrogen, and ammonia—profitable new markets, subsidized by the federal government, that could well *increase* the use of gas rather than phase it out.[5]

The History of Ammonia

To understand the promise and perils of today's planned ammonia buildout, it helps to look back in time to the roots of industrial ammonia production, nearly a hundred years ago. In the first decades of the 20th century, a German chemist named Fritz Haber invented a high-pressure method of directly synthesizing ammonia from two of the most abundant elements on earth, hydrogen and nitrogen.[6] Ammonia, or NH_3, is formed when one nitrogen atom forms covalent bonds with three hydrogen atoms ($N_2 + H_2 \rightarrow 2NH_3$).[7] This basic chemical structure forms because the nitrogen atom has five electrons and each of the three hydrogen atoms have one electron, for a combined eight electrons. Atoms have a tendency to prefer to have 8 electrons in the valence shell, or outer electron shell (except hydrogen, which prefers to have 2 electrons in its valence shell).[8] The covalent bonds between nitrogen and each hydrogen atom fills each atom's outermost electron shell.

Figure 1: Ammonia Lewis Structure[9]



Note: Figure shows eight shared electrons (left) and the three covalent bonds (right)

The first high-pressure ammonia plant in the United States was Dupont Belle Works, which began operation in 1926 in Belle, West Virginia.[10]

Then in 1931, another German chemist, Carl Bosch improved on Haber's method by using high pressure and an iron catalyst, which enabled large scale ammonia production.[11] Known today as the Haber-Bosch process, this method revolutionized the production of ammonia by making it possible to produce huge quantities of ammonia relatively cheaply.

US ammonia production scaled up during World War II in order to supply ammonium nitrate (NH4NO3) for explosives.[12] After the war, many of those plants converted to fertilizer production, contributing to the "Green Revolution," a movement towards industrializing agriculture through technological advances in crop breeding and the increased use of synthetic fertilizer and pesticides. Today, the vast majority of ammonia—an estimated 85% globally and 88% nationally—is used to make fertilizer.[13] [14] The remainder is deployed for a range of other uses in modern chemistry, including explosives, plastics, synthetic fibers and resins, and other chemical compounds.[15]

Box 1: The Problem with Ammonia Fertilizers

It is widely accepted that the use of synthetic ammonia fertilizer in agriculture boosted crop yields, making possible the global population boom from 1.65 billion in 1900 to over 8 billion today.[16] Between 1961 and 1971, for example, yields per hectare of wheat increased by about two-thirds, and those of rice by about one-third.[17]

Today, virtually all commodity crops grown in the US receive some nitrogen fertilizer input, however the four major commodity crops grown in the US—corn, cotton, soybeans, and wheat—account for 60% of crop acreage and receive over 60% of synthetic fertilizer used in the US.[18] Corn consumes more commercial fertilizer than any other crop; use of fertilizer on corn has historically accounted for more than 40% of commercial fertilizer used in the US.[19] Nearly three-quarters (74%) of US corn in turn goes towards producing biofuels and animal feed.[20]

However, decades of intensively applying synthetic fertilizers and pesticides came at devastating, and in some cases irreversible, environmental costs including water and air pollution, degraded soil quality, loss of biodiversity, and contributing to 2% of global emissions.[21] There is growing consensus among scientists that the overuse of synthetic fertilizers and pesticides results in nutrient and chemical pollution at levels that are exceeding planetary boundaries.[22]

Nitrogenous fertilizer application is one of the largest sources of water pollution in the US.[23] In fact, experts estimate that half of the nitrogen applied in agriculture is not absorbed by crops but is lost through runoff or leaching into groundwater, resulting in algal blooms and low-oxygen dead zones, including the dead zone in the Gulf of Mexico that is the largest in the world.[24] The leaching of fertilizer into groundwater increases nitrogen pollution in private drinking water wells of rural families at levels that can exceed the EPA's recommended limit for drinking water.[25]

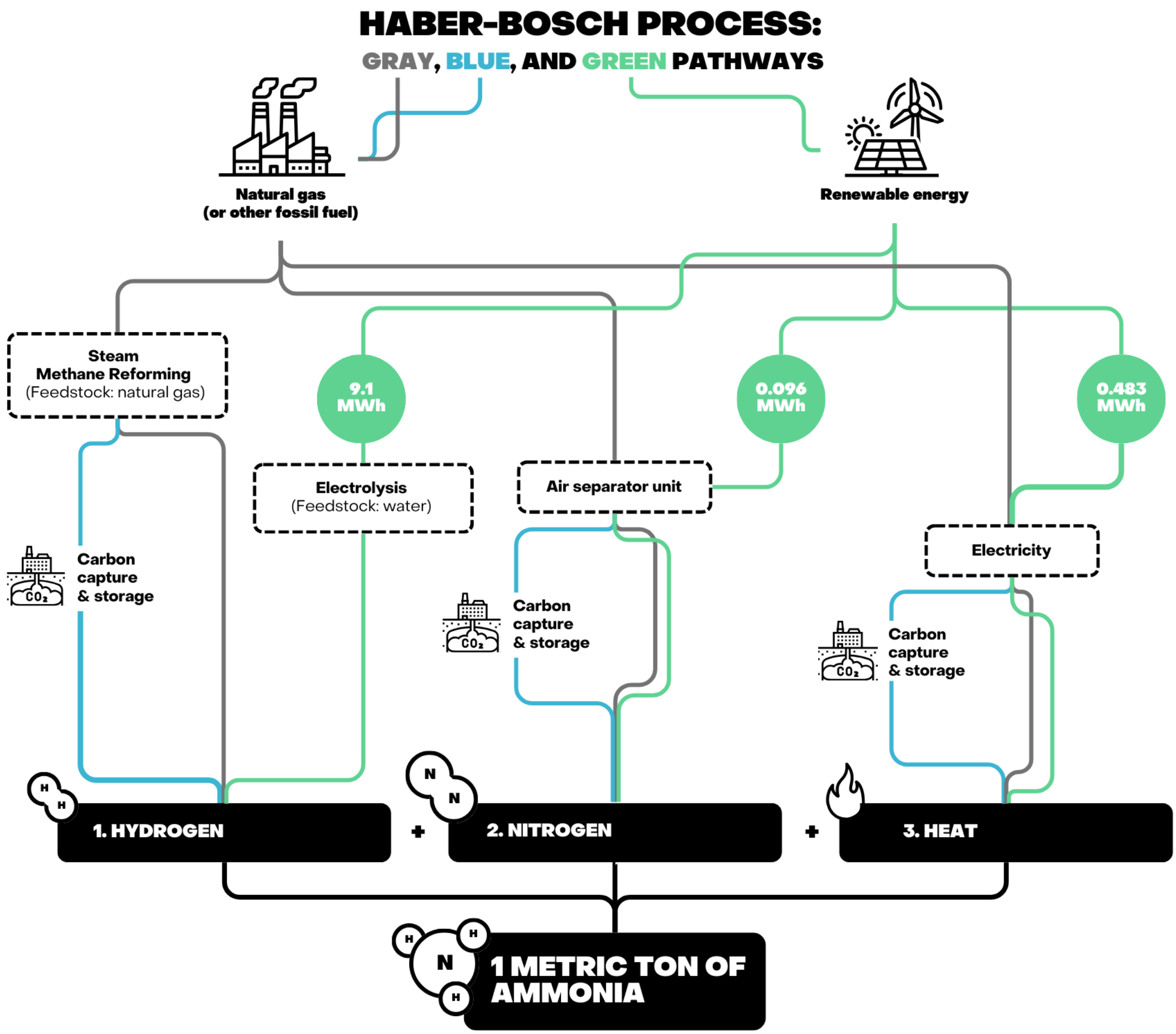
Synthetic fertilizer overuse also pollutes soil: excess nitrogen in soils can increase soil salinity and acidification.[26] Fertilizers may also contain trace metals and plastic (used as a coating or capsule), contributing to contamination and microplastic pollution in agricultural soils and the food supply.[27]

Applying nitrogen fertilizer to crops is polluting in another way too: it is a significant, though under-recognized source, of greenhouse gas emissions. According to the Center for International Environmental Law, agriculture and agricultural soils treated with nitrogen fertilizer account for roughly two-thirds of global emissions of nitrous oxide, a greenhouse gas 265 times more powerful than carbon dioxide.[28] Nitrous oxide emissions have risen by more than 45% since the 1980s[29] and today account for 7% of all global greenhouse emissions.[30]

Carbon Implications of Ammonia Production

Producing ammonia can create greenhouse gas emissions in two ways: first, by producing hydrogen using natural gas as feedstock; and second, by using natural gas or other carbon-emitting fuels to power three components (hydrogen production, nitrogen production, and heat) of the Haber-Bosch process.

Figure 2: Carbon Implications of Ammonia Production: Three Components of the Haber-Bosch Process



Source: Ohio River Valley Institute

Conventional ammonia production, or "gray" ammonia, is incredibly carbon intensive. The International Energy Agency (IEA) estimates that 2.35 metric tons of carbon dioxide equivalent (CO_2e) are emitted to produce 1 metric ton of ammonia from natural gas.[31] In 2023, the US produced 14 million tons of ammonia. Assuming that 95% of this ammonia was produced using natural gas,[32] this resulted in over 31 million metric tons of CO_2e.[3F] That is roughly the same amount of carbon as is emitted by 7.3 million gas powered cars on the road for a year, or the annual CO_2e emissions of 79 gas-fired power plants.[4]

[3F] Calculation: 14,000,000 tons ammonia * 95% produced using natural gas * 2.35 metric tons CO2e per metric ton ammonia = 31.3 million metric tons CO2e.

[4F] Assuming 4.29 metric tons CO2e per vehicle per year, and 382,205.02 metric tons CO2e per power plant annually. "Greenhouse Gas Equivalencies Calculator - Calculations and References", US Environmental Protection Agency, November 18, 2024, https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

Of the three components of the Haber-Bosch process, hydrogen production is the most energy intensive, and the most responsible for carbon emissions. “Gray” ammonia production uses hydrogen produced by the most common method, steam methane reforming. Steam methane reforming converts the methane in natural gas into hydrogen and carbon dioxide.[33] There are two steps in the process:

- First, a steam-methane reforming reaction turns methane and water into carbon monoxide and three hydrogen molecules. The chemical formula for this reaction is $CH_4 + H_2O + \text{heat} \rightarrow CO + 3H_2$.
- Second, a water-gas shift reaction turns carbon monoxide and water into carbon dioxide and hydrogen. The chemical formula for this is: $CO + H_2O \rightarrow CO_2 + H_2$

In effect, the eight hydrogen atoms found in one methane molecule (CH4) and two water molecules (H20) are converted into four hydrogen molecules (H2). The leftover atoms, one carbon and two oxygen atoms, form carbon dioxide. When this CO_2 byproduct is released the product is known as “gray” hydrogen. Fully 95% of all hydrogen produced in the US today is gray, meaning that hydrogen production emits large quantities of carbon dioxide into the atmosphere.[34, 5F]

Another method of producing hydrogen from natural gas is autothermal reforming (ATR). In the ATR process, pure oxygen is combined with methane, an exothermic reaction, to create the heat needed for the subsequent endothermic reactions of the reformation process. A drawback of ATR is it requires an expensive oxygen production plant as a startup capital cost.[35] With ATR, the carbon dioxide produced is more highly concentrated than in SMR, which may make it easier to capture and sequester.[36]

With “gray” ammonia production, natural gas (or another carbon-emitting fuel) is used as fuel to power all three components of the Haber-Bosch process. First, powering the steam-methane reforming method of producing hydrogen. Second, powering the Air Separator Unit which isolates nitrogen from the air. And third, powering the heat necessary to combine the hydrogen and nitrogen into ammonia.

To address the climate implications of hydrogen production, the energy industry has recently begun promoting—and the federal government has begun subsidizing—a new kind of ammonia, one that would allegedly eliminate harmful greenhouse gas emissions: “blue” ammonia created using “blue” hydrogen.

On closer inspection, however, “blue” ammonia turns out to be simply gray ammonia with an additional process tacked on: rather than emitting all of the carbon dioxide byproduct into the atmosphere, some of it is captured and injected underground. This process, called carbon capture and storage (CCS), is also eligible for federal subsidies,[37] though it is expensive and unproven on a large scale. As of 2023, only one US plant was actively making and selling blue hydrogen—an Air Products facility in Port Arthur, Texas.[38] Discussed in detail in the US Policy Drives Ammonia Buildout section of this report, there are at least 26 additional blue ammonia projects—that is, gray ammonia plus CCS—in the planning phase in the US.

The carbon picture gets better, at least in theory, for blue ammonia. According to IEA, producing 1 metric ton of “blue” ammonia emits just 0.12 metric tons CO_2e.[39] The IEA assumes that CCS results in a 95% reduction in emissions compared to gray ammonia production. But new analysis casts doubt on these optimistic figures. A September 2023 study by the Institute for Energy Economics and Financial Analysis (IEEFA) found

---

[5F] The remaining 4% is produced from coal gasification while electrolysis accounts for only 1%.

no evidence that commercial-scale carbon capture projects have been able to achieve an 80% capture rate, let alone the 95% capture rate assumed by the IEA.[40]

There is a more legitimately climate-friendly method for making ammonia. “Green” ammonia is ammonia produced with zero carbon emissions. To qualify, all three of the Haber-Bosch components must be powered by zero-carbon electricity. “Green” ammonia must also be sourced from “green” hydrogen.

“Green” hydrogen uses water and electrolysis (which can be powered by renewable energy, like solar, wind, or hydroelectricity) to split hydrogen (H_2) from the oxygen atoms (O) in H_2O. Only green hydrogen production is truly clean and, potentially at least, could create zero carbon emissions, but it is not yet market-ready at scale. Today, only about 1% of US hydrogen production uses electrolysis.[41]

Producing 1 metric ton of green ammonia requires approximately 9.679 MWh electricity.[6F] Green hydrogen alone accounts for over 90% of the required electricity. As discussed in the next section, the US produced 14 million metric tons of ammonia in 2023. Producing 14 million metric tons of “green” ammonia would require over 135 million MWh electricity, roughly equivalent to all electricity consumed in the state of Pennsylvania in 2023.[42]

There are potential problems with green ammonia too. That’s because green ammonia production is electricity-intensive, and it is only “green” insofar as the electricity it uses is renewable and carbon-free. If the electricity is generated at a coal- or gas-fired power plant, then it’s still a carbon-intensive production method. Across the US, 60% of electricity was generated with fossil fuels in 2023, while 40% was generated by other sources like nuclear, hydroelectricity, solar, and wind.[43]

These classifications can be nuanced. For example, ammonia produced using “green” hydrogen as feedstock but using natural gas as a fuel source for the other Haber-Bosch processes, and accompanied by carbon capture and sequestration, would be classified as “blue” ammonia.

The vast majority of new proposed hydrogen projects in the US, including those in Appalachia, are “blue” hydrogen projects that rely on natural gas as the principal input. Even if these projects successfully capture and store the carbon dioxide emissions underground—a dubious proposition at best, based on the available evidence—the process would still be dirty. Upstream from the hydrogen processing plant, the extraction and transportation of natural gas would still result in a range of emissions from the fracking wells, compressor stations, pipelines, and other infrastructure, all of which leaks methane and creates a welter of other environmental and health problems.[44]

[6F] Methodology: The Air Separator Unit used to produce nitrogen requires 0.096 kWh per kg of ammonia produced. The Haber-Bosch Synthesizer used to combine hydrogen and nitrogen requires 0.483 kWh per kg of ammonia produced. Source: Enverus Clean Fuels Model.

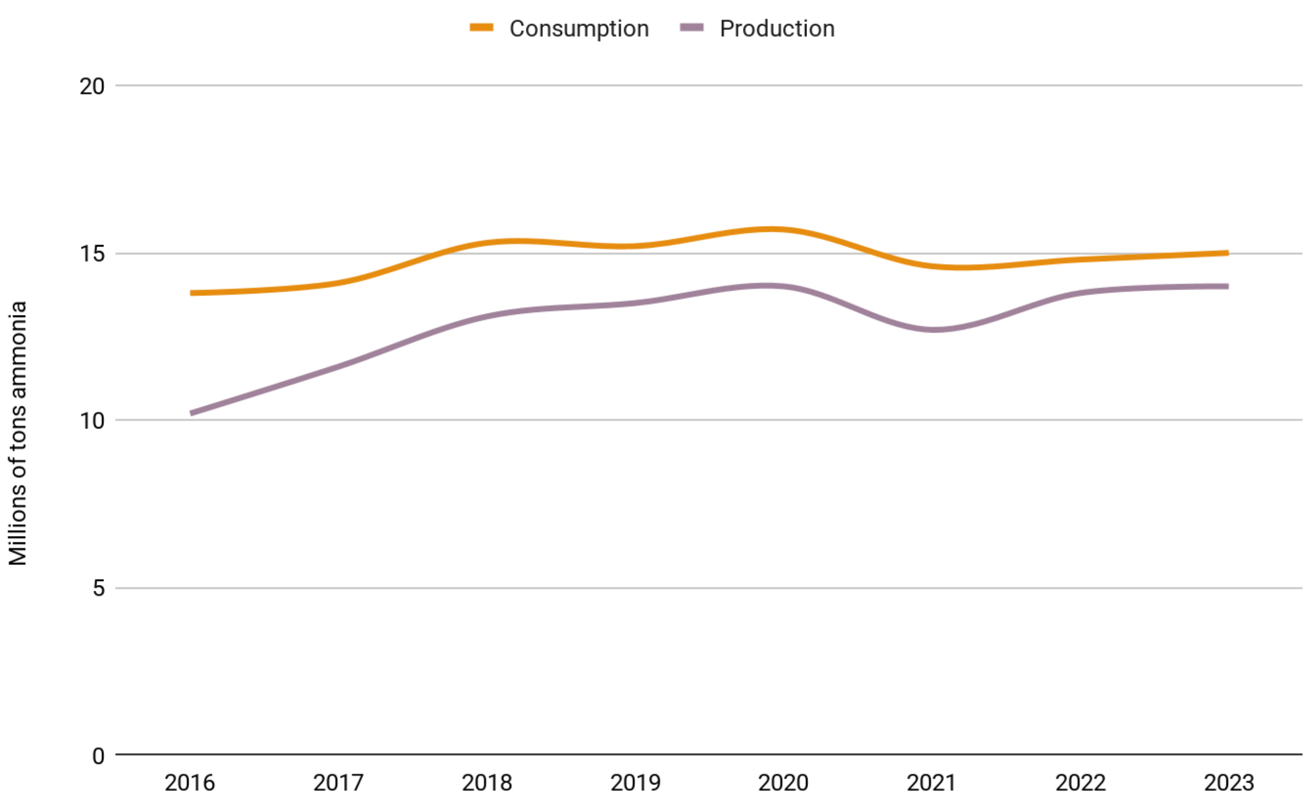
Producing 1 kg of hydrogen through electrolysis uses 50 kWh electricity. To produce 1 kg ammonia, 0.182 kg of hydrogen are needed. 50 kWh * 0.182 = 9.1 kWh per kg ammonia.
Sources: Bernard Chukwudi Tashie-Lewis and Somtochukwu Godfrey Nnabuife, “Hydrogen Production, Distribution, Storage and Power Conversion in a Hydrogen Economy - A Technology Review”, Chemical Engineering Journal Advances, September 1, 2021, https://www.sciencedirect.com/science/article/pii/S2666821121000880 ;
Massimo Rivarolo et al., “Clean Hydrogen and Ammonia Synthesis in Paraguay from the Itaipu 14 GW Hydroelectric Plant”, ChemEngineering, November 1, 2019, https://doi.org/10.3390/chemengineering3040087

Ammonia Production, Use, and Transport Today

Ammonia production in the US has nearly doubled since 2012, thanks to consistently low US natural gas prices resulting from the fracking boom.[45] A flood of cheap gas contributed to restarting ammonia plants that were closed in the early 2000s during a period of high natural gas prices, as well as to developing new ammonia production capacity. Since 2016, the United States has produced between about 10 million and 14 million metric tons of ammonia annually, while consuming between about 14 and 16 million metric tons. The difference was made up by imports from abroad, which have decreased as domestic ammonia production rose. Between 2012 and 2021, ammonia imports fell from 37% of total US ammonia supply to 14% of the total supply.[46]

Figure 3: US Ammonia Consumption Has Exceeded Production Over the Past Decade

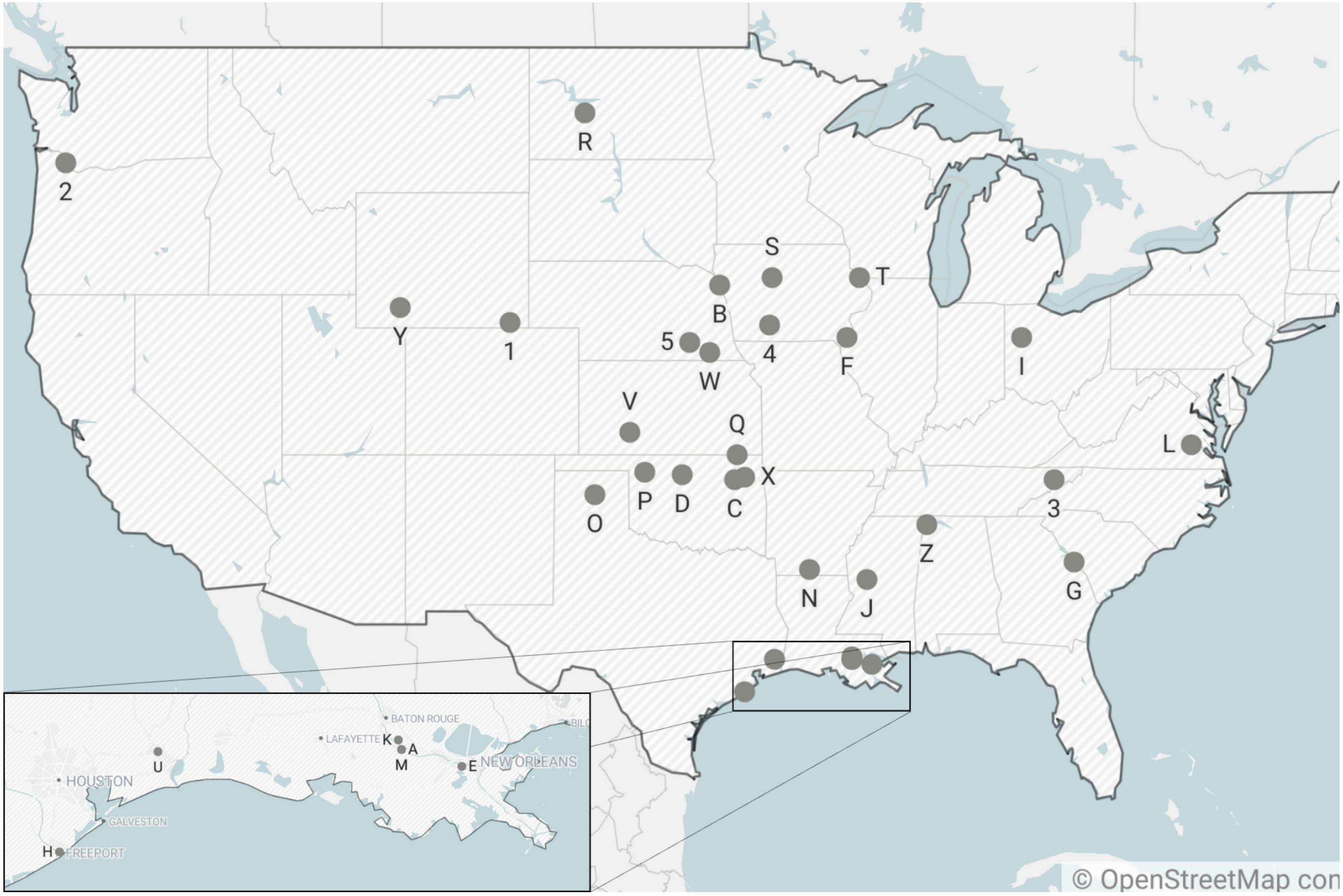
Domestic ammonia production and consumption, 2016-2023



Source: US Geological Survey, Mineral Commodity Summaries

As of 2022, ammonia was produced in one of 31 facilities across the United States[47] with a combined annual capacity of more than 18 million metric tons and an actual output of roughly 14 million metric tons. Most ammonia produced in the US comes from facilities in Louisiana, Oklahoma, and Texas. Louisiana alone has 33% of American operational ammonia production capacity (see Appendix A).

Map 1: Operational Ammonia Plants (2022)



Source: Environmental Integrity Project's Oil & Gas Watch Database
Note: See Appendix A for the full list of ammonia plants.

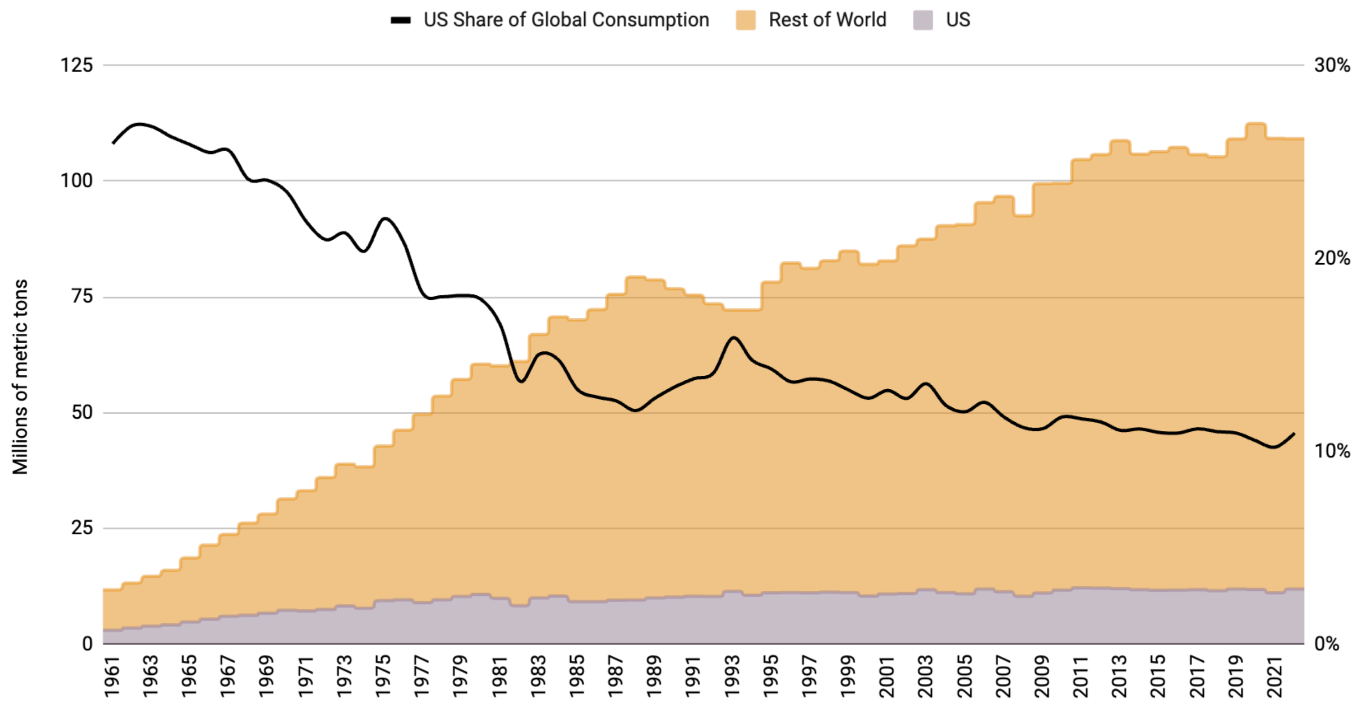
Conventional Ammonia Use

Ammonia is the world's second-most produced chemical behind sulphuric acid,[48] with global production accounting for 2% of the world's total energy use.[49] The IEA projects demand for ammonia fertilizers and other conventional uses like plastics and explosives to increase from 185 million tons in 2020 to 230 million tons in 2050.[50] Globally, most ammonia production (85%) is used directly or indirectly in agriculture, with the rest used mainly in the petrochemical industry.[51] Ammonia and ammonia-based products have wide applications including use as agricultural nitrogen fertilizer, a refrigerant gas and in air-conditioning equipment, waste and wastewater treatment, household cleaning products, cosmetics, and in the manufacture of plastics, explosives, textiles, pesticides, dyes, and other chemicals.

US consumption of nitrogen fertilizers, the primary use of ammonia today, more than tripled from just over 3 million metric tons in 1960 to over 10 million metric tons in 1980.[52] [53] Since then, US nitrogen fertilizer consumption has increased only slightly, to nearly 12 million metric tons in 2022. At the same time, global consumption of nitrogen fertilizers has skyrocketed. Not including the US, the rest of the world's nitrogen fertilizer consumption increased more than eleven-fold since 1961, from 8.7 million tons in 1961 to 97 million tons in 2022. Accordingly, the US share of global nitrogen fertilizer consumption decreased from over 25% in 1961 to 11% in 2022.

Figure 4: Nitrogen Fertilizer Consumption Is Growing Rapidly, though Faster Outside the US

Global and domestic nitrogen fertilizer consumption and the US share of global consumption, 1961-2022



Source: International Fertilizer Association, Global and US Consumption of Nitrogen Fertilizers

Ammonia Transport by Land and Sea

In the existing conventional ammonia market, large quantities of ammonia are typically transported over land as a pressurized liquid by railway in tank cars, or by highway in tanker trucks, in agricultural areas in nurse tanks (a vessel or trailer used to store and transport large amounts of water, fertilizer, herbicides, and chemicals), and also via pipelines.[54] Some ammonia is transported on water via barges, especially along the Mississippi River and its tributaries.[55] Ammonia is stored in pressurized liquid form at distribution centers, in terminals, or in production sites.[56] Ammonia is also imported and exported by the millions of tons via liquefied petroleum gas (LPG) tankers. The Gulf Coast is home to the majority of US ammonia import and export terminals.[57]

Fertilizers, on the other hand, can be transported as solids in the form of urea, ammonia nitrate, calcium nitrate, and potassium nitrate, in addition to liquid form or as a compressed gas. According to the Fertilizer Institute, rail is among the most efficient ways to transport fertilizer products long distances, especially compared to trucks. A single rail car can carry four times as much product as a tanker truck and rail transport is far less risky.[58]

The Future of Ammonia

Part 1: Uncertain Growth Forecasts

It is best to understand the 37 or more proposed new ammonia facilities in the US as part of a new ammonia market, not just an evolution of the existing market.[59] Yet the future of ammonia production is highly uncertain, ranging from modest to explosive growth. And the uncertainty arises from both the supply side and the demand side of the global ammonia market.

There is significant uncertainty on the supply side because the increase in ammonia production depends on the speed and scale at which "blue" and "green" ammonia production facilities can be built and made operational, which in turn depend on the speed and scale at which "blue" and "green" hydrogen production facilities can be built and made operational.

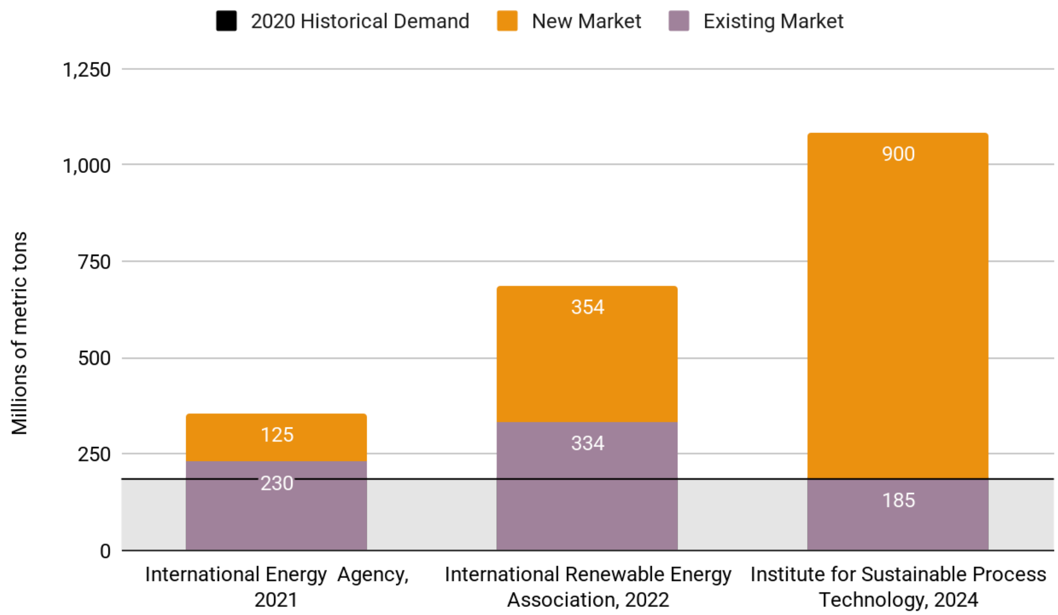
On the demand side, the existing market is relatively well understood and it is projected to grow. Demand for ammonia fertilizers and other conventional uses like plastics and explosives is projected by IEA to increase by 25% between 2020 and 2050, from 185 million metric tons to 230 million.[60] But new market demand has two facets and both are uncertain. First, ammonia could be used as a fuel, primarily in maritime vessels, or in combination with coal in power plants. Second, ammonia could be used as a carrier for hydrogen transportation. (These potential applications are explored more fully in the next section, "Possible Futures: clean energy applications.")

The growth forecasts for new markets vary wildly (Figure 5). The IEA has the most conservative growth forecast for new markets, projecting 125 million metric tons of ammonia to be used as an energy carrier by 2050.[61] This is inclusive of all energy carrier uses, including maritime fuel, co-firing in coal plants, or as a carrier for hydrogen imports.[62]

On the other end of the spectrum, the Netherlands-based Institute for Sustainable Process Technology is extremely bullish on the future of ammonia demand. Researchers there argue that, if ammonia is widely accepted as an energy carrier and becomes a go-to fuel in the power sector and shipping industry, the global clean ammonia market could grow to 900 million metric tons by 2050, in addition to the existing roughly 185 million metric ton ammonia demand.[63] In this scenario, by 2050 global ammonia demand could include 600 million metric tons for power generation, 200 million metric tons for maritime bunker fuels, and 100 million metric tons for new industrial markets such as steel production or sustainable aviation fuels.[64]

A third forecast by the International Renewable Energy Agency projects ammonia demand to be roughly 690 million metric tons by 2050.[65] This projection assumes global decarbonization in line with keeping warming to 1.5 degrees Celsius. In this scenario, by 2050, IRENA projects conventional ammonia use would increase to 334 million metric tons. New ammonia markets are projected to total 354 million metric tons: 197 million metric tons ammonia consumed as a maritime fuel, 127 million metric tons ammonia used as a hydrogen carrier, and 30 million metric tons ammonia used for power generation.[66]

Figure 5: Three Projections for Ammonia Demand Growth



Source: International Energy Agency, International Renewable Energy Association, Institute for Sustainable Process Technology

Yet CF Industries, the largest ammonia producer in the world, is far more cautious about ammonia's future demand. The CF Industries 2023 Shareholder report is worth quoting at length:

> *"The market for green and low-carbon (blue) ammonia may be slow to develop, may not develop to the size expected or may not develop at all. Moreover, we may not be successful in the development and implementation of our green and low-carbon ammonia projects in a timely or economic manner, or at all, due to a number of factors, many of which are beyond our control… We believe the demand for green and low-carbon ammonia could take several years to materialize and then ten or more years to fully develop and mature, and we cannot be certain that this market or the market for green and low-carbon hydrogen will grow to the size or at the rate we expect or at all."*[67]

In other words, industry leaders think it is possible that global ammonia consumption may never increase beyond its existing market for fertilizers, plastics, and explosives. In our opinion, the IEA forecast is the most plausible. Even so, the IEA forecast is dependent on technological advances and adoption occurring at a rate that so far has not been seen.

For example, in 2021, the IEA's Ammonia Technology Roadmap stated that the maritime engine manufacturers MAN and Wärtsilä were expecting their newly developed ammonia-fueled engines to be commercially available by 2024.[68] But both companies have delayed their timelines. As of August 2024, Wärtsilä expected to deliver its first ammonia-fueled engine on a new vessel in early 2025, with widespread sales expected in the 2030s.[69] MAN announced in December 2024 that testing of a two-stroke engine running on ammonia was moving to the next phase, with testing set to continue until mid-2025.[70]

Because there is currently no market for ammonia-as-fuel it is reasonable to conclude that virtually all of the ammonia produced over the next ten to twenty years will be used as synthetic fertilizer or in more traditional petrochemical applications like plastics and synthetic fibers.

Box 2: The Future Uncertainty of Ammonia Transport

Shipping ammonia internationally is done with ammonia carrying vessels, often Liquified Petroleum Gas (LPG) shipping vessels that have been converted to allow them to carry ammonia. Transporting ammonia presents more difficulties than transporting LPG because it can cause stress corrosion cracking in containment systems made of carbon-manganese steels.[71]

If ammonia use grows in line with the bullish projections, ammonia transport will also increase. IRENA's 2022 report states that 235 ships with capacity of 85,000 cubic meters of ammonia each will be needed to transport 300 million metric tons of ammonia per year by 2050.[72] To reach this scale, one ammonia transport ship would need to be built or converted from LPG every six weeks from 2025 through 2050.

The industry is taking steps toward increasing the size of the fleet. According to risk management and maritime advisor group Det Norske Veritas,[73] there have been more than 50 very large ammonia carriers (VLACs) ordered between November 2023 and October 2024. These carriers will likely first transport liquefied petroleum gas, before switching to transporting ammonia as the markets change over time.[74] Maersk Tankers ordered up to 10 very large ammonia carriers from South Korean manufacturer Hyundai Samho Heavy Industries in November 2023,[75] partnering with Mitsui & Co on at least 4 of the VLACs. The vessels are scheduled for delivery in late-2026.[76] Another shipping company, Naftomar Shipping, announced in December 2023 an order of 4 VLACs to be built by Hanwha Ocean. The ships would have a capacity of 93,000 cubic meters.[77]

With increased ammonia transport and use comes the increased risk of a spill. Compared to conventional oil spills, ammonia spills are less likely to widely disperse, but are more dangerous to fish.[78] Ammonia is toxic, which means that maritime workers must take extra precaution when completing ship-to-ship bunkering procedures. For example, in a successful ship-to-ship ammonia transfer that took place in September 2024 at the Port of Dampier in Western Australia,[79] workers employed a long list of safety measures based on a 2023 study commissioned by the Global Centre for Maritime Decarbonization.[80]

Part 2: Potential Clean Energy Applications

In addition to the conventional uses of ammonia, there are several potential clean energy applications if produced with zero carbon emissions: as maritime fuel, as an additive to fuel in power plants, or as a carrier for moving hydrogen.

First, ammonia can be used as a maritime fuel. It has around 40% of the energy density and volumetric density of gasoline.[81] Due to the difference in energy density, maritime vessels using ammonia fuel will either need to carry about 2.5 times the amount of fuel to go the same distance as with fossil fuels or refuel more frequently.[82] Because ammonia has no carbon atoms, it produces zero CO_2 when combusted. Greenhouse gas emissions associated with ammonia fuels are due to emissions from producing ammonia, not combusting it.

Second, ammonia can be used for power generation by co-firing it in combination with gas or coal in power plants. Replacing 20% of the coal by co-firing with blue ammonia may reduce the coal plant's emission intensity by 16%. However, ammonia co-firing would need to increase to over 60% to reduce emissions intensity below what could be achieved by burning only coal while capturing 90% of the carbon dioxide emissions.[83] Japan is one of the leading proponents of using ammonia directly for power generation, in part due to the high cost of imported fossil fuels.[84] JERA, the largest Japanese power generator, successfully conducted a three-month trial in which it co-fired 20% ammonia with coal.[85] JERA is continuing to assess the impact of ammonia on the power station's boiler and other equipment. One of JERA's goals is to increase the proportion of ammonia used in its power generation to above 50%.[86] While co-firing ammonia with coal may reduce the emissions of the coal plant, it may also extend the life of the coal plant. South Korea is another country that is moving ahead with plans to use clean ammonia in coal-plant co-firing.[87] Two proposed ammonia projects in the Gulf Coast—CF Industries' planned project in Louisiana and Exxon's Baytown facility—recently signed agreements with Japan and South Korean power companies respectively to buy ammonia to co-fire with coal.

And third, ammonia can be used as a carrier for hydrogen transportation. In a future where hydrogen is used widely across economic sectors, from fueling vehicles to powering industry,[88] hydrogen transport could greatly increase. Ammonia could be preferable for transport compared to hydrogen because it is about 1.5 times as energy dense as hydrogen, more cost-effective to liquefy, and the transportation infrastructure already exists (though it would need to be expanded in line with demand).[89] The process would look like this: first, ammonia is synthesized from hydrogen, then the ammonia is liquefied and transported, then the ammonia is converted back into hydrogen by "cracking" the molecule, and finally the hydrogen is used as energy for its final purpose.

However, using ammonia as a carrier for hydrogen transportation may not be worthwhile from an energy efficiency perspective. To start, it takes about 10 MWh of energy to produce 1 metric ton of ammonia, which carries about 5 MWh of energy.[90] Add to that the energy to transport the ammonia long-distance, the energy to convert it back to hydrogen, and the energy efficiency of the final hydrogen use. Each step in this process decreases the final energy output compared to energy inputs of producing and transporting the fuel. For many of the proposed use cases, it is unlikely that the energy output would justify the much greater energy input.

Each of these markets are new and emerging, and demand forecasts for each is highly uncertain. The technology for use of ammonia in these applications is still under development and has not been proven at scale, and even industry insiders admit that the demand for low-carbon ammonia could take several years to materialize.

Part 3: US Policy Drives Ammonia Production Buildout

The US government is forging ahead with historic investments in ammonia production across the country. The Inflation Reduction Act of 2022 offered unprecedented subsidies to scale up low-carbon energy technologies in the US, including low-carbon hydrogen and ammonia production. Many of the proposed "blue" and "green" ammonia projects have been revitalized thanks to the incentives passed as part of this legislation. Prior to carbon capture and sequestration, the 26 "blue" ammonia projects would emit 129 million metric tons of CO_2e per year if built and used at their full capacity.

There are two tax credits in the Inflation Reduction Act that are driving new ammonia projects: the Section 45Q tax credit and the Section 45V tax credit. Projects must begin construction before January 1, 2033 to qualify for either credit; 45Q tax credits apply for 12 years and 45V tax credits apply for 10 years.[91] Companies may only claim either 45V or 45Q tax credits, but not both.[92]

The Section 45Q tax credits incentivize carbon capture and sequestration. Companies may claim a 45Q tax credit for each metric ton of CO_2 captured and sequestered, defined as CO_2 that would have been released into the atmosphere if not for the company capturing and sequestering it.[93] However, because the credit is based on CO_2 sequestered, not emissions reduced, the 45Q tax credit could incentivize companies to produce hydrogen using carbon-intensive coal instead of the comparatively clean natural gas, which would produce more carbon for the companies to then sequester.[94]

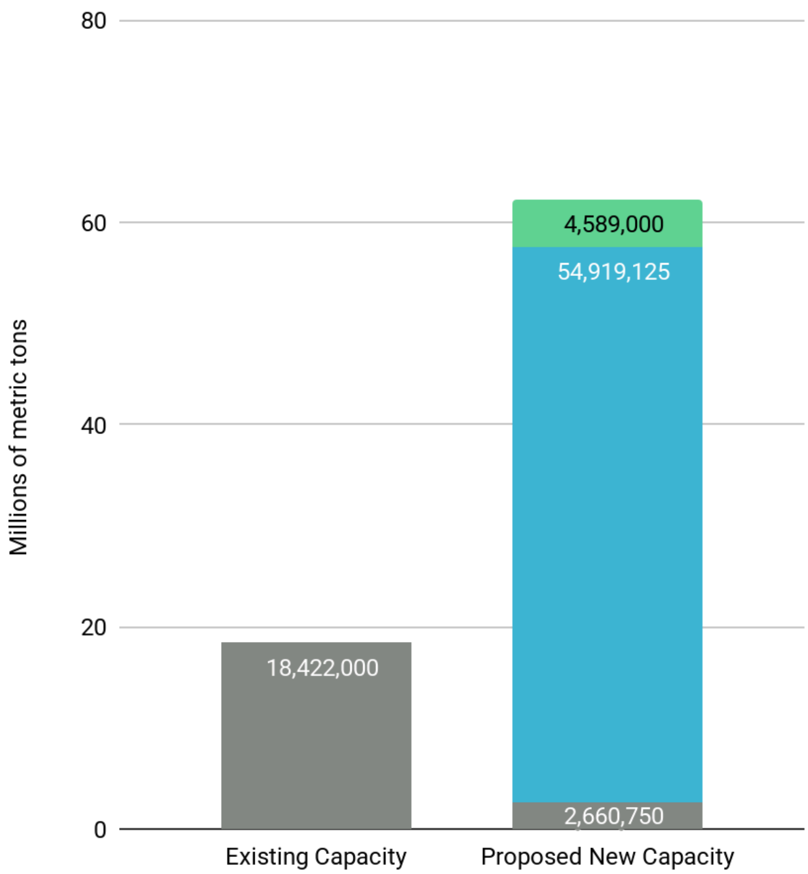
Section 45V tax credits incentivize clean hydrogen production, defined as emitting less than 4 kg CO_2e per 1 kg of hydrogen.[95] The tax credit increases as the hydrogen production gets cleaner, from $0.60 per kg of hydrogen produced that emits less than 4 kg CO_2e, up to $3.00 per kg of hydrogen produced that emits less than 0.45 kg CO_2e. Assuming the electric grid emits 0.44 kg CO_2e per kWh, hydrogen electrolyzers must be powered by zero-emission electricity for at least 84% of the time to qualify for the full $0.60 per kg hydrogen credit.[96]

These federal incentives have unleashed a torrent of new ammonia project proposals in the US. As of October 2024, there are at least 37 ammonia projects planned that will add a combined 62 million metric tons of ammonia production capacity in the United States.[7F]

In less than a decade, slated development would increase US ammonia production by nearly 350%, from 18 million metric tons per year to around 80 million. If built, these 37 projects operating at full capacity would increase global ammonia production by roughly one third. This estimate is likely low because 8 of the 37 projects have no public information about their ammonia production capacity.

[7F] Methodology: The Oil and Gas Watch Database, maintained by the Environmental Integrity Project, tracks thousands of fossil fuel infrastructure projects, including the construction of ammonia facilities. The 37 projects selected for this analysis were chosen because they are a) directly producing ammonia (as opposed to hydrogen to produce ammonia at another site or production of ammonia derived products like urea), b) are either under construction, construction is on hold, or they have been proposed, and c) would constitute an increase in ammonia production capacity.

Figure 6: Proposed Ammonia Projects Would Quadruple US Production[8F]



Source: Oil and Gas Watch Database (as of October 2024)

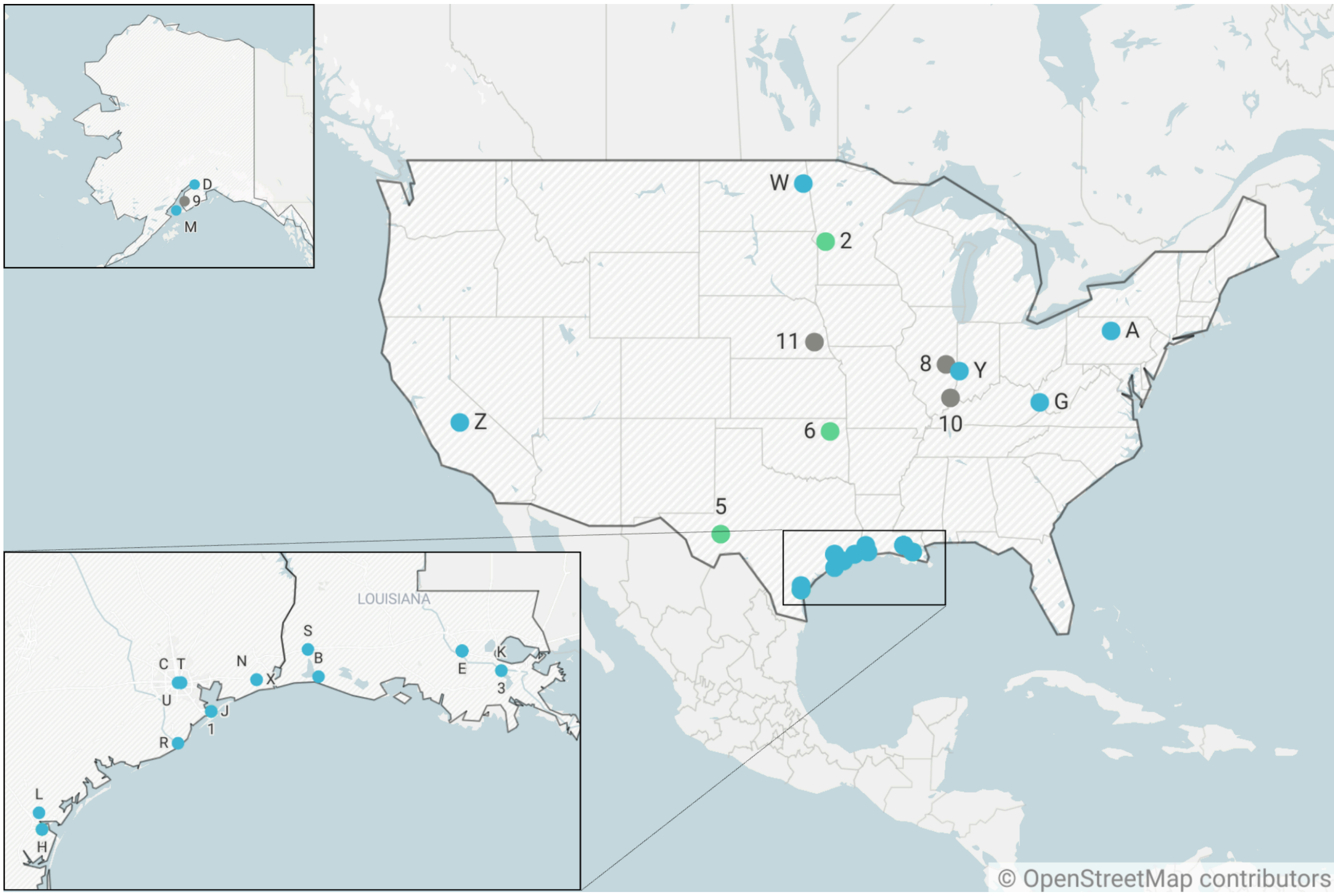
A majority of the projects, 22 of 37, are located on or near the Gulf Coast. As discussed in detail in the Appalachia's Ammonia Buildout section, only two of the projects are located in Appalachia: the TransGas Adams Fork Ammonia Plant in Mingo County, WV, and the ARCH2 KeyState Natural Gas Synthesis Plant in Clinton County, PA. Further, there are rumors of an additional ammonia project in southern West Virginia connected to ARCH2.[97]

Additionally, new ammonia projects are frequently announced, delayed, and canceled as permitting and financing processes progress, which makes it difficult to know the current status of new ammonia projects. This analysis was completed based on the status of new ammonia projects as of October 1, 2024.[9F]

[8F] There are 31 existing, operational ammonia plants which have the annual capacity to produce 18.4 million metric tons of ammonia. There are 37 proposed new ammonia projects, which would have the annual capacity of at least 62 million metric tons. The 26 blue ammonia projects have at least 54.9 million metric tons capacity. The 8 green ammonia projects have at least 4.6 million metric tons capacity. The 4 gray ammonia projects have 2.7 million metric tons capacity. The capacity for 6 blue ammonia projects and 2 green ammonia projects is unknown.

[9F] A separate analysis by the Environmental Integrity Project as of November 2024 found 37 projects promising new ammonia capacity, all of which are listed in its Oil & Gas Watch database. Thirty-four of the identified projects are the same as those analyzed here. The three projects included here but not in the November 2024 analysis are: the Nutrien Geismar Ammonia Plant, the Hanwha/Ineos Low Carbon Ammonia Facility, and the Donaldsonville Nitrogen Complex. The three projects included in OGW's November 2024 analysis but not here: the First Ammonia Port of Victoria Green Ammonia Plant (330,000 metric tons green ammonia), the Ten08 Clean Ammonia Plant (1,400,000 metric tons combined green and blue ammonia), and the ACME Port of

Map 2: Planned and Proposed Ammonia Facilities



Source: Environmental Integrity Project's Oil & Gas Watch Database, 2024
Note: The precise location for four of the projects is yet unknown: the Grannus Blue Ammonia and Hydrogen Project in California, the Gulf Coast Hydrogen Plant and the Yara/BASF Gulf Coast Blue Ammonia Plant in the Gulf Coast, and Hanwha/Ineos Low Carbon Ammonia Facility in a yet to be determined state.

Among the 37 projects are 26 blue ammonia projects, 8 green ammonia projects, and 4 gray ammonia projects.[10F]

The 26 blue ammonia projects have a combined production capacity of 55 million metric tons per year. This estimate is likely low because 6 of the projects (A-F in the table below) have no public information about their production capacity.[11F] Combined, these projects would consume 51 billion cubic meters (1.8 trillion cubic feet) of natural gas.[12F] The CO_2 equivalent emissions to produce 55 million metric tons of blue ammonia range from 6.6 million metric tons CO_2e (assuming 95% CCS) to 64.5 million metric tons CO_2e (50% CCS). If there is no CCS, these projects would emit 129 million metric tons CO_2e per year.

Victoria Green Ammonia Plant (1,200,000 metric tons green ammonia). Including these three projects in OGW's November analysis, the total new ammonia production capacity would be roughly 65 million metric tons per year.

[10F] The Port of Corpus Christi Blue and Green Ammonia Facility is double counted because it will produce both blue and green ammonia.

[11F] Lacking further information about the project, we assume that 80% of ammonia production at the Port of Christi Blue and Green Ammonia Facility will be blue ammonia, and 20% will be green ammonia.

[12F] Assuming 900 cubic meters of natural gas to produce 1 metric ton ammonia.

Table 1: Proposed Blue Ammonia Projects

Map	Facility	Location	Expected Operation	New Annual Capacity (mt/year)	50% CCS Emissions (mt/CO_2e)	95% CCS Emissions (mt/CO_2e)
A	**ARCH2 KeyState Natural Gas Synthesis Plant**	Clinton County, PA	2027/2028	Unclear	?	?
B	**G2 Net-Zero Energy Complex**	Cameron Parish, LA	2025	Unclear	?	?
C	**Gulf Coast Hydrogen Plant**	Gulf Coast, State TBD	Unknown	Unclear	?	?
D	**Grannus Alaska Blue Ammonia Plant & Offshore Terminal**	Port MacKenzie, AK	Unknown	Unclear	?	?
E	**CF Industries/POSCO Gulf Coast Blue Ammonia Plant**	Ascension Parish, LA	2028	Unclear	?	?
F	**CF Industries/Lotte Gulf Coast Blue Ammonia Plant**	Ascension Parish, LA	2027	Unclear	?	?
G	**TransGas Adams Fork Ammonia Plant**	Mingo County, WV	2025	13,140,000	15,439,500	1,576,800
H	**Port of Corpus Christi Blue and Green Ammonia Facility**	Nueces County, TX	2030	10,000,000	9,400,000	960,000
I	**Clean Hydrogen Works - Ascension Clean Energy Facility**	Ascension Parish, LA	2027	7,884,000	9,263,700	946,080
J	**Blue Bayou Ammonia Plant**	Galveston County, TX	2032	3,000,000	3,525,000	360,000
K	**St. Rose Blue Ammonia Facility**	St. Charles Parish, LA	2027	2,920,000	3,431,000	350,400
L	**Enbridge Ingleside Blue Ammonia Plant**	San Patricio County, TX	2028	2,920,000	3,431,000	350,400
M	**Cook Inlet Blue Hydrogen and Ammonia Hub**	Cook Inlet, AK	Unknown	2,200,000	2,585,000	264,000
N	**OCI Beaumont Clean Ammonia Complex**	Jefferson County, TX	2025	2,190,000	2,573,250	262,800
O	**Air Products Darrow Blue Energy Facility**	Ascension Parish, LA	2026	1,850,000	2,173,750	222,000
P	**CF Industries/Mitsui Gulf Coast Blue Ammonia Plant**	Ascension Parish, LA	2027	1,500,000	1,762,500	180,000
Q	**Nutrien Geismar Ammonia Plant**	Ascension Parish, LA	2026	1,300,000	1,527,500	156,000
R	**Yara/BASF Gulf Coast Blue Ammonia Plant**	Gulf Coast, State TBD	Unknown	1,300,000	1,527,500	156,000
S	**Lake Charles Blue Ammonia Plant**	Calcasieu Parish, LA	2030	1,200,000	1,410,000	144,000
T	**Houston Ship Channel Low-Carbon Ammonia Plant**	Harris County, TX	2027	1,100,000	1,292,500	132,000
U	**ExxonMobil Baytown Chemical Plant**	Harris County, TX	2029	1,000,000	1,175,000	120,000
V	**Hanwha/Ineos Low Carbon Ammonia Facility**	State TBD	2030	1,000,000	1,175,000	120,000
W	**Grand Forks Fertilizer Plant**	Grand Forks County, ND	Unknown	885,125	1,040,022	106,215
X	**Cormorant Clean Energy Project**	Jefferson County, TX	2027	880,000	1,034,000	105,600
Y	**Wabash Gasification Plant**	Vigo County, IN	Unknown	500,000	587,500	60,000
Z	**Grannus Blue Ammonia and Hydrogen Project**	California	2027	150,000	176,250	18,000

The 8 green ammonia projects have a combined production capacity of 4.6 million metric tons. This estimate is likely low because 2 of the projects (1 and 2 in the table below) have no information about their production capacity.[13F]

Discussed in the Carbon Implications of Ammonia Production section of this report, it takes 9.679 MWh of electricity to produce one metric ton of green ammonia. Producing the 4.6 million metric tons of green ammonia promised by these proposed projects will require 44 million MWh of electricity. To put that in perspective, the entire state of West Virginia's total net electricity generation in 2023 was 52 million MWh. For these projects to truly be zero-carbon, all of their electricity would need to come from non-carbon energy sources, such as solar, wind, hydro or nuclear (hydrogen produced by nuclear-powered electrolysis is "pink"). If the electricity is sourced from carbon-emitting fuels like coal or natural gas, these ammonia projects would not be green.

Table 2: Proposed Green Ammonia Projects

Map	Facility	Location	Expected Operation	New Annual Capacity (metric tons/year)	Electricity Needed (Mwh)
1	**Galveston Bay Clean Fuels Export Complex**	Galveston County, TX	2028	Unclear	?
2	**Heartland Hub: Morris Fertilizer Plant**	Stevens County, MN	Unknown	Unclear	?
H	**Port of Corpus Christi Blue and Green Ammonia Facility**	Nueces County, TX	2030	10,000,000	19,358,000
3	**AmmPower Green Hydrogen and Ammonia Production Facility**	St. Charles Parish, LA	Unknown	1,460,000	14,131,340
4	**Avina Nueces Green Ammonia Plant**	Nueces County, TX	2027/2028	800,000	7,743,200
5	**Trans Permian H2 Hub: MMEX Green Hydrogen to Green Ammonia Project**	Pecos County, TX	Unknown	209,000	2,022,911
6	**Verdigris Nitrogen Plant**	Rogers County, OK	Unknown	100,000	967,900
7	**Donaldsonville Nitrogen Complex**	Ascension Parish, LA	2024	20,000	193,580

[13F] Lacking further information about the project, we assume that 80% of ammonia production at the Port of Christi Blue and Green Ammonia Facility will be blue ammonia, and 20% will be green ammonia.

The 4 gray ammonia projects have a combined production capacity of 2.7 million metric tons of ammonia. Producing 2.7 million metric tons of gray ammonia would generate 6.3 million metric tons of CO_2e, adding to the climate crisis without even attempting to capture or sequester the carbon emissions.

Table 3: Proposed Gray Ammonia Projects

Map	Facility	Location	Expected Operation	New Annual Capacity (metric tons/year)	Emissions (No CCS) (mt/CO_2e)
8	**Cronus Ammonia Plant**	Douglas County, IL	2024	1,100,000	2,585,000
9	**Nutrien Kenai Nitrogen Operations**	Kenai Peninsula, AK	2027	630,000	1,480,500
10	**Posey County Midwest Fertilizer Plant**	Posey County, IN	2025	591,300	1,389,555
11	**Monolith Olive Creek Plant**	Lancaster County, NE	2024	339,450	797,708

In total, 33 of the 37 proposed ammonia projects attempt to take advantage of the 45Q or 45V tax credits implemented in the Inflation Reduction Act. It remains to be seen how many of these projects will be completed, and if they will successfully produce low-carbon ammonia.

Appalachia's Ammonia Buildout: The Gas Industry's Wishful Thinking

In October 2023, the Department of Energy selected the Appalachian Regional Clean Hydrogen Hub (ARCH2) as one of the seven hubs to receive federal funds, beginning with $30 million for its first phase granted in July 2024.[98] ARCH2 would include at least 11 facilities throughout West Virginia, eastern Ohio and western Pennsylvania and involves more than 40 entities including natural gas producers, pipeline companies, electric and gas utilities, independent power producers, industrial companies and others.[99]

Two of those projects are proposed ammonia facilities: the Adams Fork Energy project in Mingo County, West Virginia and the KeyState Natural Gas Synthesis Plant in Clinton County, Pennsylvania. Both projects were originally connected to the ARCH2 project; however, Adams Fork Energy is no longer affiliated. Both pitched as "blue," the Adams Fork and KeyState ammonia facilities would incorporate CCS, and would source natural gas (and to some extent coal mine methane) as feedstock for its hydrogen and ammonia production. Critically, both projects count on a steady supply of natural gas—and neither project incorporates plans for truly "green" or fossil fuel-free production.

Adams Fork Energy

The Adam Forks Energy project is a blue ammonia project being developed by TransGas near Wharncliffe in Mingo County, West Virginia. Located atop the Marcellus gas formation, among the most productive gas fields in the world, the project backers have proposed that the plant would use natural gas and coal mine methane as feedstock. However, Treasury guidance on 45V tax credits makes this unlikely. The plant would be powered by exothermic steam—which arises from the heat byproduct of the chemical reaction that produces hydrogen from natural gas (specifically the water-gas shift reaction that turns carbon monoxide and water into carbon dioxide and hydrogen).[100] Essentially, it is another way of using natural gas for energy. Adams Fork Energy claims it would capture 99.3% of its CO_2 emissions, which would be sequestered in a saline aquifer for long-term geologic storage 13,000 feet underneath the site.[101] However, no commercial-scale carbon capture project has yet to achieve over 80% capture.[102]

Adams Fork Energy would consist of six ammonia plants or "trains" that would produce up to 6,000 tons per day.[103] At full operating capacity, the six trains would produce a total of 13 million tons per year of ammonia. If built to full capacity, the facility would become the largest ammonia facility, blue or otherwise, in the world, eclipsing CF Industries' Donaldsonville, LA complex.

Adams Forks Energy estimates using roughly 65 billion cubic feet per year of natural gas as feedstock for its ammonia project, which would be transported to the facility using new or existing gathering lines. However the project developers in February 2024 disclosed that they intend to source coal mine methane as feedstock.[14F]

The Adams Fork Energy project would be jointly developed by Adams Fork Energy, LLC, a subsidiary of New York City-based TransGas, and the Flandreau Santee Sioux Tribe. The facility was initially announced in April 2023 as a joint venture from TransGas and CNX as one of the Appalachian Regional Clean Hydrogen Hub's (ARCH2) fifteen anchor projects. Since the announcement, however, CNX has left the project and TransGas continues to try to develop Adams Fork Energy as a standalone project outside of ARCH2.[104]

The West Virginia Department of Environmental Protection issued TransGas an initial permit to begin construction on the Adams Fork ammonia project on March 26, 2024. The state issued this minor source air permit, exempting the project from Title V permitting, which would have imposed higher emissions standards and monitoring and reporting requirements. The project will need to secure additional state permits in addition to a Class VI well permit under the EPA's Underground Injection Control program, which would be administered by the West Virginia Department of Environmental Protection following the EPA's January 2025 acceptance of West Virginia's primacy application.[105] While TransGas announced that they aim to begin construction in 2024 and initiate operations by 2027 following a 30-month construction period, there are many factors that could delay or scrap the project.

Adams Fork Energy's financial model apparently depends on its ability to receive the 45V Hydrogen Production Tax Credit, based on their plans to produce "negative carbon intensity" ammonia and hydrogen due to how coal mine-sourced methane is accounted for in emissions modeling.[106] However, the Department of the Treasury final rules for the 45V tax credit specifically reject this practice.[107] While the company intends to capture its CO_2 emissions, the project's minor source air permit does not mandate the use of carbon capture and storage, meaning the company could abandon the unproven and expensive technology and instead produce gray hydrogen in order to reduce costs. If the project's carbon sequestration and accounting method is proven legitimate—if it actually captures 99.3% of its carbon emissions and is accepted by federal regulators—TransGas could claim the highest tier of the 45V hydrogen production tax credit.

[14F] Project backers submitted a letter to the IRS on February 26, 2024 arguing its use of coal mine methane in its fuel meets eligibility for the maximum clean hydrogen tax credit.

KeyState Natural Gas Synthesis

Meanwhile, a separate blue ammonia project is under development over 400 miles to the northeast in West Keating Township in Clinton County, Pennsylvania as part of the ARCH2 regional hydrogen hub. The KeyState Natural Gas Synthesis project is a joint venture between KeyState Energy and Frontier Natural Resources. The $400 million facility would use fracked gas extracted on site from the Marcellus Shale formation to produce hydrogen, ammonia, and urea. Key to the project is the development of a massive on-site carbon capture and sequestration complex.[108]

The project would likely qualify for the 45Q tax credit that incentivizes CCS as well as the 45V hydrogen production tax credit, though it would have to choose one or the other. KeyState has yet to apply for any permits with state or federal agencies, though it has told investors it expects the project to be operating in 2028.

The Only Winners of an Ammonia Buildout in Appalachia are Gas Companies

Both projects remain in the planning stage and face many logistical and financial obstacles ahead. Project backers have pitched Appalachia as an ideal location for blue hydrogen development due to its abundant gas reserves and geological potential for CO_2 storage. For example, Keystate claims the region could be the next “hydrogen production superpower” over the next 30-plus years.[109] But where would all that hydrogen—and ammonia—go? And how would it get there?

KeyState says the ammonia it produces will be for industrial, manufacturing, medical, and agricultural uses. Project backers claim Appalachia hosts a wide range of existing and potential hydrogen end-users, including electric utilities, local gas distribution utilities, industrial companies that manufacture petrochemicals from natural gas derivatives, and several transit agencies in the region that have been exploring whether hydrogen could power buses.[110]

As for the Adams Fork project, developers have not yet shared concrete details regarding any committed or prospective customers for the ammonia. A spokesperson for the project said the plant would serve the manufacturing and agricultural sectors and the company in addition to pursuing customers in the industrial heating and power generation sectors.[111]

There are no plans to produce fertilizer on site, meaning the ammonia would need to be transported to fertilizer production facilities. Adams Fork would use two existing major rail lines for ammonia transport to downstream markets. There are six existing fertilizer production facilities within a 400-mile radius of the proposed Adams Fork plant.[112]

While the ammonia produced at Adams Fork could be sold to fertilizer and other conventional end-users, in terms of reaching global markets, ammonia produced in Appalachia is at a competitive disadvantage compared to ammonia produced on the Gulf Coast. Gulf Coast ammonia producers are also close to productive gas fields, and are nearer to both coastal export terminals and to the big commodity crop regions in the Midwest.

Petrochemical companies seem so far unwilling to pay more for cleaner hydrogen.[113] Blue ammonia producers may face a similar problem if their buyers are also unwilling to pay a higher price for cleaner ammonia.

With demand growth far from the production sites, it seems the main winners of an ammonia buildout in Appalachia are the gas companies that could supply a steady flow of natural gas to the proposed facilities.

Electricity in Appalachia: How Would Appalachia Ammonia Projects be Powered?

Producing ammonia is an energy intensive enterprise. Even considering only the Adams Fork project, producing that much blue ammonia would increase West Virginia's electricity consumption by almost one quarter. (The KeyState Natural Gas Synthesis project does not have information on its ammonia capacity.)

In 2023, West Virginia produced 52 million megawatt hours of electricity while consuming only 32 million MWh. Coal accounted for 45 million MWh of electricity, or 86% of statewide electricity generation. Nearly half (46%, or 14.7 million MWh) of West Virginia electricity consumption went toward industrial uses, while just over 10 million MWh went toward residential consumption.

Adams Fork plans to operate separately from the electric grid, instead powering its operations by cogeneration with exothermic steam.[114] However, if connected to West Virginia's grid and operating at full capacity producing 13 million metric tons of ammonia per year, the Adams Fork plant would consume more than 7.5 million MWh of electricity, approximately 0.579 kWh per kg of ammonia. This figure accounts for only the electricity used to produce nitrogen from the air and to power the Haber-Bosch synthesizer. It does not include any electricity used for CCS to turn the otherwise gray ammonia blue. It also does not include electricity used to produce hydrogen, because Adams Fork plans to produce the necessary hydrogen using natural gas or coal methane.

In other words, the completion and full-capacity operation of the TransGas Adams Fork ammonia plant would increase West Virginia's annual energy consumption by nearly 25%.

If a green ammonia plant were proposed, it would use almost 17 times the amount of electricity per kilogram of ammonia produced. Producing 1 kilogram of green ammonia requires 9.679 kWh electricity, compared to the 0.579 kWh needed to produce 1 kilogram of gray ammonia.

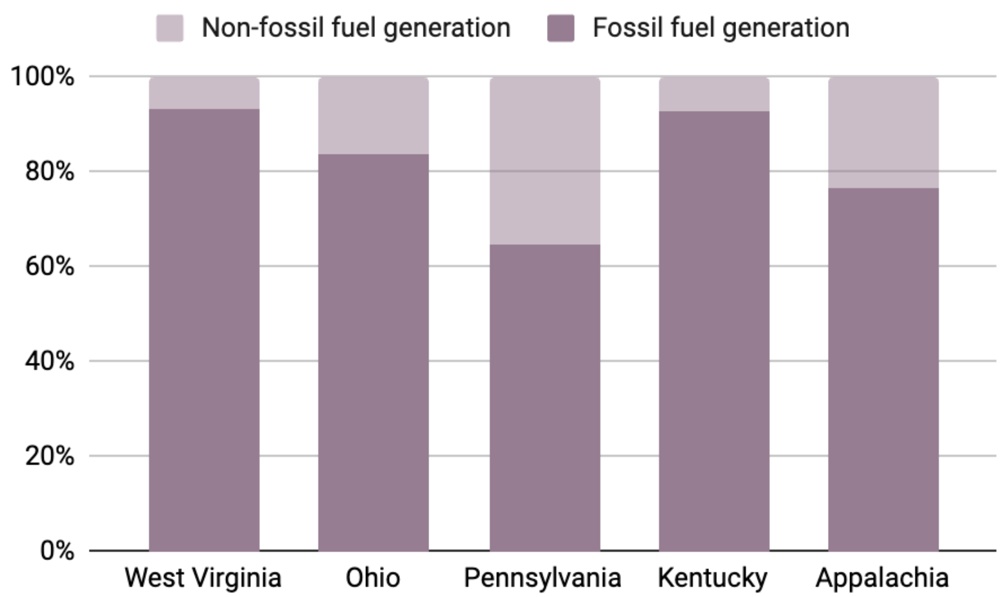
Producing green ammonia at scale requires a massive amount of electricity: producing 1 million metric tons of green ammonia requires 9.7 million MWh of electricity. This means that all the electricity produced in West Virginia in 2023, 52.3 million MWh, could produce 5.4 million metric tons of green ammonia, less than half of the proposed capacity of the Adams Fork facility.

In fact, producing green ammonia anywhere in Appalachia would require a sea change in how the region generates its electricity. In 2023, more than 75% of electricity generated across West Virginia, Kentucky, Ohio, and Pennsylvania came from fossil fuels, primarily coal and natural gas. More than 90% of the electricity generated in West Virginia and Kentucky came from fossil fuels, and Pennsylvania had the least carbon intensive electricity generation profile with 65% of its electricity generated from fossil fuels. (See Appendix B.)

Building ammonia production, blue, green, or gray, in Appalachia would mean increasing electricity demand in a region that is still highly reliant on carbon emitting fossil fuels for its electricity.

Figure 7: Appalachia's Dependence On Fossil Fuel Electricity Generation Hinders Green Ammonia Development

Share of fossil fuel electricity generation, 2023



Source: Energy Information Administration

Recommendations

To understand the future of ammonia, it's important to put ammonia production in the context of the fossil fuel industry as a whole. As it stands today, industrial-scale ammonia production is dependent on natural gas feedstock to produce hydrogen. New blue and green ammonia projects are under development; however, much of the technology is not yet market-ready. Because ammonia production still relies on fossil fuels, the fossil fuel industry stands to gain tremendously from the expansion of both blue and gray ammonia production.

Ammonia and hydrogen should be used only for applications in which there are no other cost-effective decarbonization alternatives. The industry's claims about adoption of large-scale ammonia use, particularly in unproven applications like use as a carrier for hydrogen transportation, should be viewed with skepticism. Developing additional markets and government support for ammonia—and its precursor, hydrogen—serves the interests of the fossil fuel industry and threatens to delay a truly "clean" energy transition. Any significant expansion of the hydrogen and ammonia industries in combination with CCS may have unintended—and counterproductive—consequences, further entrenching climate-killing industries both upstream and downstream.

While federal tax incentives pitch technologies like CCS as a climate solution, they stand to secure fossil fuels as an integral part of the future global economy. There is a major risk that CCS development will delay decarbonization, prolong fracking, and extend the economic failures of the fossil fuel industry.

There is also evidence that these investments still aren't enough to spur green technologies. A 2023 study published by the MIT Center for Energy and Environmental Policy Research examined the economic impact of the US Inflation Reduction Act on ammonia production and concluded that existing SMR technology—dependent on gas or coal feedstock—will always be an economically better choice for investors.[115]

Policymakers should be skeptical of the industry's claims of how carbon-free ammonia production actually is. The majority of the proposals outlined in this report rely on natural gas as the principal input and would utilize carbon capture and storage to produce "low-carbon" ammonia. Skepticism is justified given the fact that no commercial-scale carbon capture project has been able to achieve an 80% capture rate, let alone the 95-99% capture rate pitched by project backers.

There are significant climate risks of a ramped up ammonia buildout aside from carbon emissions. Princeton University researchers recently found that a mismanaged ammonia economy risks increasing emissions of nitrous oxide (NO_2), which is around 300 times as potent as CO_2 as a greenhouse gas.[116] There is also a risk of a substantial increase in emissions of nitrogen oxides (NO_x), a class of pollutants that contribute to the formation of smog and acid rain. Fugitive ammonia emissions impact water quality and stress ecosystems by disturbing the global nitrogen cycle.[117]

Given the environmental, health and economic risks, local communities should be wary of project backers. Many of the proposed projects are sited near existing gas processing and petrochemical facilities, many of which are sited in federally designated Disadvantaged Communities.[118] These fenceline communities already bear the brunt of the fossil fuel industry's impact. A quarter of the proposals, which involve large-scale production and storage of anhydrous ammonia, are sited in Louisiana's "Cancer Alley," a region between New Orleans and Baton Rouge that is already home to more than 200 fossil fuel and chemical facilities where residents face higher cancer rates.

Accidental releases of ammonia can pose significant threats to communities and to workers. Anhydrous ammonia leaks can form deadly clouds. According to research by the Environmental Integrity Project, there were at least 6,090 leaks or releases of anhydrous ammonia from 2013 to 2023 on record with the US Coast Guard's National Response Center database.[119]

Federal governments should consider tightening rules and regulations on subsidies for hydrogen and ammonia projects. The US government handed out $757 billion of subsidies to the fossil fuel industry in 2022, which exceeded revenues from the industry by $2.1 billion, resulting in a net loss for the federal government.[120] The Inflation Reduction Act of 2022 created unprecedented federal subsidies that spurred a proliferation of new proposals—at least 37 by the most recent count—to build ammonia plants in the US. Before more taxpayer dollars are poured into these projects, the costs, from gas extraction to end use, should be weighed against the alleged benefits.

Acknowledgements

Thank you to the team at Ohio River Valley Institute and all our reviewers, especially Sean O'Leary, Ben Hunkler, and Alex Cole. Any errors in this report are the sole responsibility of the authors. This field is rapidly changing due to new technological developments and changes in the regulatory environment that are difficult to predict. These changes may alter some of the findings in this report.

Cover photo: Tom Pelton, Environmental Integrity Project, 2024

Appendix A: Current US Ammonia Facilities

Table 4: Domestic Ammonia Plants Operational in 2022

Map	Company	Capacity (metric tons)	City	State
A	**CF Industries Holdings, Inc.**	4,330,000	Donaldsonville	LA
B	**CF Industries Holdings, Inc.**	1,230,000	Port Neal	IA
C	**CF Industries Holdings, Inc.**	1,210,000	Verdigris	OK
D	**Koch Fertilizer, LLC**	930,000	Enid	OK
E	**Dyno Nobel Louisiana Ammonia, LLC**	800,000	Waggaman	LA
F	**Iowa Fertilizer Co.**	770,000	Wever	IA
G	**Nutrien Ltd.**	765,000	Augusta	GA
H	**Yara Freeport LLC**	750,000	Freeport	TX
I	**Nutrien Ltd.**	725,000	Lima	OH
J	**CF Industries Holdings, Inc.**	570,000	Yazoo City	MS
K	**Nutrien Ltd.**	535,000	Geismar	LA
L	**AdvanSix Inc.**	530,000	Hopewell	VA
M	**Mosaic Company, The**	510,000	Donaldsonville	LA
N	**LSB Industries, Inc.**	490,000	El Dorado	AR
O	**Nutrien Ltd.**	490,000	Borger	TX
P	**CF Industries Holdings, Inc.**	480,000	Woodward	OK
Q	**Coffeyville Resources Nitrogen Fertilizers, LLC**	375,000	Coffeyville	KS
R	**Dakota Gasification Co.**	355,000	Beulah	ND
S	**Koch Fertilizer, LLC**	350,000	Fort Dodge	IA
T	**East Dubuque Nitrogen Fertilizers, LLC**	337,000	East Dubuque	IL
U	**OCI Partners LP**	332,000	Beaumont	TX
V	**Koch Fertilizer, LLC**	280,000	Dodge City	KS
W	**Koch Fertilizer, LLC**	265,000	Beatrice	NE
X	**LSB Industries, Inc.**	240,000	Pryor	OK
Y	**J.R. Simplot Co.**	185,000	Rock Springs	WY
Z	**LSB Industries, Inc.**	185,000	Cherokee	AL
1	**Dyno Nobel Inc.**	178,000	Cheyenne	WY
2	**Dyno Nobel Inc.**	100,000	St. Helens	OR
3	**U.S. Nitrogen, LLC**	62,000	Greenville	TN
4	**Green Valley Chemical Corp.**	32,000	Creston	IA
5	**NE Nitro Geneva, LLC**	31,000	Geneva	NE

Appendix B: Electricity Generation and Consumption in Appalachia

Table 5: Electricity Generation and Consumption Profiles in Appalachia (Megawatt-hours)

	West Virginia	Ohio	Pennsylvania	Kentucky	Total
Net Generation	52,286,784	133,223,464	235,924,937	63,217,080	**484,652,265**
Fossil Fuel Generation	48,640,054	111,190,761	152,139,743	58,598,104	**370,568,662**
Non-Fossil Fuel Generation	3,646,730	22,032,703	83,785,194	4,618,976	**114,083,603**
Coal Generation	44,797,570	31,436,341	12,834,828	43,447,449	**132,516,188**
Natural Gas Generation	3,679,658	78,704,777	139,256,047	15,089,520	**236,730,002**
Petroleum Generation	162,826	1,049,643	48,868	61,135	**1,322,472**
Nuclear Generation	0	16,206,640	75,304,581	0	**91,511,221**
Hydroelectric Generation	1,530,183	507,044	2,783,366	3,954,668	**8,775,261**
Wind Generation	2,089,439	2,819,321	3,258,324	0	**8,167,084**
Solar Generation	0	1,382,272	360,500	155,425	**1,898,197**
Other Generation	27,108	1,117,426	2,078,423	508,883	**3,731,840**
Total Sales in State (consumption)	32,070,687	146,640,983	138,710,993	71,223,021	**388,645,684**
Residential Sales	10,233,824	49,713,538	52,327,643	24,552,708	**136,827,713**
Commercial Sales	7,173,973	46,351,291	35,802,263	19,303,242	**108,630,769**
Industrial Sales	14,662,890	50,545,890	50,146,824	27,367,071	**142,722,675**
Other Sales	0	30,264	434,263	0	**464,527**

Source: 2023 State Electricity Profiles, EIA

Endnotes

1. Corrina Ricker and Warren Wilczewski, "Shale natural gas production in the Appalachian Basin sets records in first half of 2021", US Energy Information Administration, September 1, 2021, https://www.eia.gov/todayinenergy/detail.php?id=49377.
2. Eric de Place and Julia Stone, "The Meaning of MVP", Ohio River Valley Institute, September 18, 2023, https://ohiorivervalleyinstitute.org/the-meaning-of-mvp/.
3. Jamison Cocklin, "EQT Working to 'Catalyze' East Coast LNG Projects Amid Appalachian Constraints", Natural Gas Intelligence, July 28, 2022, https://www.naturalgasintel.com/news/eqt-working-to-catalyze-east-coast-lng-projects-amid-appalachian-constraints/
4. Jamison Cocklin, "EQT Working to 'Catalyze' East Coast LNG Projects Amid Appalachian Constraints", Natural Gas Intelligence, July 28, 2022, https://www.naturalgasintel.com/news/eqt-working-to-catalyze-east-coast-lng-projects-amid-appalachian-constraints/
5. "Fossils Fertilizers and False Solutions", page 28, Center for International Environmental Law, October 2022, https://www.ciel.org/reports/fossil-fertilizers/.
6. Editors of Encyclopaedia Britannica, "Nitrogen fixation", Brittanica, October 24, 2024, https://www.britannica.com/science/nitrogen-fixation.
7. Wayne Breslin, "How to Balance: N2 + H2 = NH3 (Synthesis of Ammonia)", YouTube, March 23, 2017, https://www.youtube.com/watch?v=qf_aTOEa7Zs.
8. "The Octet Rule", LibreTexts Chemistry, https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_(Physical_and_Theoretical_Chemistry)/Electronic_Structure_of_Atoms_and_Molecules/Electronic_Configurations/The_Octet_Rule.
9. Wikimedia Commons, "Ammonia Lewis Structure", January 5, 2022, https://commons.wikimedia.org/wiki/File:Ammonia_Lewis_structure.svg.
10. Andre, Richard A. "DuPont Belle Works (Now Chemours)." e-WV: The West Virginia Encyclopedia, February 20, 2024, https://www.wvencyclopedia.org/entries/1926.
11. The Editors of Encyclopaedia Britannica, "Haber-Bosch process", Britannica, November 22, 2024, https://www.britannica.com/technology/Haber-Bosch-process.
12. Gary Hergert, Rex Nielsen, and Jim Margheim, "WWII Nitrogen Production Issues in Age of Modern Fertilizers," Cropwatch, University of Nebraska-Lincoln Institute of Agriculture and Natural Resources, April 10, 2015, https://cropwatch.unl.edu/fertilizer-history-p3.
13. "Ammonia", American Chemical Society, February 8, 2021, https://www.acs.org/molecule-of-the-week/archive/a/ammonia.html#:~:text=Most%20ammonia%20production%E2%80%94%E2%89%8885,%2C%20cyanides%2C%20and%20amino%20acids.
14. Mineral Commodity Summaries, "Nitrogen - Fixed (Ammonia)", USGeological Survey, January 2024, https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-nitrogen.pdf.
15. Mineral Commodity Summaries, "Nitrogen - Fixed (Ammonia)", US Geological Survey, January 2024, https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-nitrogen.pdf.
16. Hannah Ritchie, "How many people does synthetic fertilizer feed?", Our World in Data, November 7, 2017, https://ourworldindata.org/how-many-people-does-synthetic-fertilizer-feed.
17. John Channing Briggs, "Green Revolution", International Encyclopedia of Human Geography, 2009, pgs 634–638, https://www.sciencedirect.com/science/article/abs/pii/B9780080449104000997.
18. "Fertilizer Applied for Agricultural Purposes", US Environmental Protection Agency, https://cfpub.epa.gov/roe/indicator.cfm?i=55#:~:text=The%20four%20major%20crops%20in,Daberkow%20and%20Huang%2C%202006).
19. "Fertilizer Applied for Agricultural Purposes", US Environmental Protection Agency, https://cfpub.epa.gov/roe/indicator.cfm?i=55#:~:text=The%20four%20major%20crops%20in,Daberkow%20and%20Huang%2C%202006).
20. Page 11,"Fossils Fertilizers and False Solutions", Center for International Environmental Law, October 2022, https://www.ciel.org/reports/fossil-fertilizers/.
21. Page 20, "Fossils Fertilizers and False Solutions", Center for International Environmental Law, October 2022, https://www.ciel.org/reports/fossil-fertilizers/.
22. Page 23, "Fossils Fertilizers and False Solutions", Center for International Environmental Law, October 2022, https://www.ciel.org/reports/fossil-fertilizers/.
23. Page 6, "The Fertilizer Boom", Environmental Integrity Project, April 17, 2023, https://environmentalintegrity.org/reports/the-fertilizer-boom/.

24. Duncombe, Jessica, "Index Suggests That Half of Nitrogen Applied to Crops is Lost," EOS, August 23, 2021, https://eos.org/articles/index-suggests-that-half-of-nitrogen-applied-to-crops-is-lost.
25. Dubrovsky, Neil M., et al, "Circular 1350: Nutrients in the Nation's Streams and Groundwater, 1992-2004." US Geological Survey. September 23, 2010, https://pubs.usgs.gov/circ/1350/.
26. Page 18, "Fossils Fertilizers and False Solutions", Center for International Environmental Law, October 2022, https://www.ciel.org/reports/fossil-fertilizers/.
27. Page 18, "Fossils Fertilizers and False Solutions", Center for International Environmental Law, October 2022, https://www.ciel.org/reports/fossil-fertilizers/.
28. Page 21, "Fossils Fertilizers and False Solutions", Center for International Environmental Law, October 2022, https://www.ciel.org/reports/fossil-fertilizers/.
29. Page 21, "Fossils Fertilizers and False Solutions", Center for International Environmental Law, October 2022, https://www.ciel.org/reports/fossil-fertilizers/.
30. Luana Basso et al., "WMO Greenhouse Gas Bulletin: The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2020, No. 17", World Meteorological Organization, October 25, 2021, page 7, https://library.wmo.int/records/item/58705-no-17-25-october-2021#.ZBMRW-zMJqE.
31. "IEA G20 Hydrogen report: Assumptions", page 4, International Energy Agency, December 2020, https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf.
32. Lexie Ryan, "Hydrogen Production: Overview and Issues for Congress", page 2, Congressional Research Service, October 3, 2024, https://crsreports.congress.gov/product/pdf/R/R48196/2#:~:text=Most%20of%20the%20hydrogen%20produced,produced%20globally%20(Figure%201).
33. "Hydrogen Production: Natural Gas Reforming", US Department of Energy, https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming.
34. Lexie Ryan, "Hydrogen Production: Overview and Issues for Congress", page 2, Congressional Research Service, October 3, 2024, https://crsreports.congress.gov/product/pdf/R/R48196/2#:~:text=Most%20of%20the%20hydrogen%20produced,produced%20globally%20(Figure%201).
35. P. Chiesa, "15 - Advanced technologies for syngas and hydrogen (H2) production from fossil-fuel feedstocks in power plants", Woodhead Publishing Series in Energy, 2010, https://www.sciencedirect.com/science/article/abs/pii/B9781845695156500157.
S. Assabumrungrat and N. Laosiripojana, "FUELS - HYDROGEN PRODUCTION | Autothermal Reforming", Encyclopedia of Electrochemical Power Sources, 2009, https://www.sciencedirect.com/science/article/abs/pii/B9780444527455002963.
"Autothermal Reformer", ScienceDirect, accessed January 22, 2025, https://www.sciencedirect.com/topics/engineering/autothermal-reformer.
36. Lexie Ryan, "Hydrogen Production: Overview and Issues for Congress", page 6, Congressional Research Service, October 3, 2024, https://crsreports.congress.gov/product/pdf/R/R48196/2.
37. Eric de Place, "Hydrogen 101", Ohio River Valley Institute, August 16, 2021, https://ohiorivervalleyinstitute.org/hydrogen-101/.
38. David Iaconangelo, "Is there a future for 'blue' hydrogen? 5 things to watch." E&E News, October 4, 2023, https://www.eenews.net/articles/is-there-a-future-for-blue-hydrogen-5-things-to-watch/#:~:text=Currently%2C%20one%20U.S.%20plant%20is,by%20the%20International%20Energy%20Agency.
39. "IEA G20 Hydrogen report: Assumptions", International Energy Agency, page 5, https://www.iea.org/reports/the-future-of-hydrogen/data-and-assumptions.
40. Grant Hauber, "Norway's Sleipner and Snøhvit CCS: Industry models or cautionary tales?", Institute for Energy Economics and Financial Analysis, June 14, 2023, https://ieefa.org/resources/norways-sleipner-and-snohvit-ccs-industry-models-or-cautionary-tales.
41. Lexie Ryan, "Hydrogen Production: Overview and Issues for Congress", page 2, Congressional Research Service, October 3, 2024, https://crsreports.congress.gov/product/pdf/R/R48196/2#:~:text=Most%20of%20the%20hydrogen%20produced,produced%20globally%20(Figure%201).
42. "Pennsylvania Electricity Profile", Energy Information Administration, November 6, 2024, https://www.eia.gov/electricity/state/pennsylvania/.

43. "Electricity Data Browser", Energy Information Administration, accessed 12/23/2024, https://www.eia.gov/electricity/data/browser/#/topic/0?agg=2,0,1&fuel=vvg&geo=g&sec=g&linechart=ELEC.GEN.ALL-US-99.A~ELEC.GEN.COW-US-99.A~ELEC.GEN.NG-US-99.A~ELEC.GEN.NUC-US-99.A~ELEC.GEN.HYC-US-99.A&columnchart=ELEC.GEN.ALL-US-99.A~ELEC.GEN.COW-US-99.A~ELEC.GEN.NG-US-99.A~ELEC.GEN.NUC-US-99.A~ELEC.GEN.HYC-US-99.A&map=ELEC.GEN.ALL-US-99.A&freq=A&start=2001&end=2023&ctype=linechart&ltype=pin&rtype=s&maptype=0&rse=0&pin=.
44. "Oil and Gas Drilling 101", Fractracker Alliance, https://www.fractracker.org/resources/oil-and-gas-101/.
45. Tejasvi Raghuveer and Warren Wilczewski, "US ammonia prices rise in response to higher international natural gas prices", US Energy Information Administration, May 10, 2022, https://www.eia.gov/todayinenergy/detail.php?id=52358#:~:text=Despite%20these%20capacity%20additions%2C%20the,for%20producing%20nitrogen%2Dbased%20fertilizers.
46. Tejasvi Raghuveer and Warren Wilczewski, "US ammonia prices rise in response to higher international natural gas prices", US Energy Information Administration, May 10, 2022, https://www.eia.gov/todayinenergy/detail.php?id=52358#:~:text=Despite%20these%20capacity%20additions%2C%20the,for%20producing%20nitrogen%2Dbased%20fertilizers.
47. National Minerals Information Center, "Minerals Yearbook, Nitrogen 2022 tables, xls format", US Geological Survey, https://www.usgs.gov/centers/national-minerals-information-center/nitrogen-statistics-and-information.
48. "Sulphuric Acid", Australian Government Department of Climate Change, Energy, the Environment and Water, August 15, 2022, https://www.dcceew.gov.au/environment/protection/npi/substances/fact-sheets/sulfuric-acid.
49. "Ammonia Technology Roadmap Executive Summary", International Energy Agency, October 2021, https://www.iea.org/reports/ammonia-technology-roadmap/executive-summary.
50. "Ammonia Technology Roadmap", page 67, International Energy Agency, October 2021, https://www.iea.org/reports/ammonia-technology-roadmap.
51. Peter H. Pfromm, "Towards sustainable agriculture: Fossil-free ammonia", Journal of Renewable and Sustainable Energy, June 2, 2017, https://pubs.aip.org/aip/jrse/article/9/3/034702/1058681.
52. "Fertilizer Use and Price: Summary of Findings", US Department of Agriculture Economic Research Service, October 30, 2019, https://www.ers.usda.gov/data-products/fertilizer-use-and-price/summary-of-findings/.
53. "Consumption", International Fertilizer Association, 2024, https://www.ifastat.org/databases/plant-nutrition.
54. "Feature Article: Securing Transportation of Ammonia—Agricultural Lifeline and Future Affordable, Clean Energy Source", US Department of Homeland Security Science and Technology, June 17, 2021, https://www.dhs.gov/science-and-technology/news/2021/06/17/feature-article-securing-transportation-ammonia.
55. "Feature Article: Securing Transportation of Ammonia—Agricultural Lifeline and Future Affordable, Clean Energy Source", US Department of Homeland Security Science and Technology, June 17, 2021, https://www.dhs.gov/science-and-technology/news/2021/06/17/feature-article-securing-transportation-ammonia.
56. "Ammonia Transport and Storage", International PtX Hub, January 2024, https://ptx-hub.org/wp-content/uploads/2024/01/International-PtX-Hub_202401_Ammonia-transport-and-storage.pdf.
57. "Ammonia terminals - a global view," Argus Media, 2024, https://futurefuels.imo.org/wp-content/uploads/2024/03/WorldAmmoniaMap2024.pdf.
58. "Fertilizer and Rail Transportation", The Fertilizer Institute, https://www.tfi.org/advocacy/our-issues/transportation/rail/.
59. Page 41, "Fossils Fertilizers and False Solutions", Center for International Environmental Law, October 2022, https://www.ciel.org/reports/fossil-fertilizers/.
60. "Ammonia Technology Roadmap", page 70, International Energy Agency, October 2021, https://www.iea.org/reports/ammonia-technology-roadmap.
61. "Ammonia Technology Roadmap", page 70, International Energy Agency, October 2021, https://www.iea.org/reports/ammonia-technology-roadmap.
62. "Ammonia Technology Roadmap", page 71, International Energy Agency, October 2021,. https://www.iea.org/reports/ammonia-technology-roadmap.
63. "Clean Ammonia Roadmap", page 5, Institute for Sustainable Process Technology, January 3, 2024, https://ispt.eu/publications/clean-ammonia-roadmap-public-report/.
64. "Clean Ammonia Roadmap", page 6, Institute for Sustainable Process Technology, January 3, 2024, https://ispt.eu/publications/clean-ammonia-roadmap-public-report/.
65. "Innovation Outlook Renewable Ammonia", page 92, International Renewable Energy Agency and the Ammonia Energy Association, 2022, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf.

66. "Innovation Outlook Renewable Ammonia", page 74, International Renewable Energy Agency and the Ammonia Energy Association, 2022, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf.
67. "2023 Annual Report", page 24, CF Industries, https://www.cfindustries.com/globalassets/cf-industries/media/documents/reports/annual-reports/cf_industries_2023-annual-report.pdf.
68. "Ammonia Technology Roadmap", page 72, International Energy Agency, October 2021, https://www.iea.org/reports/ammonia-technology-roadmap.
69. Jeslyn Lerh, "World's first ammonia-fuelled PSV ship to operate in 2026, says Wartsila", Reuters, August 26, 2024, https://www.reuters.com/sustainability/climate-energy/worlds-first-ammonia-fuelled-psv-ship-operate-2026-says-wartsila-2024-08-26/.
70. "Full-Scale Ammonia Engine Opens New Chapter" MAN Energy Solutions, December 3, 2024, https://www.man-es.com/company/press-releases/press-details/2024/12/03/full-scale-ammonia-engine-opens-new-chapter.
71. Martin Cartwright, "Investing in future ammonia markets", Det Norske Veritas, October 16, 2024, https://www.dnv.com/expert-story/maritime-impact/investing-in-future-ammonia-markets/.
72. "Innovation Outlook Renewable Ammonia", page 136, International Renewable Energy Agency and the Ammonia Energy Association, 2022, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf.
73. https://www.dnv.com/about/
74. Martin Cartwright, "Investing in future ammonia markets," Det Norske Veritas, October 16, 2024, https://www.dnv.com/expert-story/maritime-impact/investing-in-future-ammonia-markets/.
75. Juliane von Wiren, "Maersk Tankers to pioneer transportation of clean ammonia [Press Release]" Maersk Tankers, November 30, 2023, https://maersktankers.com/newsroom/maersk-tankers-to-pioneer-transportation-of-clean-ammonia.
76. Max Lin, " Maersk Tankers behind order for up to 10 very large ammonia carriers," S&P Global, December 1, 2023, https://www.spglobal.com/commodity-insights/en/news-research/latest-news/shipping/120123-maersk-tankers-behind-order-for-up-to-10-very-large-ammonia-carriers.
77. "World's Largest Ammonia Carriers for Naftomar Shipping to Be Built By Hanwha Ocean and Classed By Bureau Veritas [Press Release]" December 5, 2023, https://marine-offshore.bureauveritas.com/newsroom/worlds-largest-ammonia-carriers-naftomar-shipping-be-built-hanwha-ocean-and-classed-bureau.
78. "Ammonia at sea: Studying the potential impact of ammonia as a shipping fuel on marine ecosystems", Environmental Defense Fund, 2022, https://www.edfeurope.org/sites/default/files/2022-11/EDF-Europe-Ammonia-at-Sea-Summary.pdf.
79. "Successful ship-to-ship ammonia transfers pave the way for ammonia bunkering in the Pilbara region", Global Center for Maritime Decarbonization, September 16, 2024, https://www.gcformd.org/successful-ship-to-ship-ammonia-transfers-pave-the-way-for-ammonia-bunkering-in-the-pilbara-region/.
80. "Phase 1: Ammonia bunkering pilot safety study", Global Center for Maritime Decarbonization, April 27, 2023, https://www.gcformd.org/projects/ammonia-bunkering-pilot-safety-study/.
81. "Ammonia Technology Roadmap", page 71, International Energy Agency, October 2021, https://www.iea.org/reports/ammonia-technology-roadmap.
82. Jeslyn Lerh, "Zero-carbon ammonia for shipping faces cost, safety challenges", Reuters, October 30, 2024, https://www.reuters.com/markets/commodities/zero-carbon-ammonia-shipping-faces-cost-safety-challenges-2024-10-27/.
83. Deng, L., et al. "Decarbonizing of power plants by ammonia co-firing: design, techno-economic, and life-cycle analyses." International Journal of Green Energy, 21 (15), 3521–3537, July 2024, https://doi.org/10.1080/15435075.2024.2386066. https://www.tandfonline.com/doi/full/10.1080/15435075.2024.2386066#d1e2057.
84. "Innovation Outlook Renewable Ammonia", page 82, International Renewable Energy Agency and the Ammonia Energy Association, 2022, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf.

85. Yuka Obayashi, “JERA ends ammonia co-firing trial at coal power station with positive results”, Reuters, June 26, 2024, https://www.reuters.com/business/energy/jera-ends-ammonia-co-firing-trial-coal-power-station-with-positive-results-2024-06-26/.
86. “Plan A for Decarbonization: Why Is Japan Using Ammonia for Thermal Power Generation?”, JERA, October 30, 2023, https://www.jera.co.jp/en/action/discover/025.
87. Housley Carr, “It's Time - Huge Incentives, Rising Demand Drive Boom in Clean Ammonia Project Development”, RBN Energy, April 20, 2023, https://rbnenergy.com/its-time-huge-incentives-rising-demand-drive-boom-in-clean-ammonia-project-development.
88. Ben Queisser, “Unlocking hydrogen innovation: Paving the way for a sustainable future”, World Economic Forum, April 3, 2024, https://www.weforum.org/stories/2024/04/unlocking-hydrogen-innovation-paving-the-way-for-a-sustainable-future/.
89. Sheran Munasinghe and Elina Rodriguez, “Clean Energy 101: Ammonia's Role in the Energy Transition”, Rocky Mountain Institute, July 29, 2024, https://rmi.org/clean-energy-101-ammonias-role-in-the-energy-transition/.
90. Leigh Kreitsch Boerner, “Industrial ammonia production emits more CO_2 than any other chemical-making reaction. Chemists want to change that”, Chemical and Engineering News, June 15, 2019, https://cen.acs.org/environment/green-chemistry/Industrial-ammonia-production-emits-CO2/97/i24.
91. 26 U.S.C. Section 45Q.
92. 26 U.S.C. Section 45V.
93. Angela Jones and Donald Marples, “The Section 45Q Tax Credit for Carbon Sequestration,” Congressional Research Service, August 25, 2023, https://sgp.fas.org/crs/misc/IF11455.pdf.
94. Alan Krupnick and Aaron Bergman, “Incentives for Clean Hydrogen Production in the Inflation Reduction Act,” Resources for the Future, November 9, 2022, https://www.rff.org/publications/reports/incentives-for-clean-hydrogen-production-in-the-inflation-reduction-act/.
95. Yifan Ding, Chelsea Baldino, and Yuanrong Zhou, “Understanding the proposed guidance for the Inflation Reduction Act's Section 45V Clean Hydrogen Production Tax Credit,” International Council on Clean Transportation, March 2024, https://theicct.org/wp-content/uploads/2024/03/ID-132-%E2%80%93-45V-hydrogen_final2.pdf.
96. Alan Krupnick and Aaron Bergman, “Incentives for Clean Hydrogen Production in the Inflation Reduction Act,” Resources for the Future, November 9, 2022, https://www.rff.org/publications/reports/incentives-for-clean-hydrogen-production-in-the-inflation-reduction-act/.
97. Conversation with Alex Cole, Beyond Petrochemicals, February 2025.
98. “Agreement Reached to Build Appalachian Regional Clean Hydrogen Hub (ARCH2),” ARCH2, July 31, 2024, https://www.arch2hub.com/agreement-reached-to-build-appalachian-regional-clean-hydrogen-hub-arch2/#:~:text=H2Hub%20Program%20Background,Hydrogen%20Hubs%20Program%20(H2Hubs).
99. Housley Carr, “Appalachian Hydrogen Hub May Have It All, Including Support From A Key Senator,” October 6, 2022, https://rbnenergy.com/everything-appalachian-hydrogen-hub-offers-it-all-including-support-from-a-key-senator.
100. Ibrahim Dincer, Marc A. Rosen, and Maan Al-Zareer, “Chemical Energy Production”, Comprehensive Energy Systems, Volume 3, 2018, https://www.sciencedirect.com/topics/engineering/methane-steam-reforming.
101. “About the Project,” Adams Fork Energy, https://adamsforkenergy.com/.
102. Grant Hauber, “Norway's Sleipner and Snohvit CCS: Industry models or cautionary tales?? Institute for Energy Economics and Financial Analysis, June 14, 2023, https://ieefa.org/resources/norways-sleipner-and-snohvit-ccs-industry-models-or-cautionary-tales.
103. “About the Project,” Adams Fork Energy, https://adamsforkenergy.com/.
104. “CNX Resources pulls out of Adams Fork ammonia project,” Reuters, December 15, 2023, https://www.reuters.com/sustainability/cnx-resources-pulls-out-adams-fork-ammonia-project-2023-12-15/.
105. “Governor Morrisey and WVDEP Secretary Ward Announce EPA's Approval of West Virginia's Class VI Well Primacy Application,” West Virginia Office of the Governor Patrick Morrisey, January 21, 2025, https://governor.wv.gov/article/governor-morrisey-and-wvdep-secretary-ward-announce-epas-approval-west-virginias-class-vi.
106. Flandreau Santee Sioux Tribe argument to IRS re Proposed Rulemaking for Section 45V Tax Credit, February 26, 2024, https://www.bakerbotts.com/~/media/Files/Comment-Letters/TransGas-Development-Systems-LLC-Comments-1.pdf/.
107. “Credit for Production of Clean Hydrogen and Energy Credit,” Department of the Treasury, January 10, 2025, https://www.federalregister.gov/d/2024-31513/p-514.

108. “KeyState’s Clean Hydrogen and Carbon Storage Project Secures Funding through the Appalachian Regional Clean Hydrogen Hub (ARCH2) $925 Million Federal Grant”, KeyState Energy, October 31 2023, https://keystate.net/arch2/.
109. “The Next Energy Revolution”, KeyState Energy, accessed December 19, 2024, https://keystate.net/energy-transition/.
110. Housley Carr, “Appalachian Hydrogen Hub May Have It All, Including Support From A Key Senator,” October 6, 2022, https://rbnenergy.com/everything-appalachian-hydrogen-hub-offers-it-all-including-support-from-a-key-senator.
111. Josh Ewers, “Proposed Mingo County Ammonia Plant Project Announced,” April 4, 2023, https://www.wvgazettemail.com/news/proposed-mingo-county-ammonia-plant-project-announced/article_1ba6bc06-9def-532a-a383-06f79d823085.html.
112. DASCO Inc., North American Fertilizer Production Map, December 2023, https://www.dascoinc.com/wp-content/uploads/2023/12/north-american-fertilizer-production-map.pdf.
113. Rachel Parkes, “Petrochemicals industry on US Gulf Coast unwilling to pay extra for low-carbon hydrogen: analyst”, HydrogenInsight, January 8, 2025, https://www.hydrogeninsight.com/industrial/petrochemicals-industry-on-us-gulf-coast-unwilling-to-pay-extra-for-low-carbon-hydrogen-analyst/2-1-1761686.
114. Flandreau Santee Sioux Tribe argument to IRS re Proposed Rulemaking for Section 45V Tax Credit, February 26, 2024, https://www.bakerbotts.com/~/media/Files/Comment-Letters/TransGas-Development-Systems-LLC-Comments-1.pdf/.
115. Chi Kong Chyong, Eduardo Italiani, and Nikolaos Kazantzis, “Implications of the Inflation Reduction Act on Deployment of Low-Carbon Ammonia Technologies”, MIT Center for Energy and Environmental Policy Research, December 7, 2023, https://ceepr.mit.edu/wp-content/uploads/2023/11/MIT-CEEPR-WP-2023-21-Brief.pdf.
116. Colton Poore, Handling Center for Energy and the Environment, November 7, 2023, https://engineering.princeton.edu/news/2023/11/07/ammonia-fuel-offers-great-benefits-demands-careful-action.
117. Colton Poore, Handling Center for Energy and the Environment, November 7, 2023, https://engineering.princeton.edu/news/2023/11/07/ammonia-fuel-offers-great-benefits-demands-careful-action.
118. “Inflation Reduction Act Disadvantaged Communities Map”, United States Environmental Protection Agency, last updated August 7, 2024, https://www.epa.gov/environmentaljustice/inflation-reduction-act-disadvantaged-communities-map.
119. “The Fertilizer Boom”, page 27, Environmental Integrity Project, April 17, 2023, https://environmentalintegrity.org/reports/the-fertilizer-boom/.
120. Molly Brind’Amour, “Proposals to Reduce Fossil Fuel Subsidies,” Environmental and Energy Study Institute, January 30, 2024. https://www.eesi.org/papers/view/fact-sheet-proposals-to-reduce-fossil-fuel-subsidies-january-2024#:~:text=In%202022%2C%20fossil%20fuel%20subsidies,to%20$590%20million%20in%202022.