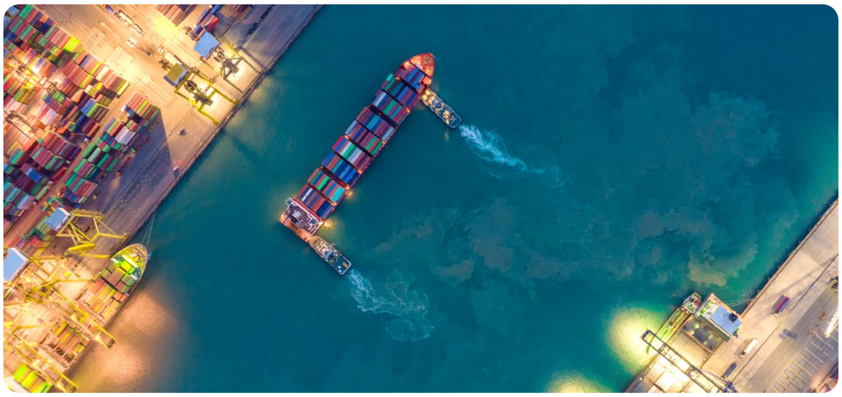
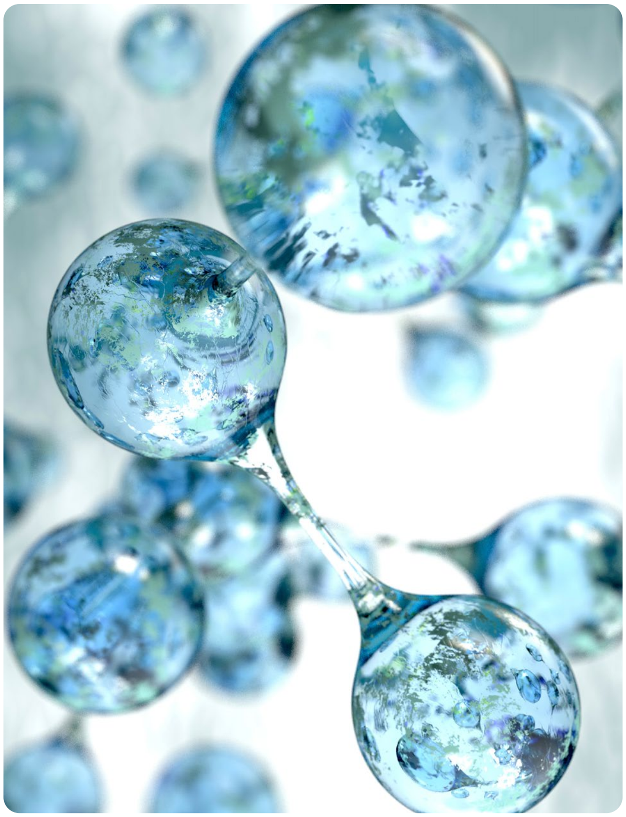
California's Blueprint to Leverage Green Ammonia Production as a Key Decarbonization Tool:

Understanding the Market and Policy Landscape to Accelerate Progress





GREEN HYDROGEN COALITION

INTRODUCTION

The urgency to combat climate change has never been greater. Globally, the United Nations finds that even if countries deliver on their pledges to reduce greenhouse gas emissions, the world is on track to far exceed both the 1.5°C and the 2°C limits that would avoid the worst impacts of climate change.[1] Within the United States (U.S.), the National Oceanic and Atmospheric Administration has deemed 2023 "a historic year of U.S. billion-dollar weather and climate disasters," with extreme weather and climate-induced events, including the Maui fires, flooding in the Northeast, tornado outbreaks in the central and southern U.S., tropical cyclones, and unprecedented rain in the Southwestern U.S.[2] Given the severity of the climate crisis, it is imperative for the nation and the world to act quickly to limit temperature rise by mitigating carbon emissions.

California has long been a leader and a model for climate action. To reach carbon neutrality by 2045, the state has led the charge to electrify large segments of the economy, from home appliances to vehicles. While electrification will be essential to decarbonizing various sectors of the economy, electrification alone will not prove sufficient to mitigate all carbon emissions since not all sectors can be readily electrified. For example, maritime shipping – which accounts for 1.0% of emissions in the state – cannot easily be electrified, as the amount of battery energy storage needed to meet a ship's energy needs would simply be too heavy and too costly.[3,4,5] Similarly, industrial sectors such as agriculture and heavy manufacturing face similar challenges: either the use of electricity is impractical given current technology, or the process requires energy in a format that cannot be delivered by electricity (e.g., high temperature heat). Therefore, maritime shipping and other hard to abate sectors need a decarbonization solution that does not rely on electrification.

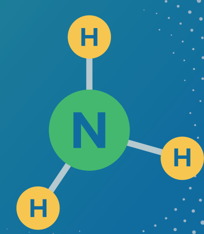
In recognition of the reality that California will need a broad portfolio of renewable resources to reach our decarbonization goals, experts and policymakers worldwide and within California are looking to renewable hydrogen to complement electrification since it can provide an alternative pathway to decarbonization for these hard-to-abate sectors.[6] Hydrogen – which is the most abundant element in the universe – can be used for energy storage and load balancing, as a feedstock, and as a fuel across the transportation, industrial, agricultural, and power sectors.[7] Interest in renewable hydrogen has only increased in the U.S. since the federal government passed two landmark laws – the Infrastructure Investment and Jobs Act[8] and the Inflation Reduction Act (IRA)[9] – which together have enabled $479 billion in new climate and energy spending. Near-term opportunities building on these laws are driving swift action from the private and public sectors alike, including the $8 billion Department of Energy (DOE) funding opportunity for regional clean hydrogen hubs that selected seven hydrogen hubs across the country. One of these selected hubs is the California Hydrogen Hub, led by the Alliance for Renewable Clean Hydrogen Energy Systems (ARCHES).[10]

1. U. N. Environment, "Emissions Gap Report 2023," UNEP - UN Environment Programme, November 8, 2023, http://www.unep.org/resources/emissions-gap-report-2023.
2. "2023: A Historic Year of U.S. Billion-Dollar Weather and Climate Disasters | NOAA Climate.Gov," accessed February 22, 2024, http://www.climate.gov/news-features/blogs/beyond-data/2023-historic-year-us-billion-dollar-weather-and-climate-disasters.
3. "Figure 2. Greenhouse Gas Emissions by Source," Next10 (blog), accessed February 22, 2024, https://greeninnovationindex.org/2021-edition/carbon-economy/figure-2-greenhouse-gas-emissions-by-source/.
4. vanStijl, "The Opportunities, Challenges, and the Latest Developments of Electrification in the Shipping Industry," Platform Zero (blog), January 18, 2023, https://platformzero.co/the-opportunities-challenges-and-the-latest-developments-of-electrification-in-the-shipping-industry/.
5. Note: Emissions share of maritime shipping may be skewed due to declines in on-road passenger vehicle volume due to COVID stay-at-home orders. Overall, the emissions share of the transportation sector dropped to 37.9% in 2020, compared to 41.2% in 2019.
6. The Green Hydrogen Coalition defines "renewable hydrogen" as hydrogen which is produced from non-fossil fuel feedstocks and has climate integrity. GHC supports a well-to-gate carbon intensity framework consistent with the International Partnership for Hydrogen and Fuel Cells in the Economy to establish climate integrity.
See "Why Renewable Hydrogen | Renewable Hydrogen Coalition," accessed February 22, 2024, https://renewableh2.eu/why-renewable-hydrogen/.
7. "Clean Hydrogen: A Versatile Tool for Decarbonization," Rhodium Group (blog), accessed February 22, 2024, https://rhg.com/research/clean-hydrogen-decarbonization/.
8. https://www.congress.gov/bill/117th-congress/house-bill/3684/text
9. https://www.whitehouse.gov/cleanenergy/inflation-reduction-act-guidebook/
10. "Regional Clean Hydrogen Hubs Selections for Award Negotiations," Energy.gov, accessed February 22, 2024, https://www.energy.gov/oced/regional-clean-hydrogen-hubs-selections-award-negotiations.

Due to this growing interest in renewable hydrogen, attention has trickled down to hydrogen derivatives, namely ammonia (NH_3). Ammonia, which is comprised of nitrogen and hydrogen, is primarily used as a fertilizer for the agricultural sector and is referred to as "brown ammonia" since it is derived through an energy-intensive process that results in sizeable carbon emissions *(see box below)*.[11] However, ammonia has the potential to be a low carbon commodity. When produced using green hydrogen in the same industrial process or via other renewable pathways, it can be key in decarbonization efforts, replacing its current primary use in fertilizer and opening potential use as a renewable fuel. Since the renewable ammonia market is nascent, it is essential to understand the status of the brown ammonia market, its current use, and production pathways. This understanding will be essential for exploring the opportunities and potential for renewable ammonia and the barriers to its uptake, as well as highlighting the key enabling policy and regulatory factors that can help the renewable ammonia market develop.

WHAT IS AMMONIA?

Ammonia is a versatile molecule comprised of hydrogen and nitrogen. Today, it is primarily used to produce nitrogen fertilizers and is also used as a feedstock in the chemical sector. Additionally, ammonia has the potential to be used as a fuel to generate electricity through fuel cells or in direct combustion, as well as a hydrogen carrier. Ammonia is categorized as "brown," "green," or "renewable," depending on the production pathway and the impact of emissions.



BLUEPRINT PROCESS

This market brief and policy blueprint highlight the potential opportunities of renewable ammonia as a resource to decarbonize hard-to-abate sectors in California. It also builds upon prior green hydrogen efforts under the Green Hydrogen Coalition's HyBuild™ Los Angeles (LA) Initiative.

HyBuild LA brought together the green hydrogen value chain and stakeholder ecosystem across the LA Basin, including green hydrogen production, transport, storage, multi-sectoral offtakers, labor unions, environmental and environmental justice leaders, tribal nations, and other interested parties. The platform combined robust technical analysis and stakeholder engagement to facilitate alignment and identify key areas for action to advance a green hydrogen economy at scale. Together, this collaborative group unlocked a vision to achieve $2.05/kilogram (kg) of delivered green hydrogen by 2030 while identifying and maximizing community benefits from the clean energy transition. Factoring in tax benefits from the IRA, this delivered cost estimate was further reduced to $0.69/kg, a target consistent with the DOE's Hydrogen Earthshot initiative, which established a goal of achieving $1/kg of hydrogen produced in one decade. HyBuild LA was a key piece of moving the green hydrogen conversation forward in the state, and the research and findings from this effort helped secure the successful California Hydrogen Hub award from the DOE.

Although primarily focused on green hydrogen, HyBuild LA highlighted opportunities for green ammonia in both Southern and Northern California. This work, as well as recent industry efforts around renewable ammonia, have catalyzed the development of this market brief and policy blueprint.

Developed through a combination of desktop research, interviews with key stakeholders, and policy expertise, this market brief and policy blueprint paints a picture of the current ammonia landscape in the state of California and across the U.S., lays out production pathways, technology trends, identifies near term opportunities for renewable ammonia, considers barriers to market development, and establishes a policy blueprint to catalyze market development.

Table 1 | Renewable Ammonia Blueprint Process

Desktop Research	Interviews
Industry and technology reports, Academic literature, Market trends and volumes, Market projections and forecasts	Developers, Maritime experts, Clean hydrogen producers, Industry trade associations

11. Charlotte Edmond "From fuel to fertilizer, how green ammonia could help curb emissions," World Economic Forum, November 30, 2023. https://www.weforum.org/agenda/2023/11/green-ammonia-climate-change-energy-transition/.

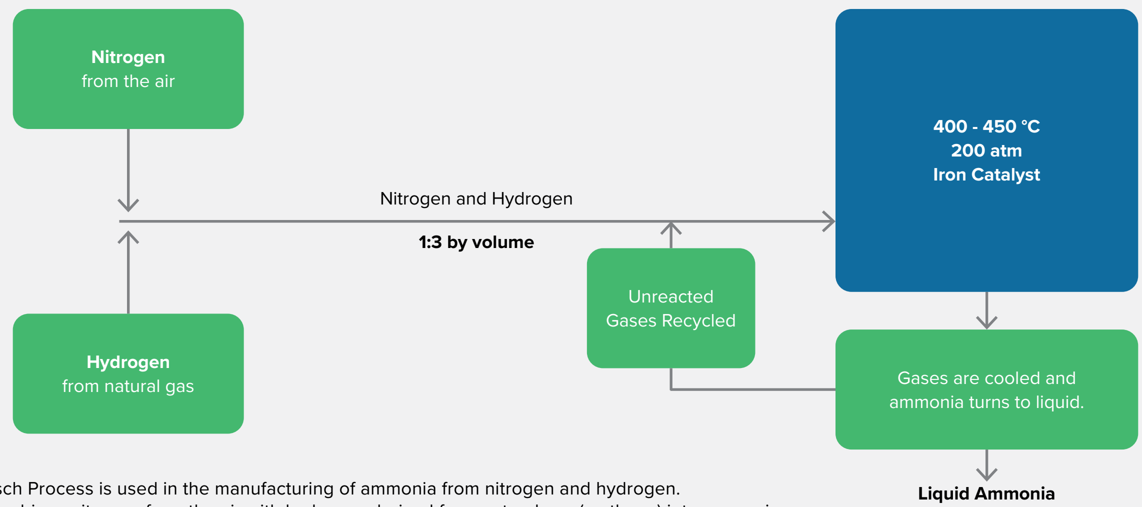
THE MARKET STATUS OF AMMONIA TODAY

Today, ammonia is a key global commodity.[12] Ammonia has been produced since the early 20th century through the Haber-Bosch process, in which nitrogen from the air is combined with hydrogen *(see below for more details on the Haber-Bosch process)*. Globally, ammonia is key to the agricultural sector since it is an important source of nitrogen, which promotes crop growth and is a key feedstock for fertilizer.

The International Energy Agency (IEA) finds that globally "about 70% of ammonia is used for fertilisers, while the remainder is used for various industrial applications, such as plastics, explosives and synthetic fibres."[13] Ammonia is produced on a massive scale, with a market value of 205 billion USD in 2022, which is expected to grow at a compound annual growth rate of 5.4% through 2030.[14] Demand for ammonia is expected to triple from around 200 million metric tons (MMt) to over 600 MMt by 2050.[15] Its production accounts for 2% of the world's total energy consumption and 1.5% of carbon emissions.[16] As of 2023, it is estimated that "half the world is fed using synthetic nitrogen-based fertilizers."[17] In the U.S., approximately 88% of domestic ammonia consumption is for fertilizer use.[18] However, the use of ammonia in the chemical industry is growing.[19] Today, it is commonly used for commercial refrigeration, purifying water supplies, and manufacturing plastics, explosives, fabrics, pesticides, dyes, and other chemicals. In 2021, the U.S. was one of the world's leading producers and consumers of ammonia.[20]

Within California, ammonia is used predominantly to make fertilizer in the Central Valley. This region of California supplies about one-fourth of the produce to the entire U.S. and is the country's most profitable agricultural region.[21] In this respect, ammonia is a key resource for California. It is important to note, however, that California must import nearly 100% of its ammonia since it has just one small production facility.[22]

Figure 1 | Ammonia Production: Haber-Bosch Process



The Haber-Bosch Process is used in the manufacturing of ammonia from nitrogen and hydrogen.
The process combines nitrogen from the air with hydrogen derived from natural gas (methane) into ammonia.

12. IRENA and AEA, "Innovation Outlook: Renewable Ammonia" (Abu Dhabi: International Renewable Energy Agency, Ammonia Energy Association, 2022), https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf.
13. International Energy Agency, "Ammonia Technology Roadmap: Towards More Sustainable Nitrogen Fertiliser Production" (OECD, October 18, 2021), https://doi.org/10.1787/f6daa4a0-en.
14. "Ammonia Market Size, Share & Growth Trends Report, 2030," accessed February 23, 2024, https://www.grandviewresearch.com/industry-analysis/ammonia-market.
15. "Consulting Strategic Report: Unlocking the Potential of Low Carbon Ammonia | S&P Global Commodity Insights," accessed February 23, 2024, https://commodityinsights.spglobal.com/LowCarbonAmmonia.html.
16. International Energy Agency, "Ammonia Technology Roadmap: Towards More Sustainable Nitrogen Fertiliser Production" (OECD, October 18, 2021), https://doi.org/10.1787/f6daa4a0-en.
17. "From Fuel to Fertilizer, How Green Ammonia Could Help Curb Emissions," World Economic Forum, November 30, 2023, https://www.weforum.org/agenda/2023/11/green-ammonia-climate-change-energy-transition/.
18. Lori E. Apodaca, "U.S. Geological Survey, Mineral Commodity Summaries: Nitrogen (Fixed)—Ammonia" (Washington, D.C.: U.S. Geological Survey, January 2022).
19. "Natural Gas Weekly Update," accessed February 23, 2024, https://www.eia.gov/naturalgas/weekly/archivenew_ngwu/2021/04_01/.
20. Lori E. Apodaca, "U.S. Geological Survey, Mineral Commodity Summaries: Nitrogen (Fixed)—Ammonia" (Washington, D.C.: U.S. Geological Survey, January 2022).
21. "California's Central Valley | USGS California Water Science Center," accessed February 23, 2024, https://ca.water.usgs.gov/projects/central-valley/about-central-valley.html#:~:text=Using%20fewer%20than%201%25%20of,nuts%2C%20and%20other%20table%20foods.
22. Nutrien, "2023 Fact Book," n.d., https://nutrien-prod-asset.s3.us-east-2.amazonaws.com/s3fs-public/uploads/2023-11/Nutrien_2023Fact%20Book_Update_112723.pdf.

Outstanding Challenge: Current Ammonia Production Pathways Rely on Fossil Fuels

While ammonia itself is carbon-free, ammonia created through the conventional ammonia production pathway– the Haber-Bosch process – is deemed "brown" since it involves using energy produced by fossil fuels, and the hydrogen itself is derived from natural gas (methane).[23] The production of ammonia is both an energy-intensive process and one that involves the release of significant carbon emissions. It is estimated that about two-thirds of the carbon dioxide (CO2) emissions in ammonia are tied to the hydrogen production process itself, typically steam methane reformation of natural gas, with the balance coming from process heat requirements for the Haber-Bosch process.[24] This current method for ammonia production results in high levels of direct and indirect greenhouse gas (GHG) emissions, both of which threaten progress toward combatting climate change.[25]

The IEA estimates that the global carbon footprint of ammonia is equivalent to the total emissions of South Africa's energy system. Within California, the agriculture sector is estimated to be responsible for approximately 8% of the state's emissions, of which about 1.8% comes from crops.[26] While this does not translate directly to the emissions from ammonia, it nonetheless serves as a proxy to estimate the emissions impacts that the ammonia for fertilizer use has on the state. Given that California is responsible for about 6% of the total carbon emissions in the U.S., the size of the ammonia emissions in the state is significant.[27]

The impact of ammonia emissions is exacerbated by the expectation that the demand for ammonia is expected to increase with global population growth and that increased fertilizer needs to support the projected growing demand for agriculture.[28] This trend, given the impact of emissions and the energy-intensive nature of ammonia, is unsustainable from a climate perspective.

23. OAR US EPA, "Importance of Methane," Overviews and Factsheets, January 11, 2016, https://www.epa.gov/gmi/importance-methane.
24. IRENA and AEA, "Innovation Outlook: Renewable Ammonia" (Abu Dhabi: International Renewable Energy Agency, Ammonia Energy Association, 2022), https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf.
25. International Energy Agency, "Ammonia Technology Roadmap: Towards More Sustainable Nitrogen Fertiliser Production" (OECD, October 18, 2021), https://doi.org/10.1787/f6daa4a0-en.
26. Ibid.
27. "California Profile," accessed February 23, 2024, https://www.eia.gov/state/print.php?sid=CA.
28. IRENA and AEA, "Innovation Outlook: Renewable Ammonia" (Abu Dhabi: International Renewable Energy Agency, Ammonia Energy Association, 2022), https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf.

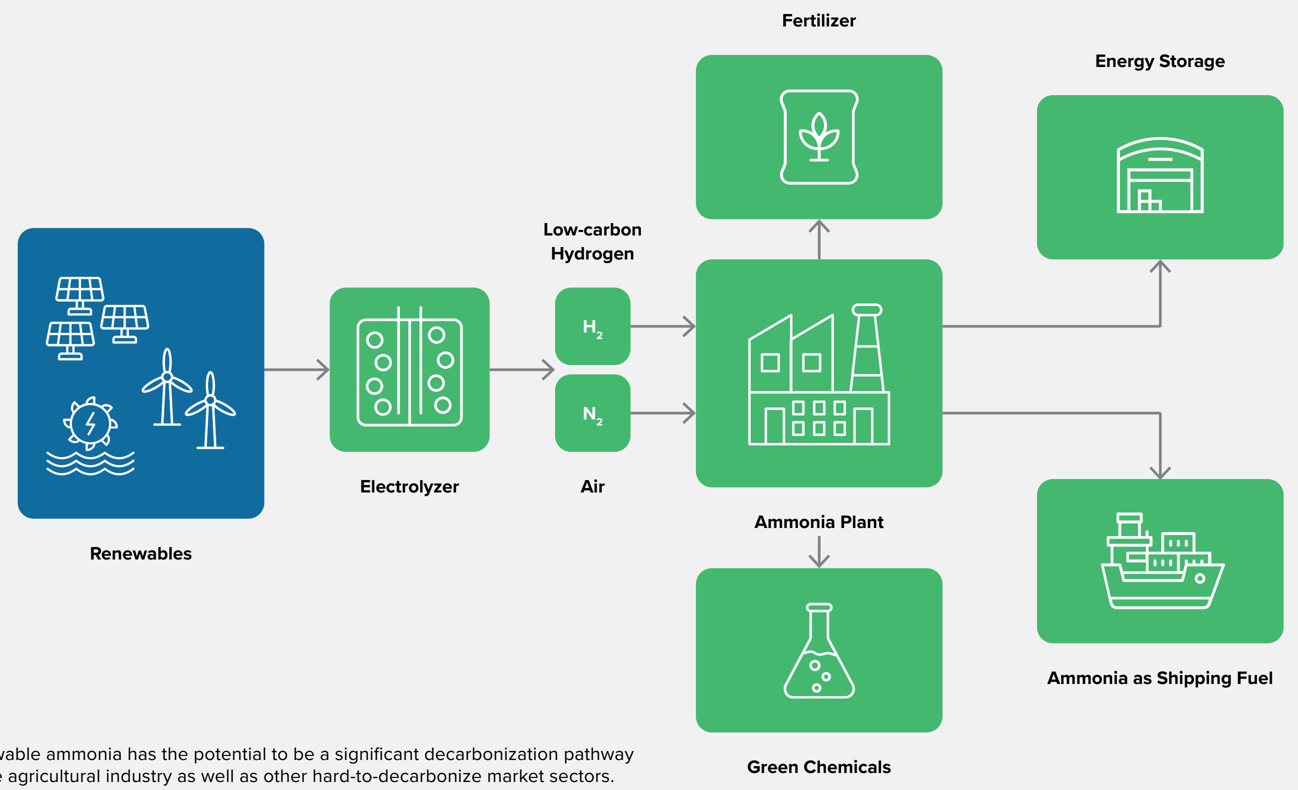
THE VALUE PROPOSITION, CURRENT STATUS, AND MARKET POTENTIAL OF RENEWABLE AMMONIA

Given the widespread use of ammonia as a feedstock for fertilizer and industrial applications, expected growth in demand from an increasingly populous and prosperous world, and the climate crisis, emissions from the use of ammonia must be addressed.

Accordingly, **the value proposition for renewable ammonia is clear:** it has the potential to replace conventional ammonia and thereby help achieve needed emissions reductions in a critically important economic sector.

In addition to replacing brown ammonia in existing uses, renewable ammonia has the potential to serve as a decarbonization pathway for the world economy, especially in some hard-to-decarbonize sectors. Specifically, there has been widespread recent interest in using renewable ammonia as a low-carbon fuel in maritime shipping, power generation, energy storage, and other sectors where electrification is impractical due to costs, technology limitations, or other challenges. Indeed, the interest in and potential for using renewable ammonia has been recognized in markets, with market analysis predicting not only a tripling of ammonia demand but also that the market share of renewable ammonia is anticipated to make up two-thirds of total ammonia demand by 2050.[29]

Figure 2 | The Green Ammonia Value Chain



Renewable ammonia has the potential to be a significant decarbonization pathway for the agricultural industry as well as other hard-to-decarbonize market sectors.

29. "Consulting Strategic Report: Unlocking the Potential of Low Carbon Ammonia | S&P Global Commodity Insights," accessed February 23, 2024, https://commodityinsights.spglobal.com/LowCarbonAmmonia.html.

California, with its significant share of the U.S. agricultural market, broad set of energy intensive industries, robust maritime transportation system, and stringent clean targets, is uniquely poised to take advantage of the potential of renewable ammonia:

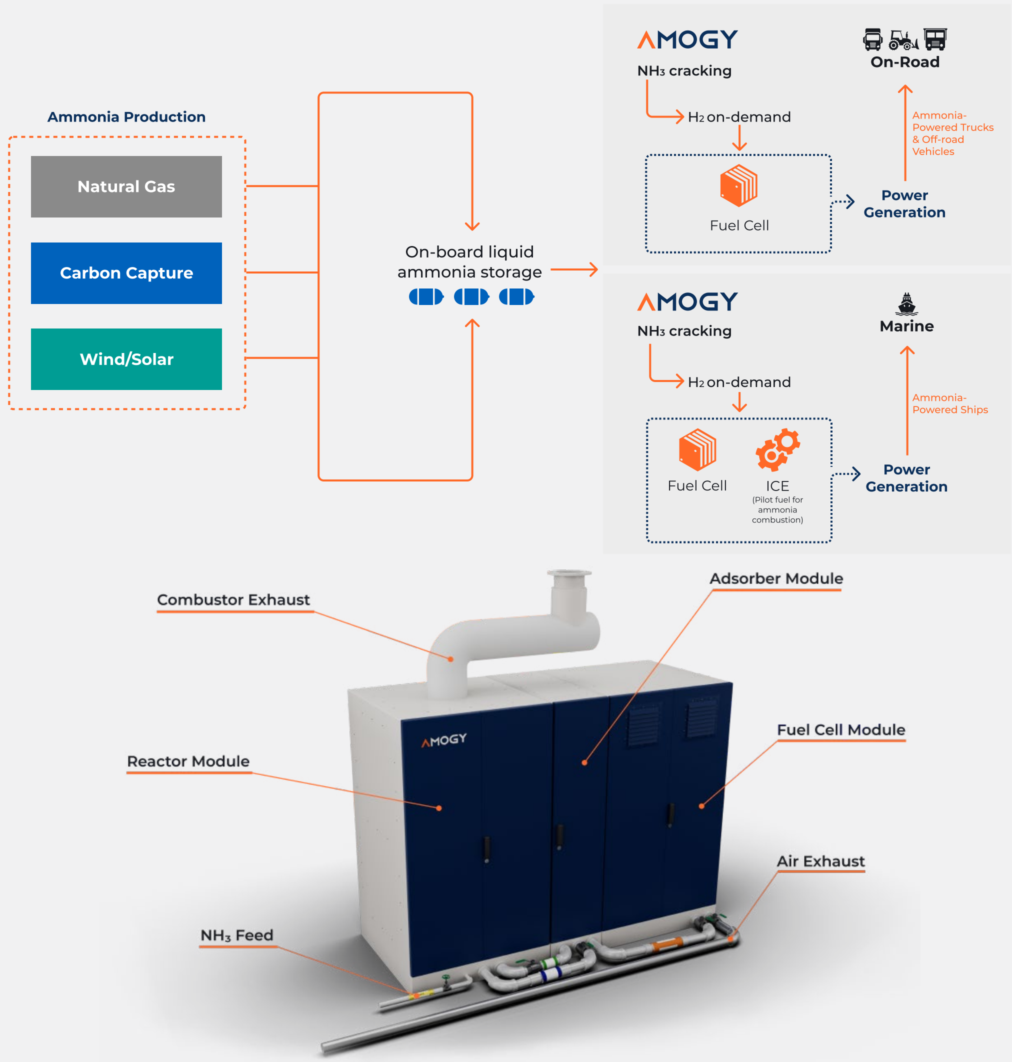
1. **Renewable ammonia can help the state decarbonize its hard-to-abate market sectors by directly replacing existing carbon-intensive ammonia use with renewable ammonia.**
2. **The state has abundant renewable energy resources and a strong potential for additional resources that can be used to produce the renewable hydrogen feedstock needed to make renewable ammonia.**
    - California produces the most electricity from solar energy and geothermal resources than any other state and continues to have a significant potential for additional solar, geothermal, and offshore wind development. The development of these resources to date has been limited by transmission interconnection, but this challenge could be bypassed by direct delivery of energy to produce renewable ammonia.
    - California, as an agricultural state, also has ample organic waste resources, which can also be used to produce renewable hydrogen for renewable ammonia production.
3. **California is home to ARCHES, the state's renewable hydrogen hub, which intends to develop a robust renewable hydrogen ecosystem.** Renewable hydrogen is a key feedstock to renewable ammonia, and hub efforts can be leveraged to enable renewable ammonia production, transportation, and use.[30]
4. **Although California does not produce any ammonia, it uses a significant amount of it, not only for agriculture but also for refrigeration and a number of industrial processes.** This ammonia must be imported at cost to the state. Local production would change this balance and could enable California to be a renewable ammonia exporter to both domestic and international markets.
5. **California possesses significant existing ammonia knowledge and expertise, including ammonia import infrastructure at the port of Stockton.[31]**
    - Example: the fertilizer industry already ships ammonia in tankers designed to carry liquefied petroleum gas.[32]

Excitingly, **the transition to renewable ammonia has begun**. As of 2021, multi-gigawatt renewable ammonia production plants are already under construction, and "the first renewable hydrogen supply was retrofitted onto an existing ammonia plant."[33] Furthermore, demonstrations and pilot projects are helping to prove technology readiness and increase interest. Additionally, demand from first movers for new uses of low-carbon ammonia is happening globally. Notable examples include:

- In 2022, JERA conducted the industry's first international bidding for the procurement of ammonia as fuel. In 2023, it plans to conduct demonstration testing in which ammonia converts 20% of the coal burned.[34]
- CF Industries: Construction of CF Industries' green ammonia project at its Donaldsonville Complex began in the fourth quarter of 2021. The Company will install a state-of-the-art electrolysis system at Donaldsonville to generate carbon-free hydrogen from water that will then be supplied to an existing ammonia plant to produce green ammonia. Once complete, the project will enable the Company to produce approximately 20,000 tons per year of green ammonia.[35]

30. ARCHES H2, Accessed March 26, 2024. https://archesh2.org/about/
31. Calamco, "A Partnership with Growers," Accessed March 26, 2024. https://calamco.com/
32. IRENA, "Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach - 2023 Update," 2023, https://iea.blob.core.windows.net/assets/9a698da4-4002-4e53-8ef3-631d8971bf84/NetZeroRoadmap_AGlobalPathwaytoKeepthe1.5CGoalinReach-2023Update.pdf.
33. Ibid.
34. Jera, "What is JERA's fuel ammonia initiative, part of its grand plan to eliminate CO2 emissions?" June 22, 2023. https://www.jera.co.jp/en/action/discover/016
35. CF Industries, "Investing in Green Ammonia Production," Accessed March 26, 2024. https://sustainability.cfindustries.com/energy-emissions-and-climate-change/decarbonizing-our-network/green-ammonia

- Brooklyn-based startup Amogy has developed a compact, highly efficient modular reactor that cracks ammonia *in-situ* and uses the resulting hydrogen to generate power through a fuel cell or in a combustion engine.[36]



Source: Amogy

- INPEX Corporation, Air Liquide, LSB Industries, and Vopak Moda are collaborating on a new low-carbon ammonia on the Houston Ship Channel. The proposed location will leverage existing infrastructure, including present ammonia handling infrastructure, storage tanks, and a ship dock. A feasibility study has already been completed, and the project is moving forward. Although not renewable ammonia, the project intends to produce 1.1 million tonnes per year of carbon-capture based ammonia by 2027.[37]
- International Energy Administration: Several major ship engine makers are in the final stages of developing ammonia two-stroke engines for commercialization by 2024, intending to also develop retrofit packages for existing vessels. These engines are intended to permit maritime operations on a variety of fuels, including renewable ammonia and renewable methanol. Shipmakers are seeing strong interest from shipping companies in new fuel technologies, with several pilot and demonstration projects underway.[38]

36. Shantanu Chakraborty, Peter Marrin, and Jacques Moss, "Ammonia as a Fuel to Decarbonize Transportation - The Inception of a New Fuel in Established Markets Amid the Energy Transition. Commissioned by Amogy." (Guidehouse Insights, 2022).
37. "Global Energy and Chemical Leaders Partner to Develop a Large-Scale, Low-Carbon Ammonia Production Export Project on the Houston Ship Channel | LSB Industries," accessed February 23, 2024, https://investors.lsbindustries.com/news-releases/news-release-details/global-energy-and-chemical-leaders-partner-develop-large-scale.
38. "The Case for Two-Stroke Ammonia Engines," MAN Energy Solutions, accessed February 23, 2024, https://www.man-es.com/discover/two-stroke-ammonia-engine.

RENEWABLE AMMONIA PRODUCTION

To understand the potential for renewable ammonia, it is vital to understand the key production pathways and the feedstocks enabling them, namely electrolytic and biological processes and renewable hydrogen. These methods represent critical strategies for sustainable ammonia production, offering alternatives to the conventional Haber Bosch process by minimizing carbon emissions and integrating renewable resources.

RENEWABLE AMMONIA

Renewable Ammonia can be produced from **renewable hydrogen** and **nitrogen**. Renewable hydrogen can be produced electrolytically, using water and renewable electricity, and from organic waste feedstocks through pyrolysis.

Electrolytic renewable ammonia production represents a significant technological advancement. This process leverages renewable energy sources, such as wind or solar power, to electrolyze water, splitting it into hydrogen and oxygen in an electrolyzer. The hydrogen produced in this manner is combined with nitrogen extracted from the air through air separation to synthesize ammonia in the Haber-Bosch process. Process energy needs can also be supplied from renewable energy sources. Unlike conventional ammonia production methods that rely on fossil fuels producing substantial carbon dioxide emissions, electrolytic renewable ammonia production emits little to no greenhouse gases, assuming the electricity is sourced from renewable energy.

Organic waste is an excellent feedstock from which renewable hydrogen can be produced via gasification or pyrolysis. The hydrogen produced in this manner can also be combined with nitrogen extracted from the air through the Haber-Bosch process. One advantage of producing renewable hydrogen from biological feedstocks is the production of hydrogen is constant vs. intermittent, which can improve the economics of the Habor-Bosch process via higher utilization factors.

BIOLOGICAL RENEWABLE AMMONIA

Biological renewable ammonia production is an approach that utilizes microorganisms or engineered biological systems to synthesize ammonia under ambient conditions, bypassing the energy-intensive processes associated with traditional methods. This method leverages the natural ability of certain bacteria and archaea, which possess the enzyme nitrogenase, to fix atmospheric nitrogen directly into ammonia. Unlike the Haber-Bosch process, biological production occurs at room temperature and atmospheric pressure, reducing the energy demand and associated carbon footprint.

This technology is particularly promising for decentralized ammonia production, making it feasible for local or on-site manufacturing in agricultural settings. As research advances, there is potential for genetically engineered microbes to enhance efficiency and yield, paving the way for a sustainable and circular nitrogen economy.

DEMONSTRATED RENEWABLE AMMONIA IN CALIFORNIA AND NATIONALLY

In December 2023, Avina Clean Hydrogen submitted a proposal to construct their "Nueces Green Ammonia Plant" at a greenfield site in Nueces County, Texas. Avina's projected electrolytic production rate is approximately 3.2 billion gallons of ammonia per year. It is estimated that the project will create 45 to 100 jobs for the community, and the project will include a detailed planning process to incorporate public feedback to help identify and mitigate potential project risks.[39]

Source: Avina Clean Hydrogen Inc.

The University of Minnesota's West Central Research and Outreach Center has led the way in pioneering "green ammonia" technology. This initiative marked a global first with the launch of a renewable hydrogen and ammonia pilot plant operating since 2013. Utilizing a 1.65 MW wind turbine, the facility can generate up to 25 tons of anhydrous ammonia annually on-site. This production capacity is sufficient to fertilize about 300 acres of farmland. The university states that "by using green ammonia for fertilizer, fuel and heat, farming's fossil energy footprint could decrease as much as 90% for corn and small grain crops."[40]

Exploring renewable ammonia production through electrolytic and biological processes is crucial for greener agriculture and energy solutions. These innovative methods, leveraging renewable energy and microorganisms for ammonia synthesis, offer a sustainable alternative to conventional production, significantly reducing carbon emissions. Initiatives like the Nueces Green Ammonia Plant in Texas and the University of Minnesota's pioneering pilot plant showcase these technologies' practical application and potential. They highlight the transformative impact renewable ammonia can have on decreasing agriculture's fossil energy footprint, underscoring the momentum towards a more sustainable and decarbonized future.

39. TRC Envrionmental Corporation, "Application for Air Source Review (NSR) Preconstruction Permit - Nueces Green Ammonia Plant," 2023, https://ewscripps.brightspotcdn.com/c8/b2/3c51379c43f882d137ad0b0bfdb8/green-ammonia-air-permit-application.pdf.
40. "Taking the Lead in Green Ammonia | College of Food, Agricultural and Natural Resource Sciences," University of Minnesota College of Food, Agricultural and Natural Resource Sciences, accessed February 23, 2024, https://cfans.umn.edu/news/lead-green-ammonia.

CALIFORNIA'S DEMAND OPPORTUNITIES

MARITIME DEMAND

In 2022, international shipping accounted for about 2% of global energy-related CO_2 emissions and 1% of California emissions.[41] To secure compliance with global emissions targets, there is broad consensus that the shipping industry needs to transition to a new suite of fuels and propulsion technologies. The United Nations body tasked with regulating the industry, the International Maritime Organization, released its initial GHG strategy in 2018, which called for a 50% reduction in GHG emissions relative to 2008 levels by 2050.[42]

> Renewable ammonia as a **maritime fuel** offers a promising pathway toward decarbonizing the shipping industry.

The Los Angeles-Shanghai Green Shipping Corridor, a pioneering initiative by the Port of LA, Port of Shanghai, and C40 Cities, aims to revolutionize one of the world's busiest maritime routes through decarbonization, including the adoption of zero-carbon fueled ships by 2030.[43] A significant component of making this green corridor feasible is the pivot towards renewable ammonia as a shipping fuel. As part of a broader strategy to mitigate the environmental impact of shipping, incorporating renewable ammonia aligns with the initiative's goals to lower emissions, enhance efficiency, and improve air quality around these major ports in China and the U.S. The collaborative effort, supported by a coalition of cities, ports, shipping companies, and cargo owners, underscores a commitment to sustainable maritime transport and serves as a model for global replication, leveraging green ammonia's potential to pave the way for a cleaner shipping industry.[44]

MAN Energy Solutions, a subsidiary of Volkswagen Group, along with partners, is working on developing renewable ammonia-fueled engines that aim to combine high efficiency with compact design, planning for a fuel mix that contains around 95% ammonia and 5% pilot fuel, which could be marine gas oil or even biofuel in the future. Despite being carbon-free, the combustion of ammonia can result in emissions of nitrogen oxides (NO_x) and nitrous oxide (N_2O), posing a pollution challenge. However, selective catalytic reduction technology, already used on many ships for NO_x abatement, could be adapted for ammonia, with combustion process tuning being explored to mitigate N_2O emissions.[45] The IEA finds that ammonia could account for around 45% of global energy demand for shipping in 2050 in its Net Zero by 2050 Roadmap.[46]

Other maritime decarbonization options, such as vessel electrification, face greater technological barriers, presenting a ripe opportunity for green ammonia development. Electrification faces challenges due to the inadequate energy density of current battery technologies, which cannot sustain long-distance voyages. The substantial weight and volume of batteries required for such operations would drastically reduce cargo capacity, undermining economic viability. Additionally, the global maritime infrastructure lacks the necessary provisions for widespread electric charging, further complicating the transition. Other alternatives include biofuels, which have thus far shown limited potential for scaling, and hydrogen, which is difficult to store at large scale on a floating vessel. This has led to the interest in renewable ammonia derived from renewable hydrogen.[47]

41. "International Shipping," IEA, accessed February 23, 2024, https://www.iea.org/energy-system/transport/international-shipping.
42. Peter Marrin, Jacques Moss, and Shantanu Chakraborty, "Ammonia as a Fuel to Decarbonize Transportation - The Inception of a New Fuel in Established Markets Amid the Energy Transition. Commissioned by Amogy." (Guidehouse Insights, 2022).
43. C40 Cities Climate Leadership Group is a group of 96 cities around the world that represents one twelfth of the world's population and one quarter of the global economy. See "Port of Los Angeles, Port of Shanghai, and C40 Cities Announce Partnership to Create World's First Transpacific Green Shipping Corridor between Ports in the United States and China," C40 Cities, accessed February 23, 2024, https://www.c40.org/news/la-shanghai-green-shipping-corridor/.
44. Ibid.
45. "The Case for Two-Stroke Ammonia Engines," MAN Energy Solutions, accessed February 23, 2024, https://www.man-es.com/discover/two-stroke-ammonia-engine.
46. IRENA, "Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach - 2023 Update," 2023, https://iea.blob.core.windows.net/assets/9a698da4-4002-4e53-8ef3-631d8971bf84/NetZeroRoadmap_AGlobalPathwaytoKeepthe1.5CGoalinReach-2023Update.pdf.
47. Ibid.

FERTILIZER PRODUCTION

Today, about 80% of the ammonia produced by industry is used in agriculture as fertilizer.[48] Specifically, ammonia is processed into downstream fertilizer products before being applied to soil. These products include urea, ammonium nitrates, sulfate, phosphates, and nitrogen solutions. These products have varying ammonia intensities, and their specific contents by weight are detailed in the table below in the form of ammonia consumption factors, that is, a measure of ammonia content. The U.S. is the leading country in terms of quantity for the direct application of anhydrous ammonia and, to a lesser extent, aqueous ammonia. Due to growing agricultural needs, the demand for these ammonia-based fertilizers is anticipated to rise in the coming decades. Interestingly, the growth in biofuel production, especially bioethanol from corn, has significantly impacted the demand for all nitrogen fertilizers.[49]

Table 2 | Consumption Factors for the Production of Various Ammonia-based Fertilizers[50]

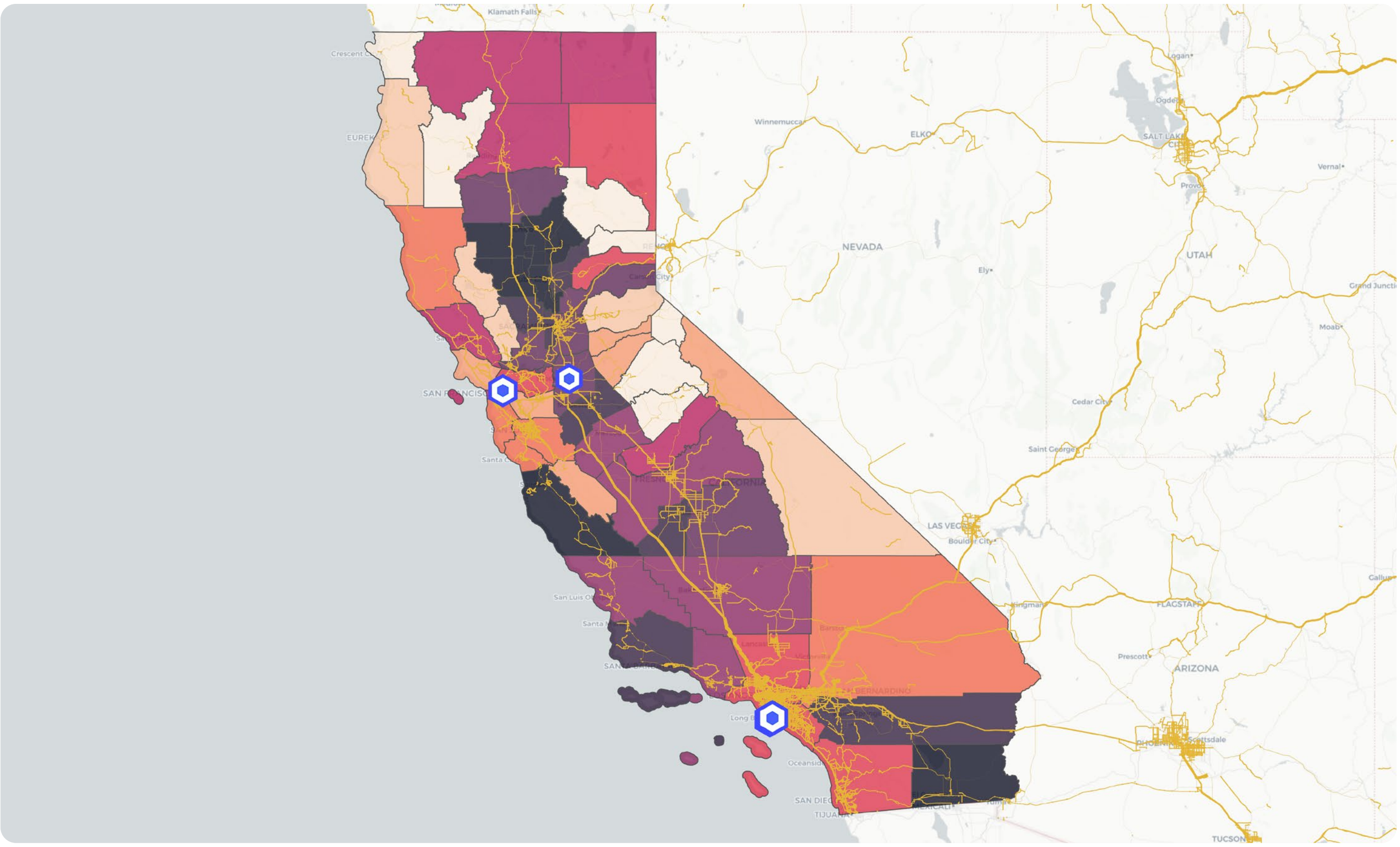
Chemical Produced	Ammonia Consumption (N basis) Factor
Acrylonitrile	.421
Ammonium Nitrate (Product Basis)	.3575
Ammonium Phosphates	.18
Ammonium Sulfate	.2134
Caprolactam	.54
Hydrogen Cyanide	.615
Methylamines	.33
Nitric Acid (100%) Basis	.2378
Urea	.46

California's agriculture sector, an industry with a market value of agricultural products totaling $63.0 billion in 2022, stands as a prominent existing user of ammonia and a potential off-taker for renewable ammonia.[51] The agricultural sector extensively uses nitrogen-based fertilizers to support its production of a vast range of crops, including over one-third of the U.S.'s vegetables and two-thirds of its fruits and nuts.[52] The state's commitment to environmental sustainability further aligns with the adoption of renewable ammonia. The integration of renewable ammonia into California's agricultural supply chain could not only meet the high fertilizer demand but also advance the state's leadership in sustainable agricultural practices. The economic stature and progressive environmental policies of California's agricultural sector thus present a compelling opportunity for renewable ammonia producers looking to engage with a substantial and forward-looking market.

Figure 3 *(on the next page)* presents a detailed visualization of ammonia consumption within California's counties, overlayed with the logistical infrastructure of road transport and major ports. The gradations of color intensity reflect varying levels of ammonia usage, which align with the agricultural output of each county. Ammonia consumption was calculated based on fertilizer use according to CDFA's fertilizing material tonnage report, scaled to Ammonia content in Table 1. Notably, counties with the highest ammonia consumption are in closer proximity to the Port of Stockton. The Port of Stockton is the only port in California that currently handles imports of ammonia, bringing in approximately 120 kilotons of ammonia imports each year to distribute to agricultural uses throughout the state.[53] This proximity is growing increasingly relevant given the identified role of ports as potential off-takers of renewable ammonia for use in reducing the maritime industry's carbon footprint. **The visual correlation between dense agricultural activity, ammonia consumption, and port access underscores the potential for integrated supply chains that leverage renewable ammonia both as an agricultural input and as a sustainable maritime fuel.**

48. IRENA and AEA, "Innovation Outlook: Renewable Ammonia" (Abu Dhabi: International Renewable Energy Agency, Ammonia Energy Association, 2022), https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf.
49. Bala Suresh, et al. "Ammonia," S&P Global Commodity Insights: Chemical Economics Handbook.
50. Ibid.
51. "Farm Sector Financial Indicators, State Rankings," accessed February 23, 2024, https://data.ers.usda.gov/reports.aspx?ID=17839.
52. Donya-Faye Wix, "The Economic Future of California Agriculture," AgAmerica, February 16, 2022, https://agamerica.com/blog/california-agriculture/.

Figure 3 | Gradation of ammonia consumption across California counties *(the darker being more intense ammonia use),* with road network tonnage depicted by line thickness and major shipping ports highlighted with blue markers.



OTHER POTENTIAL USE CASES FOR AMMONIA IN CALIFORNIA

This market and policy brief focuses on fertilizer use and maritime shipping since they are likely to be the first movers in the renewable ammonia market; however, these will not be the only use cases for renewable ammonia. As a carbon-free fuel source, renewable ammonia's capacity for combustion in gas turbines or engines or use in fuel cells offers a promising avenue for generating electricity with no carbon emissions. Research into optimizing ammonia combustion aims to mitigate any environmental impacts, such as the emission of nitrogen oxides, enhancing its potential viability as a clean energy source that could be leveraged in existing infrastructure.[54] Ammonia can also be utilized in fuel cells to produce electricity eliminating these emissions. The use of ammonia as a fuel source in the power sector can capitalize on its high energy density and its long-term use as a fertilizer to leverage existing infrastructure and safety protocols for its storage and transportation. These factors align with state efforts to diversify energy sources and reduce reliance on fossil fuels, positioning ammonia as a potential key player in the future power system energy mix.[55]

Further, the process of converting renewable electricity into ammonia and back into electricity, either via fuel cells or combustion, underscores ammonia's versatility as a storage medium in the right use case. This method effectively allows for storing surplus renewable energy, addressing the intermittent nature of sources like wind and solar. The ability to store and transport energy as ammonia opens up new possibilities for managing energy supply and demand, particularly in remote or off-grid locations.[56]

53. Port of Stockton California, "Annual Comprehensive Financial Report," June 30, 2021; CA Imports Source, State of CA Dept of Food and & Ag Report. Reference: categories 2 (anhydrous ammonia), 6 (aqua ammonia), 0 (non-farm use secondary/micronutrients).
54. IRENA and AEA, "Innovation Outlook: Renewable Ammonia" (Abu Dhabi: International Renewable Energy Agency, Ammonia Energy Association, 2022), https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf.
55. Ibid.
56. IRENA, "Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach - 2023 Update," 2023, https://iea.blob.core.windows.net/assets/9a698da4-4002-4e53-8ef3-631d8971bf84/NetZeroRoadmap_AGlobalPathwaytoKeepthe1.5CGoalinReach-2023Update.pdf.

UNDERSTANDING BARRIERS TO FUTURE RENEWABLE AMMONIA DEVELOPMENT

Given renewable ammonia's potential to provide a key decarbonization pathway for maritime shipping and fertilizer production, the question remains: **why has renewable ammonia not taken off yet?** Throughout the research process and in conversations with various key stakeholders, four key barriers rose to the forefront as limits to renewable ammonia market development:

BARRIER #1: THE GREEN PREMIUM AND ITS ROLE IN LIMITING SUPPLY & DEMAND

For the renewable ammonia market to take off, it must not only be available at the level of the current ammonia market (supply) but also have sufficient demand — both of which hinge on the cost-competitiveness of renewable ammonia itself.

Currently, renewable ammonia is far from being cost-competitive. As of 2022, it is estimated that renewable ammonia can cost around three times more than conventional ammonia.[57] This can be explained by a phenomenon known as the "green premium," in which it is more expensive to choose a clean technology over a conventional, carbon-emitting one.[58] The high cost of renewable ammonia largely hinges on the cost of renewable hydrogen, which is estimated to represent 90% of ammonia's production cost. Given how expensive renewable ammonia currently is, there is neither sufficient demand nor supply. As of 2022, renewable ammonia accounted for approximately 0.01% of global ammonia production.[59]

However, costs are expected to decline as an increasing number of large-scale production projects enter the market toward the end of this decade.[60] With the combined capacity of recently announced renewable ammonia projects, it is estimated that renewable ammonia will account for around 8% of the current global ammonia production.[61] In the U.S. and California, federal funding and hub development are catalyzing cleaner hydrogen production. As hydrogen production and demand build, the cost and availability of the feedstock for renewable ammonia (i.e., hydrogen) will become more and more economical. Hydrogen hub development may also explicitly include projects producing and using renewable ammonia. This potential for the use of renewable ammonia in California was outlined in the HyBuild LA effort.[62]

Momentum is building towards a renewable ammonia market, but the challenge remains getting policies and regulatory frameworks in place to help make renewable ammonia economical.

BARRIER #2: SAFETY CONCERNS AND SOCIAL ACCEPTANCE

Ammonia, while widely used today and important across various sectors, is toxic to humans at high exposure levels. While exposure to typical background environmental concentrations has no health effects, exposure to high levels "can cause irritation and serious burns on the skin and in the mouth, throat, lungs, and eyes" or death.[63] Therefore, the main fear about ammonia's toxicity is that it may harm those working in proximity to its use in agricultural or maritime shipping applications. In the case of maritime shipping, "to use ammonia onboard ships, fuel systems and bunkering infrastructure must be designed, manufactured, and operated to ensure the safety of ship crews, port staff, and fuel suppliers."[64] A less likely but equally harmful concern relates to the potential of an ammonia leak, which, in addition to causing harm to the workforce, could also harm local communities.

57. IRENA and AEA, "Innovation Outlook: Renewable Ammonia" (Abu Dhabi: International Renewable Energy Agency, Ammonia Energy Association, 2022), https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf.
58. "The Green Premium | Breakthrough Energy," accessed February 23, 2024, https://breakthroughenergy.org/our-approach/the-green-premium/.
59. IRENA and AEA, "Innovation Outlook: Renewable Ammonia" (Abu Dhabi: International Renewable Energy Agency, Ammonia Energy Association, 2022), https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf.
60. Shantanu Chakraborty, Peter Marrin, and Jacques Moss, "Ammonia as a Fuel to Decarbonize Transportation - The Inception of a New Fuel in Established Markets Amid the Energy Transition. Commissioned by Amogy." (Guidehouse Insights, 2022).
61. IRENA and AEA, "Innovation Outlook: Renewable Ammonia" (Abu Dhabi: International Renewable Energy Agency, Ammonia Energy Association, 2022), https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf.
62. "HyBuild Los Angeles Phase 2 Report," Green Hydrogen Coalition, March 23, 2023, https://www.ghcoalition.org/ghc-news/hybuild-la-phase-2-report.
63. "Ammonia | ToxFAQsTM | ATSDR," accessed February 23, 2024, https://wwwn.cdc.gov/TSP/ToxFAQs/ToxFAQsDetails.aspx?faqid=10&toxid=2.
64. Shantanu Chakraborty, Peter Marrin, and Jacques Moss, "Ammonia as a Fuel to Decarbonize Transportation - The Inception of a New Fuel in Established Markets Amid the Energy Transition. Commissioned by Amogy." (Guidehouse Insights, 2022).

Since the use of brown ammonia is widespread today, procedures for handling and transporting ammonia are well-known and established. For example, key standards and best practices are defined through the Ammonia Safety Training Institute.[65] Since the renewable ammonia market is nascent, it is imperative that best practices are expanded to this space and that the public and industry are educated on these new safety standards, especially as ammonia use moves to new industries. The industry is waiting on regulations and guidelines to identify optimal ways to safely employ renewable ammonia.[66]

Social acceptance, especially as it relates to the safety of renewable ammonia and its use in new applications, will prove essential in building market momentum. Ammonia's widespread and safe use, even in urban centers for commercial refrigeration, is not well known but has been in existence for decades. Greater education and awareness of this use and related safety standards can be leveraged as a starting point for new potential uses of renewable ammonia, particularly to displace fossil fuel use.

BARRIER #3: TECHNOLOGICAL READINESS FOR NEW APPLICATIONS

Given the fact that conventional ammonia has been used widely for decades, technology readiness is not a concern in the transportation of ammonia and present use cases (i.e., fertilizer production and other industrial uses), regardless of how the ammonia is produced (with or without fossil fuels). Technology and best practices with respect to operations and safety are well-established and understood. However, standards around the new applications for renewable ammonia — namely as a fuel within ships or bunkers — have not been developed previously. For this reason, demonstrations and pilot projects will be essential in proving the reliability and safety of ammonia used in new applications. For technological readiness to improve, additional demonstrations need to occur at larger scales and for new proposed end uses to create a positive feedback loop through which operating and safety practices can be replicated.[67]

On the production side, the Haber-Bosch process is well established, and the replacement of renewable hydrogen and clean energy should not represent technological barriers. However, biological renewable ammonia production pathways are still under development and have yet to be demonstrated at scale, despite promising research and demonstration production outcomes.[68]

BARRIER #4: LACK OF POLICY FRAMEWORK TO DRIVE MARKET ADOPTION

Since conventional ammonia use has been in place for many decades, policies and regulations in this space are mature and have been implemented widely. However, given the nascency of the renewable ammonia market, there is no cohesive policy or regulatory framework to push the market or incentivize greater adoption, despite the production and use of brown ammonia having been identified as a significant contributor to carbon emissions.

The differentiator of the needed framework for renewable ammonia is the focus on decarbonization, which, as expected, is not a central tenant of the policies and regulations that touch on conventional ammonia. Without a decarbonization-focused policy framework for ammonia and its existing and potential applications, it is unlikely that the current policy landscape will be sufficient to get the renewable ammonia market off the ground.

65. See Ammonia Safety Institute Report.
66. Ibid.
67. Industry expert interview.
68. Industry expert interview.

REGULATORY AND POLICY BLUEPRINT

The goal of this blueprint is to explore how California can transition towards renewable ammonia use and production by identifying the key policy levers that can be leveraged in the state. To this end, this blueprint identifies policy levers at both the state and federal levels that have no regrets and help generate concrete progress toward developing the market while also having low opportunity costs. In terms of priority, the state-level policy levers are considered first-order since they can directly incentivize renewable ammonia production within state borders and thereby support the overall focus of this blueprint. Federal policies can be understood as second-order levers since they may help drive demand and supply for renewable ammonia nationally, which in turn may indirectly shape and support the California market. In terms of political feasibility, the state-level actions are also likely to be more tenable since California is leading the nation in transitioning to a clean energy future. Accordingly, the interest in new clean energy pathways is strong, and there may be fewer political barriers that prevent progress. At the national level, the concerns around other priorities, including administration change and the potential for policy reversal, may present barriers to progress. Accordingly, the ordering of the two categories of policy levers – first state, then federal – can be understood as more feasible to less feasible. Within each category, however, the order policy levers and recommendations are listed is not indicative of their priority level or political feasibility.

Table 3 | State-Level Policy Levers[69]

Barrier Addressed	Objective	Motivation	Key Action	Notes
#4	Adopt A Statewide Mandate for Renewable Ammonia Production And Use	Currently, California does not have a mandate that requires renewable ammonia to be produced or used statewide in place of conventional ammonia in any quantity. Without such a minimum standard, there is little market certainty and, consequently, limited incentive for producers to invest in the renewable ammonia market.	In line with California's 2045 decarbonization goals under SB100, enact legislation to require that 100% of ammonia used and produced in California by 2045 must be produced using renewable hydrogen. Ideally, this legislation would include interim deadlines to ensure that the market is developing in a sustainable and predictable manner.	This may prove challenging since California failed to pass a similar version of this bill as it pertains to green hydrogen (AB 1550).[70]
#4	Explore a Fuel Standard for the Maritime Sectors Similar to the Low Carbon Fuel Standard (LCFS)	To decarbonize the maritime sector and enable renewable ammonia a fair chance to participate, California will need a fuel standard that extends beyond the land transportation sector. California could model a maritime LCFS on its existing program, which "is designed to decrease the carbon intensity of California's transportation fuel pool and provide an increasing range of low-carbon and renewable alternatives."[71]	Expand the LCFS beyond road transportation to also include the maritime sector.	California's jurisdiction with respect to non-California based vessels may represent a challenge.
#1	Create an Incentive for California-Based Production of Renewable Hydrogen or Renewable Ammonia	Currently, renewable ammonia is too expensive for widespread production and consumption. A significant portion of its cost stems from the high cost of renewable hydrogen. Providing a financial incentive for the production of renewable hydrogen or renewable ammonia directly in California may help green ammonia become an economical proposition.	Create a financial incentive that rewards California-based production or use of renewable hydrogen or renewable ammonia. For example, the incentive could cover the above-market cost for ammonia buyers to address the near-term "green premium" of renewable ammonia.	Given that California has recently been selected to be awarded H2Hub funding through the DOE (up to $1.2 billion), it is reasonable to assume follow-on effects on a hydrogen derivative.

69. For each lever within the state and federal categories, we identified the barrier from the above section that the policy seeks to address. Each policy will directly or indirectly address the fourth barrier: the need for a comprehensive policy framework to drive market adoption. However, they may additionally address other barriers as well.
70. "Bill Text - AB-1550 Renewable Hydrogen.," accessed February 23, 2024, https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=202320240AB1550.
71. "LCFS Electricity and Hydrogen Provisions | California Air Resources Board," accessed February 23, 2024, https://ww2.arb.ca.gov/resources/documents/lcfs-electricity-and-hydrogen-provisions.

Table 4 | Federal-Level Policy Levers

Barrier Addressed	Objective	Motivation	Key Action	Notes
#1	Provide an Incentive Through the U.S. Federal Crop Insurance Program (FCIP)	Currently, there is no federal incentive to incentivize the use of renewable ammonia. The FCIP, which is an existing multi-billion-dollar program, is designed to protect and stabilize both farmers' livelihoods and the U.S. food supply.	Provide a bonus within the FCIP on insurance calculations as well as the subsidy farmers receive, provided that they utilize renewable ammonia.	
#1	Provide an Incentive Through the Conservation Stewardship Program (CSP)	Similar to the above recommendation, there is no federal incentive to incentivize the use of renewable ammonia. CSP, which offers annual payments for implementing conservation practices on land, could be expanded to include a financial incentive for the use of renewable ammonia over conventional ammonia.	Add in payment through CSP for the utilization of renewable ammonia.	As this is a small program compared to FCIP, this could be somewhat easier to implement; however, it is also likely to have a smaller incentive as a result.
#2 and #3	Expand the Study Within the "Hydrogen for Industry Act" of 2023 to all Applications of Renewable Ammonia, Including Ammonia as a Fuel	Understanding the feasibility, safety, and best practices of all applications of renewable ammonia will be key to market uptake. The Hydrogen for Industry Act[72] seeks to amend the Energy Policy Act of 2005 to establish a Hydrogen Technologies for Heavy Industry Demonstration Program. The bill requires the Secretary of Energy, the Secretary of Commerce, and the Secretary of Transportation to jointly conduct a report, which will include "identify[ing] and evaluat[ing] the feasibility, safety, and best practices of the use of hydrogen and ammonia as industrial fuel and feedstock, including ways that current procedures, training, and handoffs with supply chain partners should be augmented to ensure safety for workers and neighboring communities."	Expand the bill to include the use of ammonia, a hydrogen derivative, beyond just industrial fuel and feedstock. Additionally, create a concrete pathway through which the key findings can be communicated to local communities and the public at large.	
#2 and #3	Fund Demonstrations Through the DOE's Office of Clean Energy Demonstrations (OCED)[73] for Renewable Ammonia in Maritime Shipping	Demonstrations and pilot projects are needed to illustrate the value proposition and safety of renewable ammonia. However, there is no funding opportunity to incentivize the demonstrations needed to drive widespread adoption and secure public support. However, the DOE's OCED, which manages more than $25 billion in funding to deliver clean energy demonstration projects at scale in partnership with the private sector to accelerate deployment and market adoption, has allocated significant cost-share funding in the renewable hydrogen space. This same mechanism could be employed to help the renewable ammonia market take off.	Create a cost-share program to incentivize renewable ammonia demonstrations across the U.S. Focus the funding on smaller vessels since they are easier to conduct demonstrations with and can prove the value proposition to the public at large.	OCED has been instrumental in using cost-share programs to incentivize demonstrations of clean hydrogen projects as well as research and development through the H2Hubs program. This model could be replicated or expanded to include renewable ammonia.

72. Christopher A. [D-DE Sen. Coons, "S.646 - 118th Congress (2023-2024): Hydrogen for Industry Act of 2023," legislation, March 2, 2023, 2023-03-02, https://www.congress.gov/bill/118th-congress/senate-bill/646.
73. https://www.energy.gov/oced/office-clean-energy-demonstrations

Barrier Addressed	Objective	Motivation	Key Action	Notes
#1	Adopt a Federal Mandate for Renewable Ammonia Production and Use	Currently, the U.S. does not have a mandate that requires renewable ammonia to be produced or used nationally in place of conventional ammonia. Without such a minimum standard, there is little market certainty and, consequently, less incentive for producers to invest in the renewable ammonia market.	Enact federal legislation to require that 100% of ammonia used and produced in the U.S. by a given year must be produced using renewable hydrogen. Ideally, this legislation would include interim deadlines to ensure that the market is developing in a sustainable and predictable manner.	
#1	Enact a Loan Program Under the Farm Bill for Renewable Ammonia	To scale renewable ammonia in the fertilizer space, powerful incentives need to be used in tandem with mandates. The Farm Bill,[74] a package of legislation passed roughly once every five years, contains a farm loan program that provides access to credit to help start, improve, expand, and strengthen American farms.	Enact a loan program that is specific to the use of renewable ammonia for fertilizer use in place of conventional ammonia.	
#1	Implement a Carbon Tax to Capture the GHG Costs for Conventional Ammonia Use	Given the "green premium" in effect on renewable ammonia, it is imperative to create policies that can help it become cost-competitive with conventional ammonia. This can be achieved either through adding a fee or tax to conventional ammonia for its GHG emissions, thereby raising the cost of conventional ammonia to that of renewable ammonia. Carbon pricing schemes have collectively been implemented across 40 countries and more than 20 cities, states, and provinces.[75]	Implement a federal carbon tax. At the global level, IRENA estimates that "a carbon price of around USD 150 per tonne of CO2 is required for renewable ammonia to be competitive with existing fossil-based ammonia production."[76]	The topic of a carbon tax has become politically charged in the U.S. and is unlikely to receive enough support to become enacted.
#1	Implement a Contracts-For-Difference (Cfd) Scheme for Ammonia Producers	For renewable ammonia uptake to occur, there needs to be a steady and secure supply of renewable ammonia, and costs must be minimized to the consumer. However, these both require investment in the renewable ammonia market and participation from producers. One way of achieving this is by paying ammonia producers for their investment in renewable ammonia.	Implement a CfD scheme under which the federal government pays existing ammonia producers for the difference in cost between producing renewable ammonia versus conventional ammonia. The DOE can strategically use CfDs to target sectors where renewable ammonia can have the most significant impact, such as fertilizer use and the maritime sector.	As the renewable market matures and eventually achieves economies of scale, the need for a CfD scheme is likely to decrease. The federal government can, therefore, gradually phase out this support mechanism.
All	Develop a Renewable Ammonia Advisory Committee	To facilitate the development of a robust renewable ammonia market, it is important to foster public-private partnerships so that policy work can support technology development in the supply chain, including uses for ammonia as a fuel.	Develop a renewable ammonia advisory committee through the DOE to help with the renewable ammonia research, development, and demonstration efforts at the federal level.	The DOE has previously created various advisory committees, including the Hydrogen and Fuel Cell Technical Advisory Committee.

74. "Farm Bill Home," page, national-content, September 24, 2020, https://fsa.usda.gov/programs-and-services/farm-bill/index.
75. "Pricing Carbon," Text/HTML, World Bank, accessed February 23, 2024, https://www.worldbank.org/en/programs/pricing-carbon.
76. IRENA and AEA, "Innovation Outlook: Renewable Ammonia" (Abu Dhabi: International Renewable Energy Agency, Ammonia Energy Association, 2022), https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf.

FUTURE WORK

In the next version of this analysis, it will be important to socialize the above-mentioned policy levers and determine the extent to which they are politically viable and the impact they might have on a renewable ammonia market. For those levers deemed the most efficient pathway forward, it will then be crucial to identify metrics to determine what would constitute "success" under a given policy lever. This will require engagement from stakeholders across the market, from policymakers and legislators to project developers and environmental groups. In parallel to socialization, a deeper dive into the exact working and implementation mechanisms of the different policy levels will be key to understanding both the benefits and costs associated with a particular approach.

Furthermore, greater technology and market analysis will help to explore other market opportunities beyond fertilizer and maritime shipping that could be ripe for renewable ammonia production and use in California. As discussed, the goal of focusing on these two applications is that they are likely key first movers that will help with market scaling in California. Relatedly, there may also be significant economic value in considering the potential for California to become a supplier and exporter of renewable ammonia for decarbonized fuel exports globally. Demand has already been identified in key Asian markets.

CONCLUSION

Renewable ammonia offers an opportunity to help decarbonize key segments of the Californian economy. While momentum is slowly building, for renewable ammonia to become a scaled decarbonization tool, there must be progress on the four key barriers: the green premium and its role in limiting supply and demand, current safety concerns and limited social acceptance, the need for technological readiness for new applications, and the current lack of a policy framework to drive market adoption. To that end, this document outlines a blueprint of policy levers that can help tackle these barriers by providing initial steps that can incentivize increased supply and demand as well as industry and public knowledge and acceptance. Ultimately, policy support at the state and federal levels will be essential in catalyzing the renewable ammonia market in California and nationally.

GREEN HYDROGEN COALITION

The Green Hydrogen Coalition, a 501(c)(3) educational nonprofit organization, is dedicated to facilitating practices and policies to advance the production and use of green hydrogen in all sectors where it will accelerate a carbon-free energy future. The GHC has three game-changing initiatives focused on policy and commercialization efforts that together will drive the North American green hydrogen market.

The Western Green Hydrogen Initiative is a public-private partnership to assist interested states and partners in advancing and accelerating the deployment of green hydrogen infrastructure in the Western region for the benefit of the region's economy and environment.

HyBuild™ North America is a platform to architect low-cost, mass-scale green hydrogen ecosystems throughout the continent. Each regional initiative builds around a consortium of diverse stakeholders, including multi-sectoral offtakers, and offers the potential for repurposing jobs and infrastructure.

The Consumer Education Initiative is a national effort that provides accessible, credibly sourced information to the public about the benefits of green hydrogen and dispels misconceptions.

For more information on the GHC, visit ghcoalition.org.