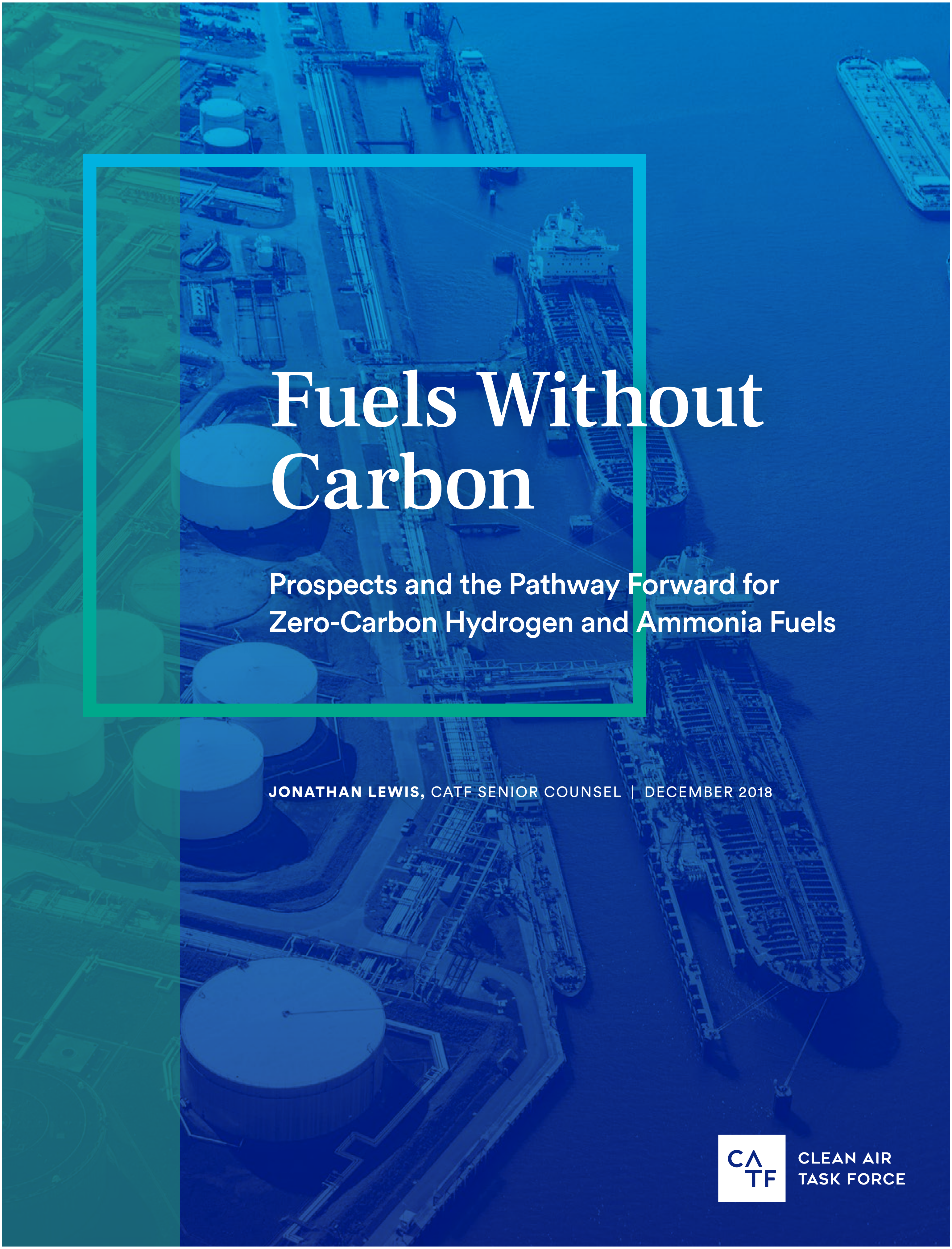

Fuels Without Carbon

Prospects and the Pathway Forward for Zero-Carbon Hydrogen and Ammonia Fuels

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Introduction

Report Summary

Because the world depends—and will continue to depend—on portable, storable, affordable, energy-dense fuels, the development of zero-carbon fuel is crucial to decarbonizing the power and transportation sectors and to climate change mitigation. **Two of the most promising zero-carbon fuel options are hydrogen (H_2) and ammonia (NH_3).**

Hydrogen and ammonia can be produced and converted into energy through processes that emit zero greenhouse gases. The production of hydrogen and ammonia is massively scalable. Hydrogen and ammonia are highly flexible as energy products—they can be produced and used in a variety of ways—and they are likely to be cost-competitive with incumbent petroleum fuels. The health, air pollution, and safety risks associated with hydrogen and ammonia fuel need more analysis—but they appear to be comparable to the risks associated with other more commonplace fuels, and similarly manageable.

Hydrogen and ammonia could also play important roles in addressing several confounding decarbonization challenges, including the short- and long-term storage of excess energy generated by wind and solar installations.

Public and private sector initiatives must be established to analyze the opportunities and challenges that hydrogen and ammonia present, to educate a range of audiences about the possible benefits and risks, to design and advocate for appropriately supportive policies, and to engage with key energy and mobility companies.

SECTION I

Zero-Carbon Fuels are Necessary Because Demand for Portable, Storable, Affordable, Energy-Dense Fuels Will Persist

The world currently uses carbon-emitting fossil fuels (oil, gas, coal) to power approximately **90% of transportation[1], 65% of electricity generation[2], and 75% of industrial energy consumption.**[3] Our dependence on fossil fuels stems partly from inertia of development patterns since the Industrial Revolution and partly from their undeniable convenience. Oil and coal are flexible enough that they can be used to make different kinds of energy in dozens of different ways. They are stable enough to be stored over long periods without degrading, and they are energy-dense enough to be highly portable. Oil, gas, and coal are plentiful enough—and the technologies we use to convert them into energy are efficient enough—that billions of people around the world can afford to use fossil fuels on a daily basis.

Liquid fuels are especially convenient. The International Energy Agency (IEA), US Energy Information Administration (EIA), and other analysts project that oil will continue to power a significant portion of the transportation sector for decades, even when high rates of future electrification are assumed. Electrification has its limits: electrifying *all* light duty vehicles by 2040 would reduce projected oil demand by almost 25 million barrels per day, but demand from the rest of the transportation sector (comprised of harder-to-electrify vehicles like trucks, trains, ships, and aircraft) would still exceed 35 million barrels of oil per day, per IEA data.[4,5]

Continued fossil fuel consumption is foreseen in other sectors, too. EIA projects that industry will use electricity to meet just 15% of its global heat demand in 2040 (amounting to 46.3 quadrillion Btu). If it is assumed that all electricity generation comes from renewables, nuclear, and other carbon-free technologies in 2040, the industrial sector would still rely on fossil fuels to produce 237.7 quadrillion Btu (76%) of its remaining demand for heat.[6]

Analysts even project lingering demand for oil in the power sector. Despite the decades-long marginalization of oil-fueled electric generating units, the IEA's New Policies Scenario expects **the global power sector will consume about 3 million barrels of oil per day in 2040.**

Safeguarding against the worst impacts of climate change will likely require a total reduction in carbon emissions from the transportation, power, and industrial sectors. In most instances, this implies a shift away from carbon-intensive fuels. Carbon-free fuels that offer the benefits of oil, gas, and coal need to be developed and deployed. Two of the most promising options are hydrogen and ammonia.

SECTION II

Expanding the Use of Zero-Carbon Fuels

Using Hydrogen and Ammonia as Fuel

An assortment of technologies suitable for use in the transportation sector and the power sector can convert hydrogen and ammonia into energy. Turbines and various types of fuel cells can run on hydrogen gas, while ammonia can power internal combustion engines, boilers, solid oxide fuel cells, and turbines.

Transportation

Hydrogen and ammonia can play a variety of roles in mobility decarbonization. Hydrogen fuel cells produce electricity, water, and heat; they do not emit CO_2 or conventional pollutants. A small-but-growing number of hydrogen-powered fuel cell vehicles (FCVs)—and, perhaps more importantly, hydrogen fueling stations—can be found in Japan, South Korea, parts of Europe, California (see box below), and the US Northeast. The currently

Hydrogen fueling station in California. Photo: NREL.

USING HYDROGEN TO COMPLY WITH CALIFORNIA'S LOW CARBON FUEL STANDARD

California's Low Carbon Fuel Standard (LCFS) requires a 10% reduction in the carbon intensity (CI) of the state's transportation fuel supply by 2020, and targets a 20% CI reduction by 2030. Fuel suppliers in California comply with LCFS by finding ways to reduce the lifecycle CI of gasoline or diesel and by promoting the use of cleaner (lower-CI) options for powering transportation, like electricity, biogas, some biofuels, and hydrogen. California Air Resources Board, the agency that administers the program, calculates CI values for six hydrogen fuel pathways by taking into account the hydrogen type (compressed or liquefied), the production method (Steam Methane Reforming (SMR) or electrolysis), the feedstock used in an SMR process (fossil natural gas or renewable biomethane), and/or the CI of the electricity used in an electrolytic process (average US grid or zero-carbon).

California created several types of special LCFS compliance credits, each intended to ease hydrogen's entry into the fuel market. At the retail level, owners of publicly accessible hydrogen fueling stations built prior to 2025 can earn infrastructure credits based on the capacity of their station and the CI of the hydrogen they sell. Further upstream, producers of electrolytic hydrogen that utilize low-carbon electricity and/or electricity that's generated during off-peak hours can earn special credits. Credits are also available to oil refineries that reduce the CI of the gasoline and diesel they produce for the California market by blending in low/zero-carbon hydrogen. Refineries can earn the credits by using hydrogen that was either produced by CCS-equipped facilities or made from biogas collected at landfills, wastewater treatment facilities, livestock operations, and other sources of non-geologic methane.

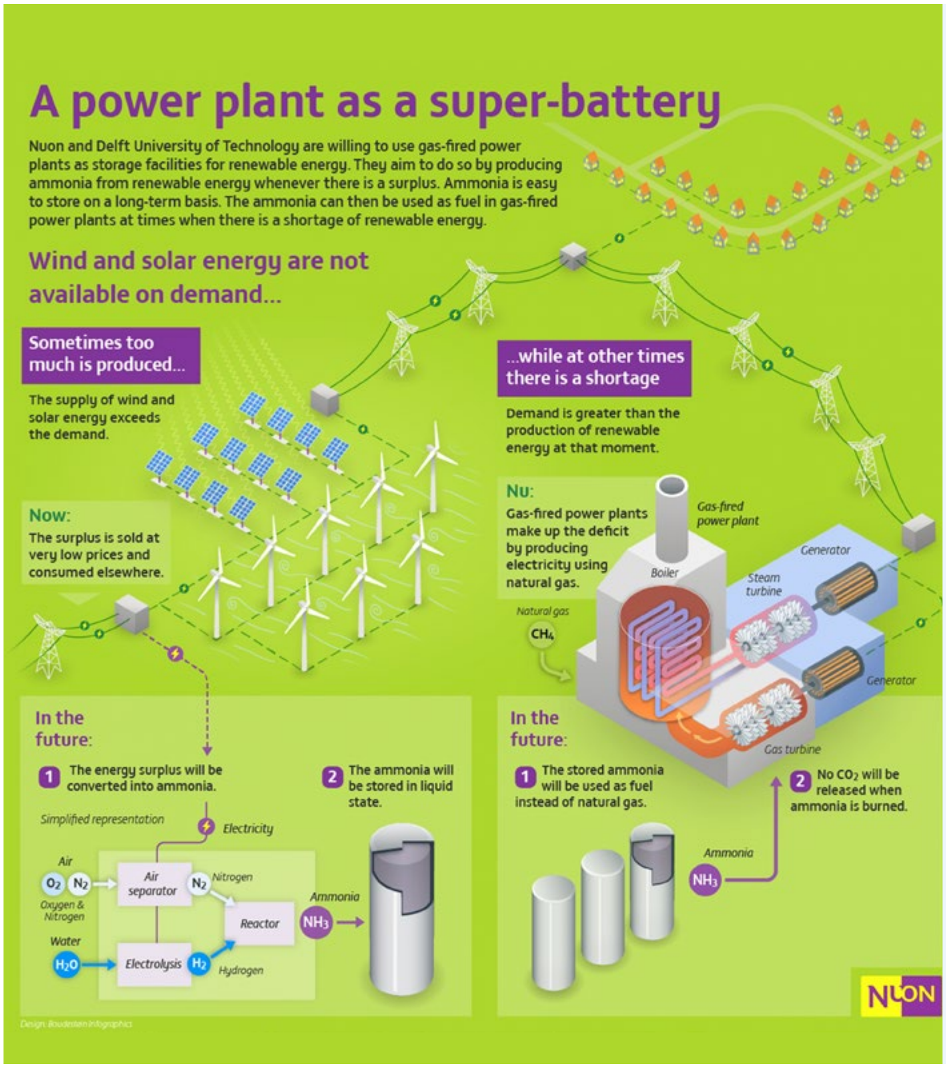
available crop of hydrogen FCVs from Toyota, Honda, and Hyundai offer reasonably long drive ranges (around 300 miles/480 kilometers[7]) and short refueling times (less than ten minutes[8]). Recent commercial demonstrations indicate that fuel cells can be used to power commercial heavy-duty trucks as well.[9]

Ammonia can also be used as fuel in both purpose-designed and modified internal combustion engines (ICEs),[10] either neat or in a blend with petroleum fuel. Ammonia's energy density is about one-half that of gasoline and diesel, but an ammonia-fueled ICE can provide about 20% more power than gasoline and diesel engines due to the higher compression ratio needed for ammonia combustion. Ammonia combustion in an ICE produces heat, water vapor, and nitrogen.

Marine vessels and trains may be best positioned to use ammonia-fueled ICEs and combustion turbines because they can accommodate heavier engines and larger fuel tanks more easily; ports and railways can site and build ammonia fueling stations, thereby avoiding the chicken-or-egg problem that confronts ammonia-powered light-duty vehicles; and, unlike most light-duty vehicles, ships and locomotives are already fueled by professionals who can be trained to manage ammonia safely. Recent reports on reducing the shipping sector's GHG emissions from Lloyd's Register, International Transportation Forum,and International Chamber of Shipping have identified fuel-switching to ammonia as one of the most compelling options for limiting the sector's contribution to global warming.[11]

Power Generation

Public and private R&D efforts in Japan, the United States, Australia, and Europe have strengthened the case that hydrogen- and ammonia-fueled power systems can help decarbonize power generation—either directly as low- and


A power plant as a super-battery

Nuon and Delft University of Technology are willing to use gas-fired power plants as storage facilities for renewable energy. They aim to do so by producing ammonia from renewable energy whenever there is a surplus. Ammonia is easy to store on a long-term basis. The ammonia can then be used as fuel in gas-fired power plants at times when there is a shortage of renewable energy.

Wind and solar energy are not available on demand...

Sometimes too much is produced...

The supply of wind and solar energy exceeds the demand.

Now: The surplus is sold at very low prices and consumed elsewhere.

...while at other times there is a shortage

Demand is greater than the production of renewable energy at that moment.

Nu: Gas-fired power plants make up the deficit by producing electricity using natural gas.

In the future:

1 The energy surplus will be converted into ammonia.

2 The ammonia will be stored in liquid state.

In the future:

1 The stored ammonia will be used as fuel instead of natural gas.

2 No CO_2 will be released when ammonia is burned.

USING AMMONIA TO STORE VARIABLE RENEWABLE ENERGY

If electricity from wind- and solar-based generation can be cost-effectively converted into ammonia, the ammonia could serve as a practical and economic medium for storing excess or remotely-generated variable renewable power. The energy could be stored for days, weeks, or months before being converted back into electricity (and/or heat) whenever variable renewable energy systems are incapable of meeting demand. Several major energy companies in Europe are pursuing the concept, in part because scaling up ammonia-based storage looks to be less expensive than scaling up electrochemical battery storage, and because ammonia-based storage faces far fewer geographic constraints than pumped hydro storage. Nuon, Siemens, and other firms are developing technologies to facilitate large-scale, long-term energy storage to serve the days-to-weeks storage market for megawatt-to-gigawatt power sources.

Carbon neutral fuels to enable the energy transition. Graphic: Vattenfall/Nuon (2017).

zero-carbon fuels or, in the case of ammonia, indirectly as a medium for storing and transporting hydrogen.

To succeed as a power generation feedstock, however, hydrogen and ammonia have to overcome the cost hurdle of being made from either natural gas or zero-carbon electricity, both of which are valuable energy products in their own right. Initial demand for low-carbon hydrogen- or ammonia-based power is therefore likely to be found among off-grid applications, on islands and in other geographically isolated markets, and in markets that need to balance their supply of variable renewable energy with a flexible, fast-ramping source low/zero-carbon power. Hydrogen and ammonia could also be used at existing fossil power stations, including coal-fired boilers, particularly in situations where it makes economic sense to postpone a generating unit's retirement by fuel-switching to a lower-carbon fuel.

Industrial Power

Zero-carbon hydrogen and ammonia could also be used to produce a significant portion of the energy and process heat required for difficult-to-decarbonize industrial operations. A 2017 report by a Japan ministerial council notes the challenge posed by direct heating and other "industrial processes that are difficult to electrify"—especially when trying to drive down CO_2 emissions below the levels that can be achieved through energy conservation and the use of cogeneration and combined heat and power measures. The council concluded that "[t]o further reduce carbon, … the industry sector will have to use hydrogen as fuel or other CO_2-free material."[12]

ENERGY END USE	HYDROGEN CONVERSION TECHNOLOGIES	AMMONIA CONVERSION TECHNOLOGIES
TRANSPORTATION HEAVY DUTY		
On/Off Road	Fuel cells (commercially available) *Possibly: Internal combustion engines (ICEs)*	ICEs *Possibly: Direct NH_3 fuel cells*
Rail	Fuel cells – some current light rails in Europe *Possibly: Fuel cells for US light rail*	ICEs *Possibly: Direct NH_3 fuel cells*
Marine	Fuel cells (short distance)	ICEs
Aviation	Unlikely (although there have been studies and designs)	Unlikely
TRANSPORTATION LIGHT DUTY		
Automobiles	Fuel cells – commercial today *Possibly: ICEs (demos exist)*	ICEs *Possibly: Direct NH_3 fuel cells*
POWER GENERATION-DIRECT		
Grid-connected/central	Combustion turbines	Combustion turbines, boilers
Remote/distributed	Fuel cells – commercial today	ICEs
POWER GENERATION-GRID BALANCING		
Variable renewable energy complement	Combustion turbines *Possibly: Fuel cells*	ICEs
INDUSTRIAL PROCESS HEAT		
Electric/steam/gaseous heat	Boilers – commercial today	Boilers – demonstration in progress in Japan

Carbon-Free Production of Hydrogen and Ammonia

Production Technologies

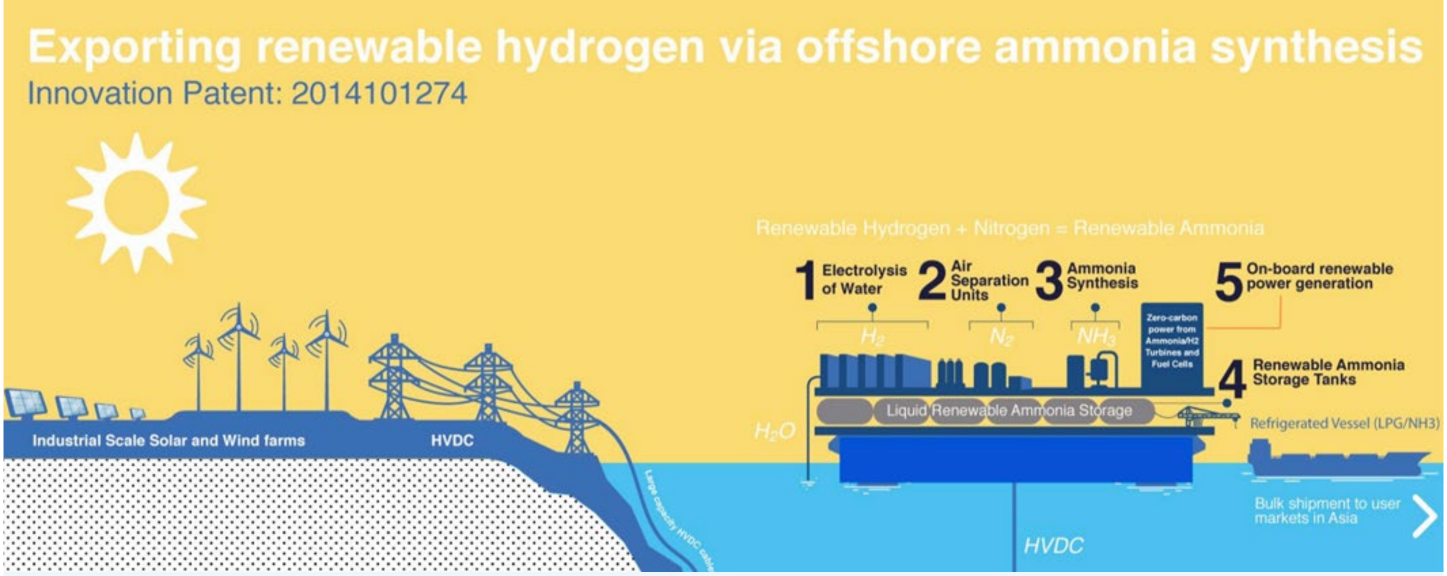
A variety of methods that emit little or no GHG can be used to produce hydrogen and ammonia. Options include:

Steam methane reforming (SMR) with carbon capture and storage (CCS). Methane reformers decompose methane (CH4) into hydrogen and carbon monoxide (CO) using pressure and high-temperature steam.[13] A water-gas shift process then converts the CO into a stream of CO_2, which accounts for about two-thirds of the total CO_2 produced during process. This CO_2 is typically vented to atmosphere, but it can be compressed, transported, and stored relatively inexpensively (the CO_2 is already segregated, so no "capture" costs are incurred).[14] The remaining CO_2 emissions associated with SMR occur when methane (or another fossil fuel) is combusted to generate the heat needed to make process steam. If this CO2—about one-third of the total—is captured and geologically sequestered by installing CCS equipment at the combustor stack, the ammonia production would be carbon-free.[15] By adding CCS technology to these processes and gradually increasing the capture rate, an ammonia production facility can meet increasingly stringent greenhouse gas limits by incrementally reducing the carbon intensity of its product.[16]

Ammonia production facility in Porsgrunn, Norway. The blue columns in the foreground remove CO_2 from the process gas; the captured CO_2 is then shipped to commercial users. Photo: Bitjungle.

Electrolysis of water with zero-carbon electricity. Electrolysis uses electricity to split water (H_2O) into hydrogen and oxygen. If a zero-carbon power source is used to generate the electricity, the resulting hydrogen is carbon-free. It currently costs more to make hydrogen with zero-carbon electrolysis than with SMR+CCS,[17] but a significant global R&D effort aims to make electrolysis less expensive. Furthermore, because electrolytic production of hydrogen can be carried out at a range of different plant scales and is amenable to modularization, building an electrolysis facility can be less capital intensive (and less complicated with respect to siting, labor, and regulatory compliance) than building an SMR plant.[18]

The hydrogen acquired through SMR+CCS or electrolysis can be combined with nitrogen to make ammonia using the Haber-Bosch process. Several developments could further reduce the cost of Haber-Bosch-derived ammonia.



Exporting Australian renewable energy to Asia in the form of ammonia. Graphic: Renewable Hydrogen and Australian Renewable Ammonia Export Marketing.

Ethanol biorefinery fall aerial view. Photo: Getty Images.

SCALING UP HYDROGEN-BASED FUELS VERSUS SCALING UP BIOFUELS

The capacity for massively scaling hydrogen and ammonia production is especially evident when compared to the scalability challenges facing low-carbon biofuels. The reason that lifecycle GHG emissions from conventional biofuels like corn ethanol and soy biodiesel are, at best, only marginally lower than those from petroleum-based fuels is that huge tracts of prime farmland are required to grow the requisite corn and soy. In order to accommodate the production of energy crops, forests, prairies, and wetlands are converted into farmland—a process that transfers millions of tons of soil carbon into the atmosphere.

As a result, would-be producers of truly low-carbon biofuels (derived from agricultural residues or perennial grasses, for instance) face a vexing supply challenge. They can make biofuels from waste matter, in which case they have to figure out how to economically aggregate enormous volumes of heavy, highly dispersed agricultural residues (like forestry slash or corn leaves, cobs, and stalks). Or the producers can try to grow dedicated energy crops, in which case they need access to land that is not currently being farmed nor already covered in plants or trees that efficiently absorb atmospheric carbon – and yet is somehow still fertile enough to support industrial-scale agriculture. The relative scarcity of these resources will make it exceedingly difficult, if not impossible, to produce low-carbon biofuels at a climate-relevant scale.

As a general matter, if the global production of ammonia increases by an order of magnitude in response to demand from energy consumers, further process optimization is likely to wring out additional cost reductions.

Electrochemical ammonia synthesis. Researchers are also working on alternatives to steam reforming and electrolysis, including some electrochemical processes that convert water and nitrogen into ammonia directly, thereby avoiding the intermediate step of hydrogen production.

Scalability

Using ammonia to fuel a substantial portion of power generation and transportation would require a massive scale-up in its production, but the scale-up would not proceed from scratch. An extensive global infrastructure for making and transporting ammonia already exists: at around 180 million metric tons per year, ammonia is the world's second most commonly synthesized chemical.

The processes for producing hydrogen and ammonia are massively scalable. For ammonia production, the key limiting factor is the availability of low-cost hydrogen. Virtually inexhaustible volumes of hydrogen are readily obtainable either from methane, especially in markets with access to low-cost natural gas, or from water, especially in markets with access to low-cost carbon-free electricity. The nitrogen needed to make ammonia can be extracted from ambient air (which is 78% nitrogen) using off-the-shelf air separation units.

Economics

Preliminary analyses suggest that hydrogen and ammonia can compete with incumbent fuels on cost.[19] Gasoline production currently costs around USD$13/mmBtu. CATF estimates that the current cost of producing zero-carbon ammonia via SMR+CCS would be approximately USD$22/mmBtu, and that the cost of producing zero-carbon ammonia at optimized, world-scale SMR+CCS facilities at climate-relevant volumes could fall below USD$10/mmBtu. Carbon-free production of hydrogen using electrolysis is currently more expensive, but substantial R&D efforts are focused on reducing those costs.[20] Production costs for zero-carbon hydrogen will likely remain well above production costs for natural gas, though, so demand for hydrogen and ammonia as power sector energy feedstocks will hinge on the market's willingness to pay a premium to eliminate carbon emissions.

SECTION III

Health and Safety Impacts Appear Manageable but Need Further Analysis

The widespread use of hydrogen and ammonia as fuels would pose various risks to public health and safety—but the same can be said of virtually all fuels.

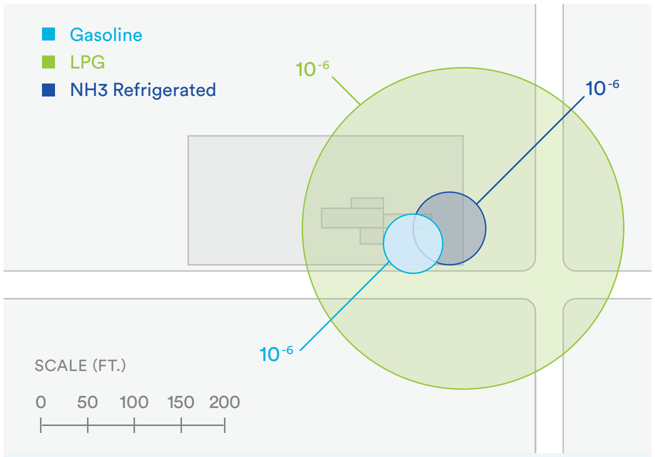
> Fuels are, by definition, high-energy materials. As such, they are intrinsically hazardous. This is true for fossil fuels, for hydrogen, and for all others. The perfectly safe and environmentally benign fuel does not exist. The best we can do is to choose from available alternatives the option with the fewest or least serious problems.... Nothing is problem-free; we must choose the least problematic.[21]

Ammonia is produced, transported, and used in enormous quantities around the world every day, and extensive safety protocols have been developed over the past century of industrial use to mitigate its toxicity risk. Not coincidentally, studies that examined ammonia's risk profile have found that it is comparable to that of gasoline and LPG.[22]

Ammonia's impact on air quality requires further analysis. When ammonia is released into the atmosphere, it can accelerate the formation of fine particulate matter. Experts are working to better understand the extent to which ammonia is currently emitted by the many participants in the ammonia value chain,[23] and to determine what the current emissions and control practices might imply about emissions risks in a future context where ammonia is commonly used as fuel.

Hydrogen presents a different set of challenges. Because hydrogen ignites easily, has low density, and can embrittle container metals, storing and transporting it requires special care and equipment. Converting hydrogen to ammonia (which is significantly denser and more difficult to ignite) for storage and transportation could be a viable strategy for mitigating hydrogen's explosion risk.

A key component of CATF's work on hydrogen- and ammonia-based energy systems is partnering with specialists to assess the health and safety risks associated with the fuels in different applications (*e.g.*, energy storage, marine fuel, distributed generation), and to identify best practices for safely managing those risks.



Graphic: based on illustration by Quest Consultants (2009).

Risk contours for gasoline (light blue), LPG (green), and ammonia fuel (dark blue). Per Quest Consultants (2009): "Risk contours define the risk of lethal exposure to any of the hazards associated with all fuel releases originating within the refueling facility. [Each] contour labeled 10^{-6} represents one chance in one million per year of being exposed to a fatal hazard from any of the possible releases associated with the unloading, storage, and dispensing of [the specified fuel] within the station. Because the risk contours are based on annual data, this level of risk is dependent on an individual being in the location where the 10^{-6} contour is shown 24 hours a day, 365 consecutive days per year."

SECTION IV

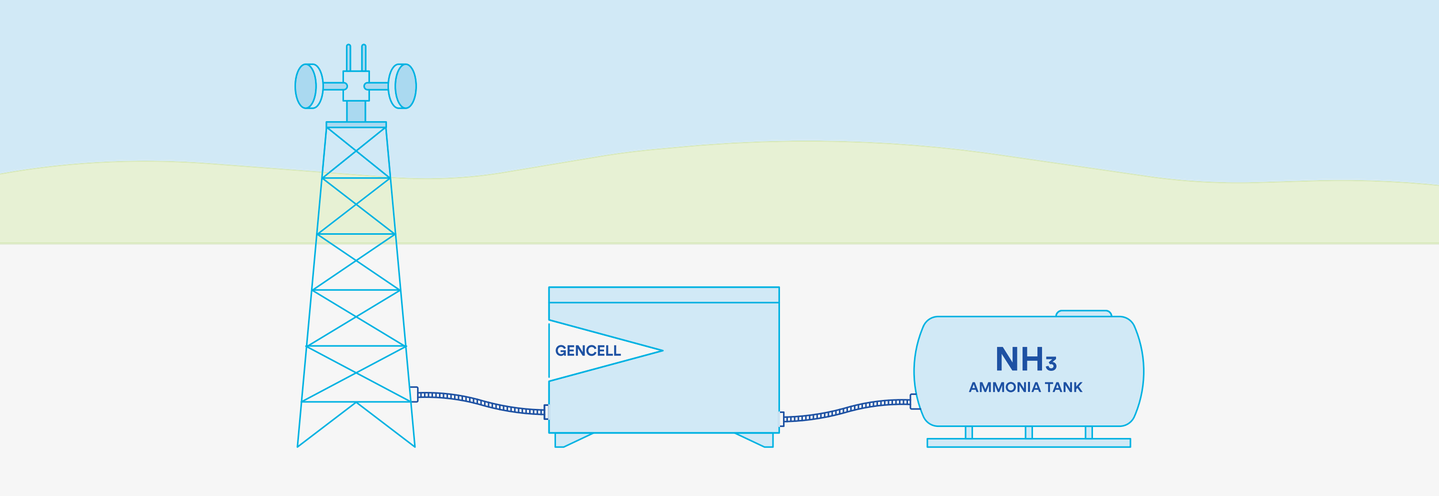
Hydrogen and Ammonia Could Help Address Several Confounding Decarbonization Challenges

Hydrogen and ammonia have several qualities that make them potentially important tools for filling troublesome gaps in decarbonization strategies. For example, a cost-effective and massively scalable mechanism is needed for storing excess energy made by variable renewable energy sources (wind and solar), while zero-carbon energy is needed for the parts of the transportation sector that cannot be electrified. Similarly, techniques for turning natural gas into zero-carbon transportation fuel would be highly useful. Ammonia, in particular, can be used to tackle these challenges—sometimes as a direct source of energy, and sometimes as a hydrogen intermediary. As a source of zero- or low-carbon energy that is stable, portable, and flexible enough to support a variety of energy conversion technologies, ammonia can potentially fill the following roles:

Store excess power produced by variable renewable energy sources. See explanatory box in Section II (page 7), featuring efforts by Nuon and others to develop ammonia as a storage medium for excess energy generated by wind turbines and solar plants.

Ramp down the carbon intensity of the energy produced by existing power plants. Co-firing hydrogen or ammonia with coal or natural gas could allow power generators to gradually reduce carbon emissions from existing generating assets without major capital investments. After Japan's Cross-Ministerial Strategic Innovation Promotion Program (SIP) called for testing of "large-scale pulverized coal-ammonia hybrid power generation," Chugoku Electric demonstrated commercial-scale coal-NH_3 combustion at its 156MW Mizushima Power Plant in 2017.[24]

Mizushima 156 MW Coal-NH3 boiler in Okayama, Japan (Chugoku Electric). Photo: Phronimoi.



GenCell A5 power system for off-grid telcom base stations with ammonia cracker and fuel cell. Graphic: based on illustration by GenCell.

Reduce the carbon content of natural gas. The United Kingdom,[25] Japan,[26] Germany,[27] and Hawaii[28] are exploring opportunities to blend hydrogen into their natural gas transportation and distribution systems, to displace some natural gas use, reduce the carbon intensity of natural gas-based energy production, and/or distribute hydrogen to filling stations and other hydrogen end-users. These pilot programs should help answer the key question of whether existing transportation and distribution systems can be fully converted to carry hydrogen instead of natural gas.

Fuel remote installations that need a constant source of power. In regions where grid expansion lags behind new demand for electricity, ammonia could expedite the development of affordable, on-demand, distributed energy. In 2018, for example, the Nairobi-based telecommunications firm Adrian Kenya announced it will install hydrogen fuel cells to power 800 off-grid telcom base stations around Kenya.[29] According to GenCell, the hydrogen fuel cell manufacturer working with Adrian Kenya, a 12-ton tank of ammonia will provide each base station with enough energy for a year of constant operation. A cracking device will convert the ammonia to hydrogen on site.[30]

Safely and efficiently transport hydrogen. As hydrogen fuel cell technology continues to improve, it becomes increasingly likely that hydrogen will power significant portions of the transportation, residential, and commercial sectors—provided, of course, that the hydrogen can be safely and efficiently delivered to the centralized power plants, distributed engine-based electrical generators (often referred to as gensets), factories, vehicle fueling stations, and other hydrogen end-users. Transporting hydrogen atoms in the form of ammonia—which is more energy-dense and less explosive than hydrogen—could play an important role in facilitating the growth of the "hydrogen economy."[31]

Allow natural gas to compete in the zero-carbon transportation market. Widespread deployment of CCS will allow natural gas to play a major role in a decarbonizing power sector—but not in the transportation sector,[32] where onboard CCS is not practical. If carbon-free processes are used to turn natural gas into hydrogen or ammonia, however, some of the planet's massive natural gas reserves[33] can be used to support zero-carbon mobility.

SECTION V

Public and Private Sector Initiatives for Exploring and Pursuing Zero-Carbon Fuels

Hydrogen and ammonia could play important roles in decarbonizing power generation, transportation, and industrial processes. Their potential as zero-carbon fuels will not be realized, however, unless deep and well-coordinated public and private sector initiatives are developed to analyze the opportunities and challenges that hydrogen and ammonia present, educate a range of audiences about the possible benefits and risks, design and advocate for appropriately supportive policies, and engage with key energy and mobility companies.

Analysis and Education

Important technology demonstrations—such as the ammonia-fueled turbine that a coalition including Siemens, Oxford University, and Cardiff University began testing in 2018—should be publicized and their results should be spotlighted. Sector-specific roadmaps that identify key actors, key regulations, and required infrastructure for real-world applications should be drawn up. The likely costs for different production and end-use options should be assessed and benchmarked against incumbent fuels systems.

The health, air pollution, and safety risks associated with hydrogen and ammonia fuels must be further examined. The best practices from companies and industries that currently manage hydrogen and ammonia should be catalogued and disseminated.

Policy Development and Advocacy

The community of people, companies, and institutions interested in exploring the production and/or use of hydrogen and ammonia as zero-carbon fuels is only loosely organized. Recent efforts in the United States and Europe have improved coordination,[34] but stronger, more cohesive networks must be built.

Policies that incentivize the production of low/zero-C hydrogen and ammonia should be drafted and discussed with policymakers.[35] A public-private coalition should begin the multi-step, multi-jurisdiction process of qualifying ammonia as an approved vehicle fuel in the United States and elsewhere; once ammonia fuel has been fully tested, certified, and approved, the coalition should work to make it eligible as compliance option in policy frameworks like the California Low Carbon Fuel Standard.

Other advocacy opportunities include: examining whether existing policies can be used to incentivize power companies to reduce the carbon intensity of coal-fired power plants by co-firing low- or zero-carbon ammonia; and pushing the International Maritime Organization, shipping companies, and other stakeholders to recognize the potential role that hydrogen and ammonia can play in helping the shipping industry achieve its long-term GHG reduction target (50% below 2008 levels by 2050).[36]

SECTION VI

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2. BP, *Statistical Review of World Energy*, at 48 (June 2018) (https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review/bp-stats-review-2018-electricity.pdf).
3. US Energy Information Administration, *International Energy Outlook* 2016, at 114 (https://www.eia.gov/outlooks/ieo/pdf/industrial.pdf).
4. International Energy Agency, *World Energy Outlook* 2016 (November 2016), Table 3.3: World oil demand by sector in the New Policies Scenario.
5. Electric vehicles garner most of the headlines but hydrogen fuel cell vehicles are competing for market share in several corners of the transportation sector, too—in part because fuel cells vehicles (FCV) may offer important advantages over battery electric vehicles (BEV) for some users. Battery weight complicates the electrification of heavy-duty vehicles (see Ivan Mareev et al. (2018), Battery Dimensioning and Life Cycle Cost Analysis for a Heavy-Duty Truck Considering the Requirements *of* Long-Haul Transportation, *Energies* (https://www.mdpi.com/1996-1073/11/1/55/pdf)), so companies are prototyping long-haul trucks, delivery trucks, and trains equipped with fuel cells (see John O'Dell, Anheuser-Busch Makes Record Order of 800 Nikola Fuel Cell Trucks, *Trucks* (May 3, 2018) (https://www.trucks.com/2018/05/03/anheuser-busch-nikola-truck-order/)). Similarly, because electrification may not work for some light-duty vehicle applications—for example, where short refueling times are required—FCVs are likely to capture a portion of the light-duty market alongside BEVs.
6. EIA projects the remaining demand—approximately 9%—would be met by biomass combustion. US Energy Information Administration, *International Energy Outlook* 2016, at 114 (https://www.eia.gov/outlooks/ieo/pdf/industrial.pdf). The climate impacts of biomass combustion depend on the type of biomass being used and several other factors, but the net CO_2 emissions from a power generation system that burns woody biomass typically exceed those from a system that burns coal, even when the forest from which the biomass was harvested is allowed to regrow and carbon absorbed during that regrowth process are credited to the biomass power system. See, for example, Joint Comments by Clean Air Task Force et al. on the Treatment of Biomass-Based Power Generation in EPA's Proposed Emission Guidelines for Greenhouse Gas Emissions from Existing Electric Utility Generating Units, at 14-21 (October 31, 2018) (https://www.catf.us/wp-content/uploads/2017/06/ACE_Joint_NGO_Comments_Biomass.pdf).
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9. See US Hybrid, Kenworth join race to develop fuel cell powered Class 8 trucks for California ports, *Fuel Cells Bulletin* (May 2017) (https://www.sciencedirect.com/science/article/pii/S1464285917301700); see John O'Dell, Toyota Unveils More Advanced Heavy-Duty Fuel Cell Truck Prototype, *Trucks* (July 30, 2018) (https://www.trucks.com/2018/07/30/toyota-advanced-fuel-cell-truck/).
10. Ammonia can potentially power fuel cells as well. Japan Ministry of Economy, Trade and Industry is working with Kyoto University and several companies to prototype a solid oxide fuel cell (SOFC) that can be directly fueled with ammonia, and Britain's Ceres Power has said that its SOFC, called SteelCell, is "fuel agnostic." Ammonia can also serve as an on-site storage medium for hydrogen, to be used in hydrogen fuel cells.
11. See Lloyd's Register and UMAS, *Zero-Emission Vessels 2030. How do we get there?* (2017) (http://www.lrs.or.jp/news/pdf/LR_Zero_Emission_Vessels_2030.pdf); International Transport Forum, *Decarbonizing Maritime Transport: Pathways to zero-carbon shipping by 2035* (2018) (https://www.itf-oecd.org/decarbonising-maritime-transport); International Chamber of Shipping, *Reducing* CO_2 *Emissions to Zero: The Paris Agreement for Shipping* (2018) (http://www.ics-shipping.org/docs/default-source/resources/reducing-co2-emissions-to-zero-the-paris-agreement-for-shipping.pdf?sfvrsn=7).
12. Ministerial Council on Renewable Energy, Hydrogen, and Related Issues, *Basic Hydrogen Strategy*, at 3.2(c) (2017) (http://www.meti.go.jp/english/press/2017/pdf/1226_003b.pdf).
13. Syngas derived from coal can also be reformed into hydrogen. See US Department of Energy, *Hydrogen Production: Coal Gasification* (https://www.energy.gov/eere/fuelcells/hydrogen-production-coal-gasification); Calla Wahlquist, Victoria's plans for hydrogen exports to Japan are 'way of making brown coal look green,' *Guardian* (January 12, 2017) (https://www.theguardian.com/environment/2017/jan/12/victorias-plans-for-hydrogen-exports-to-japan-are-way-of-making-brown-coal-look-green).
14. Global CCS Institute (2010), *Carbon capture and storage in industrial applications: technology synthesis report*, at 3.1.2 and 3.1.4 (https://hub.globalccsinstitute.com/publications/carbon-capture-and-storage-industrial-applications-technology-synthesis-report/31-high); MIT Carbon Capture & Sequestration Technologies, *Enid Fertilizer Fact Sheet* (2016) (https://sequestration.mit.edu/tools/projects/enid_fertilizer.html); Hans Askel Haugen et al. (2018), Commercial capture and transport of CO_2 from production of ammonia, *Energies* (https://www.sciencedirect.com/science/article/pii/S1876610217319525).

15. Other parts of the lifecycle—*e.g.*, methane extraction, ammonia distribution—may emit GHG.

16. New ammonia plants can potentially reduce their CO_2 capture costs by using oxy-fuel combustion to power their reformers. In an oxy-fuel combustion process, the fuel—in this case methane—is mixed with pure oxygen (rather than with air, which is mostly nitrogen). The result is a relatively rich and easier-to-capture stream of CO_2. See http://www.fossiltransition.org/pages/oxy_combustion/113.php.

17. Cedric Philibert, International Energy Agency, *Electro fuels: An introduction*, at slide 8 (September 2018) (http://ieahydrogen.org/pdfs/1CedricPhilibert.aspx).

18. SMR plants tend to be very large, in order to most efficiently accommodate the technology's high temperature and pressure requirements. As a result, the cost of building a new SMR plant can exceed USD$1 billion.

19. ARPA-E's REFUEL program estimates that ammonia from natural gas SMR/Haber Bosch (without carbon capture and sequestration) costs slightly less than gasoline on a "source to use basis." ARPA-E, Renewable Energy to Fuels Through Utilization of Energy-Dense Liquids (REFUEL) Program at Table 1 (https://arpa-e.energy.gov/?q=arpa-e-programs/refuel).

20. See, *e.g., id*.; Shigeru Muraki, *Development of Technologies to Utilize Green Ammonia in Energy Market* (November 1, 2018) (http://nh3fuelassociation.org/wp-content/uploads/2018/11/AEA-Imp-Con-01Nov18-Shigeru-Muraki-Keynote-Address.pdf).

21. William L. Ahlgren (2012), The Dual Fuel Strategy: An Energy Transition Plan, *Proceedings of the Institute of Electronics and Electrical Engineers*, at 2998, 3027.

22. Nijs Jan Duijm, et al. (2005), *Safety Assessment of Ammonia as a Transport Fuel* (http://nh3fuel.files.wordpress.com/2013/05/riso-ammonia-transport-safety-report.pdf); Quest Consultants (2009), *Comparative Quantitative Risk Analysis of Motor Gasoline, LPG, and Anhydrous Ammonia as an Automotive Fuel* (http://nh3fuel.files.wordpress.com/2013/01/nh3_riskanalysis_final.pdf).

23. The chain spans from ammonia production facilities to the pipelines, tankers, and delivery trucks that move it around the world to the farms that use ammonia as fertilizer, the automobiles and power plants that use it to control their emissions of nitrogen oxides, and the industrial cooling and HVAC systems that use it as a refrigerant.

24. Japan Cross-Ministerial Strategic Innovation Promotion Program (SIP), *2017-2018 Goals Based on Evaluation of 2016-2017*, 2, 4 (June 28, 2017); Shigeru Muraki/Japan SIP, *Energy Carrier Progress Report*, 6-7 (July 25, 2017) (Taiyo Nippon and others reported in July 2017 they had successfully reduced the carbon intensity of coal-based power generation by co-firing ammonia) (English translations on file).

25. Jillian Ambrose, Energy Networks prepare to blend hydrogen into the gas grid for the first time, The Telegraph (January 6, 2018) (https://www.telegraph.co.uk/business/2018/01/06/hydrogen/?WT.mc_id=tmg_share_tw); Adam Vaughan, Trial to phase in hydrogen as fuel to begin in north-west, *Guardian* (August 6, 2017) (https://www.theguardian.com/business/2017/aug/07/trial-to-phase-in-hydrogen-as-fuel-to-begin-in-north-west); see also Northern Gas Networks, $H_2$1 *Leeds City Gate Full Report* (2016) (https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Report-Interactive-PDF-July-2016.compressed.pdf).

26. Ministerial Council on Renewable Energy, Hydrogen, and Related Issues, *Basic Hydrogen Strategy*, at 4.2(e) (2017) (http://www.meti.go.jp/english/press/2017/pdf/1226_003b.pdf).

27. FCH2 JU, *Development of Business Cases for Fuel Cells and Hydrogen Applications for Regions and Cities*, at 6 (Fall 2017) (https://bit.ly/2FzcnRF) .

28. In Hawaii, hydrogen comprises about 10% of the synthetic natural gas system that is produced in Oahu ate and moved through the island's pipeline system. The Gas Company LLC, *Report to the Hawaii Public Utilities Commission*, at 6 (March 30, 2012) (https://puc.hawaii.gov/wp-content/uploads/2013/04/CY2011-Act-30-Report-PUC-The-Gas-Co.pdf) ("Today, Hawaii's SNG contains about 10% hydrogen produced in the manufacturing process and is distributed using existing pipeline infrastructure. This provides a cost effective means to distribute hydrogen to the point of use since it is carried within the SNG. It is possible to separate and purify the hydrogen at the point of use (fueling station) and return the non-hydrogen gas (tail gas) to the pipeline utilizing our existing pipeline system.") .

29. CTECH, *Kenya Telecom Company to Replace 800 Diesel Generators with Fuel Cells* (July 2, 2018) (https://www.calcalistech.com/ctech/articles/0,7340,L-3741528,00.html).

30. GenCell, Adrian Kenya selects new gencell a5 fuel cell solution to provide green, off-grid power to 800 telecom base stations (https://www.gencellenergy.com/news/adrian-kenya-800-telecom-base-stations/).

31. Stephen Crolius, Ammonia Positioned for Key Role in Japan's New Hydrogen Strategy, *Ammonia Energy* (January 11, 2018) (http://www.ammoniaenergy.org/ammonia-positioned-for-key-role-in-japans-new-hydrogen-strategy/).

32. At least not directly. Low/zero-C electricity derived from CCS-equipped natural gas-fired electric generating units will help power electric vehicles.

33. US Energy Information Administration projects that global natural gas production will be 209.5 TCF in 2050. EIA, *International Energy Outlook 2017*—Table: World Total Natural Gas Production by Region (https://www.eia.gov/outlooks/aeo/data/browser/#/?id=41-IEO2017&cases=Reference).

34. In particular, the recent formation of the Ammonia Energy Association (AEA) and the NH_3 Energy Implementation Conference that AEA hosted in November 2018 were important steps toward improved coordination. See Steve Crolius, NH_3 Energy Implementation Conference: A Brief Report, *Ammonia Energy* (November 14, 2018) (http://www.ammoniaenergy.org/nh3-energy-implementation-conference-a-brief-report/). AEA and the 2018 implementation conference build on the progress made by the NH_3 Fuel Association (https://nh3fuelassociation.org/), which has hosted conferences in the United States since 2004) and the NH_3 Event (https://nh3event.com/), which Proton Ventures has organized annually since 2017.

35. See CATF, *Designing policies to promote the commercialization of carbon-free ammonia energy* (presentation to ARPA-E REFUEL Program) (July 18, 2018) (https://www.catf.us/wp-content/uploads/2018/12/CATF_Presentation_AmmoniaEnergy_45Q.pdf).

36. See IMO, *UN body adopts climate change strategy for shipping* (April 13, 2018) (http://www.imo.org/en/mediacentre/pressbriefings/pages/06ghginitialstrategy.aspx). Notably, Maersk—the world's largest container shipping company—announced in December 2018 that it would cut its fleetwide carbon emissions to zero by 2050. Richard Milne, Maersk pledges to cut carbon emissions to zero by 2050, *Financial Times* (December 4, 2018) (https://www.ft.com/content/44b8ba50-f7cf-11e8-af46-2022a0b02a6c).

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