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Clean hydrogen: Outlook for freight transport in the United States

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HIGHLIGHTS

- Hydrogen is poised to play a complementary role alongside electrification and other clean fuels in decarbonizing freight transportation in the United States.
- Hydrogen is a flexible energy carrier, and low-carbon hydrogen can offer climate benefits when used directly as a fuel or as a feedstock for clean fuels.
- The use of hydrogen as a fuel or energy carrier in freight transport can greatly reduce life cycle emissions relative to conventional and alternative fuels, though the production route and end use conditions greatly affect the magnitude of these climate benefits.
- Distribution and storage present technological challenges and concerns regarding leakage and energy consumption as well as economic challenges that must be overcome for hydrogen to be cost-competitive and provide maximum climate benefits.
- Hydrogen and hydrogen-based clean fuels have the potential to offer mature, low-cost, low-carbon alternatives to conventional freight transport fuels by 2050.
- Long-haul road freight, maritime freight, air freight, and rail freight will require clean, energy-dense fuels sourced from low- and zero-carbon feedstocks in order to achieve near-term and long-term decarbonization goals.
- Hydrogen and hydrogen-based fuels are among the leading decarbonization solutions for long-haul road freight, maritime freight, air freight, and long-distance rail freight by 2050.

EXECUTIVE SUMMARY

Clean Hydrogen Production

Clean hydrogen production technologies are seeing a substantial increase in funding and development. In the United States, the Infrastructure Investment and Jobs Act allocates US$9.5 billion to clean hydrogen production and infrastructure, and the Inflation Reduction Act provides a production tax credit for low-carbon hydrogen production. Globally, climate goals are driving national-scale hydrogen initiatives and funding, with India, the European Union, China, and Japan increasing funding for hydrogen production and demonstration projects.

If hydrogen is to fulfill its promise as a low-carbon fuel fit for use across many sectors of the economy, its production must rely on low- and zero-carbon feedstocks and processes. Nearly all hydrogen produced today comes from natural gas and is used as a feedstock in refining and chemical production. Hydrogen production from renewable energy sources and low-carbon pathways are established technologies but are still costly.

Hydrogen distribution and storage must overcome technological and permitting challenges in order to meet projected hydrogen demand. While some dedicated hydrogen pipelines exist today, new pipelines, pipeline retrofits, leakage, blending standards, and separation requirements and technologies are just some of the issues that must be addressed in order for hydrogen to be distributed at scale. Transporting hydrogen by truck, ship, or rail could provide early modes of hydrogen transport until production ramps up. Producing hydrogen close to demand centers and therefore limiting transport of hydrogen will be crucial to reducing costs and infrastructure needs.

The decision to scale up hydrogen production must be made in the context of low-carbon energy supply and land use priorities in order to offer climate and societal benefits. Large-scale clean hydrogen production via electrolysis could be limited in part by zero-carbon electricity supply. However, using renewable electricity that would otherwise be curtailed for hydrogen production could offer a low-cost pathway, and this hydrogen can then be used for long-duration energy storage and clean, firm electricity generation. Hydrogen production from biomass must ensure that land use is not diverted from food production or other essential or higher uses.

Hydrogen's Role in Decarbonizing Freight Transportation

Hydrogen is one of many fuels that could play a role in decarbonizing the freight transportation sector. Hydrogen can play a complementary role alongside electrification and other potentially low-carbon fuels—such as methanol, propane, and ammonia—in the freight transportation sector. Since these fuels can be made from sustainable biomass and hydrogen or made synthetically from hydrogen and carbon dioxide from direct air capture, hydrogen could play a role as a low-carbon fuel directly or as a low-carbon fuel feedstock.

Cost, onboard storage requirements, and refueling infrastructure remain significant challenges for hydrogen use in freight transport applications. Freight transport—and the transportation sector in general—requires low-cost, widely available energy sources that offer easy and safe onboard storage. Hydrogen is an energy-dense fuel by weight, but its low boiling point and small molecular size present storage challenges regarding boil-off and energy requirements for liquefaction or compression. Hydrogen-based fuels and hydrogen carriers offer distribution and onboard storage solutions, though costs remain high.

While short-distance trucking is poised for battery electrification, long-haul, heavy-duty trucking could require an energy-dense, molecule-based fuel such as hydrogen. Fast refueling and zero emissions at the point of use make hydrogen an attractive solution for decarbonizing the heavy-duty long-haul road freight segment. However, clean hydrogen availability, distribution and storage infrastructure, and cost remain obstacles to widespread adoption. Hydrogen could be converted to usable energy in trucks via fuel cells or combustion, though conversion by fuel cells is more efficient and cleaner.

Ship vessel fleet operators are changing to cleaner fuels via retrofits and new builds, and hydrogen and hydrogen-based fuels are seen as a potential solution in the segment by midcentury. Liquid natural gas-powered ships offer near-term, low-cost greenhouse gas emissions reductions and substantial non-greenhouse gas emissions reductions, which are a major concern in ports. Increasingly strict emissions requirements in the segment will require switching to even lower-carbon fuels or energy sources, such as hydrogen, hydrogen-based fuels such as ammonia or other hydrogen carriers, or batteries. Increased efficiency in ship design and the use of wind-aided propulsion are expected to provide further emissions reductions in the segment.

Sustainable aviation fuels derived from biomass or waste are seen as a near-term decarbonization option for the air freight segment over the next couple of decades, while hydrogen and other hydrogen-based fuels are poised to play an increasing role by midcentury. Though aircraft carry only a small fraction of cargo by weight, the segment is 20 times more carbon intensive than the freight average, and it is depended on to carry higher-value, lighter cargo that calls for shorter shipping times. Developing novel aircraft designs and fuel storage technologies will be important in decarbonizing the segment in order to meet weight and efficiency constraints imposed by air freight transport.

Rail freight offers unique near-term opportunities for hydrogen as a backup power supply for freight locomotives as well as a primary fuel in rail yard switching locomotives. The segment offers energy-efficient long-distance ground freight transport, and it is crucial to movement of bulk materials and intermodal containers. Rail freight is perhaps the most flexible freight segment, given its ability to employ multiple locomotives on a single train and to store fuel in designated cars without significantly affecting efficiency.

About This Working Paper

This working paper summarizes important issues regarding clean hydrogen production and distribution and identifies opportunities and developments regarding the use of clean hydrogen in freight transport in the United States. Recent developments and research have shed new light on hydrogen's potential as a low-carbon fuel. This paper provides the latest updates on these discussions and what they might mean for hydrogen's use as a low-carbon freight transportation fuel in the air, maritime, road, and rail freight segments in the next few decades and beyond. While this working paper focuses on freight transport in the United States, it includes global market and technological developments in sections that discuss segments that are inherently international in scope, such as air and maritime freight, and where an international perspective can provide important context for developments in the United States.

Methodology

A review of peer-reviewed journals, white papers, reports, news articles, and web page resources was performed to investigate hydrogen production technologies and their emissions profiles. Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies model was used to calculate emissions profiles of production pathways not covered in the literature. The California Air Resources Board publishes carbon intensities of all fuel production pathways approved under its Low Carbon Fuel Standard, and these values were used in the context of specific project-level examples in the United States. Life cycle emissions data included in this working paper are specific to the U.S. context, unless otherwise stated. Total costs of ownership for various fuel types were taken from the literature or calculated using the National Renewable Energy Laboratory's H2A: Hydrogen Analysis Production Models. Opportunities for hydrogen in freight transportation in the United States were researched using peer-reviewed literature, trade industry reports, publicly available recordings of webinars and presentations, and publicly available white papers from nongovernmental organizations. Interviews were conducted with trade organization experts, transportation experts from nongovernmental organizations, and government officials.

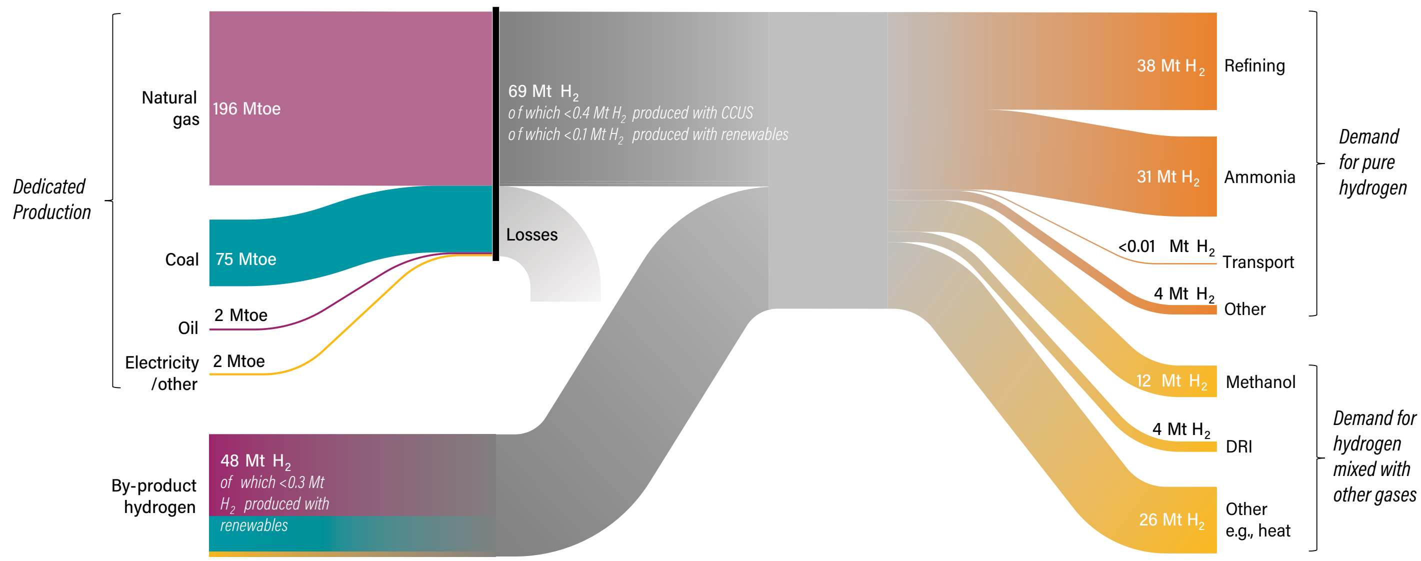
INTRODUCTION

Hydrogen—H_2 in molecular form—is a light gas that contains more energy per kilogram than almost any other substance on earth. However, hydrogen's energy content per unit volume (volumetric energy density) under normal conditions is one-third that of natural gas. It is highly flammable, with a high flame velocity, and its combustion doesn't result in the direct emission of greenhouse gases (GHGs) other than water vapor. Its combustion in the presence of nitrogen, however, produces nitrogen oxides (NO_x)—an indirect greenhouse gas and air pollutant. In a fuel cell, hydrogen combines with oxygen to produce energy, with the only by-product being water vapor.

Hydrogen is highly reactive with many elements, making it desirable as a reducing agent—to remove oxygen, sulfur, and other impurities from raw materials. In the United States and globally, hydrogen is mainly used in oil refineries, in the production of ammonia and other chemicals, and in industrial heating processes. Direct reduction of iron in the steelmaking process is a growing demand sector for hydrogen (IEA 2019a). In 2018, direct use in transport accounted for less than 0.1 percent of hydrogen use globally. Figure 1 shows hydrogen's global production and use profile in 2018.

Hydrogen's chemical and physical properties, as well as its minimal impact on the environment at its point of use, give it the potential to decarbonize a wide range of end uses in many sectors—including the power, transportation, and industrial sectors. Figure 2 portrays the U.S. Department of Energy's H2@Scale program's vision of hydrogen's potential role in a decarbonized economy. The amount of hydrogen required to fully decarbonize any one of the major sectors, however, is larger than projected hydrogen supply even by 2050 (IEA 2019a). This

Figure 1 | **Global Hydrogen Value Chain, 2018**



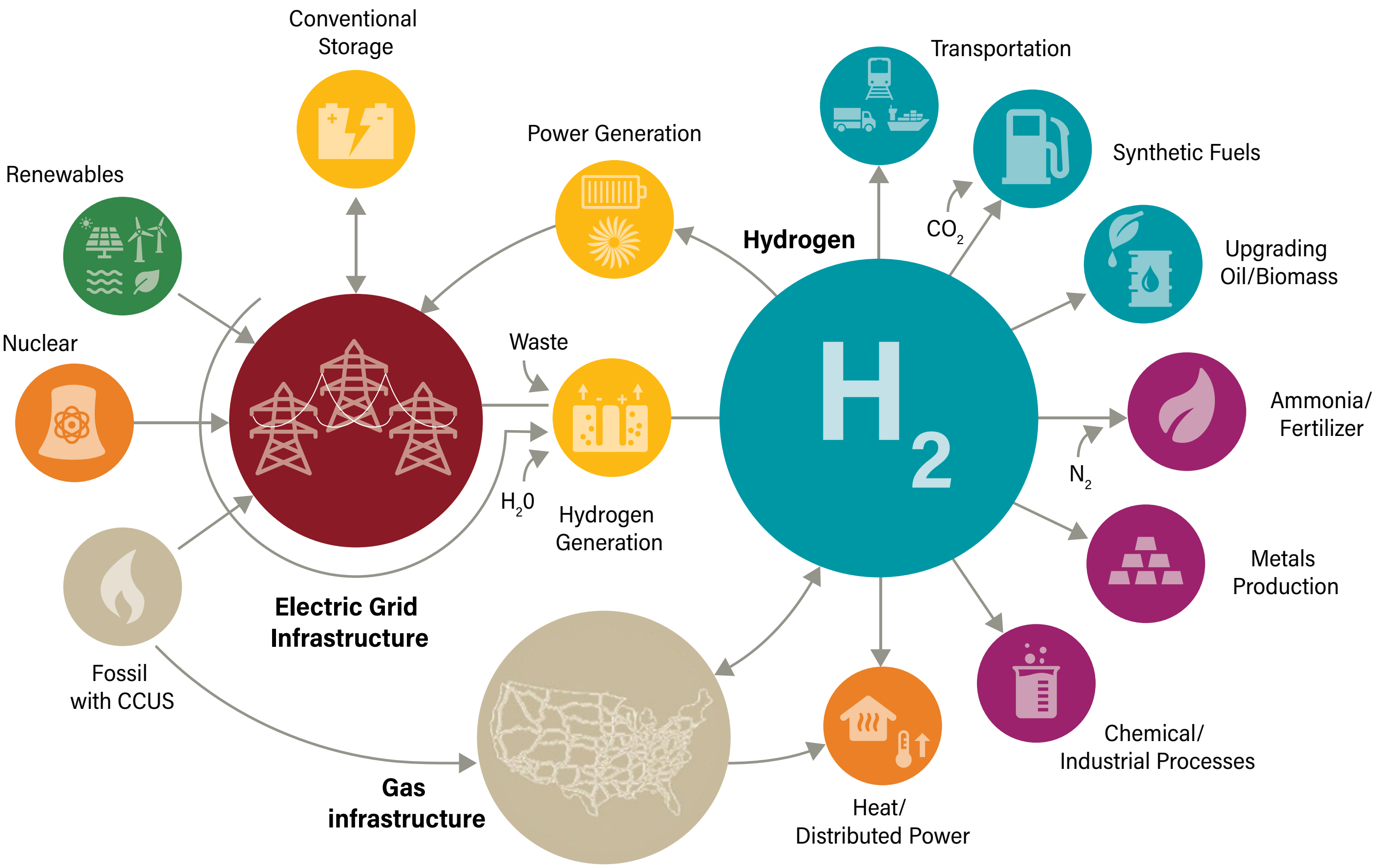
Notes: Mtoe = million tonnes of oil equivalent; Mt H_2 = million tonnes of hydrogen; CCUS = carbon capture use and storage; DRI = direct reduced iron.
Source: IEA 2019a.

limited availability will mean that end uses where hydrogen has its highest value will receive a proportionally greater share of market supply. Many factors will determine total supply and demand for hydrogen and its value related to specific end uses in the near and long term, including policy incentives, production and consumption technology learning curves, project financing, transport and storage infrastructure build-out, and supply of raw materials and feedstocks.

Policy support for and public investment in the production, transport, and use of hydrogen—in the form of research and development funding, pilot projects, tax incentives, infrastructure investment, permitting fuel and emission standards, or a carbon tax, for example—will play a role in directing financing toward hydrogen project development and in determining the market share of specific hydrogen technologies. These policies can help the development of nascent hydrogen-related technologies and reduce hydrogen production costs relative to polluting fuels.

Due to the broad range of possible policy and technology scenarios in 2050, projections of global hydrogen demand in 2050 range widely, from around 200 million to 1,370 million metric tons.[1] Estimates for U.S. demand growth project an approximately sixfold increase by 2050 (Larson et al. 2021). Industry is likely to provide most of the demand for clean hydrogen, dominated by many of the same industrial sectors that currently utilize hydrogen—oil refining, methanol production, ammonia production, and steelmaking. Of these, the demand for hydrogen for low-emission steelmaking has the greatest potential for growth, given the need for decarbonization options and the ability of hydrogen to be either blended with natural gas or used in its pure form to reduce iron ore. Given the need to decarbonize all sectors of the economy, the production and use of hydrogen in oil refining is likely to decline due to a decrease in demand for fossil fuels (Byrum et al. 2021).

Figure 2 | **The Hydrogen Economy**



Source: U.S. DOE 2020.

CLEAN HYDROGEN PRODUCTION, DISTRIBUTION, AND STORAGE

In order for hydrogen or hydrogen-based fuels to be low-carbon fuel alternatives in freight transport, the production, distribution, and storage of hydrogen must be low-carbon itself. The environmental impact of hydrogen production depends on the production pathway and any additional abatement measures used, such as carbon capture and storage and hydrogen leakage detection and prevention.

The most common production pathway in the United States is steam methane reforming (SMR), where over 100 plants operate independently or are located in refineries and ammonia production facilities. SMR uses heat and steam to convert natural gas into hydrogen and carbon dioxide (CO_2). In order for SMR hydrogen to be low-emission, carbon capture technology must be employed, which raises the costs of SMR hydrogen production. While a few plants use carbon capture technology, the vast majority of CO_2 from SMR processes is currently vented into the atmosphere.

Autothermal reforming (ATR) is similar to SMR but reacts methane with oxygen and either carbon dioxide or steam to produce hydrogen and carbon monoxide (syngas). This reaction produces excess heat that can be used to create the steam; the process can be used to adjust the ratio of hydrogen to carbon monoxide, which can be used to make other hydrogen-based fuels. ATR is more efficient than SMR and allows for smaller units relative to SMR, but its increased cost has hindered its development. However, the ability to capture a greater amount of CO_2 relative to SMR could provide cost benefits in the future.

When hydrogen is produced by water electrolysis, water is split into hydrogen and oxygen using electricity. When clean electricity is used in this production process, GHG emissions from production are minimized and mostly arise from materials manufacturing and construction (e.g., solar panels, wind turbines, electrolysis plants). Such "embodied" emissions are inherent to all hydrogen production technology. However, if water electrolysis is powered using today's grid mix rather than dedicated or curtailed renewable energy, its emission profile increases substantially.

Coal can be gasified to produce syngas, from which pure hydrogen can be obtained. Coal gasification is a lesser-used process in the United States due to the large, cheap supply of natural gas for SMR, but it is common in other heavily coal-dependent countries like China and India. Similar to SMR, gasification plants can use carbon capture technology to reduce their CO_2 emissions.

Biomass gasification is similar to coal gasification but requires extra steps due to the increased number of intermediate products that result. Since the carbon contained in the biomass feedstock was removed from the atmosphere, net emissions from this pathway can be negative when combined with carbon capture. Since emissions from land use change can be significant, waste biomass offers the greatest emissions benefits, while dedicated crop production for this pathway that uses marginal land unsuitable for food production can also provide significant climate benefits.

Hydrogen production from methane pyrolysis uses heat to thermally decompose methane into hydrogen and solid carbon. This differs from SMR as the by-product carbon is a solid, called carbon black, that can be either disposed of or used in manufacturing. Methane pyrolysis could function as a bridge between fossil and renewable-based hydrogen because it has both lower GHG emissions than SMR with carbon capture and storage and lower production costs than renewable hydrogen (Al-Qahtani et al. 2021). However, methane pyrolysis has a low technology readiness level, and the market for carbon black is limited (Sánchez-Bastardo et al. 2021). Notably, the U.S. Department of Energy's Loan Programs Office recently approved its first loan for a company to scale up its methane pyrolysis plant (U.S. DOE, n.d.).

Box 1 | Hydrogen Leakage and Its Impact on the Environment

Examining the global warming impact of hydrogen leakage is an essential component of assessing hydrogen's potential to decarbonize freight transportation and other sectors of the economy. While not represented in most life cycle assessments as a greenhouse gas, hydrogen leakage to the atmosphere drives warming indirectly by prolonging the lifetime of atmospheric methane, forming tropospheric ozone, and increasing stratospheric water vapor, yielding a 20-year global warming potential (GWP) that is around 33 times greater than CO_2.[a,b] This GWP value is approximately seven times higher than previous estimates for hydrogen's global warming potential.[c] Additional research and technology development related to hydrogen leakage detection, prevention, and mitigation will be needed if hydrogen is to offer low- or zero-carbon solutions.[d]

Sources: a: Ocko and Hamburg 2022; b: Warwick et al. 2022; c: Derwent et al. 2020; d: Fan et al. 2022.

Hydrogen can be transported as a gas via pipeline or as a gas or liquid in pressurized cylinders. Liquefaction and compression both require significant energy, however, with liquefaction and storage currently requiring around 30 to 40 percent of total energy content of delivered hydrogen, and gas compression around 5 to 10 percent. In comparison, liquifying natural gas requires 25 percent of total energy content delivered, while compression requires around 5 to 10 percent (Zhang et al. 2020).

The most cost-effective transport method for hydrogen depends on the volume being transported and the distance. Below 10 tons per day, truck transport is more economical, with gaseous and liquified hydrogen phases below and above 100 miles, respectively. Above 10 tons, pipelines of increasing capacity are more viable, particularly as distance increases (ETC 2021). Converting to ammonia, which has a higher volumetric density than pure hydrogen, results in additional energy losses but could be economical for international shipping. A variety of hydrogen carriers have been proposed as an alternative to transporting pure hydrogen, but these technologies are currently immature (Schjolberg et al. 2021).

Although a substantial portion of new production facilities could be located relatively near to hydrogen customers, new transport infrastructure and equipment will likely be needed in order to meet increased demand. As hydrogen production ramps up, it could be blended in natural gas pipelines with a range of appropriate blend proportions that will depend on the specific pipeline materials and intended end use. This transport method would require case-by-case assessments to evaluate issues like safety, pipeline durability, leakage, and downstream extraction and separation (Melaina et al. 2013).

The scale of future hydrogen pipeline build-out is uncertain and depends on which particular locations see demand growth and the geographic distribution of production, which will in part be dictated by the availability of feedstocks. Today, hydrogen production in the United States occurs mostly near the Gulf Coast, where refining and chemical manufacturing is concentrated. The United States accounts for over half of current global hydrogen pipeline length, with over 1,600 miles. The International Energy Agency estimates that global pipeline networks must increase to 10,000 miles and 20,000 miles by 2030 to meet international net-zero goals (IEA 2021). Much of this growth is likely to occur in the United States, given projected increases in U.S. demand (U.S. DOE 2020).

Hydrogen hubs have been proposed as dedicated areas of industrial activity that prioritize large-scale hydrogen supply chains. Concentrating hydrogen activity in hubs generates economies of scale and reduces transport and storage energy penalties, thereby reducing costs across the entire supply chain and generating momentum for a growing hydrogen industry (IEA 2019a). As part of the 2021 Infrastructure Investment and Jobs Act, the U.S. federal government authorized a Regional Clean Hydrogen Hub program within the U.S. Department of Energy, providing $8 billion to support the development of 6 to 10 clean hydrogen hubs (U.S. DOE 2022).

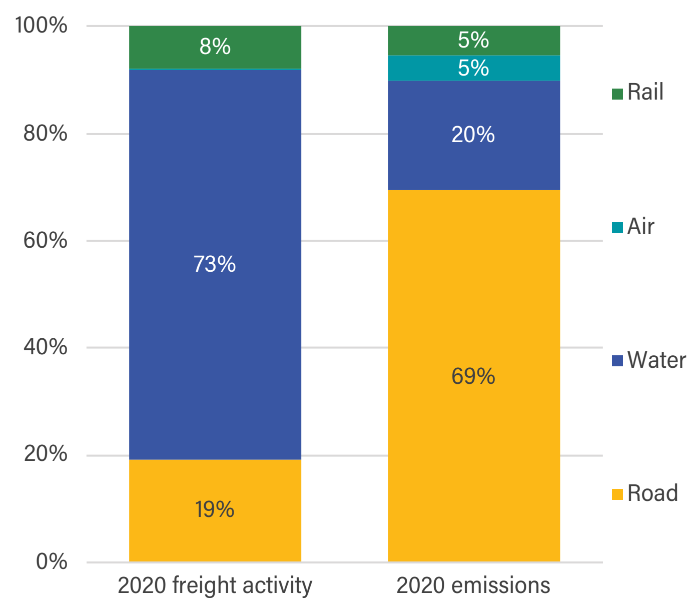
CLEAN HYDROGEN OUTLOOK IN U.S. FREIGHT TRANSPORTATION

Decarbonizing freight transportation is essential to meeting global and U.S. emissions reduction goals. U.S. freight tailpipe emissions totaled 518 million metric tons (MMT) carbon dioxide equivalent (CO_2e) in 2019, or 8 percent of total U.S. emissions and 28 percent of total U.S. transportation emissions. These emissions were split among road (436.8 MMT, 84.4 percent), maritime (26.3 MMT, 5.1 percent), air (19.3 MMT, 3.7 percent), and rail (35.4 MMT, 6.8 percent; Bureau of Transportation Statistics, n.d.-c). Figure 3 shows U.S. freight activity and tailpipe emissions by freight mode.

Each freight transportation segment has different fuel and infrastructure requirements specific to that segment's vehicle use patterns, known as duty cycles. It should be noted, however, that duty cycles and fuel requirements for a given freight segment can also be optimized and adapted to a given fuel. Therefore, existing duty cycles and use patterns, which have been optimized for the use of petroleum-derived products, could be adjusted to be more favorable for the use of hydrogen or other low-carbon fuels. An increase in autonomous operation of freight vehicles could also result in a change in duty cycles, especially in the road freight subsector. Finally, shifting freight duties from one segment to another—for example, from trucking to rail or from air to maritime shipping—could result in a decrease in emissions and a shift in demand for different fuels.

Hydrogen is one of many clean fuels being explored to decarbonize freight transportation, each having its own technological, economic, and environmental considerations. At its point of use, hydrogen can be combusted or combined with oxygen in a fuel cell. When hydrogen is combusted in air, NO_x can result from the combination of oxygen with atmospheric nitrogen. However, when hydrogen is combusted in pure oxygen, energy is produced

Figure 3 | **U.S. Freight Activity and Tailpipe Emissions by Mode, 2019**



Note: Freight activity is defined in terms of ton-miles.

Sources: Bureau of Transportation Statistics, n.d.-c, n.d.-d.

with water vapor as the sole by-product. In a fuel cell, hydrogen is combined with oxygen via a catalyst, producing energy and water vapor.

Ammonia is a carbon-free fuel that can be combusted or converted to energy via a fuel cell. It is more easily stored than hydrogen due to its higher boiling point (-33°C compared to -253°C for hydrogen). However, ammonia is toxic, and therefore environmental releases are of greater concern; combustion can lead to nitrous oxide (N_2O) emissions, a potent greenhouse gas, and harmful NO_x emissions. Methanol has an even higher boiling point, at 65°C; however, it is also toxic, and its synthesis from hydrogen and other chemicals is an energy-intensive process. Batteries and biomass-derived liquid fuels are also viable alternatives to conventional fossil fuel use in freight transport. The following sections lay out hydrogen opportunities in freight transport in the context of these and other fuel alternatives.

Road Freight

Summary: Much of road freight transport is poised to be electrified, including short-distance and urban freight transport, while long-haul, heavy-duty freight vehicles could provide opportunities for hydrogen as a low-carbon fuel. Hydrogen offers quick refueling for on-road freight vehicles and very low emissions at the point of use.

SEGMENT DESCRIPTION

Heavy-duty road freight in the United States encompasses vehicles that have a gross vehicle weight rating (total vehicle weight, fully fueled, without cargo) of over 26,000 pounds and a fully loaded maximum weight of 80,000 pounds (the maximum weight of natural gas vehicles and electric vehicles is 82,000 pounds). Duty cycles in this freight segment vary widely, with some vehicles averaging under 100 miles per day in urban areas and others traveling 600 miles or more per day across rural terrain. Heavy-duty vehicles with short duty cycles in urban areas are prime targets for electrification, while those with longer duty cycles, also known as long-haul freight trucks, are difficult to electrify due to the large and heavy battery packs and long charging times that would be required in the absence of ultrafast charging stations or battery-swapping stations. This section therefore focuses on the outlook for hydrogen use in long-haul freight trucks.[2]

FUEL AND EMISSIONS PROFILE

Long-haul trucking in the United States currently relies almost entirely on petroleum-derived diesel fuel. Corn-based ethanol and biodiesel are blended with conventional diesel in the United States and used in heavy-duty diesel vehicles, but the amount of blending is often small. In 2019, road freight emissions in the United States amounted to 437 MMT CO_2e, or 23 percent of total transportation-related GHG emissions (U.S. EPA 2022). Heavy-duty trucks also emit high levels of sulfur oxides (SO_x), NO_x, carbon monoxide (CO), and particulate matter (PM) pollutants due to the combustion of diesel fuel (see Figure 4).

A variety of alternative fuels and energy sources in addition to hydrogen—such as drop-in fuels sourced from biomass or waste, renewable natural gas, and electricity—offer life cycle emission benefits relative to conventional diesel fuel. The full environmental impact, including the energy and resources required to make these fuels and the criteria pollutant emissions associated with their production and use, must also be weighed when determining a fuel's desirability as an alternative to conventional fuels.

Figure 4 depicts the life cycle of GHG and criteria pollutant emissions associated with the production and use of various alternative long-haul freight transport fuels. While hydrogen fuel cell vehicles offer GHG and criteria pollutant emissions benefits at the point of use and often over their full life cycle, criteria pollutant emissions benefits vary by hydrogen production method, with some production pathways offering little to no benefit over conventional fossil fuels regarding some pollutants.

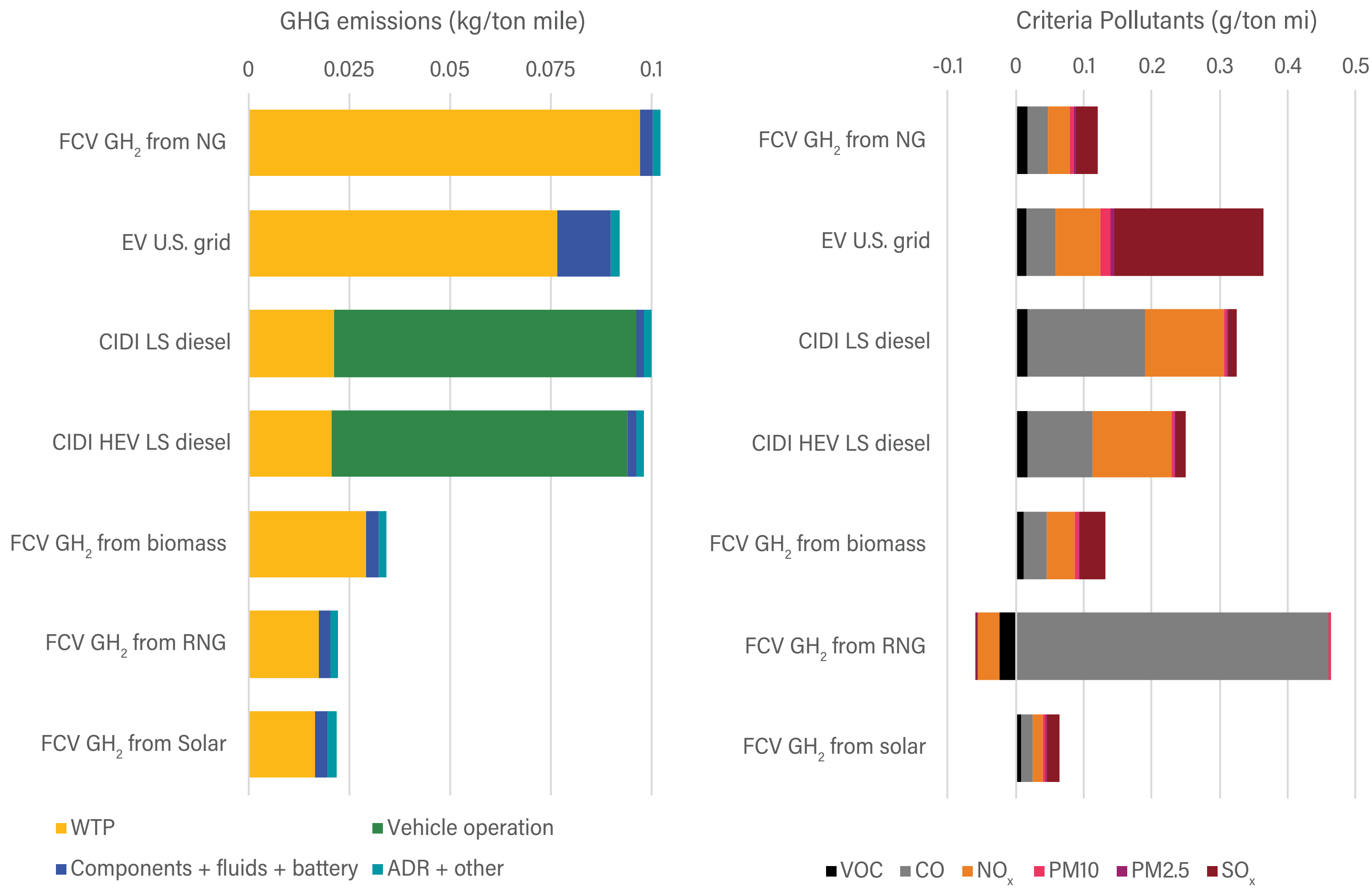
TOTAL COST OF OWNERSHIP

In long-haul trucks, diesel internal combustion engine drive trains have a much lower purchase price than either fuel cell vehicles or electric vehicles. However, maintenance costs for fuel cell electric vehicles (FCEVs) are expected to be much less than for internal combustion engine vehicles (Burnham et al. 2021). Furthermore, fuel costs for hydrogen FCEVs are expected to fall by 2050 due to the falling price of hydrogen production and expanded fueling infrastructure, making the total cost of ownership per mile for FCEVs competitive with internal combustion engine vehicles and battery electric vehicles (BEVs) by 2050. Figure 5 shows the estimated total cost of ownership for long-haul trucks in the United States with various drivetrains in 2025.

STATE OF PLAY AND OUTLOOK

While the technology for long-haul FCEVs is mature, the hydrogen fueling infrastructure required to enable widespread adoption of these vehicles in the United States does not yet exist. Long-haul BEVs face a similar issue regarding ultrafast charging infrastructure. In a scenario where both of these infrastructures exist, one relative advantage of FCEVs over BEVs in the long-haul road segment would be in refueling time. For example, a 700 kilowatt-hour (kWh) battery in a BEV long-haul truck would take 2 hours to fully charge using a 350

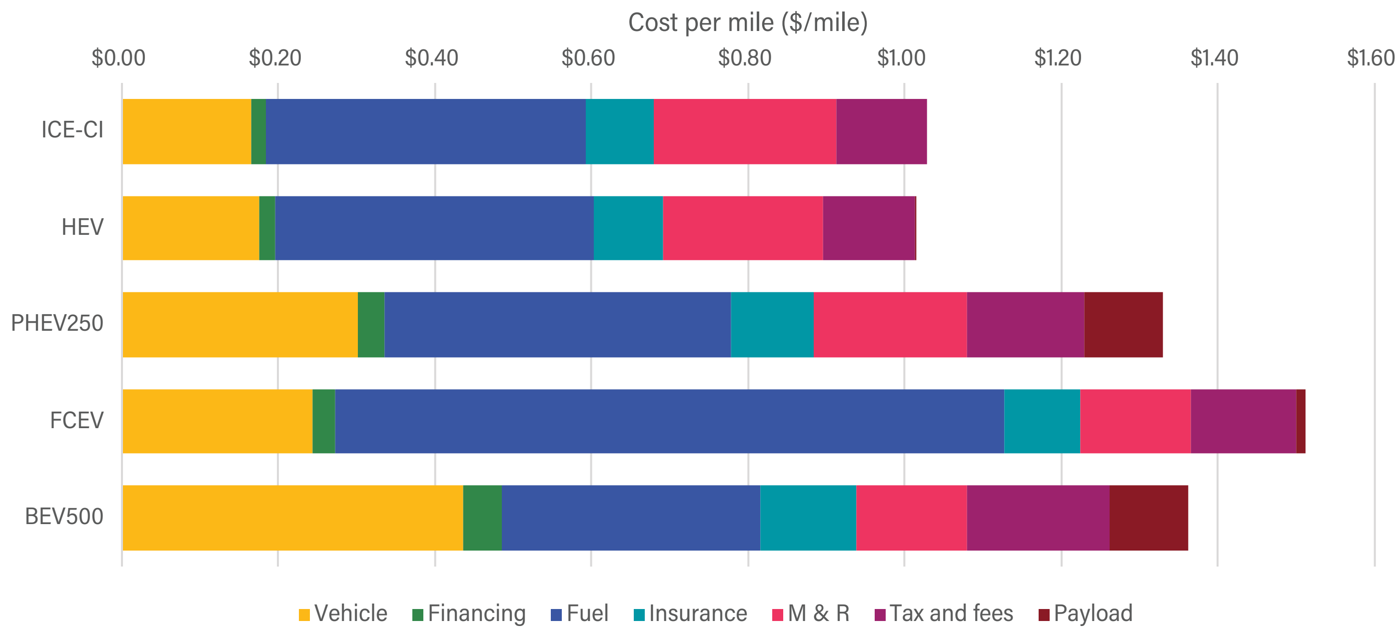
Figure 4 | **Life Cycle GHG and Criteria Pollutant Emissions of Fuels and Powertrains in Heavy-Duty Long-Haul Trucks in the United States**



Notes: GHG emissions are in terms of 20-year global warming potential; FCV = fuel cell vehicle; GH_2 = gaseous hydrogen; NG = natural gas; EV U.S. grid = electric vehicle using grid electricity in the United States; CIDI = compression ignition direct injection; LS = low-sulfur; HEV = hybrid electric vehicle; RNG = renewable natural gas; WTP = well-to-pump; ADR = assembly, disposal, and recycling; VOC = volatile organic compounds; CO = carbon monoxide; NO_x = nitrogen oxides; PM10 = particulate matter less than 10 micrometers in diameter; PM2.5 = particulate matter less than 2.5 micrometers in diameter; SO_x = sulfur dioxides. Biomass in this figure refers to farmed woody biomass (poplar). RNG in this figure refers to methane captured from landfills. Criteria pollutants are defined as air pollutants for which acceptable levels of exposure can be determined and for which an ambient air quality standard has been set (CARB, n.d.-b). Negative emissions values can result from net removals relative to a business-as-usual scenario.

Sources: Authors; Argonne National Laboratory 2022.

Figure 5 | **Average 10-Year Cost of Driving, 2025**



Notes: This figure depicts the cost of driving for a class 8 long-haul tractor trailer, equipped with sleeping quarters, per mile of operation; ICE-CI = internal combustion engine—compression ignition; HEV = hybrid electric vehicle; PHEV250 = plug-in hybrid electric vehicle with 250-mile battery range; FCEV = fuel cell electric vehicle; BEV250 = battery electric vehicle with 250-mile range; M & R = maintenance and repair. Payload costs refer to additional costs associated with payload capacity loss due to increased vehicle component weight; fuel prices are from the U.S. Energy Information Administration's Annual Energy Outlook 2020 projections and the Hydrogen and Fuel Cell Technologies Office targets; fuel prices assumed: diesel 2025/2050 = $3.08/$3.95 per gallon; hydrogen 2025/2050: $9.41/$4.00 per kilogram; electricity 2025/2050: $0.123/$0.0989 per kilowatt-hour.

Source: Burnham et al. 2021.

kilowatt (kW) ultrafast charger, while an FCEV long-haul truck could fully refuel in 15 minutes. This refueling advantage has contributed to the significant growth of FCEVs in the warehouse forklift and transit bus segments.

Another advantage of FCEV long-haul trucks over BEVs is reduced drivetrain weight. Heavy batteries in BEV long-haul trucks outweigh the lighter batteries, hydrogen storage, and fuel cells in FCEVs with similar range. The lighter and smaller drivetrain components in FCEVs mean more revenue per cargo load. In spite of FCEVs drivetrain weight advantage over BEVs, FCEVs still face the problem of added weight relative to lighter conventional diesel drivetrains. Natural gas vehicles and BEVs also face this issue, but the U.S. government permits an increase in gross weight on federal interstate highways for these vehicles, leaving it up to the states whether to allow this extra weight on nonfederal roads. California currently allows near-zero-emission or zero-emission tractor trailers to weigh up to 82,000 pounds when fully loaded with cargo. This regulation, if adopted more broadly, could ease manufacturers' and fleet owners' fears of additional costs associated with the increased drivetrain and fuel storage weight of FCEVs.

On the other hand, BEVs hold a clear energy efficiency advantage over FCEVs. Given the energy requirements of hydrogen production, distribution, and onboard storage, BEVs consume far less energy over their life cycle to deliver the same amount of freight activity, with variations depending on the hydrogen feedstock and production pathway used. This difference in energy efficiency could be important in a scenario of limited renewable energy supply.

While Nikola and Tesla are early major players in the FCEV and BEV truck market, a handful of original equipment manufacturers currently dominate the U.S. long-haul trucking segment, with four companies capturing over 99 percent of U.S. market share. These companies have also delivered hydrogen fuel cell vehicle test models to customers and are planning to begin production in the near future. For example, Toyota and Kenworth teamed up to test a 300-mile-range FCEV long-haul truck (Kenworth Truck Company 2021).

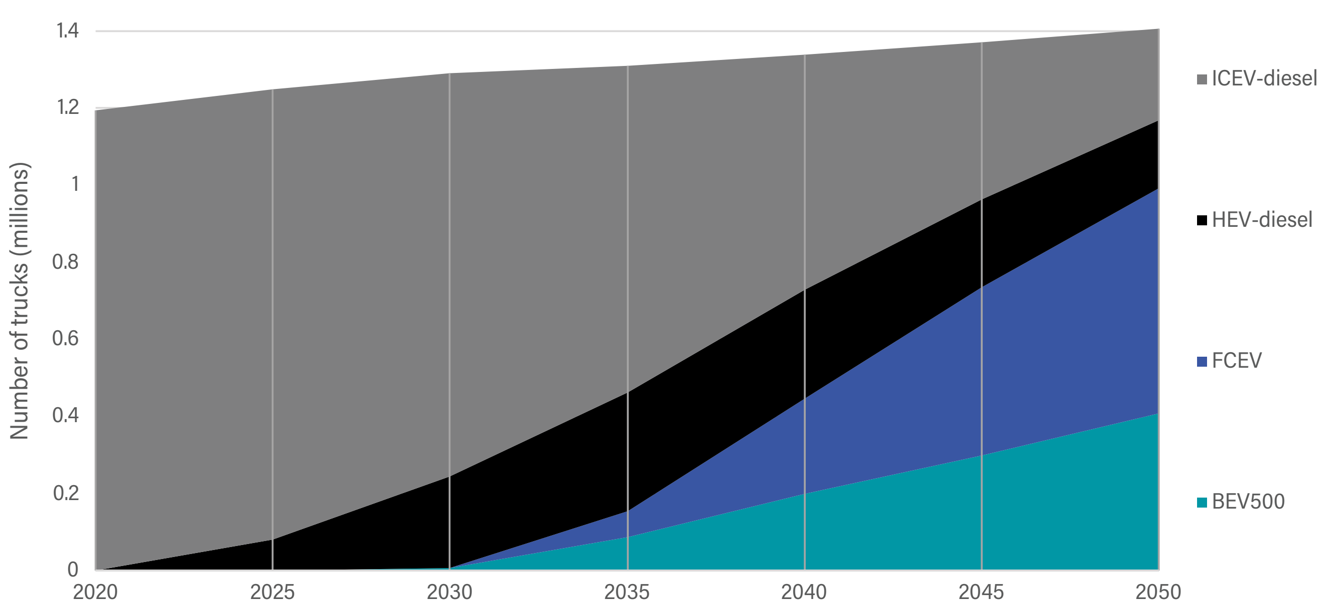
The U.S. government has made substantial recent investments in hydrogen infrastructure and demonstration FCEV projects. The U.S. Department of Energy will award over $125 million in matching grants to domestic manufacturers for the development of FCEV and BEV projects (Babcock 2021), and the 2021 Infrastructure Investment and Jobs Act includes funding for the establishment of a National Alternative Fuels Corridor (Alternative Fuels Data Center 2021). On the state level, California has drafted a rule that is expected to require the complete conversion of medium- and heavy-duty fleets to zero-emission vehicles by 2045 (CARB, n.d.-b). The rule complements the state's Advanced Clean Trucks rule, which requires manufacturers to comply with zero-emission truck sales requirements. New York has adopted an Advanced Clean Trucks rule as well, and the adoption of these and similar rules in other states will lead to important near-term demand for zero-emission trucks.

Hydrogen fuel cell opportunities in the long-haul trucking segment are not limited to primary drivetrain propulsion. Hybrid drivetrain propulsion systems and alternative power units are being explored by fleet owners and manufacturers as well.

Hybrid drivetrains allow trucks to use clean fuels to supplement battery power when needed or to smooth out battery charging cycles (North American Council for Freight Efficiency 2020). Alternative power units, which are used to supply power to the vehicle when idling, could provide important opportunities for hydrogen in the long-haul road freight transport segment. Long-haul trucks typically idle for approximately 1,800 hours per year; this resulted in emissions of 11 MMT CO_2e, 55,000 tons of NO_x, and 400 tons of particulate matter in the United States in 2015 (U.S. DOE 2015). Clean fuels such as hydrogen paired with battery storage could be used in alternative power units to provide nearly emissions-free power during idling.

The use of hydrogen in alternative power units, combined with potential future market share for hydrogen FCEVs, dual fuel vehicles, and hydrogen's use as a feedstock for synthetic fuels, make it difficult to project hydrogen's full impact on the road freight segment. Figure 6 shows projected long-haul heavy-duty U.S. truck stock through 2050, including hydrogen FCEVs, but it does not include consideration of hydrogen's use in a hybrid, dual-fuel, or alternative power unit setup.

Figure 6 | **Projected Long-Haul Heavy-Duty U.S. Truck Stock through 2050**



Notes: ICEV-diesel = internal combustion engine diesel vehicle; HEV-diesel = hybrid electric diesel vehicle; FCEV = fuel cell electric vehicle; BEV500 = battery electric vehicle with 500-mile range.

Source: Ledna et al. 2022.

Maritime Freight

Summary: Clean hydrogen is poised to play a role as a shipping fuel and in the production of hydrogen-rich, low-carbon shipping fuels such as ammonia and methanol by 2050. Liquid organic hydrogen carriers and other stable liquid and solid hydrogen-rich compounds could provide opportunities for hydrogen to function as an energy carrier and fuel feedstock in this segment.

SEGMENT DESCRIPTION

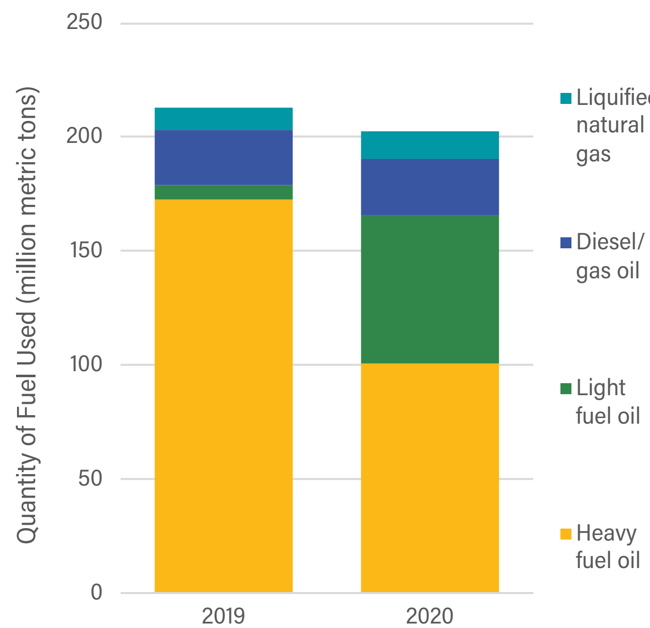
Tankers, container ships, and bulk carriers are the three main classes of large freight vessels. Tankers typically carry bulk liquids or gases such as crude oil and natural gas; container ships carry goods in intermodal shipping containers; and bulk carriers carry solid unpackaged cargo such as iron ore and coal. In the United States, as of 2021, there were 154 large merchant freight vessels (over 1,000 gross tons)—including 62 container ships, 65 tankers, and 27 cargo ships—while globally, there were approximately 44,000 large merchant freight vessels (Bureau of Transportation Statistics 2020; U.S. DOT 2021). Maritime shipping made up approximately 70 percent of total freight activity and 20 percent of freight GHG emissions globally in 2020 (ITF 2021), while in the United States, these numbers were approximately 12 percent and 5 percent, respectively (Bureau of Transportation Statistics, n.d.-c, n.d.-d).

FUEL AND EMISSIONS PROFILE

A variety of fuels can be used in large maritime freight vessels in order to meet a vessel's requirements and to meet emission standards, which vary by geographic location. Fuel oil, which is a viscous fuel that contains a mixture of petroleum distillates and residues from the distillation process, makes up a majority of maritime freight fuel used today in large vessels. Heavy fuel oil (HFO) contains a relatively greater share of residue from the distillation process, while light fuel oil (LFO) has lower residue content and higher distillate content. The combustion of fuel oils in shipping vessels emits environmentally harmful by-products due to the presence of toxic aromatics such as benzene.

Low-sulfur fuel oil use has increased to comply with recent standards from the International Maritime Organization (IMO). In 2008, the IMO ruled to limit the sulfur content in maritime fuel to 0.5 percent, down from 3.5 percent, and this rule went into effect in 2020. Figure 7 shows the amount of fuel use by fuel type in large marine vessels in 2019 and 2020—note the jump in LFO use and simultaneous drop in HFO use coinciding with the IMO's 2020 sulfur rule.

Figure 7 | **Global Marine Vessel Fuel Use, 2019 and 2020**



Note: The switch from heavy fuel oil to light fuel oil from 2019 to 2020 was a result of the International Maritime Organization's sulfur rule taking effect in 2020.

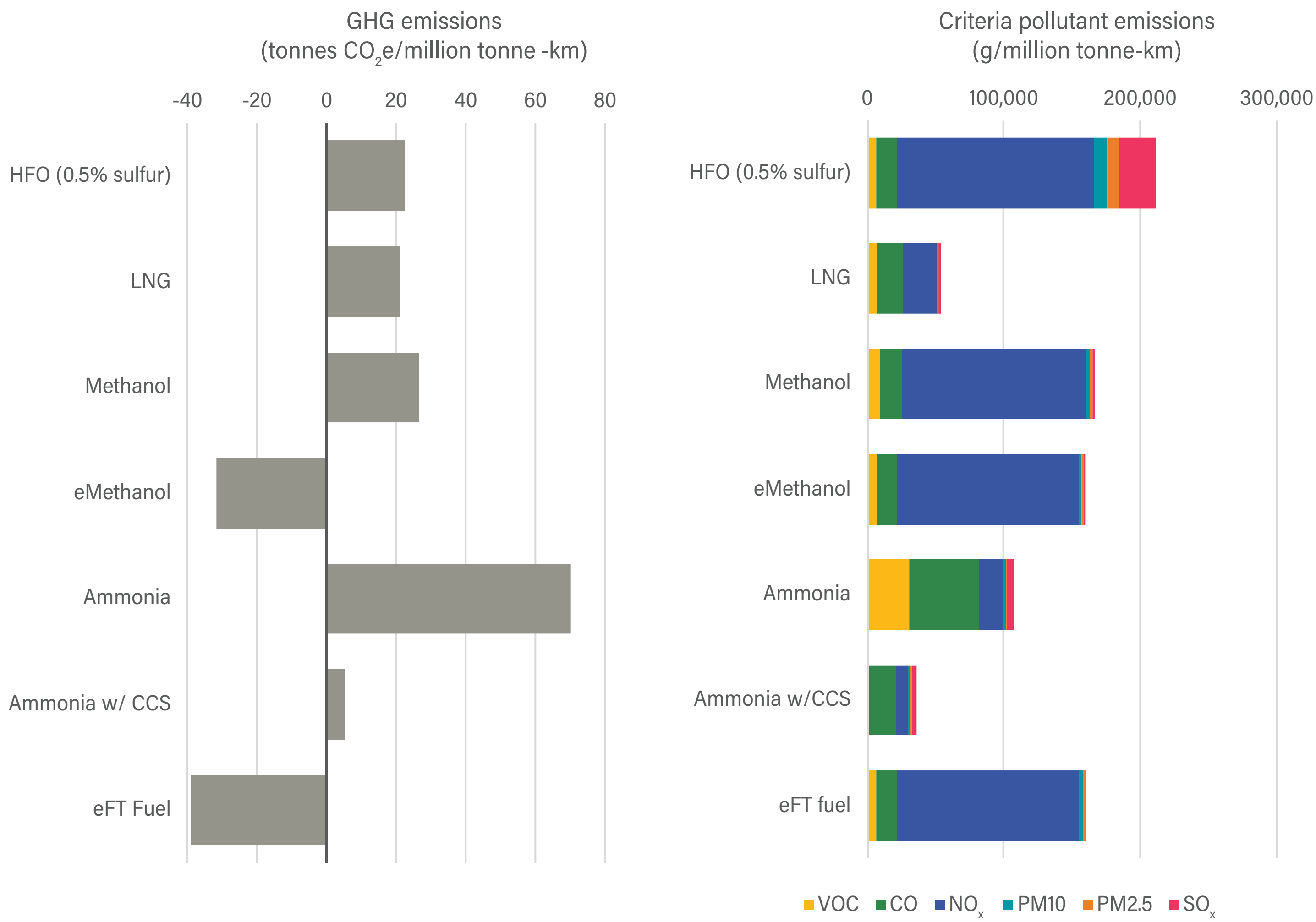
Source: Statista, n.d.

Figure 8 depicts the emissions intensities of various low-carbon shipping fuels. The figure shows the potential of renewable energy electrolysis of water to produce low-emission fuels such as methanol (also called eMethanol) or other fuels made by the Fischer-Tropsch process. Ammonia is only low-emission when made from low-carbon feedstocks and combusted cleanly, while ammonia produced from natural gas is a high-emission fuel, even when compared with incumbent fuels such as HFO.

TOTAL COST OF OWNERSHIP

Liquid natural gas (LNG) is the lowest-cost, near-term option for GHG reductions in marine freight vessels. LNG vessels, however, are only expected to reduce GHG emissions by about 14 to 23 percent compared to HFO-fueled vessels (Chryssakis et al. 2021). In order to comply with the IMO's emission-reduction schedule, fossil LNG fuel will have to be replaced by nonfossil LNG or lower-emission fuels in the long run. Vessels fueled by pure hydrogen incur substantial costs related to hydrogen storage, and fuel costs remain a limiting factor in the cost-competitiveness of hydrogen and ammonia, even in the long term. The cost of manufacturing synthetic fuels and capturing emissions make these fuels just as expensive as ammonia and hydrogen in the near and long term. It is estimated that $1.4 trillion to $1.9 trillion in investments will be needed in order to

Figure 8 | **Life Cycle GHG and Criteria Pollutant Emissions of Various Maritime Fuels in a Large Container Ship**



Notes: GHG emissions are in terms of 20-year global warming potential; HFO = heavy fuel oil; LNG = methane from fossil natural gas; methanol = methanol derived from fossil natural gas; eMethanol = methanol made with green hydrogen; ammonia = conventional ammonia derived from fossil natural gas; ammonia w/CCS = conventional ammonia derived from fossil natural gas with carbon capture and storage; eFT fuel = fuel made by the Fischer-Tropsch method using green hydrogen. The emissions shown represent fuel use in a large container ship operating in the Pacific Ocean carrying cargo from the United States to an international destination.

Source: Argonne National Laboratory 2022.

fully decarbonize global maritime shipping, of which approximately 85 percent will be needed for land-based infrastructure for the production, distribution, and storage of hydrogen, ammonia, and other low-carbon fuels (Englert 2022). Figure 9 shows the approximate total cost of ownership of a bulk carrier fueled by various alternative fuels.

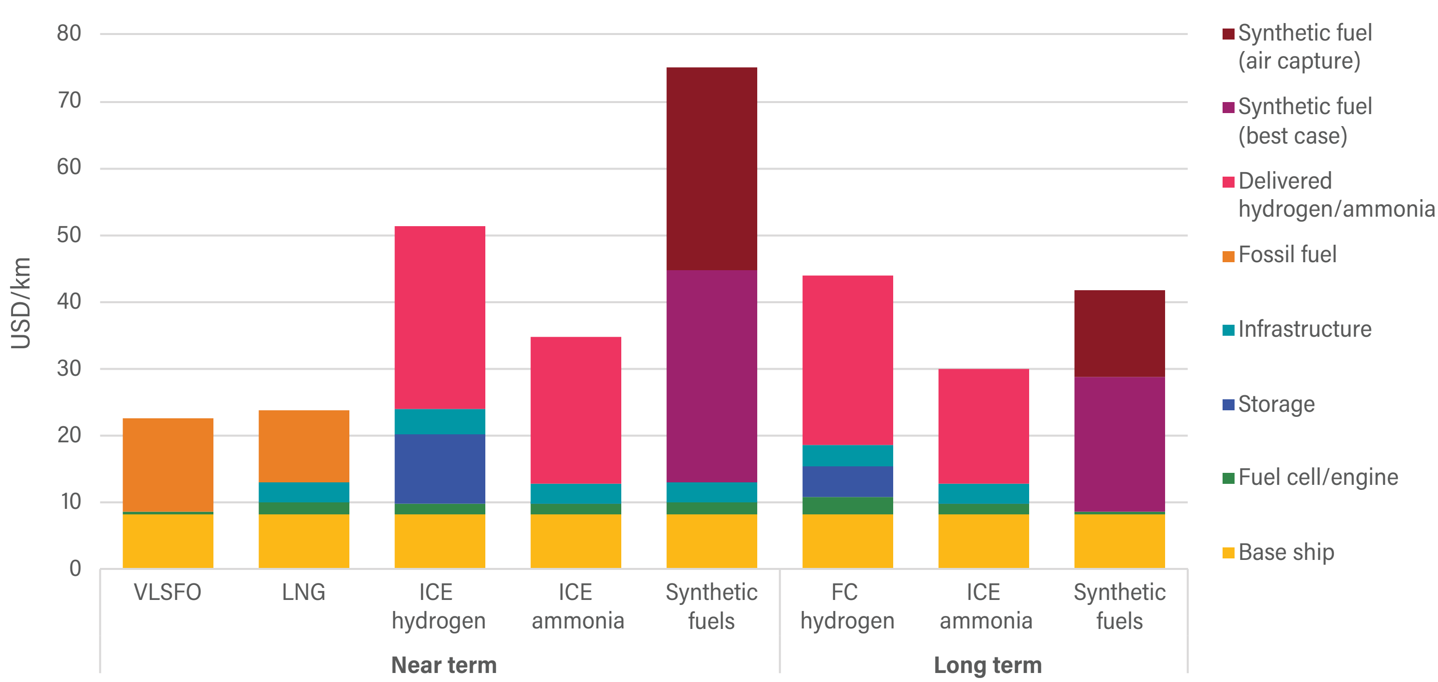
STATE OF PLAY AND OUTLOOK

Liquid natural gas vessels are poised to play a role in the next decade in replacing conventional vessels, though increasingly strict emission standards will hasten the transition to lower-carbon and less-polluting fuels (Khasawneh 2021). Hydrogen and ammonia ships are still in the pilot phase (Prevljak 2021), and widespread use in larger vessels will likely take decades (Gallucci 2021). Methanol-ready ships are seen as one way to reduce emissions in the near to mid-term; these ships are able to run on low-sulfur fuel until green methanol is available at scale (Frangoul 2021a; Jacoby 2022). Many operators are choosing to install scrubbers on their ships in order to comply in the near term with the stricter SO_x rules enforced in 2020. In order to comply with the increasingly strict GHG emission rules, however, operators will have to rely on clean alternative fuels, which will require fleet additions and retrofits of existing vessels to accommodate the use of these fuels.

Hydrogen pilot projects are underway (Hamilton 2021; Ovcina 2021), with a hydrogen-powered cargo ship to be completed in 2024 (Prevljak 2022). The ship will rely on combustion, hydrogen fuel cells, and batteries for energy, and it will have Flettner rotor sails to increase efficiency when under sail. Alternative fuels, including hydrogen, are increasingly making their way into new vessel builds and retrofits (see Figure 10). Low-carbon fuels such as biofuels, synthetic fuels, methanol, ammonia, and hydrogen have been projected to meet around 60 percent of maritime energy demand by 2050, with LNG and liquid petroleum gas supplying a combined 30 percent (American Bureau of Shipping 2022; DNV 2021). Increasing bunkering capacity and refueling locations for alternative-fueled vessels is crucial for the establishment of low-carbon global shipping routes.

Similar to road freight, hydrogen could also play a role in alternative power units in vessels that could be used while in port. Emissions in ports are of significant concern since ports are

Figure 9 | **Approximate Current and Future Total Cost of Ownership of Fuel/Powertrain Alternatives in Bulk Carriers**



Notes: VLSFO = very low sulfur fuel oil; LNG = liquid natural gas; ICE = internal combustion engine; FC = fuel cell. Synthetic fuels are liquid fuels made from fossil fuel or biomass feedstocks, which are first broken down into synthesis gas (hydrogen and carbon monoxide) and then converted to liquid fuels using a synthetic process such as the Fischer-Tropsch process. Near term refers to 2025–30; long term refers to 2050 and beyond.

Source: IEA 2019b.

often located near urban centers. Offshore hydrogen bunkering could provide storage and refueling solutions for space-constrained urban ports.

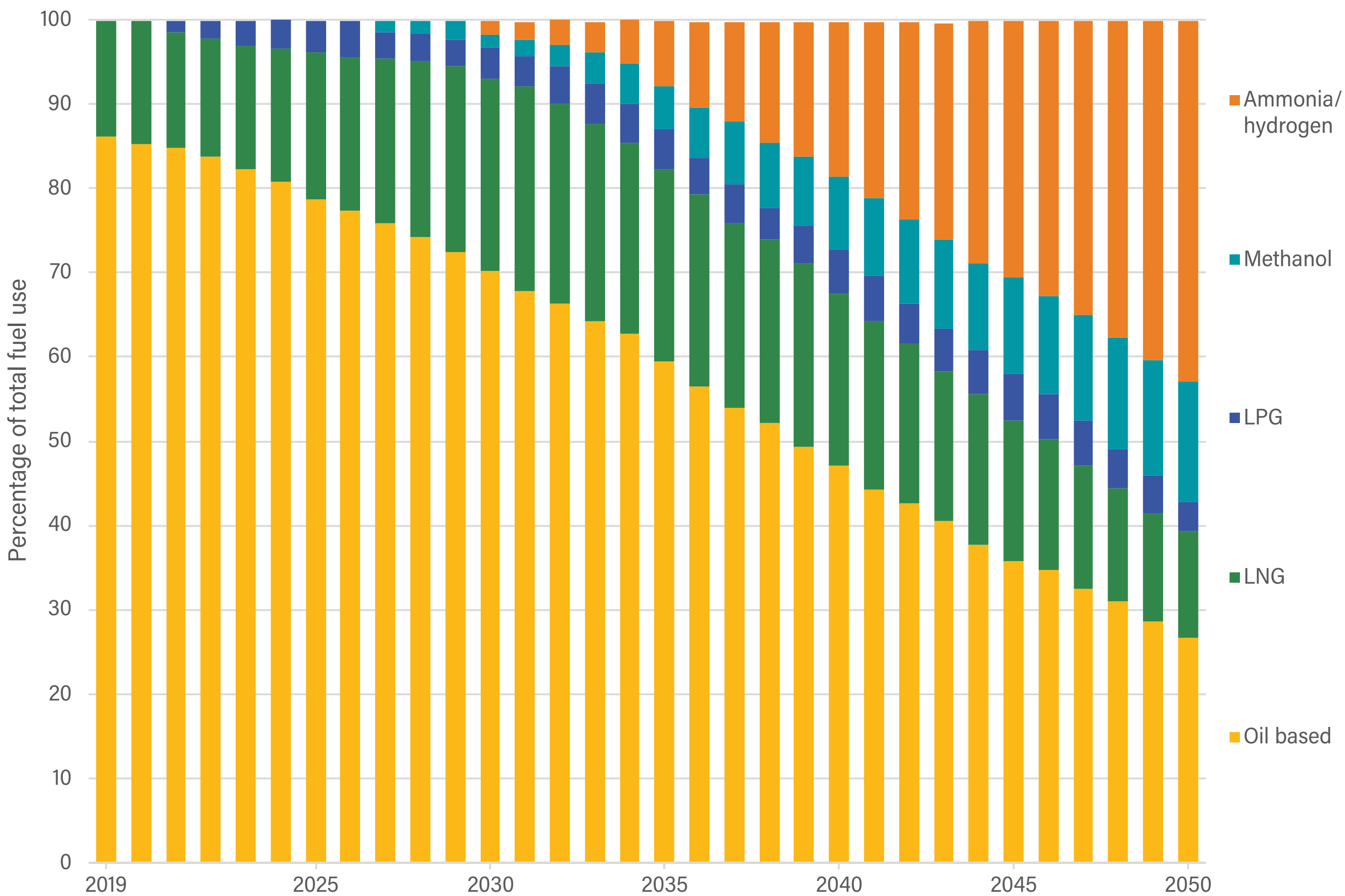
Air Freight

Summary: Air freight requires a dense and stable fuel, such as clean biofuels or synthetic fuels. Sustainable aviation fuels that can be used as drop-in fuels in existing aircraft are seen as the dominant option over the next couple of decades. Clean hydrogen is unlikely to see widespread adoption as an aviation fuel before 2040, though it will be crucial in the manufacturing of sustainable aviation fuels even in the near term.

SEGMENT DESCRIPTION

In the United States in 2021, there were about 900 cargo aircraft, nearly half of the global total, and around 90 million ton-miles of cargo were carried by U.S. air cargo and passenger planes. While only 1 percent of cargo by weight is carried by air freight carriers globally, it is estimated that the segment carries around 35 percent of total cargo value (Crabtree et al. 2020). Approximately 55 percent of air cargo (in revenue ton-miles) was carried globally by dedicated cargo aircraft in 2019, with the rest carried in commercial passenger aircraft cargo holds (Crabtree et al. 2020). Though this share fluctuates from year to year (Swegal and Wiesner 2021), decarbonizing commercial passenger aircraft will clearly play an important role in decarbonizing the air freight segment as well.

Figure 10 | **Fuel Mix Forecast for Global Shipping**



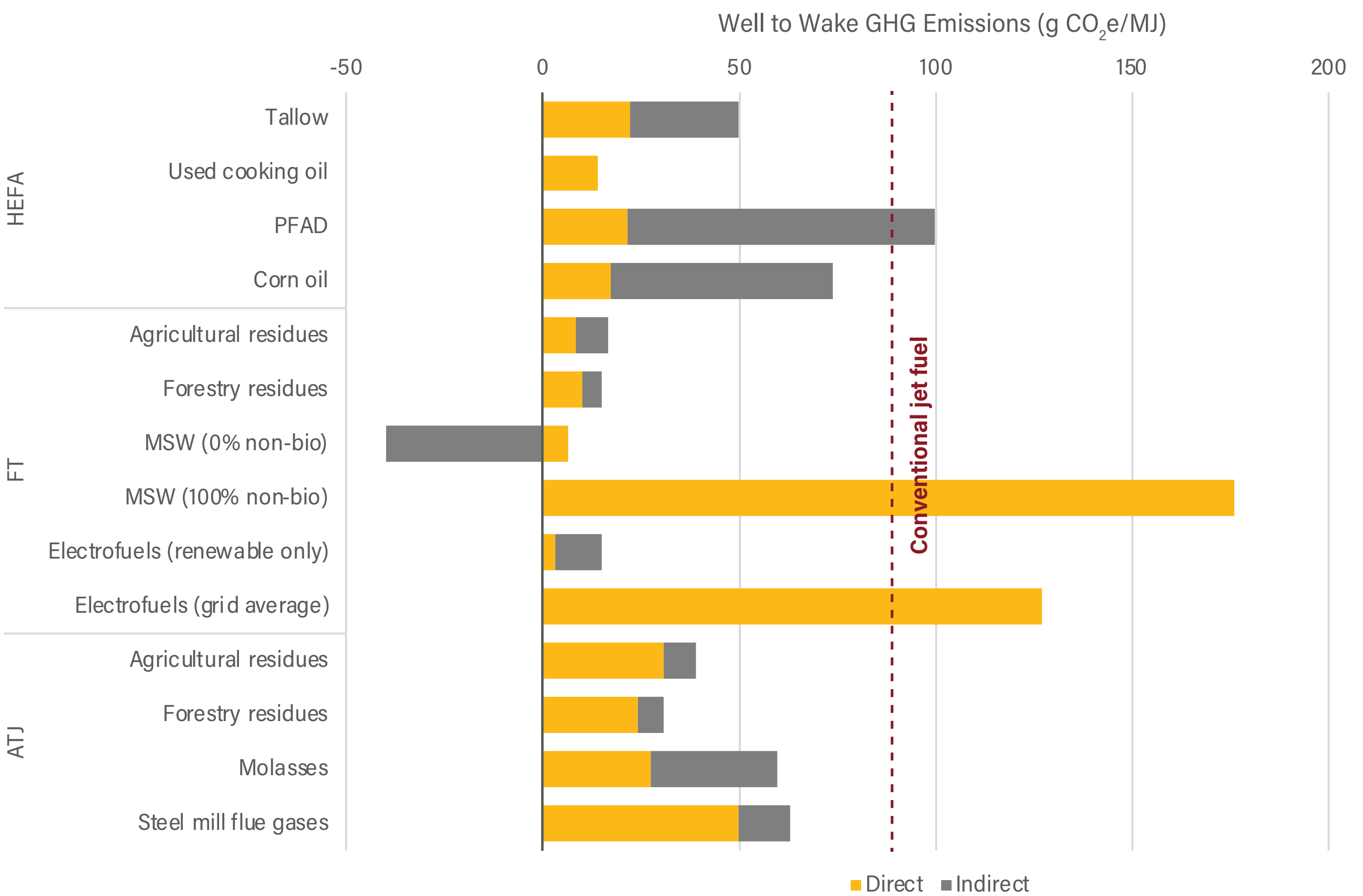
Source: American Bureau of Shipping 2022.

FUEL AND EMISSIONS PROFILE

Petroleum-derived jet fuel is the predominant fuel used in large freight aircraft. Jet fuel is standardized by its properties, such as freezing temperature and flash point, rather than by composition. Jet A fuel, which is primarily used in the United States, and Jet A-1 fuel, which is used in much of the rest of the world, are both kerosene-based fuels that are similar in composition and properties, with the main difference being Jet A-1 fuel's slightly lower freezing point (-47°C as compared to -40°C). Jet B fuel, which is naphtha- and kerosene-based, and TS-1 fuel are formulated to have an even lower freezing point (-50°C to -60°C) for use in colder climates. Typical additives present in jet fuels include antioxidants to prevent gumming, antistatic agents to prevent sparking, corrosion inhibitors, and icing inhibitors.

The International Civil Aviation Organization (ICAO)—the global regulatory body for aviation—has approved 17 sustainable aviation fuel (SAF) feedstocks and at least 34 production pathways (ICAO 2021b) using nine different conversion processes (ICAO 2021a). These SAFs are approved for various blending levels with conventional jet fuel. The life cycle emissions intensities of SAFs vary considerably, with some offering little to no benefit over conventional jet fuel (see Figure 11). In 2021, 100 million liters of SAF were used globally, making up only 0.05 percent of the 216 billion liters of global jet fuel consumption. Future orders of SAF, however, totaled 14 billion liters of SAF in 2022, though this amount will be spread out over multiple years. By 2030, it is possible that 3 percent of aviation fuel globally will be sourced from SAF, with rates in the United States and European Union reaching 5 to 6 percent (Robinson 2021).

Figure 11 | **Approximate Life Cycle Emissions of Approved Sustainable Aviation Fuels**



Notes: GHG emissions are in terms of 20-year global warming potential; CO_2e = carbon dioxide equivalent; MJ = megajoule; PFAD = palm fatty acid distillate; MSW = municipal solid waste; HEFA = hydroprocessed esters and fatty acids; FT = Fischer-Tropsch; ATJ = alcohol-to-jet fuel. The Fischer-Tropsch process uses heat and catalysts to synthesize liquid fuels out of a gasified feedstock. The ATJ process deoxygenates alcohols obtained from a feedstock and converts the alcohol into jet fuel.

Source: Pavlenko and Searle 2021.

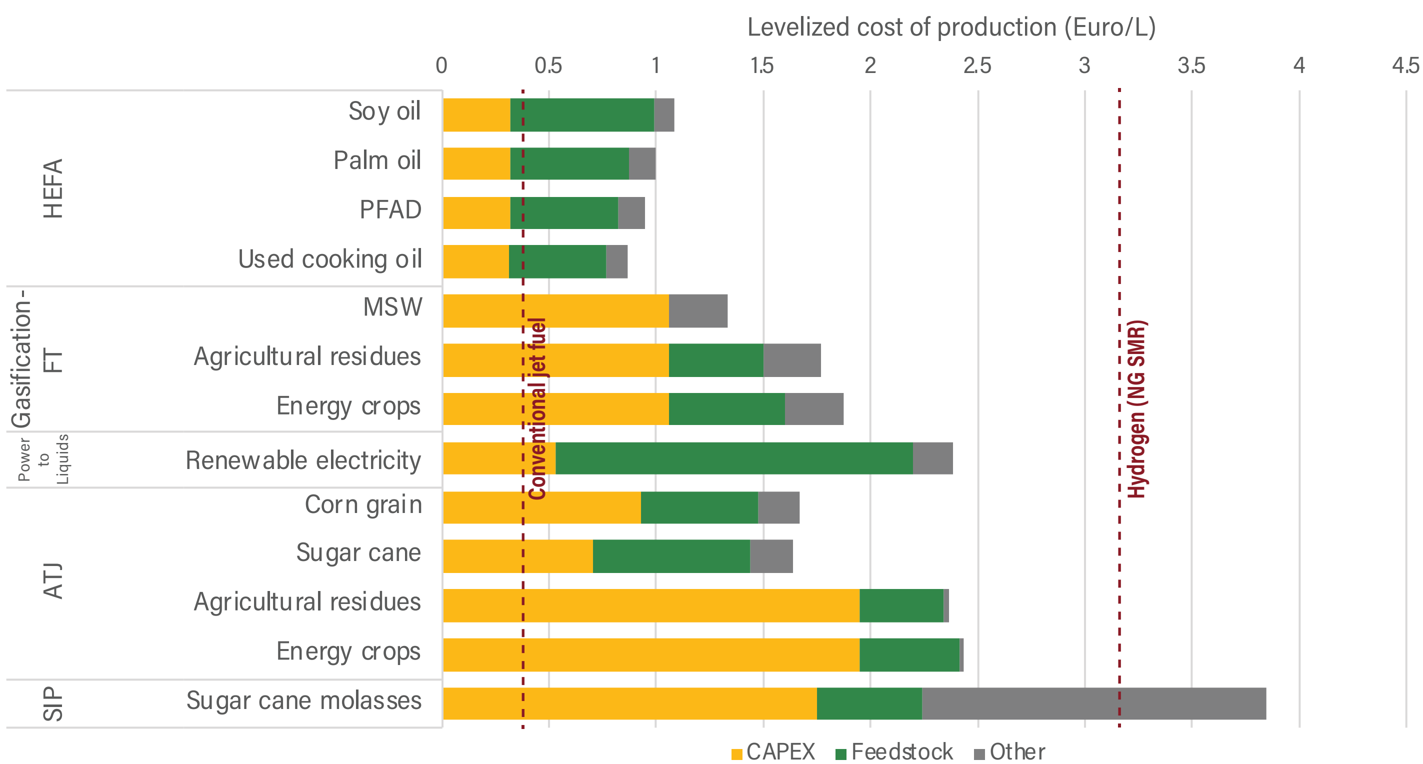
The ICAO (2017) has set GHG emissions standards for new aircraft that will take effect in 2023. The new standards set emissions intensity limits according to aircraft weight. Aircraft that do not comply with the standards by 2028 will no longer be approved for commercial use. Along with these standards, the ICAO is endorsing a suite of measures to limit emissions from the aviation sector, including technology goals and standards, SAFs, market-based measures, and operational measures, with the goal of achieving carbon-neutral growth in the sector.

TOTAL COST OF OWNERSHIP

Estimates of the total cost of ownership for alternative fuels and technologies for freight aircraft are highly uncertain and are based on a number of assumptions that include future projections of the maturity of fuel production technologies and supply chains, distribution infrastructure, production scale of hydrogen and other feedstock, aircraft engine technologies, and onboard hydrogen storage technologies. Since nearly all alternative aviation fuels and technologies are either immature or not yet in commercial production, their total cost of ownership is likely to change drastically as alternative fuel production ramps up.

While regional hydrogen fuel cell passenger aircraft have compared favorably to piston engine aircraft (Ahluwalia 2020), long-distance flights powered by hydrogen are estimated to increase costs by 50 to 60 percent over conventional jet-fueled aircraft (McKinsey & Company 2020). Sustainable aviation fuel is also expected to increase costs related to jet fuel–based travel. In 2022, the lowest-cost SAF was still 2 to 2.5 times

Figure 12 | **Levelized Cost of Production of Various Alternative Jet Fuel Production Pathways**



Notes: NG SMR = steam methane reforming of natural gas; PFAD = palm fatty acid distillate; MSW = municipal solid waste; HEFA = hydroprocessed esters and fatty acids; FT = Fischer-Tropsch; ATJ = alcohol-to-jet fuel; SIP = synthesized iso-paraffins. Hydrogen cost = 3.16 Euro/liter. Conventional jet fuel = 0.39 Euro/liter. Production costs are for Europe (2019 for sustainable aviation fuel and 2020 for hydrogen).

Sources: Pavlenko et al. 2019; Zhou and Searle 2022.

more expensive than conventional jet fuel (Frangoul 2022). Figure 12 depicts the levelized cost of production of approved alternative jet fuels—hydrogen production costs are included for comparison.

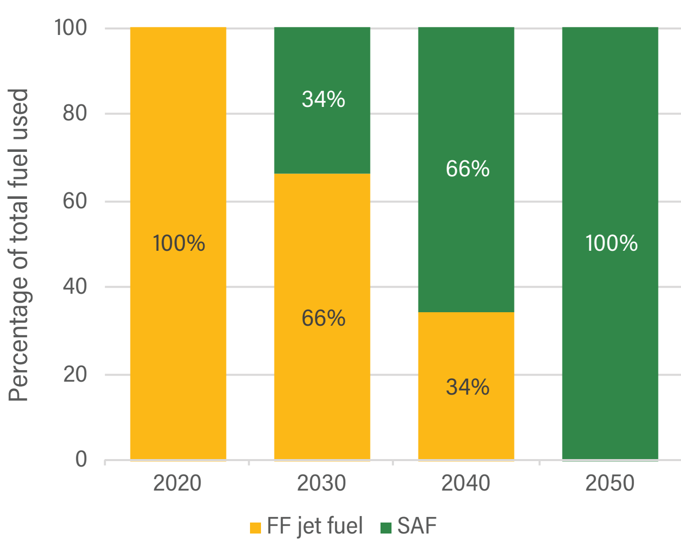
STATE OF PLAY AND OUTLOOK

Hydrogen's low boiling point presents significant challenges regarding aircraft efficiency, since it requires additional energy and onboard storage equipment. Additionally, the current high cost and low technology-readiness level of hydrogen fuel and hydrogen aviation technologies mean that hydrogen's widespread use as a fuel in aviation is likely decades away.

In spite of these challenges, Airbus, one of the largest aircraft original equipment manufacturers in the world, has announced plans to produce commercially available planes that run on pure hydrogen by 2035 as part of its zero-emission (ZEROe) initiative (Airbus, n.d.). The ZEROe program was underway as of 2022, and Airbus plans on having a mature technology ready for demonstration flights by 2025. Airbus's three proposed aircraft all have a hybrid design that increases efficiency by using hydrogen combustion engines for propulsion and hydrogen fuel cells for supplemental power. Meanwhile, ZeroAvia plans to operate small hydrogen-powered passenger flights by 2024 (Frangoul 2021b). These aircraft will use hydrogen fuel cells to power electric motor–driven propellers and will be capable of carrying around 20 passengers.

While hydrogen is seen as a potential long-term solution for aviation, SAFs are expected to offer near-term emissions reductions, though only marginal reductions are expected through 2030 and possibly even 2040 due to limited uptake. The United States has set a goal of achieving domestic production of 3 billion gallons (approximately 20 percent of current domestic jet fuel consumption) of SAF by 2030. The requirement for qualifying as SAF under this program is the utilization of an ICAO-approved production pathway that offers at least a 50 percent reduction in emissions relative to conventional jet fuel (The White House 2021). The Biden administration acknowledges the importance of hydrogen and battery technologies in decarbonizing the aviation sector in the long run, but it believes that these technologies will not contribute significantly to the segment's fuel mix until after 2050. Figure 13 depicts an illustrative fuel mix forecast for the U.S. aviation sector through 2050 that could occur as a result of achieving the SAF production goals.

Figure 13 | **Illustrative Fuel Mix Forecast for U.S. Aviation**



Notes: FF jet fuel = conventional fossil fuel-based jet fuel; SAF = sustainable aviation fuel. The Biden administration sees hydrogen and batteries as potential aviation fuels beyond 2050.

Source: The White House 2021.

Rail Freight

Summary: Hydrogen fuel cell and battery electric locomotives are over twice as efficient as current diesel electric locomotives and are top contenders to replace diesel electric locomotives in rural rail freight applications. Hydrogen-fueled yard switchers already offer cost savings relative to their diesel electric counterparts, providing an important initial opportunity for hydrogen use in rail freight. Tender cars dedicated to storing onboard hydrogen fuel will likely be necessary in order to offer sufficient range for hydrogen-powered locomotives.

SEGMENT DESCRIPTION

There are approximately 25,000 freight locomotives, which includes around 5,000 switcher cars, and around 140,000 miles of freight railroad track in the United States, which is the most in the world. In the United States, private companies own and operate freight track, and there are currently seven class 1 rail freight companies[3] that operate long-distance freight track and locomotives. Approximately half of rail freight activity in the United States is dedicated to bulk agricultural, construction, and energy products, while the rest is dedicated to moving intermodal containers of packaged consumer goods (Union Pacific 2021; U.S. DOT, n.d.).

FUEL AND EMISSIONS PROFILE

While the majority of urban rail is electrified in the United States, rail freight in the United States has been difficult to electrify, given the long-distance rural routes for which the mode is most suited. As a result, diesel electric locomotives currently move nearly all U.S. rail freight. Diesel electric locomotives use a diesel engine running at a constant rate to drive an electric generator, which then supplies the power to the electric traction motors.

U.S. federal emissions standards for locomotives limit criteria pollutant emissions based on year of manufacture, with standards tightening for newer models (Bureau of Transportation Statistics, n.d.-b). Locomotives placed in service after 2015 must meet NO_x and PM emissions standards that are around seven times stricter than standards for locomotives built before 1992 and CO standards that are 3.3 times lower. However, nearly half of the U.S. fleet of locomotives were built before 1999, and the average age of locomotives is around 28 years (Bureau of Transportation Statistics, n.d.-a). Figure 14 shows life cycle GHG and criteria pollutant emissions of rail freight fuels for locomotives built after 2015.

TOTAL COST OF OWNERSHIP

Fuel makes up the vast majority of the variable costs of ownership of modern diesel freight locomotives. For hydrogen fuel cell hybrid locomotive setups, the fuel cell powertrain is estimated to make up around 25 to 50 percent of the total cost of ownership (see Figure 15).

Electric-diesel hybrid locomotives (not to be confused with diesel electric locomotives) are equipped with a battery and a diesel engine that can operate in tandem or separately, and the battery can be recharged by electric regenerative braking or by the diesel engine. This setup has been estimated to offer 17 to 32 percent fuel savings compared to a conventional diesel locomotive (IEA 2019c). Hydrogen fuel cell locomotives and battery electric locomotives offer energy savings—they are around twice as efficient as diesel electric locomotives, since they eliminate the need for combustion of fuel, which is an inherently inefficient process.

STATE OF PLAY AND OUTLOOK

The rail freight segment offers unique opportunities for hydrogen and other clean fuels, given the anatomy of a freight train, which is characterized by a locomotive engine and additional cars in tow. In a hydrogen-fueled train, a tender car could be used to carry hydrogen fuel, which would enable hydrogen's use on long-distance routes. A dual-fuel system could also be employed, in which a hydrogen locomotive could provide propulsion for a portion of the trip, while a diesel electric locomotive could function as a backup power source or as a power source for the bulk of the trip for long journeys. Hydrogen could also provide power for auxiliary power units, which in today's diesel electric locomotives are powered by a separate diesel engine (in addition to the diesel engine that is responsible for providing power for propulsion).

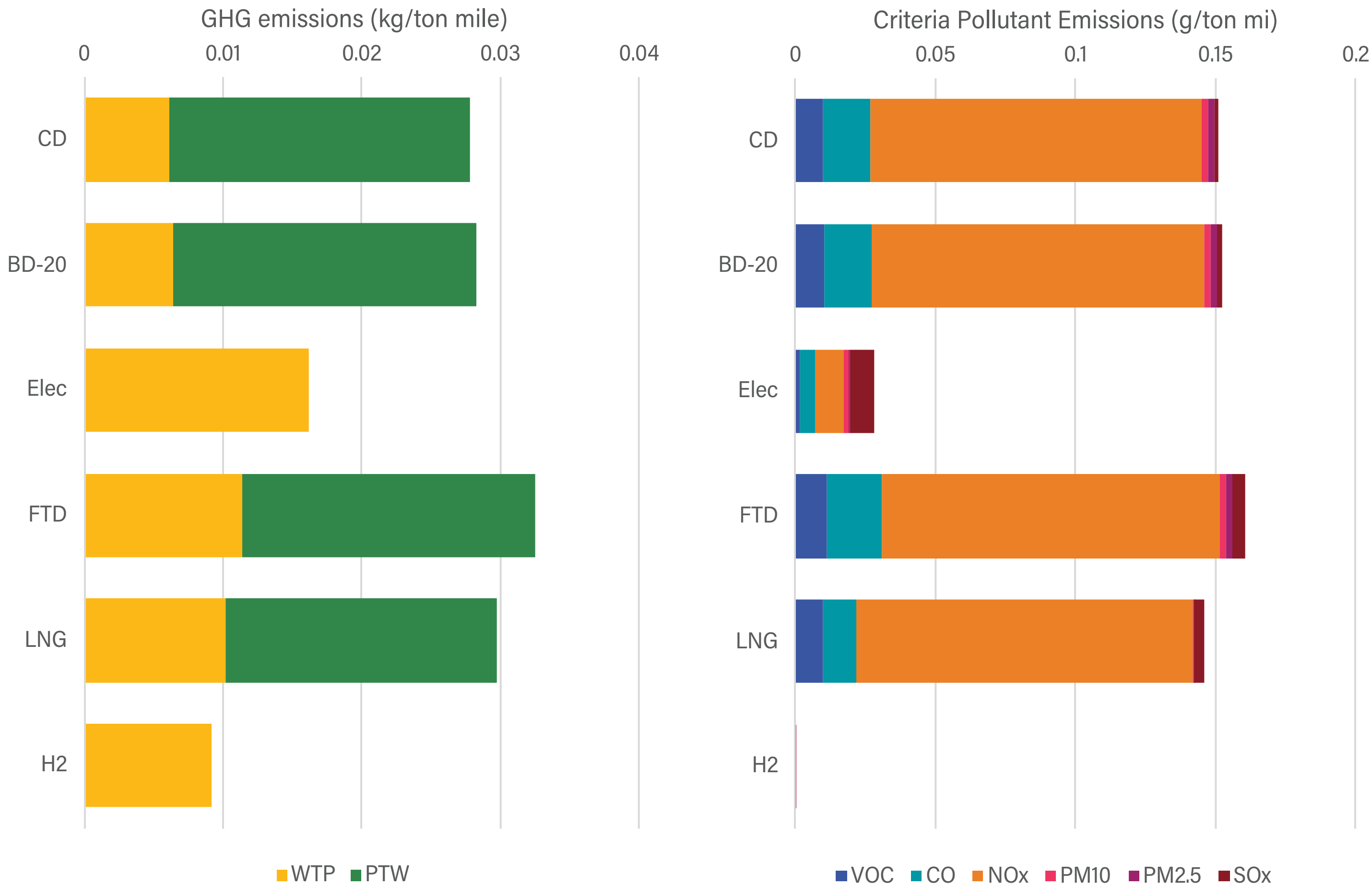
U.S. manufacturers are currently producing low- and zero-emission locomotives that could be used in series or in conjunction with existing diesel electric locomotives (General Electric 2018). In addition to its existing battery electric locomotive, Wabtec has begun development of a prototype hydrogen locomotive that would run on electricity produced by hydrogen fuel cells.

In Germany, 60 miles of track have been dedicated for operation by 14 hydrogen locomotives produced by the French company Alstom that will power passenger service in northwestern Germany (Alstom, n.d.). These locomotives have two hydrogen tanks with about 94 kilograms of capacity each, with 24 individual compressed hydrogen tanks in each. There are two fuel cells, each with a power output of 314 kW (Railvolution 2018). Similar locomotives and engine technologies could also be used in the future to provide auxiliary propulsion for freight trains.

Yard-switcher locomotives have been shown to present cost-saving opportunities relative to diesel electric switcher locomotives (Ahluwalia et al. 2019). This is a result of the power at which switcher locomotives operate, which is suboptimal for diesel engines. Increased use of low-emission locomotive technologies in yard-switching applications would further decrease emissions in densely populated urban areas, reducing human health impacts of the rail segment and offering an entry point to the freight rail locomotive segment—similar to the opportunity that warehouse forklifts offered for FCEVs in the road freight segment.

Figure 16 depicts a fuel mix forecast for the United States and other countries around the world that have significant rail freight activity. As shown in the figure, the current and projected fuel mix varies widely by country.

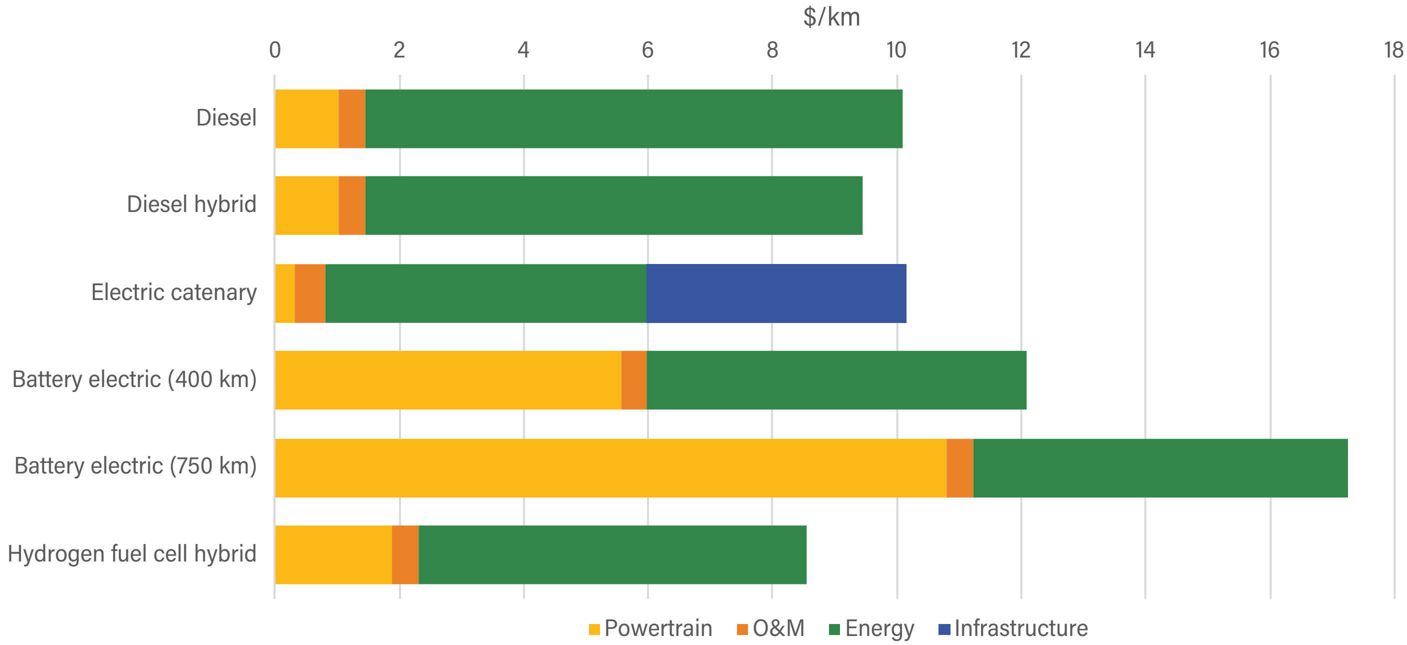
Figure 14 | **Life Cycle Emissions of Rail Freight Fuels in the United States**



Notes: GHG emissions are in terms of 20-year global warming potential; CD = conventional diesel; BD-20 = biodiesel 20%; Elec = grid electricity from catenary lines or electrified rail; FTD = Fischer-Tropsch diesel; LNG = liquid natural gas sourced from natural gas; H2 = liquid hydrogen from solar electrolysis of water; WTP = well-to-pump; PTW = pump-to-wheel; VOC = volatile organic compounds; CO = carbon monoxide; NOx = nitrogen dioxide (NO2) and nitrogen trioxide (NO3); PM10 = particulate matter emissions 10 micrometers or smaller; PM2.5 = particulate matter emissions 2.5 micrometers or smaller; SOx = sulfur dioxide (SO2) or sulfur trioxide (SO3).

Sources: Authors; Argonne National Laboratory 2022.

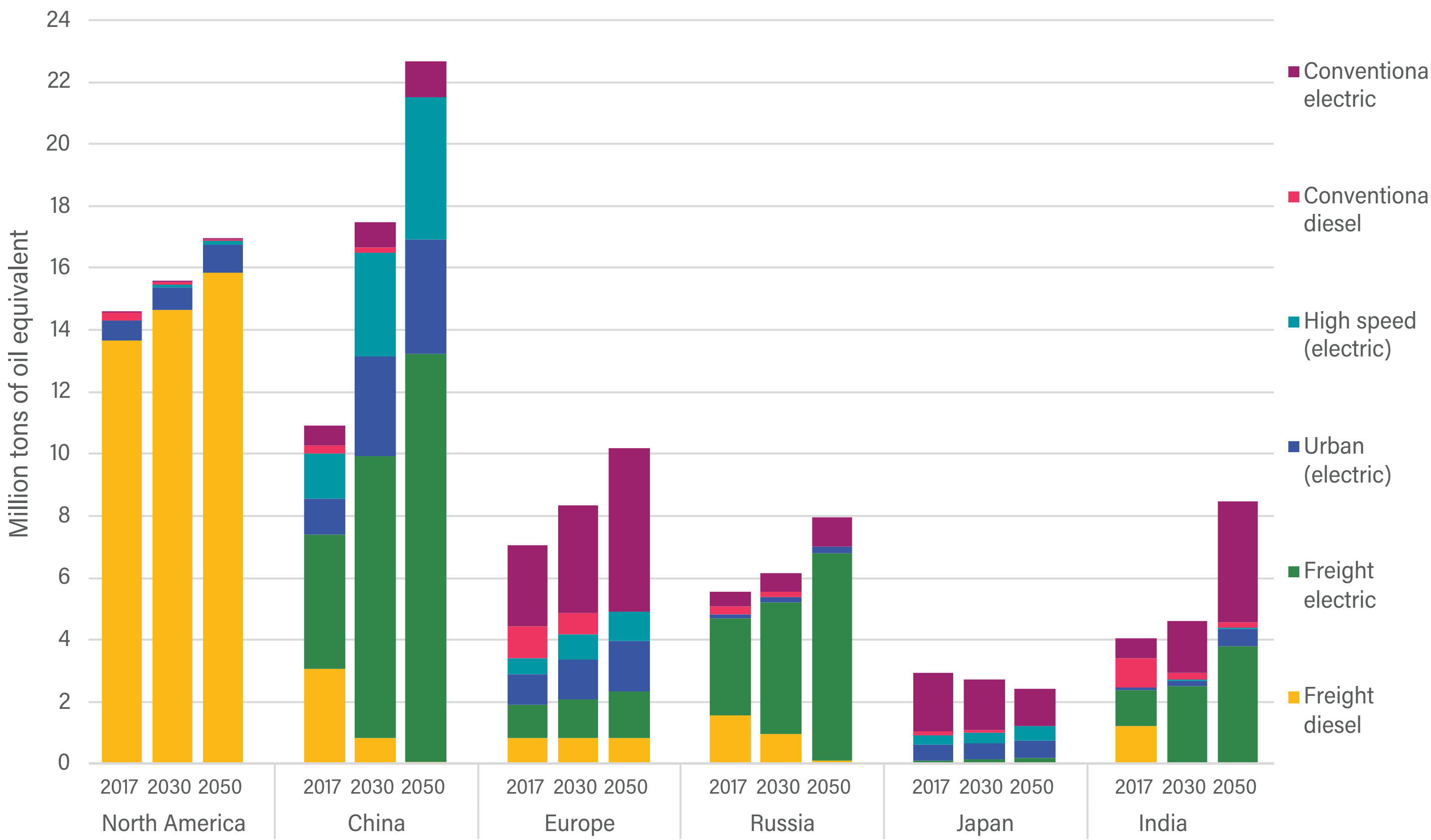
Figure 15 | **Variable Cost of Ownership for Freight Rail Locomotives**



Notes: O&M = operation and maintenance. The energy consumption assumed to be 174 kWh/train-kilometer for diesel, 162 kWh/train-kilometer for diesel hybrid, 52 kWh/train-kilometer for all-electric train, 56–60 kWh/train-kilometer for battery electric trains, and 79 kWh/train-kilometer for fuel cell hybrid train. Battery cost is assumed to be $250/kWh. Fuel cell cost is assumed to be $50/kW.

Source: IEA 2019c.

Figure 16 | **Fuel Mix Forecast for Rail Transport in the United States and Other Countries**



Notes: North America's continued reliance on diesel fuel for rail freight through 2050 as forecast by IEA is a result of the long-distance freight routes that characterize the region and the cost of electrification and alternative fuels such as hydrogen through 2050.

Source: IEA 2019c.

CONCLUSIONS

Clean hydrogen production must be prioritized in order for hydrogen to offer climate benefits over existing freight transportation fuel options. Leakage must be minimized in the production, distribution, and use phases in order to minimize GHG emissions and therefore maximize environmental benefits over conventional and alternative fuels and drivetrain technologies. When produced from zero- and low-carbon energy sources and feedstocks, hydrogen is a flexible, zero-carbon fuel that offers potential synergies between major demand sectors, especially when production and infrastructure are optimized for consumption by multiple sectors.

Competing demand from the industrial and energy sectors, however, will impose limitations on hydrogen's use as a fuel and fuel feedstock in freight transportation and in transportation in general. Industrial demand in the chemicals and steel industries, for example, has the potential to absorb projected clean hydrogen supply for decades, and renewable energy and electrolyzer supply and production costs will likely be a limiting factor in clean hydrogen production capacity in the near and mid-term.

In the long term, hydrogen has the potential to play a role in decarbonizing specific freight transportation segments either as a fuel directly or as a feedstock in the production of other clean fuels. Drop-in fuels such as biomass- and waste-derived fuels will offer near-term decarbonization opportunities in freight transportation, while hydrogen, ammonia, and methanol are expected to be cost-competitive with traditional fossil fuels and other low-carbon fuels beyond 2050.

Hydrogen supply chains, distribution, and storage are decades away from having a substantial impact on the freight transportation sector, with increasing impacts potentially coming in the second half of the century. As a complement to electrification, hydrogen can offer long-term decarbonization potential as fossil fuel use is phased out in the freight transport sector.

Technological advancements in hydrogen distribution and storage will lead to increased efficiency and therefore even greater environmental benefits over existing fossil fuel technologies and other low-carbon fuels. Hydrogen's flexibility—to be used as a feedstock, energy carrier, or directly as a fuel—could ease concerns about low future demand and drive scaled production and supply chain development.

ENDNOTES

1. See Ocko and Hamburg (2022) for a comprehensive review of estimates for future global hydrogen demand.

2. Also known as tractor trailers or semi-tractors in the United States.

3. Class 1 rail freight companies are defined as companies that earn more than approximately $500 million in revenue per year.

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ABOUT WRI

World Resources Institute is a global research organization that turns big ideas into action at the nexus of environment, economic opportunity, and human well-being.

Our challenge

Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our vision

We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our approach

COUNT IT

We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT

We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT

We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.