LOGISTICS IN TRANSITION

Exploring Geopolitical, Economic, and Technological Trends

edited by **Carlo Secchi** and **Alessandro Gili**

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Edited by Carlo Secchi and Alessandro Gili
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5. Harnessing Clean Hydrogen Mobility: Opportunities and Challenges

Nicola De Blasio

The global transition to a low-carbon economy and adopting the needed clean energy technologies at scale will significantly impact existing value chains[1] and transform production-to-consumption lifecycles. Regulatory and business models must rapidly evolve to manage the resulting substantial cost challenges and dramatic shifts in stakeholder interactions while continuing to create value.

While hydrogen has long been a staple in the energy and chemical sectors, the emergence of clean hydrogen[2] is poised to be a game-changer in the world's transition toward a carbon-free future. Its adoption at scale holds the key to decarbonizing energy-intensive industrial processes, such as steel and cement production, whose emissions are hard to abate.[3,4] However,

[1] Unlike the term supply chain, which is typically used to define a set of operational relationships designed to benefit a single stakeholder and deliver products or services, the term value chain refers to a more conceptual design of business relationships between stakeholders that support the development and adoption of a market or technology at scale.

[2] Clean hydrogen is defined as hydrogen produced either by renewable or nuclear power or by fossil fuels using carbon capture and storage (CCS).

[3] F. Pflugmann and N. De Blasio, "The Geopolitics of Renewable Hydrogen in Low-Carbon Energy Markets", *Geopolitics, History, and International Relations*, vol. 12, no. 1, 2020, pp. 9-44.

[4] L. Eicke and N. De Blasio, "Green hydrogen value chains in the industrial sector - Geopolitical and market implications", *Energy Research & Social Science*,

to take advantage of the associated economic opportunities, stakeholders must rethink their roles in a new energy landscape and define strategic industrial policies accordingly.

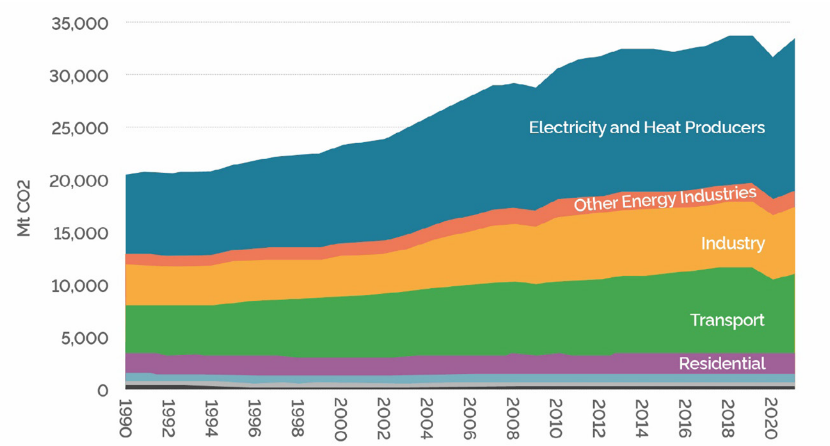
As both public and private stakeholders become increasingly committed to addressing climate change, they are also placing greater emphasis on the deep decarbonization of mobility in sectors such as aviation, shipping, rail, and long-distance road transportation. Areas were shifting to electricity as the preferred energy vector while decarbonizing its production may not be immediately feasible. At the same time, the adoption of clean hydrogen will depend on more than just its environmental benefits; economic, policy, technological, and safety factors must also be addressed.

Overall, transportation is the second-largest producer of global carbon dioxide (CO_2) emissions, after electricity and heat generation (see Figure 5.1),[5] and one of the most challenging sectors to decarbonize due to its distributed nature and the advantages provided by fossil fuels in terms of high energy densities, ease of transportation and storage. Greenhouse gas emissions from transportation primarily come from burning fossil fuel in cars, trucks, ships, trains, and planes. Globally, over 94% of transportation fuels (gasoline, diesel, and jet kerosene) are petroleum-based.

vol. 93, no. 102847, 2022.

[5] International Energy Agency (IEA), "Data & Statistics", 2023.

FIG. 5.1 - CO_2 EMISSIONS BY SECTOR, WORLD, 1990-2021



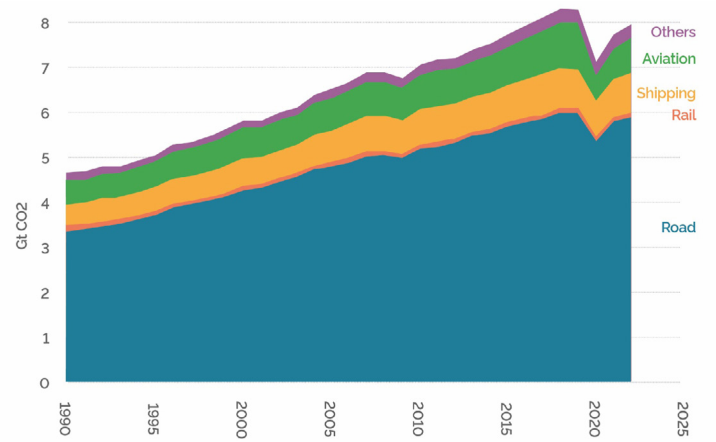
Source: IEA (2023)

According to the International Energy Agency (IEA), in 2022, global CO_2 emissions from transport grew by almost 3%, reaching 8 Giga tons (Gt) and nearly reaching pre-pandemic levels.[6] Aviation was responsible for much of this increase, as air travel rebounded from pandemic lows. See Figure 5.2 for a detailed analysis of global CO_2 emission from transport by segment.

It is key to note that while hydrogen holds significant promise for accelerating the overall decarbonization of mobility, its adoption will complement rather than compete with other decarbonization strategies. Figure 5.3 summarizes for which segments different technologies – battery electric vehicles (BEVs), hydrogen fuel cell electric vehicles (FCEVs), and vehicles running on bio- and/or synthetic fuels – are most applicable.

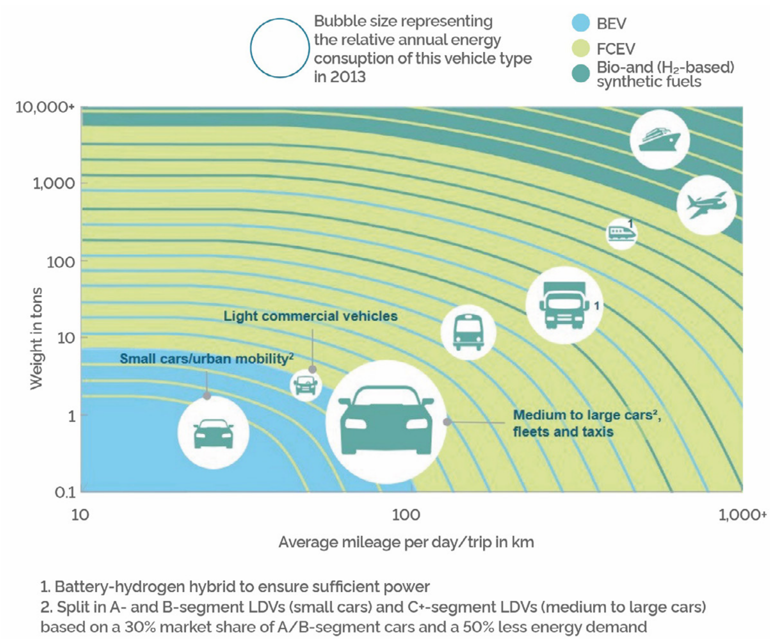
[6] IEA (2023), "Greenhouse Gas Emissions from Energy."

Fig. 5.2 - 2022 global CO_2 emissions from transport by segment



Source: IEA (2024) and author's elaboration

Fig.5.3 - Hydrogen applications in the mobility sector



Source: Hydrogen Council 2017

The Hydrogen Molecule. Production and Applications

Hydrogen is the most abundant element in the solar system but only occurs in compound form on Earth. Thus, hydrogen must be produced from molecules containing it through specific processes such as thermo-chemical conversion, biochemical conversion, or water electrolysis.

Annual global hydrogen production today stands at over 75 million tons (Mt) and stems almost entirely from natural gas (steam gas reforming) and coal (coal gasification).[7] Although hydrogen burns cleanly as a fuel at its point of use, producing it from fossil fuels without carbon capture and sequestration (CCS) simply relocates emissions. Hence, to reap hydrogen's full environmental benefits, it must be produced from zero-carbon electricity through water electrolysis, an electrochemical process that splits water into hydrogen and oxygen (green or renewable hydrogen).

Today, hydrogen is mainly used in petroleum refining and fertilizer production, while transportation and utilities are emerging markets. Yet, with growing emphasis on its decarbonization potential across sectors, hydrogen demand is projected to increase considerably in the coming decades. While recent reports vary in estimating demand by 2050, clean hydrogen could capture up to 14% of future global energy markets.

Overall, two factors will determine hydrogen's rate of adoption: competitiveness of production costs and deployment of enabling infrastructure at scale. Today, renewable hydrogen is two to three times more expensive than hydrogen produced from fossil fuels.[8] Although short-term production costs have risen significantly across the board, particularly for renewable

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[7] International Renewable Energy Agency (IRENA),"Energy Transition - Hydrogen", 2024.

[8] International Renewable Energy Agency (IRENA), "Making Green Hydrogen a Cost-Competitive Climate Solution", 2020.

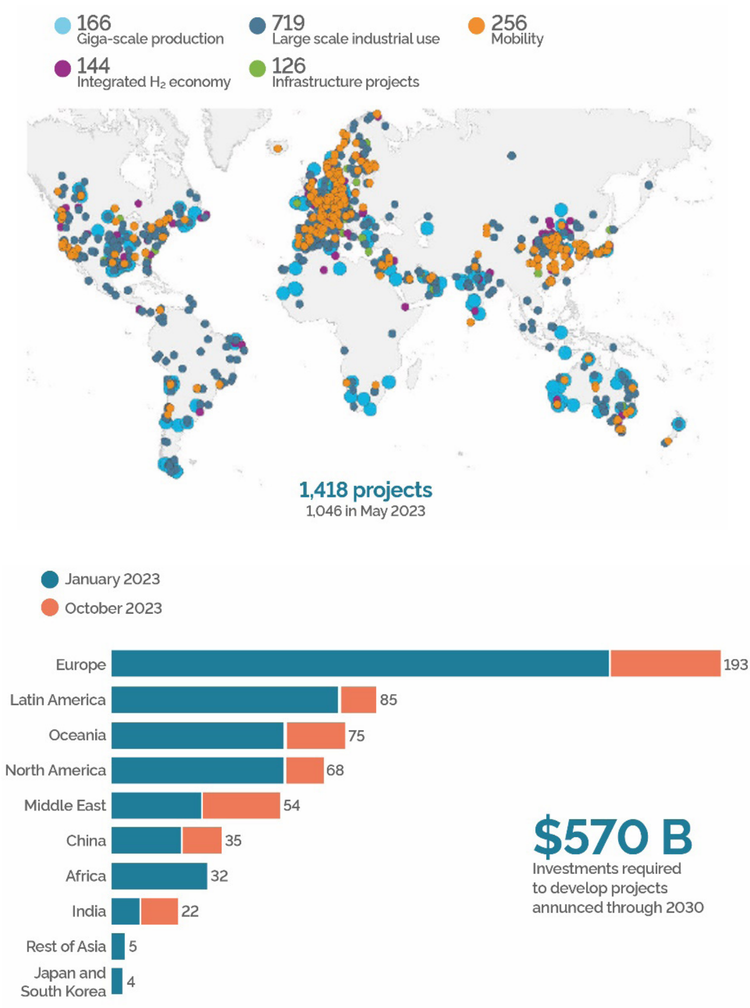
hydrogen, driven by higher capital, material, and labor costs, they are still expected to decline to 2.5 to 4.0 dollar per kilogram ($/Kg) by 2030, from today's 4.5 to 6.5 $/Kg.[9] This thanks to technology improvements, economies of scale, cost reductions along value chains, and carbon pricing policies.

Despite these challenges, the project pipeline is growing fast, with Europe, China, and North America leading the hydrogen race. As of October 2023, more than 1,400 projects had been announced globally, equating to $570 billion in investments (see Figure 5.4).

From a market perspective, clean hydrogen can be used in both stationary and mobility applications. As a readily dispatchable means of storing energy, hydrogen can help address growing intermittency and curtailment challenges associated with expanded renewable energy capacity. It can serve as a fuel in stationary systems for buildings, backup power, distributed generation, or for high-temperature industrial heat. As discussed, hydrogen could become a key sustainable energy carrier in mobility applications – whether by powering fuel-cell electric vehicles such as hydrogen cars, trucks, and trains or as a feedstock for synthetic fuels for ships and planes. It can also complement ongoing efforts to electrify road and rail transportation and provide a scalable option to decarbonize the shipping and aviation segments.

[9] Hydrogen Council and McKinsey, *Hydrogen Insights*, 2023.

Fig. 5.4 - Hydrogen momentum



Source: Hydrogen Insights (2023)

Hydrogen-powered vehicles offer key advantages, including shorter refueling times, longer ranges, and a lower material footprint than lithium battery-powered electric vehicles. However, high total costs of ownership and lack of enabling infrastructure are key challenges. Therefore, realizing the promise of hydrogen as a sustainable mobility energy carrier will require robust policy support, technological innovation, and committed investment.

Technology Focus - Hydrogen Fuel Cells and Electrolysis

Fuel cells convert hydrogen-rich fuels into electricity through a chemical reaction, with water and heat as the only by-products. A fuel cell consists of an anode, a cathode, and an electrolyte membrane. The stored hydrogen passes through the anode, where it is split into electrons and protons. Electrons pass through an external circuit, generating electric power, which can be fed directly to a vehicle's electric motor or stored in batteries. Protons pass through the membrane to reach the cathode, combining electrons and oxygen to produce water molecules.

Fuel cells offer a unique and wide range of potential applications: they can power systems as small as a laptop computer or as large as a utility power station. They can also replace internal combustion engines (ICE) in mobility applications. FCEVs use a fuel cell, rather than a battery, to power electric motors. FCEVs are a zero-emissions alternative to conventional ICE and BEVs, which use lithium-ion batteries to store electrical energy produced outside the vehicle. Hydrogen FCEVs operate near-silently since they have no moving parts and produce no tailpipe emissions. However, while clean-burning by itself, as discussed, hydrogen must be produced from renewable or nuclear energy to harness its full environmental benefits.

Electrolysis refers to the production of hydrogen and oxygen using electricity to split water, which can be thought of as the reverse process of a fuel cell. The reaction occurs within an electrolyzer unit, which can range from small appliance-sized equipment well-suited for distributed hydrogen production to large-scale, central production facilities connected directly to renewable or other zero-carbon electricity sources. Like fuel cells, electrolyzers consist of an anode and a cathode separated by an electrolyte membrane.[10]

Road Transportation

Road vehicles account for about 74% of transportation-specific emissions (Figure 5.2). In 2022, private cars and vans were responsible for more than 25% of global oil use and around 10% of global energy-related CO_2 emissions. Efforts to decarbonize the sector have thus far focused mainly on electrification (BEVs), accompanied by technologies to improve the fuel economy of ICEs. However, the rise of heavier and less efficient vehicles like SUVs continues to slow progress. Yet hydrogen-powered FCEVs offer substantial promise.

FCEVs have significant advantages over BEVs in terms of refueling times and driving ranges. Refueling times are much shorter; filling current models takes between three and five minutes and closely resembles the experience with a conventional vehicle.[11,12] In contrast, recharging a BEV can take anywhere from 20 minutes to 12 hours, depending on the battery size, charger capacity, and depth of charge.[13] Driving ranges vary but tend to be similar to those of conventional vehicles (400-600 km).[14] Fuel cells also provide higher energy

[10] N. De Blasio and F. Pflugmann, "Is China's Hydrogen Economy Coming? A Game-Changing Opportunity", Harvard University, Belfer Center for Science and International Affairs, 2020.

[11] California Air Resources Board, "Hydrogen Fueling", 2024.

[12] Department of Energy (DOE), "Alternative Fuels Data Center – Hydrogen Basics", 2020.

[13] US Environmental Protection Agency (EPA), "Green Vehicles Charging", 2024.

[14] J. Kurtz, S. Sprik et al., "Fuel Cell Electric Vehicle Driving and Fueling

densities, lower weights, and a lower material footprint than lithium batteries.[15,16] Given these benefits, FCEVs are ideally suited for end users who require low downtimes, drive long distances, and carry heavy loads, such as taxis, buses, trucks, and heavy-duty vehicles.[17]

However, widespread adoption of FCEVs is more challenging than it might seem; otherwise, they would dominate battery-powered and conventional vehicles globally. Significant issues hindering deployment at scale need to be addressed.

First, fuel cells are more expensive than comparable-sized light-duty conventional vehicles, even if leasing packages often include fuel, service, and maintenance, making the total costs of ownership relatively similar. For heavy-duty trucks, analysts foresee that hydrogen could become competitive with diesel by 2030.[18]

Second, the lack of enabling infrastructure remains a key barrier. Although hydrogen refueling infrastructure deployment continues to accelerate in China and South Korea, only about 1,100 hydrogen refueling stations are operational globally, compared to over 2.7 million public charging points worldwide.[19] Building a hydrogen fueling station currently costs between $1.5 and $2 million,[20] while an ultra-fast-charging electric vehicle station with a single 150 to 350 kW charger can cost between $85,000 and $250,000.[21] These investments are

Behavior", National Renewable Energy Laboratory (NREL), 2019.

[15] The Fuel Cell and Hydrogen Energy Association, "Roadmap to a US Hydrogen Economy", 2020.

[16] Department of Energy (DOE) (2024) "Fuel Cell Vehicles"

[17] J. Jones, A. Genovese, and A. Tob-Ogu, "Hydrogen vehicles in urban logistics: A total cost of ownership analysis and some policy implications", *Renew Sustain Energy Rev*, vol. 119, 2020.

[18] S&P Global, "Hydrogen fuel cells to compete with diesel truck engines by 2030", 2021.

[19] International Energy Agency (IEA) "Global EV Outlook 2023", 2023.

[20] Department of Energy (DOE), "Hydrogen Fueling Stations Cost", 2021.

[21] McKinsey Center for Future Mobility, "Can public EV-fast charging stations be profitable in the United States?", 2023.

significant, particularly with very few vehicles operating, yet a lack of refueling infrastructure is often cited as the key obstacle to the widespread adoption of FCEVs. Regardless, stakeholders around the globe are increasingly recognizing hydrogen's promise for the sector. Unsurprisingly, the sales of FCEVs correlate geographically with the deployment of hydrogen refueling infrastructure. South Korea leads in the light-duty sector (about 50% of the current fleet), while China leads in the global heavy-duty truck and bus markets with about 80% and 90%, respectively.

From a value chain perspective, FCEVs will complement, rather than compete with, BEVs. They will be key in the decarbonization of heavy-duty, long-distance applications, starting with captive fleets that require quick refueling and high uptimes. Government support and public-private partnerships will be key to accelerating innovation cycles and the deployment of enabling infrastructure at scale.

Next Stop - Hydrogen Trains

Rail is one of the most energy-efficient and clean transport modes. Trains carry about 7% of global motorized passengers and 6% of freight while accounting for about 1% of the overall transportation sector's CO_2 emissions. As a reference, on a well-to-wheels basis,[22] rail emissions per passenger average around one-fifth of those of air travel.[23]

As old diesel trains are phased out of rail networks, hydrogen could become the answer to the sector's complete decarbonization. Compared to other low-carbon alternatives, such as electric trains, hydrogen offers greater flexibility and affordability, particularly over long distances and in rural areas.

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[22] Well-to-wheel emissions refer to all fuel production, processing, distribution, and use emissions. Using gasoline as an example, emissions are produced during oil extraction, refining, distribution to gasoline stations, and burning in vehicles.

[23] International Energy Agency (IEA), "Transport – Rail", 2024.

Decarbonizing rail systems remains difficult, nevertheless. In many countries, diesel trains still dominate. In 2021, among EU-27 countries,[24] nearly 44 % of rail lines were still diesel-powered,[25] compared to the near totality of freight and passenger rail locomotives in the US.[26] So far, electrification has been the preferred decarbonization option, but interest in hydrogen alternatives is rising. Hydrogen-powered trains have been in service in Germany since 2018, and pilot tests have been completed in Austria, the Netherlands, and Sweden.[27] In 2023, France ordered twelve hydrogen trains to begin commercial operations by 2025,[28] and Italy allocated €300 million to new hydrogen trains and associated green hydrogen projects.[29] In February 2024, California announced a $127 million investment to double its hydrogen-powered passenger train fleet.[30] It is important to note that while, so far, advanced economies have driven most hydrogen rail projects, developing economies have also recently started to invest. Notably, India has announced a pilot project to produce hydrogen trains in Chennai.[31]

Cost is a key motivation for adoption. Hydrogen trains reduce emissions at a significantly lower cost than track electrification. While a new Alstom hydrogen-powered train can cost up to

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[24] Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, and Sweden.

[25] Statista Research Department "Share of the rail network which was electrified in Europe by 2021, by country", 2024.

[26] Department of Energy (DOE), "The U.S. National Blueprint for Transportation Decarbonization", 2023.

[27] Alstom, "Alstom's Coradia iLint hydrogen train runs for the first time in France", 2022.

[28] SNCF Group, "The First Hydrogen Trains to Circulate in 2025", 2023.

[29] "Italy allocates €300m to new hydrogen trains and associated green H2 projects", *Hydrogen Insight*, 2023.

[30] "California Continues to Expand Hydrogen-Powered Passenger Rail Fleet", *Caltrans*, 2024.

[31] "Indian Railways' Hydrogen-Powered Train Project", *Financial Express*, 2024.

$11 million,[32] an analysis of twenty railway lines in the UK and mainland Europe showed that the electrification of a single kilometer of track could cost upwards of $1 million.[33] Even if hydrogen locomotives require their own refueling and servicing infrastructure, costs will likely remain competitive because there is no need for track overhauls. This makes hydrogen trains particularly valuable in rural areas, where fewer passengers tend to travel longer distances.[34]

Another significant advantage of hydrogen-powered alternatives is their potential to serve as bi-mode trains, running on both electrified and conventional lines. This option makes hydrogen trains a flexible alternative for decarbonizing the sector, while most tracks are not yet electrified. In addition, hydrogen trains are more resilient to network-wide disruptions, as a shared electric infrastructure means that any damage would impact all electric trains running on a given line. A hydrogen train could simply switch to its fuel cell to produce electricity. Yet, hydrogen rail systems have challenges.

Deploying the required infrastructure and hydrogen's lower volumetric energy density than diesel pose substantial barriers. Since freight is heavier than passenger transportation, hydrogen trains will require more fuel than diesel trains to serve the same routes. Therefore, innovation in more efficient ways to compress and store hydrogen will be needed to improve economics and scalability.

Shipping

Despite being one of the most efficient forms of freight transport, shipping remains a challenge for decarbonization

[32] Alstom, "Alstom to supply Italy's first hydrogen trains", Press Release, 2020.

[33] Railway Industry Association, "RIA Electrification Cost Challenge", 2019.

[34] F. Zenith, R. Isaac, A. Hoffrichter, M. Thomassen, and S. Møller-Holst, "Techno-economic analysis of freight railway electrification by overhead line, hydrogen and batteries", *J Rail and Rapid Transit*, vol. 234, no. 7, 2020, pp. 791-802.

efforts. In 2022, the sector accounted for about 2% of global and about 11% of transportation-related CO_2 emissions, and it has in place a revised (now in line with the Paris Agreement) self-imposed goal of reducing emissions by 40% by 2030 from 2008 levels and be net-zero by 2050.[35]

Thus far, electrification has been the preferred decarbonization option. Battery-operated ships are already replacing vessels running on marine diesel oil (MDO) for short-distance operations like ferries.[36] But complete electrification remains a problematic value proposition due to the volume cargo operators would lose to store enough energy for long-distance shipping. Large ships crossing oceans would simply need too many batteries. Hence, low-carbon fuels with high energy densities, such as hydrogen and ammonia, are expected to play a key role in the industry moving forward. On an energy content parity, while batteries require 64 times more volume than MDO, hydrogen and ammonia only need 8 and 3 times more, respectively.[37]

Ammonia, a hydrogen-based molecule, is a fuel that can either be combusted in an engine or used in a fuel cell. Liquid ammonia not only packs twice as much energy per volume as hydrogen but is also far easier to store because it needs simple refrigeration (-35°C) and not the cryogenic temperatures of hydrogen (-253°C). Furthermore, ammonia could be converted back to hydrogen directly onboard, allowing operators to load and store ammonia but ultimately use it in a hydrogen fuel cell. However, ammonia is toxic to both humans and marine life; hence, safety and environmental hazards need careful evaluation and consideration.

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[35] International Maritime Organization, "2023 IMO Strategy on Reduction of GHG Emissions from Ships", 2023.

[36] Bastø Fosen, "The world's largest electric car ferry on the Oslo Fjord", 2021.

[37] Amplifier, ETH Zürich, SUS Lab Sustainability in Business Lab, "Towards Net- Zero: Innovating for a Carbon-free Future of Shipping in the North and Baltic Sea. DEEP-DIVE: Comparison of zero-carbon fuels", October 2019.

Costs are critical as hydrogen-based fuels are still more expensive than conventional ones. Due to the added conversion steps, costs are even more significant in the case of ammonia. Although orders for new ships are starting to show a trend toward alternative fuels – in 2022, 90 (11% by tonnage) new-build orders were for ammonia-ready vessels, and three for hydrogen-ready vessels.[38] Robust global hydrogen and ammonia networks to ensure that ships can refuel at any port will be key for the sector's transition to a low-carbon economy. Policymakers must support innovation, deployment of enabling infrastructure, and the definition of appropriate safety standards and regulations.

To date, over 160 companies have joined forces in the Getting to Zero Coalition, which aims to achieve commercially viable zero-emission shipping by 2030 and full decarbonization by 2050.[39] According to the International Council on Clean Transportation, liquid hydrogen could fuel up to 99% of existing interoceanic routes between China and the United States with the addition of a single refueling stop.[40] As of 2022, more than 203 zero-emission shipping pilot projects had been demonstrated worldwide, up from 106 and 66 in 2021 and 2020, respectively.[41]

Hydrogen Powered Skies

As international travel demand recovers after the Covid-19 pandemic, aviation emissions reached about 80% of their pre-pandemic peak. In 2022, aviation accounted for 2% of global energy-related CO_2 emissions and 11% of transportation-related CO_2 emissions. However, these seemingly small numbers

[38] Clarkson Research (2023) "Green Technology Tracker: January 2023."

[39] International Maritime Forum (2024) "Getting to Zero Coalition."

[40] The International Council on Clean Transportation, "Liquid Hydrogen Refueling Infrastructure to Support a Zero-Emission U.S.–China Container Shipping Corridor", 2021.

[41] Global Maritime Forum, "Mapping of zero-emission pilots and demonstration projects", 2022.

should not be dismissed since the sector's overall contribution to global warming is significantly higher due to emissions other than CO_2, like nitrogen oxides and soot. The sector needs scalable decarbonization pathways to reach net-zero emissions by 2050 in an environmentally and economically sustainable manner. Efficiency improvements have not been able to keep up with demand, which grew at an average rate of over 5% annually between 2010 and 2019. Sustainable aviation fuels (SAF), including hydrogen, are poised to play a key role in this transition. Currently, though, jet kerosene dominates fuel demand, while SAFs account for less than 0.1%.[42]

The advantages of hydrogen as an aviation fuel have been well-known for decades. Thanks to an energy density by mass three times higher than traditional jet fuel, liquid hydrogen has been the signature fuel for the American space program since the late 1950s. As a more scalable alternative to battery-powered aviation concepts, which present significant challenges, especially for larger aircraft applications due to energy density and safety considerations, hydrogen is now emerging as a significant component of commercial flights' future technology mix. Hydrogen can be used via direct combustion in jet engines or in fuel cells to generate electricity for electric motors or a combination of the two.

However, the road to hydrogen-powered aircrafts remains to be determined, and significant efforts will undoubtedly be required by all stakeholders to further invest in enabling technologies and overall value chains. From an innovation perspective, the aviation industry will need to borrow technologies developed for the automotive and space sectors and apply them to commercial aircraft operations, notably by reducing weight and costs. One specific challenge will be how and where to store hydrogen onboard aircrafts while achieving similar or better safety targets than existing ones. Beyond the technical aspects, this will require hydrogen-specific safety

[42] International Energy Agency (IEA), "Transport – Aviation", 2024.

and regulatory standards that currently do not exist. Adopting hydrogen at scale will also hinge on robust hydrogen-fueling infrastructure networks. While this challenge is daunting due to the high fuel demand associated with airport operations, hydrogen could also be produced directly onsite, eliminating distribution costs.

In 2023, the first test flights using fuel cell-powered electric motors took place. ZeroAvia flew a 19-seat aircraft with a hydrogen-electric engine on its left wing,[43] while Universal Hydrogen flew a 40-seat regional airliner with a fuel cell powering one of the engines.[44] In parallel, assessments of alternative propulsion systems have been conducted. Rolls-Royce and easyJet have performed a ground test combusting green hydrogen in a regional jet engine.[45] Airbus has also designed and produced the first cryogenic liquid hydrogen tank prototype.[46]

From a policy perspective, greater incentives for low-carbon aviation fuels, support for developing and deploying enabling technologies and infrastructure, and harmonizing safety standards and regulations will be key to decarbonizing aviation. Yet, due to very long aircraft development and certification lead times, these challenges demand urgent answers from industry leaders and policymakers, who must keep up to date on the opportunities and barriers facing hydrogen-powered aviation, including public perception concerns.

[43] ZeroAvia, "ZeroAvia Makes Aviation History, Flying World's Largest Aircraft Powered with a Hydrogen-Electric Engine", 2023.

[44] Universal Hydrogen, "Universal Hydrogen Successfully Completes First Flight of Hydrogen Regional Airliner", 2023.

[45] Rolls-Royce, "Rolls-Royce and easyJet set new world first", 2022

[46] Airbus, "The cold heart that powers our ZEROe aircraft", 2022.

Conclusion

Hydrogen must overcome significant barriers, mainly related to storage, infrastructure, and costs, before becoming a game changer in transportation.

In road transportation, competitiveness will depend on overall costs of ownership and availability of refueling infrastructure. Key advantages include short refueling times, lower added weight for stored energy, and zero tailpipe emissions. Fuel cells also show promise thanks to their lower material footprint than lithium batteries. Long-distance and heavy-duty segments offer the greatest potential, but investments are required to lower the delivered price of hydrogen. Captive fleets can help to overcome the challenges of low utilization of refueling stations and spearhead the adoption of hydrogen.

In the rail sector, hydrogen trains could be most competitive in rail freight and rural/regional lines where long distances and low network utilization do not justify the high costs associated with track electrification. Hydrogen trains also hold promise due to flexible bi-mode operations.

Shipping and aviation have limited low-carbon fuel options, representing a significant opportunity for hydrogen-based fuels. In maritime applications, hydrogen and ammonia can overcome the limitations of battery ships and provide a route for meeting national environmental ambitions and the sector's emission reduction targets. However, high costs compared to fossil fuels, the challenge of cargo volume loss due to fuel storage, and the deployment of global refueling networks need to be addressed.

In the aviation sector, drop-in synthetic liquid fuels provide an attractive decarbonization option at the expense of higher energy consumption and costs. Direct hydrogen use also shows promise. However, the sector will need to borrow technologies developed for the automotive and space industries and apply them to commercial aircraft operations while achieving similar or better safety targets.

Innovation will be crucial to reducing costs and improving the performance of electrolyzers, fuel cells, and hydrogen-based fuels. Progress is needed to address technological challenges around weight and hydrogen storage, particularly in the maritime and aviation sectors.

From a policy perspective, adoption at scale will require to:

- Establish a role for hydrogen in long-term domestic and international energy strategies, considering geopolitical and market implications.
- Implement policy support through low-carbon targets and carbon pricing measures to stimulate commercial demand for clean hydrogen.
- Address investment risks, especially for first movers, such as targeted and time-limited loans and guarantees.
- Focus on new hydrogen applications, clean hydrogen supply, and infrastructure projects.
- Support research and development efforts and public-private partnerships to accelerate innovation cycles.
- Harmonize standards and eliminate unnecessary regulatory barriers while developing certification systems and regulations for carbon-free hydrogen supply.

To date, technological factors, economic considerations, and consumer choices have hindered the adoption of hydrogen at scale in the transportation sector. New geopolitical forces – such as the challenges of sustainable development and climate change – are reshaping the playing field. Stakeholders around the world will need to decide their role in this transition.