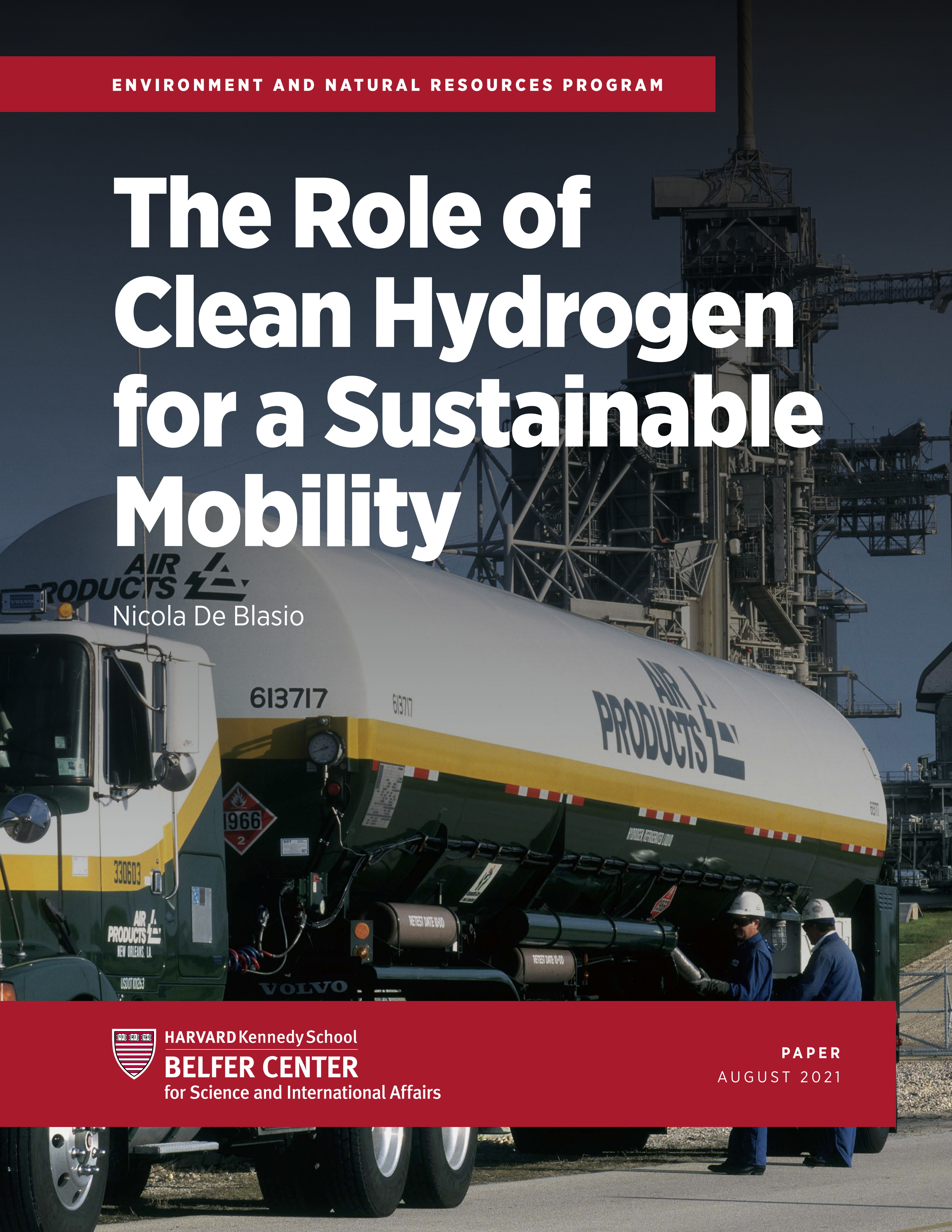
ENVIRONMENT AND NATURAL RESOURCES PROGRAM

The Role of Clean Hydrogen for a Sustainable Mobility

Nicola De Blasio



HARVARD Kennedy School
BELFER CENTER
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About the Author

Dr. **Nicola De Blasio** is a Senior Fellow at the Belfer Center, leading research on energy technology innovation and the transition to a low-carbon economy. With more than 25 years of global experience in the energy sector, Dr. De Blasio is an expert in navigating the challenges of strategic development and technology innovation toward sustainable commercial success, at scale. This coupled with his insight on the impact of an institution's development and innovation activities on other facets of business strategy, such as environmental, social, operational, geopolitical, and governmental factors.

Dr. De Blasio spent 17 years at Eni, one of the world's leading energy companies, most recently as Vice President and Head of R&D International Development. Prior to joining Harvard, Dr. De Blasio was Senior Research Scholar in the faculty of SIPA at Columbia University and Program Director Technology and Innovation at the Center on Global Energy Policy, where he was also Director of Strategic Partnerships. Dr. De Blasio holds a degree in Chemical Engineering from the Politecnico of Milan University with a thesis in industrial catalysis. He specialized at St. Andrews University, Scotland and then at Eni Corporate University, where he focused on energy economics. He is co-author of the book Value of Innovation, and has extensively published and lectured on energy, innovation, project evaluation and catalysis.

About the Program

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A tanker truck delivers liquid hydrogen to NASA's Kennedy Space Center, September 1997.

U.S. Dept. of Energy

Introduction

Hydrogen and energy have a long-shared history. Although there have been false starts in the past, this time around, hydrogen is capturing unprecedented political and business momentum as a versatile and sustainable energy carrier that could be the missing piece in the carbon-free energy puzzle. Clean hydrogen produced from zero-carbon energy sources, such as renewable (green hydrogen) and nuclear power (pink hydrogen),[1] appears ever more likely to play a prominent role in the global transition to a low-carbon economy.[2]

As governments and corporations become increasingly committed to addressing climate change and reducing emissions, they are placing greater emphasis on the deep decarbonization of energy-intensive "hard-to-abate" sectors, such as iron and steel production, high-temperature industrial heat, aviation, shipping, railway, and long-distance road transportation. These are areas where shifting to electricity as the preferred energy vector while decarbonizing its production may not be immediately feasible. At the same time, adoption of clean hydrogen at scale will depend on more than just its environmental benefits; economic, policy, technological, and safety factors must also be addressed.

This paper analyzes clean hydrogen's potential for driving emissions reductions in the mobility sector, focusing on road transportation, shipping, rail, and aviation. Overall, transportation is the second-largest producer of global CO_2 emissions, after electricity and heat generation,[3] and one of the hardest 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.

1 Green hydrogen: produced through electrolysis using renewable electricity. Pink hydrogen: produced like green hydrogen but solely using electricity from nuclear power.

2 Pflugmann, F., and De Blasio, N. (2020), "The Geopolitics of Renewable Hydrogen in Low-Carbon Energy Markets" Geopolitics, History, and International Relations 12(1): 9–44. doi:10.22381/GHIR12120201.

3 IEA (2021), "Data & Statistics" https://www.iea.org/data-and-statistics?country=WORLD&fuel=Energy%20supply&indicator=TPESbySource, accessed March 2021.

Figure 1 summarizes for which mobility segments BEVs (battery electric vehicles), FCEVs (fuel cell electric vehicles), and vehicles running on bio- and/or synthetic fuels are most applicable.

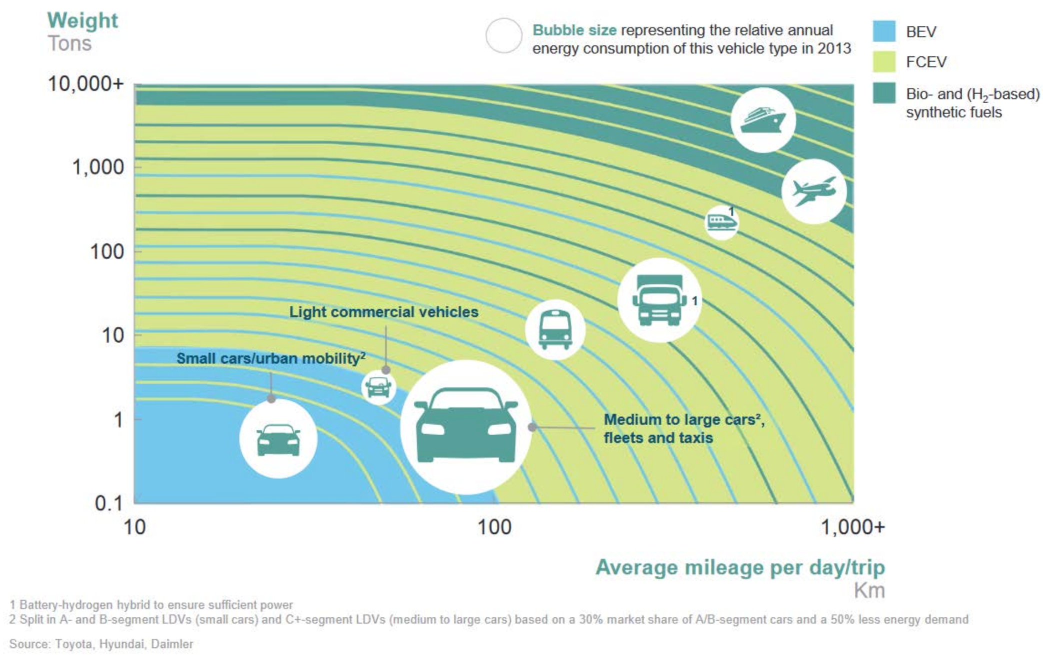

Figure 1. Hydrogen applications in the mobility sector.
Source: Hydrogen Council (2017)

The Hydrogen Molecule: Production and Applications

Hydrogen is the most abundant element in the solar system, but on Earth it only occurs in compound form. 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 about 75 million tons (Mt) or 10 exajoules (EJ)[4] and stems almost entirely from natural gas (steam gas reforming) and coal (coal gasification).[5] Although hydrogen burns cleanly as a fuel at its point of use, producing it from fossil fuels without carbon capture simply relocates emissions. Hence, to reap hydrogen's full environmental benefits, it must be produced from zerocarbon electricity through water electrolysis, an electrochemical process that splits water into hydrogen and oxygen. Currently, however, water electrolysis accounts for less than 0.1% of global hydrogen production.[6]

Overall, two factors will determine hydrogen's rate of global growth: competitiveness of production costs and deployment of enabling infrastructure at scale. Today, green hydrogen is two to three times more expensive than hydrogen produced from fossil fuels.[7] However, thanks to innovation, economies of scale, and carbon pricing policies, these costs are expected to decrease.

Hydrogen is mainly used in oil refining and the production of ammonia, fertilizers, methanol, and steel. Yet, with growing emphasis on its decarbonization potential across sectors, hydrogen demand is projected to increase considerably in the coming decades. Estimates on annual global demand by 2050 vary significantly among scenarios. The 2017 Hydrogen Council study estimates demand at approximately 78 EJ or around 14% of projected total global energy demand. Studies by BloombergNEF (2019),

4 IEA (2020), "Energy Technology Perspectives 2020."

5 IEA (2019), "The Future of Hydrogen."

6 Ibid.

7 IRENA (2020), "Making Green Hydrogen a Cost-Competitive Climate Solution." https://www.irena.org/newsroom/pressreleases/2020/Dec/Making-Green-Hydrogen-a-Cost-Competitive-Climate-Solution, accessed April 2021.

DNV (2018), and IEA (2020) are more conservative, with estimates between 5 and 40 EJ.

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. In mobility applications, hydrogen could become an essential energy carrier for sustainable transportation. 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, hydrogen can complement ongoing efforts to electrify road and rail transportation and provide a scalable option to decarbonize the shipping and aviation segments.

Hydrogen-powered vehicles offer key advantages, including shorter refueling times, longer ranges, and a lower material footprint compared to lithium battery-powered electric vehicles. However, high total costs of ownership and lack of enabling infrastructure are key challenges. Realizing the promise of hydrogen as a sustainable mobility energy carrier will therefore 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 byproducts. 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, where they combine with 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 and can 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 not only conventional ICE vehicles but also 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, hydrogen must be produced from renewable or nuclear energy to harness the full environmental benefits.

Electrolysis refers to the production of hydrogen and oxygen using electricity to split water and can be thought of as the reverse process of a fuel cell. The reaction takes place within a unit called electrolyzer, which can range from small appliance-sized equipment well-suited for distributed hydrogen production to large-scale, central production facilities that can be 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.

Road Transportation

Road vehicles account for about 20% of global CO_2 emissions from energy and 75% of transportation specific emissions.[8] Thus far, efforts to decarbonize the sector have focused mainly on BEVs for the light-duty segment. Yet hydrogen-powered FCEVs also 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 less than five minutes and closely resembles the experience with a conventional vehicle.[9] [10] 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.[11] Driving ranges vary but tend to be similar to those of conventional vehicles (400-600 km).[12] Fuel cells also provide higher energy densities, lower weights and a lower material footprint than lithium batteries.[13] 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.[14]

However, widespread adoption of FCEVs is not as easy as it might seem; otherwise, they would already dominate battery-powered and ICE vehicles globally. There are significant issues hindering deployment at scale which need to be addressed.

8 IEA (2019), "Transport sector CO2 emissions by mode in the Sustainable Development Scenario, 2000-2030" https://www.iea.org/data-and-statistics/charts/transport-sector-co2-emissions-by-mode-in-the-sustainable-development-scenario-2000-2030, accessed March 2021.

9 U.S. Department of Energy (2020), "Alternative Fuels Data Center – Hydrogen Basics" https://afdc.energy.gov/fuels/hydrogen_basics.html#fueling-times, accessed March 2021.

10 De Blasio, N., and Pflugmann, F. (2020), "Is China's Hydrogen Economy Coming? A Game-Changing Opportunity" Harvard University, Belfer Center.

11 U.S. Department of Energy (2020), "Vehicle Charging" https://www.energy.gov/eere/electricvehicles/vehicle-charging, accessed March 2021.

12 Kurtz, J., Sprik, S., Saur, G, and Onorato, S. (2019), "Fuel Cell Electric Vehicle Driving and Fueling Behavior" National Renewable Energy Laboratory https://www.nrel.gov/docs/fy19osti/73010.pdf, accessed March 2021.

13 The Fuel Cell and Hydrogen Energy Association (2020), "Roadmap to a US Hydrogen Economy."

14 Jones, J., Genovese, A., and Tob-Ogu, A. (2020), "Hydrogen vehicles in urban logistics: A total cost of ownership analysis and some policy implications" Renew Sustain Energy Rev, 119, https://doi.org/10.1016/j.rser.2019.109595.

First, fuel cells are more expensive than batteries and ICEs and, hence, less competitive due to higher total costs of vehicle ownership. Looking forward, for applications requiring fast fueling and high uptimes, analysts foresee light-duty FCEVs costs to be on par with those of conventional vehicles as soon as 2025.[15] For heavy-duty trucks, hydrogen could become competitive with diesel by 2031.[16]

Second, lack of enabling infrastructure remains a key barrier. Today, there are fewer than 1,000 hydrogen refueling stations globally, compared to over 500,000 charge points for BEVs.[17] Furthermore, building a hydrogen fueling station currently costs between US$ 1 and US$ 2 million,[18] compared to an estimated US$ 200,000 for an ultra-fast-charging electric vehicle station with a single 350-kW charger.[19] Such investments are significant, particularly with so few vehicles operating; yet, a lack of refueling infrastructure is often cited as the key obstacle to widespread adoption of FCEVs. Regardless, stakeholders around the globe increasingly recognize hydrogen's promise for the sector, and China alone plans to invest US$ 17 billion in the FCEV industry through 2023.[20]

From a value chain perspective, FCEVs will complement rather than compete with BEVs and 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 accelerate innovation cycles and the deployment of enabling infrastructure at scale.

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15 BNEF (2020), "Hydrogen Economy Outlook."

16 Ibid.

17 IEA (2019), "The Future of Hydrogen."

18 The International Council on Clean Transportation (2017), "Developing hydrogen fueling infrastructure for fuel cell vehicles."

19 Schreffler, R. (2019), "Costs Check Growth of Fuel-Cell Infrastructure" https://www.wardsauto.com/technology/costs-check-growth-fuel-cell-infrastructure, accessed April 2021.

20 Bloomberg (2019), "China's Hydrogen Vehicle Dream Chased With $17 Billion of Funding" https://www.bloomberg.com/news/articles/2019-06-27/china-s-hydrogen-vehicle-dream-chased-by-17-billion-of-funding?sref=ubpFo2VP, accessed April 2021.

Next Stop: Hydrogen Trains

Rail is one of the most energy-efficient and clean transport modes. Trains carry about 9% of global motorized passengers and 7% of freight while accounting for only 3% of energy demand and 1% of CO_2 emissions of the overall transportation sector.[21]

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

Decarbonizing rail systems remains difficult, nevertheless. In many countries, diesel trains still dominate. In 2018, among EU-28 countries,[22] nearly half of rail lines were still diesel-powered,[23] compared to the near totality of 26,000 freight and 431 passenger rail locomotives in the US.[24] So far, electrification has been the preferred option to decarbonize rail systems, but interest in hydrogen alternatives is rising, with over 22 demonstration projects across 14 countries[25] and a growing number of hydrogen train purchases.[26]

Cost is a key motivation. Hydrogen trains reduce emissions at a significantly lower cost than track electrification. While a new Alstom hydrogen-powered train can cost up to US$ 11 million,[27] an analysis of 20 railway lines in the UK and mainland Europe shows that the electrification

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21 IEA (2020), "Tracking Transport 2020."

22 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, United Kingdom (fmr member state).

23 Statista Research Department (2020), "Share of the rail network which was electrified in Europe by 2018, by country" https://www.statista.com/statistics/451522/share-of-the-rail-network-which-is-electrified-in-europe/ accessed April 2021.

24 U.S. Bureau of transportation Statistics (2021), "Rail Profile" https://www.bts.gov/content/rail-profile, accessed April 2021.

25 Joint Fuel Cell and Hydrogen Undertaking (2019), "Study on the use of fuel cells and hydrogen in the railway environment" https://shift2rail.org/wp-content/uploads/2019/04/Report-1.pdf, accessed April 2021.

26 Clemens, M. (2021), "Bourgogne-France-Comté opens the way for hydrogen trains in France" Les Echos, https://www.lesechos.fr/industrie-services/tourisme-transport/la-bourgogne-franche-comte-ouvre-la-voie-des-trains-a-hydrogene-en-france-1295890, accessed April 2021.

27 Alstom (2020), "Alstom to supply Italy's first hydrogen trains" Press Release, November 26, 2020.

of a single kilometer of track can cost upwards of US$ 1 million.[28] Even if hydrogen locomotives will require their own refueling and servicing infrastructure, costs are likely to 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.[29]

Another significant advantage of hydrogen-powered alternatives is their potential to serve as bi-mode trains, running on electrified and conventional lines alike. 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 over to its fuel cell to produce the needed electricity.

Yet, hydrogen rail systems are not without challenges. Deploying the required infrastructure and hydrogen's lower volumetric energy density compared to 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.

According to the *Road Map to a US Hydrogen Economy* report,[30] hydrogen could comprise 4% and 17% of the US rail market by 2030 and 2050, respectively. And several projects are already being piloted around the world, including HydroFLEX in the UK and Coradia iLint in Germany and Italy.

28 Railway Industry Association (2019), "RIA Electrification Cost Challenge."

29 Zenith, F., Isaac, R., Hoffrichter, A., Thomassen, M., and Møller-Holst, S. (2020), "Techno-economic analysis of freight railway electrification by overhead line, hydrogen and batteries" J Rail and Rapid Transit 234(7) 791-802 https://doi.org/10.1177%2F0954409719867495.

30 The Fuel Cell and Hydrogen Energy Association (2020), "Roadmap to a US Hydrogen Economy."

Shipping

Despite being one of the most efficient forms of freight transport, shipping remains a challenge for decarbonization efforts. The sector accounts for about 3% of global and 11% of transportation related CO_2 emissions and has a self-imposed goal of reducing emissions by 50% by 2050 from 2008 levels.[31]

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.[32] But complete electrification remains a difficult 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 require 8 and 3 times more, respectively.[33]

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 can also 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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31 International Maritime Organization (2018), “UN body adopts climate change strategy for shipping” https://www.imo.org/en/MediaCentre/PressBriefings/Pages/06GHGinitialstrategy.aspx, accessed April 2021.

32 Bastø Fosen (2021) “The world’s largest electric car ferry in scheduled traffic on the Oslo Fjord” https://basto-fosen.no/nyhetsarkiv/verdens-storste-elektriske-bilferge-i-rutetrafikk-pa-oslofjorden-article8732-832.html.

33 Sustainability in Business Lab (2019) “Towards Net-Zero: Innovating for a Carbon-free Future of Shipping in the North and Baltic Sea. DEEP-DIVE: Comparison of zero-carbon fuels.” https://fe8dce75-4c2a-415b-bfe4-e52bf945c03f.filesusr.com/ugd/0a94a7_0980799ebca344158b897f9040872d36.pdf.

Costs represent a critical factor as hydrogen-based fuels are still more expensive than conventional ones. In the case of ammonia, due to the added conversion steps, costs are even greater. Robust global hydrogen and ammonia networks to ensure that ships can refuel at any port will also be essential to enable the sector's transition to a low-carbon economy. Policymakers will need to support innovation, deployment of enabling infrastructure at scale, and the definition of appropriate safety standards and regulations.

To date, over 140 companies have joined forces in the Getting to Zero Coalition,[34] which aims to achieve commercially viable zero-emission shipping by 2030. According to the International Council on Clean Transportation, liquid hydrogen could fuel up to 99% of existing interoceanic routes with the addition of a single refueling stop.[35] And, as of 2020, more than 66 zero-emission shipping pilot projects have already been demonstrated worldwide.[36]

34 Getting to Zero Coalition (2021), https://www.globalmaritimeforum.org/getting-to-zero-coalition, accessed April 2021.

35 The International Council on Clean Transportation (2021), https://theicct.org/marine, accessed April 2021.

36 Sogaard, K., and Bingham, C. (2020), "Mapping of zero emission pilots and demonstration projects" Global Maritime Forum www.globalmaritimeforum.org/news/mapping-of-zero-emission-pilots-and-demonstration-projects/, accessed March 2021.

Hydrogen Powered Skies

Aviation, the fastest-growing transportation segment until 2019, is at a crossroads. Faced with the dual challenge of significant disruption to air travel due to the Covid-19 pandemic and growing pressure to curb emissions, the sector needs scalable decarbonization pathways to reach net-zero emissions by 2050 in an environmentally and economically sustainable manner.[37] [38]

In 2019, aviation accounted for around 3% of global energy-related CO_2 emissions and 12% of the transportation sector emissions.[39] [40] This seemingly small number should not be dismissed, though, since the sector's overall contribution to global warming is significantly higher due to emissions other than CO_2, like nitrogen oxides and soot. Although the pandemic has caused the largest retrenchment in the history of aviation, it also provides a unique opportunity for the sector to restructure itself toward a low-carbon future. Renewable fuels, including hydrogen, are poised to play a crucial role in this transition.

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 that of 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.

However, the road to hydrogen-powered aircrafts remains uncertain, and it will undoubtedly require significant efforts by all stakeholders to further invest in enabling technologies and the overall value chain. From an innovation perspective, the aviation industry will need to borrow technologies

37 Air Transportation Action Group (2021), https://www.atag.org/, accessed March 2021.

38 Airlines4Europe (2021), "Destination 2050. A route to net zero European aviation" https://www.destination2050.eu/, accessed April 2021.

39 IEA (2020), "World Energy Outlook."

40 Air Transportation Action Group (2021), "Facts and Figures" https://www.atag.org/, accessed March 2021.

developed for the automotive and space industries and apply them to commercial aircraft operations, notably by bringing weight and costs down. One specific challenge will be how and where to store hydrogen onboard aircrafts while achieving similar or better safety targets than existing aircrafts. Beyond the technical aspects, this will require hydrogen-specific safety and regulatory standards that currently do not exist. Adoption of hydrogen at scale will also hinge on robust hydrogen fueling infrastructure networks. While this challenge is daunting, with high fuel demand associated with airport operations, hydrogen could also be produced directly on-site, eliminating distribution costs.

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

Conclusion

Hydrogen must overcome significant barriers, mainly related to storage, infrastructure, and costs before it can truly become a game-changer in the transportation sector.

In road transportation, competitiveness will depend on overall costs of ownership and availability of refueling infrastructure. Short refueling times, lower added weight for stored energy, and zero tailpipe emissions are key advantages. Fuel cells also show promise thanks to their lower material footprint compared to lithium batteries. Long-distance and heavy-duty segments offer the most significant 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 available and represent 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 both 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 potentially higher costs. Direct hydrogen use also shows promise, but 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.

Overall, innovation will be crucial to reduce costs and improve performances of electrolyzers, fuel cells, and hydrogen-based fuels. Technological challenges around weight and hydrogen storage need progress, 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, taking into consideration geopolitical and market implications.
- Implement policy support in the form of 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.

This article first appeared in the report "The Global Quest for Sustainability - The Role of Green Infrastructure in a Post-Pandemic World," published by Italian Institute for International Political Studies (ISPI) and McKinsey in July 2021.

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