Testimony Before the United States Senate Committee on Energy & Natural Resources

FULL COMMITTEE HEARING ON CLEAN HYDROGEN

Testimony of Mike Fowler, Director of Advanced Energy Technology Research

Clean Air Task Force

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Mr. Chairman, Ranking Member, and Distinguished Members of the Committee:

My name is Mike Fowler, and I am the Director of Advanced Energy Technology Research at Clean Air Task Force (CATF), an environmental organization founded in 1996. CATF is a global nonprofit organization working to safeguard against the worst impacts of climate change by catalyzing the rapid development and deployment of low-carbon energy and other climate-protecting technologies. With 25 years of internationally recognized expertise on climate policy and a fierce commitment to exploring all potential solutions, CATF is a pragmatic, non-ideological advocacy group with the bold ideas needed to address climate change. CATF has offices in Boston, Washington D.C., and Brussels, with staff working virtually around the world. I appreciate the opportunity to testify today.

I will share CATF's thoughts on how hydrogen—a versatile and carbon-free "energy carrier"—can help meet the challenge of fully decarbonizing the U.S. economy by mid-century, which sectors are likely to require hydrogen to decarbonize, and what types of research, development, demonstration, and deployment programs for hydrogen will help the United States meet its ambitious climate goals.

[1] <u>The climate challenge is vast and urgent. Achieving net-zero emissions across the energy system within several decades will require transitions in energy production and varied end-use sectors.</u>

Earth's atmosphere now has more carbon dioxide ("CO_2") than at any previous time in human history, and most of that CO_2 was added to the atmosphere in just the last half century. According to the Intergovernmental Panel on Climate Change (IPCC), temperatures are rising, weather and precipitation patterns are changing, and keeping global temperature increases at the end of this century to less than 1.5^{o}C over pre-industrial times will likely require a complete elimination of net CO_2 emissions to the atmosphere within several decades, as well as other measures.[1] This means essentially zero net CO_2 emissions from the global energy system, a monumental task.

The challenge is not just the scale of the energy system that must be decarbonized but also its complexity. Energy is used in a wide array of end-use sectors, each with special demands. In the United States, the electricity and natural gas used in homes and the petroleum used in cars results in only about 40% of our energy-related CO_2 emissions.[2] 60% of our energy-related CO_2 emissions arise from other activities, including heavy surface transportation, shipping, and aviation as well as from heavy industries like chemicals and steel. Decarbonizing our cars and homes is important, but the climate challenge is far larger and more varied. This creates opportunities for hydrogen.

[2] <u>Four fifths of end-use energy today is provided by fuel molecules. Electrification is an essential decarbonization strategy, and we will need even more than that. We also need zero-carbon fuels.</u>

Electricity is extremely clean at its point of use, and although the challenge of decarbonizing electricity production is great, technologies are available to do so. Electricity is currently only around one fifth of

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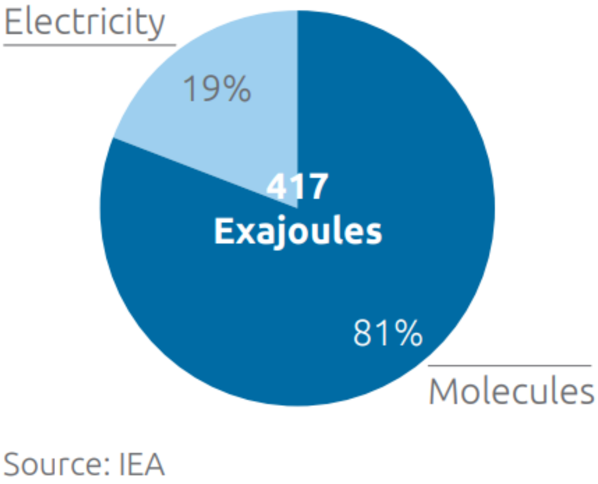
[1] Intergovernmental Panel on Climate Change (IPCC), Basic Slide Pack with Figures (Aug. 9, 2021), https://www.ipcc.ch/report/ar6/wg1/downloads/outreach/IPCC_AR6_WGI_SPM_Basic_Slide_Deck_Figures.pdf

[2] CATF from U.S. Energy Info. Admin., *U.S. CO2 emissions from energy consumption by source and sector, 2020*, https://www.eia.gov/energyexplained/energy-and-the-environment/images/CO2_emissions_spaghetti_2020.pdf (last visited Feb. 7, 2022); *see also* Env't Prot. Agency, *Fast Facts on Transportation Greenhouse Gas Emissions*, https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions (last visited Feb. 7, 2022).

the final energy consumed in the United States, however. A full four fifths of our final energy needs are met directly by fuels: gasoline for cars, diesel fuel for trucks, kerosene for airplanes, bunker oil for ships, natural gas and petroleum for industrial feedstock and process heating, coal for cement production and ironmaking, and similar needs.[3] The global breakdown is similar and indicated in the figure below.[4] Fuel molecules, which can be stored easily in large quantities, literally drive our economy.



Source: IEA

Figure 1: Global breakdown of final energy needs (An "Exajoule" is ten to the power eighteen Joules and is nearly equivalent to a "quad" of energy in United States. A "quad" is ten to the power fifteen British Thermal Units and roughly 1% of U.S. energy consumption.)

Extending the scope of electrification into new areas such as plug-in battery electric vehicles (BEVs) and electric heat pumps for building heating is important for climate change mitigation. In the United States, however, gasoline is only about 60% of the petroleum consumption by the transportation sector. The remaining 40% is diesel fuel (primarily used in trucks), jet fuel (primary used in aviation), and residual fuel oil (primarily used in ships).[5] Similarly, homes consume only 16% of total natural gas in the United States[6] . The remaining gas is used elsewhere, primarily the industrial sector and electric power generation. If we do not address our substantial fuel use in heavy transportation and heavy industry, we will not meet the decarbonization goals necessary for the climate imperative.

A recent study of the possible transition to a global net-zero energy system by the International Energy Agency (IEA) suggests that electrification could more than double from 20% today to around 50% by

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[3] Of the 69.7 quads of total energy delivered in the U.S., 12.5 quads—or 18%—are from electricity. *See* U.S. Energy Info. Admin., *U.S. energy consumption by source and sector, 2020*, https://www.eia.gov/energyexplained/us-energy-facts/images/consumption-by-source-and-sector.pdf (last visited Feb. 7, 2022).

[4] BloombergNEF, International Gas Union, & Snam, *Global Gas Report 2020* 49, https://data.bloomberglp.com/professional/sites/24/BNEF-IGU-Snam-2020-Global-Gas-Report_FINAL.pdf (note that one exajoule is approximately one quad).

[5] *See* U.S. Energy Info. Admin., DOE/EIA-0035(2022/1), January 2022 Monthly Energy Review at Table 3.8c, data for 2019, https://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf.

[6] *See id.* at Table 4.3, data for 2019. The fraction increases to 27% if we include commercial buildings, and slightly more if fuel used in natural gas production and transportation is allocated to building end-uses.

2050, including almost complete electrification of cars and significant electrification (approaching 70%) of buildings.[7] Further electrification, however, raised concerns in IEA's analysis based on materials availability, system reliability, and economic considerations.[8] Because so much energy is used today outside the current electricity system, integrating large new uses for electricity is far from trivial. Analysis by the California Fuel Cell Partnership suggests that electrifying all 17,000 drayage trucks at the San Pedro Bay ports alone could require six gigawatts (GW) peak electric generation and local distribution capacity for nightly charging, for example.[9] Six GW is approximately the capacity of all the wind turbines currently installed in California. The challenges of this electrification create an opportunity for hydrogen, which can be produced over time and stored for later use.[10]

[3] Hydrogen is a versatile, carbon-free "energy carrier" that can substitute for some conventional fuels. We already have considerable industrial experience making and using hydrogen.

Hydrogen is the simplest, most abundant element in the universe, consisting of a single proton and single electron. It is a reactive element and on Earth is generally found bonded to another element like oxygen (in water), carbon (in methane), or nitrogen (in ammonia). When isolated, hydrogen is usually a diatomic molecule—called "H_2"—which takes the form of an odorless, colorless gas. Hydrogen is a useful element because it releases significant energy when it reacts with oxygen from the air. One kilogram of hydrogen has a similar heating value (i.e., releases the same amount of heat during combustion) as one gallon of gasoline, but creates no CO_2 when used.[11] As a result hydrogen could be extremely useful as a carbon-free fuel molecule. Unfortunately, natural sources of hydrogen appear to be limited on Earth, so we need to manufacture it from other energy sources first. For this reason,

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[7] Int'l Energy Agency, *Net-Zero by 2050: A Roadmap for the Global Energy Sector* (May 2021), https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf.

[8] *Id.* at 140. Battery technology limitations including energy density and material requirements, as well as peak electric capacity and grid load limitations, constrain further electrification in the IEA scenario. An alternative All-Electric looks at the implications of electrifying all road vehicles, but IEA cautions that the additional battery development, production, charging infrastructure, peak grid loads, and grid energy storage "create additional challenges" and "undesirable side effects" "requiring significant additional investment" and "increasing the vulnerability of the transport system".

[9] *See* Cal. Fuel Cell P'ship, *Fuel Cell Electric Trucks: Vision for Freight Movement in California—and Beyond* 10 (July 2021), https://app.greenrope.com/content/Fuel-Cell-Electric-Trucks-Vision-CaFCP.pdf.

[10] Bioenergy also often plays a prominent role in many U.S. and global decarbonization models. IEA's recent net-zero-by-2050 scenario, for example, projects that global modern bioenergy production would increase from 34 Quads to 97 Quads by mid-century. Even at its current level, though, bioenergy production—especially the production of feedstocks used to make liquid biofuels—poses substantial sustainability challenges. *See* Int'l Energy Agency, *Net-Zero by 2050: A Roadmap for the Global Energy Sector*, Table 2.8 (May 2021), https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf (indicating 36 and 102 exajoules of modern bioenergy in 2020 and 2050, respectively); *see also* Energy Transitions Comm'n, *Bioresources Within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible* (Jul. 6, 2021), https://www.energy-transitions.org/energy-transitions-commission-warns-demand-for-biomass-likely-to-exceed-sustainable-supply/.

[11] According to U.S. EPA, combustion of motor gasoline emits 8.78 kg of CO_2 per gallon. *See* Env't Prot. Agency, *Emission Factors for Greenhouse Gas Inventories* (Mar. 9, 2018), https://www.epa.gov/sites/default/files/2018-03/documents/emission-factors_mar_2018_0.pdf

hydrogen is sometimes called an "energy carrier" rather than a source of primary energy like natural gas, wind, and sunlight.

Around 70 million metric tons[12] of hydrogen are currently produced each year around the world (about 10 million metric tons of which are produced in the U.S.) primarily by natural gas reforming with lesser amounts from coal gasification and a small percentage by electrolysis.[13] In natural gas reforming, high temperatures drive conversion of hydrocarbons such as methane into a mixture of hydrogen, carbon monoxide, and carbon dioxide, which is then further converted to carbon dioxide and additional hydrogen by reaction with water. In electrolysis, an electric current (and sometimes thermal energy) is used to split water molecules into hydrogen and oxygen. In both processes the hydrogen product contains roughly 70% of the energy used to make it.[14] Although the hydrogen product itself contains no carbon and produces no carbon dioxide when used, the greenhouse gas emissions from either the reforming process or the electricity for the electrolysis process can be significant.

The vast majority of the hydrogen produced globally today is used in the refining industry and the fertilizer industry.[15] Where additional hydrogen is available it is usually used, however. Hydrogen is regularly blended into fuel gas systems where it occurs in industrial processes.[16] In Singapore, hydrogen can account for more than half the gas used in cooking and water heating.[17] Natural gas in Hawaii has an elevated hydrogen content due to its production.[18] In California, where some hydrogen fueling infrastructure has been developed, around 10,000 fuel cell vehicles are registered.[19]

[4] In the U.S., hydrogen could contribute to a billion metric tons per year CO_2 opportunity. Special uses will include heavy transportation and heavy industry.

Although hydrogen may be useful for decarbonizing many parts of the economy, several special hydrogen opportunities are highlighted below, particularly in heavy transportation and heavy industry.

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[12] One metric ton is 1000 kilograms (equal to 2,205 pounds).

[13] U.S. Dep't of Energy, Office of Fossil Energy, *Hydrogen Strategy: Enabling A Low-Carbon Economy* at Fig. 3 (Jul. 2020), https://www.energy.gov/sites/prod/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf. According to IEA, an additional 40 million metric tons per year are produced as mixed gas streams such as used in methanol production. *See* Int'l Energy Agency, *The Future of Hydrogen* at Fig. 6 (Jun. 2019), https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf.

[14] *See* Int'l Energy Agency*, The Future of Hydrogen: Data and Assumptions* (Jun. 2019), https://www.iea.org/reports/the-future-of-hydrogen/data-and-assumptions.

[15] *See* Int'l Energy Agency*, The Future of Hydrogen* at Fig. 6 (Jun. 2019), https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf.

[16] Robert G. Kunz, *Environmental Calculations: A Multimedia Approach* 385, Appendix L. Combustion of Refinery Fuel Gas (2009).

[17] *See* Clean Air Task Force, *Decarbonization in Singapore: Hydrogen and the Long-Term Low-Emissions Development Strategy (LEDS)* (April 2021), https://cdn.catf.us/wp-content/uploads/2021/04/21092359/CATF-Singapore-Decarbonization-Final.pdf.

[18] Hawaii Gas, *Hydrogen*, https://www.hawaiigas.com/clean-energy/hydrogen/ (last visited Feb. 7, 2022).

[19] *See* California Air Resources Board, 2021 Annual Evaluation of Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development, Sept. 2021, https://ww2.arb.ca.gov/sites/default/files/2021-09/2021_AB-8_FINAL.pdf

The total CO_2 emissions for these sectors of the U.S. economy are over 1 billion metric tons per year, on par with CO_2 emissions from all U.S. cars and light trucks.[20]

Trucking

Heavy trucking produces around 2.3 billion metric tons[21] per year of CO_2, of which about 450 million metric tons[22] per year are in the U.S. Electric drivetrains with onboard battery energy storage similar to electric cars appear likely to be a powerful decarbonization tool for the heavy trucking sector. Electrification with catenary wires and other continuous electricity delivery systems are also the subject of research and may play a role in very high-throughput corridors. The fundamentals of onboard fuel and battery energy storage suggest that hydrogen or other zero-carbon fuels could play a substantial role in long-haul heavy trucking, however.

The table below provides recent estimates from the National Renewable Energy Laboratory (NREL) on the weight, range, and refueling time for heavy trucks with plug-in battery electric vehicle (BEV) and hydrogen fuel cell electric vehicle (FCEV) drivetrains. These drivetrains are similar in many ways, but the FCEV drivetrain has a much smaller battery and includes several compressed gaseous hydrogen storage tanks and fuels cells that the BEV does not have.

	Plug-In Battery Electric Vehicle (BEV)	**Hydrogen Fuel Cell Electric Vehicle (FCEV)**
Range (Nominal with NREL Speed Profile)	750 miles	750 miles
Drivetrain Weight (Including Batteries)	21,000 pounds	6,000 pounds
Battery Weight	19,500 pounds	220 pounds
Charging or Fueling Time (Regular/Fast)*	3 hours 36 minutes / 1 hour 48 minutes	14 minutes / 7 minutes

* Regular charging and fueling assumes 500 kW and 5 kg/min respectively. Fast charging and fueling assumes 1000 kW and 10 kg/min respectively

Figure 2: Long-Haul Class 8 Truck Drivetrain Comparison with Current Technology[23]

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[20] See https://www.epa.gov/system/files/documents/2021-12/420f21076.pdf.

[21] Calculated by CATF based on fuel consumption data of 31 quads, assuming 74 kg of CO_2 per MMBtu of fuel. *See* U.S. Energy Info. Admin, *International Energy Outlook 2019*, https://www.eia.gov/outlooks/aeo/data/browser/#/?id=51-IEO2019&region=0-0&cases=Reference&start=2010&end=2050&f=A&linechart=~Reference-d080819.14-51-IEO2019&map=&ctype=linechart&sourcekey=0 (last visited Feb. 7, 2022).

[22] *See* Env't Prot. Agency, *Fast Facts on Transportation Greenhouse Gas Emissions*, https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions (last visited Feb. 7, 2022); *see also* Env't Prot. Agency, Greenhouse Gas Inventory Data Explorer, https://cfpub.epa.gov/ghgdata/inventoryexplorer/#allsectors/allsectors/allgas/econsect/current (last visited Feb. 7, 2022).

[23] *See* Nat'l Renewable Energy Lab'y, *Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks* Figures 13 and 14, Tables 1 and 7 (Sept. 2021), https://www.nrel.gov/docs/fy21osti/71796.pdf.

Overall, for a long-haul heavy-duty truck, the hydrogen system saves nearly 10 tons in battery weight, preserves more than 7 tons in payload capacity, and reduces charging or refueling time by several hours per stop. According to recent NREL research, these advantages of the hydrogen fuel cell drivetrain lead to reduced costs for truck owners on certain routes. That reduced cost, in addition to the operational flexibility of hydrogen drivetrains, suggests that availability of hydrogen fuel cell electric trucks and fueling infrastructure would be a significant decarbonization promoter. Major manufacturers see this opportunity and are developing commercial products to pursue it.[24]

While not the majority of truck activity, long-haul (e.g., sleeper) routes, defined by NREL as greater than 500 miles, make up approximately 49%[25] of fuel consumption in the U.S. heavy truck sector.

Aviation

The global aviation sector released about 1 billion metric tons of CO_2 in 2019,[26] rising fast from only 713 million metric tons in 2009,[27] and the United States is responsible for approximately 24% of those emissions.[28] This is a sector that needs zero- carbon fuels for a significant portion of its operations. Two-thirds of the fuel consumed in the aviation sector is for flights in excess of 1500 kilometers (km)[29] and nearly 90% of the fuel is used in flights longer than 750 km.[30] Electrifying these would be exceedingly difficult. The engines of a very large commercial airliner can produce as much as 300 MW peak power – the size of a modest power plant – and on-board fuel storage can exceed 3,400 MWh.[31] A recent analysis indicates that at least a 50-fold decrease in the weight of batteries would be necessary to achieve a range of 1500 km in a typical commercial airliner similar to a Boeing 737.[32]

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[24] Air Products and Cummins to Accelerate Development and Deployment of Hydrogen Fuel Cell Trucks, July 2021, available at https://www.cummins.com/news/releases/2021/07/26/air-products-and-cummins-accelerate-development-and-deployment-hydrogen. See also https://www.greencarcongress.com/2021/06/20210614-pola.html and https://www.cnbc.com/2021/11/12/too-risky-to-not-use-battery-and-hydrogen-tech-daimler-truck-ceo.html.

[25] *See* Dep't of Transp., *Freight Facts and Figures 2017*, Table 2-3, Figure 2-1, Table 6-8, Table 6-9 (Oct. 13, 2017), https://www.bts.dot.gov/sites/bts.dot.gov/files/docs/FFF_2017.pdf.

[26] Int'l Energy Agency, *Aviation* (Nov. 2021), https://www.iea.org/reports/aviation (CO_2 emissions); Env't Prot. Agency, *Emission Factors for Greenhouse Gas Inventories* (Mar. 9, 2018), https://www.epa.gov/sites/default/files/2018-03/documents/emission-factors_mar_2018_0.pdf (energy and fuel consumption back-calculated using U.S. EPA factors).

[27] *See* Int'l Energy Agency, *Aviation* (Nov. 2021), https://www.iea.org/reports/aviation.

[28] *See* Our World in Data, *Share of global CO_2 emissions from aviation, 2018*, https://ourworldindata.org/grapher/share-co2-emissions-aviation?country= (last visited Feb. 7, 2022).

[29] *See* Hannah Ritchie, *Short-haul vs. long-haul; rich vs. poor countries: where do global CO_2 emissions from aviation come from?*, Our World in Data (Oct. 23, 2020), https://ourworldindata.org/breakdown-co2-aviation.

[30] Alan H. Epstein & Steven M. O'Flarity*, Considerations for Reducing Aviation's CO_2 with Aircraft Electric Propulsion*, 35 J. of Propulsion and Power 572, 580 (May 2019).

[31] This is more than a California utility battery reported to be the largest in the world. *See* Burns & McDonnell, *Burns & McDonnell Completes Construction at Largest Battery Storage Facility in the World* (Aug. 19, 2021), https://www.burnsmcd.com/insightsnews/in-the-news/2021/08/largest-battery-storage-facility-in-world.

[32] Alan H. Epstein & Steven M. O'Flarity*, Considerations for Reducing Aviation's CO_2 with Aircraft Electric Propulsion*, 35 J. of Propulsion and Power 572, 574 (May 2019).

"Sustainable aviation fuels" ("SAF") is a catch-all phrase for drop-in liquid fuel replacements for conventional kerosene used in aviation.[33] Often these are actually biofuels, which are not always carbon neutral or sustainably produced and can have high land, energy, and water requirements. According to multiple recent analyses of feasible projected biofuels production over the next three decades, even total projected biofuels production would be insufficient to meet increased aviation energy demand (and assuming that all biofuels could be directed towards the aviation sector).[34]

Major manufacturers are developing new hydrogen-fueled propulsion systems for next-generation flight[35] and it is claimed that hydrogen has been used as experimental fuel in large jet aircraft in the past.[36] These appear to have promise and should be part of the research, design, and development (RD&D) portfolio of decarbonization solutions pursued by the United States and other countries. Compressed hydrogen occupies 6.5 times[37] more space than kerosene however, and cryogenic hydrogen must be maintained at temperatures around -423 Fahrenheit.[38] As a result, it remains an open question how useful hydrogen itself will be in the aviation sector. Synthetic kerosene or similar manufactured hydrocarbons may have a much larger role.

Hydrocarbons generally, and fuels in particular, can be synthesized artificially from mixtures of hydrogen and carbon monoxide, such as has been done for decades at the Dakota Gasification Company plant in the U.S. and similar facilities in South Africa. When the carbon monoxide is derived from CO_2 extracted from the air (e.g., "direct air capture" or DAC) and the required hydrogen produced without CO_2 emissions, the resulting fuel theoretically can be carbon-neutral over its lifecycle (or possibly carbon-negative depending on the source of the CO_2). Synthetic kerosene, which could be a drop-in replacement for current aviation fuels, has been identified as a leading candidate for decarbonizing the aviation sector alongside biomass-derived SAF, to the extent those can be produced sustainably with very low greenhouse gas footprint.

Marine Shipping

The marine shipping sector emits about 1 billion metric tons of CO_2 – similar to the global aviation sector. If the global shipping sector were a country, it would rank sixth on a list of countries with the

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[33] *See* Int'l Air Transp. Ass'n, *What is SAF?*, https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/saf-what-is-saf.pdf (last visited Feb. 7, 2022).

[34] For projected aviation energy demand, see: (1) DNV-GL's Energy Transition Outlook 2021; (2) EIA's 2021 International Energy Outlook; (3) Organization of the Petroleum Exporting Countries' (OPEC) World Oil Outlook 2021; and (4) IEA's World Energy Outlook 2021. For projected biofuels production, *see* Int'l Energy Agency, *Transport Biofuels* (Nov. 2021), https://www.iea.org/reports/transport-biofuels.

[35] Sabri Ben-Achour, *How close are hydrogen planes, really?*, Marketplace (Oct. 28, 2021), https://www.marketplace.org/2021/10/28/how-close-are-hydrogen-planes-really/.

[36] Tupolev, *The 95th anniversary of Aleksey Tupolev's birth*, (May 20, 2020), https://www.tupolev.ru/en/press/news/2020/the-95th-anniversary-of-aleksey-tupolev-s-birth/?sphrase_id=52122.

[37] *See* Bernard Chukwudi Tashie-Lewis & Somtochukwu Godfrey Nnabuife, *Hydrogen Production, Distribution, Storage and Power Conversion in a Hydrogen Economy - A Technology Review*, 8 Chem. Eng'g J. Advances 100172, Table 1 (Nov. 15, 2021).

[38] *See* Dep't of Energy, Office of Energy Efficiency & Renewable Energy, *Module 1: Hydrogen Properties* 1-4 (Dec. 2001), https://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/fcm01r0.pdf.

highest greenhouse gas emissions. Approximately 13% of these emissions are attributable to ships calling on U.S. ports.[39] Trade, in particular, places special demands on shipping. In fact, half of marine shipping container traffic at U.S. ports is with China and Taiwan, South Korea, and Japan, all located on the far side of the Pacific Ocean.[40]

Like trucking, some marine routes may be served by batteries, but longer transoceanic routes are widely acknowledged to require onboard fuel storage. In a 2020 comparative analysis of multiple fuel options for transoceanic cargo vessels, Lloyd's Register and UMAS (a consultancy affiliated with University College London) determined that "battery technology is simply not competitive and still requires significant development in terms of size, weight and cost of operation before it could be a viable technology as a main propulsion."[41] Energy analyst Vaclav Smil calculates that the battery pack needed to power a large container ship from Asia to Europe would weigh approximately 100,000 metric tons and fill roughly 40% of the vessel's available cargo space—"an economically ruinous proposition."[42] Biofuels offer better energy density than batteries, but as with aviation, the supply of sustainable, climate-beneficial biofuels is insufficient to meet projected demand from the marine sector.

Ammonia (produced from low-carbon hydrogen combined with nitrogen from the air) has emerged as the key decarbonized fuel for this service, and numerous companies are working to develop low-carbon ammonia as a shipping fuel.[43] Ammonia is often preferred as a solution in the marine shipping sector compared to hydrogen due to its energy density: gaseous hydrogen, liquid hydrogen, and liquid ammonia have volumetric energy densities of 7.5 GJ/m^3, 8.5 GJ/m^3, and 12.7 GJ/m^3, respectively.[44]

Marine vessels, especially the transoceanic container ships, bulk carriers, and oil tankers that collectively account for 55% of the marine sector's GHG emissions, are particularly well positioned for a shift to ammonia fueled internal combustion engines and combustion turbines (and possibly solid oxide fuel cells). Container ships and bulk carriers consumed 118 million metric tons of heavy fuel oil-equivalent fuel in 2018. If those same ships ran on ammonia instead of conventional fuel oil, they would have consumed 223 million metric tons of ammonia. The supply chain for ammonia bunker fuel can build on an existing industrial base that produces approximately 180 million metric tons of ammonia annually.

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[39] Estimate by International Council on Clean Transportation (ICCT) based on assessment that imports and exports to and from the U.S. represent 13% of global trade by mass. Communications with ICCT on file with CATF.

[40] Calculated by CATF from U.S. government data available at https://www.maritime.dot.gov/data-reports/data-statistics/us-waterborne-foreign-trade-trading-partners

[41] Lloyd's Register & University Maritime Advisory Services (UMAS), *Techno-Economic Assessment of Zero-Carbon Fuels* 34 (Mar. 2020), https://www.lr.org/en/insights/global-marine-trends-2030/techno-economic-assessment-of-zero-carbon-fuels/.

[42] Vaclav Smil, *Electric Container Ships Are Stuck on the Horizon: Batteries still can't scale up to power the world's biggest vessels,* IEEE SPECTRUM (Feb. 27, 2019), https://spectrum.ieee.org/transportation/marine/electric-container-ships-are-stuck-on-the-horizon.

[43] *Singapore port authority backs project to use ammonia as marine fuel*, Reuters (Feb. 24, 2021), https://www.reuters.com/article/us-singapore-bunker/singapore-port-authority-backs-project-to-use-ammonia-as-marine-fuel-idUSKBN2AO0H0.

[44] Tugce Ayvali et al., *The Position of Ammonia in Decarbonising Maritime Industry: An Overview and Perspectives: Part I*, 65 Johnson Matthey Technol. Rev. 275 (2021).

Low-carbon ammonia can be integrated gradually into the shipping sector's fuel mix, which allows stakeholders to manage the cost of their transition to cleaner fuel.[45]

The shipping industry has already taken notice. AP Møller Maersk AS, the world's largest container ship and supply vessel company, announced it would reduce CO_2 emissions from operations to zero (on a net-basis) by 2050, identified ammonia as one of the low-carbon fuel options it would pursue, and backed the development of Europe's largest "green ammonia" production facility.[46] MAN Energy Solutions, whose engines "cover an estimated 50% of the power needed for all-world trade," is both designing new ammonia-compatible dual-fuel engines and developing the capacity to retrofit its existing engines to accommodate ammonia fuel. Engine maker Wärtsilä is working with Samsung Heavy Industries and other companies to develop ammonia-fueled ships,[47] and announced that its first ammonia engine model would be ready in 2023.[48] Finally, Australian mining major Fortescue announced in 2021 that it is retrofitting a ship "so that it can run almost totally on green ammonia" by the end of 2022.[49]

Power Sector

Despite the challenges of the scale of the energy system decarbonization problem, which are substantial, we are fortunate to have multiple technical options for decarbonizing the electric power sector. With policy support, renewables including wind and solar, fossil fuels with carbon capture, and nuclear energy could all play a meaningful role in reaching a zero- or near-zero carbon power sector by mid-century.

Deployment levels of wind and solar are growing fast and should be accelerated, but at very high levels of variable generation on the electric grid there arise prolonged periods where available resources may be insufficient to meet demand.[50] To provide required energy when variable resources are insufficient, most projections of electric system decarbonization with high levels of variable generation also retain

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[45] *See* Clean Air Task Force, *Bridging the Gap: How Nuclear-Derived Zero-Carbon Fuels Can Help Decarbonize Marine Shipping* (Aug. 2021), https://www.catf.us/wp-content/uploads/2021/08/NuclearZCFMarineShipping.pdf.

[46] Maersk, *Maersk backs plan to build to Europe's largest green ammonia production facility* (Feb. 23, 2021), https://www.maersk.com/news/articles/2021/02/23/maersk-backs-plan-to-build-europe-largest-green-ammonia-facility.

[47] Ship Technology, *Wartsila, SHI to develop ammonia-fuelled engines for upcoming newbuilds* (Sept. 22, 2021), https://www.ship-technology.com/news/wartsila-shi-ammonia-fuelled-engines/.

[48] Argus, *Wartsila targets ammonia-ready engine in 2023* (Jul. 14, 2021), https://www.argusmedia.com/en/news/2234110-wartsila-targets-ammoniaready-engine-in-2023.

[49] Fatima Bahtic, *Fortescue eyes 1st green ammonia-fuelled vessel by end of 2022*, Offshore Energy (Nov. 11, 2021), https://www.offshore-energy.biz/fortescue-eyes-1st-green-ammonia-fuelled-vessel-by-end-of-2022/.

[50] Dan Tong et al., *Geophysical constraints on the reliability of solar and wind power worldwide*, 12 Nature Commc'ns 6146 (2021).

significant "dispatchable" generation capacity, which must be clean to completely eliminate CO_2 emissions from the sector.[51, 52]

CATF's own research in California, conducted with collaborators at Environmental Defense Fund, Stanford University, Princeton University, Energy & Environmental Economics (E3), University of San Diego, and The Brookings Institution, examined alternative system configurations for 100% decarbonization of the California electric grid by 2045 using an assortment of technology assumptions and several different modeling platforms. The models consistently demonstrated the significant technical and economic importance of maintaining clean firm power in highly renewable energy systems.[53]

Hydrogen is one option to provide this clean dispatchable generation. Large utility gas turbines are available today with capability to fire hydrogen mixed with natural gas, and several original equipment manufacturers have committed to offering 100%-hydrogen capable machines by 2030. Geological storage of hydrogen is already used in the industrial sector in several locations in the U.S. and Europe, especially in salt caverns, with several hundred GW-hours of energy stored at multiple sites.[54] Early research suggests suitable geology for hydrogen storage may be reasonably widespread in the U.S.[55] and several power-sector projects under development are evaluating this type of capacity.[56]

Industrial Sector

Heavy industry uses large quantities of coal, petroleum, and natural gas globally, around 90 quads annually including petroleum feedstocks.[57] Combustion of fuels for process heating alone in US industry results in more than 400 million metric tons of CO_2 annually, not including emissions from steel production (addressed below).[58] Some of these fuel loads can undoubtedly be electrified, but hydrogen is already burned in some industries and appears to have potential as a relatively direct substitute for

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[51] *See* The NorthBridge Group, "Review and Assessment of Literature on Deep Decarbonization in the United States: Importance of System Scale and Technological Diversity" (2021). https://www.catf.us/wp-content/uploads/2021/06/NorthBridge_Deep_Decarbonization_Literature_Review.pdf.

[52] Julianne DeAngelo et al., Energy systems in scenarios at net-zero CO2 emissions, 12 Nature Commc'ns 6096 (2021).

[53] Jane Long et al., *Clean firm power is the key to California's carbon-free energy future*, Issues in Sci. and Techn. (Mar. 24, 2021), https://issues.org/california-decarbonizing-power-wind-solar-nuclear-gas/.

[54] *See e.g.*, Dr. Grégoire Hévin-Storengy, *Underground storage of Hydrogenin salt caverns* 16, European Workshop on Underground Energy Storage (Nov. 7-8, 2019), https://energnet.eu/wp-content/uploads/2021/02/3-Hevin-Underground-Storage-H2-in-Salt.pdf.

[55] Anna S. Lord et al, *Geologic storage of hydrogen: Scaling up to meet city transportation demands*, 39 Int'l J. of Hydrogen Energy 15570 (2014), https://www.sciencedirect.com/science/article/abs/pii/S0360319914021223.

[56] *See* Green Hydrogen Coal., *Conversion of Intermountain Power Project to Green Hydrogen*, https://www.ghcoalition.org/green-hydrogen-at-scale (last visited Feb. 8, 2022); *see also* Entergy Corp., *Building the Premier Utility* 22 (Aug. 4, 2021), https://entergycorporation.gcs-web.com/static-files/86da9e87-aabd-455e-8891-f08c99df517a.

[57] Int'l Energy Agency, *World Energy Outlook 2017* 648 (Nov. 2017), https://iea.blob.core.windows.net/assets/4a50d774-5e8c-457e-bcc9-513357f9b2fb/World_Energy_Outlook_2017.pdf.

[58] Colin A. Macmillan & Mark Ruth, *Using facility-level emissions data to estimate the technical potential of alternative thermal sources to meet industrial heat demand*, 239 Applied Energy at Table 2 (Feb. 11, 2019).

conventional fuels in some applications.[59] In the photograph below, 95% hydrogen is being burned in an ultra low-NO_X industrial burner in Oklahoma.

Figure 3: Hydrogen Combustion in Industrial Burner Test[60]

Hydrogen could be particularly useful in certain industries, notably ironmaking. The basic process of converting iron ore (an oxide) to iron metal requires a chemical reducing agent. This is typically accomplished with blast furnace technology using carbon derived from coal and resulting in the release of CO_2. Around 2.5 billion metric tons of CO_2 are emitted each year around the globe by this production process.[61] But hydrogen could be used for iron reduction instead of carbon, resulting in the co-production of water instead of CO_2. Pilot plants that utilize this “direct reduced iron” technology with hydrogen are being built in Europe—some with support from U.S. companies.[62]

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[59] Cliff Lowe et al., *Technology assessment of hydrogen firing of process heaters*, 4 Energy Procedia 1058 (2011).

[60] *Id.*

[61] Estimate by CATF. Global crude steel production by the blast furnace /basic oxygen furnace route was about 1.2 billion metric tons in 2017 according to worldsteel. Typical emissions from the blast furnace / basic oxygen furnace route are around 2.2 metric tons of CO2 per ton of crude steel. *See* https://worldsteel.org/wp-content/uploads/Fact-sheet-steel-and-raw-materials.pdf and https://www.responsiblesteel.org/wp-content/uploads/2020/09/ResponsibleSteel-GHG-Requirements-for-Steel-Product-Certification-for-Consultation-Draft-1-0.pdf

[62] *See* Hybrit, Pilot scale direct reduction with hydrogen, https://www.hybritdevelopment.se/en/a-fossil-free-development/direct-reduction-hydrogen-pilotscale/ (last visited Feb. 7, 2022); *see also* Midrex, German Federal Government to Provide €55 Million for ArcelorMittal’s Hydrogen DRI Plant (Sept. 2021), https://www.midrex.com/company-news/german-federal-government-to-provide-e55-million-for-arcelormittals-hydrogen-dri-plant/.

[5] Demand for clean hydrogen is projected to grow due to net-zero goals. Demand in the U.S. could be 10 quadrillion Btu or more by mid-century.

Analysts differ in their projections of potential future hydrogen demand, particularly in two main areas of assumptions. First, differences in hydrogen demand projections stem primarily from differences in assumptions about decarbonization targets and policies. Second, these differences can also stem from differences in assumptions about the evolution of availability and costs for both hydrogen and competing technologies (for example, improvements in batteries and roll-out of charging infrastructure).

Overall, IEA's net-zero analysis of global energy system decarbonization includes 530 million metric tons of hydrogen production in 2050 (about 70 quads) with use spread across power generation, heavy transportation, and industry. Analysis firm BNEF suggests that a theoretical maximum of nearly 1.4 billion metric tons of hydrogen (around 200 quads) could be used in some decarbonization scenarios, and that even in a more modest role hydrogen could serve as much as one quarter of global final energy demand.[63]

For the U.S., analysis by McKinsey for the Fuel Cell and Hydrogen Energy Alliance suggests that around 63 to 74 million metric tons of hydrogen could be required for decarbonization by 2050 (around 10 quads), with primary application in heavy transportation and heavy industry.[64] This represents around 14% of final energy demand in the U.S. in 2050 in the McKinsey analysis. An examination by the American Council for an Energy Efficient Economy concluded that even in a "fully electrified" U.S. economy, around 9 quads of hydrogen could be required, primarily in heavy industry and heavy transportation.

CATF modeling analyses of the U.S. comes to similar conclusions. In particular, analysis by CATF, Bipartisan Policy Center, and Third Way finds that hydrogen will be essential to decarbonize the U.S. by mid-century, in addition to other tools. These modeling results, shown in the three charts below, suggest 8 to 18 quads of hydrogen per year could be required for full decarbonization in the U.S. by 2050.[65]

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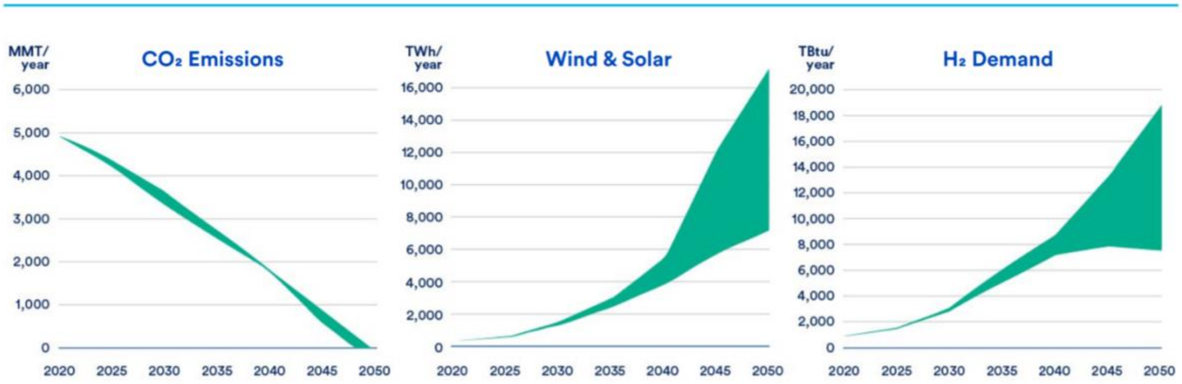
[63] BloombergNEF, Hydrogen Economy Outlook (Mar. 30, 2020), https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf.

[64] Fuel Cell & Hydrogen Energy Association, Roadmap to a US Hydrogen Economy, 2020, available at https://www.fchea.org/reports

[65] *See* Decarb America, https://decarbamerica.org (last visited Feb. 7, 2022).



From left to right, these three graphs show the range for CO_2 emissions reductions in the energy and industrial sectors, total wind and solar generation, and hydrogen demand, from the recent Decarb America analysis by CATF, Bipartisan Policy Center, and ThirdWay. The graphs show the range of modeling results for the U.S. from 2020 to 2050 across five different modeling scenarios, highlighting the upper and lower bound possibilities for each outcome.

Figure 4: Decarb America Net Zero by 2050 Modeling Results

Producing all the clean hydrogen that may be needed for decarbonizing difficult-to-electrify activities (i.e., the sectors discussed above) will be a significant challenge. Consider the Atlanta Hartsfield-Jackson airport, for example. This facility consumes more than 1 billion gallons of jet fuel each year.[66] Just on a direct energy basis replacing that much jet fuel with hydrogen produced from solar electricity would require around 24 GW of photovoltaic installations.[67] This is more than the total photovoltaic power currently installed in Florida, Georgia, South Carolina, and North Carolina combined.[68] Providing hydrogen just to replace the energy demand of the Atlanta airport would require more than doubling the installed photovoltaic power in the region. And that solar power is needed for other purposes as well, like directly decarbonizing the electricity grid.

The land use and infrastructure challenges of this additional renewable energy build-out, and the potential for delay in making this hydrogen available, suggest that additional hydrogen supplies, including hydrogen made from fossil fuels, would be beneficial for decarbonization. Requirements for how “clean” this hydrogen must be depend on the context and should evolve over time, but they must include a very high level of carbon capture for reformers, extremely low methane loss rates for natural gas used in production, and low CO_2 intensity of net electricity used in producing hydrogen.[69] For

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[66] *See* Hartsfield-Jackson Atlanta International Airport, *Sustainable Management Plan* 4-3 (Sept. 16, 2011), https://www.faa.gov/airports/environmental/sustainability/media/ATLSustainableMasterPlan.pdf.

[67] Based on typical jet fuel energy content, typical electrolyzer efficiency, and a solar photovoltaic capacity factor of 20%.

[68] *See* Solar Energy Industries Association, *Solar State by State*, https://www.seia.org/states-map, (last visited Feb. 7, 2022).

[69] According to the IPCC’s latest assessment, a release of methane warms the planet 83 times more over 20 years than would the same-sized release of CO_2, and 30 times more over 100 years. Methane arises from agricultural operations and industrial operations including coal mining and oil and gas production and use and is the principal constituent of natural gas. Leaks and other losses of methane in the natural gas supply chain are a significant driver of climate change. *See* Intergovernmental Panel on Climate Change, *Climate Change 2021: The Physical Science Basis* 1739 (Aug. 2021), https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf#page=1739 (global warming potentials (GWPs)).

electrolyzers, which under the right circumstances will provide an important source of clean hydrogen in the United States, supplies of clean electricity need to be additional to baseline clean generation.

[6] The road to decarbonization with hydrogen is not entirely clear today. But federal R&D and demonstration programs will play a key role in building scale, industry learning, and seeding growth. Deployment support will also be essential.

Developing and commercializing the technologies needed for affordable and clean hydrogen production, transportation, and use across varied supply chains will require sustained and committed funding support from the U.S. government. This includes research, development, and demonstrations of electrolyzer technology, natural gas reforming with carbon capture, hydrogen storage, pipeline materials and operations, fuel cells, fuel dispensing, gas turbines, industrial technologies like hydrogen DRI, and decarbonization of the full natural gas value chain. Recently U.S. hydrogen R&D funding for key areas like electrolyzers has increased and important new funding for hydrogen hubs demonstrations has been added. These are critical steps in the right direction.

In particular, the Regional Clean Hydrogen Hub program established in the Infrastructure Investment and Jobs Act (IIJA) is a necessary and impactful step towards creating well-functioning, regional clean hydrogen economies. A hydrogen hub is a close-proximity network of zero-carbon fuels production and end-use demonstrations that supports industry learning at a large scale and achieves net-greenhouse gas emissions reductions and other regional environmental benefits. With support from DOE, regional demonstration hydrogen hubs can help solve the chicken-and-egg problem with clean hydrogen – where neither the low-carbon hydrogen producers nor the new end-use sectors want to be the first movers – until it is clear that there will be a critical mass of supply and demand. Regional hubs can help by building up both the clean hydrogen supply and the additional demand from end-use sectors that need low-carbon hydrogen to meet decarbonization goals, while also supporting all of the necessary connective tissue such as storage and transportation infrastructure.

By demonstrating a successful localized clean hydrogen economy, regional hubs will enable learning and encourage other low-carbon hydrogen producers and consumers around the country to accelerate their efforts. Eventually, hydrogen hubs may become interconnected, building out the structure needed for a national clean hydrogen economy. These connections might be through new, dedicated hydrogen pipeline infrastructure similar to that currently in place at a small scale along the Gulf Coast, or repurposing of some existing natural gas infrastructure or rights-of-way as is being considered in Europe,[70] and could develop along transportation fueling infrastructure corridors.

R&D efforts and demonstration programs like hydrogen hubs are valuable in showcasing opportunities for clean hydrogen and getting costs down. These government programs also have value as an enabler, and hubs that are able to build out successful production and end-uses will enable additional synergies. For example, development of hydrogen refueling infrastructure may also play synergistic benefits by reducing the barrier to zero emissions vehicles for the segment of the population for whom range is a

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[70] *See* European Union Agency for the Cooperation of Energy Regulators, *Transporting Pure Hydrogen by Repurposing Existing Gas Infrastructure* (Jul. 16, 2021), https://documents.acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/Transporting%20Pure%20Hydrogen%20by%20Repurposing%20Existing%20Gas%20Infrastructure_Overview%20of%20studies.pdf.

hindrance to plug-in battery electric vehicles. Pipeline blending of hydrogen with natural gas could also provide important opportunities for scaling production and experience with hydrogen handling across many end-use sectors, which may ultimately expand hydrogen's decarbonization reach. Technical cross-over between sectors, for example innovations in fuel cells for transportation and for power generation, could provide additional benefits. These types of synergies and co-benefits provide even more reason to kickstart the clean hydrogen economy and start learning from innovative demonstration regions.

Although RD&D support is extremely useful, it will likely not be enough to overcome cost and buildout challenges for hydrogen. To maximize the hydrogen decarbonization opportunity, support for broader clean hydrogen deployment will be needed. This support may take a variety of forms, with tax incentives for hydrogen a key tool currently under discussion in Congress. Production tax incentives especially are important and can be geared towards greater support for cleaner hydrogen production. With deployment, we can expect costs to come down dramatically. The figure below is an example of potential cost trajectory for hydrogen delivered to the transportation sector in Europe. Great reductions come through scaling not just of production but delivery and dispensing infrastructure, with increased utilization rates for fuel stations a key driver.

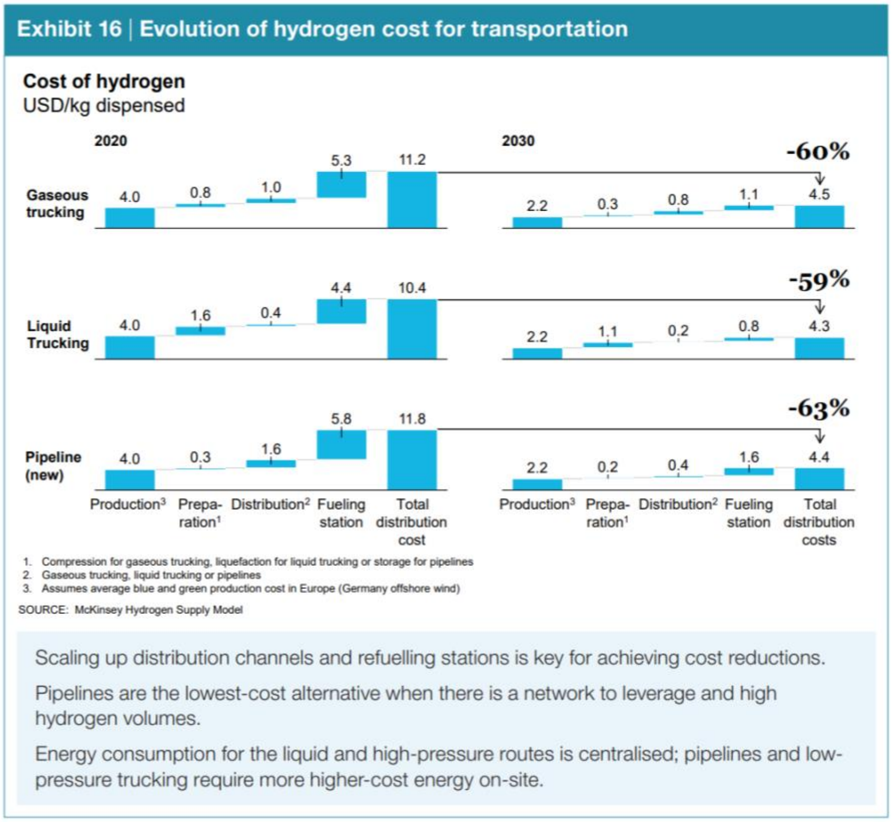
Exhibit 16 | Evolution of hydrogen cost for transportation

1. Compression for gaseous trucking, liquefaction for liquid trucking or storage for pipelines
2. Gaseous trucking, liquid trucking or pipelines
3. Assumes average blue and green production cost in Europe (Germany offshore wind)

SOURCE: McKinsey Hydrogen Supply Model

Scaling up distribution channels and refuelling stations is key for achieving cost reductions.

Pipelines are the lowest-cost alternative when there is a network to leverage and high hydrogen volumes.

Energy consumption for the liquid and high-pressure routes is centralised; pipelines and low-pressure trucking require more higher-cost energy on-site.

Figure 5: Example of evolution of potential delivered hydrogen costs in transportation. Larger scales and increased utilization are key to delivery cost reductions.[71]

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[71] Hydrogen Council, *Path to Hydrogen Competitiveness: A cost perspective* (Jan. 20, 2020), https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf.