CARBONDIRECT

Driving Transportation Decarbonization: From Theory to Action

Insights by Carbon Direct in partnership with Shopify

November 2021

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1. Introduction

To maintain a habitable planet, the world must act with urgency to mitigate the effects of human-induced climate change. For a fighting chance at limiting global warming to 1.5℃ above pre-industrial levels - the threshold for avoiding the most disastrous impacts of climate change in alignment with the Paris Climate Agreement - the world must cut greenhouse gas (GHG) emissions in half by 2030 and drive them down to net-zero by 2050.[1] Achieving this will require major changes across all sectors of the economy, with transportation being one of the most important. Given the need to move people and goods around the world, it currently accounts for around one-quarter of carbon dioxide (CO_2) emissions from fossil fuel combustion.[2]

The transportation sector today relies on petroleum for 90% of its fuel.[3] Combusting petroleum-based fuels in road vehicle, ship, and aircraft engines leads to the formation of CO_2 and other GHGs. While some large ships may be able to adopt forms of on-board carbon capture technology, in general it will not be feasible to efficiently capture CO_2 at the point of combustion for mobile emissions sources (i.e., from vehicle tailpipes). Because of this, achieving the 1.5℃ climate goal will require a concerted effort focused on reducing demand, improving efficiency, and transitioning transportation drivetrains towards low- or zero-emissions alternatives. Achieving the latter will most likely involve largely, or entirely, replacing the current world's liquid transportation fuel markets and infrastructure.

Policymakers, manufacturers, innovators, and consumers have made steady progress towards decarbonizing transportation. For example, California's Low Carbon Fuel Standard (LCFS) has reduced the carbon intensity[4] of transportation fuels by 7.4% from 2010 and adherence to the US Corporate Average Fuel Economy (CAFE) standards is expected to avoid 748 million metric tons of CO_2-equivalent (CO_2e[5]) road transport emissions from vehicles made in 2016-2025.[6,7] Additionally, electric vehicle adoption has risen steadily over the last decade, reaching around 11 million vehicles on the road globally in 2020 and avoiding at least 50 million tons of CO_2e emissions in 2020 alone.[8] Nevertheless, the emissions reductions needed to align with the goal of net-zero emissions by mid-century will require a greater rate and magnitude of transformation.

Population and economic growth are expected to more than double demand for freight and personal transportation in the next 30 years, creating additional challenges to transportation

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[1] Jeff Tollefson, "IPCC Says Limiting Global Warming to 1.5 °C Will Require Drastic Action", *Nature* 562, no. 7726, (2018): 172–73, https://doi.org/10.1038/d41586-018-06876-2.
[2] 'Transport – Topics', *International Energy Agency (IEA)*, Accessed 19 November 2021, https://www.iea.org/topics/transport.
[3] IEA (2021), "Net Zero by 2050", IEA, Paris https://www.iea.org/reports/net-zero-by-2050. All rights reserved.
[4] Carbon intensity is a measurement of GHG emissions across the life-cycle of a fuel (including production, distribution, and use).
[5] CO_2-equivalent (CO_2e) reflects a standardized way of representing global warming potential, normalized to that of carbon dioxide. CO_2e includes both CO_2 emissions and those from other greenhouse gases (GHGs), such as methane, black carbon, and hydrofluorocarbons (HFCs).
[6] "Data Dashboard", *California Air Resources Board*, Accessed 18 November 2021, https://ww3.arb.ca.gov/fuels/lcfs/dashboard/dashboard.htm
[7] "Light Duty CAFE Midterm Evaluation: Model Years 2022-2025", *National Highway Traffic Safety Administration*, (2016) https://www.nhtsa.gov/corporate-average-fuel-economy/light-duty-cafe-midterm-evaluation
[8] "Global EV Outlook 2021 – Analysis", *International Energy Agency (IEA)*, Accessed 18 November 2021, https://www.iea.org/reports/global-ev-outlook-2021.

decarbonization.[9] Fortunately there are numerous options in development for decarbonizing transportation across different vehicle classes and modes of travel. On-road transport currently enjoys more commercial-ready decarbonization options compared to other transportation modes. For example, a commercial market for electric light-duty passenger vehicles is developing with substantive percentage sales and infrastructure development in some countries, and battery- and hydrogen fuel cell electric trucks are starting to become available for medium- and heavy-duty vehicles. Other modes of transport, such as rail, marine shipping, and aviation currently present specific technology challenges that provide comparatively fewer decarbonization options ready for deployment. However, promising innovations and fuel technology advancements such as sustainable aviation fuels (SAFs), ammonia, hydrogen, and electrification are rapidly developing.

While reducing GHG emissions at the tailpipe is necessary for meeting climate goals, this alone is not sufficient. In some cases, fuels that have low emissions at the point of use may have high emissions earlier in the value chain, including conversion and processing steps, land-use change, and even electric grid emissions. Therefore, the GHG emissions of transportation fuels must be considered on a systems level, encompassing their life-cycle from upstream production to downstream point of use.

A combination of electrification and low-carbon liquid fuels along with efficiency improvements, decarbonizing the electricity grid, and behavioral changes will thus be essential elements of any pathway to decarbonize transportation supply chains in line with climate targets. In addition to reducing GHG emissions, a transition away from fossil fuels to cleaner alternatives for transportation would provide important health benefits for local air quality by reducing air pollutants from fuel combustion (e.g., sulfur, VOCs[10], PM[11], and smog).

This report provides information to manufacturers, carriers, corporate actors, and customers on how to reduce the carbon footprint of transportation (with a focus on transport of goods) and accelerate the transition to a net-zero emissions economy. The report details the importance of decarbonizing the transportation sector, assesses impact levers and fuel options (including their state of development, cost, and carbon footprint) and identifies key areas that need support.

2. Why do we need to decarbonize the transportation sector?

The global transportation sector is composed of numerous modes of transport including road, rail, air, and sea. The journey of a package to a customer usually spans multiple modes and vehicle types: marine shipping or aviation for global routes, rail or long-haul trucking between large storage facilities, medium-distance trucking to distribution centers, and “the last mile” from distribution centers to a customer’s door. Upstream, there is also the transportation of base materials and components to the producers of goods. The vast majority of these activities are powered by fossil fuels (primarily petroleum-based) and result in emissions of CO_2 and other greenhouse gases that are changing the Earth’s climate.

[9] “Vision 2050: A Strategy to Decarbonize the Global Transport Sector by Mid-Century”, *International Council on Clean Transportation (ICCT)*, (2020), https://theicct.org/publications/vision2050.
[10] Volatile organic compounds
[11] Particulate matter

Non-CO_2 climate forcing emissions

Carbon dioxide accounts for approximately 95% of the greenhouse gas emissions from the transportation sector.[12] However, other transportation-related emissions also cause climate impacts. Black carbon (soot), for example, has a high short-term global warming potential because it readily absorbs sunlight. Methane, a potent greenhouse gas, has a climate forcing effect more than 80-times that of carbon dioxide on a 20-year timescale and releases particulate pollution during combustion (e.g., in compressed natural gas [CNG] vehicles).[13] Other byproducts of fossil fuel combustion, such as nitrogen oxides (NO_x), are also deleterious to humans and the environment. In the United States, medium- and heavy-duty vehicles account for nearly half of NO_x emissions and approximately 60% of the fine particulate emissions from on-road vehicles.[14] Vehicles with transport refrigeration units powered by an auxiliary diesel engine emit greater than 16 times more NO_x and 40 times more particulate matter than the main engine of a truck per unit of energy produced.[15] These emissions are known to cause respiratory and cardiovascular disease, cancer, and premature death.[16,17] This also has adverse social effects as emissions from trucking disproportionately affect disadvantaged communities that live along trucking routes.[18] Electrification of these vehicles will ameliorate these negative public health impacts.

In addition, where refrigerants are required, such as in temperature-controlled transport or passenger air conditioning, leakage of these substances can have non-negligible climate impacts as they typically have global warming potentials thousands of times greater than that of CO_2. For example, hydrofluorocarbons (HFCs), which came into widespread use as a non ozone-depleting alternative to chlorofluorocarbons (CFCs),[19] have a global warming potential (GWP) that can range up to 14,800 times that of carbon dioxide.

Greenhouse gas emissions come from sources across the value chain, including fuel production, processing, distribution, onboard end-use, and associated land-use changes.[20] This makes it vital to assess the full "well-to-wheels"[21] emissions of transportation when considering sectoral decarbonization options. Upstream processes related to use of fossil gas, for example, can release significant fugitive methane emissions during gas extraction and distribution. When crops are diverted for use in biofuels, other land may be converted for crop production to meet other demands. If the land is already storing large amounts of carbon (i.e., in soils or vegetation), conversion can result in significant net greenhouse gas emissions.

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[12] "Transportation GHG Emissions and Trends", *US Department of Transportation,* Accessed 22 November, 2021. https://www.transportation.gov/sustainability/climate/transportation-ghg-emissions-and-trends

[13] Krajinska, Anna "Are Compressed Natural Gas Vehicles a Clean Solution for Transport?", *Transport & Environment*, (2020), https://www.transportenvironment.org/discover/are-compressed-natural-gas-vehicles-clean-solution-transport/.

[14] Zhiyuan, Fan, et al., "Green Hydrogen in a Circular Carbon Economy: Opportunities and Limits", *Columbia University - Center on Global Energy Policy*, (2021). https://www.energypolicy.columbia.edu/research/report/green-hydrogen-circular-carbon-economy-opportunities-and-limits

[15] "Refrigerated-Transport-White-Paper.Pdf", accessed 13 October 2021, https://www.cenex.co.uk/app/uploads/2021/04/Refrigerated-Transport-White-Paper.pdf.

[16] "Particulate Matter (PM) Pollution", *US Environmental Protection Agency (EPA)*, Accessed 22 November, 2021, https://www.epa.gov/pm-pollution

[17] O'Connor, Timothy. "100% Zero-Emissions Trucks. How Close Are We?" *Environmental Defense Fund*, September 16, 2021. https://www.edf.org/blog/2020/09/16/100-zero-emissions-trucks-how-close-are-we.

[18] Jaller, Miguel, Anmol Pahwa, and Michael Zhang, "Cargo Routing and Disadvantaged Communities", *UC Davis, Institute for Transportation Studies,* (2021) https://escholarship.org/content/qt9qg2318x/qt9qg2318x_noSplash_ca0d415cc00215766667d80c5c2b8ca0.pdf?t=qzsog5

[19] CFCs were successfully phased out by the Montreal Protocol.

[20] "Vision 2050: A Strategy to Decarbonize the Global Transport Sector by Mid-Century".

[21] Including upstream emissions from fuel or electricity production.

Together, passenger and freight transportation account for approximately one-quarter of CO_2 emissions from fossil fuel combustion and are therefore of great importance to address.[22,23] The transportation sector is responsible for approximately 8.5 billion metric tons (gigatons, or Gt) or more[24] of CO_2e emissions each year.[25,26]

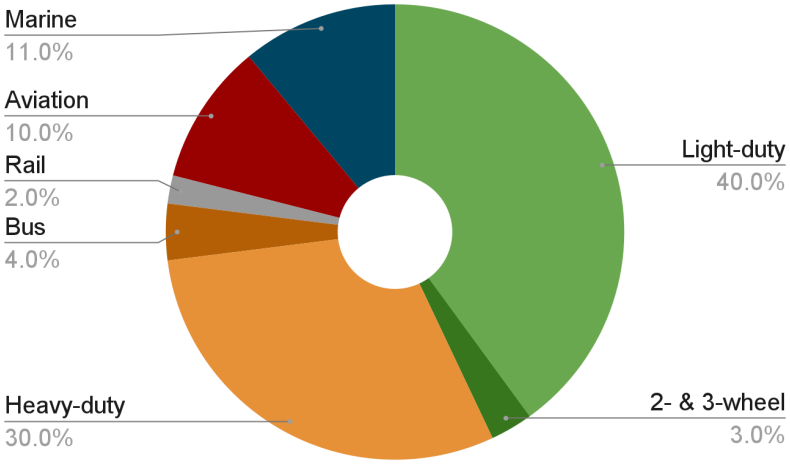


Figure 1. Global well-to-wheel CO_2 transportation emissions by mode of transport.[27]

Road transport accounts for more than 75% of CO_2 emissions in the transportation sector (Figure 1), with heavy-duty vehicles (HDVs: trucks, buses, tractor trailers) contributing only slightly less than light-duty vehicles (LDVs: passenger cars, light commercial vehicles, two- and three-wheeled vehicles) despite there being many fewer HDVs on the road. This is primarily due to higher use rates (duty cycles), greater emissions per distance traveled, and non-CO_2 emissions such as black carbon (from diesel-burning HDVs in particular) compared to LDVs.[28]

Emissions intensity varies substantially by mode and is often reported in a form normalized to economic activity (per-tonne-mile for HDV and per passenger-mile for LDV, as in Figure 2); regardless, absolute emissions are what matter for climate. Transport by air or road requires more energy and results in more greenhouse gas emissions than transport by rail or sea. This is at odds with the growing expectation of consumers for fast deliveries.

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[22] Tollefson, Jeff, "IPCC Says Limiting Global Warming to 1.5 °C Will Require Drastic Action", *Nature*, (2018) https://www.nature.com/articles/d41586-018-06876-2

[23] Wang, Shiying and Mengpin Ge, "Everything You Need to Know About the Fastest-Growing Source of Global Emissions: Transport", *World Resources Institute,* (2019) https://www.wri.org/insights/everything-you-need-know-about-fastest-growing-source-global-emissions-transport.

[24] Estimates from the International Council on Clean Transportation (ICCT) suggest that present day transportation emissions may be as high as 11.9 Gt/year based on higher estimates of life-cycle emissions from biofuels due to indirect land-use change.

[25] "Tracking Transport 2020 – Analysis", *International Energy Agency (IEA)*, accessed 6 October 2021, https://www.iea.org/reports/tracking-transport-2020.

[26] "Vision 2050: A Strategy to Decarbonize the Global Transport Sector by Mid-Century", *International Council on Clean Transportation (ICCT)* (2020): 5, https://theicct.org/publications/vision2050

[27] Figure adapted from "Vision 2050: A Strategy to Decarbonize the Global Transport Sector by Mid-Century".

[28] Kholod, Nazar, Meredydd Evans, and Teresa Kuklinski. "Russia's Black Carbon Emissions: Focus on Diesel Sources." *Atmospheric Chemistry and Physics* 16:1-15. DOI: 10.5194/acp-2016-475 https://www.pnnl.gov/science/highlights/highlight.asp?id=4425

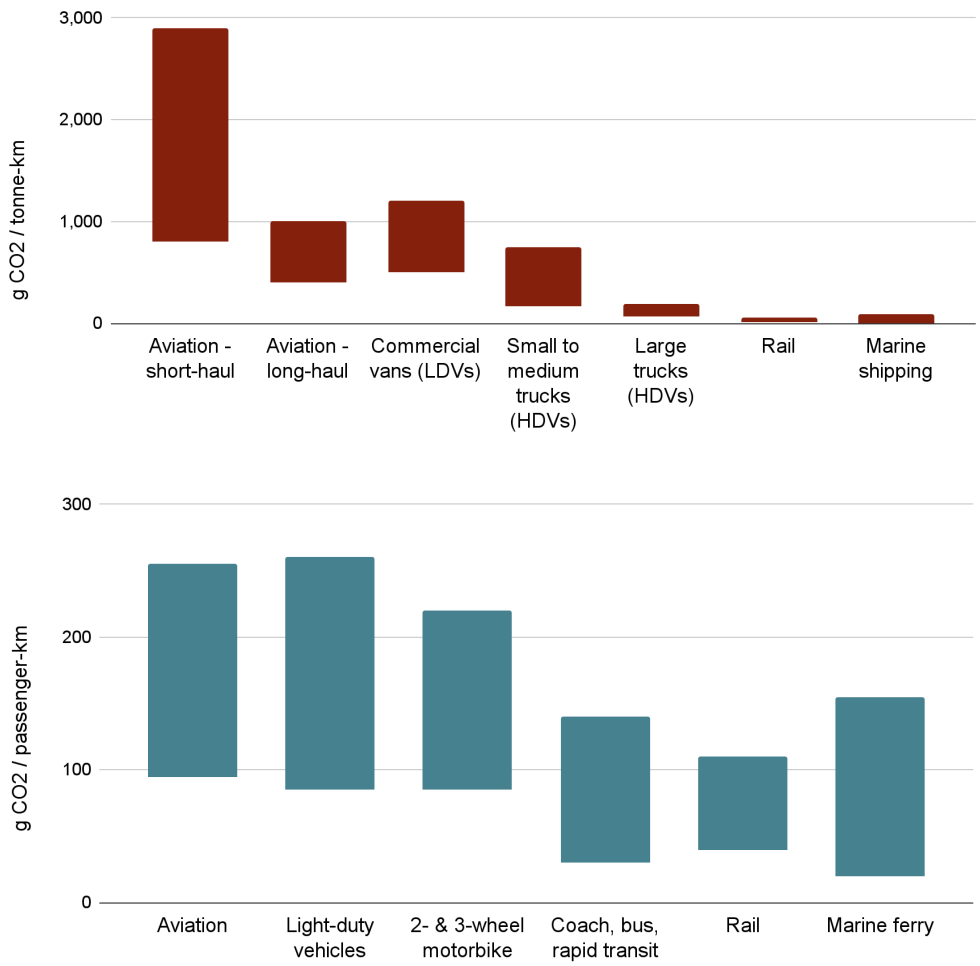


Figure 2. Approximate range of direct CO_2 emissions by different modes of freight and passenger transport when fueled by fossil energy. The red bars show emissions from transporting one tonne of goods a distance of one km, while the blue bars show the emissions from transporting one passenger the same distance.[29]

Under current policies,[30] the "baseline trajectory" of GHG emissions from the transportation sector is expected to nearly double by 2050.[31] Almost all (~90%) of this demand-led growth is expected to come from rapidly growing areas (China, Asia-Pacific, India, Africa), as well as global marine shipping and aviation segments which are expected to double under business-as-usual scenarios (Figure 3). Emissions from North America are projected to stay largely unchanged while current policies in the European Union will reduce ground transport emissions by about one-third by 2050.

Given that emissions from transportation are a large proportion of total global emissions, decarbonization of this sector is required to address climate change. To be compatible with limiting global warming to 1.5˚C above pre-industrial levels, the transportation sector must reduce absolute annual emissions despite an estimated increase in demand under current policies.

[29] "Transport — IPCC", *Intergovernmental Panel on Climate Change (IPCC),* accessed 15 November 2021, https://www.ipcc.ch/report/ar5/wg3/transport/.
[30] Policies adopted by 2019.
[31] "Vision 2050: A Strategy to Decarbonize the Global Transport Sector by Mid-Century".

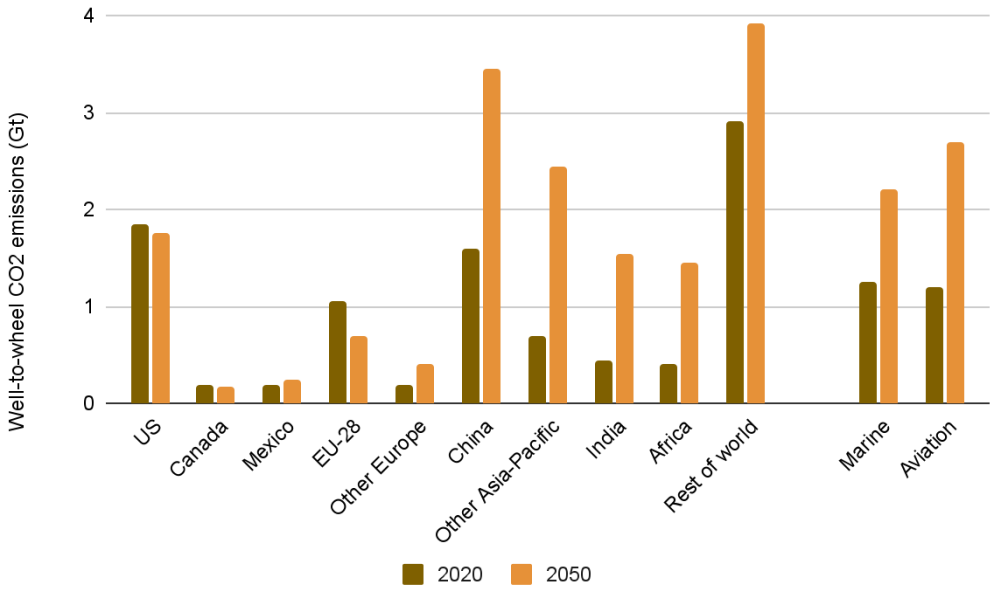


Figure 3. Transportation emissions by geographical region and those from marine and aviation transport segments, today (brown) and by projected for mid-century (orange).[32,33]

The International Council on Clean Transportation (ICCT) estimates that ambitious, yet feasible, policies could successfully drive 85% of the required reductions in the entire sector, with the largest opportunities being improvements in efficiency and the electrification of road transport. The final 15% of required reductions modeled by the ICCT could be achieved through reduction in demand such as by mode shifting (e.g., cycling instead of driving).[34]

Health effects

The climate challenges from transportation are compounded by their negative impact on human health, especially from HDV and marine transportation. Air pollution affects developing and developed nations alike. The World Health Organization estimates that exposure to outdoor air pollution causes 4.2 million premature deaths each year, and more than 7 billion people - 90% of the world - live in areas where air quality is outside healthy limits, including places in North America and Europe.[35] It is estimated that the transportation sector, specifically, is responsible for about 11% of deaths from fine particulate matter ($PM_{2.5}$ [36]) and ozone, with diesel-burning road transport being the largest contributor. Of these deaths, nearly one-quarter occur in North America and Europe.[37,38]

While the development of new low-carbon transportation systems will require management of health and safety challenges (e.g., ammonia handling), eliminating transport emissions would provide both climate and human health benefits that could potentially save hundreds of thousands of lives worldwide each year.

[32] Figure adapted from "Vision 2050: A Strategy to Decarbonize the Global Transport Sector by Mid-Century".
[33] Note: this chart reflects ICCT emission estimates from transportation (11.9 Gt/year today) which are greater than those of the IEA (8.5 Gt/year) based on higher estimates of life-cycle emissions from biofuels due to indirect land-use change.
[34] "Vision 2050: A Strategy to Decarbonize the Global Transport Sector by Mid-Century".
[35] "Air Pollution", *World Health Organization,* accessed 11 October 2021, https://www.who.int/westernpacific/health-topics/air-pollution.
[36] Particulate matter with a diameter less than 2.5 microns.
[37] In 2015, 385,000 premature deaths were attributed to transportation-related pollutants of fine particulate matter and ozone. Approximately 8% were in North America, 15% in Europe, 30% in China, and 22% in India.
[38] "Vision 2050: A Strategy to Decarbonize the Global Transport Sector by Mid-Century".

3. Options for decarbonizing transportation and current state of development

There are three fundamental strategies for decarbonizing transportation: **reducing the demand** for transport services, reducing the energy intensity of freight and passenger transport through **efficiency improvements**, and **reducing the carbon intensity of fuels** (including transitioning to new fuel/power technologies).

Reducing demand

A straightforward way to reduce transportation emissions is by simply reducing demand. Opportunities to do so may exist as a result of technological innovations as well as behavioral changes, and can be encouraged by regulatory mechanisms.

Innovations with the potential to reduce demand for transportation include new ways to produce and consume goods, such as the transition to electronic products (e.g., non-fungible tokens) and services, and opportunities to share vehicles. Car share schemes and use of public transit can reduce car ownership by up to 35%, and a shift towards shared vehicle and low-carbon modes of transportation has the potential to reduce more than 320 Mt of CO_2 emissions in total in the mid-2030s.[39]

Behavioral changes can also have a big impact on transportation emissions. Limiting long-haul flights and shifting modes of transit (e.g., use of high-speed rail instead of air transport or walking/biking and taking public transit instead of driving) reduces demand for carbon-intensive alternatives. Studies have shown that the impact of modal shifts can be significant—as one example, the IEA estimates that 15% of regional flights could be switched to existing rail options today.[40]

Regulatory mechanisms, such as congestion charges, can also support demand reduction for carbon intensive transportation. To reduce carbon emissions and the density of vehicles on the road, various municipalities have introduced congestion pricing with positive effects. London, Singapore, and Stockholm experienced a 10-16% reduction in carbon dioxide emissions following implementation.[41,42] In aviation, carbon pricing and consumer information has led to a reduction in growth of baseline passenger-kilometers by about 1-4% per year.[43]

Improving efficiency

We have an opportunity to be judicious with the energy that we use in the transportation sector. Engine and vehicle efficiencies have a long history of improvement for better fuel economy, which

[39] IEA (2021), "Net Zero by 2050", IEA, Paris https://www.iea.org/reports/net-zero-by-2050. All rights reserved.
[40] IEA (2021), "Net Zero by 2050", IEA, Paris https://www.iea.org/reports/net-zero-by-2050. All rights reserved.
[41] Provonsha, Emily and Nickolas Sifuentes, "Road Pricing in London, Stockholm, and Singapore: A Way Forward for New York City". *Tri-State Transportation Campaign,* Accessed 22 November 2021, https://nyc.streetsblog.org/wp-content/uploads/2018/01/TSTC_A_Way_Forward_CPreport_1.4.18_medium.pdf
[42] IEA (2021), "Net Zero by 2050", IEA, Paris https://www.iea.org/reports/net-zero-by-2050. All rights reserved.
[43] "Vision 2050: A Strategy to Decarbonize the Global Transport Sector by Mid-Century", *International Council on Clean Transportation (ICCT)*, (2020), https://theicct.org/publications/vision2050.

translates to lower carbon emissions, but there is room for further innovation. As they have in the past, efficiency improvements are likely to be achieved through engineering advancements. Examples include switching from internal combustion engines to electric drivetrains, the use of lighter materials, streamlining vehicles for better aerodynamics, use of regenerative braking, implementation of "eco-mode" programs that slow acceleration (among other optimizations), and predictive cruise control including platooning (driving trucks close together at constant speed).[44] Behavioral changes, such as use of these emissions-optimization tools, are also important and may be supported by driver education and real-time metering. Additional actions that improve efficiency are lowering of highway speed limits, route optimization (e.g., of ships and planes for weather), and use of low resistance and adequately pressurized tires.[45]

The effects of efficiency improvements can be meaningful. For example, research has shown that reducing the speed of ships, a strategy referred to as 'slow steaming', by 10% can reduce total emissions by 19%.[46] (To truly mitigate these emissions, it is important that the delay in transport time does not encourage an increase in the number of transport vessels, since that has the potential to counteract the reduced emissions.)

There are a number of efficiency standards in effect, in particular for road transport. For example, in the US, CAFE Standards regulate how far vehicles (light- and heavy-duty) must travel on a gallon of fuel.[47] In the EU, Carbon Intensity standards are targeting a 15% reduction of vehicle emissions from recent levels by 2025 and a 30% reduction or more, depending on the vehicle type, by 2030.[48, 49] There are also incentive schemes for low- or zero-emissions vehicles and fuel economy labelling directives.

Several regions have announced targets to phase out new internal combustion engine (ICE) cars in favor of low-carbon drivetrains (Figure 4).[50] Some industry associations have also made separate voluntary commitments to phase out fossil fuel use in vehicles.[51]

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[44] "Decarbonising Shipping", *Shell International B.V.,* (2020) https://www.shell.com/promos/energy-and-innovation/decarbonising-shipping-all-hands-on-deck/_jcr_content.stream/1594141914406/b4878c899602611f78d36655ebff06307e49d0f8/decarbonising-shipping-report.pdf

[45] "Decarbonising Shipping", *Shell International B.V.,* (2020) https://www.shell.com/promos/energy-and-innovation/decarbonising-shipping-all-hands-on-deck/_jcr_content.stream/1594141914406/b4878c899602611f78d36655ebff06307e49d0f8/decarbonising-shipping-report.pdf

[46] Degiuli, Nastia, et al., "The Impact of Slow Steaming on Reducing CO_2 Emissions in the Mediterranean Sea. Energy Reports", *ScienceDirect*, (2021) https://doi.org/10.1016/j.egyr.2021.02.046.

[47] "Corporate Average Fuel Economy (CAFE) - Self-Service Reporting Data Portal", *National Highway Traffic Safety Administration,* Accessed 22 November 2021. https://one.nhtsa.gov/cafe_pic/cafe_pic_home.htm

[48] "CO_2 emission performance standards for cars and vans", *European Commission,* Accessed 22 November 2021. https://ec.europa.eu/clima/eu-action/transport-emissions/road-transport-reducing-co2-emissions-vehicles/co2-emission_en

[49] "Reducing CO_2 emissions from heavy-duty vehicles", *European Commission,* Accessed 22 November 2021. https://ec.europa.eu/clima/eu-action/transport-emissions/road-transport-reducing-co2-emissions-vehicles/reducing-co2-emissions-heavy-duty-vehicles_en

[50] Wappelhorst, Sandra, "Update on government targets for phasing out new sales of internal combustion engine passenger cars", *International Council on Clean Transportation (ICCT)*, (June 2020) https://theicct.org/sites/default/files/publications/update-govt-targets-ice-phaseouts-jun2021_0.pdf

[51] For example, EU truck manufacturers: https://www.acea.auto/press-release/all-new-trucks-sold-must-be-fossil-free-by-2040-agree-truck-makers-and-climate-researchers/

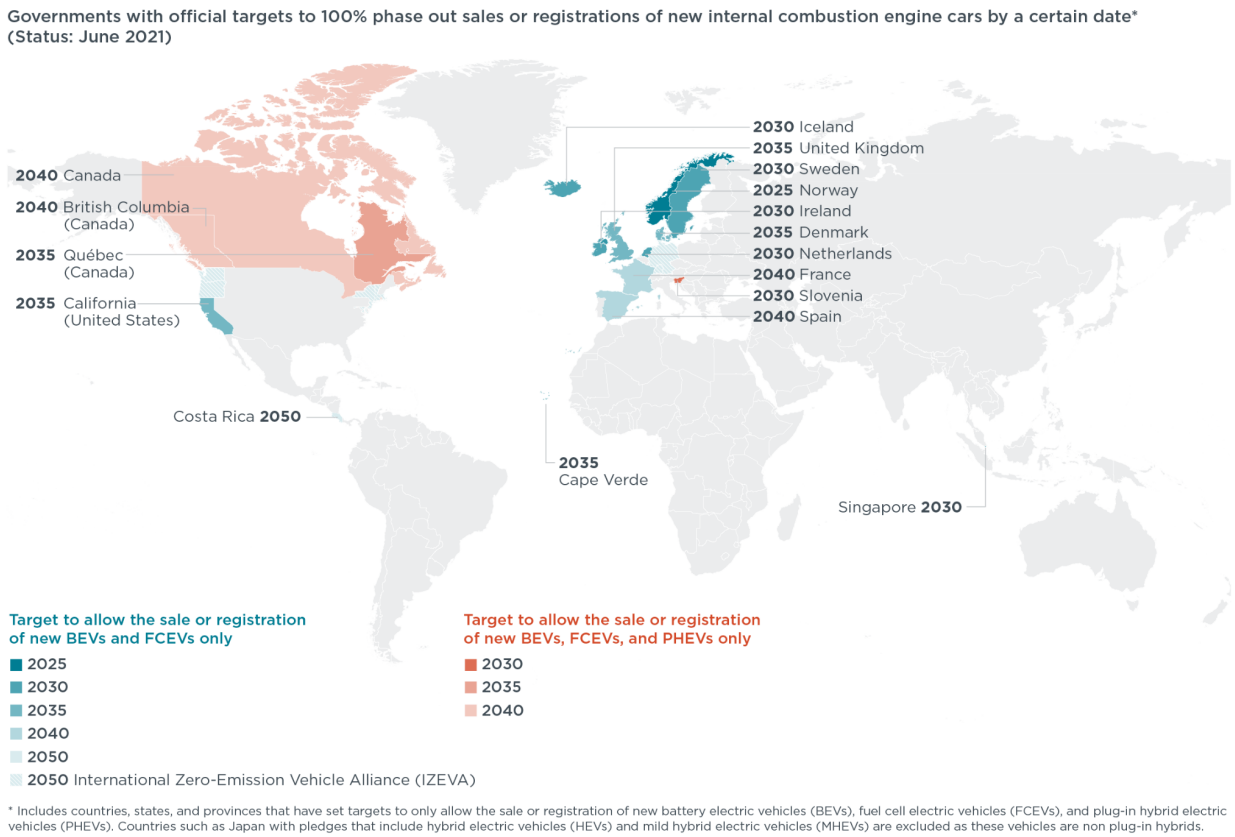


Figure 4. Government targets to completely phase out sales or registrations of new internal combustion engine cars.[52]

For both shipping and aviation, fuel economy has been a continuous focus of fleet owners from a total cost of ownership perspective as fuel costs are a significant part of the operating costs. Industry associations like the International Marine Organization (IMO), International Civil Aviation Organization (ICAO), and International Air Transport Association (IATA) are the de facto global standardization bodies (to which country regulations align) for the marine shipping and aviation industries. They give guidance, set efficiency and carbon standards, and have set carbon intensity reduction aspirations for the industries.[53]

[52] Reprinted with permission from Wappelhorst, Sandra "Update on Government Targets for Phasing out New Sales of Internal Combustion Engine Passenger Cars". *The International Council on Clean Transportation (ICCT),* (June 2021) https://theicct.org/publications/update-govt-targets-ice-phaseouts-jun2021

[53] IATA 1.5% efficiency per year, net cap from 2020 and 50% reduction by 2050 https://www.iata.org/en/programs/ops-infra/fuel/fuel-efficiency/ , IMO Energy Efficiency Desing Index https://www.imo.org/en/OurWork/Environment/Pages/Technical-and-Operational-Measures.aspx , IMO ambition for 40% carbon intensity reduction by 2030 (vs 2008) https://www.imo.org/en/MediaCentre/PressBriefings/pages/42-MEPC-short-term-measure.aspx , ICAO: In order to be certified under the standard and sold internationally, each aircraft/engine combination produced by a manufacturer will need to meet a ICAO Metric Value limithttps://theicct.org/sites/default/files/publications/ICCT-ICAO_policy-update_revised_jan2017.pdf

Reducing the carbon intensity of fuels

Biofuels

Fuel/technology
Biofuels are liquid hydrocarbon fuels made using carbon from recent plant growth. Biodiesel is an established industry with very simple technology (transesterification) and growing demand. 'Drop-in' biofuels can be directly used in existing vehicle engines and fueling infrastructure, whereas other forms of biofuels may require engine modifications or be restricted to limited blending with conventional fuels. Deployment of this fuel is primarily a function of economics (cooking/vegetable oils are expensive), but renewable fuel standards and tax credits have supported the industry in recent years. In the US, the national average price of biodiesel (B99-100) was $3.63 in July 2021 (compared to $3.26 for fossil diesel).[54]

Decarbonization opportunity
Plant growth removes carbon from the atmosphere. It is possible for the use of recently grown plants in producing biofuel to lead to lower net emissions impact than the production of fossil fuels. In contrast, the latter extracts fossilized carbon that is securely stored beneath the Earth's surface and combusts it, adding this carbon to the atmosphere with no corresponding process to recapture it. When made from waste oil feedstocks, the life-cycle GHG emissions from biodiesel (B100) are approximately 80% lower than those from petroleum diesel.[55] Combustion of biodiesel emits fewer harmful pollutants such as carbon monoxide and sulfur dioxide than combustion of petroleum diesel, but may produce more nitrogen oxide emissions.[56]

However, not all biofuels are helpful for mitigating climate change. Emissions associated with biomass production (including potential land-use change), harvesting, and transport of the plant material used to produce biofuels (the biomass "feedstock") can in certain cases cumulatively outweigh the emissions benefits to the point where the use of biofuels may have a worse climate outcome than the use of fossil fuels. Some harvesting practices can also harm biodiversity and have a range of negative impacts on a broad range of other ecosystem services.

Limitations
Because of this, there are limits to the total amount of biomass that can be sourced sustainably, which includes waste and residual biomass (e.g., from forestry, agriculture, and municipal and industrial sources) as well as other non-food biomass. Sustainable biomass feedstocks are also in high demand for other applications such as for building materials, negative emissions[57], and other energy needs. Biomass is often allocated to other uses, making regional & long-term availability of sustainable biomass a limitation to scaling biofuels.

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[54] Alternative Fuels Data Center. "Fuel Prices." *US Department of Energy: Energy Efficiency & Renewable Energy*, (July 2021) afdc.energy.gov/fuels/prices.html, https://afdc.energy.gov/files/u/publication/alternative_fuel_price_report_july_2021.pdf.
[55] Calculated based on sources within: "LCFS Pathway Certified Carbon Intensities", *California Air Resources Board*, accessed 18 November 2021, https://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities.
[56] "Biofuels explained: Biomass-based diesel and the environment." *US Energy Information Administration.* (10 December 2020) https://www.eia.gov/energyexplained/biofuels/biodiesel-and-the-environment.php
[57] Also commonly referred to as carbon dioxide removals.

Feedstocks for "first-generation" biodiesel encompass edible oil crops such as soybean, palm, canola, or sunflower, which are associated with high land use/land-use change, nutrient requirements, and water demand. Using food crops for biodiesel positions these crops in direct competition with existing supply chains and can be a stressor on critical resources. While palm oil plantations have exceptionally high yields compared to other feedstocks, there are several cost and sustainability disadvantages that present challenges to supply at scale.

One current issue is a widening gap between supply and demand for oilseed crops, as potential uses including biodiesel for road transport, bio-derived SAFs for air transport, and numerous non-transportation applications compete for limited supply.[58][59] The surging demand has caused the price of exported oils to double in the past year.[60] In addition to driving up prices, high demand for refined oilseed products increases the risk of land-use change as suppliers are incentivized to increase production. For example, in regions where oil palm production has expanded, it has resulted in deforestation and loss of biodiversity of tropical forests.[61] Palm plantations have also been associated with draining of peatlands, an act which changes the landscape from one that stores significant amounts of carbon to one that emits substantial amounts of GHGs.[62] Ensuring that more sustainable practices are adopted would be challenging since 40% of the supply chain is made up of small landholders.[63]

Trying to optimize oilseed selection to avoid competition for land may be ineffective because refined oils are interchangeable for many uses, meaning demand for one type of oil can affect demand for others. As sustainable sourcing is difficult to ensure, the use of biofuels to mitigate emissions in the transportation sector should be approached with caution. More broadly, where biofuels are applied, the safest bet is to source waste biomass feedstocks rather than food crops and to prioritize their application in use cases without abundant alternatives (e.g., for air rather than road transportation).

Electrification

Fuel/technology

Electrification involves fundamental changes to vehicle drivetrains by replacing internal combustion engines with batteries and electric motors. This also requires a new "fueling" infrastructure based on the electric power grid rather than liquid fuel distribution. The economics for transportation electrification are influenced by multiple factors such as battery and electricity costs, of which battery pack costs have declined 89% since 2010 (from $1,100/kWh in 2010 to $137/kWh in 2020), and are expected to further decline to $100/kWh by 2023.[64]

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[58] Doliente, Stephen S. et al., "Bio-aviation Fuel: A Comprehensive Review and Analysis of the Supply Chain Components", *Frontiers in Energy Research,* (2021). https://doi.org/10.3389/fenrg.2020.00110
[59] Radich, Tony, "The Flight Paths for Biojet Fuel", *U.S. Energy Information Administration*, (2015): 18. https://www.eia.gov/workingpapers/pdf/flightpaths_biojetffuel.pdf
[60] "Oilseed: World Markets and Trade", *USDA Foreign Agricultural Service*, (2021), https://downloads.usda.library.cornell.edu/usda-esmis/files/tx31qh68h/2v23wp329/6t054b55w/oilseeds.pdf.
[61] Doliente, Stephen S. et al., "Bio-Aviation Fuel". (2015)
[62] Doliente, Stephen S. et al., 'Bio-Aviation Fuel'. (2015)
[63] "RSPO Smallholders", *Roundtable on Sustainable Palm Oil*, (2021) https://rspo.org/smallholders.
[64] Bloomberg New Energy Finance. "Battery Pack Prices Cited Below $100/kWh for the First Time in 2020, While Market Average Sits at $137/kWh." *BloombergNEF.* (2020) https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/.

Consumer adoption of electric vehicles has experienced considerable growth over the last decade, with the global stock increasing 43% from 2019 to 2020 alone and three million new electric vehicles being registered in 2020 (out of a total stock of 10 million that year).[65] By 2025, the International Energy Agency projects that global electric vehicle deployment will be on track to meet its Sustainable Development Scenario, which aligns with the Paris Climate Agreement and efforts to limit warming to no more than 2°C.[66] In 2019, 90% of all electric vehicle sales occurred in China, the United States, and Europe, which also constitute the largest global markets for electric vehicles at present.[67]

Decarbonization opportunity

Electrification is positioned to considerably reduce both greenhouse gas emissions and criteria air pollutants[68] from the transportation sector, assuming an ample supply of clean electricity from various generation sources. Electrified vehicles do not produce tailpipe emissions, but may have upstream emissions depending on the source of electricity used to charge their batteries. Therefore, electrification as a strategy for decarbonizing transport is closely tied to decarbonizing the power grid. Any potential emissions associated with transportation electrification will stem from upstream electricity generation and the embodied emissions in the capital stock of physical assets (e.g., mining emissions associated with materials used to manufacture electric vehicles). Criteria air pollutants would also exist at the point of electricity generation if fossil fuels are used as a fuel source. However, neither greenhouse gas emissions nor criteria air pollutants would be released at the point of use for any fully-electrified mode of transportation, improving air quality in cities and communities located close to highways.

The emissions reduction potential of transportation electrification is predicated on increasing the share of clean energy technologies, such as renewables, nuclear, and carbon capture with storage in the electricity generation mix. Electric vehicles will therefore become less emissions-intensive over time and across their product life-cycle as the carbon intensity of the electricity supply in their location decreases.

Limitations

Reducing the emissions intensity of the power grid represents a major hurdle to this decarbonization strategy. Another key challenge of vehicle electrification is managing battery weight/volume and energy density, which compete with the space and weight available to transport goods and/or people.[69] Improvements in lithium-ion battery performance have made this feasible for light-duty vehicles and potentially heavy-duty vehicles. Electrifying other end-uses in the transportation sector such as marine shipping and aviation is more difficult given these limitations. A closely related challenge is vehicle range and the logistics of battery charging, which is generally much slower than liquid refueling unless battery swapping or expensive “fast charging” equipment

[65] “Trends and Developments in Electric Vehicle Markets – Global EV Outlook 2021 – Analysis”, *International Energy Agency (IEA)*, accessed 17 October 2021 https://www.iea.org/reports/global-ev-outlook-2021/trends-and-developments-in-electric-vehicle-markets.
[66] “Electric Vehicles”, *International Energy Agency (IEA)*, (2020), Paris https://www.iea.org/reports/electric-vehicles.
[67] “Electric Vehicles”, *International Energy Agency (IEA)*, (2020)
[68] Criteria air pollutants are carbon monoxide, lead, nitrogen oxides, ground-level ozone, particle pollution (sometimes called particulate matter), and sulfur oxides. These pollutants are regulated and thresholds for permissible levels are guided by science-based criteria.
[69] “Aircraft Technology Roadmap to 2050”, *International Air Transport Association (IATA)*, (n.d.) https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/technology20roadmap20to20205020no20foreword.pdf.

is used. For vehicles with high utilization, particularly freight, this "refueling" (battery charging) time may be a major limitation.[70]

The pace and scale of transportation electrification will vary over time across different modes of travel. This depends on a range of factors related to technology (continued breakthroughs in different battery technologies, advanced battery and electric vehicle manufacturing capabilities), economics (deployment through new market applications, favorable economics for consumer mass adoption of electric vehicles), and infrastructure/supply (infrastructure buildout of electric vehicle charging stations, sufficient supply of clean electricity, supply chain readiness to source critical minerals for batteries such as lithium, cobalt, and nickel).

Hydrogen

Fuel/technology

Hydrogen (H_2) has been an area of active research and development in transportation since first being used as liquid rocket fuel by NASA in the 1950s.[71] Versatility and high energy density are key characteristics of hydrogen that make it attractive for transport applications, particularly for transporting heavy loads across long distances. Hydrogen is an extremely energy dense fuel on a mass basis, containing three times the energy per kilogram than diesel and gasoline (Figure 5).[72,73] This means that the weight of hydrogen fuel does not significantly reduce the amount of freight that can be carried by vehicles that have gross vehicle weight limits. Also, on-board hydrogen tanks can be refueled quickly, making the refueling process very similar to diesel or gasoline refueling. As an energy carrier, hydrogen can either be combusted in an engine similar to jet-fuel powered gas turbines used in aviation or it can undergo an electrochemical reaction within a fuel cell to produce electricity used to drive an electric motor.[74] Vehicle drivetrains, fuel storage, and fueling infrastructure must therefore undergo modifications to use hydrogen as a fuel.

[70] Zhiyuan, Fan, et al., 'Green Hydrogen in a Circular Carbon Economy: Opportunities and Limits', *Columbia University - Center on Global Energy Policy*, August 2021.
[71] Dawson, Virginia P. and Mark D. Bowles, "Taming Liquid Hydrogen", *National Aeronautics and Space Administration (NASA),* (2004) https://history.nasa.gov/SP-4230.pdf
[72] Gasoline has a density of 32 MJ/L.
[73] One kilogram of hydrogen contains as much energy as a gallon of gasoline.
[74] Some OEM's are building and testing H2 fuelled ICEs which are at lower technology readiness level than H2 fuel cells.

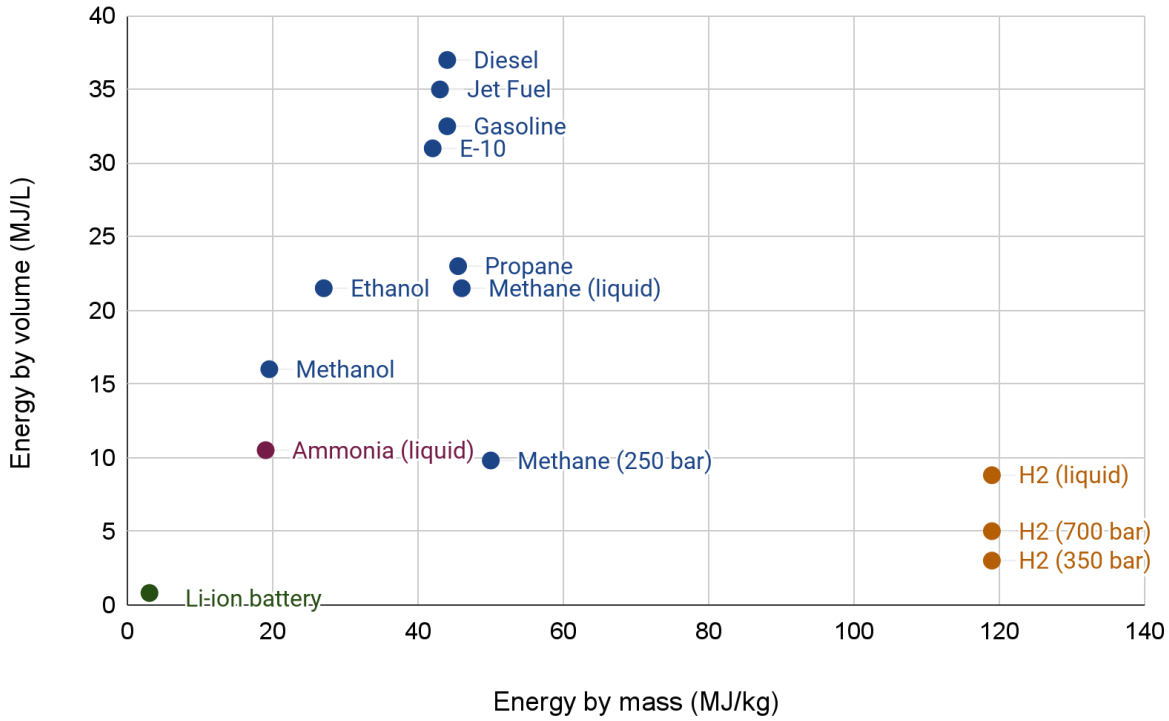


Figure 5. Energy densities of different energy storage and fuel technologies by mass and volume; hydrocarbons are shown in blue. To the top of the chart are fuels with more energy in a given amount of space; to the right of the chart are fuels with more energy per kilogram of fuel.[75]

While battery-electric vehicles (BEVs) are the clear contender over fuel cell electric vehicles (FCEVs) for light-duty applications, it remains an open question as to which will be preferential in a heavy-duty vehicle fleet. From a systems perspective, the overall energy efficiency of BEVs (powered through clean electricity) is higher than that of FCEVs, but the latter enjoy some advantages for fleet owners. Refueling hydrogen tanks is significantly faster than charging vehicle batteries, even with fast-charging equipment that can reduce vehicle operational time. Battery swapping can eliminate this delay, but requires different infrastructure. Also, fleet owners with centralized depots can potentially produce and store "green" hydrogen on-site to satisfy refueling needs rather than relying on broad penetration of hydrogen infrastructure. How the costs and energy density of lithium-ion batteries evolve in comparison with the cost of hydrogen production and the cost and efficiency of fuel cell technologies will determine the preferred drivetrain technology for various HDVs. Regardless, FCEVs have a role to play in decarbonizing heavy-duty transport and may be preferential to BEVs for offroad use, transport of particularly heavy loads, and transport of goods over short distances in logistics operations in locations producing "green" hydrogen (e.g., ports).[76]

Hydrogen as a fuel for road transport is more developed than for other modes of transport, such as by rail, sea, or air. Hydrogen fuel cell trains are an alternative low-carbon rail option where direct

[75] Adapted from Davis, Stephen J. et al., "Net-Zero emissions energy systems". *Science*, (2018) https://www.science.org/doi/10.1126/science.aas9793
[76] "Why the Future of Long-Haul Trucking Is Electric", *Transport & Environment*, (2021) https://www.transportenvironment.org/discover/why-the-future-of-long-haul-trucking-is-electric/.

electrification of trains is not suitable.[77] There are several trials using hydrogen for rail in the European Union, with 100-200 km commercial services already in operation in Germany and Austria.[78,79]

For shipping, commercial operation of hydrogen fuel cell ferries is starting and other short- and medium-range vessels are expected to be deployed in the near future. Hydrogen for air transport can be applied via fuel cells (for flights <1,600 km) or combustion for other short-haul flights. The IEA estimates that up to 75% of commercial flights are of a suitable distance to employ hydrogen fuel cells (though hydrogen would only account for one-third of total aviation fuel since liquid/carbon-based fuels would still be needed for long-haul flights).[80] Airbus, Boeing, and innovators such as ZeroAvia are in development of suitable aircrafts for use of hydrogen via fuel cells and/or direct combustion.[81,82,83]

The three main ways to produce hydrogen with little to no associated carbon emissions are the "green", "blue", and biomass-derived routes.[84] "Green" hydrogen is produced from the electrolysis of water (i.e., using electricity to separate H_2 and O_2 from H_2O) using clean power. "Blue" hydrogen is produced from fossil gas via a steam methane reformer (SMR) or similar technology with applied carbon capture and storage (CCS). Biohydrogen is typically produced from biomass feedstocks through conversion processes such as gasification and pyrolysis.[85]

The cost of fuel cells has fallen 70% since 2008, but the cost of low-emissions hydrogen is still high.[86] The cost of "green" hydrogen production is heavily dependent on the electricity price and thus varies by geography, but it is generally greater than $3/kg; meanwhile, "blue" hydrogen costs can range between $1.3-2.9/kg, depending on gas prices and the cost of carbon capture.[87] The cost of biohydrogen is projected to be about $3/kg, although no commercial scale plants are in operation.[88] In comparison with these low-carbon options, hydrogen from fossil gas without CCS is the cheapest option at just $0.5-2.2/kg without a carbon price. However, by 2030, anticipated reductions in electrolyzer costs are expected to facilitate production of "green" hydrogen at less than or equal to $2/kg, making it more economically competitive.[89]

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[77] Where it is not feasible to electrify a third rail, the use of hydrogen can be a viable low-carbon option as the fuel will displace a relatively small amount of the weight available for carrying freight compared to other fuels.
[78] "Global Hydrogen Review", *International Energy Agency (IEA),* (2021)
https://www.iea.org/reports/global-hydrogen-review-2021/
[79] "Decarbonising Shipping", *Shell International B.V.,* (2020)
https://www.shell.com/promos/energy-and-innovation/decarbonising-shipping-all-hands-on-deck/_jcr_content.stream/1594141914406/b4878c899602611f78d36655ebff06307e49d0f8/decarbonising-shipping-report.pdf
[80] "Global Hydrogen Review", *International Energy Agency (IEA),* (2021)
[81] "ZEROe", *Airbus,* Accessed 22 November 2021,
https://www.airbus.com/innovation/zero-emission/hydrogen/zeroe.html
[82] Temminghoff, Bruce S, et al., "Opportunities for hydrogen in aviation", *CSIRO*. (2020)
https://www.csiro.au/-/media/Do-Business/Files/Futures/Boeing-Opportunities-for-hydrogen-in-commercial-aviation.pdf
[83]"Decarbonising Shipping", *Shell International B.V.,* (2020)
[84] "Pink/purple" hydrogen can be produced from nuclear power through electrolysis or thermochemical routes. "Turquoise" hydrogen can be produced from methane pyrolysis, yielding hydrogen and solid carbon.
[85] E.g., through gasification and syngas separation.
[86] "Global Hydrogen Review", *International Energy Agency (IEA),* (2021
[87] "Making the Hydrogen Economy Possible", *Energy Transitions Commission*, (2021)
https://www.energy-transitions.org/publications/making-clean-hydrogen-possible/
[88] Whitty, Kevin, Jitka Hrbek, and Jim Spaeth, "Task 33: Gasification of Biomass and Waste", *IEA Bioenergy,* (2019): 7
https://www.ieabioenergy.com/wp-content/uploads/2019/11/IEA-Bioenergy_Task-33-Triennium-2016-2018-2.pdf
[89] "Making the Hydrogen Economy Possible", *Energy Transitions Commission*, (2021)
https://www.energy-transitions.org/publications/making-clean-hydrogen-possible/

Decarbonization opportunity

Currently, ~90 Mt/yr of hydrogen is produced globally and almost entirely from fossil fuels without CCS, resulting in annual emissions totaling nearly 0.9 Gt CO_2.[90] Almost all of this demand comes from refining, production of ammonia and methanol, and other industrial uses. Demand for H_2 is expected to grow as hydrogen is increasingly adopted for new decarbonization applications. While the direct use of hydrogen in a fuel cell electric vehicle produces no tailpipe carbon emissions nor criteria air pollutants such as NO_x and particulate matter, the full life-cycle carbon footprint of the hydrogen fuel can vary widely depending on the production technology. When produced with clean electricity, the resulting "green" hydrogen is carbon neutral, but without low-carbon electricity, emissions from hydrogen production via electrolysis can be significant . During "blue" hydrogen production, carbon dioxide emissions are captured and stored, generally at a high capture rate. However, this route is challenging to fully decarbonize as it requires mitigation of methane leakage and combustion of methane via flares in the fossil gas supply chain. Finally, biohydrogen produced with waste biomass and CCS can lead to carbon neutral or carbon-negative hydrogen (Figure 6).

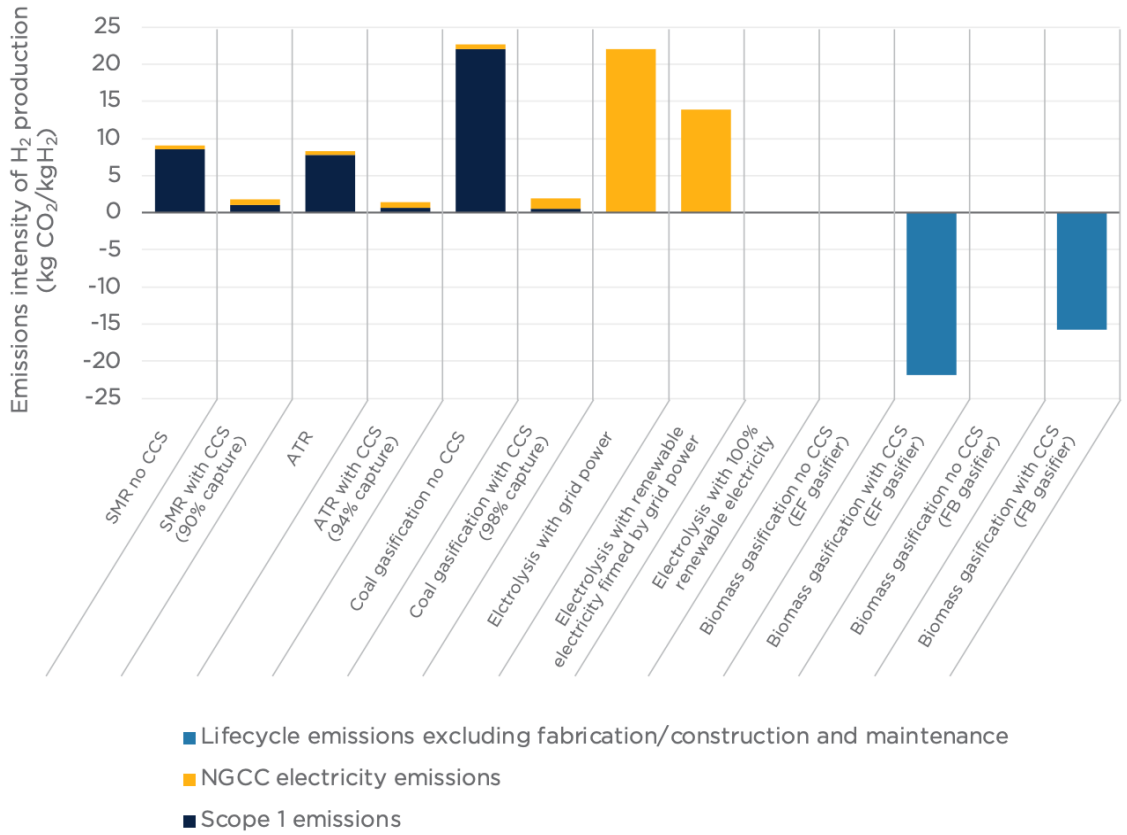


Figure 6. This figure demonstrates the emissions intensity across various hydrogen production methods.[91] 'Scope 1 emissions' refers to the direct GHG emissions produced by owned operations of an agency (i.e.,

[90] "Global Hydrogen Review", *International Energy Agency (IEA),* (2021)

[91] Assumes emissions intensity of natural gas combined cycle (NGCC) of 400 $kgCO_2$/MWh, 55kWH/kgH_2 for electrolysis, and 37% of production from grid firmed electrolysis utilizes zero emissions renewable electricity. EF = entrained flow. FB = fluidized bed. ATR = autothermal reforming. Electricity required for methane and coal production pathways are full-lifecycle including power used in methane and coal production. Fugitive emissions from natural gas and coal production are not explicitly considered and will add to the total lifecycle emissions from fossil pathways. Lifecycle emissions from construction and maintenance of renewable generation facilities and biomass production are also not fully considered and will add to the emission intensity of those production pathways.

the emissions from a boiler at a power plant). Natural gas combined cycle (NGCC) refers to power plants where, to improve fuel to power efficiency, the exhaust of a gas turbine cycle is integrated with a steam cycle. This figure was published with research from the Center on Global Energy Policy at Columbia University based on data published by the Global CCS Institute.[92, 93]

Limitations

The use of hydrogen in the transportation sector is currently limited; today, it accounts for <0.01% of final energy used in the sector. There are nearly 43,000 fuel cell electric vehicles (FCEVs) on the road globally, approximately 20% of which are buses and trucks (nearly all of which are in China). This is nearly a six-fold increase from 2017, but it is far smaller than the 11 million battery electric vehicles on the road today. While only five models of fuel cell trucks are currently available, 11 more are expected in the next year or two. For example, Volvo and Daimler have teamed up to address long-haul trucking with hydrogen. The capacity of hydrogen refueling stations, however, is lagging, and further buildout of associated infrastructure is needed.[94]

Hydrogen can be transported and stored in either a liquid or gaseous state. Very low temperatures (-253°C) are required to transport hydrogen in a liquid state, while maintaining hydrogen in a gaseous state requires high pressures (350-700 bar). Currently, hydrogen is commonly carried as a liquid in cryogenic tanker trucks and railcars, and as a gas by pipeline.[95] Existing natural gas pipelines can carry approximately 10%[96] hydrogen ("hydrogen blending") without significant upgrades, and some can be fully repurposed to transport 100% gaseous hydrogen at lower cost than new builds.[97,98]

The first ocean-going liquid hydrogen tanker was launched in 2019, but transport of hydrogen by sea remains almost non-existent.[99] As the hydrogen industry scales, longer term and larger scale options for hydrogen storage will need to be explored. For large scale stationary storage, salt caverns and depleted natural gas reservoirs can be used; there are four salt caverns in current use for gaseous hydrogen storage to date.[100]

Low-carbon hydrogen production technologies are still nascent and need to be scaled faster. To meet the anticipated demand for "green" hydrogen in a net-zero emissions economy, all sources of low-carbon electricity supply will need to be considered to ensure sufficient production capabilities and the costs of electrolyzers must fall to help facilitate deployment. Europe is leading in deployment of electrolyzers to produce "green" hydrogen and global capacity has doubled over the past five years. There are now nearly 400 projects under development; nevertheless, their success

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[92] Zhiyuan, Fan, et al., "Green Hydrogen in a Circular Carbon Economy: Opportunities and Limits", *Columbia University - Center on Global Energy Policy*, (2021).
[93] Zapantis, Alex, "Blue Hydrogen", *Global CCS Institute,* (2021)
https://www.globalccsinstitute.com/wp-content/uploads/2021/04/CCE-Blue-Hydrogen.pdf
[94] "Global Hydrogen Review", *International Energy Agency (IEA),* (2021)
[95] Brown, Andy, "Hydrogen Transport", *The Chemical Engineer*, (2019)
https://www.thechemicalengineer.com/features/hydrogen-transport/
[96] With some sources suggesting blending of up to 30% could be possible.
https://www.energy.gov/sites/default/files/2021-08/hyblend-tech-summary.pdf
[97] Altfeld, Klaus and Dave Pinchbeck, "Admissible hydrogen concentrations in natural gas systems", *Gas for Energy*, ISSN 2192-158X, (2013) https://gerg.eu/g21/wp-content/uploads/2019/10/HIPS_Final-Report.pdf
[98] "Global Hydrogen Review", *International Energy Agency (IEA),* (2021)
[99] "World first for liquid hydrogen transportation", *Lloyd's Register*, (2020)
https://www.lr.org/en/insights/articles/world-first-for-liquid-hydrogen-transportation/
[100] Laban, Maarten Pieter, "Hydrogen Storage in Salt Caverns", *Delft University of Technology*, (2019)
http://repository.tudelft.nl/.

will only supply one-tenth as much "green" hydrogen as is necessary to be on track for net-zero emissions by mid-century.[101] Current production of "blue" hydrogen from fossil gas with CCS is also limited today and capacity is primarily concentrated in Canada and the US. Hydrogen from biowaste gasification is technically viable and extensively studied; however, it is not operated in commercial plants, either with or without CCS.[102] A recent UK government report suggested that biowaste hydrogen with CCS may have the lowest overall hydrogen production cost in the future (due to the carbon removal income), but the overall capacity will be constrained with limited supply of biowaste and smaller scale gasification plants.[103] Similar to concerns with biofuels, the sustainability is highly dependent on sourcing of the biomass feedstock, which can result in significant carbon emissions and has competing uses.

To date, 12 countries in addition to the European Union have published national strategies to support the growing hydrogen economy and 19 more are expecting to publish their strategies by the end of this year.[104] International organizations, such as the Green Hydrogen Coalition, the Hydrogen Council and the Fuel Cell and Hydrogen Energy Association are driving research, development, and deployment of hydrogen technologies and are encouraging private sector investment. Economy-wide adoption of hydrogen fuels will nevertheless require private and public sector cooperation.[105]

Methanol

Fuel/technology

Methanol (CH_3OH) has been used and marketed in the United States as an alternative transportation fuel to fossil fuels since the 1990s. It can be used in a combustion engine in place of diesel either in its pure form (M100) or mixed with unleaded gasoline (in a 85:15 ratio, M85). Methanol has an energy density of about two-thirds by mass of typical hydrocarbon fuels and about half the energy density by volume (Figure 5). Methanol is a liquid at ambient temperature and pressures, and so is straightforward to store, transport and distribute. Its compatibility with existing ships, for example, makes methanol attractive as a near term decarbonization solution.[106] The International Maritime Organization has already approved interim safety and fuel handling regulations for methanol, but not yet for ammonia and hydrogen.[107] Maersk recently announced a $1.4 billion purchase of eight large shipping vessels, each capable of carrying 16,000 containers, powered by dual fuel engines capable of running on methanol or conventional low sulphur fuel.[108]

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[101] "Global Hydrogen Review", *International Energy Agency (IEA),* (2021)
[102] Binder, Matthias, et al. "Hydrogen from biomass gasification", *IEA Bioenergy,* (2019): ISBN, 978-1-910154-59-5 https://www.ieabioenergy.com/wp-content/uploads/2019/01/Wasserstoffstudie_IEA-final.pdf
[103] "Hydrogen Production Costs 2021", *UK Department for Business, Energy, and Industrial Strategy,* (2021) https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011506/Hydrogen_Production_Costs_2021.pdf
[104] "Working Paper | National Hydrogen Strategies", *World Energy Council,* (2021) https://www.worldenergy.org/assets/downloads/Working_Paper_-_National_Hydrogen_Strategies_-_September_2021.pdf
[105] "The Future of Clean Hydrogen in the United States." *Energy Futures Initiative.* (2021) https://static1.squarespace.com/static/58ec123cb3db2bd94e057628/t/614a8729e756155644c6250c/1632274226712/EFI+Future+of+Clean+Hydrogen+in+the+U.S.+Report.pdf
[106] "Global Hydrogen Review", *International Energy Agency (IEA),* (2021)
[107] "The Next Wave: Green Corridors". *Global Maritime Forum,* (2021) https://www.globalmaritimeforum.org/publications/the-next-wave-green-corridors.
[108] Frangoul, Anmar, "Maersk Spends $1.4 Billion on Ships That Can Run on 'Carbon Neutral' Methanol", *CNBC*, (2021) https://www.cnbc.com/2021/08/24/maersk-spends-1point4-billion-on-ships-that-can-run-on-methanol.html

Nearly 100 million tonnes of methanol are produced globally per annum, approximately 31% of which is used as fuel, with the majority used for producing other chemicals such as formaldehyde, acetic acid, and plastics.[109] Methanol is most commonly produced from fossil fuel feedstocks, but "green" methanol is a lower-emissions option that can be produced using either sustainable biomass or clean electricity, to yield "green" hydrogen, combined with captured carbon dioxide.[110]

The production cost of fossil fuel-based methanol is relatively low at $0.10-0.25/kg, while the cost of "green" methanol produced with renewable energy varies greatly but is generally estimated to be much higher.[111]

Decarbonization opportunity
Current methanol production and use result in life-cycle CO_2 emissions of around 0.3 Gt per year; of total methanol production, less than 0.2 Mt is currently produced from low-carbon methods.[112] Conventional production via steam methane reforming using fossil gas emits criteria air pollutants such as NO_x, sulfur, mercury, and various particulate matter. Methanol combustion emits CO_2 at point of use; but compared to gasoline, it has the potential to reduce carbon emissions by 80% with M100 and 30-40% with M85.[113]

Limitations
The use of renewable methanol as a fuel for transportation decarbonization is limited in the short term by cost compared to conventional fossil-fuel based methods and feedstock availability. "Green" methanol requires either sustainable biomass supply, for which there are constraints and competing uses, or capture of CO_2 for which commercialization is nascent and expensive (for Direct Air Capture in particular).[114] In the long term, methanol is limited by its economic viability compared to "green" ammonia, which is expected to have a cost advantage on major shipping routes.[115]

Ammonia

Fuel/technology
Ammonia has been widely used in the production of fertilizers, household cleaning chemicals, and in refrigeration systems for years.[116] It has attracted increasing attention as a hydrogen transport medium and a zero-carbon fuel due to its desirable properties. Ammonia has an energy density

[109] "Innovation Outlook : Renewable Methanol", *IRENA and the Methanol Institute*, (2021)
[110] Martin, Abigail, "A Step Forward for 'Green' Methanol and Its Potential to Deliver Deep GHG Reductions in Maritime Shipping", *International Council on Clean Transportation (ICCT)*. (2021). https://theicct.org/blog/staff/green-methanol-ghg-reductions-marine-sept21.
[111] "Innovation Outlook : Renewable Methanol", *IRENA and the Methanol Institute*, (2021)
[112] "Innovation Outlook : Renewable Methanol", *IRENA and the Methanol Institute*, (2021)
[113] "Clean Alternative Fuels: Methanol", *National Service Center for Environmental Publications (NSCEP),* (2002) https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100PKAC.TXT#:~:text=Methanol%20is%20also%20available%20as,one%20carbon%20atom%20per%20molecule
[114] Martin, Abigail, "A Step Forward for 'Green' Methanol and Its Potential to Deliver Deep GHG Reductions in Maritime Shipping", *International Council on Clean Transportation (ICCT)*. (2021). https://theicct.org/blog/staff/green-methanol-ghg-reductions-marine-sept21.
[115] "The Next Wave: Green Corridors". *Global Maritime Forum,* (2021) https://www.globalmaritimeforum.org/publications/the-next-wave-green-corridors.
[116] Erdemir, Dogan and Ibrahim Dincer, "A perspective on the use of ammonia as a clean fuel: Challenges and solutions", *International Journal of Energy Research 45,* Iss. 4, (2021): 4827-4834 https://doi.org/10.1002/er.6232

about half of that for typical hydrocarbon fuels on both a mass and volume basis. It is easier to transport in liquid form than hydrogen, requiring less pressure and a more mild temperature to liquify. The energy carrier is also versatile - ammonia can be consumed in a combustion engine or used in a fuel cell. Finally, infrastructure for large-scale production and distribution of ammonia already exists worldwide.

Ammonia can be used in many modes of transit (e.g., to power cars, trucks, ferries, ships, and trains).[117] In particular, ammonia has been viewed as a more suitable option to decarbonize the marine shipping sector than either hydrogen or electrification.[118] Liquid hydrogen cannot be blended with conventional marine fuel and must be kept under high pressure or at extremely cold temperatures.[119] Batteries are impractical for marine applications due to their limited range and relatively heavy weight. Ammonia, on the other hand, has a higher energy density, can be directly blended with existing marine fuels, and can be stored in cheaper tanks without the high-pressure requirement.[120]

In the past century, ammonia has been primarily produced from the Haber-Bosch process, which is notably energy-intensive due to its requirement of high heat and high pressure.[121] The global annual ammonia production volume is currently 176 million metric tons, with China being one of the world's largest producers of ammonia (48 million metric tons), followed by Russia (12.5 million metric tons), India (11 million metric tons), and the United States (9.8 million metric tons).[122,123] Ammonia can also be produced using clean power; as of now, all "green" ammonia projects are still in the development and planning phase. Several leading ammonia producers outside of China have announced plans to either construct a new "green" ammonia plant, or upgrade existing facilities to produce "green" ammonia, including the Norwegian fertilizer giant Yara, it's US competitor CF Industries, BASF in Germany, and Casale in Switzerland.[124,125,126,127]

The infrastructure for large-scale production and distribution already exists for ammonia worldwide, due to ammonia's extensive use in fertilizer production and as a major input to the chemical

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[117] Zhiyuan, Fan, et al., 'Green Hydrogen in a Circular Carbon Economy: Opportunities and Limits', *Columbia University - Center on Global Energy Policy*, August 2021.
[118] Hansson, Julia, et al., "The Potential Role of Ammonia as Marine Fuel—Based on Energy Systems Modeling and Multi-Criteria Decision Analysis", *Sustainability 12,* no. 8, (2020): 3265. https://doi.org/10.3390/su12083265
[119] "Hydrogen Storage", *US Department of Energy,* Accessed 22 November 2021 https://www.energy.gov/eere/fuelcells/hydrogen-storage
[120] "Hydrogen Storage", *US Department of Energy*
[121] "Ammonia: zero-carbon fertiliser, fuel and energy store", *The Royal Society*, (2020) https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/green-ammonia/.
[122] Wood, Johnny, "Scaling Ammonia Production For The World's Food Supply", *Forbes,* (2021) https://www.forbes.com/sites/mitsubishiheavyindustries/2021/10/29/scaling-ammonia-production-for-the-worlds-food-supply/?sh=65d4824468d1
[123] "Ammonia: zero-carbon fertiliser, fuel and energy store", *The Royal Society*, (2020)
[124] "Green ammonia from HEGRA to secure Norwegian competitiveness", *Yara*, (2021) https://www.yara.com/corporate-releases/green-ammonia-from-hegra-to-secure-norwegian-competitiveness/
[125] "CF Industries Signs Engineering and Procurement Contract with thyssenkrupp for Green Ammonia Project", *Business Wire*, Deerfield, IL. (2021) https://www.businesswire.com/news/home/20210421005948/en/CF-Industries-Signs-Engineering-and-Procurement-Contract-with-thyssenkrupp-for-Green-Ammonia-Project
[126] "Yara and BASF open world-scale ammonia plant in Freeport, Texas", *BASF - Business & Financial News,* Oslo, Norway and Florham Park, NJ. (2018) https://www.basf.com/global/en/media/news-releases/2018/04/P-US-18-044.html
[127] "Casale to participate in green ammonia pilot project in USA", *Casale*, (2021) https://www.casale.ch/news-events/news/casale-to-participate-in-green-ammonia-pilot-project-in-usa

industry. About 120 ports in the world are equipped with ammonia terminals, which can be further upgraded into ammonia bunkering to enable large-scale deployment of ammonia as a marine fuel.[128] In a mapping of current zero emission pilots and demonstration projects for the maritime industry, the majority were found to be focused on hydrogen-based fuels; a quarter of all projects were dedicated to the use of ammonia with a notable increase in large ship projects targeting use of this fuel.[129]

Decarbonization opportunity
Similar to hydrogen, ammonia (NH_3) is a carbon-free fuel that emits no carbon dioxide when combusted; however, this produces substantial NO_x emissions.[130] More than 96% of the ammonia consumed in the world today is produced through the Haber-Bosch process using fossil fuels as feedstock for H_2; this process is currently responsible for 1.2% of global anthropogenic CO_2 emissions.[131] Using H_2 produced via clean electricity to make "green" ammonia can reduce the carbon footprint of ammonia production by 75%-90%.[132] Ammonia with low carbon emissions can also be produced if CCS is applied on hydrogen production at existing Haber-Bosch plants where high (>90%) at plant capture efficiencies are achievable.[133]

Limitations
Despite these positive attributes, use of ammonia raises significant health, safety, and environmental risks both for people and the environment. Ammonia evaporation and NO_x emissions from combustion are both dangerous and can cause environmental damage.[134] However, because ammonia is already produced, shipped, and consumed in the world on a large-scale, technologies and safety regulations exist for its use in industrial settings, and appropriate training and protective equipment can feasibly be put in place to manage health, safety, and environmental concerns for other applications.

Sustainable Aviation Fuels (SAFs)

Fuel/technology
Sustainable Aviation Fuels (SAFs) are biofuels or synthetic fuels that are blended with conventional jet fuel to varying degrees. Of the technology options available for reducing emissions from air transportation, sustainable aviation fuel has many advantages given its alignment with existing aircraft design, operation, and infrastructure. It is expected that future generations of jet engine designs will be capable of handling 100% SAF.

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[128]Smith, Colin, et al. "Current and future role of Haber–Bosch ammonia in a carbon-free energy landscape", *Energy & Environmental Science,* (2020)
[129] "New Mapping of Zero Emission Pilots and Demonstration Projects in Shipping Reveals a Notable Increase in the Uptake of Large Ammonia Vessels", *Global Maritime Forum*, (2021) https://www.globalmaritimeforum.org/press/new-mapping-of-zero-emission-pilots-and-demonstration-projects-in-shipping-reveals-a-notable-increase-in-the-uptake-of-large-ammonia-vessels
[130] Kobayashi, Hideaki et al. "Science and technology of ammonia combustion", *Proceedings of the Combustion Institute*, Vol. 37, Iss. 1, (2019) https://www.sciencedirect.com/science/article/pii/S1540748918306345.
[131] Smith, Colin, et al. "Current and future role of Haber–Bosch ammonia in a carbon-free energy landscape", *Energy & Environmental Science,* Iss. 2, (2020)
[132] "Ammonia: zero-carbon fertiliser, fuel and energy store", *The Royal Society*, (2020)
[133] Masanti, Matteo "Reducing the Carbon Footprint of Ammonia As Green Energy Carrier", *Ammonia Energy Association*, (2019) https://www.ammoniaenergy.org/paper/reducing-the-carbon-footprint-of-ammonia-as-green-energy-carrier/
[134] "Hydrogen Storage", *US Department of Energy*

Certain SAFs are already approved for use in commercial jets.[135] These SAFs can be produced from synthesis gas (syngas, a mixture of hydrogen and carbon monoxide), lipids (fats, oils, greases), sugars, and alcohols through a variety of pathways (Figure 7). All of these processes yield not only SAF, but also a range of other commercially-relevant products such as diesel, naphtha, biochar, or chemicals.

Pathway	Hydrotreated Esters and Fatty Acids (HEFA)	Alcohol-to-Jet (ATJ)	Fischer-Tropsch (FT)	Hydrotreated Depolymerized Cellulosic Jet (HDCJ)	Sugar-to-Jet	Air-to-Fuels (ATF)
Technology Summary	A series of chemical processes to convert oil-based feedstocks to SAF.	Use of alcohols, such as ethanol to produce SAF. The upstream production of ethanol can proceed via commercially available fermentation technology, or other novel production methods.	A catalytic chemical process that yields liquid hydrocarbon fuels, including SAF, from a mixture of carbon monoxide (CO) and hydrogen (H_2) called synthesis gas or syngas.	A pyrolysis-based process whereby feedstocks, such as lignocellulose, are heated in the absence of oxygen to produce biochar, biogas and bio-liquids. The bio-liquids, also called pyrolysis oils or biocrude, are then upgraded to liquid hydrocarbon fuels.	A series of biological and chemical processes to convert sugars, such as from sugar beets, sugar cane, or lignocellulose, into liquid hydrocarbon fuel.	Carbon dioxide can be recycled to produce fuels. Syngas is first produced through a combination of: electrolysis of air-captured CO_2 to CO, electrolysis of water to H_2, and/or a reaction between CO_2 and H_2. Syngas is then converted to jet fuel via the Fischer-Tropsch process.
Feedstocks	Oil crops (soy, palm, jatropha), Used cooking oils	Corn, Sugarcane, Cellulosic biomass	Cellulosic biomass, Municipal solid waste	Cellulosic biomass, Municipal solid waste	Corn, Sugarcane, Cellulosic biomass	Carbon dioxide, Hydrogen
Maximum approved blending limit (vol%)	50	50	50	0	10	50

Figure 7. Sustainable aviation fuel production pathways and approved blending limits.

[135] "Sustainable Aviation Fuel: Review of Technical Pathways". *US Department of Energy,* (2020) https://www.energy.gov/sites/prod/files/2020/09/f78/beto-sust-aviation-fuel-sep-2020.pdf

Decarbonization opportunity

Aviation is a particularly hard-to-abate sector and currently contributes about 3% of total global GHG emissions.[136] Existing aircrafts can undergo minor modifications to use SAF which would not incur reductions in refueling efficiency nor changes to existing airport infrastructure and would reduce climate impact by 30-60%.[137] Pathways that employ waste biomass feedstocks and CCS on the production technologies can also enable carbon-negative sustainable aviation fuel.

Recent announcements by both public and private sector actors suggest a growing interest in the production and scale-up of SAF as a major near-term decarbonization option for aviation. For example, multiple federal agencies in the US have announced a Sustainable Aviation Fuel Grand Challenge that seeks to develop a comprehensive strategy for commercial-scale SAF production. The strategy aims to reduce GHG emissions by 50% compared to conventional jet fuel and produce enough SAF to meet all aviation fuel demand by mid-century, with production milestones of 3 billion gallons by 2030 and 35 billion gallons per year by 2050.[138] Similar intentions to support the SAF industry have also been announced by several aviation companies as shown in Figure 8.

Company	SAF Announcement
Alaska Airlines	Procure SAF for corporate travel on specific flight routes; existing agreements with SAF producers SkyNRG Americas and Neste.
American Airlines	Procure 10 million gallons of SAF by 2025 from Prometheus Fuels.
Delta Airlines	Replace 10% of conventional fuel supply with SAF by 2030; existing agreements with SAF producers Neste, Gevo, and Northwest Advanced Biofuels.
Southwest Airlines	Partnering with the National Renewable Energy Laboratory (NREL), one of the US Department of Energy National Labs, to produce and commercialize SAF.
United Airlines	Procure 1.5 billion gallons of SAF over the next two decades through its co-investment with Honeywell into Alder Fuels, which aims to produce and scale carbon-negative SAF.

Figure 8. Selection of SAF announcements by aviation companies.

Limitations

The opportunities to use SAFs to reduce transportation emissions from aviation are controlled by The American Society for Testing and Materials (ASTM) which limits the blending fraction of SAFs, depending on the production pathway, to ensure full compatibility with existing aircrafts.[139] There are several pathways to SAF production that have been ASTM approved, and others that have not yet gained approval. Current production pathways are limited to blends up to 50%.

The technological maturity of the various pathways to make SAFs varies, with Hydrotreated Esters and Fatty Acids (HEFA) being the most mature, Alcohol-to-Jet (ATJ) and Fischer-Tropsch (FT) in commercial pilot, and other pathways (e.g., Air-to-Fuels) still in development.

[136] "Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation", *World Economic Forum and McKinsey & Company*, (2021) https://www.weforum.org/reports/a356c865-311e-45ca-845d-efe5f762a820/
[137] "Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation", *World Economic Forum and McKinsey & Company*, (2021) https://www.weforum.org/reports/a356c865-311e-45ca-845d-efe5f762a820/
[138] "Sustainable Aviation Fuel Grand Challenge", *US Department of Energy*, Bioenergy Technologies Office, Accessed 24 November 2021 https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuel-grand-challenge
[139] "Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation", *World Economic Forum and McKinsey & Company*, (2021)

In 2019, less than 6 million gallons of SAF were produced globally, which corresponds to less than 0.1% of the 90 billion gallons of aviation fuels used globally.[140] Well over 70% of current and projected SAF production is via the HEFA pathway, despite concerns about the scalability, life-cycle, sustainability, and true carbon intensity of this pathway. The remainder of production is expected to be provided by ATJ, FT, and other pathways, but the contribution of each to total production is projected to remain relatively small through 2025 due to their currently low levels of deployment and relatively low technology maturities.

4. What we can do - impact opportunities and ways to activate

Policy levers and regulatory environment

Public policy has a crucial role in transportation decarbonization and is evolving rapidly. The most important policy priority is to send a market signal by setting specific decarbonization targets and timelines, for instance California's goal to phase out internal combustion engine sales by 2035. Such goals, coupled with mandates and/or incentives, can develop markets with multiple technology and fuel options by providing market certainty to technology developers. In some cases, policy can support development of options through funding of research and deployment of infrastructure. As a result, the costs for changing transportation fuels are likely to become much cheaper, and technologies far better, which will lower hurdles for corporate entry in the space.

Policies should aim to embrace optionality of fuel types rather than pick winners upfront because, as discussed in the above sections, fuels vary in their development needs and adoption stages and it is likely we will need a variety of options to fit different applications. However, care should be taken to recognize sustainability limits (e.g., on bioresources) when prioritizing use of resources for different applications. Adopting policy aligned with rates of technology innovation could be a useful lever to drive adoption of decarbonized transportation. For example, heavy-duty trucks have a relatively short expected operational life of approximately six years due to wear and tear.[141] This provides an opportunity to ratchet down allowable emissions with every new vintage of vehicle, paving the way to substantially decrease sector carbon emissions over relatively compressed timeframes. With proper guidance, vehicle providers can plan accordingly for this trajectory.

For use of electricity and/or biofuels, policies may rely on a system of tax incentives and deterrents. For example, Canada's Clean Fuel Standard establishes a credit market to increase the production of low-carbon fuels by incentivizing electrification, adoption of low-carbon fuels, and deployment of carbon capture technologies.[142] Electrification efforts in Canada are also bolstered by the country's goal of 100% zero emission vehicles by 2040.[143] Canada has chosen to encourage the use of

[140] "Economic Performance of the Airline Industry", *International Air Transport Association (IATA)*, 2020 https://www.iata.org/en/iata-repository/publications/economic-reports/airline-industry-economic-performance-june-2020-report

[141] Terrazas, Aaron, "Survival of the Fittest: How Convoy Data Science Used Survival Analysis to Estimate the Class 8 Truck Replacement Rate", *Convoy,* (2021) https://convoy.com/blog/class-8-truck-order-replacement-rate/

[142] "What is the clean fuel standard?", *Government of Canada*, Accessed 22 November 2021, https://www.canada.ca/en/environment-climate-change/services/managing-pollution/energy-production/fuel-regulations/clean-fuel-standard/about.html

[143]"Canada's Energy Future 2020", *Canada Energy Regulator*, (2020) https://www.cer-rec.gc.ca/en/data-analysis/canada-energy-future/2020/canada-energy-futures-2020.pdf.

biodiesel through a combination of exempting the fuel from the federal carbon tax while raising the tax on fossil diesel fuel to 25% in 2022.[144]

For hydrogen production, the US offers tax credits, exemptions, bond grants, and infrastructure incentives, with economic incentives available for owners of hydrogen fueling equipment and hydrogen fuel cell vehicles. Hydrogen policy in Europe is more focused on research, development, and deployment. The UK allocated $9.8 million in research funds for electrolysis technology and the EU committed $609 billion to "green" hydrogen production and infrastructure development.[145] Hydrogen for transport is an integrated part of the ambitious hydrogen strategies and plans that numerous countries are progressing.

In addition to some examples of executive action and voluntary support mechanisms for SAF mentioned in Section 3, there is also a growing chorus of support for SAF through industry trade groups, national legislation, and private sector alliances. For example, the International Air Transportation Association has set a target to achieve net-zero emissions by 2050, which includes a dedicated commitment to SAF that is expected to account for a majority of the emissions reduction needs in the aviation sector by mid-century.[146] Airlines for America, an industry trade group for US-based aviation companies, has also announced a commitment on behalf of its member carriers to support the rapid development and scale up of SAF by 2030.[147] Related to national legislation, Europe's ReFuelEU requires aviation fuel supplies to blend a minimum of 2% SAF into their fuel by 2025, with gradual increases to reach 63% SAF in 2050.[148] In the US, a SAF tax credit has been proposed through the Biden Administration's Build Back Better framework to help facilitate the rapid scale-up of SAF production and lower attendant costs.[149] The private sector also continues to signal major support for SAF, including through the newly-formed Sustainable Aviation Buyers Alliance which aims to invest in SAF, support technology innovation and address barriers to scale up, and engage in member education and policy support efforts.[150]

Areas most in need of support

Scenarios modeling the reductions necessary to reach future emissions targets identify three transportation segments in particular need of support: heavy-duty road transport, shipping, and

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[144] Kotrba, Ron, "Biodiesel More Cost Competitive under Canada's New Carbon Tax." *Biodiesel Magazine*, (2019) www.biodieselmagazine.com/articles/2516651/biodiesel-more-cost-competitive-under-canadaundefineds-new-carbon-tax

[145] "Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5^{0}C Climate Goal", *International Renewable Energy Agency (IRENA)*, Abu Dhabi. (2020)

[146] "Net-Zero Carbon Emissions by 2050", *International Air Transport Association (IATA),* No: 66, (2021) https://www.iata.org/en/pressroom/2021-releases/2021-10-04-03/

[147] "U.S. Airlines Announce 3-Billion-Gallon Sustainable Aviation Fuel Production Goal", *Airlines for America,* (2021) https://www.airlines.org/news/u-s-airlines-announce-3-billion-gallon-sustainable-aviation-fuel-production-goal/

[148] Abnett, Kate and Tim Hepher, "EU targets airlines in major climate policy shakeup", *Reuters - Aerospace & Defense,* (2021) https://www.reuters.com/business/aerospace-defense/eu-climate-blueprint-pressures-airlines-cut-emissions-2021-07-14/

[149] "FACT SHEET: Biden Administration Advances the Future of Sustainable Fuels in American Aviation", *The White House - Briefing Room*, (2021) https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/

[150] "Sustainable Aviation Buyers Alliance (SABA)", *RMI*, Accessed 22 November 2021 https://rmi.org/saba/

aviation. Decarbonizing these segments depends heavily on technologies that are in early stages of development (Figure 9).

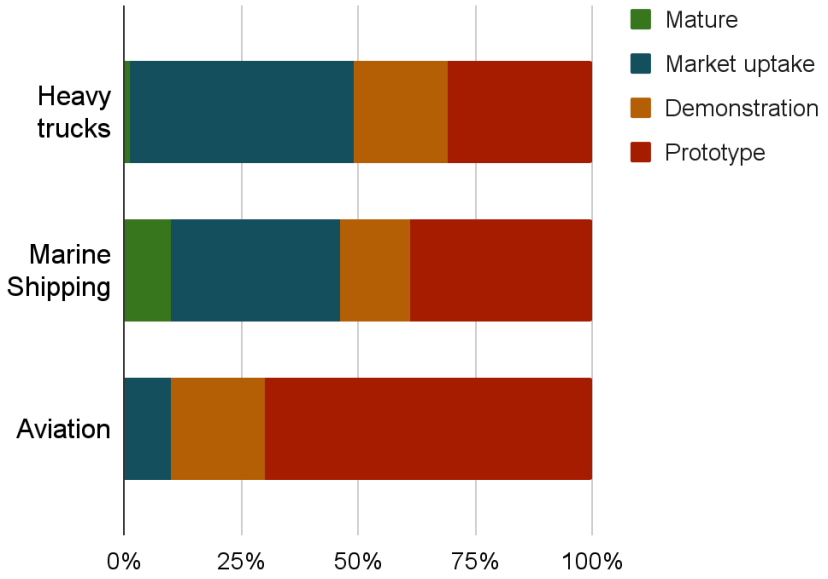


Figure 9. Technology maturity within heavy-duty trucks, marine shipping, and aviation segments as a share of the emissions reductions required to 2050 in each segment as modeled by the International Energy Agency (IEA) in their Net-Zero Energy scenario.[151]

Significant investment and policy support will be needed to encourage the crucial development of these sectors. The shipping industry alone estimates that the level of investment required to reach net-zero CO_2 is approximately $2.4 trillion, 70% of which is needed for development of cleaner fuel production, storage, and distribution.[152]

Levers for decarbonization

To succeed at rapid and profound decarbonization, we must accelerate smart and productive investment. There has been a notable uptick in both consumer spending on electric vehicles and investments in new electric vehicle models by automotive manufacturers.[153] In addition to electrification of on-road transport for both passenger and freight applications, private sector investment in transportation decarbonization is spurring the creation of new companies and business models in this evolving ecosystem. Companies are also making commitments to improve their practices; recently, Amazon, Ikea, Unilever, Maersk, and other major companies committed to net-zero shipping by 2040.[154] (Additional examples of private sector support for freight transportation decarbonization are provided in Figure A2 of the Appendix.)

[151] IEA (2021), "Net Zero by 2050", IEA, Paris https://www.iea.org/reports/net-zero-by-2050. All rights reserved.
[152] "Funds Are Getting Excited by Shipping's Future Fuels, BCG Says", *Bloomberg*, Accessed 14 October 2021, https://www.bloomberg.com/news/articles/2021-10-11/funds-are-getting-excited-by-shipping-s-future-fuels-bcg-says?sref=oUjKJw8m&utm_campaign=Clean%20Energy%20News&utm_medium=email&_hsmi=170409225&_hsenc=p2ANqtz-9F52H767I1z0si1Io2rtasx7thMVUqTvKNhE-OTiOzYgginLsI-FRPLnNcIplOcZSyHAA4PMv2V_cCuX7vBCpI9-rH2w&utm_content=170409225&utm_source=hs_email.
[153] "World Energy Investment 2021", *International Energy Agency (IEA)*, Paris (2021) https://www.iea.org/reports/world-energy-investment-2021
[154] Shaban, Hamza, "Amazon, Ikea and other big companies commit to zero-emission shipping by 2040", *Washington Post,* (2021) https://www.washingtonpost.com/business/2021/10/19/zero-carbon-fuel-shipping-amazon-ikea/

While all of this is encouraging, much remains to be done. Individuals and corporate actors alike should pursue strategies to reduce emissions sources within their immediate control or value chain. At the same time, they should consider supporting emissions reductions and removals outside of their activities to offset any residual emissions that are technologically or economically infeasible to eliminate. Crucially, these "carbon offsets" should not be applied to emissions that can be reduced through available means, but reserved for (a) profoundly hard-to-abate emissions sources, and (b) drawing down legacy (historical) emissions that are already in the atmosphere.

As discussed, there are several pathways available to reduce emissions from transportation: reducing our overall demand for transportation, improving energy efficiency (including modal shifts such as from air transport to rail), and reducing the carbon intensity of fuels.[155,156] Currently, emphasis is on reducing fuel carbon intensity through the phase-in of electricity, biofuels, synthetic fuels, and hydrogen-powered drivetrains across different modes of transportation. Companies and investors can consider these pathways opportunities and levers to accelerate reductions.

Road transportation represents the most commercially mature subsector, with multiple manufacturers producing models of various capabilities to address passenger and freight transport needs. However, as noted, such vehicles make up only a small fraction of the total fleet currently deployed, given cost-competitiveness, duty-cycle needs, the long life of the vehicles, and the required refueling infrastructure build-out for fuels such as hydrogen. One strategy to increase the share of zero-emissions vehicles on the road in the near term is through bulk orders (e.g., Amazon's order for 100,000 electric trucks from Rivian) or mandates (e.g., California's Advanced Clean Truck and Innovative Clean Transit mandates).[157,158,159] The magnitude of such signals can lower the purchasing cost of both vehicle and charging/fueling infrastructure through economies of scale as well as lower the barrier to policy making. Put another way, it is easier for policymakers to set mandates if leading firms are already adopting technologies. As for last mile transportation, combined policy actions are needed to increase the deployment of zero-emission options like electric city vans and small trucks, such as rapidly building out adequate charging infrastructure while imposing emissions-related congestion charges on those vehicles which have emissions above a given threshold (as currently deployed in the City of London with its Ultra Low Emissions Zone 24/7 charge).[160]

Low-carbon marine, rail, and aviation transportation modes are less mature in terms of commercially available options and could benefit from a long-term strategy. In the near term, a fuels emissions intensity requirement, such as the California Low Carbon Fuel Standard and existing or proposed legislation in Washington State, Oregon, and New Mexico, would allow owners/operators

[155] Broadly, there are 5 phases within a product life-cycle: material extraction, manufacturing, packaging, use and end-of-life. Given the relatively long operational lives of transportation methods, the vast majority of the emissions is attributed to the use phase.
[156] Working Group III Technical Support Unit, "Climate Change 2014 Mitigation of Climate Change", *Intergovernmental Panel on Climate Change (IPCC)*, (2014)
https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_frontmatter.pdf
[157] Bellan, Rebecca and Kirsten Korosec, "Rivian expands into fleet business beyond amazon deal", *Tech Crunch,* (2021)
https://techcrunch.com/2021/11/08/rivian-expands-into-fleet-business-beyond-amazon-deal/
[158] "Advanced Clean Trucks Fact Sheet", *California Air Resource Board,* (2021)
https://ww2.arb.ca.gov/resources/fact-sheets/advanced-clean-trucks-fact-sheet
[159] "Innovative Clean Transit (ICT) Regulation Fact Sheet", *California Air Resource Board,* (2019)
https://ww2.arb.ca.gov/resources/fact-sheets/innovative-clean-transit-ict-regulation-fact-sheet
[160] "Ultra Low Emission Zone", *Transit for London - Mayor of London,* Accessed 22 November 2021
https://tfl.gov.uk/modes/driving/ultra-low-emission-zone?intcmp=26434

of these vehicles to choose from a mix of fuel and efficiency improvement options.[161,162,163,164] Further, joining or building a globally focused coalition of like-minded bulk transport users could work as one coordinated voice for change. Such alliances, focused on best practices development, capability building and knowledge sharing, and demand aggregation have already formed in sectors such as freight and logistics (e.g., The Smart Freight Centre), aviation (e.g., Sustainable Aviation Buyers Alliance) and marine shipping (e.g., Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping).[165,166,167] Another shipping alliance - the Aspen Shipping Decarbonization Initiative - has recently coordinated a commitment from a group of global cargo owners to use only zero-carbon ocean shipping by 2040, accelerating investment in infrastructure to create, bunker, and use low-carbon shipping fuels.[168] Also, blending less carbon-intensive fuels into existing drivetrains (e.g., SAF, methanol, biofuels) through large, long-term purchasing agreements could bring newer transport fuels and technologies to market while reducing emissions immediately. Of course, numerous actors such as fuel producers, policymakers, state agencies, and buyers must ensure that the life-cycle emissions of utilizing these fuels truly lead to reductions in emission intensity of transport (e.g., through a regulatory validation scheme) by avoiding processes that use carbon-intensive feedstocks or energy. At the same time, they should seek to avoid lock-in technologies that are only short-term solutions.

The preceding has focused on fuel carbon intensity and energy intensity; however, behavior changes and mode switching can also reduce emissions. Intelligent co-location of product/service demand and supply as well as better access to and use of data for efficient routing and asset utilization can play a significant role in reducing congestion and emissions while also increasing quality of life, especially in urban areas and heavy transport corridors. Cities can play a substantial role in shaping such behaviors on crowded inner-city streets. For instance, a World Economic Forum study found that allowing only EVs for inner-cities, requiring deliveries during night/off-peak times, implementing dynamic rerouting and load-pooling, and installing parcel lockers could reduce CO_2 emissions by 30%, congestion by 30%, and delivery costs by 25% by 2030 when compared to a "do nothing" baseline, not to mention the benefits for human health.[169]

[161] "Low Carbon Fuel Standard", *California Air Resource Board,* Accessed 22 November 2021 https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard
[162] "Clean Fuel Standard", *State of Washington,* Department of Ecology, Accessed 23 November 2021. https://ecology.wa.gov/Air-Climate/Climate-change/Reducing-greenhouse-gases/Clean-Fuel-Standard.
[163] "Oregon Clean Fuels Program", *State of Oregon*, Department of Environmental Quality, Accessed 23 November 2021. https://www.oregon.gov/deq/ghgp/cfp/Pages/default.aspx.
[164] "Clean Fuel Standard Act: Driving Economic Investment and Innovation While Reducing Greenhouse Gas Emissions", *Office of the Governor - Michelle Lujan Grisham*, (2021) https://www.governor.state.nm.us/2021/01/20/clean-fuel-standard-act-driving-economic-investment-and-innovation-while-reducing-greenhouse-gas-emissions/.
[165] "Towards efficient and zero emissions global freight and logistics", *Smart Freight Center*, Accessed 22 November 2021, https://www.smartfreightcentre.org/en/
[166] "Sustainable Aviation Buyers Alliance (SABA)", *RMI*, Accessed 22 November 2021
[167] "Decarbonizing the global maritime industry", *Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping*, Accessed 22 November 2021 https://www.zerocarbonshipping.com/
[168] Irigoyen, Ingrid, et al., "Companies Aim to Use Only Zero-Carbon Ocean Shipping by 2040", *Aspen Institute*, (2021) https://www.aspeninstitute.org/blog-posts/companies-aim-to-use-only-zero-carbon-ocean-shipping-by-2040/
[169] "The Future of the Last-Mile Ecosystem", *World Economic Forum*, (2020) https://www.weforum.org/reports/the-future-of-the-last-mile-ecosystem

Leading actions and actors in the transportation value chain

The table below contains examples of actions taken by early-acting companies, ports, and other actors, and follows stages that cargo may pass through from the point of manufacture to a customer's doorstep. Originating in another country, cargo moves from manufacturer to intermodal hubs, onward to warehouses and distribution centers and finally through fulfillment centers to the point of delivery. At each hand-off point, the cargo may be transferred from one transportation mode to another, usually within large shipping containers. Toward the end of its journey, the cargo is taken to individual customers or users.

Stage of Delivery	Description	Transportation modes or hubs	Example leading action(s)	Example actor(s)
Unit shipping (international)	Transporting cargo from manufacturing to next value-add stage (further manufacturing/ assembly, or retail)	• Rail • Marine shipping • Long-haul trucking • Aviation	• Ammonia-powered ships • Blending SAF into jet fuel • Electric or hydrogen trucks • Hydrogen planes	• Maersk • Jetblue • DHL • Daimler • Volvo • Boeing • Airbus
Intermodal hubs	Transferring cargo from one transportation mode to another (e.g. rail to marine shipping)	• Seaports • Inland ports • Airports	• Electrification of crane operations • Electrification at-berth • Hydrogen heavy-duty port vehicles	• Port of Long Beach
Logistics/ warehousing	Temporary storage and sorting of cargo to make ready for next stage transport	• Rail • Marine shipping • Long-haul trucking • Drayage trucking • Powered industrial trucking	• Hydrogen or electricity powered drayage trucks and forklifts	• Nikola Motors • TTSi • PlugPower • Walmart
Distribution shipping	Long-distance unit shipping	• Rail • Long-haul trucking	• Fleet-wide electrification	• Purolator • FedEx
Fulfillment/ distribution centers	Sorting of cargo to make ready for final delivery	• Medium-duty vehicles • Powered industrial trucking	• Fleet-wide electrification • Hydrogen forklifts	• Home Depot • Walmart • DSV
Last mile delivery	Transportation of goods to final destination; high frequency/low volume	• Light- and medium-duty vehicles • 2-3 wheel scooters	• Fleet-wide electrification	• Amazon • FedEx

Additional opportunities in the transportation value chain

Transportation emissions largely emanate from the use of vehicles, and thus vehicle owners and operators. Nonetheless, multiple supporting actors provide near-term and long-term decarbonization opportunities for rapid and profound CO_2 reductions. Companies have opportunities to drive change within these ecosystems and achieve reductions through partnerships with these actors.

One of the most important types of actors is the original equipment manufacturer (OEM). OEMs are the firms that design and manufacture the vehicles. Their design and technology choices, to a material extent, essentially "lock-in" the emissions profile of a vehicle, given that dimensions like drivetrain, fuel type, materials, efficiency and vehicle mass are largely fixed before reaching the owner/operator. OEMs will react to buyer preferences and requirements - in addition to regulatory requirements - to provide vehicles that align with decarbonization ambitions (or not). The demand signal, regulatory structure, and willingness to perhaps pay a short-term "green premium" (vis-a-vis incumbent offerings), must be present to give OEMs confidence to invest in such solutions.

As mentioned previously, one way to signal demand effectively is through industry associations that can aggregate intent and coordinate actions within and across subsectors. The energy transition and decarbonization efforts have been broadly included as key topics in existing global and regional industry associations and public/private collaborations, often acting as aggregators/coordinators for ambitions and targets of their members. Examples include the International Marine Organization (marine shipping), the International Air Transport Association (aviation) and the European Automobile Manufacturers Association (ground transportation).[170,171,172] One cross-sector alliance that has recently announced its intention to preferentially purchase low embodied carbon materials such as "green" steel - a key component in the manufacturing of vehicles - is the First Movers Coalition.[173,174]

Other supporting actors include fueling infrastructure providers. Electrify America is working on public EV charging buildout, Shell Hydrogen is a leading developer of hydrogen fueling stations in California, and Shore Power (available at the Port of Long Beach) enables ocean-bound vessels to use electricity instead of burning diesel while loading, anchoring, and/or unloading cargo at berth.[175,176,177] What is common across these examples is the need for convenient, available, cost-effective, and reliable provision of fuels required to power decarbonized vehicles. This infrastructure is critical to enable transportation decarbonization and has featured prominently in

[170] International Marine Organization, Accessed at: https://www.imo.org/
[171] International Air Transport Association, Accessed at: https://www.iata.org/
[172] European Automobile Manufacturers Association, Accessed at: https://www.acea.auto/
[173] Lobet, Ingrid, "Steelmakers forge ahead on cleaning up their notoriously dirty industry", *Canary Media*, (2021) https://www.canarymedia.com/articles/clean-industry/steelmakers-forge-ahead-on-cleaning-up-their-notoriously-dirty-industry
[174] First Movers Coalition, "Steel", *World Economic Forum,* (2021) https://www3.weforum.org/docs/WEF_Steel_2021.pdf
[175] "Electrify America: UE EV Public Charging Network", *Electrify America,* Accessed 22 November 2021 https://www.electrifyamerica.com/
[176] "Nikola Energy and TravelCenters of America to Deploy Hydrogen Fueling Infrastructure", *Nikola,* (2021) https://nikolamotor.com/press_releases/nikola-energy-and-travelcenters-of-america-to-deploy-hydrogen-fueling-infrastructure-117
[177] "Shore Power", *Port of Long Beach*, Accessed 22 November 2021 https://polb.com/environment/shore-power/#shore-power-program-details

the $1.2 trillion Infrastructure Investment and Jobs Act that was recently signed into US law by the Biden Administration.[178,179]

Driving impact through collective action

Transportation constitutes a small share of the total cost of a product, with the proportion decreasing further down the value chain to the ultimate consumer. At the same time, there is a growing demand for reduced emissions shipping, both from cargo producers and end customers. With respect to producers of goods, a mix of voluntary carbon reduction pledges and compliance requirements promulgated by regulation have motivated the search for “green” methods of shipping. Consumers have become increasingly aware of the footprint of shipping and are demanding solutions from retailers. Taken together, these “leading actors” seem to be willing to shoulder some “green” premium in the service of searching for at-scale solutions accessible to the broader market. How to share the cost of this premium remains an open question, but at the very least should consider multiple parties including manufacturers, freight and shipping companies, and end customers to cover this cost gap.

In terms of the changes that need to be made for which "green" premiums would provide support, there are three categories: drivetrains, infrastructure, and fuels. Depending on the transportation mode, there will be different needs across these categories. For LDVs used for high-frequency, low volume deliveries, battery-electric drivetrains have clear operational and total cost of ownership advantages over the fossil fuel equivalents. As OEMs of such vehicles continue to drive down the cost of production and drive up range and efficiencies, there is an increased need to ensure that cost-effective charging infrastructure is available to support required duty-cycles. Doing so requires the collaboration of multiple actors, such as community planners, energy regulators, utilities, OEMs, financiers, and environmental justice advocates. Lending voice to these activities, along with signaling of direct intent to install such capacity, could increase needed deployment to scale alongside the vehicles themselves. For other transportation modes, early adopters that pay a “green premium” for clean fuel procurement such as SAF for aviation or methanol for maritime shipping could help spur new markets to facilitate decarbonization efforts.

Of equal consequence is provision of zero-emissions electricity, which is essential to support decarbonized electrified transportation. Emissions-free, reliable, cost-effective and accessible electricity supply that meets the increasing transportation demand is critical and could be a substantial bottleneck to the speed and success of transport decarbonization. Aside from clean energy standards set by various governments (e.g., California), collective corporate buying actions could increase the speed of deployment and aid in cost reductions, the latter having rippling effects through the transportation cost chain. One example of this is the Renewable Energy Buyers Alliance.[180] An extension of this strategy could be similar to Google’s 24/7 Carbon-Free Commitment, which, in a transportation application, aligns charging with emissions free electricity irrespective of duty cycle.[181] This level of ambition and necessary cross-industry collaboration is

[178] Boston, William, “The Electric-Truck Battle to Come: Batteries versus Hydrogen Fuel Cells”, *Wall Street Journal,* (2021) https://www.wsj.com/articles/the-electric-truck-battle-to-come-batteries-versus-hydrogen-fuel-cells-11636466414
[179] Congress.gov., "H.R.3684 - 117th Congress (2021-2022): Infrastructure Investment and Jobs Act." (2021) https://www.congress.gov/bill/117th-congress/house-bill/3684
[180] Clean Energy Buyers Association (CEBA), Accessed at: https://rebuyers.org/
[181] “Operating on 24/7 Carbon-Free Energy by 2030” *Sustainability - Google,* Accessed 22 November 2021 https://sustainability.google/progress/energy/

worthy of further consideration; Google's collaboration with Engie is an example.[182] With respect to financiers, there will be a material need for funding products tailored to the fragmented value chain and reflecting the characteristics of alternative technologies.[183]

Acting now

It is clear that we need to quickly transition away from fossil fuels and that transportation has a leading role to play. Decarbonizing transportation will not only benefit our shared climate - mitigating the enormous environmental, financial, and social costs of climate change - but it also presents an economic opportunity to develop low- and zero-emission fuels and vehicles. When displacing fossil fuels, use of these alternatives can have substantial benefits for both human health and the environment. Encouragingly, the world is making steady progress and there are now many cost-effective options to decarbonize and improve how we use energy in transportation. In aggregate, all of these options should be pursued simultaneously. But we need to move faster.

So what should we do? Both individuals and corporations can advocate for public policy and investment towards rapid deployment of clean electricity (a cornerstone of zero-emissions transportation) as well as the development of low-carbon fuels, vehicles, and supporting infrastructure. Willingness to pay a short-term green premium to induce subsequent cost reductions is a clear and powerful signal. All actors - including consumers, corporations, and governments - can drive demand for net-zero emissions transportation through collective and sustained action. Corporate actors in concert with the financial sector can seize the opportunity to invest in decarbonized vehicle fleets to meet this demand. Innovation and multiparty alignment to drive at-scale deployment are key to rapid and lasting emissions reductions within the transportation sector.

We know what needs to be done - transition vehicle fleets to electrification or the use of low-carbon fuels, improve energy efficiency and emissions standards, develop and adopt zero-emissions technologies for marine shipping, rail and aviation, invest in human capital, and lower the barriers to infrastructure build-out. We have the opportunity to avoid the most severe consequences of climate change; our actions today can improve not only our lives but those of generations to come. We can - and must - move fast.

[182] "ENGIE and Google Sign 24/7 Carbon-Free Energy Supply Agreement in Germany and Strengthen Existing Collaboration", *ENGIE*, (2021)
https://www.engie.com/en/journalists/press-releases/engie-and-google-sign-24-7-carbon-free-energy-supply-agreement-in-germany-and-strengthen-existing-collaboration
[183] "Decarbonising Road Freight: Getting into Gear", *Shell International B.V.,* (2021)
https://www.shell.com/promos/energy-and-innovation/decarbonising-road-freight-getting-into-gear/_jcr_content.stream/1617804891378/3efb462f0ef05d4273d2eda5339d510c91ee1cde/decarbonising-road-freight-industry-report.pdf

Appendix

Additional information on alternative energy sources - projections for future growth

State-of-the-art today: high-level assessment overview

Summary

	Fuel cell electric	Battery electric	Lower-carbon fuels	Synthetic fuels/ e-fuels	Catenary and trolley
Technology Readiness Level	**TRL 7: Prototype stage**	**TRL 7-8: Pre-series-stage**	**TRL 9: Fully commercial**	**TRL 8: Technological readiness at pilot stage**	**TRL 6: Prototype developing ongoing**
Use Case	> Considered for long-haul range	> Mainly low-medium range/drayage	> Medium and long-haul range	> Medium and long-haul range	> Long-haul range with limited flexibility of routes
Cost[1]	> Relatively high vehicle and fuel cost	> High battery cost, but potentially lower fuel costs	> Lower fuel costs	> Very high fuel production costs	> High battery and infrastructure cost
Emission	> Potential to meet emission regulation standards	> Potential to meet emission regulation standards	> Limited emission reduction potential[1]	> Local emissions (NO_x) remain	> Potential to meet emission regulation standards
Operational Flexibility	> Long daily driving ranges; shorter refuelling times (compared to battery-electric trucks)	> Long recharging time; size/weight of battery limits payload; battery capacity limits range	> Similar to diesel (LNG), some range constraints with CNG	> Same as diesel; use of e-diesel for currently available trucks without retrofitting possible	> Charging while driving; smaller batteries; limited flexibility of routes
Infrastructure	> Limited refuelling infrastructure available > Refuelling station utilisation challenges in early rollout years	> Limited charging infrastructure available > Recharging station utilisation and grid upgrade challenges	> Growing refuelling infrastructure	> Use of existing infrastructure[2]	> Only short test tracks available > Infrastructure utilization, investment and grid upgrade challenges

1) Compared to equivalent diesel performance 2) Refers to existing infrastructure of conventional diesel fuel

Figure A1 portrays the technological readiness of vehicle electrification and low-carbon fuels today as well as the current state of development. Copyright © Fuel Cells and Hydrogen 2 Joint Undertaking. Republished with permission.

Electrification

The International Energy Agency estimates that electrifying transport will overtake liquid fuels between 2040-2045 in its net-zero emissions scenario, constituting around 45% of final energy consumption in the transportation sector by 2050 (with major contributions from electrifying on-road vehicles and rail systems). Comparatively less electricity is expected to be used by mid-century for energy end uses that are more difficult to electrify such as shipping and aviation, which are expected to see a greater adoption of low-carbon fuels including ammonia and hydrogen for shipping and sustainable aviation fuels for aviation.[184] However, the pace of clean energy innovation across transportation electrification will affect its prospects for decarbonization and unlocking new markets. For example, there are already operational electric ships in Europe and China.[185] Furthermore, recent announcements pertaining to the aviation sector by United Airlines (intending to purchase 100 electric for use in 2026) and DHL (placed a purchase order for 12 eCargo planes from Eviation for delivery in 2024) could give rise to an early market for small aircraft

[184] IEA (2021), "Net Zero by 2050", IEA, Paris https://www.iea.org/reports/net-zero-by-2050. All rights reserved.
[185] "Electric Vehicles", *International Energy Agency (IEA)*, (2020)

used for short-haul flights, along with the possibility of electric aircraft that can seat up to 100 people coming online by 2035.[186] [187] [188]

Select examples of private sector support for freight transportation decarbonization[189]

Company	Transportation Mode	Decarbonization Strategy	Description
Amazon	On-road	Electrification	Aims to achieve zero-emission shipping by 2040. By 2030, 50% of all Amazon's shipments will be net-zero and 100,000 of their delivery vehicles will be electric.[190] The electric delivery vehicles will be purchased from Rivian.[191]
UPS	On-road	Electrification	Purchased 10,000 all-electric delivery vehicles from Arrival and also made an equity investment into the company, along with further electric vehicle purchase orders from Workhorse Group Inc. and Tesla Inc.[192] [193]
DHL Express	Aviation	Electrification; SAF	Purchased 12 electric e-Cargo planes from Eviation and has committed to 30% SAF blending in certain segments of its business operations by 2030.[194] [195]
FedEx	On-road	Electrification	Committed to transitioning their entire delivery fleet to electric vehicles by 2040 (including the purchase of vehicles from BrightDrop and Chanje Energy Inc.). FedEx offers carbon-neutral shipping to its customers and will continue to invest in low-emissions fuels for its carrier fleet (including aircraft).[196] [197] [198]

[186] "United Airlines to Buy 100, 19-Seat Electric Planes from Heart Aerospace." *Reuters*, (2021) https://www.reuters.com/business/sustainable-business/united-airlines-buy-100-19-seat-electric-planes-heart-aerospace-2021-07-13/.
[187] Eviation. "DHL Express Shapes Future of Sustainable Aviation with the Order of First-Ever-All Electric Cargo Planes from Eviation," *DHL.* (2021) https://www.dhl.com/global-en/home/press/press-archive/2021/dhl-express-shapes-future-for-sustainable-aviation-with-the-order-of-first-ever-all-electric-cargo-planes-from-eviation.html
[188] "Aircraft Technology Roadmap to 2050", *International Air Transport Association (IATA)*, (n.d.)
[189] Private sector demand for zero-emission commercial vehicles amplifies market signals for OEMs to develop EVs. See also: "Trends and Developments in Electric Vehicle Markets", *International Energy Agency (IEA)*, (2021) https://www.iea.org/reports/global-ev-outlook-2021/trends-and-developments-in-electric-vehicle-markets
[190] Amazon, "Amazon Sustainability", Accessed 22 November 2021 https://sustainability.aboutamazon.com/
[191] Amazon, "Amazon's custom electric delivery vehicles are starting to hit the road." (2021) https://www.aboutamazon.com/news/transportation/amazons-custom-electric-delivery-vehicles-are-starting-to-hit-the-road
[192] Bloomberg Opinion, "Amazon and UPS are Kingmakers in EV Bubble", (2021) https://www.bloomberg.com/opinion/articles/2021-02-16/amazon-and-ups-are-kingmakers-in-electric-vehicle-bubble
[193] Bloomberg Opinion, "Amazon and UPS are Kingmakers in EV Bubble", (2021)
[194] DHL, "DHL Express Shapes Future for Sustainable Aviation with the Order of First-Ever All-Electric Cargo Planes from Eviation", (2021) https://www.dhl.com/global-en/home/press/press-archive/2021/dhl-express-shapes-future-for-sustainable-aviation-with-the-order-of-first-ever-all-electric-cargo-planes-from-eviation.html
[195] DHL, "Clean Operations for Climate Protection", Accessed 22 November 2021 https://www.dhl.com/global-en/home/about-us/sustainability/environment.html
[196] FedEx, "FedEx Commits to Carbon-Neutral Operations by 2040", (2021) https://newsroom.fedex.com/newsroom/sustainability2021/
[197] Brightdrop, "BrightDrop Completes Record-Setting Build of its First Electric Light Commercial Vehicle; Unveils New Vehicle and Ikns Deal with Verizon", (2021) https://www.gobrightdrop.com/newsroom/brightdrop-completes-record-setting-build-of-first-electric-light-commercial-vehicle
[198] Bloomberg Opinion, "Amazon and UPS are Kingmakers in EV Bubble", (2021) https://www.bloomberg.com/opinion/articles/2021-02-16/amazon-and-ups-are-kingmakers-in-electric-vehicle-bubble

International Chamber of Shipping	Marine	Clean fuels	Committed to investment, development, and procurement of clean fuels.[199]
Maersk	Marine	Methanol	Purchased eight vessels that can run on methanol (to be delivered in 2024).[200]
Merchants Fleet	On-road	Electrification	Purchasing 12,600 electric delivery vehicles from BrightDrop.[201]
Verizon	On-road	Electrification	Purchasing electric service vehicles from BrightDrop.[202]

Figure A2 shows growing support for private sector-led efforts to decarbonize freight transport.

[199] International Chamber of Shipping, "Shipping industry sets otu bold plan to global regulatory to deliver net-zero by 2050", Accessed October 13, 2021: https://www.ics-shipping.org/press-release/shipping-industry-sets-out-bold-plan-to-global-regulator-to-deliver-net-zero-by-2050/

[200] Bloomberg Green, "Maersk Makes $1.4 Billion Green Bet on Methanol-Fueled Ships", (2021) https://www.bloomberg.com/news/articles/2021-08-24/maersk-makes-1-4-billion-green-bet-on-methanol-powered-ships

[201] BrightDrop, "Merchants Fleet is Slated to be BrightDrop's Second Major Customer", (2021) https://www.gobrightdrop.com/newsroom/merchants-fleet-slated-to-be-brightdrops-second-major-customer

[202] Brightdrop, "BrightDrop Completes Record-Setting Build of its First Electric Light Commercial Vehicle; Unveils New Vehicle and Ikns Deal with Verizon", (2021)