Foreign Policy at BROOKINGS

THE CHALLENGE OF DECARBONIZING HEAVY TRANSPORT

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EXECUTIVE SUMMARY

Many jurisdictions are focused on achieving very low or net-zero greenhouse gas (GHG) emissions by mid-century, bringing a spotlight to the biggest challenges in decarbonization. The transportation sector is responsible for about one-quarter of global GHG emissions and emissions are growing, even in the developed world where other emissions are generally flat. Liquid fuels made from oil dominate the sector; they are easy to transport and store, contain a great deal of energy for their weight and volume, and enable use of internal combustion engines. The degree of difficulty in decarbonizing transport varies across the sector. Electrification is relatively easy for smaller vehicles that travel shorter distances carrying lighter loads. For these vehicles, the added weight of a battery is less of a hindrance and the inherently simpler and more efficient electric motor and drivetrain (the system that delivers power from the motor to the wheels) make up for some of the weight penalty. However, the heavier forms of transportation are among the fastest growing, meaning that we must consider solutions for these more difficult vehicles as well. The challenge of decarbonizing these sectors and the technologies to overcome these challenges are global, but this paper focuses on policy options in the United States.

Medium and heavy trucking and other forms of heavy ground transportation represent a middle ground in the decarbonization challenge. Vehicles that travel set routes in limited areas represent the low-hanging fruit for electrification. City buses, urban delivery vehicles, and equipment at ports can be recharged at a central location or at wireless pads along the way, and these vehicles are leading the way in heavy vehicle decarbonization. Longer distances and heavier loads bring additional challenges, especially the weight of the battery and the very high power needs for fast charging. Chargers rated as high as 3 megawatts are under development to charge tractor-trailers and West Coast utilities are looking at building charging stations with a maximum load of 23.5 megawatts. Such heavy loads for vehicle charging will require grid upgrades, especially in rural areas.

Aviation and maritime shipping share important characteristics, despite being the most and least GHG-intensive forms of transport, respectively. These modes carry heavy loads with little or no opportunity for frequent refueling, except for short shuttle flights for airliners or ferries for maritime transport. The energy density of oil-based fuels is particularly important in these sectors. Low carbon fuels that can be dropped into the current fuel mix are likely to be important in decarbonizing both sectors, allowing progress despite 25- to 30-year lifespans of airliners and container ships. In aviation, efficiency is already reducing per-mile emissions; new planes are as much as 25% more efficient than older models and more improvements are expected. Biomass-derived jet fuel is available today, but the supply of waste oil feedstock is not sufficient to meet demand. Biofuels from cellulosic crops and agricultural wastes are possibilities for the future, as

are hydrogen and fuels made from hydrogen and captured carbon dioxide. Liquified natural gas (LNG) is a lower-carbon option for maritime shipping that also meets the low-sulfur fuel requirement that took effect in January 2020. Bio- and waste-based fuels are also longer-term options in shipping, similar to aviation.

Decarbonization of heavy transport lags behind other sectors, but spillover effects can help. For example, some advanced biofuel technologies produce a range of fuels, similar to making a range of fuels from crude oil. Today's supply of bio-jet fuel comes from such processes, despite a lack of policy for jet fuel decarbonization. More synergies could emerge if carbon capture becomes a common way to decarbonize difficult stationary sources of GHGs, like some industrial processes. Captured carbon dioxide (CO_2) can be combined with hydrogen produced with renewable electricity to make liquid fuels. Technology exists to decarbonize the heavy transport sector, although many advanced technologies are expensive and not proven at scale. The challenge for policymakers will be keeping technology advances and policy in alignment as the technology advances. The COVID-19 pandemic adds a degree of difficulty, since it is unclear how it may shift demand and consumer preferences in transport. For example, consumers may remain reluctant to use urban public transport, and shorter supply chains may be attractive to businesses seeking to become more resilient in the face of a global disruption.

DECARBONIZATION GOALS GET SERIOUS

In October 2018, the Intergovernmental Panel on Climate Change (IPCC) issued a warning that the world needs to reduce global greenhouse gas (GHG) emissions by 45% by around 2030 and reach net-zero emissions by 2050 to avert the worst impacts of climate change.[1] However, meeting these goals would require very deep cuts in GHG emissions in the coming decades. For this reason, scientific focus and political momentum toward deep decarbonization of the economy has been growing recently.

The European Union, through its European Green Deal, aims to achieve net-zero GHG emissions by 2050.[2] Meanwhile, several U.S. states have also enacted long-term emissions reductions goals. California[3] and Hawaii[4] are targeting net-zero emissions by 2045, while New York[5] aims to reach that goal by 2050. Colorado has a goal to achieve 90% reductions by 2050,[6] with Maine[7] and New Jersey[8] seeking 80% reductions by mid-century.

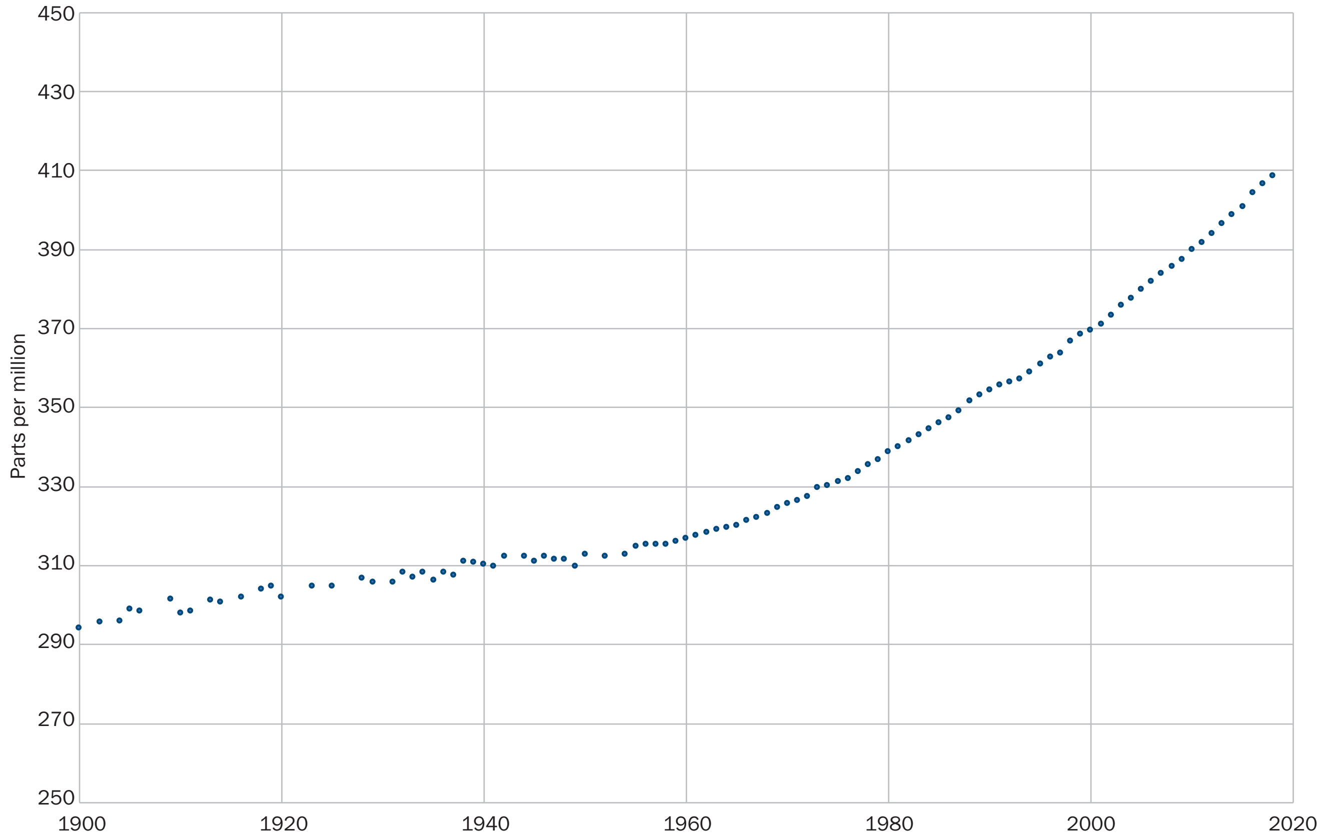
Nonetheless, emissions continue apace. May 2020 saw the highest concentration of carbon dioxide ever recorded at the Mauna Loa Observatory,[9] where emissions have been monitored since 1959, despite recent short-term emissions reductions due to the COVID-19 pandemic. Additionally, as states across the nation and the globe have reopened their economies, emissions have begun to increase rapidly.[10]

Most discussion about reducing emissions focuses on the power sector, and for good reason. Costs for renewable electricity generation have plummeted in recent years and emissions reductions in the power sector are generally easiest and cheapest. But if the world is to achieve deep decarbonization to avoid the worst impacts of climate change, decarbonizing the electricity sector is not enough.

Moving away from oil in the transportation sector is not as simple as an electric vehicle in every driveway. Electric vehicles work well for many applications, but for others, oil's nature as an energy-dense liquid is more difficult to replace.

The IPCC Fifth Assessment Report reflects that global transportation emissions continue to rise significantly, and projects that transport sector emissions may rise faster than other end-uses by 2050, if no new mitigation actions are taken.[11]

FIGURE 1: ATMOSPHERIC CARBON DIOXIDE CONCENTRATION, MAUNA LOA OBSERVATORY



Source: National Oceanic Atmospheric Administration[12]

When one thinks about technologies that are emblematic of the fight against climate change, electric vehicles (EVs) are high on the list. Oil is the dominant fuel for transportation today, but oil companies are now facing public backlash, with pressure on banks to stop funding oil projects[13] and lawsuits attempting to hold oil companies accountable for climate damage.[14] EVs are a pathway away from oil, allowing transportation to tap into abundant and inexpensive renewable power. Global electric vehicle sales have surged over the last decade[15] particularly in China, which accounted for approximately 45% of EVs on the road in 2018.[16]

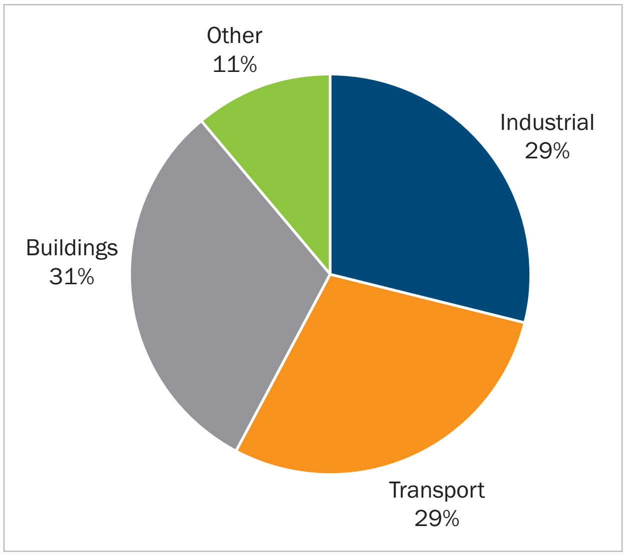
Yet moving away from oil in the transportation sector is not as simple as an electric vehicle in every driveway. Electric vehicles work well for many applications, but for others, oil's nature as an energy-dense liquid is more difficult to replace.[17]

TRANSPORTATION IS A SIGNIFICANT PORTION OF ENERGY USE AND GREENHOUSE GAS EMISSIONS

Transportation is a central feature of modern life. Globalization has steadily increased the movement of goods and people, and transportation is one of the largest energy use sectors. Pre-pandemic, transport made up 29% of global primary energy use[18] and around 25% of global energy-related carbon dioxide (CO_2) emissions.[19]

During the COVID-19 pandemic, transportation has taken a particularly large hit, as people stopped commuting and travelling, and factories shut down. In areas with tight lockdowns due to the virus, road transportation saw declines of 50 to 75%.[20] Meanwhile, freight transport has declined somewhat during the pandemic[21] and passenger aviation demand has plummeted.[22] It remains to be seen how quickly transportation and overall economic activity will recover as the pandemic recedes, but

FIGURE 2: GLOBAL FINAL ENERGY CONSUMPTION BY SECTOR, 2018



Source: International Energy Agency[23]

the underlying systems of transportation have not changed as a result of the virus.

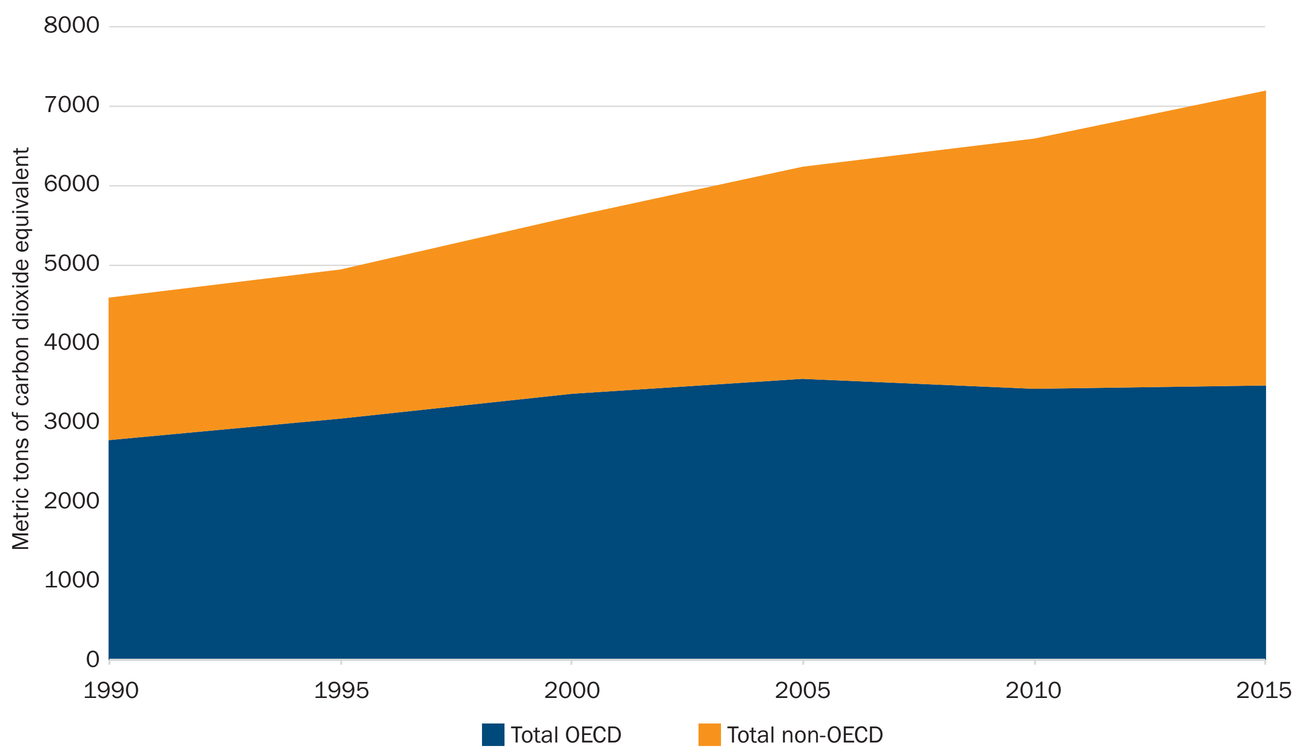
Transport emissions are particularly large in the developed world. In the United States, transportation is the largest source of greenhouse gas emissions, with 29% of the total.[24] The transportation sector has not benefitted from the tailwinds that have reduced GHG emissions in the electricity sector, namely, plummeting prices for renewable electricity and inexpensive natural gas in the United States. In 2017, the transportation sector made up 27% of emissions in the EU and is the only main European economic sector in which GHG emissions have *increased* compared to 1990 levels.[25]

In middle-income and developing countries, lower ownership of personal vehicles and smaller distances traveled result in lower GHG emissions from transportation than in more developed economies, totaling 8.6% of total emissions in China[26] and 12% in India.[27] Still, global transportation emissions have more than doubled since 1970,[28] and transport emissions are projected to continue to rise at faster rates in these countries than in the developed world, as consumer demand for personal transport rises.[29]

OIL DOMINATES TRANSPORTATION FUEL TODAY

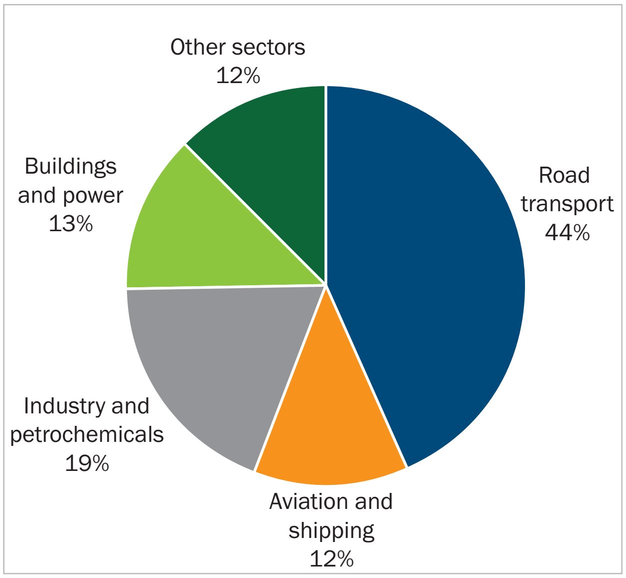
The transport sector is the least-diversified energy-end use sector, dominated by oil. In 2019, petroleum fuels accounted for 91% of U.S. transportation,[30] and 95% in the EU as of 2018.[31] Road transport

FIGURE 3: TRANSPORTATION EMISSIONS, OECD VERSUS NON-OECD COUNTRIES, 1990-2015



Sources: Transportation sector data by country, 2016, World Resources Institute's CAIT emissions data[32] *and OECD country delineations*[33] is the largest segment of global oil demand today, making up 42.2 million barrels per day (mbd) out of 97.7 mbd of global oil demand, or 43%.[34]

FIGURE 4: GLOBAL OIL DEMAND BY SECTOR, 2018



Source: International Energy Agency[35]

Why does oil dominate the transportation sector? The reason is simple — fuels made from oil have attributes that make them nearly ideal transportation fuels. Modes of transport don't just carry their passengers or freight; they also carry the fuel required to make the journey. Thus, the ideal transportation fuel is energy dense — meaning that it contains a lot of energy for its weight and volume. Petroleum-based fuels meet this criterion. Liquid fuels enabled the development of the internal combustion engine, which powers the overwhelming majority of today's transport. Finally, liquid fuels are ideal for transportation because they are easy to move from production to storage to final use in a vehicle — they can be easily pumped into an on-board tank.

However, the transportation sector is not homogenous. Some parts will be easier to decarbonize than others. Replacing oil will be easier in smaller vehicles carrying lighter loads with frequent opportunities for refueling. Each of these qualities makes the energy density of oil-based fuels less important, making way for alternative on-board energy sources, like batteries or hydrogen.

The transition away from oil in light vehicles has begun...

Cars, light trucks, and two-wheelers are the easiest place to start in decarbonizing the transportation sector, and that transition has already begun. From 2011 to 2018, EV sales in the United States grew 91%,[36] and the International Energy Agency projects that there will be 125 million electric cars on the road by 2030.[37] Longer-term estimates of EV sales vary considerably, based on assumptions about policy and technology. Low-penetration scenarios call for 305 million passenger EVs by 2040,[38] 15% of the global fleet, while very optimistic scenarios call for as many as 900 million EVs by that time, accounting for nearly half of the fleet.[39] While estimates of electric vehicle growth vary, there is consensus that increased cost-competitiveness and government regulations will push both supply and demand.

Pre-pandemic, transport made up 29% of global primary energy use and around 25% of global energy-related carbon dioxide emissions.

Electric vehicles and greater efficiency in vehicles with internal combustion engines are reducing the oil consumption of the light vehicle fleet. The International Energy Agency estimates in its New Policies Scenario that oil demand from light vehicles will peak in the early 2020s,[40] despite strong growth in the number of vehicles on the road. Efficiency improvements are the most important contribution to this trend in the near term, with fuel substitution, especially electrification, also contributing. Electric vehicles are currently leading the race to remake the light vehicle fleet, but other technologies, especially hydrogen fuel cells, also have great potential.

In the United States, cars and light trucks accounted for 55% of U.S. transportation energy use in 2017.[41] Commercial and freight transport accounted for 24%, non-highway transport for 22%. The breakdown between on-road and non-highway transport is similar in Europe, where 82% of transport energy use is on the road.[42]

...But heavy transportation lags behind

However, displacing oil in the non-light vehicle portion of the transportation sector is more difficult. In heavy trucking, shipping, and aviation, moving people or goods over long distances makes the energy density of fuel particularly important. The energy density of batteries is orders of magnitude lower than petroleum fuels, making heavy transport more difficult to electrify. For these sectors, lower carbon fuels that mimic the useful characteristics of petroleum fuels are a promising pathway for decarbonization. Biofuels or fuels produced using electricity, such as hydrogen and synthetic fuels, are the likely substitutes in long-distance transport, but these fuels have their own inherent limitations. Since liquid fuels are so important in these sectors, minimizing liquid fuel use in light transportation (and in other sectors of the economy) will be crucial to saving those fuels for where they are most needed. This issue is especially important in the case of biofuels, where land use constraints limit their production.

Unfortunately, the harder-to-abate portions of transportation are also among the fastest growing. The International Energy Agency estimates that oil demand in aviation will increase more than 50%[43] and in trucking by 25% by 2040.[44] Miles traveled in these sectors tend to track closely with economic growth; they have declined rapidly during the COVID-19 pandemic but are likely to recover as the economy does.

In these sectors, a number of strategies will be needed for decarbonization. Substitution with lower-carbon biofuels, hydrogen, or synthetic fuels made with captured CO_2 are options. But the expense and land use implications (in the case of biofuels) of these fuels means that efficiency improvements and changes to vehicle operation will be needed to keep overall costs down.

A number of studies have considered pathways to achieve the decarbonization goals of the Paris Agreement. Even in the most ambitious scenarios, decarbonization of the transportation sector is incomplete. The Sustainable Development Solutions Network's "Pathways to Deep Decarbonization" study found that freight transport is one of the most difficult sectors to decarbonize.[45] In the International Energy Agency's "Below 2 Degree Scenario," only two- and three-wheeled vehicles and rail completely decarbonize by 2060. In Shell's "Sky Scenario," more than half of global car sales are electric by 2030, extending to all cars by 2050. However, across all other forms of transport, the Sky Scenario relies on biofuels as the energy-dense liquid fuel of choice.[46]

Even in the heavy transportation sector, the different forms of transport face different challenges. For this paper, I've separated road transport from aviation and marine shipping to discuss the challenges and possibilities of decarbonization for each sector.

ENERGY DENSITY AND BATTERIES

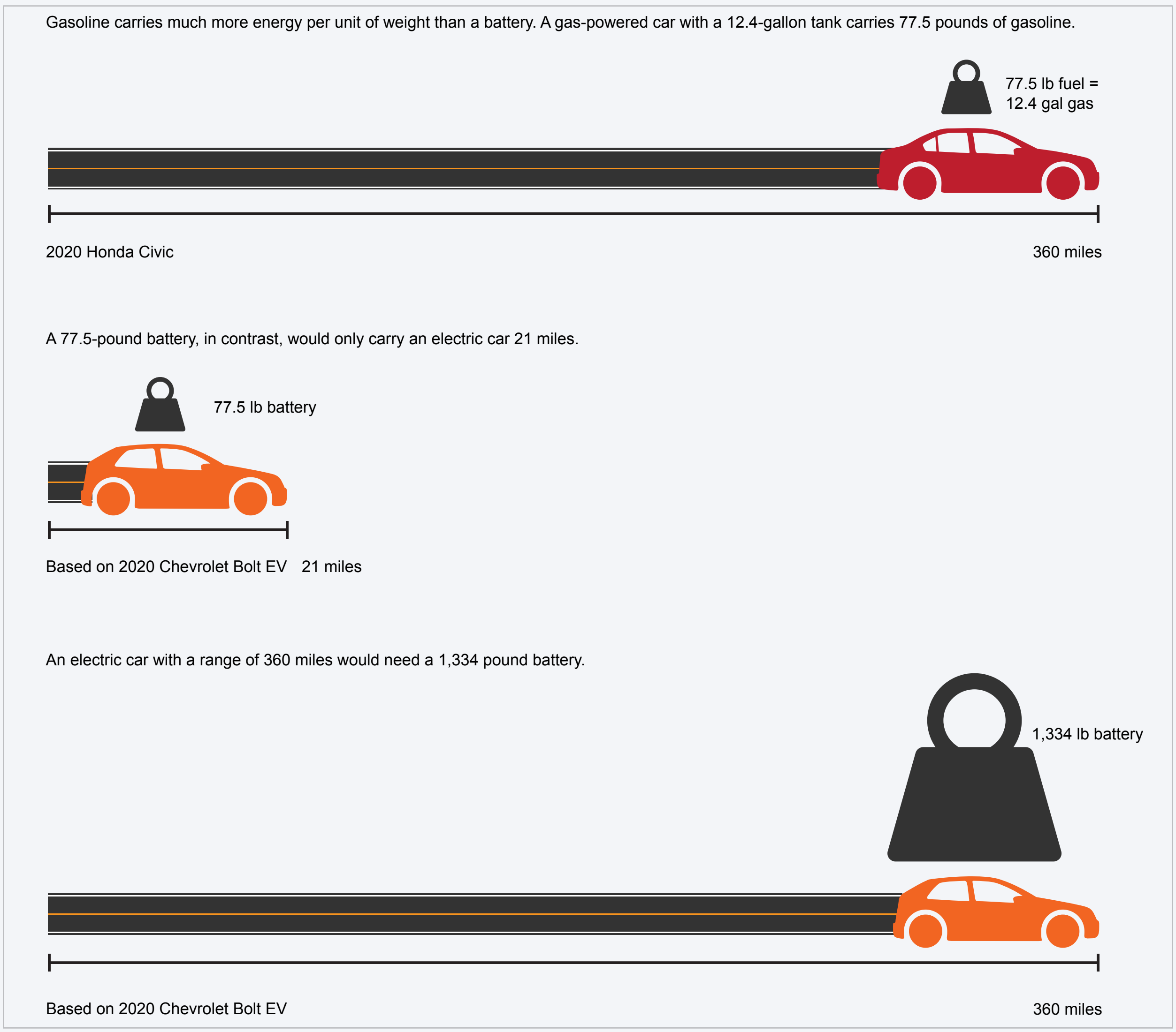
Why can't we electrify all of the transportation sector? Why are we not talking about battery powered ocean liners or jets? Energy density provides the answer.

Pound for pound, gasoline is much more energy dense than today's electric vehicle batteries. With today's best battery technology, you need about 40 pounds of battery to store the same energy as one pound of gasoline, or 240 pounds of battery per gallon.

This extreme difference in energy density might make electrifying any vehicle seem difficult, but electricity also has some factors working in its favor. Electric motors are a lot more efficient than internal combustion engines at transferring energy to the car's wheels — they don't waste nearly as much energy in the form of heat. Drivetrains in electric vehicles are also simpler and lighter, so some of the extra battery weight is offset by less weight in other parts of the car. For both of these reasons, you don't need to carry as much energy in an electric vehicle to travel the same distance. For example, the 2020 Chevy Bolt has a 259-mile range, but its battery only holds the equivalent of 1.8 gallons of gasoline in terms of energy.[47]

Factoring in efficiency and the lighter drivetrain, a passenger car needs about 50 pounds of battery today to provide the same travel range as a gallon of gasoline, or about nine pounds of battery per pound of gasoline. This differential in energy per unit of weight explains why battery powered airplanes or ships for all but short distances are not on the menu of options. Batteries are just not energy dense enough to do the job. Researchers are hard at work on lighter and less expensive batteries, but the level of improvement required will be too much for these long-distance forms of transportation in the foreseeable future. Deep decarbonization in these sectors will require a different solution.

FIGURE 5: WEIGHT OF FUEL



Source:The Brookings Institution[48]

MEDIUM AND HEAVY-DUTY ROAD TRANSPORTATION

Medium- and heavy-duty vehicles constitute a middle ground between the relatively easy to electrify light vehicle sector and the very difficult aviation and marine sectors. Numerous vehicle types and duty cycles make up the sector, and these characteristics determine what decarbonization options work best. Data for road shipment of freight is widely available and an important component of fuel use and greenhouse gas emissions in the sector, but the sector also consists of buses and service vehicles, like garbage trucks and specialized construction equipment.

Road transportation of freight accounts for 20% of global oil demand and has been the fastest sector of oil demand growth since 2000.[49] Road freight transport is a flexible, but inefficient way of moving goods. Rail and marine transport of goods both use about 15% of the energy of road transport.[50]

The rise of e-commerce is rapidly changing the market for smaller, more local delivery vehicles. These vehicles are prime targets for electrification, since they typically travel short distances in a day and return to central terminals.

Road freight transport accounts for half of global diesel demand.[51] With globalization, trade, and increasing consumer demand, the freight intensity of the economy is increasing.[52] The International Energy Agency estimates road freight comprises approximately 7% of world energy-related CO_2 emissions (nearly double that of aviation).[53] Global freight demand is strongly correlated with gross domestic product (GDP) — demand for goods drives further need for their transport.[54] Freight carbon dioxide emissions comprise 12% of U.S. emissions.[55]

The rise of e-commerce is rapidly changing the market for smaller, more local delivery vehicles. These vehicles are prime targets for electrification, since they typically travel short distances in a day and return to central terminals. Unlike consumers, such companies are less likely to suffer from sticker shock at the higher upfront cost of electric vehicles, and instead consider lower fuel and maintenance costs. Finally, many of these companies have a public face and environmental policies are an important part of their engagement with customers. In this vein, companies like Amazon and DHL are working to electrify their local delivery fleets.[56] Nonetheless, heavier vehicles traveling longer distances are more difficult to decarbonize, and are the focus of this section.

Efficiency can begin the decarbonization process

Efficiency standards for medium- and heavy- duty vehicles are at a much earlier stage of development than those for light-duty vehicles. Additionally, the wide range in vehicle types and duty cycles makes regulating efficiency more challenging than for light duty vehicles. In 2005, Japan became the first country to establish heavy-duty vehicle efficiency standards, whereas the United States established the world's first light-duty standards in the 1970s. By 2020, several countries had developed heavy-duty vehicle fuel efficiency standards, including Argentina,[57] Brazil,[58] Canada,[59] China,[60] India,[61] Japan,[62] Mexico,[63] and the United States,[64] as well as the European Union.[65]

Economics drives efficiency improvements in road freight transport, even in the absence of regulation. Improvements in system efficiency can deliver emissions reductions. For example, Germany and Austria have used dedicated freight corridors for enhanced efficiency[66] and urban consolidation centers centralize the distribution of goods in many cities in the Netherlands.[67] Truck operation can make a difference as well. Vehicle speeds and weight can be optimized for fuel-efficiency.[68] The practice of platooning — or connecting the acceleration and braking of two or more trucks together in a convoy using sensors — could save up to 4% of total fuel consumption.[69]

There are significant efficiency gains available in diesel engines. Improvements in turbocharging technology allow smaller diesel engines to provide the same level of performance. IHS Markit estimates that achieving a 43% reduction in CO_2 emissions (over a 2015 baseline) in a Class 8 truck (one weighing more than 33,000 pounds) by 2030 to meet EU standards would cost about $40,000 per vehicle.[70] For comparison, a typical new Class 8 truck costs about $120,000.[71] Most of the additional cost is in light-weighting the vehicle and in maximizing engine efficiency.

Deeper decarbonization requires new technology

Improvements in diesel truck technology raise the bar that new decarbonized technologies must meet to be competitive. Electrification is a good option for medium- and heavy-duty vehicles that operate in limited areas and follow set routes, since they can refuel frequently at a central location. Buses are the low-hanging fruit; more than 136,000 electric buses were sold in 2019, mostly in China.[72] The city of Shenzhen has entirely electrified its fleet of more than 16,000 buses.[73] Urban delivery vehicles, drayage trucks and other vehicles at ports, and service vehicles like garbage trucks are other relatively easy targets for electrification. Amazon has committed to purchasing 100,000 electric delivery vans from Rivian, with delivery starting in 2021.[74]

Electrification is a good option for medium- and heavy-duty vehicles that operate in limited areas and follow set routes, since they can refuel frequently at a central location. Buses are the low-hanging fruit.

For long-haul electric trucks, range and payload are the primary and interrelated challenges. Batteries are heavy compared to liquid fuel — extending the truck's range with extra batteries takes away from the weight of freight that it can haul. Long-haul Class 8 trucks, like tractor-trailers, or semi-trucks, have a total weight limit of 80,000 pounds, including the vehicle and payload. A battery with 500 miles of range would add 10,000 pounds to the vehicle weight, a substantial cut in hauling capacity.[75] Raising the weight limit somewhat for electric trucks could help with this challenge, as could a smaller battery, resulting in shorter vehicle range.

Electric heavy-duty trucks also pose charging challenges. Because they will have much larger battery storage than an electric passenger vehicle, they will also require more power for charging. Fast chargers for personal vehicles deliver 50 to 150 kilowatts (kW) of electricity, charging a vehicle completely in roughly 30 minutes to two hours, depending on the battery size and charging rate.[76] (Level 2 home chargers deliver around 10 kW, for four to 10 hours of charging time.) The scale changes completely for large trucks. Battery sizes as large as 1000 kW-hours require very high-power flows to charge quickly. A light vehicle fast charger could take as long as 20 hours to charge such a large battery. Overnight charge times might be fine for many local applications but raise a serious challenge for long-haul trucking.

Chargers with very high rates are one potential solution. Chargers rated as high as 3 megawatts (MW), or 3000 kW, are in development for heavy duty trucks.[77] These have the advantage of charging trucks in a similar time to refueling with diesel, making long-haul battery trucks more economic for hauling companies, since time is money in this application. However, these chargers have serious implications for the power grid, particularly if there are several of them in a single location, such as at a highway truck stop. This high level of discontinuous, "lumpy" power draw is a challenge for the grid and will require battery storage or distributed generation to balance the load. Proactive grid expansion of electrical infrastructure at designated truck charging stops would be needed as such heavy trucks are deployed. Slower chargers lighten the load on the power grid but raise challenges of land use and space to accommodate trucks for the longer charging time, in addition to the economic challenge of more downtime for refueling.

Wireless charging imbedded in road surfaces or charging from overheard wires are both possible but require very large infrastructure investments.

Charging along a route is an additional possibility for electric heavy vehicles. Applications of wireless charging technology are already in use in fleets where vehicles follow a set route. For example, in California, the Antelope Valley Transit Authority operates a fleet of electric buses with 250 kW inductive charging pads in the pavement at some transit centers. The all-electric buses can top off their batteries during planned longer stops at these centers, meaning that they can run for the same number of hours per day as the diesel buses they replaced.[78] This technology is more difficult for large vehicles that need route flexibility, like long-haul trucks. Wireless charging imbedded in road surfaces or charging from overheard wires are both possible but require very large infrastructure investments. Such infrastructure could be built on main shipping routes, with vehicles relying on battery storage for "last mile" travel on smaller roads.

In addition to electrification, alternative fuels could provide pathways to decarbonization. Biofuels and other liquid fuel types that are compatible with today's infrastructure and engines provide an easy pathway. However, these types of fuels are more needed in the harder to decarbonize aviation and maritime sectors. Diesel made from agricultural products or waste is blended into some fuel today, for compliance with the Federal Renewable Fuels Standard and the California Low Carbon Fuel Standard. Even if road transport is not the highest and best use of these fuels over time, regulations for the trucking industry are encouraging development and scale-up of the technology.

Hydrogen is another alternative fuel that has potential in trucking. Hydrogen-fueled trucks have electric drivetrains and use the hydrogen to produce electricity in a fuel cell. Thus, these trucks have many of the same advantages as electric vehicles — a lighter, simpler, and more efficient drivetrain — without the disadvantage of the heavy battery and long refueling time. However, the hydrogen truck market is less advanced than that for electric trucks, primarily because of the need for extensive infrastructure to produce and distribute hydrogen. Also, to achieve its potential, hydrogen for trucking would need to be produced by splitting water molecules through the process of electrolysis, using renewable electricity, rather than the process of steam reforming methane that is more common today. Nonetheless, hydrogen trucks are under development. Kenworth and Toyota are partnering to develop a hydrogen-fueled Class 8 truck,[79] Cummins has hydrogen trucks in development,[80] and start-up Nikola has hydrogen trucks on the market today.[81]

In addition to the technology, the fragmented structure of the long-haul trucking industry raises challenges for decarbonization investments. In the United States, a strong majority of trucks are owned by companies that operate 20 trucks or fewer.[82] In Asia, nearly 90% of trucks are owned by individual drivers.[83] Smaller companies are less able to take risks on new technology or provide dedicated refueling infrastructure, and they have less access to capital to cover up-front costs of trucks and changing technology. Smaller companies are also less likely to face public pressure to take the lead in new technology, since they are not household names and are often privately owned, and thus do not face pressure from shareholders or investors. Smaller companies operate in a competitive market with thin margins. Operators of 20 trucks or fewer only consider technologies with paybacks ranging from six to 36 months (averaging a year), while those operating fleets of 500 trucks or more still only consider a payback periods of 18-48 months (averaging two years).[84] Lack of information about efficient technologies and split incentive problems (especially when the operator does not own the truck) are additional barriers to investments in efficient and alternative fuel trucks.

Freight trucking conclusions

In the heavy road transport sector, the easiest parts to decarbonize are vehicles that follow set routes for relatively short distances per day, like buses, delivery trucks, and garbage trucks. Alternative vehicles for these applications are in commercial production and fleet operators are gaining experience in their deployment. The question is, how will this experience carry over to heavy vehicles that travel longer routes without such easy access to refueling infrastructure, like long-distance freight trucks? Additionally, short haul applications like drayage are today where old trucks go to die. Changing these applications into hotbeds of innovation will increase costs for operators, and likely require government support to finance the change.

Policy is needed to encourage the switch to low-carbon heavy vehicles, but establishing large-scale infrastructure requires a clear technology winner.

Chicken-and-egg problems are likely with any infrastructure-heavy solution, like hydrogen-fueled vehicles, fast chargers along freight routes, or on-route charging. Policy is needed to encourage the switch to low-carbon heavy vehicles, but establishing large-scale infrastructure requires a clear technology winner. In short-haul applications, operators are experimenting with different energy carriers, like hydrogen or batteries, and different refueling mechanisms, like fast-charging or on-route charging. However, given the urgency of the climate challenge and some jurisdictions' very ambitious decarbonization goals, clear winners may not emerge fast enough to enable the infrastructure buildout. Policy has the potential to drive vehicle uptake and infrastructure development, but at the risk of not allowing the technology competition to fully play out.

The California Air Resources Board (CARB) is testing the principles for decarbonizing heavy transport with a new rule passed in June 2020. The rule requires growing numbers of zero-emissions medium- and heavy-duty truck sales over time, beginning in 2024, with all sales being zero-emissions by 2045.[85] CARB does not specify the technology in the rule, but electric trucks are certainly ahead of other technologies in development, particularly in the medium-duty segment. At the same time, utilities on the U.S. West Coast are working to provide the charging infrastructure that new electric vehicles will need. The West Coast Clean Transit Corridor Initiative is a consortium of utilities in Washington, Oregon, and California. It issued a report in June 2020, just days before the new CARB rule, recommending the development of charging stations at 50-mile intervals along Interstate 5, the main artery connecting the three states. The first phase of these stations would be designed for medium-duty vehicles and completed by 2025, with the second stage adding charging for heavy-duty trucks at half the stations by 2030.[86] Providing sufficient power to the stations will be a challenge that will require new infrastructure, especially those stations located in rural areas. At the medium-duty phase, peak demand from a station would be 3.5 MW, but those stations upgraded to handle heavy-duty trucks will have up to 10 additional charging stations with a capacity of 2 MW each, for a peak load of 23.5 MW.[87]

The combination of the new CARB rule and a utility push for charging infrastructure may overcome the chicken-and-egg problem of vehicles and infrastructure. Although the rule is technology neutral, it will give electric trucks a firm head start in the California market. Fifteen Northeast states and the District of Columbia have signed a memorandum of understanding to follow the California standard.[88] The size of these markets combined might be enough to compel the construction of charging infrastructure on the East Coast as well. Although these policy developments may jump start the construction of charging infrastructure for heavy and medium trucks, they risk leaving development of hydrogen infrastructure and vehicles behind. Hydrogen has advantages in the overall energy system, particularly its ability to act as a storage mechanism when excess zero-carbon electricity is available. While pushing the adoption of electric vehicles that can reduce emissions today, policymakers would do well to not abandon hydrogen, even though it is at an earlier stage of development. There may be room in the heavy ground transport sector for both electric and hydrogen-fueled vehicles, and hydrogen could provide synergies with the rest of a decarbonized energy system.

THE BIGGEST CHALLENGES: AVIATION AND MARINE SHIPPING

Although aviation is the most energy-intensive way of moving people and freight and marine shipping is the least intensive, aviation and shipping share important characteristics. Both generally involve large vehicles traveling long distances. Frequent refueling is often not possible, except in the case of city-to-city air shuttles or ferries. Both also share the challenge of emissions that occur in international airspace or waters, outside of country boundaries.[89] Aviation and marine shipping have strong international governing bodies that set goals for decarbonization and environmental performance. The much more diffuse global trucking industry does not have this level of organization or centralized goal setting. Finally, the aviation and shipping industries are much more concentrated in their ownership than freight trucking. The top 10 commercial airlines own nearly one-quarter of the world's commercial aircraft fleet.[90]

Aviation

Of all the sectors in transportation, the energy density challenge is most acute and easy to understand in aviation. The airplane has to lift enough fuel for the entire flight to its cruising altitude, a clear energy challenge. This fact makes energy efficiency a key consideration in aircraft design and airline profitability. New airplanes are significantly more fuel-efficient than older models, with improvements in engine efficiency and aerodynamics, and more lightweight materials. Airplanes recently designed from scratch, like the Boeing 787 and the Airbus A350, take maximum advantage of these changes and are as much as 25% more efficient than older similar models.[91] Improvements are likely to continue over time. A recent study found that the fuel consumption of new aircraft can be cost-effectively reduced by 25% in 2024 and 40% in 2034.[92] This calculation only considers airline profitability and cost of capital; if a carbon price or ecological considerations were added, further improvements would become cost effective.

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Fuel weight even factors into what routes airlines choose to fly. In 2013, Singapore Airlines cancelled its Newark to Singapore non-stop flight amid high oil prices, because the amount of fuel needed severely limited the number of passengers the flight could carry. The flight carried only 100 passengers, all in business class, on the more than 9,300-mile flight. The airplane was basically a flying fuel tanker. More efficient airplanes (and lower fuel prices) have made such ultra-long flights possible again, this time in a more efficient carbon-fiber plane with 161 passengers. The new flight on that route carries 44,000 gallons of jet fuel for the journey, one-quarter less than the previous flight.[93]

Pre-pandemic, aviation was responsible for two to four percent of global CO_2 emissions,[94] but this sector was projected to grow rapidly, as economic growth made air travel accessible to more people. However, the aviation industry has been particularly hard-hit during the global pandemic. Consumer demand for flying plummeted, with commercial flights dropping 74% from their 2019 level by mid-April 2020.[95] Prior to the pandemic, the International Energy Agency estimated that fuel demand in aviation would increase more than 50% by 2040 and the International Civil Aviation Organization (ICAO) estimated even greater growth, with 2.2 to 3.1 times greater fuel consumption projected by 2045, even with continued improvements in aircraft technology and operations efficiency.[96]

The air transport industry has ambitious goals to prevent a rapid rise in emissions. The International Air Transport Association (IATA), the trade association for the world's airlines, has established goals of carbon-neutral growth in aviation after 2020 and of reducing the sector's net greenhouse gas emissions to 50% below 2005 levels by 2050.[97] Given how difficult emissions reductions are in aviation, IATA established the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) to finance emissions reductions in other sectors. Airlines from countries participating in the first phase will require offsets to account for growth in emissions beginning in 2021.[98] Alternative plane designs,[99] engine efficiency, weather-optimized routes,[100] and improved air traffic control[101] are some tools to reduce emissions over time.

Given the energy density challenge, alternative liquid fuels that mimic the useful qualities of fossil fuels, including bio-based fuels, alcohol-to-jet, and power-to-liquids, are the best options for the aviation sector. However, some estimates indicate that even 100% replacement of petroleum jet fuel with alternative fuels in 2050 could result in an absolute *increase* in total GHG emissions from the sector over their 2005 level, owing to growth in demand for air travel.[102]

BIOFUELS, LAND USE, AND GREENHOUSE GAS EMISSIONS

Biofuels often come up in discussions of how to decarbonize heavy transportation. They share an important advantage with fossil fuels — they are energy dense liquids. Biofuels make up a significant part of road transportation fuel in some countries today. Much of the gasoline pool in the United States contains 10% ethanol, mostly produced from corn. Brazil is the second largest producer of biofuel after the United States, with ethanol (mostly from sugarcane) blended into gasoline at 27% and biodiesel at 10%.[103]

However, biofuels are not a panacea. First generation biofuels — those produced from food crops — can cause rising food prices and competition for arable land. They also provide a relatively small improvement over fossil fuels in terms of GHG emissions. Ethanol produced from corn averages only a 20% reduction in GHG emissions compared to gasoline,[104] and if biofuel production from food crops displaces forest, the net GHG emissions can actually be higher than fossil fuels.[105] More relevant to the heavy transport market, the production of palm oil, a source of heavier biofuels like diesel, is a key driver of tropical deforestation. Biofuels made from palm oil do not reduce GHG emissions compared to fossil diesel unless the palm plantation was already in production or was established on degraded land, rather than cleared forest.[106]

Land use is an even bigger challenge to relying on biofuels to fuel heavy transport. Biomass is used to meet a number of human needs, including food, feed for livestock, and fiber. In a low-carbon world, demand for biological feedstocks in other sectors, such as bioplastics, will grow. Yet the earth's ability to provide these feedstocks has limits, especially the need to conserve forests and other ecosystems. Alexandre Strapasson, Jeremy Woods, Helena Chum, Nicole Kalas, Nilay Shah, and Frank Rosillo-Calle note that bioenergy's potential is limited by "land availability, photosynthetic constraints, the sustainable management of nutrients and water resources, and the nature and rate of investments toward these ends."[107] A high biofuel scenario, where biofuels provide 170 exojoules (EJ) per year of energy by 2050 (18% of primary energy supply), would use approximately 390 million hectares of dedicated cropland, an area equal to 8% of today's global agricultural land.[108] However, the world's population is projected to reach 9.8 billion people by 2050 and food demand is on course to rise by more than 50%.[109] A focus on agricultural efficiency will be crucial to achieve this level of food and fuel production, along with a systems approach to land management. Nonetheless, bioenergy crops could be helpful to ecosystems in some places, for instance in restoring degraded lands, improving water quality by absorbing excess nutrients, and restoring habitats for wildlife.[110]

Biofuels are the only alternative aviation fuels available today. Small quantities of aviation biofuels, produced from waste fats and vegetable oils, are used today in the United States[111] and Europe,[112] blended into the existing supply of petroleum-based jet fuel. One manufacturer of such fuel claims that its GHG emissions are as much as 80% lower than those from petroleum jet fuel.[113] However, the supply of waste fats and oils for use as feedstock is small compared to jet fuel demand. Additional sustainable sources for jet fuel feedstock include vegetable oils (such as soy or canola), cellulosic energy crops (such as switchgrass or Miscanthus) grown on unused land, waste destined for landfills, and crop and forestry residues (such as corn stover or small branches from logging). Drop-in jet fuel produced from these feedstocks could deliver 80% to 90% reductions in fuel carbon intensity.[114]

Some estimates indicate that even 100% replacement of petroleum jet fuel with alternative fuels in 2050 could result in an absolute *increase* in total GHG emissions from the sector over their 2005 level, owing to growth in demand for air travel.

Biofuels for aviation today make up much less than 1% of total aviation fuel demand.[115] Such fuels are expensive and current policy incentivizes biofuels for the road transport sector, rather than aviation. Although aviation biofuel can be used to comply with the U.S. Renewable Fuel Standard's advanced biofuel target, no regulation compels blending of biofuel into aviation fuel, unlike the road sector.

Hydrogen is another possibility for decarbonization of aviation. Hydrogen has some advantages over fossil jet fuel and similar biofuels — the energy density by weight of liquid hydrogen is 2.5 times that of fossil jet fuel. However, its energy density by volume is four times smaller than fossil jet, meaning that fuel tanks would be larger even though the fuel inside would weigh less.[116] Additionally, although the use of hydrogen in aviation brings to mind the Hindenburg for many people, hydrogen is more difficult to ignite than jet fuel, dissipates quickly if the fuel tank is breached, and burns at a lower temperature if ignited, all features that make it safer in case of an accident.[117]

Hydrogen can be used in aviation in two different ways: in a fuel cell to make electricity or through direct combustion as a fuel. Electricity could be used to power a propeller in a small plane, but jet engines need the thrust that direct combustion provides.[118] Hydrogen fuel cells could also be used along with a normal jet engine to power the non-propulsion systems on the aircraft; Airbus and Boeing are both researching the use of fuel cells in this way.[119]

An important impediment to the use of hydrogen in aviation is that it would require redesigned airplanes and completely new infrastructure. Liquid hydrogen fuel tanks must be very insulated to keep the fuel at low temperature and do not fit in the aircraft wings, where standard jet fuel tanks are located.[120]

Marine shipping

Fuel demand and GHG emissions in marine shipping are following a similar trajectory to aviation. Estimates suggest that 90% of global trade is conducted via the seas[121] and sea trade is projected to grow by about 3% per year into the early 2020s.[122] Shipping is responsible for approximately 2.2[123] to 3% of global CO_2 emissions,[124] and, as of 2016, 12% of global transport sector energy use was for marine freight.[125] Nonetheless, marine freight has the lowest energy use and GHG emissions of freight transport methods; emissions can be less than one-tenth of those from transporting freight by truck.[126]

A transition is currently occurring in marine fuel, as the International Maritime Organization (IMO) regulation limiting the sulfur content of marine fuels to no more than 0.5% came into effect in January 2020.[127] Ships with exhaust gas scrubbers can continue to use the higher sulfur fuel, while others are switching to lower sulfur fuels, including liquified natural gas (LNG). In its Stated Policies Scenario, the International Energy Agency (IEA) forecasts that LNG consumption in marine freight could comprise 13% of shipping fuel by 2040, reaching nearly 50 billion cubic meters.[128] The new IMO regulation is an important change in marine fuels, which up to now have been the dirtiest, bottom-of-the-barrel fuels, although the sulfur limit is still much higher than that allowed in road fuels in the United States and Europe. Using more "premium" fuels today, such as marine diesel or LNG, may begin the process of thinking of marine fuel differently, and pave the way toward more decarbonized fuels later. The goal of IMO rule is reducing air pollution, rather than GHG emissions. Nonetheless, estimates suggest that switching to LNG could achieve a 10-28% reduction in CO_2 emissions, though some of these reductions might be offset through increased methane emissions from evaporating fuel.[129]

In April 2018, the IMO announced a goal of reducing greenhouse gas emissions from the shipping sector by at least 50% by 2050 compared with 2008.[130] A follow-up implementing plan was released in October 2018,[131] with member states invited to submit proposals on short- and medium-term plans, and working group meetings held throughout 2019.[132] Measures to reduce marine emissions include retrofitting vessels for efficiency,[133] enhancing shipping route efficiency[134] or alternative methods of propulsion such as sails, hybrid electric engines, or hydrogen fuel cell powered vessels. Deployment of alternative fuels for maritime shipping is behind even the aviation sector. Biofuels in the diesel range could be drop-in fuels, but are much more expensive than heavy fuel oil or marine gas oil, even with the low-sulfur requirement. Alternative fuels like methanol and dimethyl ether could be used in dual fuel engines.

Aviation and marine shipping conclusions

Aviation and marine shipping are likely to be among the last sectors to completely decarbonize, because of their need for zero-carbon energy-dense fuels. Commercial airplanes and container ships both have longer lifespans than heavy trucks, up to 25 to 30 years. Their use doesn't change significantly over their lifetime, although short-haul airplanes have shorter lives than long-haul, since the number of pressurization cycles limits their longevity. Trucks, on the other hand, have useful lives of 15 years or so, and tend to change use as they age. New trucks are used for long-haul fleets, while older trucks go to lower mileage uses.

The lower turnover rate for airplanes and ships sounds like a challenge, but an important part of the decarbonization solution for these sectors is likely to be drop-in fuels that can be blended with fossil fuels and used in existing engines. Newer equipment is more efficient, but reductions in GHG emissions will be obtainable from older equipment using new fuels. Additionally, airliners and container ships often do not follow regular routes. Therefore, whatever fuel they use must be widely available, furthering the argument for fuels that can be used in today's equipment. Completely new fuels, such as hydrogen, will face the same chicken-and-egg infrastructure challenge as highway vehicles. Large ports and airports may represent an easier target than making hydrogen widely available on a nation's highways, but would require coordination across the globe, a challenge not present in road transport.

CONCLUSIONS

This paper has focused on decarbonizing the transportation modes themselves, rather than on shifting transport to lower-emissions modes. This is not an accident — goods tend to travel by the cheapest method that meets business needs, and the cost of transportation is strongly correlated with GHG emissions. Goods that are less perishable or time-sensitive generally travel long distances via ship, the mode with the lowest emissions. Switching from air to sea isn't practical for perishable goods like fresh flowers or fish. On land, a shift from trucking to rail might be possible in some areas. However, goods that can travel by rail generally do, because of its lower per-mile cost.

Nonetheless, the ongoing COVID-19 pandemic may bring about a long-term shift in transportation patterns. Some pundits have begun to speculate about how the pandemic may shift consumer transport preferences, such as a preference for personal vehicle travel over public transit for those who can afford it,[135] particularly as early studies find correlations between public transit use and higher death rates from COVID-19.[136] Meanwhile, other analyses point to adaptations public transport authorities may need to take to make passengers feel safer and to regain ridership rates, such as increased disinfection or touchless payment systems.[137] Freight transport may also be affected if businesses decide that shorter supply chains or more local goods are more resilient in the face of a global disruption like COVID-19.

Goods tend to travel by the cheapest method that meets business needs, and the cost of transportation is strongly correlated with GHG emissions.

Unlike modal shifts, efficiency will be a crucial part of decarbonizing heavy transport. Even as zero-carbon fuels become more available, they are likely to be more expensive than their fossil counterparts. (A carbon price high enough to equalize these prices is unlikely to be politically palatable.) Therefore, continuing advancements in efficiency will make the low-carbon transition easier and cheaper. Already, efficiency is a strong consideration for those operating fleets of airliners and long-distance trucks. Higher fuel prices could further push efficiency improvements in a virtuous cycle.

Producing low-carbon fuels for one part of the transportation sector can have positive spillover effects for other sectors. Two proven technologies for producing fuels for heavy transportation from sustainable biomass or waste — hydrotreating fatty materials or gasifying solid materials and applying Fischer-Tropsch synthesis — produce a range of hydrocarbons, similar to refining crude oil to produce a range of products.[138] For example, the one plant that produces bio-jet fuel in the United States today also produces renewable diesel, gasoline, and propane.[139] Today's requirements for advanced biofuels to be blended with gasoline and diesel are driving some production of bio-jet fuel, even though the aviation sector is not included in the blending law. As technologies to produce advanced biofuels become more mature and less expensive, these biorefineries could meet the needs of multiple parts of the transportation system.

Nonetheless, today's policies that concentrate on low-carbon fuels for road transportation may become more problematic over time. The road transport sector has multiple options for decarbonization and is somewhat easier to decarbonize than aviation and maritime transport. Policies aimed at road transport can begin the process of developing and commercializing alternative energy-dense liquid fuels, but the highest and best use of these fuels is likely to be in aviation and maritime, where their qualities are most needed. Over time, policy will need to adjust to directing these fuels to where they are most needed, as it aims to move the entire transportation system toward zero emissions.

Further in the future, CO_2 from carbon capture technologies may be combined with hydrogen produced from renewable electricity to produce liquid fuels. In this world, difficult-to-decarbonize industrial processes could be symbiotic with transportation applications that need energy-dense liquid fuels. The technologies needed to make this happen exist today, but not at scale, and the overall process is very expensive compared to existing sources of low-carbon liquids. It is akin to running the combustion process backwards, with the corresponding input of energy. However, as both carbon capture and renewable electricity become more widespread, conversion of CO_2 to liquid fuels could provide a robust market for captured CO_2 and a new source of fuel.

Ultimately, the difficulty of decarbonizing heavy transport raises challenges for policymakers.

Policymakers generally want the market to pick winning technologies, but the scale and pace of change necessary in heavy transport may make that process too slow to meet mid-century decarbonization goals. When should policy move away from a focus on improving efficiency in existing fuels and engine types to move forward with new technology? Is there a time at which policy must pick a winner in this sector, even if a clear winner hasn't emerged in the market?

Policymakers must take care to strike a balance between requiring improvements today while still supporting development and pilot projects of next generation fuels.

To date, technology-neutral standards, like California's zero emissions requirements for heavy trucks, or standards that allow for offsets, like the CORSIA program for airlines, are the policy levers in use for reducing emission from heavy transport. However, even these standards can pick winners by forcing reliance on currently proven technology, especially battery electric vehicles. Policymakers must ensure that their actions do not crowd out further advances in new fuels, especially hydrogen. Hydrogen could have advantages over battery electric vehicles in some applications, as well as allowing a storage option for excess renewable electricity generation, potentially aiding in grid decarbonization as well. However, policy that locks in an all-battery future today would preclude these benefits. Policymakers must take care to strike a balance between requiring improvements today while still supporting development and pilot projects of next generation fuels. Efficiently regulating and transforming the heavy transport market will rely on close coordination between technology and policy.

REFERENCES

1 "Global warming of 1.5°C," (Geneva: Intergovernmental Panel on Climate Change, 2018), https://www.ipcc.ch/sr15/.

2 "The European Green Deal," (Brussels: European Commission, December 11, 2019), https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1576150542719&uri=COM%3A2019%3A640%3AFIN.

3 Renewables Portfolio Standard Program: emissions of greenhouse gases, California Senate Bill 100 (2018), https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB100.

4 A Bill for an Act Relating to Environmental Protection, Hawaii House of Representatives Bill 2182 (2018), https://www.capitol.hawaii.gov/session2018/bills/HB2182_CD1_.htm.

5 Relates to the New York state climate leadership and community protection act, New York Senate Bill 6599 (2019), https://www.nysenate.gov/legislation/bills/2019/s6599.

6 Climate Action Plan to Reduce Pollution, Colorado General Assembly Bill 1261 (2019), https://leg.colorado.gov/bills/hb19-1261.

7 "Governor Mills Signs Major Renewable Energy and Climate Change Bills Into Law,"

State of Maine, Office of Governor Janet T. Mills, June 26, 2019, https://www.maine.gov/governor/mills/news/governor-mills-signs-major-renewable-energy-and-climate-change-bills-law-2019-06-26.

8 "Statewide Greenhouse Gas Inventory: 2050 GHG EMISSIONS SCENARIOS REPORT ON-LINE," State of New Jersey Department of Environmental Protection Air Quality, Energy, and Sustainability, May 4, 2017, https://www.state.nj.us/dep/aqes/sggi.html#:~:text=Goal%20Statement,tons%20(MMT)%20CO2%20equivalent.

9 "Trends in Atmospheric Carbon Dioxide: Mauna Loa, Hawaii," Global Monitoring Laboratory, Earth System Research Laboratories, https://www.esrl.noaa.gov/gmd/ccgg/trends/data.html.

10 Brad Plumer and Nadja Popovich, "Emissions Are Surging Back as Countries and States Reopen," *The New York Times*, June 17, 2020, https://www.nytimes.com/interactive/2020/06/17/climate/virus-emissions-reopening.html.

11 Ralph Sims, Roberto Schaeffer, Felix Creutzig, Xochitl Cruz-Núñez, Marcio D'Agosto, Delia Dimitriu, Maria Josefina Figueroa Meza, Lew Fulton, Shigeki Kobayashi, Oliver Lah, Alan McKinnon, Peter Newman, Minggao Ouyang, James Jay Schauer, Daniel Sperling, and Geetam Tiwari, "Transport," in "Climate Change 2014: Mitigation of Climate Change," (Geneva: Intergovernmental Panel on Climate Change, 2014), https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter8.pdf.

12 "Trends in Atmospheric Carbon Dioxide: Mauna Loa, Hawaii," Global Monitoring Laboratory, Earth System Research Laboratories.

13 Nathanial Gronewold, "Development bank stops giving loans for fossil fuel projects," E&E News, November 15, 2019, https://www.eenews.net/climatewire/stories/1061552241.

14 Rachel Frazin, "DC sues oil companies over climate change," *The Hill*, June 25, 2020, https://thehill.com/policy/energy-environment/504515-dc-sues-oil-companies-over-climate-change; David Hasemyer,

“Fossil Fuels on Trial: Where the Major Climate Change Lawsuits Stand Today,” InsideClimateNews, January 17, 2020, https://insideclimatenews.org/news/04042018/climate-change-fossil-fuel-company-lawsuits-timeline-exxon-children-california-cities-attorney-general.

15 “Global EV Outlook 2019,” (Paris: International Energy Agency, 2019), https://www.iea.org/reports/global-ev-outlook-2019.

16 Ibid.

17 Samantha Gross, “Why are fossil fuels so hard to quit?” (Washington, DC: The Brookings Institution, June 2020), https://www.brookings.edu/essay/why-are-fossil-fuels-so-hard-to-quit/.

18 “Table 1.3 Final energy consumption by sector, fuel, and scenario” in “World Energy Outlook 2019,” (Paris: International Energy Agency, 2019), 42, https://www.iea.org/reports/world-energy-outlook-2019.

19 Yoichi Kaya, Mitsutsune Yamaguchi, and Oliver Geden, “Towards net zero CO2 emissions without relying on massive carbon dioxide removal,” *Sustainability Science* 14 (March 9, 2019): 1739–1743, https://link.springer.com/article/10.1007/s11625-019-00680-1.

20 “Transport,” International Energy Agency, https://www.iea.org/topics/transport.

21 “Changes in transport behaviour during the Covid-19 crisis,” International Energy Agency, May 27, 2020, https://www.iea.org/articles/changes-in-transport-behaviour-during-the-covid-19-crisis.

22 “Effects of Novel Coronavirus (COVID-19) on Civil Aviation: Economic Impact Analysis,” (Montreal: International Civil Aviation Organization, June 29, 2020), https://www.icao.int/sustainability/Documents/COVID-19/ICAO_Coronavirus_Econ_Impact.pdf.

23 “World Energy Outlook 2019,” (Paris: International Energy Agency, 2019), https://www.iea.org/reports/world-energy-outlook-2019.

24 William J. Mallett, “Climate Change and the America’s Transportation Infrastructure Act of 2019,” (Washington, DC: Congressional Research Service, September 3, 2019), https://crsreports.congress.gov/product/pdf/IF/IF11299.

25 “Greenhouse gas emissions from transport in Europe,” European Environment Agency, https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-12.

26 “Co_2 Emissions from Transport (% of total fuel combustion),” The World Bank, https://data.worldbank.org/indicator/en.co2.tran.zs.

27 “Co_2 Emissions from Transport (% of total fuel combustion),” The World Bank, https://data.worldbank.org/indicator/en.co2.tran.zs.

28 Ralph Sims, Roberto Schaeffer, Felix Creutzig, Xochitl Cruz-Núñez, Marcio D’Agosto, Delia Dimitriu, Maria Josefina Figueroa Meza, Lew Fulton, Shigeki Kobayashi, Oliver Lah, Alan McKinnon, Peter Newman, Minggao Ouyang, James Jay Schauer, Daniel Sperling, and Geetam Tiwari, “Transport.”

29 Ibid.

30 “Use of energy explained: Energy use for transportation,” U.S. Energy Information Administration, https://www.eia.gov/energyexplained/use-of-energy/transportation.php.

31 “Progress of EU transport sector towards its environment and climate objectives,” (Copenhagen: European Environment Agency, November 22, 2018), https://www.eea.europa.eu/themes/transport/term/term-briefing-2018.

32 Mengpin Ge and Johannes Friedrich, “4 Charts Explain Greenhouse Gas Emissions by Countries and Sectors,” World Resources Institute, February 6, 2020, https://www.wri.org/blog/2020/02/greenhouse-gas-emissions-by-country-sector.

33 “Where: Global Reach,” Organisation for Economic Co-operation and Development, https://www.oecd.org/about/members-and-partners/.

34 Table 3.1 in “World Energy Outlook 2019,” International Energy Agency, 132.

35 “World Energy Outlook 2019,” International Energy Agency.

36 “U.S. Plug-in Electric Vehicle Sales by Model,” U.S. Department of Energy, https://afdc.energy.gov/data/10567.

37 “Strong policy and falling battery costs drive another record year for electric cars,” International Energy Agency, May 30, 2018, https://www.iea.org/newsroom/news/2018/may/strong-policy-and-falling-battery-costs-drive-another-record-year-for-electric-ca.html.

38 “World Oil Outlook 2040,” (Vienna: Organization of Petroleum Exporting Countries, 2019), https://woo.opec.org/pdf-download/.

39 “World Energy Outlook 2019,” International Energy Agency.

40 “World Energy Outlook 2019,” International Energy Agency, 26.

41 “Use of energy explained: Energy use for transportation: In Depth,” U.S. Energy Information Administration, https://www.eia.gov/energyexplained/use-of-energy/transportation-in-depth.php.

42 “Progress of EU transport sector towards its environment and climate objectives,” European Environment Agency.

43 “World Energy Outlook 2019,” International Energy Agency, 137.

44 Ibid., 136.

45 “Pathways to deep decarbonization: 2014 report,” (Paris: Institute for Sustainable Development and International Relations and Sustainable Development Solutions Network, September 2014), https://www.globalccsinstitute.com/archive/hub/publications/184548/pathways-deep-decarbonization-2014-report.pdf.

46 “Shell Scenarios: Sky: Meeting the Goals of the Paris Agreement: An Overview,” (The Hague, Shell, 2018), https://www.shell.com/promos/business-customers-promos/overview-of-sky/_jcr_content.stream/1556211464715/08824370d34ccbe871b0b813f9afdff96d8c267b/sky-scenarios-leaflet.pdf.

47 “Chevrolet Bolt EV -2020,” Chevrolet, https://media.chevrolet.com/media/us/en/chevrolet/vehicles/bolt-ev/2020.tab1.html.

48 Graphic by Rachel Slattery, originally published in Samantha Gross, “Why are fossil fuels so hard to quit.”

49 Jacob Teter, Pierpaolo Cazzola, and Timur Ğul, “The Future of Trucks: Implications for energy and the environment,” (Paris: International Energy Agency, July 3, 2017), https://webstore.iea.org/the-future-of-trucks.

50 Ibid.

51 Ibid.

52 Jacques Leonardi, Christophe Rizet, Laetitia Davlanc, Martin Martin, and Simon Bohne, “Decarbonising urban freight transport: Experimentations in European Research Projects,” (London: University of Westminster, 2016), https://westminsterresearch.westminster.ac.uk/item/q27zy/decarbonising-urban-freight-transport-experimentations-in-european-research-projects.

53 Jacob Teter, Pierpaolo Cazzola, and Timur Ğul, “The Future of Trucks.”

54 Esra Bennathan, Julie Fraser, and Louis S. Thompson, “What Determines Demand for Freight Transport?” (Washington, DC: The World Bank, 1992), documents.worldbank.org/curated/en/683781468739249005/What-determines-demand-for-freight-transport.

55 Francis Vanek, “Mode and Commodity perspectives on U.S. freight energy consumption and CO_2 emissions: Insights and directions for improvement,” *International Journal of Sustainable Transportation* 13, no. 10 (January 19, 2019), https://doi.org/10.1080/15568318.2018.1512690.

56 Camila Domonoske, “From Delivery Trucks To Scooter-Moving Vans, Fleets Are Going Electric,” NPR, February 7, 2020, https://www.npr.org/2020/02/07/803145517/from-delivery-trucks-to-scooter-moving-vans-fleets-are-going-electric.

57 “Resolución 1464/2014” [Resolution 1464/2014], Government of Argentina, http://servicios.infoleg.gob.ar/infolegInternet/anexos/240000-244999/240942/norma.htm.

58 Joshua Miller and Francisco Posada, “Brazil PROCONVE P-8 emission standards,” The International Council on Clean Transportation, February 27, 2019, https://theicct.org/publications/brazil-proconve-p-8-emission-standards.

59 “Canada’s heavy-duty vehicle regulations,” Government of Canada, https://www.canada.ca/en/environment-climate-change/news/2018/06/canadas-heavy-duty-vehicle-regulations.html.

60 “关于发布国家污染物排放标准《重型柴油车污染物排放限值及测量方法（中国第六阶段）》的公告” [Announcement on Issuing National Pollutant Emission Standards Limits and Measurement Methods for Pollutant Emissions of Heavy-Duty Diesel Vehicles (China Phase 6)], Ministry of Ecology and Environment of the People‘s Republic of China, June 28, 2018, http://www.mee.gov.cn/xxgk2018/xxgk/xxgk01/201807/t20180703_629590.html.

61 “Fuel Efficiency,” Bureau of Energy Efficiency, Government of India, https://beeindia.gov.in/content/fuel-efficiency.

62 "“合同会議 とりまとめ（重量車燃費基準等）” [Joint meeting summary (heavy vehicle fuel economy standards, etc.)], Ministry of Land, Infrastructure, Transport, and Tourism, Government of Japan, December 29, 2018, https://www.mlit.go.jp/common/001212395.pdf.

63 "NORMA Oficial Mexicana NOM-044-SEMARNAT-2017" [Official Mexican Standard NOM-044-SEMARNAT-2017], Secretariat of Environment and Natural Resources of the Government of Mexico, http://dof.gob.mx/nota_detalle.php?codigo=5513626&fecha=19/02/2018.

64 "EPA Emissions Standards for Heavy-Duty Highway Engines and Vehicles," U.S. Environmental Protection Agency, https://www.epa.gov/emission-standards-reference-guide/epa-emission-standards-heavy-duty-highway-engines-and-vehicles.

65 "Reducing CO_2 emissions from heavy-duty vehicles," European Commission, https://ec.europa.eu/clima/policies/transport/vehicles/heavy_en.

66 Ravi Shankar, Devendra Kumar Pathaka, and Devendra Choudhary, "Decarbonizing freight transportation: An integrated EFA-TISM approach to model enablers of dedicated freight corridors," *Technological Forecasting and Social Change* 143 (June 2019): 85-100, https://doi.org/10.1016/j.techfore.2019.03.010.

67 Jacques Leonardi, Christophe Rizet, Laetitia Davlanc, Martin Martin, and Simon Bohne, "Decarbonising urban freight transport."

68 Matteo Muratori, Steven J. Smith, Page Kyle, Robert Link, Bryan K. Mignone, Haroon S. Kheshgi, "Role of the Freight Sector in Future Climate Change Mitigation Scenarios," *Environmental Science and Technology* 51, no. 6 (February 27, 2017), https://www.osti.gov/servlets/purl/1349019.

69 "Platooning Trucks to Cut Cost and Improve Efficiency," U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, February 5, 2018, https://www.energy.gov/eere/articles/platooning-trucks-cut-cost-and-improve-efficiency.

70 Kurt Barrow, Daniel Evans, Kate Hardin, Anthony Palmer, Pat McSpadden, Andrej Divis, Mark Griffith, Aleksandra Maguire, Jamie Stevenson, Chelsea Havill, James Coan, Terine Ooi, and Matt Trentacosta, "Reinventing the Truck," (London: IHS Markit, July 2018) https://ihsmarkit.com/products/reinventing-the-truck.html.

71 "Average price of new Class 8 trucks in the United States from 2010 to 2018," Statistica, https://www.statista.com/statistics/937418/new-truck-average-price-in-the-united-states/.

72 "Global Electric Bus Market Analysis and Forecast, 2019-2027 – Increasing Focus of Countries on Electrification of Their Public Transport Fleets, Increasing Awareness Toward Ecofriendly Vehicles," Global NewsWire, January 10, 2020, https://www.globenewswire.com/news-release/2020/01/10/1968931/0/en/Global-Electric-Bus-Market-Analysis-and-Forecast-2019-2027-Increasing-Focus-of-Countries-on-Electrification-of-Their-Public-Transport-Fleets-Increasing-Awareness-Towards-Ecofriendl.html.

73 Lu Lu, Lulu Xue, and Weimin Zhou, "How Did Shenzhen, China Build World's Largest Electric Bus Fleet?" World Resources Institute, April 4, 2018, https://www.wri.org/blog/2018/04/how-did-shenzhen-china-build-world-s-largest-electric-bus-fleet.

74 "Rivian announces $1.3 billion funding round led by T. Rowe Price," Rivian, https://media.rivian.com/rivian-announces-1-3-billion-funding-round-led-by-t-rowe-price/.

75 Marianne Kah, “Workshop: Prospects for global truck electrification and autonomy and new delivery models,” (New York: Global Energy Dialogue, Columbia University, June 26, 2019), https://energypolicy.columbia.edu/research/global-energy-dialogue/prospects-global-truck-electrification-and-autonomy-and-new-delivery-models.

76 Chris Nelder, “Electric Vehicle Charging for Dummies,” Rocky Mountain Institute, June 10, 2019, https://rmi.org/electric-vehicle-charging-for-dummies/.

77 Mark Kane, “Daimler Aims For 3 MW Charging For Electric Trucks,” InsideEVs, April 29, 2019, https://insideevs.com/news/347121/daimler-3-mw-charging-electric-trucks/.

78 Rich Piellisch, “Bus Fleet Implements High-Power Inductive Charging,” Next-Gen Transportation, January 30, 2019, https://ngtnews.com/bus-fleet-implements-high-power-inductive-charging.

79 Roger Gilroy, “Kenworth, Toyota Partner on Hydrogen Fuel Cell Class 8 Trucks,” Transport Topics, October 27, 2019, https://www.ttnews.com/articles/kenworth-toyota-partner-hydrogen-fuel-cell-class-8-trucks.

80 Byron Hurd, “Cummins joins for hydrogen fuel-cell semis with demonstrator,” Green Car Reports, October 31, 2019, https://www.greencarreports.com/news/1125784_cummins-joins-push-for-hydrogen-fuel-cell-semis-with-demonstrator.

81 “Nikola Motor Company,” Nikola, https://nikolamotor.com/motor.

82 Kurt Barrow, Daniel Evans, Kate Hardin, Anthony Palmer, Pat McSpadden, Andrej Divis, Mark Griffith, Aleksandra Maguire, Jamie Stevenson, Chelsea Havill, James Coan, Terine Ooi, and Matt Trentacosta, “Reinventing the Truck.”

83 Jacob Teter, Pierpaolo Cazzola, and Timur Ġul, “The Future of Trucks.”

84 Brandon Schoettle, Michael Sivak, and Michael Tunnell, “Survey of Fuel Economy and Fuel Usage by Heavy-Duty Truck Fleets,” (Arlington, VA: University of Michigan and American Transportation Research Institute, October 2016), https://truckingresearch.org/wp-content/uploads/2016/10/2016.ATRI-UMTRI.FuelEconomyReport.Final_.pdf.

85 “California takes bold step to reduce truck pollution,” California Air Resources Board, June 25, 2020, https://ww2.arb.ca.gov/news/california-takes-bold-step-reduce-truck-pollution.

86 See “Full Report: Executive Summary,” (West Coast Clean Transit Corridor Initiative, June 17, 2020), XIV, https://westcoastcleantransit.com/.

87 Ibid., XI.

88 “Multi-State Medium- and Heavy-Duty Zero Emissions Vehicle Memorandum of Understanding,” Northeast States for Coordinated Air Use Management, July 2020, https://www.nescaum.org/documents/multistate-truck-zev-governors-mou-20200714.pdf.

89 Alice Bows-Larkin, “All adrift: aviation, shipping, and climate change policy,” *Climate Policy* 15, no. 6 (2015): 681-702, https://www.tandfonline.com/doi/full/10.1080/14693062.2014.965125.

90 Benjamin Zhang, “The 20 Biggest Airlines in the World, Ranked,” Business Insider, March 6, 2019, https://www.businessinsider.com/biggest-airlines-world-oag-2019-3; Tom Cooper, John Smiley, Chad

Porter, and Chris Precourt, "2017-2027 Fleet & MRO Forecast," (New York: Oliver Wyman, 2017), https://www.oliverwyman.com/our-expertise/insights/2017/feb/2017-2027-fleet-mro-forecast.html.

91 See, for example, "A350-1000," Airbus, https://www.airbus.com/aircraft/passenger-aircraft/a350xwb-family/a350-1000.html.

92 "Final Report: Aviation Fuel Efficiency Technology Assessment," (Washington, DC: International Council on Clean Transportation, December 2015), https://www.theicct.org/sites/default/files/publications/Aviation%20Fuel%20Efficiency%20Technology%20Assessment%20%28AFETA%29%202015%20Final%20Report%2018Jan2016.pdf.

93 Mayuko Tani, "Singapore Airlines races oil price with world's longest flight," *Nikkei Asian Review*, October 11, 2018, https://asia.nikkei.com/Business/Companies/Singapore-Airlines-races-oil-price-with-world-s-longest-flight.

94 Adam Klauber and Isaac Toussie, "A Radical New Plan for Aviation," Rocky Mountain Institute, 2019, https://rmi.org/wp-content/uploads/2019/01/wef-action-brief.pdf.

95 Ian Petchenik, "Scraping along the bottom: April Air Traffic Statistics," Flight Radar, May 1, 2020, https://www.flightradar24.com/blog/scraping-along-the-bottom-april-air-traffic-statistics/.

96 "Trends in Emissions that affect Climate Change" International Civil Aviation Organization, https://www.icao.int/environmental-protection/Pages/ClimateChange_Trends.aspx.

97 "Fact sheet: CORSIA," International Aviation Transportation Authority, https://www.iata.org/contentassets/fb745460050c48089597a3ef1b9fe7a8/corsia-fact-sheet.pdf.

98 "Consolidated statement of continuing ICAO policies and practices related to environmental protection - Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)," International Civil Aviation Organization, 2016, https://www.icao.int/environmental-protection/Documents/Assembly/Resolution_A40-19_CORSIA.pdf.

99 Alice Bows-Larkin, "All adrift."

100 Volker Grewea, Thierry Champougny, Sigrun Matthes, Christine Frömming, Sabine Brinkop, Ole Amund Søvde, Emma A.Irvine, and Lucia Halscheidt, "Reduction of the air traffic's contribution to climate change: A REACT4C case study," *Atmospheric Environment* 94 (September 2014): 616-625, https://doi.org/10.1016/j.atmosenv.2014.05.059.

101 David B. Sandalow, "Statement before the Committee on Energy and Natural Resources, United States Senate," (Congressional testimony, April 11, 2019), https://www.energy.senate.gov/public/index.cfm/files/serve?File_id=455220F8-538F-4725-BB89-1C9084338A48.

102 Mark D. Staples, Robert Malina, Pooja Suresh, James I. Hileman, and Steven R.H. Barrett, "Aviation CO_2 emissions reductions from the use of alternative jet fuels," *Energy Policy* 114 (March 2018): 342-354, https://www.sciencedirect.com/science/article/pii/S0301421517308224.

103 Sergio Barros, "Brazil: Biofuels Annual 2019," (Washington, DC: USDA Foreign Agricultural Service Global Agricultural Information Network, August 9, 2019), https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=Biofuels%20Annual_Sao%20Paulo%20ATO_Brazil_8-9-2019.pdf.

104 S. Kent Hoekman and Amber Broch, "Environmental implications of higher ethanol production and use in the U.S.: A literature review. Part II – Biodiversity, land use change, GHG emissions, and sustainability," *Renewable and Sustainable Energy Reviews* 81 (January 2018): 3159-3177, https://www.sciencedirect.com/science/article/abs/pii/S1364032117306883.

105 Stephanie Searle, Nikita Pavlenko, Anastasia Kharina, and Jacopo Giuntoli, "Long-term aviation fuel decarbonization: Progress, roadblocks, and policy opportunities," (Washington, DC: International Council on Clean Transportation, January 2019), https://www.theicct.org/sites/default/files/publications/Alternative_fuel_aviation_briefing_20190109.pdf.

106 Ana Meijide, Cristina de la Rua, Thomas Guillaume, Alexander Röll, Evelyn Hassler, Christian Stiegler, Aiyen Tjoa, Tania June, Marife D. Corre, Edzo Veldkamp, and Alexander Knohl, "Measured greenhouse gas budgets challenge emission savings from palm-oil biodiesel," *Nature Communications* 11 (February 27, 2020), https://www.nature.com/articles/s41467-020-14852-6.

107 Alexandre Strapasson, Jeremy Woods, Helena Chum, Nicole Kalas, Nilay Shah, and Frank Rosillo-Calle, "On the global limits of bioenergy and land use for climate change mitigation," *Global Change Biology Bioenergy* 9 (2017): 1721-1735, https://onlinelibrary.wiley.com/doi/epdf/10.1111/gcbb.12456.

108 Ibid.

109 Tim Searchinger, Richard Waite, Craig Hanson, and Janet Ranganathan, "Creating a Sustainable Food Future, A Menu of Solutions to Feed Nearly 10 Billion People by 2050," (Washington, DC: World Resources Institute, December 2018), https://www.wri.org/publication/creating-sustainable-food-future.

110 Alexandre Strapasson, Jeremy Woods, Helena Chum, Nicole Kalas, Nilay Shah, and Frank Rosillo-Calle, "On the global limits of bioenergy and land use for climate change mitigation."

111 "United Airlines Expands Industry-Leading Commitment to Biofuel, Powering More Flights With More Biofuel Than Any Other U.S. Carrier," United Airlines, May 22, 2019, https://hub.united.com/united-expands-commitment-biofuel-powering-flights-2637791857.html.

112 "Renewable waste and residue raw materials," Neste, https://www.neste.com/companies/products/aviation/raw-materials.

113 "Neste MY Renewable Jet Fuel," Neste, https://www.neste.com/companies/products/aviation.

114 Stephanie Searle, Nikita Pavlenko, Anastasia Kharina, and Jacopo Giuntoli, "Long-term aviation fuel decarbonization."

115 Daniel Evans, "Biojet for aviation – A growth story for the 2020s?" IHS Markit, March 6, 2020, https://ihsmarkit.com/research-analysis/biojet-for-aviation--a-growth-story-for-the-2020s.html.

116 Ahmad Baroutaji, Tabbi Wilberforce, Mohamad Ramadan, and Abdul Ghani Olabi, "Comprehensive investigation on hydrogen and fuel cell technology in the aviation and aerospace sectors," *Renewable and Sustainable Energy Reviews* 106 (May 2019): 31-40, https://doi.org/10.1016/j.rser.2019.02.022.

117 Jim Moore, "Flying on hydrogen: California Firm Advancing Fuel Cell Development Overseas," AOPA, March 5, 2020, https://www.aopa.org/news-and-media/all-news/2020/march/05/flying-on-hydrogen.

118 Quailan Homann, "Aviation," Fuel Cell & Hydrogen Energy Association, December 9, 2019, http://www.fchea.org/in-transition/2019/11/25/aviation.

118 Ahmad Baroutaji, Tabbi Wilberforce, Mohamad Ramadan, and Abdul Ghani Olabi, "Comprehensive investigation on hydrogen and fuel cell technology in the aviation and aerospace sectors."

120 Ibid.

121 Paul Balcombe, James Brierley, Chester Lewis, Line Skatvedt, Jamie Speirs, Adam Hawkes, and Iain Staffell, "How to decarbonise international shipping: options for fuels, technologies and policies," *Energy Conversion and Management* 182 (February 15, 2019): 72-88, https://www.sciencedirect.com/science/article/pii/S0196890418314250.

122 Ibid.

123 Michael Traut, Alice Larkin, Kevin Anderson, Christophe McGlade, Maria Sharmina, and Tristan Smith, "CO2 abatement goals for international shipping," *Climate Policy* 18, no. 8 (April 19, 2018): 1066-1075, https://www.tandfonline.com/doi/full/10.1080/14693062.2018.1461059.

124 Naya Olmer, Bryan Comer, Biswajoy Roy, Xiaoli Mao, and Dan Rutherford, "Greenhouse Gas Emissions From Global Shipping, 2013-2015," (Washington, DC: International Council on Clean Transportation, October 2017), https://theicct.org/sites/default/files/publications/Global-shipping-GHG-emissions-2013-2015_ICCT-Report_17102017_vF.pdf; Mia Rahim Mahmudur, Md. Tarikul Islam, and Sanjaya Kuruppu, "Regulating global shipping corporations' accountability for reducing greenhouse gas emissions in the seas," *Marine Policy* 69 (July 2016): 159-170, https://www.sciencedirect.com/science/article/pii/S0308597X16301907.

125 "Chapter 8: Transportation sector energy consumption," in "International Energy Outlook 2016," (Washington, DC: U.S. Energy Information Administration, 2016), https://www.eia.gov/outlooks/ieo/pdf/transportation.pdf.

126 "Carbon Emissions," World Shipping Council, http://www.worldshipping.org/industry-issues/environment/air-emissions/carbon-emissions.

127 "Sulphur 2020-cutting sulphur oxide emissions," International Maritime Organization, http://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx.

128 "World Energy Outlook 2019," International Energy Agency.

129 Jamie Speirs, Paul Balcombe, Paul Blomerus, Marc Stettler, Nigel Brandon, and Adam Hawkes, "Can natural gas reduce emissions from shipping?" (London: Sustainable Gas Institute, Imperial College London, January 2019), https://www.imperial.ac.uk/sustainable-gas-institute/research-themes/white-paper-series/white-paper-4-can-natural-gas-reduce-emissions-from-transport/.

130 Paul Gilbert and Alice Bows, "Exploring the scope for complementary sub-global policy to mitigate CO_2 from shipping," *Energy Policy* 50 (November 2012): 613-622, https://www.sciencedirect.com/science/article/pii/S0301421512006593.

131 "Next steps to deliver IMO GHG strategy," International Maritime Organization, October 22, 2018, http://www.imo.org/en/MediaCentre/PressBriefings/Pages/18-MEPCGHGprogramme.aspx.

132 “IMO pushes forward with work to meet ship emission reduction targets,” International Maritime Organization, November 15, 2019, http://www.imo.org/en/MediaCentre/PressBriefings/Pages/26-ISWG-GHG.aspx.

133 Paul Gilbert and Alice Bows, “Exploring the scope for complementary sub-global policy to mitigate CO2 from shipping”; Zheng Wan, Abdel Makhloufi, Yang Chen, and Jiayuan Tang, “Decarbonizing the international shipping industry: Solutions and policy recommendations,” *Marine Pollution Bulletin* 126 (January 2018): 428-435, https://doi.org/10.1016/j.marpolbul.2017.11.064.

134 Paul Gilbert, Alice Bows-Larkin, Sarah Mander, and Conor Walsh, “Technologies for the high seas: meeting the climate challenge,” *Carbon Management 5*, no. 4 (2014): 447-461. https://www.tandfonline.com/doi/full/10.1080/17583004.2015.1013676.

135 Brad Templeton, “Will COVID-19 Sound The Permanent Death Knell For Public Transit?” *Forbes*, April 28, 2020, https://www.forbes.com/sites/bradtempleton/2020/04/28/will-covid19-sound-the-permanent-death-knell-for-public-transit/.

136 David Harrison, “Public Transit Use Is Associated With Higher Coronavirus Death Rates, Researchers Find,” *The Wall Street Journal*, June 28, 2020, https://www.wsj.com/articles/public-transit-use-is-associated-with-higher-coronavirus-death-rates-researchers-find-11593342001.

137 Joris D’Incà and Jean-Pierre Cresci, “Here’s how to make public transport safer during COVID-19,” World Economic Forum, July 1, 2020, https://www.weforum.org/agenda/2020/07/masks-subway-disinfectant-how-to-make-commuters-feel-safe-after-covid-19/.

138 Stephanie Searle, Nikita Pavlenko, Anastasia Kharina, and Jacopo Giuntoli, “Long-term aviation fuel decarbonization.”

139 “World Energy to complete Paramount Refinery conversion to renewable fuels,” Bioenergy International, October 30, 2018, https://bioenergyinternational.com/biofuels-oils/world-energy-to-complete-paramount-refinery-conversion-to-renewable-fuels.

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