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Part 2: Major greenhouse gas emitting sectors
Sectors

Chapter 3-3

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3.3 Traffic

According to the IEA report for 2020, the transport sector accounts for about 8 Gt/a of the global CO_2 emissions. In the IEA Sustainable Development Scenario, these are expected to fall to 1.7 Gt/a by 2070, and the remaining emissions will have to be offset by negative emission technologies.

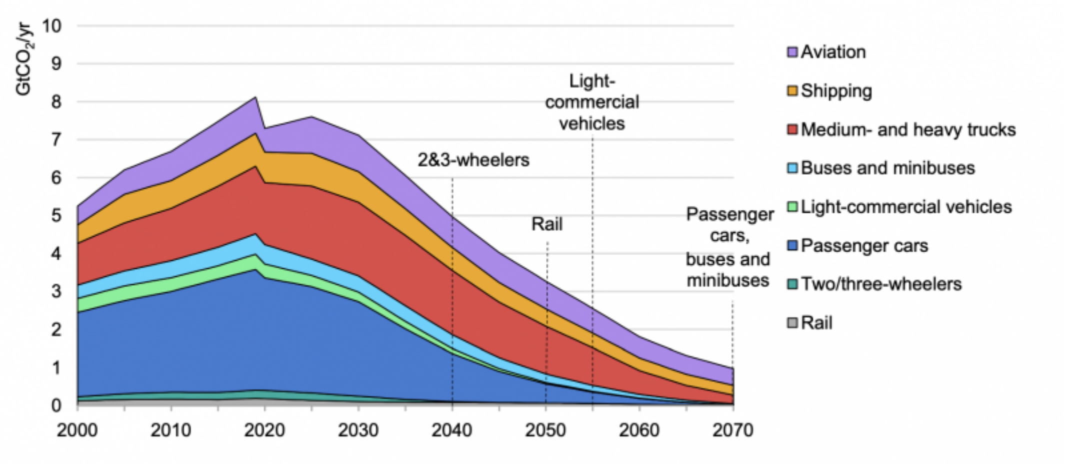

Figure 56Global CO_2 emissions from the transport sector.

Source: Our World in Data, 2020.

The vertical lines in Figure 56 indicate that no further use of fossil fuels may be permitted above the values on the abscissa in the corresponding sectors. The five countries with the highest CO_2 emissions in this sector are the USA, China, India, Russia and Japan with 1.7 Gt/a, 0.9 Gt/a, 0.3 Gt/a, 0.26 Gt/a and 0.2 Gt/a, respectively. The top five per capita emitters from the transport sector are Luxembourg, the USA, Canada, Qatar and Saudi Arabia with 10 Mt/capita/a, 5.4 Mt/capita/a, 5 Mt/capita/a, 4.2 Mt/capita/a and 4 Mt/capita/a respectively. Low-income countries such as Yemen, Somalia, Ethiopia and Niger have per capita emissions from transport ranging from 0.09 Mt/capita/a to 0.01 Mt/capita/a.[174]

The largest absolute and per capita emitters have the main responsibility to reduce their emissions, develop efficient forms of mobility and introduce, through "know-how transfer", more energy efficient, affordable, climate neutral and safer modes of transport in the underdeveloped and developing countries. This helps these countries to leapfrog inefficient transport models. A paradigm shift in the way we commute, the fuels we use and the vehicles we use will ensure more sustainable mobility for all.

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[174] Cf. Our World in Data, 2020.

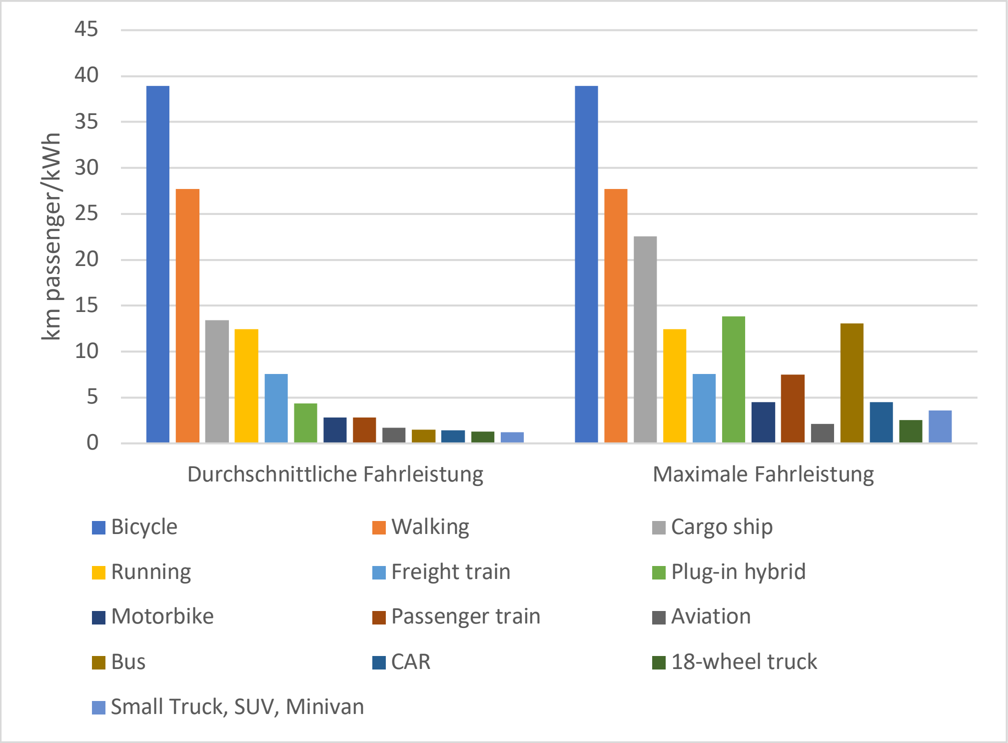

Figure 57: Mileage of various means of transport in (km-passenger/kWh).

Source: Truecostblog, 2021.

Figure 57 shows the distance travelled per passenger per kWh of energy consumed. It is clear that cycling and walking are superior to other modes of transport in terms of efficiency. Safe, pedestrian- and bicycle-friendly infrastructure can help people in both developed and developing countries to travel shorter distances by bicycle or on foot. Buses, cars and plug-in hybrids can become more efficient on a km-passenger/kWh basis if utilisation is increased by promoting car sharing and the use of public transport, and if the automotive industry shifts its business model to e.g. Mobility as a Service. Such measures can help maximise the use of existing infrastructure - cars, e-mobility, mopeds, e-fuelled vehicles, roads, etc. For long-distance passenger and freight rail transport, increasing passenger load factors improves efficiency. Renewable energy electrification of rail transport should reduce the CO_2 footprint of passengers and improve air quality. Cargo ships and trains are already optimised to carry maximum cargo, but the fuel used in ships and some trains contributes to global warming. This may require a switch to sustainable fuels, which poses some technical and logistical challenges that will be discussed later.

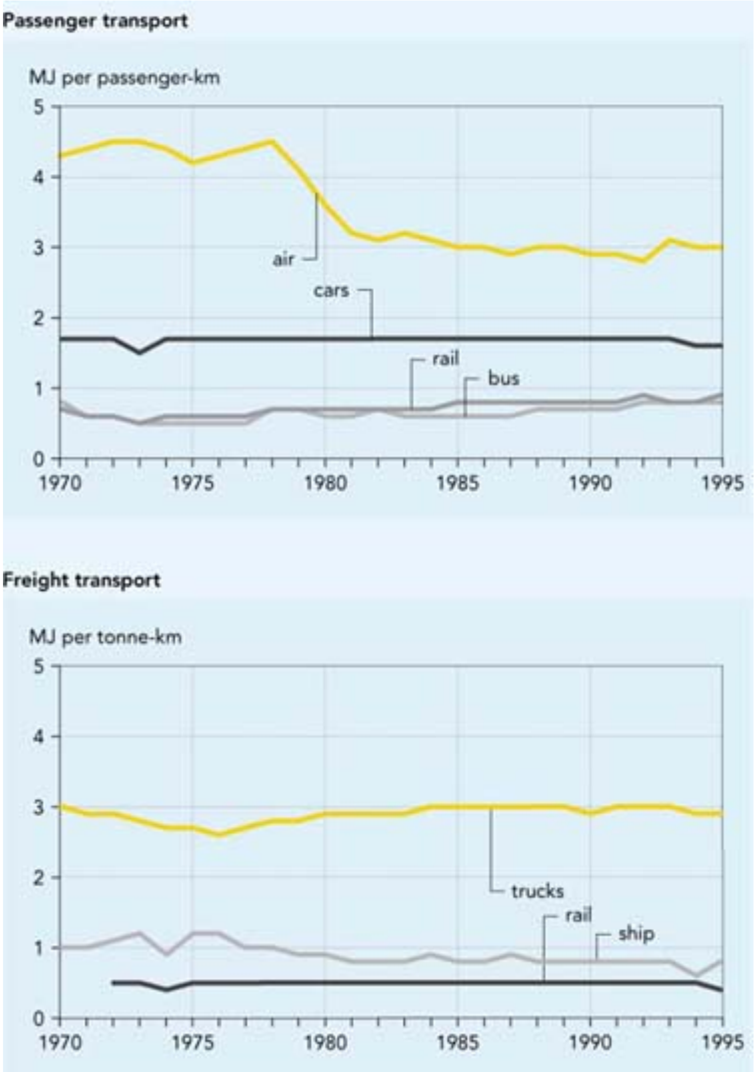

Figure 58: Energy intensity of passenger and freight transport (8 EU countries).

Source: European Environment Agency, 2020.

Air transport is one of the most inefficient means of transport,[175] if one disregards the costs of providing the transport routes, but it is the fastest way to cover long distances. In an overall consideration of CO_2 emissions, air transport is clearly better than rail and car transport because of the lack of CO_2 emissions during the construction of the transport routes. Rail and passenger cars could catch up if the load factor were improved.[176] One of the ways to decarbonise this sector is to use e-fuels. The remainder of this chapter discusses the electricity needed to synthesise e-fuels for the aviation sector.

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[175] Cf. IEA, 2020; European Environment Agency, 2020.
[176] Cf. Radermacher & Hermann, 2021.

3.3.1 Road traffic

3.3.1.1 Sources of CO_2 emissions

In 2011, there were more than one billion motor vehicles in operation worldwide.[177] US publisher Ward's estimates that by 2019 there will be 1.4 billion motor vehicles in operation worldwide. Global vehicle ownership per capita was 148 operating vehicles per 1,000 people in 2010. China has the largest motor vehicle fleet in the world with 322 million vehicles registered at the end of September 2018. The United States has the highest vehicle ownership in the world with 832 in-service vehicles per 1,000 people in 2016.

In a study the emission intensity of different fuels for transport was calculated.[178] For hydrogen production by water electrolysis and electric vehicles, an emission intensity of 260 g-CO_2 /kWh was assumed.[179] Another method for hydrogen production was methane steam reforming. This study showed that bio-CNG had the lowest carbon intensity of about 20 g CO_2 /kWh, while hydrogenated oil from vegetable/oil from bio-waste had the second lowest emission intensity. Electrification of mobility has an emission intensity of 260 g-CO_2 /kWh of electricity consumption, based on the average emission intensity in the EU. This can be lower if the electricity is generated with lower CO_2, e.g. as in France[180] or Norway. [181]

The lower heating values of liquid fossil fuels such as diesel, petrol and biodiesel are between 36 and 32 MJ/litre, while ethanol blended with liquid fossil fuels has a lower heating value of 23 MJ/litre. Propane and CNG are used as fuel for buses, 3-wheelers and cars in developing countries such as India and China. They have a relatively low calorific value of 23 MJ/litre and 13 kWh/kg (CNG is compressed in tanks). Methanol, which can be produced from natural gas, bio-waste or even green hydrogen and captured CO_2, is considered a substitute for liquid fossil fuels and has a lower calorific value of 16 MJ/litre.

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[177] Off-road vehicles and heavy construction machinery

[178] Cf. Gustafsson et al., 2021.

[179] EU average emission intensity from electricity in 2021

[180] 68 g-CO /kWh 2

[181] 26 g-CO /kWh2

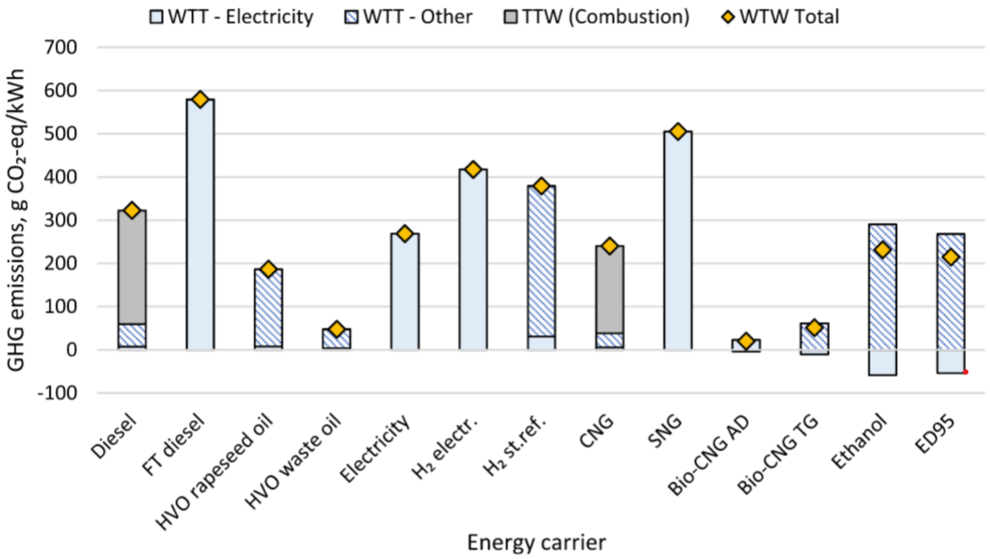
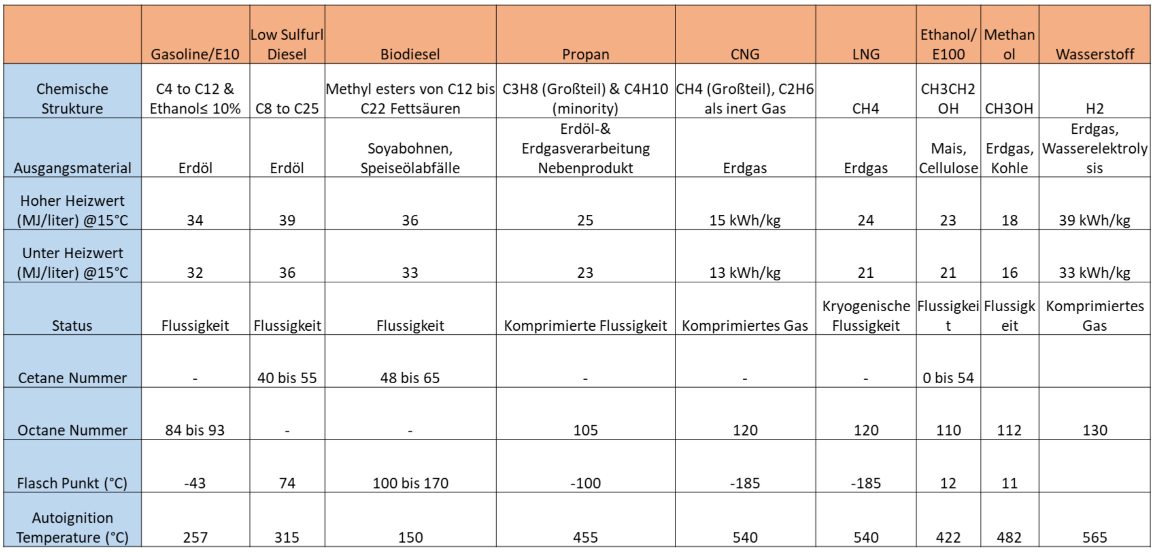


Figure 59Emission intensity of different energy sources in the transport sector. Emission intensity of EU 27 electricity in 2021 was 270 gCO /kWh. ₂

Source: Gustafsson et al., 2021.

Hydrogen, usually produced from natural gas using steam reforming, can be used as fuel for fuel cells in trucks and buses. Hydrogen is the lightest element in nature and must be compressed at high pressure and has a lower calorific value of 33 kWh/kg. The chemical properties of various fuels are shown in Table 10.

Octane number and cetane number are the standards for measuring the tendency of a fuel to self-ignite. Octane number refers to petrol, while cetane number refers to diesel. The octane number of a fuel indicates the percentage of iso-butene in the mixture of iso-octane and heptane under standard operating conditions. The octane number indicates the resistance to spontaneous ignition when used in a petrol engine. Due to the compression of air and fuel, petrol tends to ignite at the end of compression due to the spark produced by the spark plug. The use of low octane petrol causes ignition problems. The high octane fuel takes more time to burn but provides maximum efficiency to the petrol engine and in contrast, low octane fuel tends to self-ignite easily due to the effect of over-heating and pressure.



	Gasoline/E10	Low Sulfurl Diesel	Biodiesel	Propan	CNG	LNG	Ethanol/ E100	Methanol	Wasserstoff
Chemische Strukture	C4 to C12 & Ethanol≤ 10%	C8 to C25	Methyl esters von C12 bis C22 Fettsäuren	C3H8 (Großteil) & C4H10 (minority)	CH4 (Großteil), C2H6 als inert Gas	CH4	CH3CH2OH	CH3OH	H2
Ausgangsmaterial	Erdöl	Erdöl	Soyabohnen, Speiseölabfälle	Erdöl-& Erdgasverarbeitung Nebenprodukt	Erdgas	Erdgas	Mais, Cellulose	Erdgas, Kohle	Erdgas, Wasserelektrolysis
Hoher Heizwert (MJ/liter) @15°C	34	39	36	25	15 kWh/kg	24	23	18	39 kWh/kg
Unter Heizwert (MJ/liter) @15°C	32	36	33	23	13 kWh/kg	21	21	16	33 kWh/kg
Status	Flussigkeit	Flussigkeit	Flussigkeit	Komprimierte Flussigkeit	Komprimiertes Gas	Kryogenische Flussigkeit	Flussigkeit	Flussigkeit	Komprimiertes Gas
Cetane Nummer	-	40 bis 55	48 bis 65	-	-	-	0 bis 54		
Octane Nummer	84 bis 93	-	-	105	120	120	110	112	130
Flasch Punkt (°C)	-43	74	100 bis 170	-100	-185	-185	12	11	
Autoignition Temperature (°C)	257	315	150	455	540	540	422	482	565

Table 10: Thermochemical properties of various fuels used in road transport.

Source: US Department of Energy, 2020.

Cetane is also known as hexadecane as a chemical compound. This hydrocarbon chain tends to ignite spontaneously under compression and is therefore known as the cetane number of one hundred. The cetane number of a particular fuel can be defined as the percentage of n-hexadecane in the mixture of n-hexadecane and 1-methylnaphthalene that is responsible for the ignition delay. It is the exact opposite of the octane number, and all diesel fuels are indexed by the cetane number based on their ignition behaviour under compression. The cetane number measures the ignition retardation of the fuel in a diesel engine. When the cetane number is higher, the ignition delay is short and the fuel with a high cetane number is considered the ideal fuel for the diesel engine.

Road transport consumed more than 40 % of total oil demand in 2019, contributing to about 75 % of total transport sector emissions.[182] Growth in the sector has accounted for more than half of total oil demand growth since 2000, and both manufacturers and forecasters expect there to be more growth.[183] The different types of fuels used in the transport sector are diesel, petrol, hydrogen, CNG and the direct use of electricity for BEVs[184] and PHEVs.[185] Combustion of petrol, CNG from shale gas and Fischer-Tropsch diesel from natural gas have emissions between 25 and 21 kg-CO_2 /100km, while combustion of diesel is relatively lower in CO_2 than the aforementioned fuels at 18 kg-CO /100km.$_2$

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[182] Cf. Our World in Data, 2020.
[183] Cf. BNEF, 2020.
[184] Battery Electric Vehicle (E-cars)
[185] Plug-in Hybrid

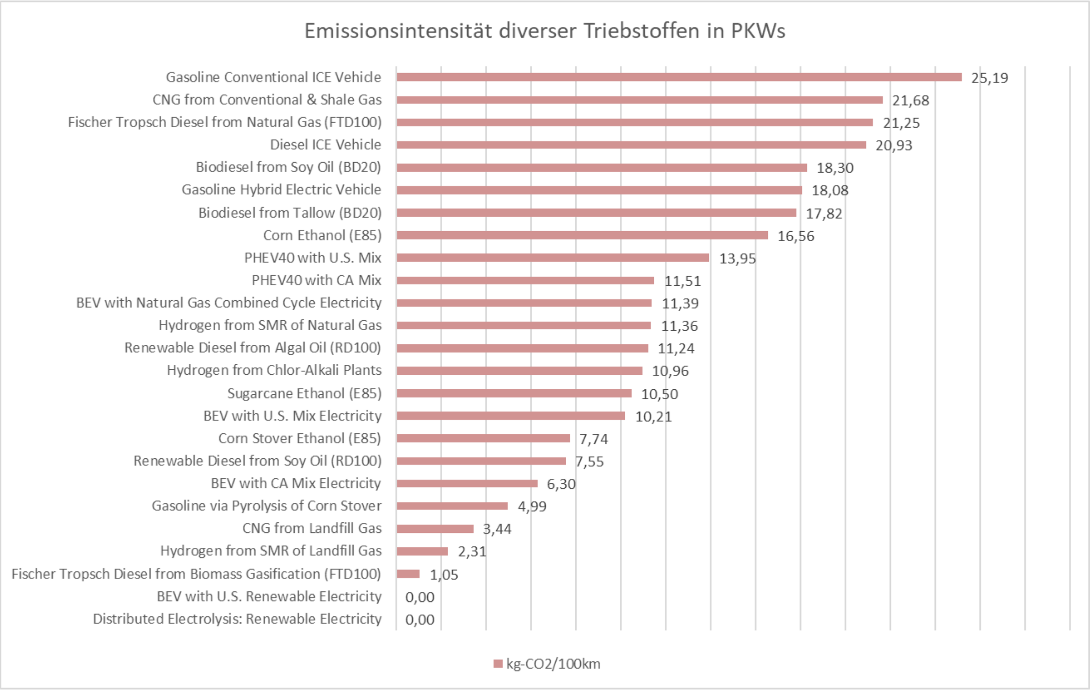

Illustration 60. Emission characteristics of various road transport fuels.

Source: Argonne National Laboratory, GREET WTW Calculator, 2021.

With a US electricity mix, BEVs are already 60 % lower in CO_2 than petrol. Fischer-Tropsch diesel from biomass gasification, hydrogen from SMR of methane from landfills and the use of renewable electricity for BEVs or FCEVs are some of the most climate-friendly fuel sources (see Illustration 60).

Certain types of vehicles are more polluting than others. On average, SUVs consume about a quarter more energy than a standard family car because they are larger, heavier and create more drag. Between 2010 and 2018, the increase of SUVs on roads worldwide led to an increase in petrol consumption of 3.3 million barrels per day.[186] The share of SUVs has doubled in the last decade, leading to a shift towards larger and heavier cars. As a result, there are now more than 200 million SUVs worldwide, up from about 35 million in 2010, accounting for 60 % of the increase in the global vehicle fleet since 2010. SUVs now account for around 40 % of annual car sales, compared to less than 20 % ten years ago. Emissions from the global SUV fleet have increased by almost 0.55 Gt CO_2 to around 0.7 Gt CO_2 over the last decade.[187] In addition, the "load factor" (number of passengers per car) is lower in developed countries, resulting in lower passenger kilometers per kWh. Car occupancy[188] continues to decline, but at a slower rate than in the 1980s and 1990s. The most recent data for the average number of passengers per car, including drivers, for the sampled countries is about 1.45 passengers per car.[189] Possible reasons for this are the greater individualisation of society, reflected in the decrease in household sizes, and the increase in car ownership. The occupancy

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[186] Cf. Forbes, 2020.
[187] Cf. Cozzi & Petropoulos, 2021.
[188] Number of persons per car
[189] In the UK - 1.58; Germany - 1.42 and the Netherlands - 1.38 passengers per vehicle.

rate in the US, on the other hand, was reported at 1.5 and today almost half of all cars sold in the United States are SUVs.[190]

For e-mobility, we would need a large amount of production, distribution and recycling facilities for lithium batteries, as well as an upgrade of the electricity grid to avoid grid failures when too much electric vehicles are connected to the grid at the same time. The production and use of e-fuels, on the other hand, is energy inefficient, especially for cars. To run cars and 3-wheelers on compressed e-methane, the engine and fuel tanks need to be modified, and the cost of this has to be taken over by the owners. The use of pure e-methanol in vehicles is limited to high-performance vehicles, and there are currently hardly any methanol-powered cars on the market. According to reports from DOE[191] , some filling stations mix up to 16 % methanol into their fuels. Such high percentages reduce the energy density of the fuel so much that starting difficulties and engine stalling become a problem for some drivers.[192] According to one study, there would be no further reductions in NO_X emissions by putting alleged e-fuels in a Mercedes A-180 and carbon monoxide emissions were even three times higher in a WTLC[193] test and 1.2 higher in RDE[194] test than fossil gasoline.[195]

3.3.1.2 Technical options for CO_2 reduction

An electric car requires about 15 kWh/100 km to 25 kWh/100 km, while e-mopeds, which can replace petrol mopeds in the global south, require about 2.2 kWh/100 km to 3 kWh/100 km. A petrol-engine car and a petrol-engine moped/motorcycle require about 7 litres of petrol per 100 km and 1.5 litres of petrol per 100 km, respectively, according to global average data in the literature. The emission intensities of petrol/diesel range from 2.3 kg-CO_2 /litre to 2.8 kg-CO_2 /litre. Considering these figures and the carbon intensity of electricity from 2021 in different countries, comparisons of carbon emissions between the operation of conventional mopeds and cars and electric mopeds and cars with the current electricity mix in the respective countries were made.

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[190] Cf. University of Michigan, 2022.

[191] Department of Energy for the United States of America

[192] Cf. Top Gear, 2017.

[193] Worldwide harmonised Light Duty Test Cycle

[194] Real Driving Emissions

[195] Cf. Transport & Environment, 2021.

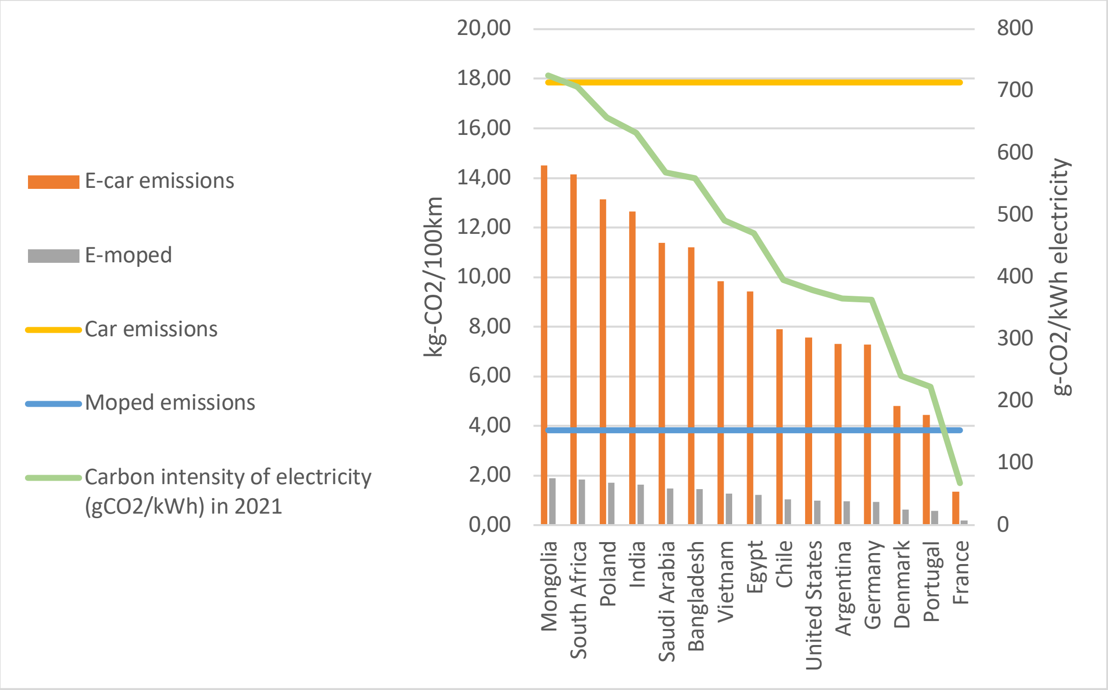

Figure 61: Emissions from e-mopeds and e-cars in different countries loaded with current electricity mix in the respective country.

The baseline emissions for conventional mopeds and cars are about 18 kg CO_2 /100 km and 4 kg CO_2 /100 km respectively (see Figure 61). If the emissions from driving an electric moped or car charged with the current electricity mix are lower than the above baseline emissions, then driving an electric car or e-moped is already more environmentally friendly than driving conventional cars and mopeds. Furthermore, charging during off-peak periods or when surplus green electricity is available can reduce the emission intensity of e-mobility solutions. Figure 61 shows that this parity has already been achieved in most countries.

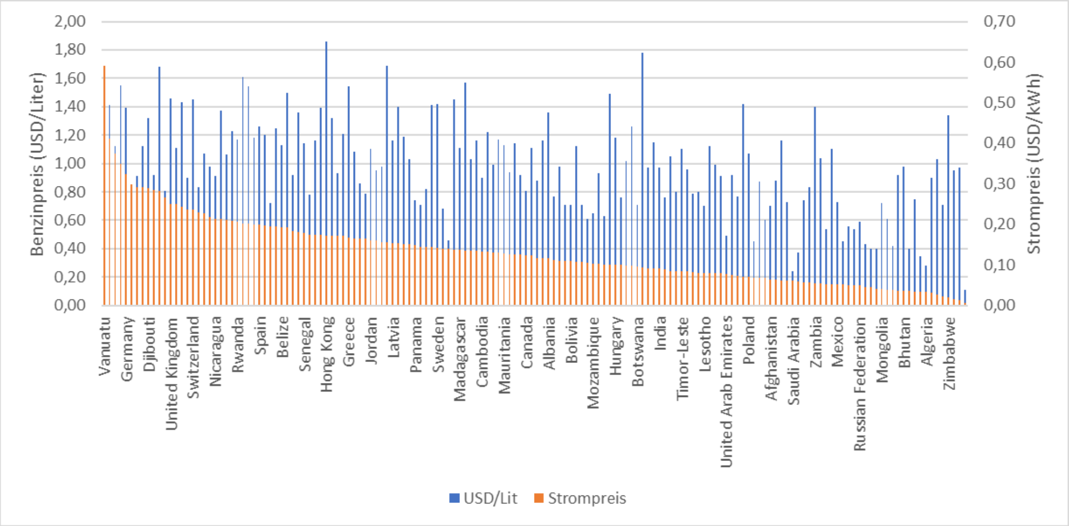

Figure 62: Petrol price and electricity price comparison of different countries.

Data source petrol price: Statisticstimes, 2022; Data source electricity price: Cable, 2022.

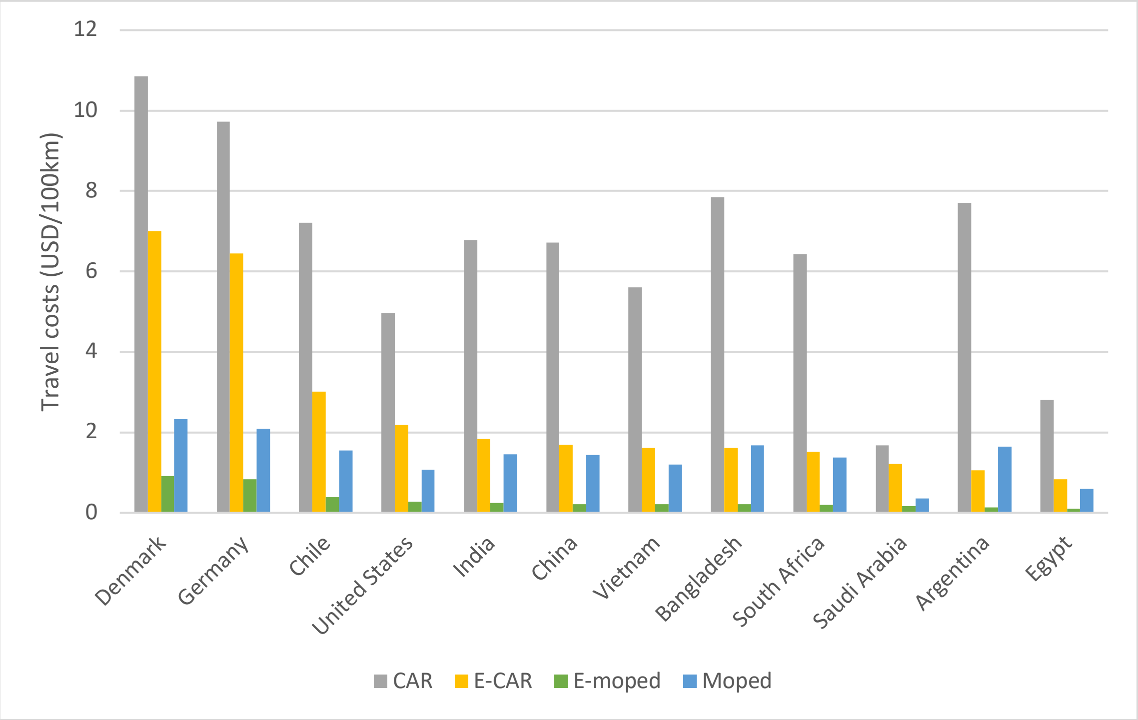

Figure 63: Cost comparison for driving conventional mopeds, cars, e-mopeds and e-cars.

Source: IEA (2019a)

Based on petrol costs, electricity prices and mileages of average cars, mopeds, e-cars, e-mopeds, the economic efficiency over a 100 km driving distance of aforementioned road transport modes was compared for various countries. From the 156 countries included in the database, in only two countries driving a conventional car was cheaper than driving an e-car, while in all countries driving an e-moped was cheaper than driving a fossil-fuelled moped.

A second solution is to use different e-fuels made from green hydrogen and CO_2 from the air or point sources.[196] For CNG vehicles, the e-methane can be compressed in tanks and burned in CNG engines, e-methanol can be mixed with diesel or petrol or burned in methanol-powered engines. Hydrogen can also be used directly to power fuel cell vehicles. However, this requires a higher primary energy input, as several intermediate steps are required in the synthesis of e-fuel. To understand the upstream green power demand, installed capacities of renewables, water, CO_2, N_2 and conversion efficiencies of e-fuels, a simplified model was developed. This model has a 7 MW Siemens SWT-7.0-154 wind turbine running 4,000 h/a. The electricity from this turbine is used for a different number of vehicles - e-cars and e-fuel powered cars.

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[196] Natural gas power plants, coal-fired power plants, cement/steel plants

	Electricity demand (kWh/10,000 km-a)	Water requirement (kg/10,000 km-a)	CO_2 demand/ N_2 demand (kg/10,000km-a)	Fuel requirement (kg/10,000km-a)	Well to Tank Efficiency	Well to Wheel Efficiency	Number of cars
E-car	2.000	0	0	0	-	60 %	14.000
F-burner	0	0	0	0	-	28 %	-
E-hydrogen	5.440	13	0	97	62 %	37 %	5.440
E-methane	12.929	1.125	1.375	500	45 %	16 %	2.166
E-methanol	13.725	1.575	1.925	1.400	57 %	20 %	2.040
E-Diesel	15.811	3.290	2.100	700	52 %	18 %	1.771

Table 11: Primary energy, water and carbon dioxide requirements for the synthesis of various e-fuels.

The summary of the model in Table 11 shows that a fuel cell vehicle requires about 5,400 kWh/10,000km-a of green electricity (row "E-hydrogen"). If it has a mileage of 0.97 kg-H_2/100km,[197] and the fuel cells have an efficiency of about 60 %, this gives a well-to-wheel efficiency of 37 % for e-hydrogen fuel cell vehicles. This means that a 7 MW wind turbine with 4,000 full load hours could indirectly power about 5,400 fuel cell vehicles, each travelling 10,000 km/a.

In contrast, a compressed e-methane car requires about 12,930 kWh/10,000 km of green electricity, about 1,100 kg-H_2O/10,000 km-a and 1,400 kg-CO_2 /10,000 km-a for e-methane synthesis. A 7 MW wind turbine with 4,000 full load hours per year can power about 2.040 such cars. The power-to-methane solution for passenger cars has a well-to-wheel efficiency of about 16 %. This calculation is made under the assumption that the mileage of a CNG combustion car is about 5 kg-CNG/100 km.[198] With the methanol route, the aforementioned wind turbine configuration can power about 2,000 cars at 10,000 km/a each. The upstream green electricity demand for e-methanol synthesis is about 13,700 kWh/10000 km-a and requires about 1,600 kg-H_2 O/10,000 km-a and 1,900 kg-CO_2 /10,000 km-a in contrast to an electric car. This route has a slightly better well-to-wheel efficiency of 20 % than e-methane.

The most energy-intensive solution succeeds with E-Fischer-Tropsch-Fuels (EFT): according to one study, the synthesis of Fischer-Tropsch-Fuels by means of high-temperature co-electrolysis needs about 22 kWh/kg-EFT.[199] Other sources mention a primary energy demand for electricity of 25 to 29 kWh/kg-EFT.[200] Assuming an energy demand of 22 kWh/kg-EFT and a driving performance of 7 litres of petrol/100 km, a combustion engine needs 15,800 kWh of electricity to drive 10,000 km.

Oil consumption in global road transport is about 22,260 TWh/a[201] oil equivalent and replacing this amount with e-fuels will require 37,000 to 49,000 TWh/a of green electricity.[202] Furthermore, this solution requires a global upscaling of Direct Air Capture to eventually capture and compress the CO_2 emitted by combustion engines. Capturing CO_2 using low-temperature temperature swing

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[197] Cf. Duan et al., 2021.
[198] For Mercedez Benz B 180; cf. CNG-Europe, 2017.
[199] Cf. Peters et al., 2022.
[200] Cf. Prognos, 2020.
[201] 43 million barrels per day according to BNEF, 2020.
[202] Assuming a well-to-tank efficiency of 60 % to 45 % for the synthesis of e-fuels

absorption direct air capture processes requires approximately 180 kWh/t-CO_2 of electricity, 722 kWh/t-CO_2 of heat, 7 kg/ t-CO_2 of sorbent and 118 kWh/t-CO_2 of electricity for compression and underground injection of captured CO_2 from the air.[203]

Compared to these solutions, an e-car needs 2,000 kWh/10,000km-a and neither water nor CO_2 for fuel synthesis. Nevertheless, the water consumption for mining and processing lithium must not be ignored. Each kWh of battery storage capacity in an e-car requires about 100g of lithium and 2 million litres of water are consumed per tonne of lithium extraction,[204] according to available data. A Nissan Leaf has a 25 kWh Li battery, and this is equivalent to a one-off water consumption of 5,000 kg in the extraction of lithium for battery production, and this is in very dry regions of the world such as the Atacama in Chile. However, the exact demand for raw water for lithium extraction and battery production remains unclear due to a lack of transparency on the part of mining companies and battery manufacturers.

A rethinking of mobility would be necessary globally, because replacing combustion engines with electric vehicles or vehicles powered by e-fuel also poses technical-economic and environmental obstacles. Therefore, there is no "silver bulltet" solution. Supplying the existing fleet with e-fuels and replacing internal combustion vehicles with e-cars/e-mopeds has an increasing demand for resources such as green electricity, lithium, charging infrastructure. Supply chains for e-fuels are also limited and lead to new geopolitical dependencies.

3.3.2 Rail traffic

Rail is one of the most energy-efficient modes of transport: it is responsible for 9 % of global motorised passenger transport and 7 % of freight transport but consumes only 3 % of transport energy.[205] The average intensity of rail transport worldwide is 63 g-CO_2 /passenger-km. Rail transport consumes 80 % less energy than trucks per tonne of freight carried and has a four-to-one advantage over cars in terms of emissions intensity. As a result, rail accounted for only 4 % of global transport industry emissions in 2019.[206]

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[203] Cf. Madhu et al., 2021.
[204] Cf. Danwatch 2019; Xanders, 2019.
[205] Cf. IEA, 2021.
[206] Cf. BCG, 2022.

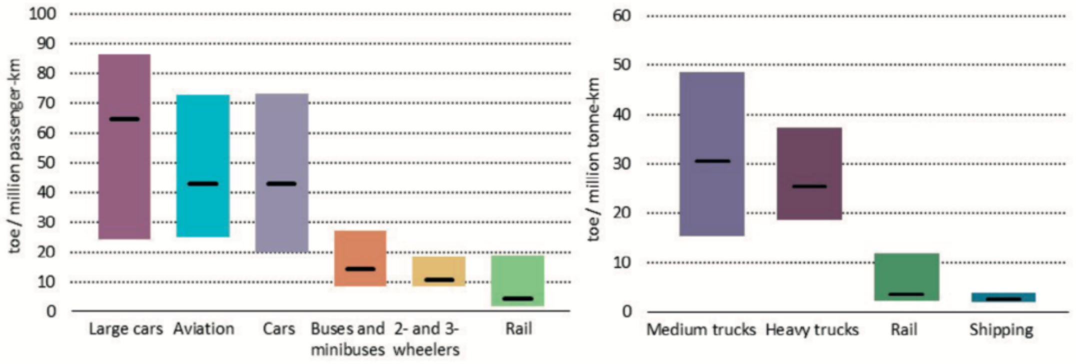


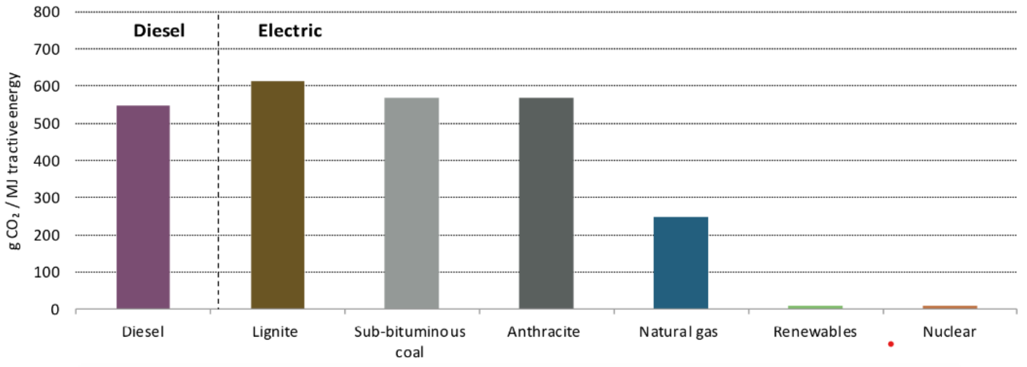
Figure 64: Energy consumption of transport modes from 2017. Left: Passenger transport in TOE (tonnes of oil equivalent) per million passenger-kilometers, right: Freight transport in TOE per million tonne-kilometers.

Source: IEA (2019a), CarbonBrief (2019)

3.3.2.1 Sources of CO emissions$_2$

According to the GHG Protocol, emissions from the rail sector can be divided into the following three classes:

- Scope 1 emissions include direct emissions by railway companies from their trains, machinery and buildings. They are mainly generated by fossil fuels that power the company's locomotives, wagons and trucks
- Scope 2 emissions arise indirectly from the purchase of non-renewable electricity, which is used not only to power locomotives, but also for administrative operations, station operations, maintenance and other activities.
- Scope 3 emissions include other indirect GHG emissions from the value chain of railway companies, such as the upstream emissions generated in the production of locomotives and rolling stock and in the construction of railway infrastructure.



Average well-to-wheel (WTW) carbon intensities for diesel powertrains and electric powertrains using various primary sources, in grammes of CO2e per megajoule. Source: IEA 2019.

Illustration 65: Well-to-wheel emission intensities of different train propulsion systems ; Source: IEA 2019

The direct or indirect emissions from diesel and electric trains are shown in Illustration 65 is shown. A diesel train causes about 550 g-CO_2 /MJ train energy, electric trains powered by electricity from coal-fired power plants are almost as harmful to the climate as diesel. The better solutions for rail electrification are electricity from natural gas and renewable energy plants. According to the International Energy Agency, by 2020, 55 % of the energy consumed by the global rail industry will be generated by diesel (85 % of which is used to power trains), 44 % by electricity and 1 $ by biofuels.

3.3.2.2 Technical options for CO_2 reduction

Reducing Scope 1 emissions resulting from the combustion of diesel fuel - some 300 million tonnes of greenhouse gas emissions per year - will therefore be critical to the sustainability of the industry. If global rail is to achieve net-zero emissions by 2050, it will need to reduce its diesel consumption to just 4 % of total energy use and replace its propulsion with either renewable electricity or another form of propulsion.[207] If rail is to expand and grow, it must continue to attract passengers and freight customers who want to reduce their own carbon footprint, as rail has better km-passenger/kWh values than cars or trucks. [208]

There are large regional differences in the energy efficiency of trains (see Figure 66). Passenger trains are less energy efficient in the US and EU than in Asia, mainly due to lower load factors.

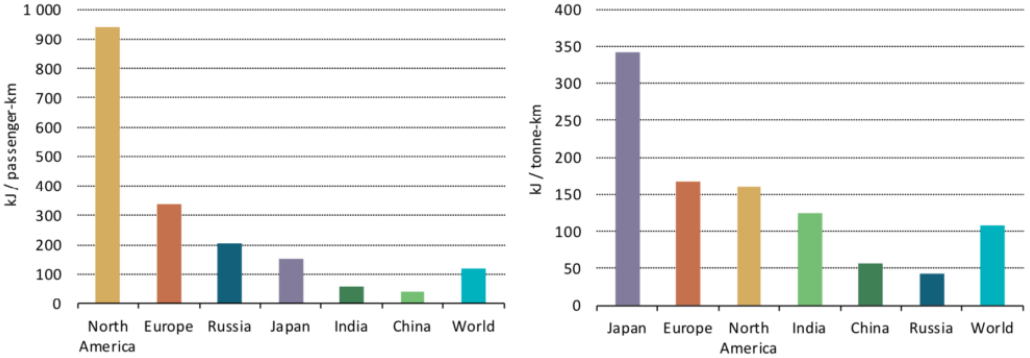


Figure 66: Passenger and freight rail mileage in various countries.
Source: IEA (2019a) p. 54

In 2016, electric locomotives were responsible for 70 % of passenger kilometers travelled and 48 % of freight kilometers transported.[209] However, the share of diesel locomotives remains high worldwide. About 50 % of all trains in Western Europe and Asia are diesel-powered, 75 % in the Middle East and Africa and a staggering 99 % in the Americas, with the highest share of rail electrification in Korea at around 85 %. By further electrifying rail transport and promoting passenger rail transport,

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[207] Cf. BCG, 2022.
[208] Passenger train 2.83 passenger-km/kWh; passenger car 1.41 passenger-km/kWh
[209] Cf. BCG, 2022.

railways could transport more efficiently and in a more climate-friendly way. Last-mile travel can be done using bicycles, shared mobility, buses, or safe pedestrian zones.

Local and high-speed rail infrastructure has been rapidly developed over the past decade, providing the foundation for convenient, low-emission travel within and between cities. China is leading the introduction of high-speed rail with unprecedented expansion. In India, which has the second longest railway infrastructure after China, extensive electrification of railway lines is underway. China had expanded 45,000 km of high-speed rail services in 2017 on routes between Taipei-Kaoshiung, Wuhan-Guangzhou, Beijing-Shanghai. [210]

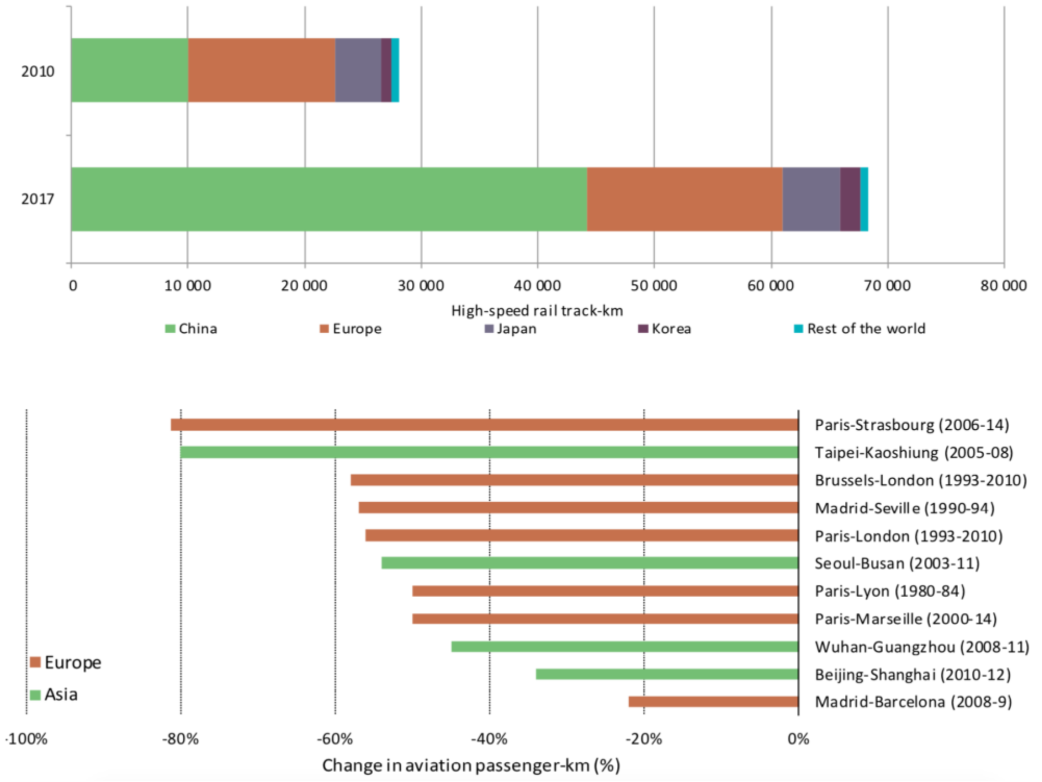

Figure 67: Expansion of high-speed rail in Europe and China (top) Source: IEA (2019a) p.31. Reduction in air travel due to high-speed rail expansion in Europe and China (bottom).
Source: IEA (2019a) p.99

Therefore, there was a reduction of 80 % to 30 % in air passenger-km due to this type of rail transport (see Figure 67). In Europe, due to the Paris-Strasbourg route, there was a reduction of 80 % in air passenger-km. An expansion of such high-speed rail services can reduce the dependency on short-haul air transport.

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[210] In comparison, during the same period, about 10,000 km of high-speedrail was built in Europe

3.3.3 Air traffic

3.3.3.1 Sources of CO emissions₂

Nearly 88 million jobs were in aviation and related tourism worldwide before Covid-19 hit the industry. Of these, 11.3 million people worked directly in the aviation industry. Globally, the "load factor" in the aviation sector is 83 %, the highest among other modes of transport. 1,478 airlines operate a fleet of 33,299 commercial aircraft serving 3,780 airports across a multi-million kilometre route network managed by 162 air navigation service providers. In 2019, flights worldwide produced 915 million tons of CO_2 and 4.5 billion passengers flew worldwide.[211]

Oil consumption by all commercial aircraft in the aviation sector was approximately 360 billion litres in 2019 before the start of the pandemic and 216 billion litres in 2020.[212] This corresponds to an energy demand of 3,312 TWh/a in 2019 and 1,987 TWh/a in 2021.[213]

Assuming a large wind farm operating at full load of 6,000 hours per year and taking into account the efficiency of E-Fischer-Tropsch-Fuels of 52 % in the conversion from well-to-tank, the wind farm needs to generate about 6,369 TWh per year of clean electricity to cover the fuel demand in 2019 before the pandemic. This is equivalent to an installed capacity of about 1 TW. To understand the magnitude of the task, it is important to consider that the current total installed capacity of wind power worldwide is about 0.75 TW. Describing the additional infrastructure required, such as CO_2 capture and delivery, transport, refineries, delivery tankers, labour, project duration and logistics for such a large-scale project is beyond the scope of this article.

	Boeing 747-200B	Boeing 777-300ER	Airbus A350-1000
kg-fuel/passenger-100km	4,96	3,65	2,93
kg-fuel/payload-100km	4,56	1,65	1,51

Table 12: Mileage of different aircraft types for a 9166 km flight between Hong Kong and Frankfurt.

Source: Burzlaff, 2017.

According to a study by HAW Hamburg, the "mileage" of modern aircraft is on average about 3.3 kg-fuel/passenger-100 km. The flight performance of various aircraft types such as Boeing 747-200B, Boeing 777-300ER & Airbus A350-100 measured over the Hong Kong-Frankfurt route are shown in Table 12 can be seen.

Based on gravimetric energy density, Aviation Gasoline has an energy density of 12.14 kWh/kg and a volumetric energy density of 8.61 kWh/litre. Because of its relatively higher density, kerosine has

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[211] Cf. Air Transport Action Group, 2020.
[212] Cf. Statista, 2021; 1 US gallon = 3.79 litres
[213] The energy density 9.2 kWh/litre

the highest volumetric energy density of 9.74 kWh/litre. The properties of three types of fuels are compiled in Table 13.

Fuels	Density (kg/litre)	Gravimetric energy density (kWh/kg)	Volumetric energy density (kWh/litre)
Aviation Gasoline	715	12,14	8,61
Jet Fuel - Widecut	762	12,09	9,22
Kerosine	810	12,02	9,74

Table 13: Density, gravimetric and volumetric energy density of various aviation fuels.

Source: Chevron, 2007.

3.3.3.2 Technical options for CO_2 reduction

This chapter discusses the replacement of aviation fuel with E-Fischer-Tropsch fuel. Since the average fuel consumption of a passenger aircraft is about 3.3 kWh/passenger-km,[214] electrical energy of the order of 75 kWh/passenger-100 km would be required for EFT synthesis, assuming an electricity demand of 22 kWh/kg-EFT by co-electrolysis of CO_2 and H_2 O for EFT synthesis.[215]

3.3.4 Shipping

3.3.4.1 Sources of CO emissions$_2$

Comparing the world merchant fleet data from 2021 with that from 2016, the three largest ship-owning countries have remained the same: Greece, Japan and China. In total, the world merchant fleet comprises 2,116,401Thousand DWT and 53,973 vessels over 1,000 GRT. The ships covered include all seagoing merchant vessels with propulsion and a GRT of 1,000 and over, including offshore drilling vessels and floating production, storage and offloading units (FPSOs). Military vessels, yachts, watercraft, fishing vessels and fixed and mobile offshore platforms and vessels are excluded.

Emissions (g/kg fuel)	Heavy Fuel Oil (HFO)	Marine Gas Oil (MGO)
PM	3	2
NOx	45	47
CO	4	3
CO_2	3210	3180
SO_2	24	0,7

Table 14: Greenhouse gas emissions from marine fuels.[214]

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[214] Cf. Burzlaff, 2017.
[215] Cf. Peters et al., 2022.

Larger ships, such as tankers, travel at lower speeds and have better fuel consumption, but also a larger DWT, resulting in higher net fuel consumption. In general, it can also be said that large ships are more efficient than smaller ones, i.e. the energy consumption per transport work decreases with size. This is mainly due to the fact that the wetted area increases proportionally with length, while the cargo capacity increases with length in the cube, so that the energy demand grows more slowly than the transport capacity.[216] The energy consumptions as a function of the speed of different types of vessels are shown in Figure 68 graphically. The larger ship can also travel at higher speeds before facing the problem of large wave resistance.

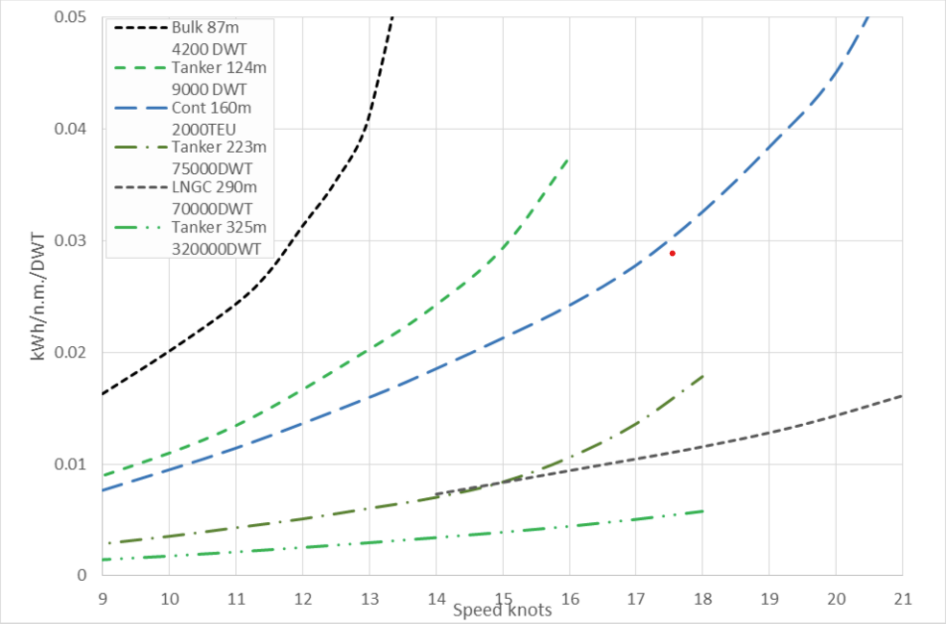

Figure 68: Energy consumption as a function of speed of different types of vessels are.

Source: von Knorring et al., 2016.

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[216] Cf. von Knorring et al., 2016.

3.3.4.2 Technical options for CO_2 reduction

Based on these data, the green power requirements for the synthesis of various e-fuels per 10,000 km/DWT and at a mileage of 1.64 kWh/100 km-DWT[217] were calculated in Table 15 is shown. The lowest electricity demand would be via the e-hydrogen rail, but this does not take into account the energy required to compress or liquefy hydrogen. The production of other fuels such as e-methane, e-ammonia and e-Fischer-Tropsch Fuels requires 292 to 366 kWh/(10,000 km-DWT) of green electricity. The water and CO_2 consumptions for their synthesis are shown in Table 15 listed. The highest water and CO_2 consumption is found in the synthesis of E-Fischer-Tropsch-Fuels.

	E-hydrogen	E-methane	E-methanol	E-ammonia	EFT Fuel
Electricity demand kWh/(10,000km-DWT)	265	366	292	348	317
Water requirement kg/(10,000km-DWT)	0,56	29	33	51	66
CO_2 -requirement/ N_2 - requirement kg/(10,000km-DWT)	0	35	41	26	42

Table 15: Electricity, water & CO_2 Demand for the synthesis of different e-fuels for the marine industry.

There are some measures of reduction such as the use of kites or Flettner rotors for ship propulsion, but their use remains largely impractical in modern shipping. Nevertheless, the use of sea winds for shipping was not uncommon in the pre-industrial world. One company is trying to change that by helping the humble kites reach new heights. Airseas, a French technology company founded by former Airbus engineers, has invented the "Seawing", a 1000 m² hydrofoil that uses wind power to generate 90 tonnes of tractive force, according to its website. It is estimated that this could reduce the fuel consumption and emissions of cargo ships by 10 to 40 %.[218]

3.3.5 Application examples

The global electric motorbike market is expected to reach USD 37 billion by 2028, growing at a cumulative annual growth rate (CAGR) of 13 % from 2022 to 2028.[219] Electric scooters offer more cost-effective last-mile mobility. The use of electric motorbikes is increasing in emerging markets. For example, sales of electric motorbikes in India grew by 16.5 % in 2019-20. The Indian government has introduced tax incentives to encourage the use of electric bikes. The Goods and Sales Tax in India (GST) on electric bikes has been reduced from 12 $ to 5 %. According to industry experts, most of the electric two-wheelers sold in India and China by major players are in the range of USD

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[217] 0.03 kWh/nm/DWT
[218] Cf. Airseas, 2022.
[219] Cf. Yahoo Finance, 2023.

400 to 900 due to consumer behaviour and current riding needs.[220] For instance, companies like Hero Electric, Pure EV, Okinawa, Ampere and TVS cater to the economy segment in the Indian market. Similarly, the Chinese market is dominated by electric motorbikes from manufacturers Yadea, Jiangsu Xinri and Luyuan.

For applications where space and weight constraints limit the use of batteries, such as shipping and aviation, the use of green hydrogen derivatives will play a crucial role in decarbonising these industries. For example, Maersk has ordered 19 transport ships that can run on green methanol. The six ships are being built by Hyundai Heavy Industries and have a nominal capacity of about 17,000 containers.[221] They have dual-fuel engines that can run on green methanol. Maersk has signed an agreement with the company SunGas, which will produce green methanol from wood and forestry waste.

Sustainable Aviation Fuel (SAF) is an alternative to conventional fossil aviation fuel that is produced from biological and non-biological resources. The various raw materials used to produce SAF can come from both plant and animal materials and range from cooking oil and vegetable oils to agricultural residues and municipal waste.[222] Among the major sustainable aviation fuel companies, Finnish, refiner Neste is the world leader and well on its way to becoming the world's largest renewable fuel supplier with global capacity and production sites in North America, Asia and Europe. Airlines flying on Neste's fuel include three of the largest US carriers: Alaska Airlines, American Airlines and JetBlue Airways. World Energy is a major SAF supplier in the US. A leader in the production and distribution of low-carbon fuels for more than two decades and operating the world's first and America's only commercial-scale SAF production facility, the company plans to produce 150 million gallons of SAF annually by 2024. Globally, SAF still accounts for less than 0.1 $ of aviation fuel and costs about four times as much as kerosine.[223]

3.3.6 Developmental relevance

The global transport sector is a major cause of this health burden through its contribution to elevated concentrations of particulate matter (PM2.5), ozone and nitrogen dioxide. Transport generates tailpipe emissions, evaporative emissions, resuspension of road dust and particulate matter from brake and tyres. Other important health impacts of the sector are noise, impairment of physical activity and traffic accidents. Nearly half of all deaths from traffic-related air pollution are caused by diesel exhaust, and one in three deaths is linked to emissions from off-road vehicles and international

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[220] Cf. GlobeNewswire, 2022.
[221] Cf. Maersk, 2022.
[222] Cf. Earth.Org, 2022
[223] Cf. Bloomberg, 2021.

shipping, a new study finds.[224] In cities such as Jakarta, Shanghai, New Delhi, Riyadh, Seoul and Lahore, where the air quality index is above 130, there is therefore a higher risk for the residents.[225]

A strategic shift to electric scooters, electric buses, electrification of rail transport and an absolute reduction in private car ownership through carbon taxes and higher parking fees can help reduce hazardous emissions in developing country cities. New mobility services such as car sharing, bike sharing and autonomous transport could reduce private car use, emissions and air pollution. Cooperation between public authorities, the private sector and communities is key to improving air quality and clean mobility. For example, in Helsinki, the HOPE project developed the Green Path app, which guides cyclists and pedestrians to less polluted routes. The app uses real-time air quality data and a database that is co-designed by the population to promote healthier mobility. The city of Bielefeld in Germany has set a strategy to have only 25 % of local trips made by car by 2030. Measures include investing in infrastructure and promoting cycling and walking. Cities are also exploring new ways to improve residents' access to public transport. The INNOAIR project in Sofia, Bulgaria is introducing electric buses that follow timetables and routes based on passenger requests in an app as an alternative to short car journeys. China is poised to become one of the largest MaaS markets in the world, according to ARK Invest. Mobile app-based ridesharing services have grown rapidly in China, as has the urban population. ARK estimates that the market for MaaS in China could grow to $2.5 trillion by 2030.[226] China is particularly suitable for MaaS as the majority of the population does not have a driving licence,[227] average income is low relative to vehicle prices, and it is difficult to get a car in China. With increasing urbanisation, most trips fall into the category of micromobility and are therefore ideal candidates for the use of bicycles and scooters. In the US, about 60 % of all trips are 5 miles or less, and the micromobility market will be worth $200-300 billion by 2030, according to McKinsey.[228] Since 2017, investors worldwide have invested USD 14 billion in equity in micromobility start-ups. Figure 69 shows several growing companies in the US and globally that offer mobility as a service.

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[224] Cf. ICCT & CCAC, 2019.
[225] Cf. IQAir, 2022.
[226] Cf. ARK Invest, 2017.
[227] 80 %
[228] Cf. CSBInsights, 2021.

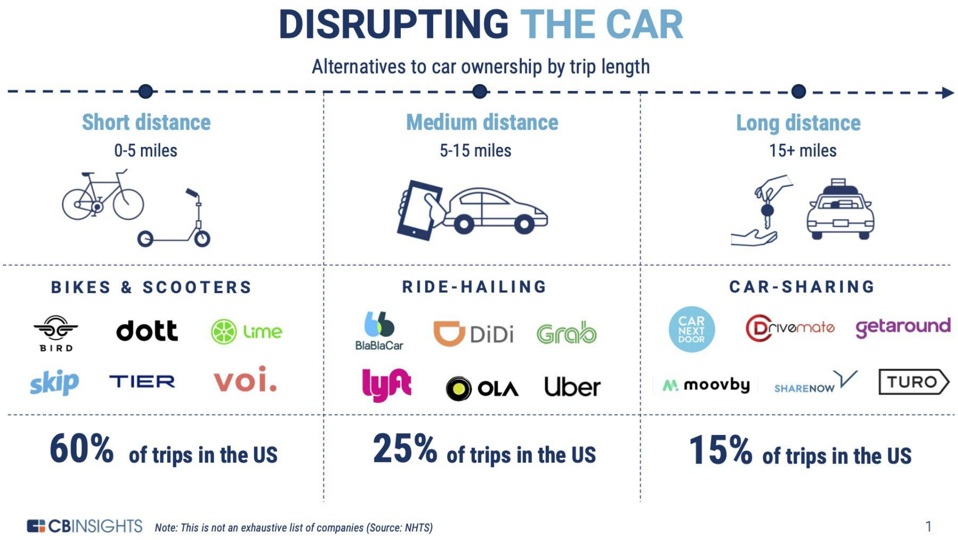

Figure 69: Mobility as a service provider for various routes.

Source: CSBInsights, 2021.

Men and women have different travel patterns. Women's labour market participation is lower than men's, and women do 75 % of the unpaid care work in the world.[229] This means that women are more likely to make multiple, shorter trips while transporting groceries and/or accompanying children or elderly family members. Men's journeys are more likely to be single trips to and from work. This means that transport networks mostly do not meet women's needs for multiple, shorter trips outside peak travel times.[230] Fear of harassment and assault also leads women to be more concerned than men about what routes they take and at what times. Public transport hubs and stations are not always designed for people travelling with children, prams and groceries, or accompanying people with reduced mobility, especially in developing countries.

Almost 53 % of public transport users in Germany are women, worldwide the share is as high as 66 %. If a functioning multimodal transport system is not available, women have to use mopeds or combustion engines - at the expense of the environment. Otherwise, women stay at home and consequently miss out on further education opportunities or jobs. Therefore, the infrastructure must also be adapted to women's commuting behaviour. Gender sensitisation will create a safer atmosphere for women on public transport, pedestrian zones and bicycle routes. This will provide women with better jobs, education and access to healthcare.

Electrification is not a viable solution for the other "hard-to-abate" sectors such as aviation and shipping, for which e-fuels could be a solution. A massive deployment of wind and photovoltaic farms, electrolysis stations, refineries and e-fuel supply chains can help provide needed fuel for aviation and shipping fleets. Developing such a large-scale project to power internal combustion engines or

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[229] Cf. OXFAM International, 2021.
[230] Cf. Ramboll, 2021.

turbines can create jobs in Africa, Latin America and Asia. However, scaling up such projects also means that the workforce will have to work in conditions of high winds, occasional dust storms and intense sun. It may be possible in the future to use AI or robots for such massive project development, thus avoiding the approach of labour in the know. Furthermore, long-term effects of occupying large areas in the oceans, the Sahara or the Atacama with wind and photovoltaic plants on local and global wind conditions, precipitation and climate are not understood by massive wind and photovoltaic plants for the synthesis of e-fuels.

Currently, the supply chains of important metals for wind turbines and batteries are heavily controlled by China, with almost 87 % of rare earth being processed in China.[231] For large-scale production of e-fuels, China needs to ensure a stable and reliable supply of components and key metals over a long period of time. This requires unprecedented geopolitical cooperation and will plunge us into new dependencies. It also raises the ethical question of who benefits from such large-scale projects. Will the financial gains from such projects largely go to African nations to redress global socio-economic, racial inequalities, or will billionaires pocket a lion's share of the profits? A passport is the key to travelling abroad. However, some passports are considered "stronger" than others. The strongest passports in the world are those that offer the greatest freedom to travel. Many African countries do not have freedom of travel like the northern countries in North America, Europe, Japan as well as South Korea. [232]

A concerted reduction in the number of global aviation and shipping fleets through carbon taxes, a shift from consumerism to essentialism, a focus on local production of goods and services can facilitate the deployment of e-fuels. Automation of large-scale e-fuel projects through automation and AI can avoid the approach of people in hazardous working conditions. Redirecting profits from such projects through taxation to benefit human welfare and climate change mitigation efforts in local economies may well be the way to reduce emissions from "hard-to-abate" sectors such as aviation and shipping and secure prosperity in developing countries.

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[231] Cf. Visual Capitalist, 2022.

[232] Cf. Henley & Partners, 2022.