WG III contribution to the Sixth Assessment Report

List of corrigenda to be implemented

The corrigenda listed below will be implemented in the Chapter during copy-editing.

CHAPTER 10

Document (Chapter, Annex, Supp. Material)	Page (Based on the final pdf FGD version)	Line	Detailed information on correction to make
Chapter 10	6	12-14	Replace: Some literature suggests that explicitly including international shipping and aviation under the governance of the Paris Agreement could spur stronger decarbonisation efforts in these segments. with: Some authors in the literature have argued that including international shipping and aviation under the the Paris Agreement could spur stronger decarbonisation efforts in these segments.
Chapter 10	96	3-5	Replace: Some literature suggests that the governance of the international transport systems could be included the Paris Agreement process With Some authors in the literature have argued that the governance of the international transport systems could be included in the Paris Agreement process
Chapter 10	96	36-43	Some commentators have suggested that emissions from international aviation and shipping should be part of the Paris Agreement With Some authors in the literature have argued that emissions from international aviation and shipping should be part of the Paris Agreement
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Chapter 10: Transport

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Executive summary

Meeting climate mitigation goals would require transformative changes in the transport sector *(high confidence*). In 2019, direct greenhouse gas (GHG) emissions from the transport sector were 8.7 Gt CO_2-eq (up from 5.0 Gt CO_2-eq in 1990) and accounted for 23% of global energy-related CO_2 emissions. 70% of direct transport emissions came from road vehicles, while 1%, 11%, and 12% came from rail, shipping, and aviation, respectively. Emissions from shipping and aviation continue to grow rapidly. Transport-related emissions in developing regions of the world have increased more rapidly than in Europe or North America, a trend that is likely to continue in coming decades (*high confidence*). {10.1, 10.5, 10.6}.

Since AR5 there has been a growing awareness of the need for demand management solutions combined with new technologies, such as the rapidly growing use of electromobility for land transport and the emerging options in advanced biofuels and hydrogen-based fuels for shipping and aviation. There is a growing need for systemic infrastructure changes that enable behavioural modifications and reductions in demand for transport services that can in turn reduce energy demand. The response to the COVID-19 pandemic has also shown that behavioural interventions can reduce transport-related GHG emissions. For example, COVID-19-based lockdowns have confirmed the transformative value of telecommuting replacing significant numbers of work and personal journeys as well as promoting local active transport. There are growing opportunities to implement strategies that drive behavioural change and support the adoption of new transport technology options. {Chapter 5, 10.2, 10.3, 10.4, 10.8}

Changes in urban form, behaviour programs, the circular economy, the shared economy, and digitalisation trends can support systemic changes that lead to reductions in demand for transport services or expands the use of more efficient transport modes (*high confidence*). Cities can reduce their transport-related fuel consumption by around 25% through combinations of more compact land use and the provision of less car-dependent transport infrastructure. Appropriate infrastructure, including protected pedestrian and bike pathways, can also support much greater localised active travel[1]. Transport demand management incentives are expected to be necessary to support these systemic changes *(high confidence)*. There is mixed evidence of the effect of circular economy initiatives, shared economy initiatives, and digitalisation on demand for transport services. For example, while dematerialisation can reduce the amount of material that need to be transported to manufacturing facilities, an increase in online shopping with priority delivery can increase demand for freight transport. Similarly, while teleworking could reduce travel demand, increased ridesharing could increase vehicle-km travelled. {Chapter 1, Chapter 5, 10.2, 10.8}

Battery-electric vehicles (BEVs) have lower life cycle greenhouse gas emissions than internal combustion engine vehicles (ICEVs) when BEVs are charged with low carbon electricity (*high confidence*). Electromobility is being rapidly implemented in micro-mobility (e-autorickshaws, e-scooters, e-bikes), in transit systems, especially buses, and, to a lesser degree, in the electrification of personal vehicles. BEVs could also have the added benefit of supporting grid operations. The commercial availability of mature Lithium-Ion Batteries (LIBs) has underpinned this growth in electromobility.

As global battery production increases, unit costs are declining. Further efforts to reduce the GHG footprint of battery production, however, are essential for maximising the mitigation potential of BEVs. The continued growth of electromobility for land transport would require investments in electric charging and related grid infrastructure (*high confidence*). Electromobility powered by low-carbon

FOOTNOTE [1] Active travel is travel that requires physical effort, for example journeys made by walking or cycling.

electricity has the potential to rapidly reduce transport GHG and can be applied with multiple co-benefits in the developing world's growing cities (*high confidence*). {10.3, 10.4, 10.8}

Land-based, long-range, heavy-duty trucks can be decarbonised through battery-electric haulage (including the use of Electric Road Systems), complemented by hydrogen- and biofuel-based fuels in some contexts (*medium confidence*). These same technologies and expanded use of available electric rail systems can support rail decarbonisation *(medium confidence*). Initial deployments of battery-electric, hydrogen- and bio-based haulage are underway, and commercial operations of some of these technologies are considered feasible by 2030 (*medium confidence*). These technologies nevertheless face challenges regarding driving range, capital and operating costs, and infrastructure availability. In particular, fuel cell durability, high energy consumption, and costs continue to challenge the commercialisation of hydrogen-based fuel cell vehicles. Increased capacity for low-carbon hydrogen production would also be essential for hydrogen-based fuels to serve as an emissions reduction strategy (*high confidence*). {10.3, 10.4, 10.8}

Decarbonisation options for shipping and aviation still require R&D, though advanced biofuels, ammonia, and synthetic fuels are emerging as viable options *(medium confidence*). Increased efficiency has been insufficient to limit the emissions from shipping and aviation, and natural gas-based fuels are likely inadequate to meet stringent decarbonisation goals for these segments (*high confidence*). High energy density, low carbon fuels are required, but they have not yet reached commercial scale. Advanced biofuels could provide low carbon jet fuel (*medium confidence*). The production of synthetic fuels using low-carbon hydrogen with CO_2 captured through DAC/BECCS could provide jet and marine fuels but these options still require demonstration at scale (*low confidence*). Ammonia produced with low-carbon hydrogen could also serve as a marine fuel (*medium confidence*). Deployment of these fuels requires reductions in production costs. {10.2, 10.3, 10.4, 10.5, 10.6, 10.8}.

Scenarios from bottom-up and top-down models indicate that without intervention, CO_2 emissions from transport could grow in the range of 16% and 50% by 2050 (*medium confidence)*. The scenarios literature projects continued growth in demand for freight and passenger services, particularly in developing countries in Africa and Asia (*high confidence*). This growth is projected to take place across all transport modes. Increases in demand not-withstanding, scenarios that limit warming to 1.5°C degree with no or limited overshoot suggest that a 59% reduction (42-68% interquartile range) in transport-related CO_2 emissions by 2050, compared to modelled 2020 levels is required. While many global scenarios place greater reliance on emissions reduction in sectors other than transport, a quarter of the 1.5°C degree scenarios describe transport-related CO_2 emissions reductions in excess of 68% (relative to modelled 2020 levels) (*medium confidence)*. Illustrative mitigation pathways 1.5 REN and 1.5 LD describe emission reductions of 80% and 90% in the transport sector, respectively, by 2050. Transport-related emission reductions, however, may not happen uniformly across regions. For example, transport emissions from the Developed Countries, and Eastern Europe and West-Central Asia (EEA) countries decrease from 2020 levels by 2050 across all scenarios compatible with a 1.5°C degree goal (C1 - C2 group), but could increase in Africa, Asia and developing Pacific (APC), Latin America and Caribbean, and the Middle East in some of these scenarios. {10.7}

The scenarios literature indicates that fuel and technology shifts are crucial to reducing carbon emissions to meet temperature goals. In general terms, electrification tends to play the key role in land-based transport, but biofuels and hydrogen (and derivatives) could play a role in decarbonisation of freight in some contexts (*high confidence*). Biofuels and hydrogen (and derivatives) are likely more prominent in shipping and aviation (high confidence). The shifts towards these alternative fuels must occur alongside shifts towards clean technologies in other sectors (*high confidence*). {10.7}.

There is a growing awareness of the need to plan for the significant expansion of low-carbon energy infrastructure, including low-carbon power generation and hydrogen production, to support emissions reductions in the transport sector (*high confidence*). Integrated energy planning and operations that take into account energy demand and system constraints across all sectors (transport, buildings, and industry) offer the opportunity to leverage sectoral synergies and avoid inefficient allocation of energy resources. Integrated planning of transport and power infrastructure would be particularly useful in developing countries where 'greenfield' development doesn't suffer from constraints imposed by legacy systems. {10.3, 10.4, 10.8}

The deployment of low-carbon aviation and shipping fuels that support decarbonisation of the transport sector could require changes to national and international governance structures (*medium confidence*). Currently, the Paris Agreement does not specifically cover emissions from international shipping and aviation. Instead, accounting for emissions from international transport in the Nationally Determined Contributions is at the discretion of each country. While the ICAO and IMO have established emissions reductions targets, only strategies to improve fuel efficiency and demand reductions have been pursued, and there has been minimal commitment to new technologies. Some literature suggests that explicitly including international shipping and aviation under the governance of the Paris Agreement could spur stronger decarbonisation efforts in these segments. {10.5, 10.6, 10.7}

There are growing concerns about resource availability, labour rights, non-climate environmental impacts, and costs of critical minerals needed for LIBs (*medium confidence*). Emerging national strategies on critical minerals and the requirements from major vehicle manufacturers are leading to new, more geographically diverse mines. The standardisation of battery modules and packaging within and across vehicle platforms, as well as increased focus on design for recyclability are important. Given the high degree of potential recyclability of LIBs, a nearly closed-loop system in the future could mitigate concerns about critical mineral issues (*medium confidence*). {10.3, 10.8}

Legislated climate strategies are emerging at all levels of government, and, together with pledges for personal choices, could spur the deployment of demand and supply-side transport mitigation strategies (***medium confidence*).** At the local level**,** legislation can support local transport plans that include commitments or pledges from local institutions to encourage behaviour change by adopting an organisational culture that motivates sustainable behaviour with inputs from the creative arts. Such institution-led mechanisms could include bike-to-work campaigns, free transport passes, parking charges, or eliminating car benefits. Community-based solutions like *solar sharing*, *community charging*, and *mobility as a service* can generate new opportunities to facilitate low-carbon transport futures. At the regional and national levels, legislation can include vehicle and fuel efficiency standards, R&D support, and large-scale investments in low-carbon transport infrastructure. {10.8, Chapter 15}

10.1 Introduction and overview

This chapter examines the transport sector's role in climate change mitigation. It appraises the transport system's interactions beyond the technology of vehicles and fuels to include the full life cycle analysis of mitigation options, a review of enabling conditions, and metrics that can facilitate advancing transport decarbonisation goals. The chapter assesses developments in the systems of land-based transport and introduces, as a new feature since AR5, two separate sections focusing on the trends and challenges in aviation and shipping. The chapter assesses the future trajectories emerging from global, energy, and national scenarios and concludes with a discussion on enabling conditions for transformative change in the sector.

This section (10.1) discusses how transport relates to virtually all the Sustainable Development Goals (SDGs), the trends and drivers making transport a big contributor in greenhouse gas (GHG) emissions, the impacts climate change is having on transport that can be addressed as part of mitigation, and the overview of emerging transport disruptions with potential to shape a low carbon transport pathway.

10.1.1 Transport and the sustainable development goals

The adoption of the 2030 Agenda for Sustainable Development by the United Nations (UN) has renewed international efforts to pursue and accurately measure global actions towards sustainable development (United Nations 2015). The 17 SDGs set out the overall goals that are further specified by 169 targets and 232 SDG indicators, many of which relate to transport (United Nations 2017; Lisowski et al. 2020). A sustainable transport system provides safe, inclusive, affordable, and clean passenger and freight mobility for current and future generations (Williams 2017; Litman 2021) so transport is particularly linked to SDGs 3, 7, 8, 9, 11, 12, and 13 (Move Humanity 2018; WBA 2019; SLoCaT 2019; Yin 2019; IRP 2019). Table 10.1 summarises transport-related topics for these SDGs and corresponding research. Section 17.3.3.7 (in Chapter 17) also provides a cross sectoral overview of synergies and trade-offs between climate change mitigation and the SDGs.

Table 10.1 Main transport-related SDGs

	Sustainable Development Goals: Synergies and trade-offs				
	Basic human needs	**Earth preconditions**	**Sustainable resource use**	**Social and economic development**	**Universal values**
	1 No poverty; 2 Zero hunger	13 Climate action; 14 Life below water; 15 Life on land	6 Clean water and sanitation; 7 Affordable and clean energy; 12 Responsible consumption and production	8 Decent work and economic growth; 9 Industry, innovation and infrastructure; 11 Sustainable cities and communities	4 Quality education; 5 Gender equality; 10 Reduced inequalities; 17 Partnerships for the goals
Transport-related topics (Low carbon Transport; Active transport; Electric vehicles.	- Lower air pollution contributes to positive health outcomes. - Energy access can contribute to poverty alleviation.	- Reduction of GHG emissions along the entire value chain, e.g. Well-to-Wheel (WTW). - Further development addressing minor GHG emissions and pollutants.	- Share of renewable energy use. - Energy efficiency of vehicles. - Clean and affordable energy off-grid.	- Role of transport for economic and human development. - Decarbonised public transport rather than private vehicle use.	- Gender equality in transport. - Reduced Inequalities. - Enables access to quality education.

	- Transport planning a major player in reducing poverty in cities. - Access to healthcare Diseases from air pollution. - Injuries and deaths from traffic accidents. - Reduced stress level from driving. - Links between active transport and good health with positive effects of walking and cycling. - Improving road accessibility to disabled users. - Reduce time spent on transport/mobility.	- Transport Oriented to Sustainable Development (TOD). - Circular economy principle applied to transport.	- Reduce material consumption during production, life cycle analysis of vehicles and their operations including entire value chains. - Close loop carbon and nutrient cycle linked to circular economy.	- Transport Oriented to Sustainable Development (TOD). - Sustainable transport infrastructure and systems for cities and rural areas. - Affordability of mobility services, this can also be covered under "universal access" to public transport. - Accessibility vs. mobility: Mobility to opportunities; Transport equity; Development as freedom. - Positive economic growth (employment) outcomes due to resource efficiency and lower productive energy cost. - Role of transport provision in accessing work, reconfiguration of social norms, as working from home. - Transport manufacturers as key employers changing role of transport-related labour due to platform economy, and innovations in autonomous vehicles.	- Partnership for the goals.

References	(Grant et al. 2016; Haines et al. 2017; Cheng et al. 2018; Nieuwenhuijsen 2018; Smith et al. 2018; Sofiev et al. 2018; Peden and Puvanachandra 2019; King and Krizek 2020; Macmillan et al. 2020)	(Farzaneh et al. 2019); see particularly following chapters.	(SLoCaT 2019); see particularly following chapters.	(Bruun and Givoni 2015; Pojani and Stead 2015; Hensher 2017; ATAG 2018; Grzelakowski 2018; Weiss et al. 2018; Brussel et al. 2019; Gota et al. 2019; Mohammadi et al. 2019; Peden and Puvanachandra 2019; SLoCaT 2019; Xu et al. 2019)	(Hernandez 2018; Prati 2018; Levin and Faith-Ell 2019; Vecchio et al. 2020)

10.1.2 Trends, drivers and the critical role of transport in GHG growth

The transport sector directly emitted around 8.9 Gt Carbon dioxide equivalent (CO_2eq) in 2019, up from 5.1 Gt CO_2eq in 1990 (Figure 10.1). Global transport was the fourth largest source of GHG emissions in 2019 following the power, industry, and the Agriculture, Forestry and Land Use (AFOLU) sectors. In absolute terms, the transport sector accounts for roughly 15% of total greenhouse gas (GHG) emissions and about 23% of global energy-related CO_2 emissions (IEA 2020a). Transport GHG emissions have increased fast over the last two decades, and since 2010, the sector's emissions have increased faster than for any other end-use sector, averaging +1.8% annual growth (see Section 10.7). Addressing emissions from transport is crucial for GHG mitigation strategies across many countries, as the sector represents the largest energy consuming sector in 40% of countries worldwide. In most remaining countries, transport is the second largest energy-consuming sector, reflecting different levels of urbanisation and land use patterns, speed of demographic changes and socio-economic development (IEA 2012; Hasan et al. 2019; Xie et al. 2019; Gota et al. 2019).

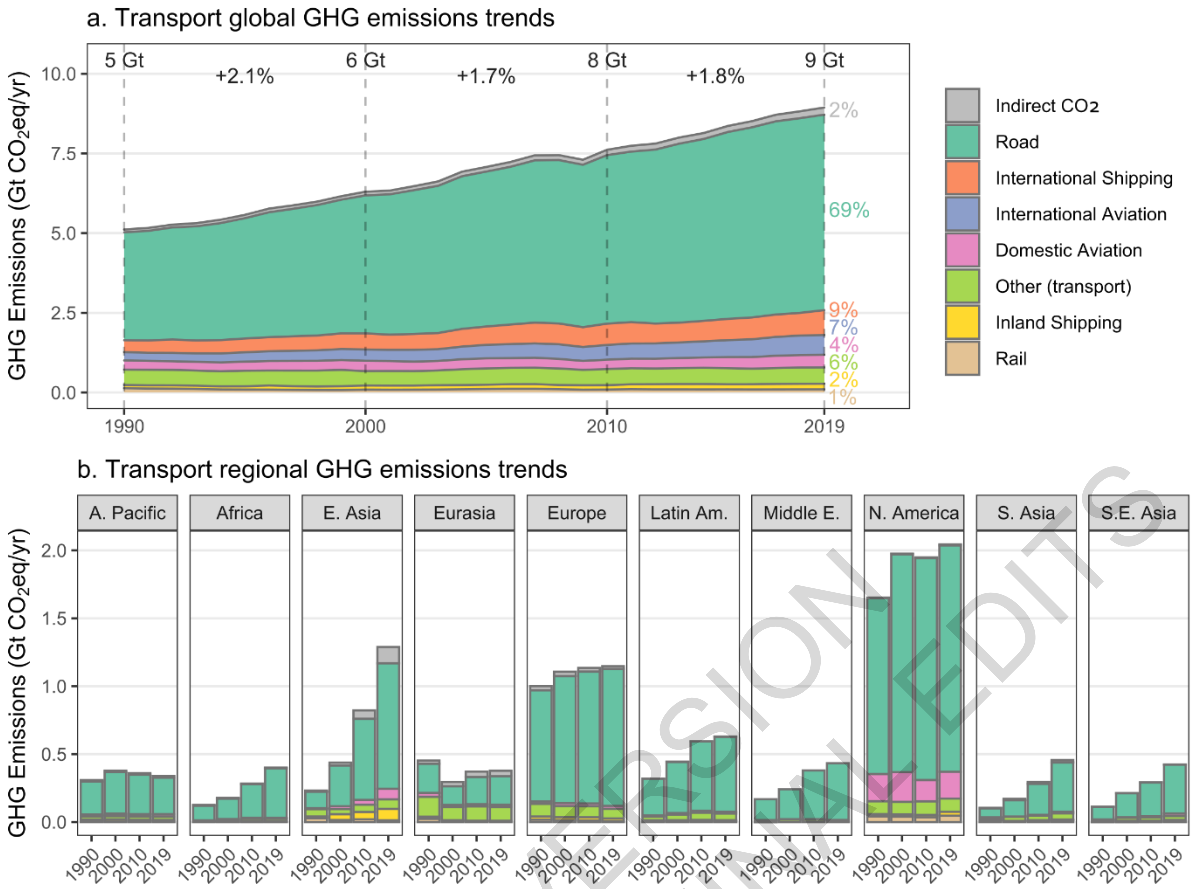

Figure 10.1 Global and regional transport GHG emissions trends. Indirect emissions from electricity and heat consumed in transport are shown in panel (a) and are primarily linked to the electrification of rail systems. These indirect emissions do not include the full life cycle emissions of transportation systems (e.g., vehicle manufacturing and infrastructure), which are assessed in section 10.4. International aviation and shipping are included in panel (a), but excluded from panel (b). Indirect emissions from fuel production, vehicle manufacturing and infrastructure construction are not included in the sector total. Source: Adapted from (Lamb et al. 2021) using data from (Minx et al. 2021)**.**

As of 2019, the largest source of transport emissions is the movement of passengers and freight in road transport (6.1 Gt CO_2eq, 69% of the sector's total). International shipping is the second largest emission source, contributing 0.8 Gt CO_2eq (9% of the sector's total), and international aviation is third with 0.6 Gt CO_2eq (7% of the sector's total). All other transport emissions sources, including rail, have been relatively trivial in comparison, totalling 1.4 Gt CO_2eq in 2019. Between 2010-2019, international aviation had one of the fastest growing GHG emissions among all segments (+3.4% per year), while road transport remained one of the fastest growing (+1.7% per year) among all global energy using sectors. Note that the COVID-19-induced economic lockdowns implemented since 2020 have had a very substantial impact on transport emissions – higher than any other sector (see chapter 2). Preliminary estimates from Crippa et al. (2021) suggest that global transport CO_2 emissions declined to 7.6 GtCO_2 in 2020, a reduction of 11.6% compared to 2019 (Crippa et al. 2021; Minx et al. 2021). These lockdowns affected all transport segments, and particularly international aviation (estimated -45% reduction in 2020 global CO_2 emissions), road transport (-10%), and domestic aviation (-9.3%). By comparison, aggregate CO_2 emissions across all sectors are estimated to have declined by 5.1% as a result of the COVID-19 pandemic (Chapter 2, section 2.2.2).

Growth in transport-related GHG emissions has taken place across most world regions (see Figure 10.1, panel b). Between 1990 and 2019, growth in emissions was relatively slow in Europe, Asia Pacific, Eurasia, and North America while it was unprecedently fast in other regions. Driven by economic and population growth, the annual growth rates in East Asia, South Asia, South East Asia, and Africa were 6.1%, 5.2%, 4.7%, and 4.1%, respectively. Latin America and the Middle East have seen somewhat slower growth in transport-related GHG emission (annual growth rates of 2.4% and 3.3%, respectively) (ITF 2019; Minx et al. 2021). Section 10.7 provides a more detailed comparison of global transport emissions trends with those from regional and sub-sectoral studies.

The rapid growth in global transport emissions is primarily a result of the fast growth in global transport activity levels, which grew by 73% between 2000 and 2018. Passenger and freight activity growth have outpaced energy efficiency and fuel economy improvements in this period (ITF 2019) . The global increase in passenger travel activities has taken place almost entirely in non-OECD countries, often starting from low motorization rates (SLoCaT 2018a). Passenger cars, two-and-three wheelers, and mini buses contribute about 75% of passenger transport-related CO_2 emissions, while collective transport services (bus and railways) generates about 7% of the passenger transport-related CO_2 emissions despite covering a fifth of passenger transport globally (Rodrigue 2017; Halim et al. 2018; Sheng et al. 2018; SLoCaT 2018a; Gota et al. 2019). While alternative lighter powertrains have great potential for mitigating GHG emissions from cars, the trend has been towards increasing vehicle size and engine power within all vehicle size classes, driven by consumer preferences towards larger sport utility vehicles (SUVs) (IEA 2020a). On a global scale, SUV sales have been constantly growing in the last decade, with 40% of the vehicles sold in 2019 being SUVs (IEA 2020a) – see Section 10.4, Box 10.3.

Indirect emissions from electricity and heat shown in Figure 10.1 account for only a small fraction of current emissions from the transport sector (2%) and are associated with electrification of certain modes like rail or bus transport (Lamb et al. 2021). Increasing transport electrification will affect indirect emissions, especially where carbon-intense electricity grids operate.

Global freight transport, measured in tonne-kilometres (tkm), grew by 68% between 2000 and 2015 and is projected to grow 3.3 times by 2050 (ITF 2019). If unchecked, this growth will make decarbonisation of freight transport very difficult (McKinnon 2018; ITF 2019). International trade and global supply chains from industries frequently involving large geographical distances are responsible for the fast increase of CO_2 emissions from freight transport (Yeh et al. 2017; McKinnon 2018), which are growing faster than emissions from passenger transport (Lamb et al. 2021). Heavy-duty vehicles (HDVs) make a disproportionate contribution to air pollution, relative to their global numbers, because of their substantial emissions of particulate matter and of black carbon with high short-term warming potentials (Anenberg et al. 2019).

On-road passenger and freight vehicles dominate global transport-related CO_2 emissions and offer the largest mitigation potential (Taptich et al. 2016; Halim et al. 2018). This chapter examines a wide range of possible transport emission reduction strategies. These strategies can be categorised under the 'Avoid- Shift-Improve' (ASI) framework described in Chapter 5 (Taptich et al. 2016). Avoid strategies reduce total vehicle-travel. They include compact communities and other policies that minimise travel distances and promote efficient transport through pricing and demand management programs. Shift strategies shift travel from higher-emitting to lower-emitting modes. These strategies include more multimodal planning that improves active and collective transport modes, complete streets roadway design, High Occupant Vehicle (HOV) priority strategies that favour shared mode, Mobility as a Service (MaaS), and multimodal navigation and payment apps. Improve strategies reduce per-kilometre emission rates. These strategies include hybrid and electric vehicle incentives, lower carbon and cleaner fuels, high emitting vehicle scrappage programs, and efficient driving and anti-idling campaigns (Lutsey and Sperling 2012; Gota et al. 2015). These topics are assessed within the rest of this chapter including how combinations of ASI with new technologies can potentially lead from incremental interventions into low carbon transformative transport improvements that include social and equity benefits (see section 10.8).

10.1.3 Climate adaptation on the transport sector

Climate change impacts such as extremely high temperatures, intense rainfall leading to flooding, more intense winds and/or storms, and sea level rise can seriously impact transport infrastructure, operations, and mobility for road, rail, shipping, and aviation. Studies since AR5 confirm that serious challenges to all transport infrastructures are increasing, with consequent delays or derailing (Miao et al. 2018; Moretti and Loprencipe 2018; Pérez-Morales et al. 2019; Palin et al. 2021). These impacts have been increasingly documented but, according to (Forzieri et al. 2018), little is known about the risks of multiple climate extremes on critical infrastructures at local to continental scales. All roads, bridges, rail systems, and ports are likely to be affected to some extent. Flexible pavements are particularly vulnerable to extreme high temperatures that can cause permanent deformation and crumbling of asphalt (Underwood et al. 2017; Qiao et al. 2019). Rail systems are also vulnerable, with a variety of hazards, both meteorological and non-meteorological, affecting railway asset lifetimes. Severe impacts on railway infrastructure and operations can arise from the occurrence of temperatures below freezing, excess precipitation, storms and wildfires (Thaduri et al. 2020; Palin et al. 2021) as are underground transport systems (Forero-Ortiz et al. 2020).

Most countries are examining opportunities for combined mitigation-adaptation efforts, using the need to mitigate climate change through transport-related GHG emissions reductions and pollutants as the basis for adaptation action (Thornbush et al. 2013; Wang et al. 2020). For example, urban sprawl indirectly affects climate processes, increasing emissions and vulnerability, which worsens the potential to adapt (Congedo and Munafò 2014; Macchi and Tiepolo 2014). Hence, using a range of forms of rapid transit as structuring elements for urban growth can mitigate climate change-related risks as well as emissions, reducing impacts on new infrastructure, often in more vulnerable areas (Newman et al. 2017). Such changes are increasingly seen as having economic benefit (Ha et al. 2017), especially in developing nations (Chang 2016; Monioudi et al. 2018).

Since AR5 there has been a growing awareness of the potential and actual impacts from global sea level rise due to climate change on transport systems (Dawson et al. 2016; Rasmussen et al. 2018; IPCC 2019; Noland et al. 2019), particularly on port facilities (Stephenson et al. 2018; Yang et al. 2018b; Pérez-Morales et al. 2019). Similarly, recent studies suggest changes in global jet streams could affect the aviation sector (Staples et al. 2018; Becken and Shuker 2019), and extreme weather conditions can affect runways (heat buckling) and aircraft lift. Combined, climate impacts on aviation could result in payload restrictions and disruptions (Coffel et al. 2017; Monioudi et al. 2018). According to (Williams 2017), studies have indicated that the amount of moderate-or-greater clear-air turbulence on transatlantic flight routes in winter will increase significantly in the future as the climate changes. More research is needed to fully understand climate induced risks to transportation systems.

10.1.4 Transport disruption and transformation

Available evidence suggests that transport-related CO_2 emissions would need to be restricted to about 2 to 3 Gt in 2050 (1.5°C scenario-1.5DS, B2DS), or about 70 to 80% below 2015 levels, to meet the goals set in the Paris Agreement. It also indicates that a balanced and inter-modal application of Avoid, Shift, and Improve measures is capable of yielding an estimated reduction in transport emissions of 2.39 Gt of CO_2-equivalent by 2030 and 5.74 Gt of CO_2-equivalent by 2050 (IPCC 2018; Gota et al. 2019). Such a transformative decarbonisation of the global transport system requires, in addition to technological changes, a paradigm shift that ensures prioritisation of high-accessibility transport solutions that minimise the amount of mobility required to meet people's needs, and favours transit and active transport modes (Lee and Handy 2018; SLoCaT 2021). These changes are sometimes called disruptive as they are frequently surprising in how they accelerate through a technological system.

The assessment of transport innovations and their mitigation potentials is at the core of how this chapter examines the possibilities for changing transport-related GHG trajectories. The transport technology innovation literature analysed in this chapter emphasises how a mixture of mitigation technology options and social changes are now converging and how, in combination, they may have potential to accelerate trends toward a low carbon transport transition. Such changes are considered disruptive or transformative (Sprei 2018). Of the current transport trends covered in the literature, this chapter focuses on three key technology and policy areas: electro-mobility in land-based transport vehicles, new fuels for ships and planes, and overall demand reductions and efficiency. These strategies are seen as being necessary to integrate at all levels of governance and, in combination with the creation of fast, extensive, and affordable multi-modal public transport networks, can help achieve multiple advantages in accordance with SDGs

Electrification of passenger transport in light-duty vehicles (LDVs) is well underway as a commercial process with socio-technical transformative potential and will be examined in detail in Sections 10.3 and 10.4. But the rapid mainstreaming of EV's will still need enabling conditions for land transport to achieve the shift away from petroleum fuels, as outlined in Chapter 3 and detailed in Section 10.8. The other mitigation options reviewed in this chapter are so far only incremental and are less commercial, especially shipping and aviation fuels, so stronger enabling conditions are likely, as detailed further in Sections 10.5 to 10.8. The enabling conditions that would be needed for the development of an emerging technological solution for such fuels are likely to be very different to electromobility, but nevertheless they both will need demand and efficiency changes to ensure they are equitable and inclusive.

Section 10.2 sets out the transformation of transport through examining systemic changes that affect demand for transport services and the efficiency of the system. Section 10.3 looks at the most promising technological innovations in vehicles and fuels. The next three sections (10.4, 10.5, and 10.6) examine mitigation options for land transport, aviation, and shipping. Section 10.7 describes the space of solutions assessed in a range of integrated modelling and sectoral transport scenarios; Finally, Section 10.8 sets out what would be needed for the most transformative scenario that can manage to achieve the broad goals set out in Chapter 3 and the transport goals set out in Section 10.7.

10.2 Systemic changes in the transport sector

Systemic change is the emergence of new organisational patterns that affect the structure of a system. While much attention has been given to engine and fuel technologies to mitigate GHG emissions from the transport sector, population dynamics, finance and economic systems, urban form, culture, and policy also drive emissions from the sector. Thus, systemic change requires innovations in these components. These systemic changes offer the opportunity to decouple transport emissions from economic growth. In turn, such decoupling allows environmental improvements like reduced GHG emissions without loss of economic activity (UNEP 2011, 2013; Newman et al. 2017; IPCC 2018).

There is evidence that suggests decoupling of transport emissions and economic growth is already happening in developed and developing countries. Europe and China have shown the most dramatic changes (Huizenga et al. 2015; Gao and Newman 2018; SLoCaT 2018b) and many cities are demonstrating decoupling of transport-related emissions through new net zero urban economic activity (Loo and Banister 2016; SLoCaT 2018a). A continued and accelerated decoupling of the growth of transport-related GHG emissions from economic growth is crucial for meeting the SDGs outlined in

Section 1. This section focuses on several overlapping components of systemic change in the transport sector that affect the drivers of GHG emissions: Urban form, physical geography, and infrastructure; behaviour and mode choice; and new demand concepts. Table 10.3, at the end of the section provides a high-level summary of the effect of these systemic changes on emissions from the transport sector.

10.2.1 Urban form, physical geography, and transport infrastructure

The physical characteristics that make up built areas define the urban form. These physical characteristics include the shape, size, density, and configuration of the human settlements. Urban form is intrinsically coupled with the infrastructure that allows human settlements to operate. In the context of the transport sector, urban form and urban infrastructure influence the time and cost of travel, which, in turn, drive travel demand and modal choice (Marchetti and Ausubel 2004; Newman and Kenworthy 2015).

Throughout history, three main urban fabrics have developed, each with different effects on transport patterns based on a fixed travel time budget of around one hour (Newman et al. 2016). The high-density urban fabric developed over the past several millennia favoured walking and active transport for only a few kilometres (kms). In the mid-19th century, urban settlements developed a medium density fabric that favoured trains and trams traveling over 10 to 30-km corridors. Finally, since the mid-20th century, urban form has favoured automobile travel, enabling mass movement between 50-60 kms. Table 10.2 describes the effect of these urban fabrics on GHG emissions and other well-being indicators.

Table 10.2 The systemic effect of city form and transport emissions

Annual Transport Emissions and Co-Benefits	Walking Urban Fabric	Transit Urban Fabric	Automobile Urban Fabric
Transport GHG	4 t/person	6 t/person	8 t/person
Health benefits from walkability	High	Medium	Low
Equity of locational accessibility	High	Medium	Low
Construction and household waste	0.87 t/person	1.13 t/person	1.59 t/person
Water consumption	35 kl/person	42 kl/person	70 kl/person
Land	133 m^2/person	214 m^2/person	547 m^2/person
Economics of infrastructure and transport operations	High	Medium	Low

Source: (Newman et al. 2016; Thomson and Newman 2018; Seto et al. 2021)

Since AR5, urban design has increasingly been seen as a major way to influence the GHG emissions from urban transport systems. Indeed, research suggests that implementing urban form changes could reduce GHG emissions from urban transport by 25% in 2050, compared with a business-as-usual scenario (Creutzig et al. 2015b; Creutzig 2016). Researchers have identified a variety of variables to study the relationship between urban form and transport-related GHG emissions. Three notable aspects summarise these relationships: urban space utilisation, urban spatial form, and urban transportation infrastructure (Tian et al. 2020). Urban density (population or employment density) and land use mix define the urban space utilisation. Increases in urban density and mixed function can effectively reduce per capita car use by reducing the number of trips and shortening travel distances. Similarly, the continuity of urban space and the dispersion of centres reduces travel distances (Tian et al. 2020), though such changes are rarely achieved without shifting transport infrastructure investments away from road capacity increases (Newman and Kenworthy 2015; McIntosh et al. 2017) For example, increased investment in public transport coverage, optimal transfer plans, shorter transit travel time, and improved transit travel efficiency make public transit more attractive (Heinen et al. 2017; Nugroho et al. 2018a,b) and hence increase density and land values (Sharma and Newman 2020). Similarly, forgoing the development of major roads for the development of pedestrian and bike pathways enhances the attractiveness of active transport modes (Zahabi et al. 2016; Keall et al. 2018; Tian et al. 2020).

Ultimately, infrastructure investments influence the structural dependence on cars, which in turn influence the lock-in or path dependency of transport options with their greenhouse emissions (Newman et al. 2015b; Grieco and Urry 2016). The 21st century saw a new trend to reach peak car use in some countries as a result of a revival in walking and transit use (Grieco and Urry 2016; Newman et al. 2017; Gota et al. 2019). While some cities continue on a trend towards reaching peak car use on a per-capita basis, for example Shanghai and Beijing (Gao and Newman 2020), there is a need for increased investments in urban form strategies that can continue to reduce car-dependency around the world.

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Cross-Chapter Box 7 Urban Form: Simultaneously reducing urban transport emissions, avoiding infrastructure lock-in, and providing accessible services

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Urban transport is responsible for about 8% of global CO_2 emissions or 3 Gt CO_2 per year (see Chapters 5 and 8). In contrast to energy supply technologies, urban transport directly interacts with mobility lifestyles (see Section 5.4). Similarly, non-GHG emission externalities, such as congestion, air pollution, noise, and safety, directly affect urban quality of life, and result in considerable welfare losses. Low-carbon, highly accessible urban design is not only a major mitigation option, it also provides for more inclusive city services related to wellbeing (Chapter 5, Sections 5.1 and 5.2). Urban planning and design of cities for people are central to realise emission reductions without relying simply on technologies, though the modes of transport favoured will influence the ability to overcome the lock-in around automobile use (Gehl 2010; Creutzig et al. 2015b).

Where lock-in has occurred, other strategies may alleviate the GHG emissions burden. Urban planning still plays a key role in recreating local hubs. Available land can be used to build rail-based transit, made financially viable by profiting from land value captured around stations (Ratner and Goetz 2013). Shared or pooled mobility can offer flexible on-demand mobility solutions that are efficient also in suburbs and for integrating with longer commuting trips (ITF 2017).

Global emission trajectories of urban transport will be decided in rapidly urbanising Asia and Africa. Urban transport-related GHG emissions are driven by incomes and car ownership but there is considerable variation amongst cities with similar income and car ownership levels (Newman and Kenworthy 2015). While electrification is a key strategy to decarbonise urban transport, urban infrastructures can make a difference of up to a factor of 10 in energy use and induced GHG emissions (Erdogan 2020). Ongoing urbanisation patterns risk future lock-in of induced demand on GHG emissions, constraining lifestyles to energy intensive and high CO_2-related technologies (See Section 5.4; 8.2.3; 10.2.1; (Erickson and Tempest 2015; Seto et al. 2016). Instead, climate solutions can be locked into urban policies and infrastructures (Ürge-Vorsatz et al. 2018) especially through the enhancement of the walking and transit urban fabric. Avoiding urban sprawl, associated with several externalities (Dieleman and Wegener 2004), is a necessary decarbonisation condition, and can be guided macro-economically by increasing fuel prices and marginal costs of motorised transport (Creutzig 2014). Resulting urban forms not only reduce GHG emission from transport but also from buildings, as greater compactness results in reduced thermal loss (Borck and Brueckner 2018). Health benefits from reduced car dependence are an increasing element driving this policy agenda (Section 10.8; (Speck 2018)).

Low-carbon highly accessible urban design is not only a major mitigation option, it also provides for more inclusive city services related to wellbeing (Chapter 5, Sections 5.1 and 5.2). Solutions involve planning cities around walkable sub-centres, where multiple destinations, such as shopping, jobs, leisure activities, and others, can be accessed within a 10 minute walk or bicycle ride (Newman and Kenworthy 2006). Overall, the mitigation potential of urban planning is about 25% in 2050 compared with a business as usual scenario (Creutzig et al. 2015a,b). Much higher levels of decarbonisation can be achieved if cities take on a regenerative development approach and act as geo-engineering systems on the atmosphere (Thomson and Newman 2016).

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10.2.2 Behaviour and mode choice

Behaviour continues to be a major source of interest in the decarbonisation of transport as it directly addresses demand. Behaviour is about people's actions based on their preferences. Chapter 5 described an 'Avoid, Shift, Improve' process for demand-side changes that affect sectoral emissions. This section discusses some of the drivers of behaviour related to the transport sector and how they link to this 'Avoid, Shift, Improve' process.

Avoid - the effect of prices and income on demand: Research has shown that household income and price have a strong influence on people's preferences for transport services (Bakhat et al. 2017; Palmer et al. 2018). The relationship between income and demand is defined by the income elasticity of demand. For example, research suggests that in China, older and wealthier populations continued to show a preference for car travel (Yang et al. 2019) while younger and low-income travellers sought variety in transport modes (Song et al. 2018). Similarly, (Bergantino et al. 2018b) evaluated the income elasticity of transport by mode in the UK. They found that the income elasticity for private cars is 0.714, while the income elasticities of rail and bus use are 3.253 (The greater elasticity the greater the demand will grow or decline, depending on income). Research has also shown a positive relationship between income and demand for air travel, with income elasticities of air travel demand being positive and as large as 2 (Gallet and Doucouliagos 2014; Valdes 2015; Hakim and Merkert 2016, 2019; Hanson et al. 2022). A survey in 98 Indian cities also showed income as the main factor influencing travel demand (Ahmad and de Oliveira 2016). Thus, as incomes and wealth across the globe rise, demand for travel is likely to increase as well.

The price elasticity of demand measures changes in demand as a result of changes in the prices of the services. In a meta-analysis of the price elasticity of energy demand, (Labandeira et al. 2017) report the average long-term price elasticity of demand for gasoline and diesel to be -0.773 and -0.443, respectively. That is, demand will decline with increasing prices. A similar analysis of long-term data in the United States (US), the United Kingdom (UK), Sweden, Australia, and Germany reports the gasoline price elasticity of demand for car travel (as measured through vehicle-kilometre -vkm- per capita) ranges between -0.1 and -0.4 (Bastian et al. 2016). For rail travel, the price elasticity of demand has been found to range between -1.05 and -1.1 (Zeng et al. 2021). Similarly, price elasticities for air travel range from -0.53 to -1.91 depending on various factors such as purpose of travel (business or leisure), season, and month and day of departure (Morlotti et al. 2017). The price elasticities of demand suggest that car use is inelastic to prices, while train use is relatively inelastic to the cost of using rail. Conversely, consumers seem to be more responsive to the cost of flying, so that strategies that increase the cost of flying are likely to contribute to some avoidance of aviation-related GHG emissions.

While the literature continues to show that time, cost, and income dominate people's travel choices (Ahmad and de Oliveira 2016; Capurso et al. 2019; He et al. 2020), there is also evidence of a role for personal values, and environmental values in particular, shaping choices within these structural limitations (Bouman and Steg 2019). For example, individuals are more likely to drive less when they care about the environment (De Groot et al. 2008; Abrahamse et al. 2009; Jakovcevic and Steg 2013; Hiratsuka et al. 2018; Ünal et al. 2019). Moreover, emotional and symbolic factors affect the level of car use (Steg 2005). Differences in behaviour may also result due to differences in gender, age, norms, values, and social status. For example, women have been shown to be more sensitive to parking pricing than men (Simićević et al. 2020).

Finally, structural shocks, such as a financial crisis, a pandemic, or the impacts of climate change could affect the price and income elasticities of demand for transport services (van Ruijven et al. 2019). COVID-19 lock-downs reduced travel demand by 19% (aviation by 32%) and some of the patterns that have emerged from the lockdowns could permanently change the elasticity of demand for transport (Tirachini and Cats 2020; Hendrickson and Rilett 2020; Newman 2020a; SLoCaT 2021; Hanson et al. 2022). In particular, the COVID-19 lock-downs have spurred two major trends: electronic communications replacing many work and personal travel requirements; and, revitalised local active transport and e-micro-mobility (Newman 2020a; SLoCaT 2021). The permanence of these changes post- COVID-19 is uncertain but possible ((Early and Newman 2021); see Box on COVID-19, chapter 1). However, these changes will require growth of infrastructure for better ICT bandwidths in developing countries, and better provision for micro-mobility in all cities.

Shift - Mode choice for urban and intercity transport: Shifting demand patterns (as opposed to avoiding demand) can be particularly important in decarbonising the transport sector. As a result, the cross-elasticity of demand across transport modes is of particular interest for understanding the opportunities for modal shift. The cross-elasticity represents the demand effect on mode i (e.g. bus) when an attribute of mode j (e.g. rail) changes marginally. Studies on the cross-elasticities of mode choice for urban travel suggest that the cross-elasticity for car demand is low, but the cross-elasticities of walking, bus, and rail with respect to cars are relatively large (Fearnley et al. 2017; Wardman et al. 2018). In practice, these cross-elasticities suggest that car drivers are not very responsive to increased prices for public transit, but transit users are responsive to reductions in the cost of driving. When looking at the cross-elasticities of public transit options (bus vs. metro vs. rail), research suggests that consumers are particularly sensitive to in-vehicle and waiting time when choosing public transit modes (Fearnley et al. 2018). These general results provide additional evidence that increasing the use of active and public transport requires interventions that make car use more expensive while making public transit more convenient (e.g. with smart apps that explain the exact time for transit arrival, see Box 10.1).

The literature on mode competition for intercity travel reveals that while cost of travel is a significant factor (Zhang et al. 2017), sensitivity decreases with increasing income as well as when the cost of the trip was paid by someone else (Capurso et al. 2019). Some research suggests little competition between bus and air travel but the cross-elasticity between air and rail suggest strong interactions (Wardman et al. 2018). Price reduction strategies such as discounted rail fares could enhance the switch from air travel to high-speed rail. Both air fares and flight frequency impact high speed rail (HSR) usage (Zhang et al. 2019b). Airline companies reduce fares on routes that are directly competing with HSR (Bergantino et al. 2018a) and charge high fares on non-HSR routes (Xia and Zhang 2016). On the Rome-Milan route, better frequency and connections, and low costs of HSR resulting from competition between HSR companies has significantly reduced air travel and shares of buses and cars (Desmaris and Croccolo 2018).

Finally, and as noted in Chapter 5, recent research shows that individual, social, and infrastructure factors also affect people's mode choices. For example, perceptions about common travel behaviour (what people perceive to be "normal" behaviour) influences their travel mode choice. The research suggests that well-informed individuals whose personal norms match low-carbon objectives, and who believe they have control over their decisions are most motivated to shift mode. Nonetheless, such individual and social norms can only marginally influence mode choice unless infrastructure factors can enable reasonable time and cost savings (Convery and Williams 2019; Javaid et al. 2020; Feng et al. 2020; Wang et al. 2021).

Improve – consumer preferences for improved and alternative vehicles: While reductions in demand for travel and changes in the mode choice can contribute to reducing GHG emissions from the transport sector, cars are likely to continue to play a prominent role. As a result, improving the performance of cars will be crucial for the decarbonisation of the transport sector. Sections 10.3 and 10.4 describe the technological options available for reduced CO_2 emissions from vehicles. The effectiveness in deploying such technologies will partly depend on consumer preferences and their effect on adoption rates. Given the expanded availability of electric vehicles, there is also a growing body of work on the drivers of vehicle choice. A survey in Nanjing found women had more diverse travel purposes than men, resulting in a greater acceptance of electric bikes (Lin et al. 2017). Individuals are more likely to adopt an electric vehicle (EV) when they think this adoption benefits the environment or implies a positive personal attribute (Noppers et al. 2014, 2015; Haustein and Jensen 2018). Other work suggests that people's preference for EVs depends upon vehicle attributes, infrastructure availability, and policies that promote EV adoption, specifically, purchasing and operating costs, driving range, charging duration, vehicle performance, and brand diversity (Liao et al. 2016). Behaviour change to enable transport transformations will need to make the most of these factors whilst also working on the more structural issues of time, space, and cost.

10.2.3 New demand concepts

Structural and behavioural choices that drive transport-related GHG emissions, such as time and cost based on geography of freight and urban fabric, are likely to continue to be major factors. But there is also a variation within each structural choice that is based around personal demand factors related to values that indirectly change choices in transport. Chapter 5 identified three megatrends that affect demand for services, including circular economy, the shared economy, and digitalisation. These three megatrends can have specific effect on transport emissions, as described below.

Circular Economy: The problem of resources and their environmental impacts is driving the move to a circular economy (Bleischwitz et al. 2017). Circular economy principles include increased material efficiency, re-using or extending product lifetimes, recycling, and green logistics. Dematerialisation, the reduction in the quantity of the materials used in the production of one unit of output, is a circular economy principle that can affect the operations and emissions of the transport sector, as reductions in the quantities of materials used reduces transport needs, while reductions in the weight of products improves the efficiency of transporting them. Dematerialisation can occur through more efficient production processes but also when a new product is developed to provide the same functionality as multiple products. The best example of this trend is a smart phone, which provides the service of at least 22 other former devices (Rivkin 2019). A move to declutter lifestyles can also drive dematerialisation (Whitmarsh et al. 2017). Some potential for dematerialisation has been suggested due to 3-D printing, which would also reduce transport emissions through localised production of product components (d'Aveni 2015; UNCTAD 2018). There is evidence to suggest, however, that reductions in material use resulting from more efficient product design or manufacturing are offset by increased consumer demand (Kasulaitis et al. 2019). Whether or not dematerialisation can lead to reduction of emissions from the transport sector is still an open questions that requires evaluating the entire product ecosystem (Van Loon et al. 2014; Coroama et al. 2015; Kasulaitis et al. 2019).

Shared Economy. Shared mobility is arguably the most rapidly growing and evolving sector of the sharing economy and includes bike sharing, e-scooter sharing, car-sharing, and on-demand mobility (Greenblatt and Shaheen 2015). The values of creating a more shared economy are related to both reduced demand and greater efficiency, as well as the notion of community well-being associated with the act of sharing instead of simply owning for oneself (Maginn et al. 2018; Sharp 2018). The literature on shared mobility is expanding, but there is much uncertainty about the effect shared mobility will have on transport demand and associated emissions (Nijland and Jordy 2017; ITF 2018a; Tikoudis et al. 2021).

Asia represents the largest car-sharing region with 58% of worldwide membership and 43% of global fleets deployed (Dhar et al. 2020). Europe accounts for 29% of worldwide members and 37% of shared vehicle fleets (Shaheen et al. 2018). Ride-sourcing and carpooling systems are amongst the many new entrants in the short-term shared mobility options. On-demand transport options complemented with technology have enhanced the possibility of upscaling (Alonso-González et al. 2018). Car-sharing could provide the same level of service as taxis, but taxis could be three times more expensive (Cuevas et al. 2016). The sharing economy, as an emerging economic-technological phenomenon (Kaplan and Haenlein 2010), is likely to be a key driver of demand for transport of goods although data shows increasing container movement due to online shopping (Suel and Polak 2018).

There is growing evidence that this more structured form of behavioural change through shared economy practices, supported by a larger group than a single family, has a much greater potential to save transport emissions, especially when complemented with decarbonised grid electricity (Greenblatt and Shaheen 2015; Sharp 2018). Carpooling, for example, could result in an 11% reduction in vkm and a 12% reduction in emissions, as carpooling requires less empty or non-productive passenger-kilometres (pkm) (ITF 2020a,b). However, the use of local shared mobility systems such as on-demand transport may create more transport emissions if there is an overall modal shift out of transit (ITF 2018a; Schaller 2018). Similarly, some work suggests that commercial shared vehicle services such as Uber and Lyft are leading to increased vehicle kms travelled (and associated GHG emissions) in part due to deadheading (Schaller 2018; Tirachini and Gomez-Lobo 2020; Ward et al. 2021). Successful providers compete by optimising personal comfort and convenience rather than enabling a sharing culture (Eckhardt and Bardhi 2015), and concerns have been raised regarding the wider societal impacts of these systems and for specific user groups such as older people (Fitt 2018; Marsden 2018). Concerns have also been expressed over the financial viability of demand-responsive transport systems (Ryley et al. 2014; Marsden 2018), how the mainstreaming of shared mobility systems can be institutionalised equitably, and the operation and governance of existing systems that are only mode and operator-focused (Akyelken et al. 2018; Jittrapirom et al. 2018; Pangbourne et al. 2020; Marsden 2018).

Digitalisation: In the context of the transport sector, digitalisation has enabled teleworking, which in turn reduces travel demand. On the other hand, the prevalence of online shopping, enabled by the digital economy, could have mixed effects on transport emissions (Le et al. 2021). For example, online shopping could reduce vkm travelled but the move to expedited or rush delivery could mitigate some benefits as they prevent consolidation of freight (Jaller and Pahwa 2020).

Digitalisation could also lead to systemic changes by enabling smart mobility. The smart mobility paradigm refers to the process and practices of assimilation of ICTs and other sophisticated hi-technology innovations into transport (Noy and Givoni 2018). Smart mobility can be used to influence transport demand and efficiency (Benevolo et al. 2016). The synergies of emerging technologies (ICT, IOT, Big Data) and shared economy could overcome some of the challenges facing the adoption of emerging technologies (Marletto 2014; Chen et al. 2016; Weiss et al. 2018; Taiebat and Xu 2019) and enable the expected large growth in emerging cities to be more sustainable (Docherty et al. 2018). However, ICT, in particular IoT, could also cause more global energy demand (Hittinger and Jaramillo 2019). Box 10.1 summarises the main smart technologies being adopted rapidly by cities across the world and their use in transport. There is a growing body of literature about the effect of smart technology (including sensors guiding vehicles) on the demand for transport services. Smart technologies can improve competitiveness of transit and active transport over personal vehicle use by combining the introduction of new electro-mobility that improves time and cost along with behaviour change factors (Henrik et al. 2017; SLoCaT 2018a,b, 2021). However, it is unclear what will be the net effect of smart technology on the GHG emissions from the transport sector (Debnath et al. 2014; Lenz and Heinrichs 2017).

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Box 10.1 Smart city technologies and transport

Information and Communication Technology (ICT): ICT is at the core of Smart Mobility and will provide the avenue for data to be collected and shared across the mobility system. The use of ICT can help cities by providing real-time information on mobility options that can inform private vehicles along with transit users or those using bikes, or who are walking. ICT can help with ticketing and payment for transit or for road user charges (Tafidis et al. 2017; Gössling 2018) when combined with other technologies such as Blockchain (Hargroves et al. 2020).

Internet of Things (IoT) Sensors: Sensors can be used to collect data to improve road safety, improve fuel efficiency of vehicles, and reduce CO_2 emissions (Kubba and Jiang 2014; Kavitha et al. 2018). Sensors can also provide data to digitally simulate transport planning options, inform the greater utilisation of existing infrastructure and modal interconnections, and significantly improve disaster and emergency responses (Hargroves et al. 2017). In particular, IoT sensors can be used to inform the operation of fast-moving Trackless Tram and its associated last mile connectivity shuttles as part of a transit activated corridor (Newman et al. 2019, 2021).

Mobility as a Service (MaaS): New, app-based mobility platforms will allow for the integration of different transport modes (such as last mile travel, shared transit, and even micro-transit such as scooters or bikes) into easy-to-use platforms. By integrating these modes, users will be able to navigate from A to B to C based on which modes are most efficient with the necessary bookings and payments being made through the one service. With smart city planning, these platforms can steer users towards shared and rapid-transit (which should be the centre-piece of these systems), rather than encourage more people to opt for the perceived convenience of booking a single-passenger ride (Becker et al. 2020). In low density car-dependent cities, however, MaaS services such as the use of electric scooters/bikes are less effective as the distances are too long and they do not enable the easy sharing that can happen in dense station precincts (Jittrapirom et al. 2017).

Artificial Intelligence (AI) and Big Data Analytics: The rapidly growing level of technology enablement of vehicles and urban infrastructure, combined with the growing ability to analyse larger and larger data sets, presents a significant opportunity for transport planning, design, and operation in the future. These technologies are used together to enable decisions about what kind of transport planning is used down particular corridors. Options such as predictive congestion management of roads and freeways, simulating planning options, and advanced shared transit scheduling can provide value to new and existing transit systems (Toole et al. 2015; Anda et al. 2017; Hargroves et al. 2017).

Blockchain or Distributed Ledger Technology: Blockchain Technology provides a non-hackable database that can be programmed to enable shared services like a local, solar microgrid where both solar and shared electric vehicles can be managed (Green and Newman 2017). Blockchain can be used for many transport-related applications including being the basis of MaaS or any local shared mobility service as it facilitates shared activity without intermediary controls. Other applications include verified vehicle ownership documentation, establishing identification, real-time road user pricing, congestion zone charging, vehicle generated collision information, collection of tolls and charges, enhanced freight tracking and authenticity, and automated car parking and payments (Hargroves et al. 2020). This type of functionality will be particularly valuable for urban regeneration along a transit-activated corridor where it can be used for managing shared solar in and around station precincts as well as managing shared vehicles linked to the whole transport system (Newman et al. 2021). This technology can also be used for road user charging along any corridor and by businesses accessing any services and in managing freight (Carter and Koh 2018; Nguyen et al. 2019; Sedlmeir et al. 2020; Hargroves et al. 2020).

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Autonomous vehicles are the other emerging transport technology that have the potential to significantly improve ride quality and safety. Planes and high-speed trains are already largely autonomous as they are guided in all their movements, especially coming into stations and airports, although that does not necessarily mean they are driverless. Automation is also being used in new on-road transit systems like Trackless Trams (Ndlovu and Newman 2020)). Private vehicles are being fitted with more and more levels of autonomy and many are being trialled as 'driverless' in cities (Aria et al. 2016; Skeete 2018). If autonomous systems can be used to help on-road transit become more time and cost competitive with cars, then the kind of transformative and disruptive changes needed to assist decarbonisation of transport become more feasible (Bösch et al. 2018; Kassens-Noor et al. 2020; Abe 2021). Similarly, vehicle automation could improve vehicle efficiency and reduce congestion, which would in turn reduce emissions (Vahidi and Sciarretta 2018; Massar et al. 2021). On the other hand, if autonomous cars make driving more convenient, they could reduce demand for transit (Auld et al. 2017; Sonnleitner et al. 2021). Paradoxically, autonomous cars could provide access to marginal groups such as the elderly, people with disabilities, and those who cannot drive, which could in turn increase travel demand (as measured by pkm) (Harper et al. 2016).

Heavy haulage trucks in the mining industry are already autonomous (Gaber et al. 2021) and automation of long-haul trucks may happen sooner than automation of LDVs (Hancock et al. 2019). Autonomous trucks may facilitate route, speed optimisation, and reduced fuel use, which can in turn reduce emissions (Nasri et al. 2018; Paddeu and Denby 2021). There is growing interest in using drones for package delivery. Drones could have lower impacts than ground-based delivery and, if deployed carefully, drones could reduce energy use and GHG emissions from freight transport (Stolaroff et al. 2018). Overall, some commentators are optimistic that smart and autonomous technologies can transform the GHG from the transport sector (Seba 2014; Rivkin 2019; Sedlmeir et al. 2020). Others are more sanguine unless policy interventions can enable the technologies to be used for purposes that include zero carbon and the SDGs (Faisal et al. 2019; Hancock et al. 2019).

10.2.4 Overall perspectives on systemic change

The interactions between systemic factors set out here and technology factors discussed in much more detail in the next sections, show that there is always going to be a need to integrate both approaches. Good technology that has the potential to transform transport will not be used unless it fulfils broad mobility and accessibility objectives related to time, cost, and well-being. Chapter 5 has set out three transport transformations based on demand-side factors with highly transformative potential. Table 10.3 provides a summary of these systemic changes and their likely impact on GHG emissions. Note that the quantitative estimates provided in the table may not be additive and the combined effect of these strategies on GHG emissions from the transport sector require additional analysis.

Table 10.3 Components of systemic change and their impacts on the transport sector

Systemic Change	**Mechanisms through which it affects emissions in transport sector and likely impact on emissions**
Changes in urban form	Denser, more compact polycentric cities with mixed land use patterns can reduce the distance between where people live, work, and pursue leisure activities, which can reduce travel demand. Case studies suggest that these changes in urban form could reduce transport-related GHG emissions between 4-25%, depending on the setting (Creutzig et al. 2015a,b; Pan et al. 2020).
Investments in transit and active transport infrastructure	Improving public transit systems and building infrastructure to support active transport modes (walking and biking) could reduce car travel. Case studies suggest that active mobility could reduce emissions from urban transport by 2%-10% depending on the setting (Creutzig et al. 2016; Zahabi et al. 2016; Keall et al. 2018; Gilby et al. 2019; Neves and Brand 2019; Bagheri et al. 2020; Ivanova et al. 2020; Brand et al. 2021). A shift to public transit modes can likely offer significant emissions reductions, but estimates are uncertain.
Changes in economic structures	Higher demand as a result of higher incomes could increase emissions, particularly in aviation and shipping. Higher prices could have the opposite effect and reduce emission. Structural changes associated with financial crises, pandemics, or the impacts of climate change could affect the elasticity of demand in uncertain ways. Thus, the effect of changes in economic structures on the GHG emissions from the transport sectors is uncertain.
Teleworking	A move towards a digital economy that allows workers to work remotely and access information remotely could reduce travel demand. Case studies suggest that teleworking could reduce transport emissions by 20% in some instances, but are likely 1%, at most, across the entire transport system (Roth et al. 2008; O'Keefe et al. 2016; Shabanpour et al. 2018; O'Brien and Aliabadi 2020).
Dematerialisation of the economy	A reduction in goods needed due to combining multiple functions into one device would reduce the need for transport. Reduced weights associated with dematerialisation would improve the efficiency of freight transport. However, emissions reductions from these efforts are likely dwarfed by increased consumption of goods.
Supply chain management	Supply chains could be optimised to reduce the movement or travel distance of product components. Logistics planning could optimise the use of transport infrastructure to increase utilization rates and decrease travel. The effect of these strategies on the GHG emissions from the transport sector is uncertain.
e-commerce	The effect of e-commerce on transport emissions is uncertain. Increased e-commerce would reduce demand for trips to stores but could increase demand for freight transport (particularly last-mile delivery) (Jaller and Pahwa 2020; Le et al. 2021).
Smart mobility	ICT and smart city technologies can be used to improve the efficiency of operating the transport system. Furthermore, smart technologies can improve competitiveness of transit and active transport over personal vehicle use by streamlining mobility options to compete with private cars. The effect of smart mobility on the GHG emissions from the transport sector is uncertain (Creutzig 2021).

Shared mobility	Shared mobility could increase utilisation rates of LDVs, thus improving the efficiency of the system. However, shared mobility could also divert users from transit systems or active transport modes. Studies on ride-sourcing have reported both potential for reductions and increases in transport-related emissions (Schaller 2018; Ward et al. 2021). Other case studies suggests that carpooling to replace 20% of private car trips could result in a 12% reduction in GHG (ITF 2020a,b).Thus, the effect of shared mobility on transport-related GHG emissions is highly uncertain.
Vehicle automation	Vehicle automation could have positive or negative effects on emissions. Improved transit operations, more efficient traffic management, and better routing for light- and heavy-duty transport could reduce emissions (Vahidi and Sciarretta 2018; Nasri et al. 2018; Massar et al. 2021; Paddeu and Denby 2021). However, autonomous cars could make car travel more convenient, removing users from transit systems and increasing access to marginalised groups, which would in turn increase vkms travelled (Harper et al. 2016; Auld et al. 2017; Sonnleitner et al. 2021). Drones could reduce energy use and GHG emissions from freight transport (Stolaroff et al. 2018)

10.3 Transport technology innovations for decarbonisation

This section focuses on vehicle technology and low-carbon fuel innovations to support decarbonisation of the transport sector. Figure 10.2 summarises the major pathways reviewed in this section. The advancements in energy carriers described in Figure 10.2 are discussed in greater detail in Chapter 6 (Energy) and Chapter 11 (Industry) but the review presented in this chapter highlights their application in the transport sector. This section pays attention to the advancements in alternative fuels, electric, and fuel cell technologies since AR5.

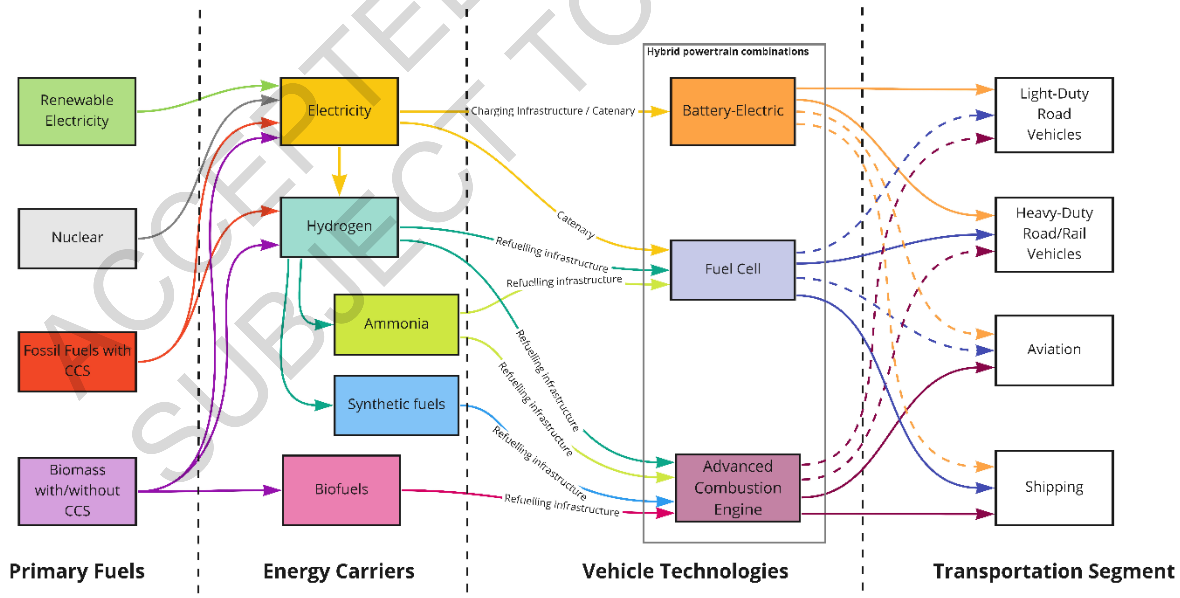


Figure 10.2 Energy pathways for low-carbon transport technologies. Primary energy sources are shown in the far left, while the segments of the transport system are in the far right. Energy carriers and vehicle technologies are represented in the middle. Primary pathways are shown with solid lines, while dashed lined represent secondary pathways.

10.3.1 Alternative fuels – an option for decarbonising internal combustion engines

The average fuel consumption of new Internal Combustion Engine (ICE) vehicles has improved significantly in recent years due to more stringent emission regulations. However, improvements are now slowing down. The average fuel consumption of LDVs decreased by only 0.7 % between 2016 and 2017, reaching 7.2 litres of gasoline-equivalent (Lge) per 100 km in 2017, much slower than the 1.8 % improvement per year between 2005 and 2016 (GFEI 2020). Table 10.4 summarises recent and forthcoming improvements to ICE technologies and their effect on emissions from these vehicles. However, these improvements are not sufficient to meet deep decarbonisation levels in the transport sector. While there is significant and growing interest in electric and fuel-cell vehicles, future scenarios indicate that a large number of LDV may continue to be operated by ICE in conventional, hybrid, and plug-in hybrid configurations over the next 30 years (IEA 2019a) unless they are regulated away through ICE vehicle sales bans (as some nations have announced) (IEA 2021a). Moreover, ICE technologies are likely to remain the prevalent options for shipping and aviation. Thus, reducing CO_2 and other emissions from ICEs through the use of low-carbon or zero-carbon fuels is essential to a balanced strategy for limiting atmospheric pollutant levels. Such alternative fuels for ICE vehicles include natural gas-based fuels, biofuels, Ammonia, and other synthetic fuels.

Table 10.4 Engine technologies to reduce emissions from light-duty ICE vehicles and their implementation stage. Table nomenclature: GDI = Gasoline direct injection, VVT = Variable valve technology, CDA = Cylinder deactivation, CR = compression ratio, GDCI = Gasoline direct injection compression ignition, EGR = exhaust gas recirculation, RCCI = Reactivity controlled compression ignition, GCI = Gasoline compression ignition. Source: (Joshi 2020)

Implementation Stage	Engine Technology	CO_2 Reduction (%)
Implemented	Baseline: GDI, turbo, stoichiometry.	0
Development	Atkinson cycle (+ VVT)	3 - 5
	Dynamic CDA + Mild Hybrid or Miller	10 -15
	Lean-burn GDI	10 - 20
	Variable CR	10
	Spark assisted GCI	10
	GDCI	15 - 25
	Water Injection	5 - 10
	Pre-chamber concepts	15 - 20
	Homogeneous Lean	15 - 20
	Dedicated EGR	15 - 20
	2-stroke opp. piston Diesel	25 - 35
	RCCI	20 - 30

Natural Gas: Natural gas could be used as an alternative fuel to replace gasoline and diesel. Natural gas in vehicles can be used as compressed natural gas (CNG) and liquefied natural gas (LNG). CNG is gaseous at relatively high pressure (10 to 25 MPa) and temperature (-40 to 30ºC). In contrast, LNG is used in liquid form at relatively low pressure (0.1 MPa) and temperature (-160ºC). Therefore, CNG is particularly suitable for commercial vehicles and light- to medium-duty vehicles, whereas LNG is better suited to replace diesel in HDVs (Dubov et al. 2020; Dziewiatkowski et al. 2020; Yaïci and Ribberink 2021). CNG vehicles have been widely deployed in some regions, particularly in Asian-Pacific countries. For example, there are about 6 million CNG vehicles domiciled in China, the most of any country (Qin et al. 2020). However, only 20% of vehicles that operate using CNG were originally designed as CNG vehicles, with the rest being gasoline-fuelled vehicles that have been converted to operate with CNG (Chala et al. 2018).

Natural gas-based vehicles have certain advantages over conventional fuel-powered ICE vehicles, including lower emissions of criteria air pollutants, no soot or particulate, low carbon to Hydrogen ratio, moderate noise, a wide range of flammability limits, and high-octane numbers (Kim 2019; Bayat and Ghazikhani 2020). Furthermore, the technology readiness of natural gas vehicles is very high (TRL 8-9), with direct modification of existing gasoline and diesel vehicles possible (Transport and Environment 2018; Peters et al. 2021; Sahoo and Srivastava 2021). On the other hand, methane emissions from the natural gas supply chain and tailpipe CO_2 emissions remain a significant concern (Trivedi et al. 2020). As a result, natural gas as a transition transportation fuel may be limited due to better alternative options being available and due to regulatory pressure to decarbonise the transport sector rapidly. For example, the International Maritime Office (IMO) has set a target of 40% less carbon intensity in shipping by 2030, which cannot be obtained by simply switching to natural gas.

Biofuels: Since AR5, the faster than anticipated adoption of electromobility, primarily for LDVs, has partially shifted the debate around the primary use of biofuels from land transport to the shipping and aviation sectors (Davis et al. 2018; IEA 2017a).At the same time, other studies highlight that biofuels may have to complement electromobility in road transport, particularly in developing countries, offering relevant mitigation opportunities in the short- and mid-term (up to 2050) (IEA 2021b). An important advantage of biofuels is that they can be converted into energy carriers compatible with existing technologies, including current powertrains and fuel infrastructure. Also, biofuels can diversify the supply of transport fuel, raise energy self-sufficiency in many countries, and be used as a strategy to diversify and strengthen the agro-industrial sector (Puricelli et al. 2021). The use of biofuels as a mitigation strategy is driven by a combination of factors, including not only the costs and technology readiness levels of the different biofuel conversion technologies, but also the availability and costs of both biomass feedstocks and alternative mitigation options, and the relative speed and scale of the energy transition in energy and transport sectors (Box 10.2).

START BOX HERE

Box 10.2 – Bridging land use and feedstock conversion footprints for biofuels

Under specific conditions, biofuels may represent an important climate mitigation strategy for the transport sector (Muratori et al. 2020; Daioglou et al. 2020). Both SR1.5 and SRCCL highlighted that biofuels could be associated with climate mitigation co-benefits and adverse side effects to many SDGs. These side-effects depend on context-specific conditions, including deployment scale, associated land-use changes and agricultural management practices (see Section 7.4.4 and Box 7.10 in Chapter 7). There is broad agreement in the literature that the most important factors in determining the climate footprint of biofuels are the land use and land use change characteristics associated with biofuel deployment scenarios e.g. (Elshout et al. 2015; Daioglou et al. 2020). This issue is covered in more detail in Chapter 7, Box 7.1. While the mitigation literature primarily focuses on the GHG-related climate forcings, note that land is an integral part of the climate system through multiple geophysical and geochemical mechanisms (albedo, evaporation, etc.). For example, Sections 2.2.7, 7.3.4 in the WGI report indicate that geophysical aspects of historical land use change outweigh the geochemical effects, leading to a net cooling effect. The land-related carbon footprints of biofuels presented in sections 10.4-10.6 are adopted from Chapter 7 (See section 7.4.4 and Box 7, Figure 7.1). The results show how the land-related footprint increases due to an increased outtake of biomass, as estimated with different models that rely on global supply scenarios of biomass for energy and fuel of 100 EJ. The integrated assessment models and scenarios used include the EMF 33 scenarios (IAM-EMF33), from partial models with constant land cover (PM-CLC), and from partial models with natural regrowth (PM-NGR). These results are combined with both biomass cultivation emission ranges for advanced biofuels aligned with (Edwards et al. 2017; El Akkari et al. 2018; Jeswani et al. 2020; Puricelli et al. 2021) and conversion efficiencies and conversion phase emissions as described in Table 10.5. The modelled footprints resulting from land use changes related to delivering 100 EJ of biomass at global level are in the range of 3 – 77 $gCO_2eq./MJ$ of advanced biofuel (median 38 $gCO_2eq./MJ$) at an aggregate level for IAMs and partial models, with constant land cover (Rose et al. 2020; Daioglou et al. 2020). The results for partial models with natural regrowth are much higher (91-246 $CO_2eq./MJ$ advanced biofuel. The latter ranges may appear in contrast with the results from the scenario literature in 10.7, where biofuels play a role in many scenarios compatible low warming levels. This contrast is a result of different underlying modelling practices. The general modelling approach used for the scenarios in the AR6 database accounts for the land-use change and all other GHG emissions along a given transformation trajectory, enabling assessments of the warming level incurred. The results labelled "EMF33" and "partial models with constant land cover" are obtained with this modelling approach. The results in the category "partial models with natural regrowth" attribute additional CO_2 emissions to the bioenergy system, corresponding to estimated uptake of CO_2 in a counterfactual scenario where land is not used for bioenergy, but instead subject to natural vegetation regrowth. While the partial analysis provides insights into the implications of alternative land-use strategies, such analysis does not identify the actual emissions of bioenergy production. As a result, the partial analysis is not compatible with the identification of warming levels incurred by an individual transformation trajectory, and therefore not aligned with the general approach applied for the scenarios in the AR6 database.

More details on land-use change impacts and the potential to deliver the projected demands of biofuels at the global level are further addressed in Chapter 7. While, in general, the above results cover most of the variety of GHG range intensities of biofuel options presented in the literature, the more specific LCA literature should be consulted when considering specific combinations of biomass feedstock and conversion technologies in specific regions.

END BOX HERE

Many studies have addressed the life cycle emissions of biofuel conversion pathways for land transport, aviation, and marine applications, e.g. (Edwards et al. 2017; Staples et al. 2018; Tanzer et al. 2019). Bioenergy technologies generally struggle to compete with existing fossil fuel-based ones because of the higher costs involved. However, the extent of the cost gap depends critically on the availability and costs of biomass feedstock (IEA 2021b). Ethanol from corn and sugarcane is commercially available in countries such as Brazil and the US. Biodiesel from oil crops and hydro-processed esters and fatty acids are available in various countries, notably in Europe and parts of Southeast Asia. On the infrastructure side, biomethane blending is being implemented in some regions of the US and Europe, particularly in Germany, with the help of policy measures (IEA 2021b). While many of these biofuel conversion technologies could also be implemented using seaweed feedstock options, these value chains are not yet mature (Jiang et al. 2016).

Technologies to produce advanced biofuels from lignocellulosic feedstocks have suffered from slow technology development and are still struggling to achieve full commercial scale. Their uptake is likely to require carbon pricing and/or other regulatory measures, such as clean fuel standards in the transport sector or blending mandates. Several commercial-scale advanced biofuels projects are in the pipeline in many parts of the world, encompassing a wide selection of technologies and feedstock choices, including carbon capture and sequestration (CCS) that supports carbon dioxide removal (CDR). The success of these projects is vital to moving forward the development of advanced biofuels and bringing many of the advanced biofuels' value chains closer to the market (IEA 2021b). Finally, biofuel production and distribution supply chains involve notable transport and logistical challenges that need to be overcome. (Mawhood et al. 2016; Skeer et al. 2016; IEA 2017a; Puricelli et al. 2021).

Table **10.5** summarises performance data for different biofuel technologies, while Figure 10.3 shows the technology readiness levels, which are based on (Mawhood et al. 2016; Skeer et al. 2016; IEA 2017a; Puricelli et al. 2021).

Table 10.5 Ranges of efficiency, GHG emissions, and relative costs of selected biofuel conversion technologies for road, marine, and aviation biofuels.

Main application	Conversion technology	Energy efficiency of conversion[a]	GHG emissions of conversion process ($gCO_{2eq.}/MJ_{fuel}$)[b]	Relative cost of conversion process
Road	Lignocellulosic ethanol	35%[c]	5[d]	Medium
Road/Aviation	Gasification and Fischer-Tropsch synthesis	57%[e]	<1[d]	High
Road	Ethanol from sugar and starch	60-70%[f]	1 – 31[d]	Low
Road	Biodiesel from oil crops	95%[g]	12 - 30 [d]	Low
Marine	Upgraded pyrolysis oil	30 - 61%[h]	1-4[h]	Medium
Aviation/Marine	Hydro-processed esters and fatty acids	80%[i]	3[i]	Medium
Aviation	Alcohol to jet	90%[j]	<1[k]	High
Road/Marine	Biomethane from residues	60%[l]	n.a.	Low
Marine/Aviation	Hydrothermal liquefaction	35-69%[h]	<1[h]	High
Aviation	Sugars to hydrocarbons	65%[m]	15[m]	High

Road	Gasification and syngas fermentation	40%n	30-40n	High

Notes: [a]Calculated as liquid fuels output divided by energy in feedstock entering the conversion plant; [b]GHG emission here refers only the conversion process. Impacts form the different biomass options are not included here as they are addressed in Chapter 7; [c](Olofsson et al. 2017); [d](Edwards et al. 2017); [e](Simell et al. 2014); [f](de Souza Dias et al. 2015); [g](Castanheira et al. 2015); [h](Tanzer et al. 2019); [i](Klein et al. 2018); [j](Narula et al. 2017); [k](de Jong et al. 2017); [l](Salman et al. 2017); [m](Moreira et al. 2014; Roy et al. 2015; Handler et al. 2016)

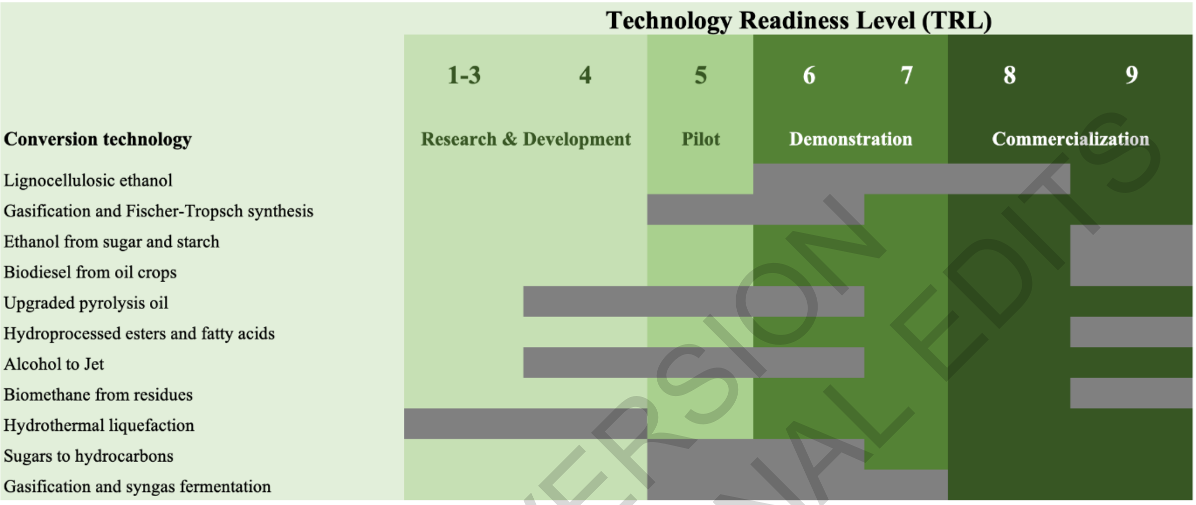


Figure 10.3 Commercialisation status of selected biofuels conversion technologies. The grey boxes represent the current TRL of each conversion technology.

Within the aviation sector, jet fuels produced from biomass resources (so-called sustainable aviation fuels, SAF) could offer significant climate mitigation opportunities under the right policy circumstances. Despite the growing interest in aviation biofuels, demand and production volumes remain negligible compared to conventional fossil aviation fuels. Nearly all flights powered by biofuels have used fuels derived from vegetable oils and fats, and the blending level of biofuels into conventional aviation fuels for testing is up to 50% today (Mawhood et al. 2016). To date, only one facility in the US is regularly producing sustainable aviation fuels based on waste oil feedstocks. The potential to scale up bio-based SAF volumes is severely restricted by the lack of low cost and sustainable feedstock options (see Chapter 7). Lignocellulosic feedstocks are considered to have a great potential for the production of financially competitive bio-based SAF in many regions. However, production facilities involve significant capital investment and estimated levelised costs are typically more than twice the selling price of conventional jet fuel. In some cases (notably for vegetable oils), the feedstock price is already higher than that of the fossil jet fuel (Mawhood et al. 2016). Some promising technological routes for producing SAF from lignocellulosic feedstocks are below technology readiness level (TRL) 6 (pilot scale) with just a few players involved in the development of these technologies. Although it would be physically possible to address the mid-century projections for substantial use of biofuels in the aviation sector (from IEA and other sectoral organisations (ICAO 2017)), this fuel deployment scale could only be achieved with very large capital investments in bi-based SAF production infrastructure, and substantial policy support.

In comparison to the aviation sector, the prospects for technology deployment are better in the shipping sector. The advantage of shipping fuels is that marine engines have a much higher operational flexibility on a mix of fuels, and shipping fuels do not need to undergo as extensive refining processes as road and aviation fuels to be considered drop-in. However, biofuels in marine engines have only been tested at an experimental or demonstration stage, leaving open the question about the scalability of the operations, including logistics issues. Similar to the aviation sector, securing a reliable, sustainable biomass feedstock supply and mature processing technologies to produce price-competitive biofuels at a large scale remains a challenge for the shipping sector (Hsieh and Felby 2017). Other drawbacks include industry concerns about oxidation, storage, and microbial stability for less purified or more crude biofuels. Assuming that biofuels are technically developed and available for the shipping sector in large quantities, a wider initial introduction of biofuels in the sector is likely to depend upon increased environmental regulation of particulate and GHG emissions. Biofuels may also may offer a significant advantage in meeting ambitious sulphur emission reduction targets set by the sectoral organisations. More extensive use of marine biofuels will most likely be first implemented in inner-city waterways, inland river freight routes, and coastal green zones. Given the high efficiency of the diesel engine, a large-scale switch to a different standard marine propulsion method in the near to medium-term future seems unlikely. Thus, much of the effort has been placed on developing biofuels compatible with diesel engines. So far, biodiesel blends look promising, as used in land transport. Hydrotreated vegetable oil (HVO) is also a technically good alternative and is compatible with current engines and supply chains, while the introduction of multifuel engines may open the market for ethanol fuels (Hsieh and Felby 2017).

Ammonia: At room temperature and atmospheric pressure, Ammonia is a colourless gas with a distinct odour. Due to relatively mild conditions for liquefaction, Ammonia is transferred and stored as a liquefied or compressed gas and has been used as an essential industrial chemical resource for many products. In addition, since the chemical structure of Ammonia is without carbon molecules, Ammonia has attracted attention as a carbon-neutral fuel that can also improve combustion efficiency (Gill et al. 2012). Furthermore, Ammonia could also serve as a Hydrogen carrier and used in fuel cells. These characteristics have driven increased interest in the low-carbon production of Ammonia, which would have to be coupled to low-carbon Hydrogen production (with low-carbon electricity providing the needed energy or with CCS).

For conventional internal combustion engines, the use of Ammonia remains challenging due to the relatively low burning velocity and high ignition temperature. Therefore, Frigo and Gentili (2014) have suggested a dual-fuelled spark-ignition engine operated by liquid Ammonia and Hydrogen, where Hydrogen is generated from Ammonia using the thermal energy of exhaust gas. On the other hand, the high-octane number of Ammonia means good knocking resistance of spark ignition engines and is promising for improving thermal efficiency. For compression ignition engines, the high-ignition temperature of Ammonia requires a high compression ratio causing an increase in mechanical friction. Since Gray et al. (1966), many studies have shown that the compression ratio can be reduced by mixing combustion with secondary fuels such as diesel and Hydrogen with low self-ignition temperatures, as summarised by Dimitriou and Javaid (2020). Using a secondary fuel with a high cetane number and the adoption of a suitable fuel injection timing has enabled highly efficient combustion of compression ignition engines in the dual fuel mode with Ammonia ratios up to 95% (Dimitriou and Javaid 2020). One major challenge for realising an Ammonia-fuelled engine is the reduction of unburned Ammonia, as described in Section 6.4.5. (Reiter and Kong 2011). Processes being examined include the use of exhaust gas recirculation (EGR) (Pochet et al. 2017) and after treatment systems. However, these processes require space, which is a constraint for LDVs and air transport but more practical for ships. Shipbuilders are developing an Ammonia engine based on the existing diesel dual-fuel engine to launch a service in 2025 (Brown 2019; MAN-ES 2019). Ammonia could therefore contribute significantly to decarbonisation in the shipping sector (as expanded in section 10.6) with potential niche applications elsewhere.

Synthetic fuels: Synthetic fuels can contribute to transport decarbonisation through synthesis from electrolytic Hydrogen produced with low carbon electricity or Hydrogen produced with CCS, and captured CO_2 using the Fischer-Tropsch process (Liu et al. 2020a). Due to similar properties of synthetic fuels to those of fossil fuels, synthetic fuels can reduce GHG emissions in both existing and new vehicles without significant changes to the engine design. While the Fischer-Tropsch process is a well-established technology (Liu et al. 2020a), low-carbon synthetic fuel production is still in the demonstration stage. Even though their production costs are expected to decline in the future due to lower renewable electricity prices, increased scale of production, and learning effects, synthetic fuels are still up to 3 times more expensive than conventional fossil fuels (Section 6.6.2.4). Furthermore, since the production of synthetic fuels involves thermodynamic conversion loss, there is a concern that the total energy efficiency is lower than that of electric vehicles (Soler 2019). Given these high costs and limited scales, the adoption of synthetic fuels will likely focus on the aviation, shipping, and long-distance road transport segments, where decarbonisation by electrification is more challenging. In particular, synthetic fuels are considered promising as an aviation fuel (as expanded in section 10.5).

10.3.2 Electric technologies

Widespread electrification of the transport sector is likely crucial for reducing transport emissions and depends on appropriate energy storage systems (EES). However, large-scale diffusion of EES depends on improvements in energy density (energy stored per unit volume), specific energy (energy stored per unit weight), and costs (Cano et al. 2018). Recent trends suggest EES-enabled vehicles are on a path of becoming the leading technology for LDVs, but their contribution to heavy-duty freight is more uncertain.

Electrochemical storage of light and medium-duty vehicles: Electrochemical storage, i.e., batteries, are one of the most promising forms of energy storage for the transport sector and have dramatically improved in their commerciality since AR5. Rechargeable batteries are of primary interest for applications within the transport sector, with a range of mature and emerging chemistries able to support the electrification of vehicles. The most significant change since AR5 and SPR1.5 is the dramatic rise in lithium-ion batteries (LIB), which has enabled electromobility to become a major feature of decarbonisation.

Before the recent growth in market share of LIBs, lead-acid batteries, nickel batteries, high-temperature sodium batteries, and redox flow batteries were of particular interest for the transport sector (Placke et al. 2017). Due to their low costs, lead-acid batteries have been used in smaller automotive vehicles, e.g. e-scooters and e-rickshaws (Dhar et al. 2017). However, their application in electric vehicles will be limited due to their low specific energy (Andwari et al. 2017). Nickel-metal hydride (NiMH) batteries have a better energy density than lead-acid batteries and have been well-optimised for regenerative braking (Cano et al. 2018). As a result, NiMH batteries were the battery of choice for hybrid electric vehicles (HEVs). Ni-Cadmium (NiCd) batteries have energy densities lower than NiMH batteries and cost around ten times more than lead-acid batteries (Table 6.5, Chapter 6). For this reason, NiCd batteries do not have major prospects within automotive applications. There are also no examples of high-temperature sodium or redox flow batteries being used within automotive applications.

Commercial application of LIBs in automotive applications started around 2000 when the price of LIBs was more than 1,000 USD per kWh (Schmidt et al. 2017). By 2020, the battery manufacturing capacity for automotive applications was around 300 GWh per year (IEA 2021a). Furthermore, by 2020, the average battery pack cost had come down to 137 USD per kWh, a reduction of 89% in real terms since 2010 (Henze 2020). Further improvements in specific energy, energy density (Nykvist et al. 2015; Placke et al. 2017) and battery service life (Liu et al. 2017) of LIBs are expected through additional design optimisation (Table 6.5, Chapter 6). These advancements are expected to lead to EVs with even longer driving ranges, further supporting the uptake of LIBs for transport applications (Cano et al. 2018). However, the performance of LIBs under freezing and high temperatures is a concern (Liu et al.

2017) for reliability. Auto manufacturers have some pre-heating systems for batteries to see that they perform well in very cold conditions (Wu et al. 2020).

For EVs sold in 2018, the material demand was about 11 kilotonnes (kt) of optimised lithium, 15 kt of cobalt, 11 kt of manganese, and 34 kt of nickel (IEA 2019a, 2021a). IEA projections for 2030 in the EV 30@30 scenario show that the demand for these materials would increase by 30 times for lithium and around 25 times for cobalt. While there are efforts to move away from expensive materials such as cobalt (IEA 2019a, 2021a), dependence on lithium will remain, which may be a cause of concern (Olivetti et al. 2017; You and Manthiram 2018). A more detailed discussion on resource constraints for lithium is provided in Box 10.6 on critical materials.

Externalities from resource extraction are another concern, though current volumes of lithium are much smaller than other metals (steel, aluminium). As a result, lithium was not even mentioned in the global resource outlook of UNEP (IRP 2019). Nonetheless, it is essential to manage demand and limit externalities since the demand for lithium is going to increase many times in the future. Reuse of LIBs used in EVs for stationary energy applications can help in reducing the demand for LIBs. However, the main challenges are the difficulty in accessing the information on the health of batteries to be recycled and technical problems in remanufacturing the batteries for their second life (Ahmadi et al. 2017). Recycling lithium from used batteries could be another possible supply source (Winslow et al. 2018). While further R&D is required for commercialisation (Ling et al., 2018), recent efforts at recycling LIBs are very encouraging (Ma et al. 2021). The standardisation of battery modules and packaging within and across vehicle platforms, increased focus on design for recyclability, and supportive regulation are important to enable higher recycling rates for LIBs (Harper et al. 2019).

Several next-generation battery chemistries are often referred to as post-LIBs (Placke et al. 2017). These chemistries include metal-sulphur, metal-air, metal-ion (besides Li) and all-solid-state batteries (ASSB). The long development cycles of the automotive industry (Cano et al. 2018) and the advantages of LIBs in terms of energy density and cycle life (Table 6.5, Chapter 6) mean that it is unlikely that post-LIB technologies will replace LIBs in the next decade. However, lithium-sulphur, lithium-air, and zinc-air have emerged as potential alternatives for LIBs. These emerging chemistries may also be used to supplement LIBs in dual-battery configurations, to extend the driving range at lower costs or with higher energy density (Cano et al. 2018). Lithium-sulphur (Li-S) batteries have a lithium metal anode with a higher theoretical capacity than lithium-ion anodes and much lower cost sulphur cathodes relative to typical Li-ion insertion cathodes (Manthiram et al. 2014). As a result, Li-S batteries are much cheaper than LIB to manufacture and have a higher energy density (Table 6.5, Chapter 6). Conversely, these batteries face challenges from sulphur cathodes, such as low conductivity of the sulphur and lithium sulphide phases, and the relatively high solubility of sulphur species in common lithium battery electrolytes, leading to low cycle life (Cano et al. 2018). Lithium-air batteries offer a further improvement in specific energy and energy density above Li–S batteries owing to their use of atmospheric oxygen as a cathode in place of sulphur. However, their demonstrated cycle-life is much lower (Table 6.5, Chapter 6). Lithium-air batteries also have low specific power. Therefore, lithium-air require an extra battery for practical applications (Cano et al. 2018). Finally, zinc–air batteries could more likely be used in future EVs because of their more advanced technology status and higher practically achievable energy density (Fu et al. 2017). Like Li-air batteries, their poor specific power and energy efficiency will probably prevent zinc-air batteries from being used as a primary energy source for EVs. Still, they could be promising when used in a dual-battery configuration (Cano et al. 2018).

The technological readiness of batteries is a crucial parameter in the advancement of EVs (Manzetti and Mariasiu 2015). Energy density, power density, cycle life, calendar life, and the cost per kWh are the pertinent parameters for comparing the technological readiness of various battery technologies (Manzetti and Mariasiu 2015; Andwari et al. 2017; Lajunen et al. 2018). Table 6.5 in Chapter 6 provides a summary of the values of these parameters for alternative battery technologies. LIBs comprehensively dominate the other battery types and are at a readiness level where they can be applied for land transport applications (cars, scooters, electrically assisted cycles) and at battery pack costs below 150 USD per kWh, making EVs cost-competitive with conventional vehicles (Nykvist et al. 2019). In 2020 the stock of battery-electric LDVs had crossed the 10 million mark (IEA 2021a). (Schmidt et al. 2017) project that the cost of a battery pack for LIBs will reach 100 USD per kWh by 2030, but more recent trends show this could happen much earlier. For example, according to IEA, battery pack costs could be as low as 80 USD per kWh by 2030 (IEA 2019a). In addition, there are clear trends that now vehicle manufacturers are offering vehicles with bigger batteries, greater driving ranges, higher top speeds, faster acceleration, and all size categories (Nykvist et al. 2019). In 2020 there were over 600,000 battery-electric buses and over 31,000 battery-electric trucks operating globally (IEA 2021a).

LIBs are not currently envisaged to be suitable for long-haul transport. However, several battery technologies are under development (Table 6.5, Chapter 6), which could further enhance the competitiveness of EVs and expand their applicability to very short-haul aviation and ships, especially smaller vehicles. Li-S, Li-air, and Zn-air hold the highest potential for these segments (Cano et al. 2018). All three of these technologies rely on making use of relatively inexpensive elements, which can help bring down battery costs (Cano et al. 2018). The main challenge these technologies face is in terms of the cycle life. Out of the three, Li-S has already been used for applications in unmanned aerial vehicles (Fotouhi et al., 2017) due to relatively high specific energy (almost double the state of art LIBs). However, even with low cycle life, Li-air and Zn-air hold good prospects for commercialisation as range extender batteries for long-range road transport and with vehicles that are typically used for city driving (Cano et al. 2018).

Alternative electricity storage technologies for heavy-duty transport: While LIBs described in the previous section are driving the electrification of LDVs, their application to railways, aviation, ships, and large vehicles faces challenges due to the higher power requirements of these applications. The use of a capacitor with a higher power density than LIBs could be suitable for the electrification of such vehicles. It is one of the solutions for regenerating large and instantaneous energy from regenerative brakes. Classical capacitors generally show more attractive characteristics in power density (8,000-10,000 W/kg) than batteries. However, the energy density is poor (1-4 Wh/kg) compared to batteries, and there is an issue of self-discharge (González et al. 2016; Poonam et al. 2019). To improve the energy density, electrochemical double layer capacitors (EDLCs; supercapacitor) and hybrid capacitors (10-24 Wh/kg, 900-9000 W/kg in the product-level) such as Li-ion capacitors (LICs) have been developed. The highest energy density of the LIC system (100-140 Wh/kg in the research stage) are approaching that of the Li-ion battery systems (80-240 Wh/kg in the product stage) (Naoi et al. 2012; Panja et al. 2020). Examples of effective use of capacitors include a 12 tonne truck with a capacitor-based kinetic energy recovery system (KERS) that has been reported to save up to 32% of the fuel use of standard truck (Kamdar 2017). Similarly, an EDLC bank applied to electric railway systems has been shown to result in a 10% reduction in power consumption per day (Takahashi et al. 2017). Finally, systems in which capacitors are mounted on an electric bus for charging at a stop have been put into practical use, e.g., Trackless Tram (Newman et al. 2019). At the bus stop, the capacitor is charged at 600 kW for 10 ~ 40 seconds, which provides enough power for 5 ~ 10 km (Newman et al. 2019). In addition, more durable capacitors can achieve a longer life than LIB systems (ADB 2018).

Hybrid energy storage (HES) systems, which combine a capacitor and a battery, achieve both high power and high energy, solving problems such as capacity loss of the battery and self-discharge of the capacitor. In these systems, the capacitor absorbs the steeper power, while the LIB handles the steady power, thereby reducing the power loss of the EV to half. Furthermore, since the in-rush current of the battery is suppressed, there is an improvement in the reliability of the LIB (Noumi et al., 2014). In a hybrid diesel train, 8.2% of the regenerative energy is lost due to batteries' limited charge-discharge performance; however, using an EDLC with batteries can save this energy (Takahashi et al. 2017; Mayrink et al. 2020)

The development of power storage devices and advanced integrated system approaches, including power electronics circuits such as HES and their control technologies, are important for the electrification of mobility. These technologies are solutions that could promote the electrification of systems, reduce costs, and contribute to the social environment through multiple outcomes in the decarbonisation agenda.

10.3.3 Fuel cell technologies

In harder-to-electrify transport segments, such as heavy-duty vehicles, shipping, and aviation, Hydrogen holds significant promise for delivering emissions reductions if it is produced using low-carbon energy sources. In particular, Hydrogen fuel cells are seen as an emerging option to power larger vehicles for land-based transport (Tokimatsu et al. 2016; IPCC 2018; IEA 2019b). Despite this potential, further advancements in technological and economic maturity will be required in order for Hydrogen fuel cells to play a greater role. While this section focuses primarily on Hydrogen fuel cells, Ammonia and Methanol fuel cells may also emerge as options for low power applications.

During the last decade, Hydrogen fuel cell vehicles (HFCVs) have attracted growing attention, with fuel cell technology improving through research and development. Fuel cell systems cost 80 to 95 per cent less than they did in the early 2000s, at approximately $50 per kW for light-duty (80 kW) and $100 per kW for medium-heavy duty (160 kW). These costs are approaching the US Department of Energy's (US DOE) goal of $40 per kW in 2025 at a production target of 500,000 systems per year(IEA 2019c). In addition to cost reductions, the power density of fuel cell stacks has now reached around 3.0 kW/L, and average durability has improved to approximately 2,000-3,000 hours (Jouin et al. 2016; Kurtz et al. 2019). Despite these improvements, fuel cell systems are not yet mature for many commercial applications. For example, the US DOE has outlined that for Hydrogen fuel cell articulated trucks (semi-trailers) to compete with diesel vehicles, fuel cell durability will need to reach 30,000 hours (US DOE 2019). While some fuel cell buses have demonstrated durability close to these targets (Eudy and Post 2018a), another review of light fuel cell vehicles found maximum durability of 4,000 hours (Kurtz et al. 2019). As more fuel cell vehicles are trialled, it is expected that further real-world data will become available to track ongoing fuel cell durability improvements.

Ammonia and Methanol fuel cells are considered to be less mature than Hydrogen fuel cells. However, they offer the benefit of using a more easily transported fuel that can be directly used without converting to Hydrogen (Zhao et al. 2019). Conversely, both Methanol and Ammonia are toxic, and in the case of Methanol fuel cells, carbon dioxide is released as a by-product of generating electricity with the fuel cell (Zhao et al. 2019). Due to the lower power output, Methanol and Ammonia fuel cells are also not well-suited to heavy duty vehicles (Jeerh et al. 2021). They are therefore unlikely to compete with Hydrogen fuel cells. However, Ammonia and Methanol could be converted at refuelling stations to Hydrogen as an alternative to being directly used in fuel cells (Zhao et al. 2019).

Several FCV-related technologies are fully ready for demonstration and early market deployment, however, further research and development will be required to achieve full-scale commercialisation, likely from 2030 onwards (Staffell et al. 2019; Energy Transitions Commission 2020; IEA 2021b). Some reports argue that it may be possible to achieve serial production of fuel cell heavy-duty trucks in the late 2020s, with comparable costs to diesel vehicles achieved after 2030 (Jordbakker et al. 2018). Over the next decade or so, Hydrogen FCVs could become cost-competitive for various transport applications, potentially including long-haul trucks, marine ships, and aviation (FCHEA 2019; FCHJU 2019; BloombergNEF 2020; Hydrogen Council 2017, 2020). The speed of fuel cell system cost reduction is a key factor for achieving widespread uptake. Yet, experts disagree on the relationship between the scale of fuel cell demand, cost, and performance improvements (Cano et al. 2018). Costs of light-, medium-, and heavy-duty fuel cell powertrains have decreased by orders of magnitude with further reductions of a factor of two expected with continued technological progress (Whiston et al. 2019). For example, the costs of platinum for fuel cell stacks have decreased by an order of magnitude (Staffell et al. 2019); current generation FCVs use approximately 0.25 g/kW Pt and a further reduction of 50-80% is expected by 2030 (Hao et al. 2019).

Hydrogen is likely to take diverse roles in the future energy system: as a fuel in industry and buildings, as well as transport, and as energy storage for variable renewable electricity. Further research is required to understand better how a Hydrogen transport fuel supply system fits within the larger Hydrogen energy system, especially in terms of integration within existing infrastructure, such as the electricity grid and the natural gas pipeline system (IEA 2015).

Strong and durable policies would be needed to enable widespread use of Hydrogen as a transport fuel and to sustain momentum during a multi-decade transition period for Hydrogen FCVs to become cost-competitive with electric vehicles (IEA 2019c; FCHEA 2019; FCHJU 2019; BNEF 2020; Hydrogen Council 2017, 2020). The analysis suggests that Hydrogen is likely to have strategic and niche roles in transport, particularly in long-haul shipping and aviation. With continuing improvements, Hydrogen and electrification will likely play a role in decarbonising heavy-duty road and rail vehicles.

10.3.4 Refuelling and charging infrastructure

The transport sector relies on liquid gasoline, and diesel for land-based transport, jet fuel for aviation, and heavy fuel oil for shipping. Extensive infrastructure for refuelling liquid fossil fuels already exists. Ammonia, synthetic fuels, and biofuels have emerged as alternative fuels for powering combustion engines and turbines used in land, shipping, and aviation (Figure 10.2). Synthetic fuels such as e-Methanol and Fischer-Tropsch liquids have similar physical properties and could be used with existing fossil fuel infrastructure (Soler, 2019). Similarly, biofuels have been used in several countries together with fossil fuels (Panoutsou et al. 2021). Ammonia is a liquid, but only under pressure, and therefore will not be compatible with liquid fossil fuel refuelling infrastructure. Ammonia is, however, widely used as a fertiliser and chemical raw material and 10% of annual Ammonia production is transported via sea (Gallucci 2021). As such, a number of port facilities include Ammonia storage and transport infrastructure and the shipping industry has experience in handling Ammonia (Gallucci 2021). This infrastructure would likely need to be extended in order to support the use of Ammonia as a fuel for shipping and therefore ports are likely to be the primary sites for these new refuelling facilities.

EVs and HFCV require separate infrastructure than liquid fuels. The successful diffusion of new vehicle technologies is dependent on the preceding deployment of infrastructure (Leibowicz 2018), so that the deployment of new charging and refuelling infrastructure will be critical for supporting the uptake of emerging transport technologies like EVs and HFCVs, where it makes sense for each to be deployed. As a result, there is likely a need for the simultaneous investment in both infrastructure and vehicle technologies to accelerate decarbonisation of the transport sector.

Charging infrastructure: Charging infrastructure is important for a number of key reasons. From a consumer perspective, robust and reliable charging infrastructure networks are required to build confidence in the technology and overcome the often-cited barrier of 'range anxiety' (She et al. 2017). Range anxiety is where consumers do not have confidence that an EV will meet their driving range requirements. For LDVs, the majority of charging (75-90%) has been reported to take place at or near homes (Figenbaum 2017; Webb et al. 2019; Wenig et al. 2019). Charging at home is a particularly significant factor in the adoption of EVs as consumers are less willing to purchase an EV without home charging (Berkeley et al. 2017; Funke and Plötz 2017; Nicholas et al. 2017). However, home charging may not be an option for all consumers. For example, apartment dwellers may face specific challenges in installing charging infrastructure (Hall and Lutsey 2020). Thus, the provision of public charging infrastructure is another avenue for alleviating range anxiety, facilitating longer distance travel in EVs, and in turn, encouraging adoption (Hall and Lutsey 2017; Melliger et al. 2018; Narassimhan and Johnson 2018; Melton et al. 2020). Currently, approximately 10% of charging occurs at public locations, roughly split equally between AC (slower) and DC (fast) charging (Figenbaum 2017; Webb et al. 2019; Wenig et al. 2019). Deploying charging infrastructure at workplaces and commuter car parks is also important, particularly as these vehicles are parked at these locations for many hours. Indeed, around 15-30% of EV charging currently occurs at these locations (Figenbaum 2017; Webb et al. 2019; Wenig et al. 2019). It has been suggested that automakers and utilities could provide support for the installation of home charging infrastructure (Hardman et al. 2018), while policy-makers can provide support for public charging. Such support could come via supportive planning policy, building regulations, and financial support. Policy support could also incentivise the deployment of charging stations at workplaces and commuter car parks. Charging at these locations would have the added benefit of using excess solar energy generated during the day (Hardman et al. 2018; Webb et al. 2019).

While charging infrastructure is of high importance for the electrification of light-duty vehicles, arguably, it is even more important for heavy-duty vehicles given the costs of high-power charging infrastructure. It is estimated that the installed cost of fast-charging hardware can vary between approximately USD 45,000 to 200,000 per charger, depending on the charging rate, the number of chargers per site, and other site conditions (Nicholas 2019; Hall and Lutsey 2019; Nelder and Rogers 2019). Deployment of shared charging infrastructure at key transport hubs, such as bus and truck depots, freight distribution centres, marine shipping ports and airports, can encourage a transition to electric vehicles across the heavy transport segments. Furthermore, if charging infrastructure sites are designed to cater for both light and heavy-duty vehicles, infrastructure costs could decrease by increasing utilisation across multiple applications and/or fleets (Nelder and Rogers 2019).

There are two types of charging infrastructure for electric vehicles: conductive charging involving a physical connection and wireless/induction charging. The majority of charging infrastructure deployed today for light and heavy-duty vehicles is conductive. However, wireless charging technologies are beginning to emerge – particularly for applications like bus rapid transit – with vehicles able to charge autonomously while parked and/or in motion (IRENA 2019). For road vehicles, electric road systems, or road electrification, is also emerging as an alternative form of conductive charging infrastructure that replaces a physical plug (Ainalis et al. 2020; Hill et al. 2020). This type of charging infrastructure is particularly relevant for road freight where load demand is higher. Road electrification can take the form of a charging rail built into the road pavement, run along the side of the road, through overhead catenary power lines - similar to electrical infrastructure used for rail - or at recharging facilities at stations along the route. This infrastructure can also be used to directly power other electrified powertrains, such as hybrid and HFCV (Hardman et al. 2018; Hill et al. 2020).

Charging infrastructure also varies in terms of the level of charging power. For light vehicles, charging infrastructure is generally up to 350 kW, which provide approximately 350 kilometres for every 10 minutes of charging. For larger vehicles, like buses and trucks, charging infrastructure is generally up to 600 kW, providing around 50-100 km for every 10 minutes of charging (depending on the size of the bus/truck). Finally, even higher power charging infrastructure is currently being developed at rates greater than 1 MW, particularly for long-haul trucks and for short-haul marine shipping and aviation. For example, one of the largest electric ferries in the world, currently operating in Denmark, uses a 4.4 MW charger (Heinemann et al. 2020).

Finally, there are several different charging standards, varying across transport segments and across geographical locations. Like electrical appliances, different EV charging connectors and sockets have emerged in different regions, e.g. CCS2 in Europe (ECA 2021), GB/T in China (Hove and Sandalow 2019). Achieving interoperability between charging stations is seen as another important issue for policy-makers to address to provide transparent data to the market on where EV chargers are located and a consistent approach to paying for charging sessions (van der Kam and Bekkers 2020). Interoperability could also play an important role in enabling smart charging infrastructure (Neaimeh and Andersen 2020).

Smart charging - electric vehicle-grid integration strategies: EVs provide several opportunities for supporting electricity grids if appropriately integrated. Conversely, a lack of integration could negatively affect the grid, particularly if several vehicles are charged in parallel at higher charging rates during peak demand periods (Webb et al. 2019; Jochem et al. 2021). There are three primary approaches to EV charging. In unmanaged charging, EVs are charged ad-hoc, whenever connected, regardless of conditions on the broader electricity grid (Webb et al. 2019; Jochem et al. 2021). Second, in managed charging, EVs are charged during periods beneficial to the grid, e.g. high renewable generation and/or low demand periods. Managed charging also allows utilities to regulate the rate of charge and can thus provide frequency and regulation services to the grid (Weis et al. 2014). Finally, in bidirectional charging or vehicle-to-grid (V2G), EVs are generally subject to managed charging, but an extension provides the ability to export electricity from the vehicle's battery back to the building and/or wider electricity grid (Ercan et al. 2016; Noel et al. 2019; Jochem et al. 2021). The term 'smart charging' has become an umbrella term to encompass both managed charging (often referred to as a V1G) and vehicle-to-grid (V2G). For electric utilities, smart charging strategies can provide backup power, support load balancing, reduce peak loads (Zhuk et al. 2016; Noel et al. 2019; Jochem et al. 2021), reduce the uncertainty in forecasts of daily and hourly electrical loads (Peng et al. 2012), and allow greater utilisation of generation capacity (Hajimiragha et al. 2010; Madzharov et al. 2014).

Smart charging strategies can also enhance the climate benefits of EVs (Yuan et al. 2021). Controlled charging can help avoid high carbon electricity sources, decarbonisation of the ancillary service markets, or peak shaving of high carbon electricity sources (Jochem et al. 2021). V2G-capable EVs can result in even lower total emissions, particularly when compared to other alternatives (Reddy et al. 2016). Noel et al.(2019) analysed V2G pathways in Denmark and noted that at a penetration rate of 75% by 2030, $34 billion in social benefits could be accrued (through things like displaced pollution). These social benefits translate to $1,200 per vehicle. V2G-capable EVs were found to have the potential to reduce carbon emissions compared to a conventional gasoline vehicle by up to 59%, assuming optimised charging schedules (Hoehne and Chester 2016).

Projections of energy storage suggest smart charging strategies will come to play a significant role in future energy systems. Assessment of different energy storage technologies for Europe showed that V2G offered the most storage potential compared to other options and could account for 200 GW of installed capacity by 2060, whereas utility-scale batteries and pumped hydro storage could provide 160 GW of storage capacity (Després et al., 2017). Another study found that EVs with controlled charging (V1G) could provide similar services to stationary storage but at a far lower cost (Coignard et al. 2018). While most deployments of smart charging strategies are still at the pilot stage, the number of projects continues to expand, with the V2G Hub documenting at least 90 V2G projects across 22 countries in 2021 (Vehicle to Grid (VG) 2021). Policymakers have an important role in facilitating collaboration between vehicle manufacturers, electricity utilities, infrastructure providers, and consumers to enable smart charging strategies and ensure EVs can support grid stability and the uptake of renewable energy. This is a critical part of decarbonising transport.

Hydrogen infrastructure: HFCVs are reliant on the development of widespread and convenient Hydrogen refuelling stations (FCHEA 2019; IEA 2019c; BNEF 2020). Globally, there are around 540 Hydrogen refuelling stations, with the majority located in North America, Europe, Japan, and China (IEA 2021a). Approximately 70% of these refuelling stations are open to the public (Coignard et al. 2018). Typical refuelling stations currently have a refuelling capacity of 100 to 350 kg/day (CARB

2019, 2020; H2 Tools 2020; AFDC 2021). At most, current Hydrogen refuelling stations have daily capacities under 500 kg/day (Liu et al. 2020b).

The design of Hydrogen refuelling stations depends on the choice of methods for Hydrogen supply and delivery, compression and storage, and the dispensing strategy. Hydrogen supply could happen via on-site production or via transport and delivery of Hydrogen produced off-site. At the compression stage, Hydrogen is compressed to achieve the pressure needed for economic stationery and vehicle storage. This pressure depends on the storage strategy. Hydrogen can be stored as a liquid or a gas. Hydrogen can also be dispensed to the vehicles as a gas or a liquid, depending on the design of the vehicles (though it tests the extremes of temperature range and storage capacity for an industrial product). The technological and economic development of each of these components continues to be researched.

If Hydrogen is produced off site in a large centralised plant, it must be stored and delivered to refuelling stations. The cost of Hydrogen delivery depends on the amount of Hydrogen delivered, the delivery distance, the storage method (compressed gas or cryogenic liquid), and the delivery mode (truck vs. pipeline). Table 10.6 describes the three primary options for Hydrogen delivery. Most Hydrogen refuelling stations today are supplied by trucks and, very occasionally, Hydrogen pipelines. Gaseous tube trailers could also be used to deliver Hydrogen in the near term, or over shorter distances, due to the low fixed cost (although the variable cost is high). Both liquefied truck trailers and pipelines are recognised as options in the medium to long-term as they have higher capacities and lower costs over longer distances (FCHJU 2019; Li et al. 2020; EU 2021). Alternatively, Hydrogen can be produced on site using a small-scale onsite electrolyser or steam methane reforming unit combined with CCS. Hydrogen is generally dispensed to vehicles as a compressed gas at pressures 350 or 700 bar, or as liquified Hydrogen at – 253ºC (Hydrogen Council 2020).

Table 10.6 Overview of three transport technologies for Hydrogen delivery in the transport sector showing relative differences. Source: (IEA 2019c)

	Capacity	***Delivery distance***	***Energy loss***	***Fixed costs***	***Variable costs***	***Deployment phase***
Gaseous tube trailers	Low	Low	Low	Low	High	Near term
Liquefied truck trailers	Medium	High	High	Medium	Medium	Medium to long term
Hydrogen pipelines	High	High	Low	High	Low	Medium to long term

The costs for Hydrogen refuelling stations vary widely and remain uncertain for the future (IEA 2019c). The IEA reports that the investment cost for one Hydrogen refuelling station ranges between USD 0.6–2 million for Hydrogen at a pressure of 700 bar and a delivery capacity of 1,300 kg per day. The investment cost of Hydrogen refuelling stations with lower refuelling capacities (~50 kg H_2 per day) delivered at lower pressure (350 bar) range between USD 0.15–1.6 million. A separate estimate by the International Council for Clean Transport suggests that at a capacity of 600 kg of Hydrogen per day, the capital cost of a single refuelling station would be approximately USD 1.8 million (ICCT 2017). Given the high investment costs for Hydrogen refuelling stations, low utilisation can translate into a high price for delivered Hydrogen. In Europe, most pumps operate at less than 10% capacity. For small refuelling stations with a capacity of 50 kg H_2 per day, this utilisation rate translates to a high price of around USD 15–25 per kg H_2 – in line with current retail prices (IEA 2019c). The dispensed cost of

Hydrogen is also highly correlated with the cost of electricity, when H_2 is produced using electrolysis, which is required to produce low-carbon Hydrogen.

10.4 Decarbonisation of land-based transport

10.4.1 Light-duty vehicles for passenger transport

LDVs represent the main mode of transport for private citizens (ITF 2019) and currently represent the largest share of transport emissions globally (IEA 2019d). Currently, powertrains depending on gasoline and diesel fuels remain the dominant technology in the LDV segment (IEA 2019d). HEVs, and fully battery electric vehicles (BEVs), however, have become increasingly popular in recent years (IEA 2021a). Correspondingly, the number of life cycle assessment (LCA) studies investigating HEVs, BEVs, and fuel cell vehicles have increased. While historically the focus has been on the tailpipe emissions of LDVs, LCA studies demonstrate the importance of including emissions from the entire vehicle value chain, particularly for alternative powertrain technologies.

Figure 10.4 presents the cumulative life cycle emissions for selected powertrain technologies and fuel chain combinations for compact and mid-sized LDV. This figure summarizes the harmonized findings from the academic literature reviewed and the data submitted through an IPCC data collection effort, as described in Appendix 10.1 (Cusenza et al. 2019; Hawkins et al. 2013; Tong et al. 2015b; Bauer et al. 2015; Gao et al. 2016; Ellingsen et al. 2016; Kim and Wallington 2016; Cai et al. 2017; Ke et al. 2017; Lombardi et al. 2017; Miotti et al. 2017; Evangelisti et al. 2017; Valente et al. 2017; de Souza et al. 2018; Elgowainy et al. 2018; Luk et al. 2018; Bekel and Pauliuk 2019; Messagie et al. 2014; Hoque et al. 2019; IEA 2019a; Rosenfeld et al. 2019; Shen et al. 2019; Wang et al. 2019; Wu et al. 2019; Benajes et al. 2020; Ambrose et al. 2020; Hill et al. 2020; Knobloch et al. 2020; JEC 2020; Qiao et al. 2020; Cox et al. 2018; Sacchi 2021; Zheng et al. 2020; Wolfram et al. 2020; Valente et al. 2021). The values in the figure (and the remaining figures in this section) depend on the 100-year GWP used in each study, which may differ from the recent GWP updates from WGI. However, it is unlikely that the qualitative insights gained from the figures in this section would change using the update 100-year GWP values.

Furthermore, note that the carbon footprint of biofuels used in Figure 10.4 are aggregate numbers not specific to any individual value chain or fuel type. They are derived by combining land use-related carbon emissions from Chapter 7 with conversion efficiencies and emissions as described in Section 10.3. Specifically, land use footprints derived from the three modelling approaches employed here are: 1) Integrated Assessment Models – Energy Modelling Forum 33 (IAM EMF33); 2) Partial models assuming constant land cover (CLC), and, 3) Partial models using natural regrowth (NRG). The emissions factors used here correspond to scenarios where global production of biomass for energy purposes are 100 EJ/year, with lower emissions factors expected at lower levels of consumption and vice-versa. Further details are available in Box 10.2 and Chapter 7.

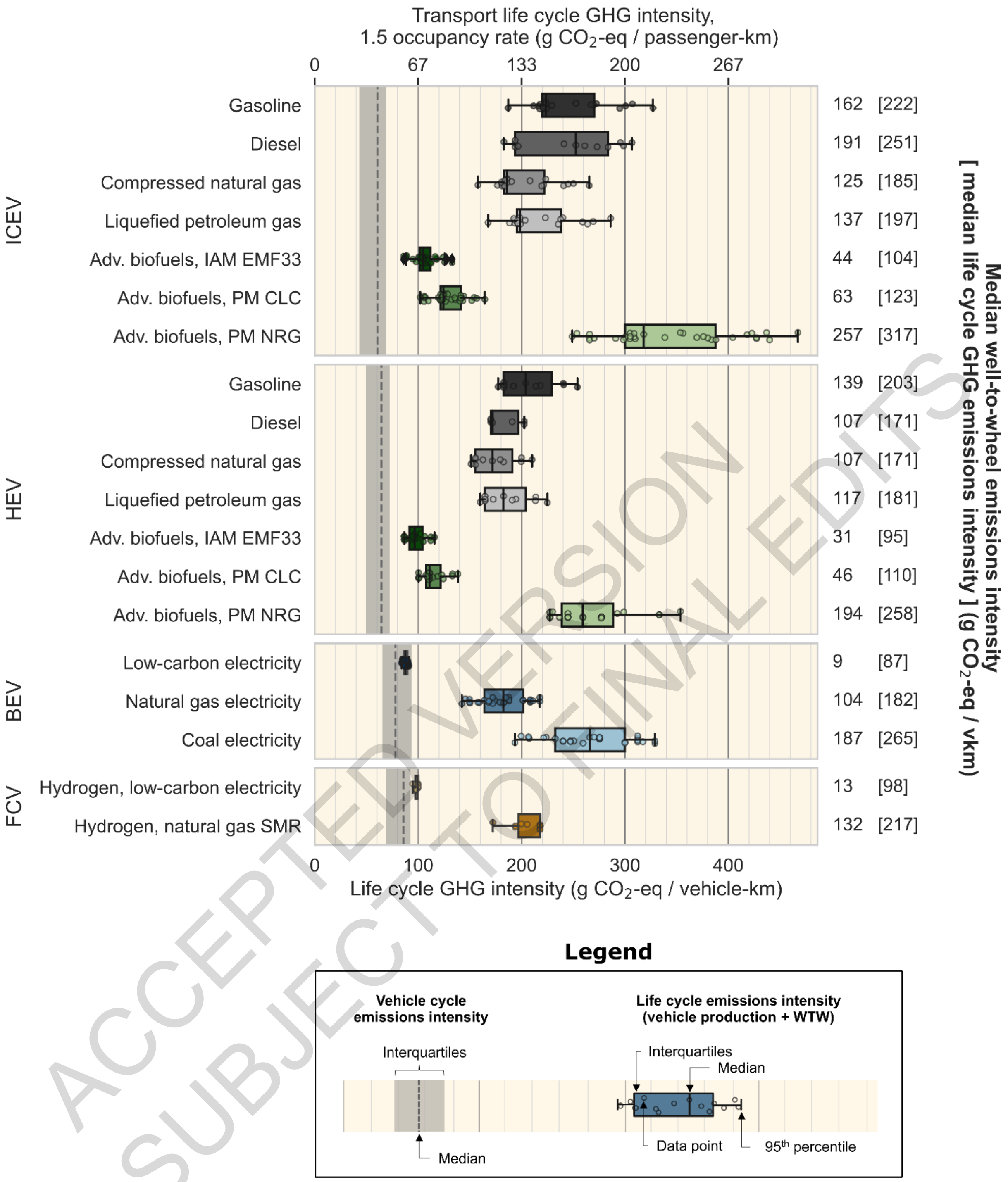


Figure 10.4 Life cycle GHG emissions intensities for mid-sized light-duty vehicle and fuel technologies from the literature. The primary x-axis reports units in g CO_2-eq vkm^{-1}, assuming a vehicle life of 180,000 km. The secondary x-axis uses units of g CO_2-eq pkm^{-1}, assuming a 1.5 occupancy rate. The values in the figure rely on the 100-year GWP value embedded in the source data, which may differ slightly with the updated 100-year GWP values from WGI. The shaded area represents the interquartile range for combined vehicle manufacturing and end-of-life phases. The length of the box and whiskers represent the interquartile range of the operation phase for different fuel chains, while their placement on the x-axis represents the absolute life cycle climate intensity, that is, includes manufacturing and end-of-life phases. Each individual marker indicates a data point. 'Adv. Biofuels' i.e., advanced biofuels, refers to the use of

second-generation biofuels and their respective conversion and cultivation emission factors. 'IAM EMF33' refers to emissions factors for advanced biofuels derived from simulation results from the integrated assessment models EMF33 scenarios. 'PM' refers to partial models, where 'CLC' is with constant land cover and 'NRG' is with natural regrowth. 'Hydrogen, low-carbon electricity' is produced via electrolysis using low-carbon electricity. 'Hydrogen, natural gas SMR' refers to fuels produced via steam methane reforming of natural gas.

The tailpipe emissions and fuel consumption reported in the literature generally do not use empirical emissions data. Rather, they tend to report fuel efficiency using driving cycles such as New European Driving Cycle (NEDC) or the US EPA Federal Test Procedure. As a result, depending on the driving cycle used, operating emissions reported in literature are possibly underestimated by as much as 15-38%, in comparison to actual real driving emissions (Fontaras et al. 2017; Tsiakmakis et al. 2017; Triantafyllopoulos et al. 2019). The extent of these underestimations, however, vary between powertrain types, engine sizes, driving behaviour and environment.

Current average life cycle impacts of mid-size ICEVs span from approximately 65 g CO_2-eq pkm^{-1} to 210 g CO_2-eq pkm^{-1}, with both values stemming from ICEVs running on biofuels. Between this range of values, the current reference technologies are found, with diesel-powered ICEVs having total median life cycle impacts of 130 g CO_2-eq pkm^{-1} and gasoline-fuelled vehicles with 160 g CO_2-eq pkm^{-1}. Fuel consumption dominates the life cycle emissions of ICEVs, with approximately 75% of these emissions arising from the tailpipe and fuel chain.

HEVs and plug-in HEVs (PHEVs) vary in terms of degree of powertrain electrification. HEVs mainly rely on regenerative braking for charging the battery. PHEVs combine regenerative braking with external power sources for charging the battery. Operating emissions intensity is highly dependent on the degree to which electrified driving is performed, which in turn is user- and route-dependent. For PHEVs, emissions intensity is also dependent on the source of the electricity for charging. HEV and PHEV production impacts are comparable to the emissions generated for producing ICEVs as the batteries are generally small compared to those of BEVs. Current HEVs may reduce emissions compared to ICEVs by up to 30%, depending on the fuel, yielding median life cycle intensities varying between 60 g CO_2-eq pkm^{-1} (biofuels, EMF33) and 165-170 g CO_2-eq pkm^{-1} (biofuels, partial models NRG). Within this wide range, all the combinations of electric/fossil driving can be found, as well as the life cycle intensity for driving 100% on fossil fuel. Because HEVs rely on combustion as the main energy conversion process, they offer limited mitigation opportunities. However, HEVs represent a suitable temporary solution, yielding a moderate mitigation potential, in areas where the electricity mix is currently so carbon intensive that the use of PHEVs and BEVs is not an effective mitigation solution (Wolfram and Wiedmann 2017; Wu et al. 2019).

In contrast to HEVs, PHEVs may provide greater opportunities for use-phase emissions reductions for LDVs. These increased potential benefits are due to the ability to charge the battery with low-carbon electricity and the longer full-electric range in comparison to HEVs (Laberteaux et al. 2019). Consumer behaviour (e.g., utility factor (UF) and charging patterns), manufacturer settings, and access to renewable electricity for charging strongly influence the total operational impacts (Wu et al, 2019). The UF is a weighting of the percentage of distance covered using the electric charge (charge depleting (CD) stage) versus the distance covered using the internal combustion engine (charge sustaining (CS) stage) (Paffumi et al. 2018). When the PHEV operates in CS mode, the internal combustion engine is used for propulsion and to maintain the state of charge of the battery within a certain range, together with regenerative braking (Plötz et al. 2018; Raghavan and Tal 2020). When running in CS mode, PHEVs have a reduced mitigation potential and have impacts comparable to those of HEVs. On the other hand, when the PHEV operates in CD mode, the battery alone provides the required propulsion energy (Plötz et al. 2018; Raghavan and Tal 2020). Thus, in CD mode, PHEVs hold potential for higher mitigation potential, due to the possibility of charging the battery with low carbon electricity sources. Consequently, the UF greatly influences the life cycle emissions of PHEVs. The current peer-reviewed literature presents a wide range of UFs mainly due to varying testing protocols applied for estimating the fuel efficiency and user behaviour (Pavlovic et al. 2017; Paffumi et al. 2018; Plötz et al. 2018, 2020; Raghavan and Tal 2020; Hao et al. 2021). These factors make it difficult to harmonize and compare impacts across PHEV studies. Due to the low number of appropriate PHEV studies relative to the other LDV technologies and the complications in harmonizing available PHEV results, this technology is omitted from Figure 10.4. However, due to the dual operating nature of PHEV vehicles, one can expect that the life cycle GHG emissions intensities for these vehicles will lie between those of their ICEV and BEV counterparts of similar size and performance.

Currently, BEVs have higher manufacturing emissions than equivalently sized ICEVs, with median emissions of 14 t CO_2-eq/vehicle against approximately 10 t CO_2-eq/vehicle of their mid-sized fossil-fuelled counterparts. These higher production emissions of BEVs are largely attributed to the battery pack manufacturing and to the additional power electronics required. As manufacturing technology and capacity utilization improve and globalizes to regions with low-carbon electricity, battery manufacturing emissions will likely decrease. Due to the higher energy efficiency of the electric powertrain, BEVs may compensate for these higher production emissions in the driving phase. However, the mitigation ability of this technology relative to ICEVs is highly dependent on the electricity mix used to charge the vehicle. As a consequence of the variety of energy sources available today, current BEVs have a wide range of potential average life cycle impacts, ranging between 60 and 180 g CO_2-eq pkm^{-1} with electricity generated from wind and coal, respectively. The ability to achieve large carbon reductions via vehicle electrification is thus highly dependent on the generation of low-carbon electricity, with the greatest mitigation effects achieved when charging the battery with low-carbon electricity. The literature suggests that current BEVs, if manufactured on low carbon electricity as well as operated on low carbon electricity would have footprints as low 22 g CO_2-eq pkm^{-1} for a compact sized car (Ellingsen et al. 2014, 2016). This value suggests a reduction potential of around 85% compared to similarly sized fossil fuel vehicles (median values). Furthermore, BEVs have a co-benefit of reducing local air pollutants that are responsible for human health complications, particularly in densely populated areas (Hawkins et al. 2013; Ke et al. 2017).

As with BEVs, current HFCVs have higher production emissions than similarly sized ICEVs and BEVs, generating on average approximately 15 t CO_2-eq/vehicle. As with BEVs, the life cycle impacts of FCVs are highly dependent on the fuel chain. To date, the most common method of Hydrogen production is steam methane reforming from natural gas (Khojasteh Salkuyeh et al. 2017), which is relatively carbon intensive, resulting in life cycle emissions of approximately 88 g CO_2-eq pkm^{-1}. Current literature covering life cycle impacts of the FCVs show that vehicles fuelled with Hydrogen produced from steam methane reforming through natural gas offer little or no mitigation potential over ICEVs. Other available Hydrogen fuel chains vary widely in carbon intensity, depending on the synthesis method and the energy source used (electrolysis or steam methane reforming; fossil fuels vs. renewables). The least carbon-intensive Hydrogen pathways rely on electrolysis powered by low-carbon electricity. Compared to ICEVs and BEVs, FCVs for LDVs are at a lower technology readiness level as discussed in section 10.3.

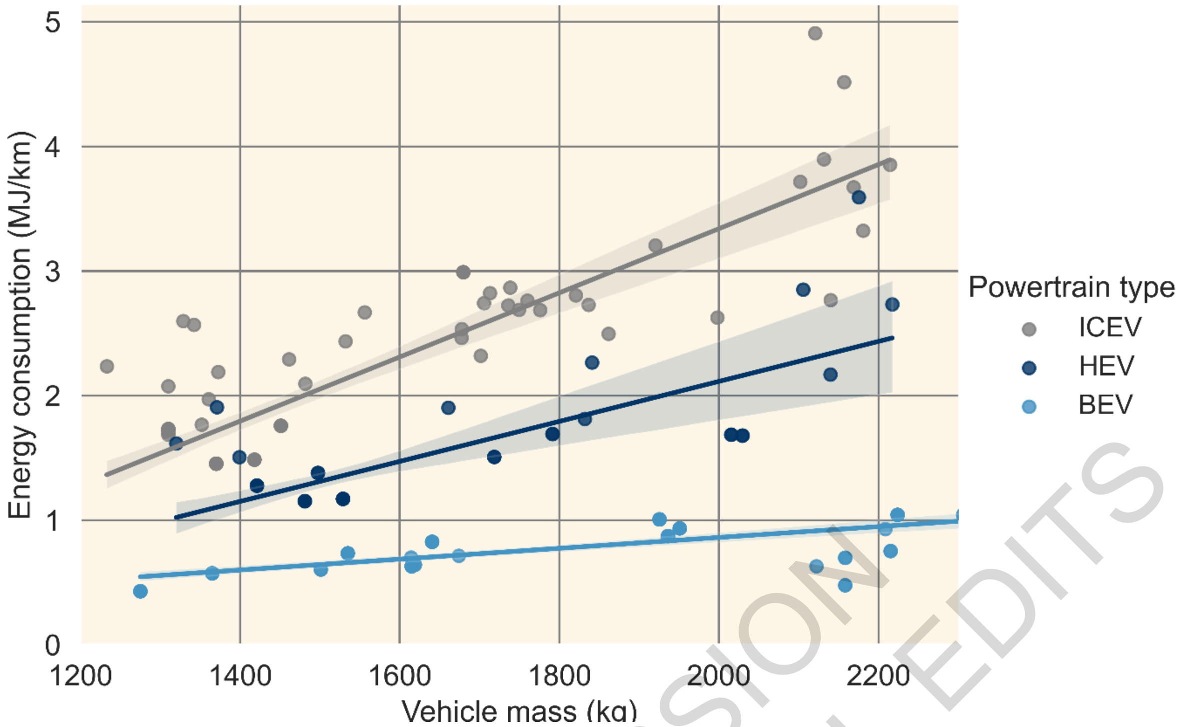
START BOX HERE

Box 10.3 – Vehicle size trends and implications on the fuel efficiency of LDVs

Vehicle size trends: On a global scale, SUV sales have been constantly growing in the last decade, with 39% of the vehicles sold in 2018 being SUVs (IEA 2019d). If the trend towards increasing vehicle size and engine power continues, it may result in higher overall emissions from the LDV fleet (relatively to smaller vehicles with the same powertrain technology). The magnitude of the influence vehicle mass has on fuel efficiency varies with the powertrain, which have different efficiencies. Box 10.3 Figure 1 highlights this relationship using data from the same literature used to create Figure 10.4. Higher powertrain efficiency results in lower energy losses in operation, and thus requires less energy input to move a given mass than a powertrain of lower efficiency. This pattern is illustrated by the more gradual slope of BEVs in Box 10.3 Figure 1. The trend towards bigger and heavier vehicles with consequently higher use phase emissions can be somewhat offset by improvements in powertrain design, fuel efficiency, light weighting, and aerodynamics (Gargoloff et al. 2018; Wolfram et al. 2020). The potential improvements provided by these strategies are case-specific and not thoroughly evaluated in the literature, either individually or as a combination of multiple strategies.

Light weighting: There is an increasing use of advanced materials such as high-strength steel, aluminium, carbon fibre, and polymer composites for vehicle light weighting (Hottle et al. 2017). These materials reduce the mass of the vehicle and thereby also reduce the fuel or energy required to drive. Light-weighted components often have higher production emissions than the components they replace due to the advanced materials used (Kim and Wallington 2016). Despite these higher production emissions, some studies suggest that the reduced fuel consumption over the lifetime of the light-weighted vehicle may provide a net mitigation effect in comparison to the non-light-weighted vehicle (Hottle et al. 2017; Kim and Wallington 2013; Upadhyayula et al. 2019; Milovanoff et al. 2019; Wolfram et al. 2020). However, multiple recent publications have found that in some cases, depending on, for example, vehicle size and carbon intensity of the light weighting materials employed, the GHG emissions avoided due to improved fuel efficiency do not offset the higher manufacturing emissions of the vehicle (Luk et al. 2018; Wu et al. 2019). In addition, these advanced materials may be challenging to recycle in a way that retains their high technical performance (Meng et al. 2017).

Co-effects on particulate matter: Light weighting may also alleviate the particulate matter (PM) emissions arising from road and brake wear. BEVs are generally heavier than their ICEV counterparts, which may potentially cause higher stress on the road surfaces and tires, with consequently higher PM emissions per kilometre driven (Timmers and Achten 2016). Regenerative braking in HEVs, BEVs and FCVs, however, reduces the mechanical braking required, and therefore may compensate for the higher brake wear emissions from these heavier vehicle types. In addition, BEVs have no tailpipe emissions, which further offsets the increased PM emissions from road and tire wear. Therefore, light-weighting strategies may offer a carbon and particulates mitigation effect; however, in some cases, other technological options may reduce CO_2 emissions even further.



Box 10.3, Figure 1 Illustration of energy consumption as a function of vehicle size (using mass as a proxy) and powertrain technology. FCVs omitted due to lacking data.

END BOX HERE

Two-wheelers, consisting mainly of lower-powered mopeds and higher-powered motorcycles, are popular for personal transport in densely populated cities, especially in developing countries. LCA studies for this class of vehicle are relatively uncommon compared to four-wheeled LDVs. In the available results, however, two-wheelers exhibit similar trends for the different powertrain technologies as the LDVs, with electric powertrains having higher production emissions, but usually lower operating emissions. The life cycle emissions intensity for two-wheelers is also generally lower than four-wheeled LDVs on a vehicle-kilometre basis. However, two-wheelers generally cannot carry as many passengers as four-wheeled LDVs. Thus, on a passenger-kilometre basis, a fully occupied passenger vehicle may still have lower emissions than a fully occupied two-wheeler. However, today, most passenger vehicles have relatively low occupancy and thus have a correspondingly high emissions intensity on a pkm basis. This points to the importance of utilization of passenger vehicles at higher occupancies to reduce the life cycle intensity of LDVs on a pkm basis. For example, the median emissions intensity of a gasoline passenger vehicle is 222 g CO_2-eq vkm^{-1}, and 160 g CO_2-eq vkm^{-1} for a gasoline two-wheeler (Cox and Mutel 2018). At a maximum occupancy factor of four and two passengers, respectively, the transport emissions intensity for these vehicles are 55 and 80 g CO_2-eq pkm^{-1}. Under the same occupancy rates assumption, BEV two-wheelers recharged on the average European electricity mix, achieve lower life cycle GHG intensities than BEV four-wheeled LDVs. On the other hand, FCV two-wheelers with Hydrogen produced via steam methane reforming present higher GHG intensity than their four-wheeled counterparts, when compared on a pkm basis at high occupancy rates.

ICEV, HEV, and PHEV technologies, which are powered using combustion engines, have limited potential for deep reduction of GHG emissions. Biofuels offer good mitigation potential if low land use change emissions are incurred (e.g., the IAM EMF33 and partial models, CLC biofuels pathways shown in Figure 10.4). The literature shows large variability, depending on the method of calculating associated land use changes. Resolving these apparent methodological differences is important to consolidating the role biofuels may play in mitigation, as well as the issues raised in Chapter 7 about the conflicts over land use. The mitigation potential of battery and fuel cell vehicles is strongly dependent on the carbon intensity of their production and the energy carriers used in operation. However, these technologies likely offer the highest potential for reducing emissions from LDVs. Prior work on the diffusion dynamics of transport technologies suggests that "the diffusion of infrastructure precedes the adoption of vehicles, which precedes the expansion of travel" (Leibowicz 2018). These dynamics reinforce the argument for strong investments in both the energy infrastructure and the vehicle technologies.

To successfully transition towards LDVs utilizing low-carbon fuels or energy sources, the technologies need to be accessible to as many people as possible, which requires competitive costs compared to conventional diesel and gasoline vehicles. The life cycle costs (LCCs) of LDVs depend on the purchasing costs of the vehicles, their efficiency, the fuel costs, and the discount rate. Figure 10.5 shows the results of a parametric analysis of LCC for diesel LDVs, BEVs, and FCVs. The range of vehicle efficiencies captured in Figure 10.5 are the same as the ranges used for Figure 10.4, while the ranges for fuel costs and vehicle purchase prices come from the literature. The assumed discount rate for this parametric analysis is 3%. Appendix 10.2 includes the details about the method and underlying data used to create this figure.

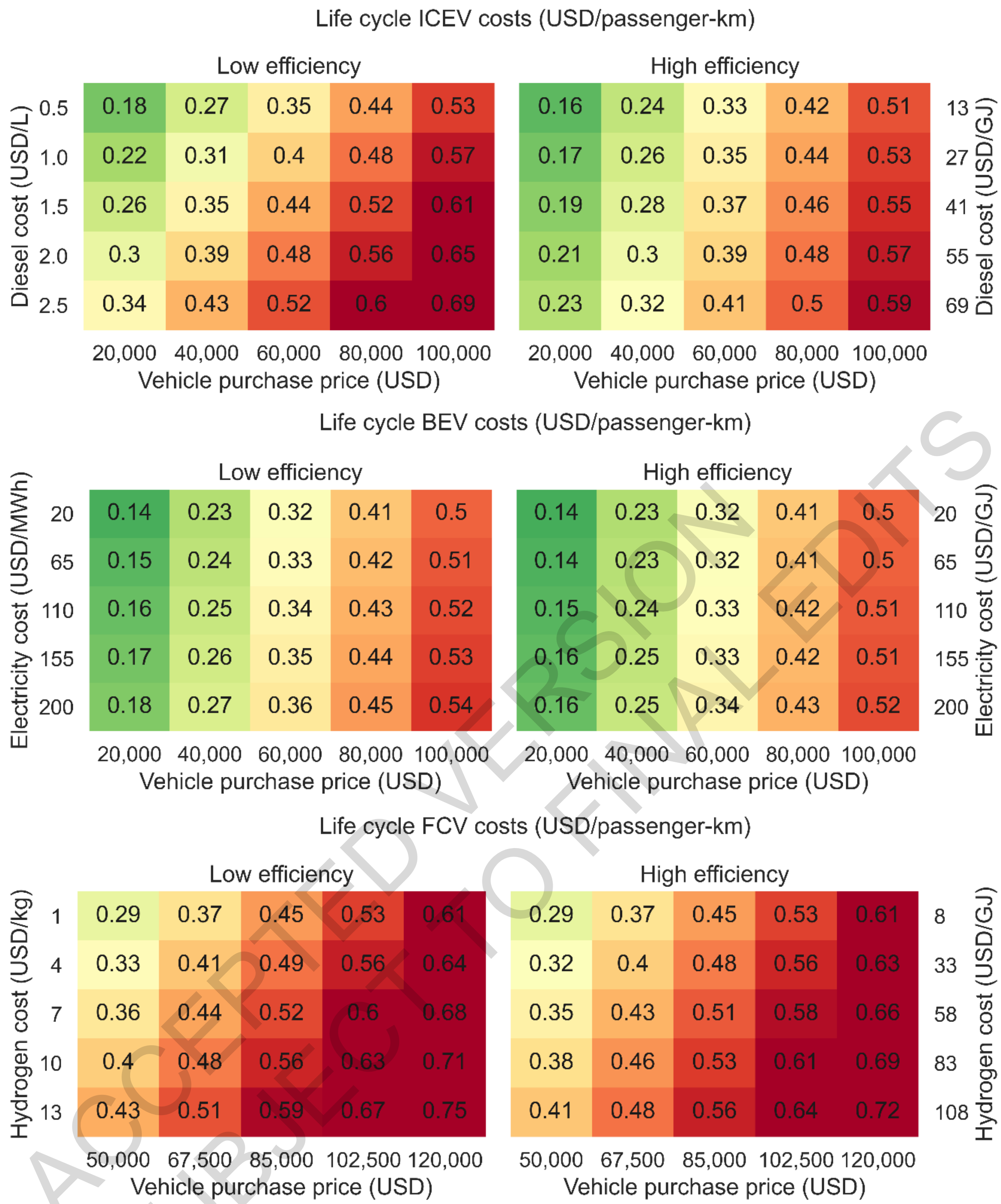


Figure 10.5 LCC for light-duty ICEVs, BEVs, and HFCVs. The results for ICEVs represent the LCC of a vehicle running on gasoline. However, these values are also representative for ICEVs running on diesel as the costs ranges in the literature for these two solutions are similar. The secondary y-axis depicts the cost of the different of the energy carriers normalized in USD/GJ for easier cross-comparability.

Figure 10.5 shows the range of LCC, in USD per pkm, for different powertrain technologies, and the influence of vehicle efficiency (low or high), vehicle purchase price, and fuel/electricity cost on the overall LCC. For consistency with Figure 10.4, an occupancy rate of 1.5 is assumed. Mid-sized ICEVs have a purchase price of USD 20,000-40,000, and average fuel costs are in the range of 1-1.5 USD/L. With these conditions, the LCC of fossil-fuelled LDVs span between 0.22-0.35 USD per pkm or between 0.17-0.28 USD per pkm, for low and high efficiency ICEVs respectively (Figure 10.5).

BEVs have higher purchase prices than ICEVs, though a sharp decline has been observed since AR5. Due to the rapid development of the lithium-ion battery technology over the years (Schmidt et al. 2017) and the introduction of subsidies in several countries, BEVs are quickly reaching cost parity with ICEVs. Mid-sized BEVs average purchase prices are in the range of USD 30,000-50,000 but the levelised cost of electricity shows a larger spread (65-200 USD/MWh) depending on the geographical location and the technology (see Chapter 6). Therefore, assuming purchase price parity between ICEVs and BEVs, BEVs show lower LCC (Figure 10.5) due to higher efficiency and the lower cost of electricity compared to fossil fuels on a per-GJ basis (secondary y-axis on Figure 10.5).

FCVs represent the most expensive solution for LDV, mainly due to the currently higher purchase price of the vehicle itself. However, given the lower technology readiness level of FCVs and the current efforts in the research and development of this technology, FCVs could become a viable technology for LDVs in the coming years. The issues regarding the extra energy involved in creating the Hydrogen and its delivery to refuelling sites remain, however. The levelized cost of Hydrogen on a per GJ basis is lower than conventional fossil fuels but higher than electricity. In addition, within the levelized cost of Hydrogen, there are significant cost differences between the Hydrogen producing technologies. Conventional technologies such as coal gasification and steam methane reforming from natural gas, both with and without carbon capture and storage, represent the cheapest options (Bekel and Pauliuk 2019; Parkinson et al. 2019; Khzouz et al. 2020; Al-Qahtani et al. 2021). Hydrogen produced via electrolysis is currently the most expensive technology, but with significant potential cost reductions due to the current technology readiness level.

10.4.2 Transit technologies for passenger transport

Buses provide urban and peri-urban transport services to millions of people around the world and a growing number of transport agencies are exploring alternative-fuelled buses. Alternative technologies to conventional diesel-powered buses include buses powered with CNG, LNG, synthetic fuels, and biofuels (e.g., biodiesel, renewable diesel, dimethyl ether); diesel hybrid-electric buses; battery electric buses; electric catenary buses, and Hydrogen fuel cell buses. Rail is an alternative mode of transit that could support decarbonisation of land-based passenger mobility. Electric rail systems can provide urban services (light rail and metro systems), as well as longer distance transport. Indeed, many cities of the world already have extensive metro systems, and regions like China, Japan and Europe have a robust high-speed inter-city railway network. Intercity rail transport can be powered with electricity; however, fossil fuels are still prevalent for long-distance rail passenger transport in some regions. Battery electric long-distance trains may be a future option for these areas.

Figure 10.6 shows the life cycle GHG emissions from different powertrain and fuel technologies for buses and passenger rail. The data in each panel came from a number of relevant scientific studies (IEA 2019e; Tong et al. 2015a; Dimoula et al. 2016; de Bortoli et al. 2017; Meynerts et al. 2018; Cai et al. 2015; de Bortoli and Christoforou 2020; Hill et al. 2020; Liu et al. 2020a; Valente et al. 2021, 2017). The width of the bar represents the variability in available estimates, which is primarily driven by variability in reported vehicle efficiency, size, or drive cycle. While some bars overlap, the figure may not fully capture correlations between results. For example, low efficiency associated with aggressive drive cycles may drive the upper end of the emission ranges for multiple technologies; thus, an overlap does not necessarily suggest uncertainty regarding which vehicle type would have lower emissions for a comparable trip. Additionally, reported life cycle emissions do not include embodied GHG emissions associated with infrastructure construction and maintenance. These embodied emissions are potentially a larger fraction of life cycle emissions for rail than for other transport modes (Chester and Horvath 2012; Chester et al. 2013). One study reported values ranging from 10-25 g CO_2 per passenger-kilometre (International Union of Railways 2016), although embodied emissions from rail are known to vary widely across case studies (Olugbenga et al. 2019). These caveats are also applicable to the other figures in this section.

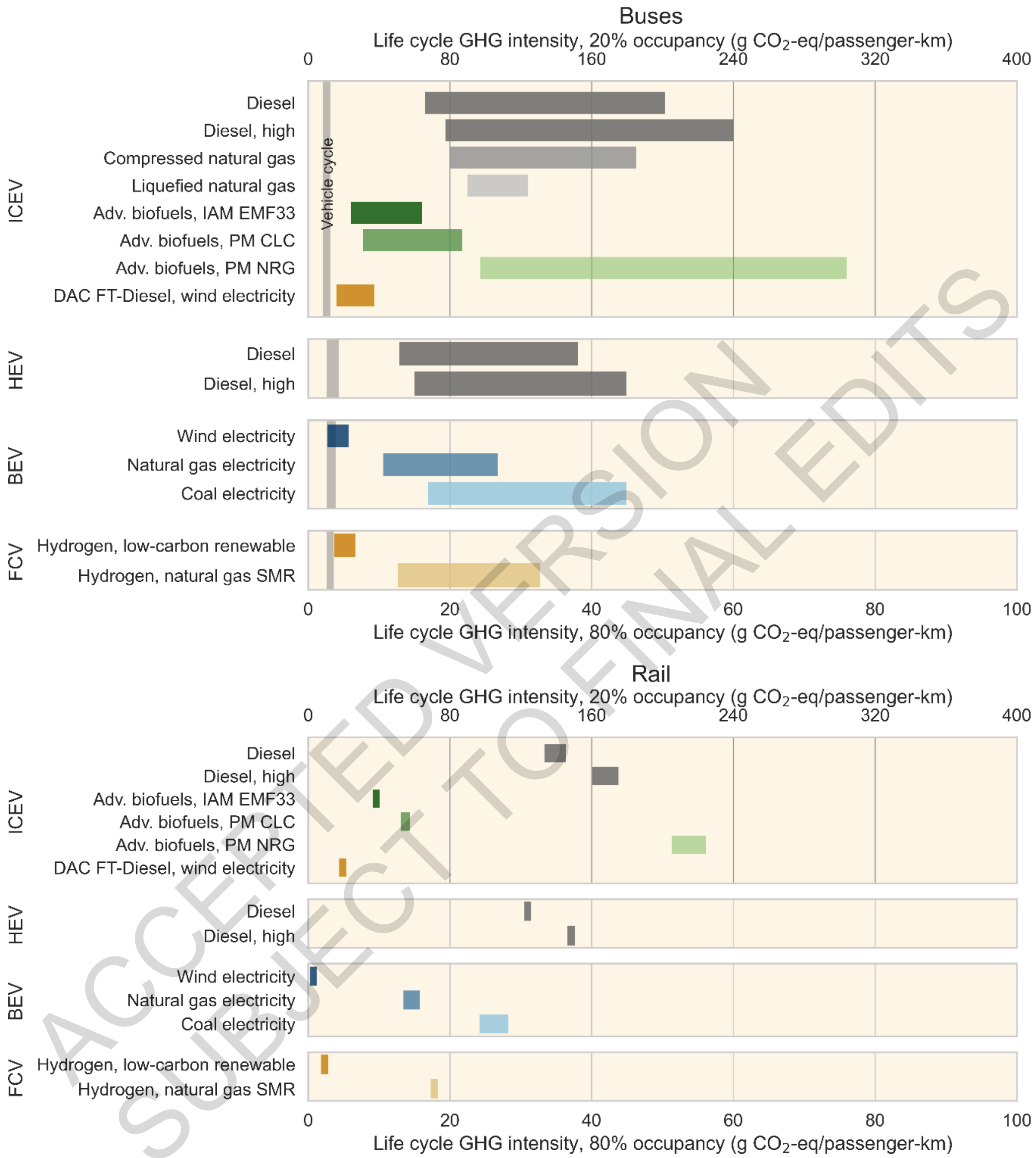


Figure 10.6 Life cycle GHG intensity of land-based bus and rail technologies. Each bar represents the range of the life cycle estimates, bounded by minimum and maximum energy use per pkm, as reported for each fuel/powertrain combination. The ranges are driven by differences in vehicle characteristics and operating efficiency. For energy sources with highly variable upstream emissions low, medium and/or high representative values are shown as separate rows. The primary x-axis shows life cycle GHG emissions, in g CO_2-eq per pkm, assuming 80% occupancy; the secondary x-axis assumes 20% occupancy. The values in the figure rely on the 100-year GWP value embedded in the source data, which may differ slightly with the updated 100-year GWP values from WGI. For buses, the main bars show full

life cycle, with vertical bars disaggregating the vehicle cycle. 'Diesel, high' references emissions factors for diesel from oil sands. 'Adv. Biofuels' i.e., advanced biofuels, refers to the use of second-generation biofuels and their respective conversion and cultivation emission factors. 'IAM EMF33' refers to emissions factors for advanced biofuels derived from simulation results from the integrated assessment models EMF33 scenarios. 'PM' refers to partial models, where 'CLC' is with constant land cover and 'NRG' is with natural regrowth. 'DAC FT-Diesel, wind electricity' refers to Fischer-Tropsch diesel produced via a CO_2 direct air capture process that uses wind electricity. 'Hydrogen, low-carbon renewable' refers to fuels produced via electrolysis using low-carbon electricity. 'Hydrogen, natural gas SMR' refers to fuels produced via steam methane reforming of natural gas. Results for ICEVs with 'high emissions DAC FT-Diesel from natural gas' are not included here since the life cycle emissions are estimated to be substantially higher than petroleum diesel ICEVs.

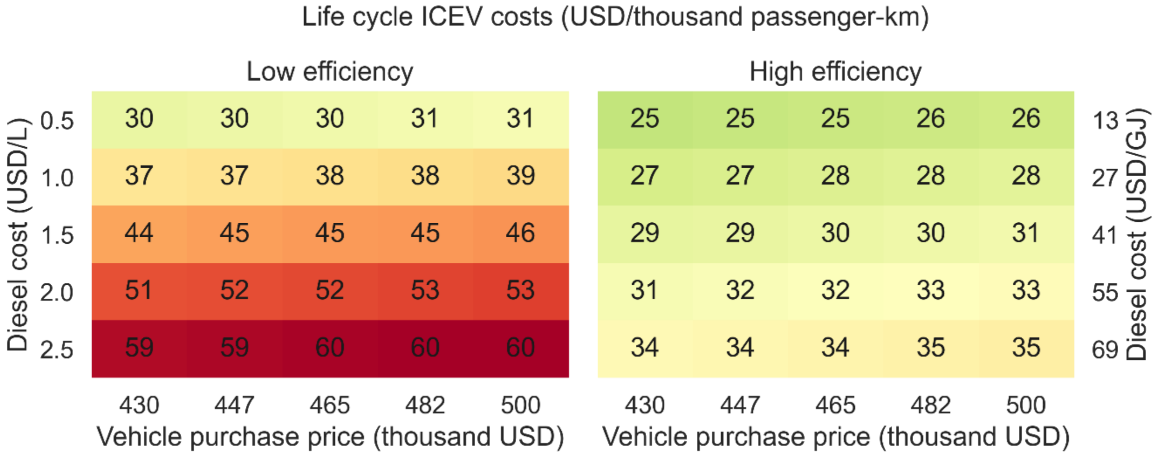
Figure 10.6 highlights that BEV and FCV buses and passenger rail powered with low carbon electricity or low carbon Hydrogen, could offer reductions in GHG emissions compared to diesel-powered buses or diesel-powered passenger rail. However, and not surprisingly, these technologies would offer only little emissions reductions if power generation and Hydrogen production rely on fossil fuels. While buses powered with CNG and LNG could offer some reductions compared to diesel-powered buses, these reductions are unlikely to be sufficient to contribute to deep decarbonisation of the transport sector and they may slow down conversion to low or zero-carbon options already commercially available. Biodiesel and renewable diesel fuels (from sources with low upstream emissions and low risk of induced land use change) could offer important near-term reductions for buses and passenger rail, as these fuels can often be used with existing vehicle infrastructure. They could also be used for long haul trucks and trains, shipping and aviation as discussed below and in later sections.

There has been growing interest in the production of synthetic fuels from CO_2 produced by direct air capture (DAC) processes. Figure 10.6 includes the life cycle GHG emissions from buses and passenger rail powered with synthetic diesel produced through a DAC system paired with a Fischer-Tropsch (FT) process based on (Liu et al. 2020a). This process requires the use of Hydrogen (as shown in Figure 10.2 in section 10.3), so the emissions factors of the resulting fuel depend on the emissions intensity of Hydrogen production. An electricity emissions factor less than 140 g CO_2-eq kWh^{-1} would be required for this pathway to achieve lower emissions than petroleum diesel (Liu et al. 2020a); e.g., this would be equivalent to 75% wind and 25% natural gas electricity mix (see Appendix 10.1). If the process relied on steam methane reforming for Hydrogen production or fossil-based power generation, synthetic diesel from the DAC-FT process would not provide GHG emissions reductions compared to conventional diesel. DAC-FT from low-carbon energy sources appears to be promising from an emissions standpoint and could warrant the R&D and demonstration attention outlined in the rest of the chapter, but it cannot be contemplated as a decarbonisation strategy without the availability of low-carbon Hydrogen.

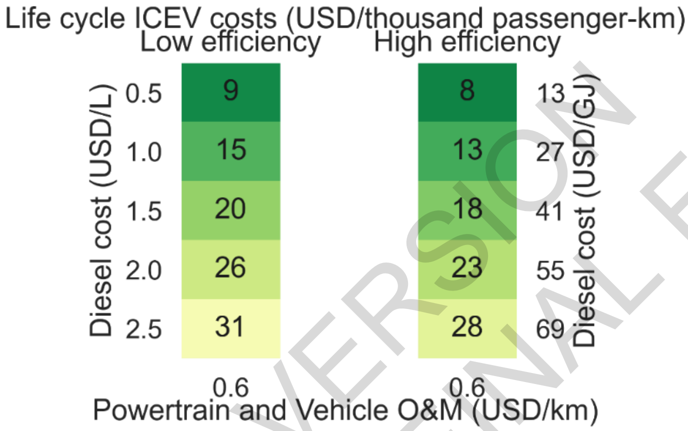
At high occupancy, both bus and rail transport offer substantial GHG reduction potential per pkm, even compared with the lowest-emitting private vehicle options. Even at 20% occupancy, bus and rail may still offer emission reductions compared to passenger cars, especially notable when comparing BEVs with low-carbon electricity (the lowest emission option for all technologies) across the three modes. Only when comparing a fossil fuel-powered bus at low occupancy with a low-carbon powered car at high occupancy is this conclusion reversed. Use of public transit systems, especially those that rely on buses and passenger rail fuelled with the low carbon fuels previously described would thus support efforts to decarbonise the transport sector. Use of these public transit systems will depend on urban design and consumer preferences (as described in Section 10.2 and Chapters 5 and 8), which in turn depend on time, costs, and behavioural choices.

Figure 10.7 shows the results of a parametric analysis of the LCCs of transit technologies with the highest potential for GHG emissions reductions. As with Figure 10.5, the vehicle efficiency ranges are the same as those from the LCA estimates (80% occupancy). Vehicle, fuel, and maintenance costs represent ranges in the literature (Eudy and Post 2018b; IEA 2019e; Argonne National Laboratory 2020; BNEF 2020; Eudy and Post 2020; Hydrogen Council 2020; IEA 2020b,c; IRENA 2020; Johnson et al. 2020; Burnham et al. 2021; IEA 2021c,d; U.S. Energy Information Administration 2021), and the discount rate is 3% where applicable. Appendix 10.2 of the chapter provides the details behind these estimates. The panels for the ICEV can represent buses and passenger trains powered with any form of diesel, whether derived from petroleum, synthetic hydrocarbons, or biofuels. For reference, global average automotive diesel prices from 2015-2020 fluctuated around 1 USD/L, and the 2019 world average industrial electricity price was approximately 100 USD/MWh (IEA 2021d). Retail Hydrogen prices in excess of 13 USD/kg have been observed (Eudy and Post 2018a; Argonne National Laboratory 2020; Burnham et al. 2021) though current production cost estimates for Hydrogen produced from electrolysis are far lower ((IRENA 2020), and as reported in Chapter 6), at around 5-7 USD/kg with future forecasts as low as 1 USD/kg ((IRENA 2020; BNEF 2020; Hydrogen Council 2020), and as reported in Chapter 6).

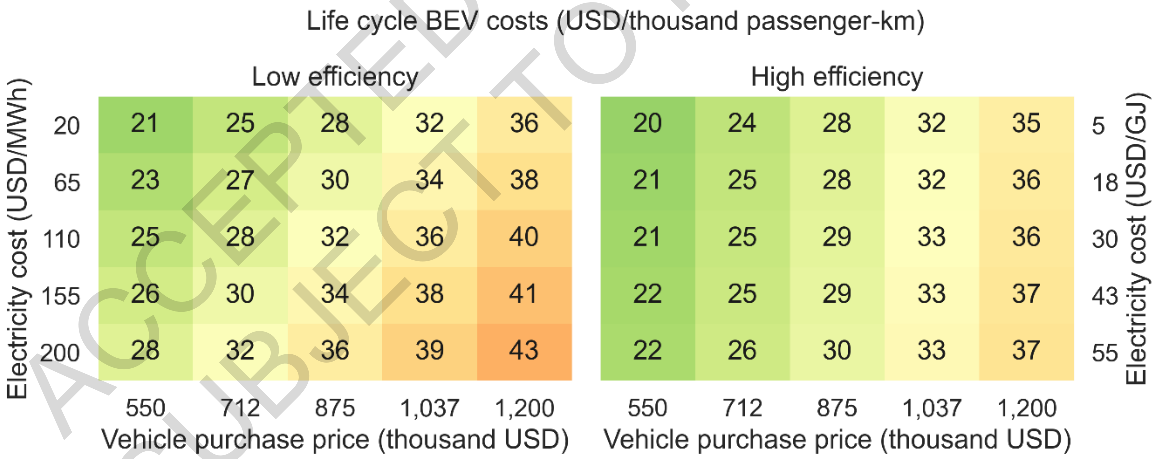
Under most parameter combinations, rail is the most cost-effective option, followed by buses, both of which are an order of magnitude cheaper than passenger vehicles. Note that costs per pkm are strongly influenced by occupancy assumptions; at low occupancy (e.g., <20% for buses and <10% for rail), the cost of transit approaches the LCC for passenger cars. For diesel rail and buses, cost ranges are driven by fuel costs, whereas vehicle are both important drivers for electric or Hydrogen modes due to high costs (but also large projected improvements) associated with batteries and fuel cell stacks. Whereas the current state of ICEV technologies is best represented by cheap vehicles and low fuel costs for diesel (top left of each panel), these costs are likely to rise in future due to stronger emission/efficiency regulations and rising crude oil prices. On the contrary, the current status of alternative fuels is better represented by high capital costs and mid-to-high fuel costs (right side of each panel; mid-to-bottom rows), but technology costs are anticipated to fall with increasing experience, research, and development. Thus, while electric rail is already competitive with diesel rail, and electric buses are competitive with diesel buses in the low efficiency case, improvements are still required in battery costs to compete against modern diesel buses on high efficiency routes, at current diesel costs. Similarly, improvements to both vehicle cost and fuel costs are required for Hydrogen vehicles to become cost effective compared to their diesel or electric counterparts. At either the upper end of the diesel cost range (bottom row of ICEV panels), or within the 2030-2050 projections for battery costs, fuel cell costs and Hydrogen costs (top left of BEV and FCV panels) – both battery and Hydrogen powered vehicles become financially attractive.



Life cycle ICEV costs (USD/thousand passenger-km)
Low efficiency
High efficiency
Diesel cost (USD/L)
0.5
1.0
1.5
2.0
2.5
30 30 30 31 31
37 37 38 38 39
44 45 45 45 46
51 52 52 53 53
59 59 60 60 60
25 25 25 26 26
27 27 28 28 28
29 29 30 30 31
31 32 32 33 33
34 34 34 35 35
13
27
41
55
69
Diesel cost (USD/GJ)
430 447 465 482 500
Vehicle purchase price (thousand USD)
430 447 465 482 500
Vehicle purchase price (thousand USD)



Life cycle ICEV costs (USD/thousand passenger-km)
Low efficiency
High efficiency
Diesel cost (USD/L)
0.5
1.0
1.5
2.0
2.5
9
15
20
26
31
8
13
18
23
28
13
27
41
55
69
Diesel cost (USD/GJ)
0.6
0.6
Powertrain and Vehicle O&M (USD/km)



Life cycle BEV costs (USD/thousand passenger-km)
Low efficiency
High efficiency
Electricity cost (USD/MWh)
20
65
110
155
200
21 25 28 32 36
23 27 30 34 38
25 28 32 36 40
26 30 34 38 41
28 32 36 39 43
20 24 28 32 35
21 25 28 32 36
21 25 29 33 36
22 25 29 33 37
22 26 30 33 37
5
18
30
43
55
Electricity cost (USD/GJ)
550 712 875 1,037 1,200
Vehicle purchase price (thousand USD)
550 712 875 1,037 1,200
Vehicle purchase price (thousand USD)

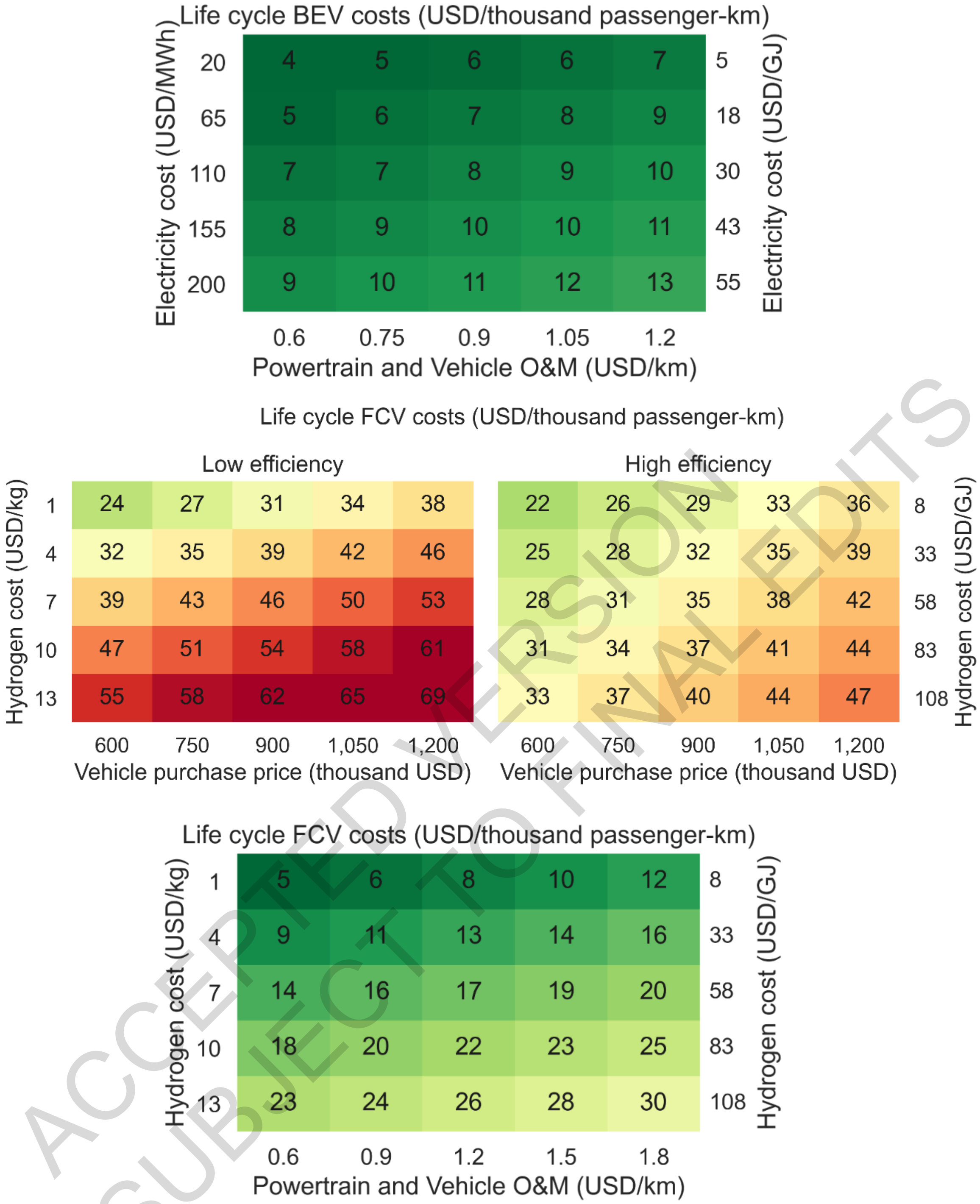


Figure 10.7 Life cycle costs for internal combustion engine vehicles ICEV, BEV, and HFCV for buses and passenger rail. The range of efficiencies for each vehicle type are consistent with the range of efficiencies in Figure 10.6 (80% occupancy). The results for the ICEV can be used to evaluate the life cycle costs of ICE buses and passenger rail operated with any form of diesel, whether from petroleum, synthetic hydrocarbons, or biofuel, as the range of efficiencies of vehicles operating with all these fuels is similar. The secondary y-axis depicts the cost of the different energy carriers normalized in USD/GJ for easier cross-comparability.

10.4.3 Land-based freight transport

As is the case with passenger transport, there is growing interest in alternative fuels that could reduce GHG emissions from freight transport. Natural gas-based fuels (e.g., CNG, LNG) are an example, however these may not lead to drastic reductions in GHG emissions compared to diesel. Natural gas-powered vehicles have been discussed as a means to mitigate air quality impacts (Khan et al. 2015; Pan et al. 2020; Cai et al. 2017) but those impacts are not the focus of this review. Decarbonisation of medium and heavy-duty trucks would likely require the use of low-carbon electricity in battery-electric trucks, low-carbon Hydrogen or Ammonia in fuel-cell trucks, or bio-based fuels (from sources with low upstream emissions and low risk of induced land use change) used in ICE trucks.

Freight rail is also a major mode for the inland movement of goods. Trains are more energy efficient (per tkmm) than trucks, so expanded use of rail systems (particularly in developing countries where demand for goods could grow exponentially) could provide carbon abatement opportunities. While diesel-based locomotives are still a major propulsion used in freight rail, interest in low-carbon propulsion technologies is growing. Electricity already powers freight rail in many European countries using overhead catenaries. Other low-carbon technologies for rail may include advanced storage technologies, biofuels, synthetic fuels, Ammonia, or Hydrogen.

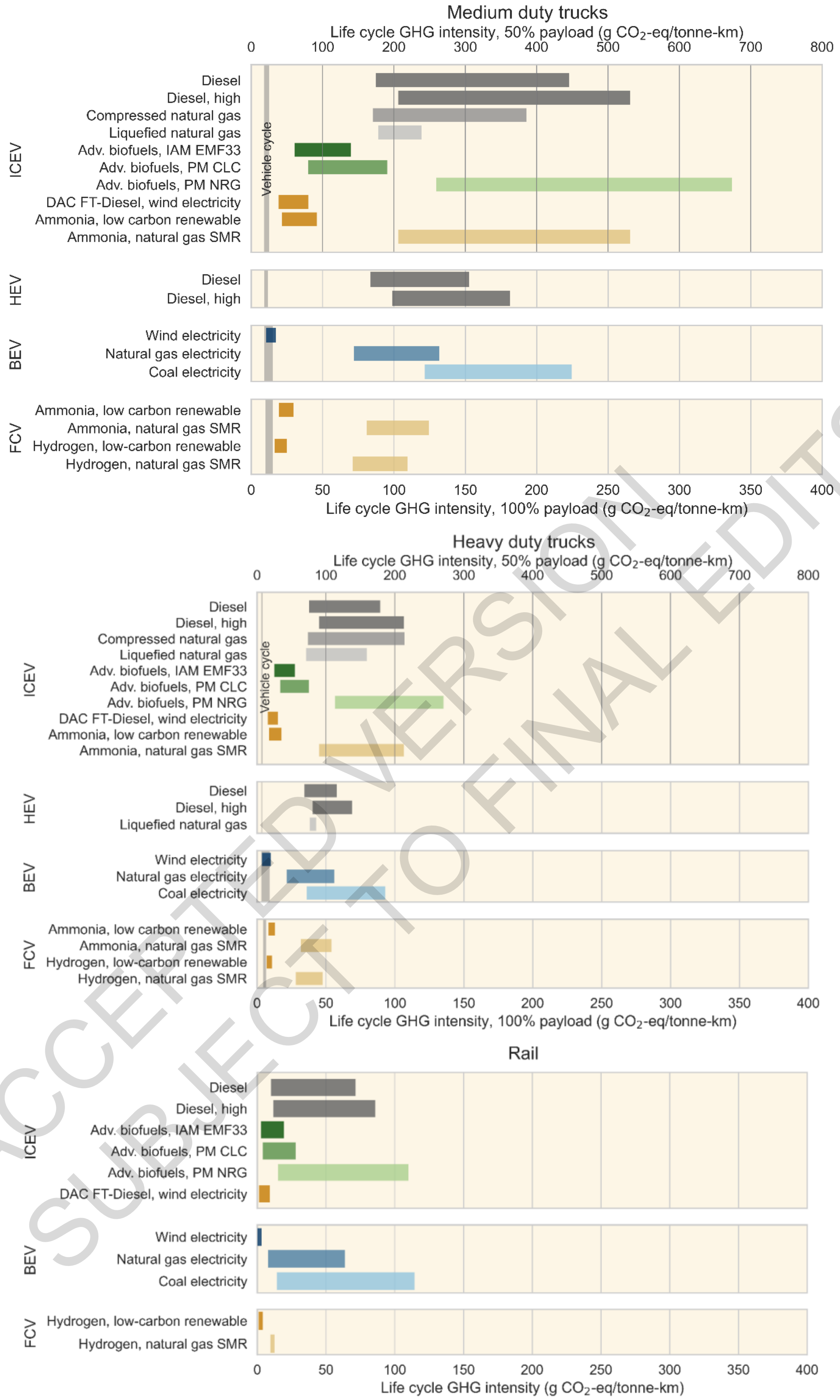


Figure 10.8 Life cycle GHG intensity of land-based freight technologies and fuel types. Each bar represents the range of the life cycle estimates, bounded by minimum and maximum energy use per tkm, as reported for each fuel/powertrain combination. The ranges are driven by differences in vehicle characteristics and operating efficiency. For energy sources with highly variable upstream emissions, low, medium and/or high representative values are shown as separate rows. For trucks, the primary x-axis

shows life cycle GHG emissions, in g CO_2-eq per tkm, assuming 100% payload; the secondary x-axis assumes 50% payload. The values in the figure rely on the 100-year GWP value embedded in the source data, which may differ slightly with the updated 100-year GWP values from WGI. For rail, values represent average payloads. For trucks, main bars show full life cycle, with vertical bars disaggregating the vehicle cycle. 'Diesel, high' references emissions factors for diesel from oil sands. 'Adv. Biofuels' refers to the use of second-generation biofuels and their respective conversion and cultivation emission factors. 'IAM EMF33' refers to emissions factors for advanced biofuels derived from simulation results from the EMF33 scenarios. 'PM' refers to partial models, where 'CLC' is with constant land cover and 'NRG' is with natural regrowth. DAC FT-Diesel, wind electricity refers to Fischer-Tropsch diesel produced via a CO_2 direct air capture process that uses wind electricity. 'Ammonia and Hydrogen, low-carbon renewable' refers to fuels produced via electrolysis using low-carbon electricity. 'Ammonia and Hydrogen, natural gas SMR' refers to fuels produced via steam methane reforming of natural gas.

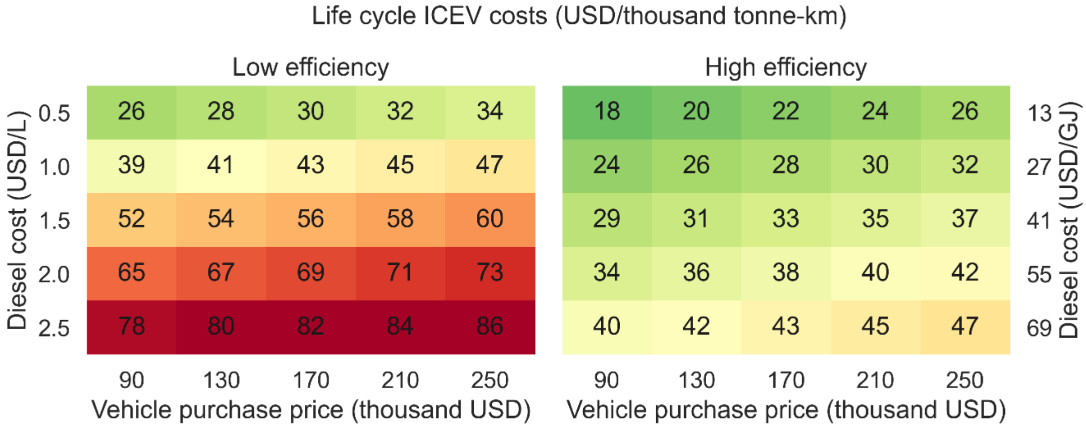
Figure 10.8 presents a review of life cycle GHG emissions from land-based freight technologies (heavy and medium-duty trucks, and rail). Each panel within the figure represents data in GHG emissions per tkm of freight transported by different technology and/or fuel types, as indicated by the labels to the left. The data in each panel came from a number of relevant scientific studies (Merchan et al. 2020; Frattini et al. 2016; Zhao et al. 2016; CE Delft 2017; Isaac and Fulton 2017; Song et al. 2017; Cooper and Balcombe 2019; S. Mojtaba et al. 2019; Nahlik et al. 2016; Prussi et al. 2020; Hill et al. 2020; Liu et al. 2020a; Valente et al. 2021; Gray et al. 2021; Valente et al. 2017; Tong et al. 2015a). Similar to the results for buses, technologies that offer substantial emission reductions for freight include: ICEV trucks powered with the low carbon variants for biofuels, Ammonia or synthetic diesel; BEVs charged with low carbon electricity; and FCVs powered with renewable-based electrolytic Hydrogen, or Ammonia. Since Ammonia and Fischer-Tropsch diesel are produced from Hydrogen, their emissions are higher than the source Hydrogen, but their logistical advantages over Hydrogen are also a consideration (as discussed in Section 10.3).

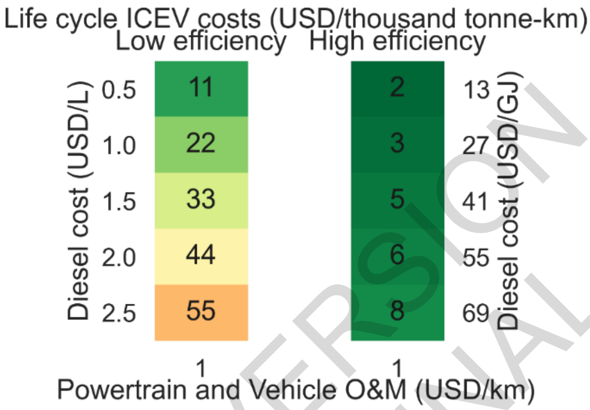
Trucks exhibit economies of scale in fuel consumption, with heavy duty trucks generally showing lower emissions per tkm than medium duty trucks. Comparing the life cycle GHG emissions from trucks and rail, it is clear that rail using internal combustion engines is more carbon efficient than using internal combustion trucks. Note that the rail emissions are reported for an average representative payload, while the trucks are presented at 50% and 100% payload, based on available data. The comparison between trucks and rail powered with electricity or Hydrogen is less clear – especially considering that these values omit embodied GHG from infrastructure construction. One study reported embodied rail infrastructure emissions of 15 g CO_2 per tonne-kilometre for rail (International Union of Railways 2016), although such embodied emissions from rail are known to vary widely across case studies (Olugbenga et al. 2019). Regardless, trucks and rail with low carbon electricity or low-carbon Hydrogen have substantially lower emissions than incumbent technologies.

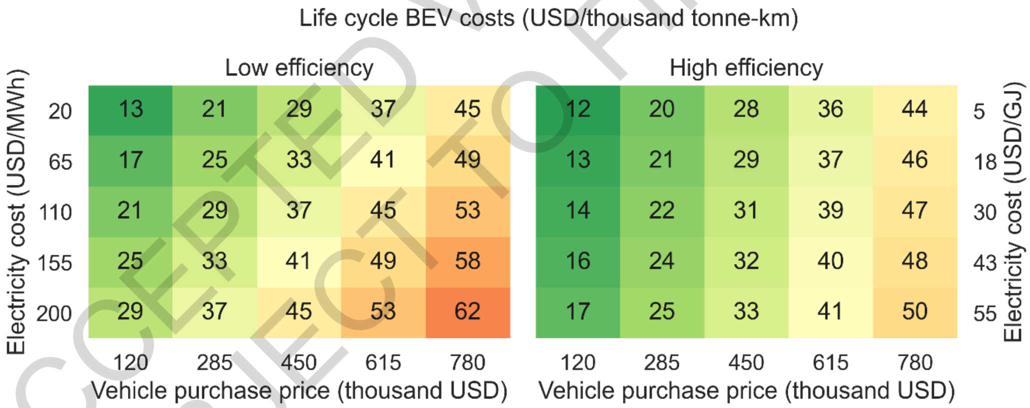
For trucks, Figure 10.8 includes two x-axes representing two different assumptions about their payload, which substantially influence emissions per tonne-kilometre. These results highlight the importance of truckload planning as an emissions reduction mechanism, for example, as also shown in (Kaack et al. 2018). Several studies also point to improvements in vehicle efficiency as an important mechanism to reduce emissions from freight transport (Taptich et al. 2016; Kaack et al. 2018). However, projections for diesel vehicles using such efficiencies beyond 2030 are promising, but still far higher emitting than vehicles powered with low carbon sources.

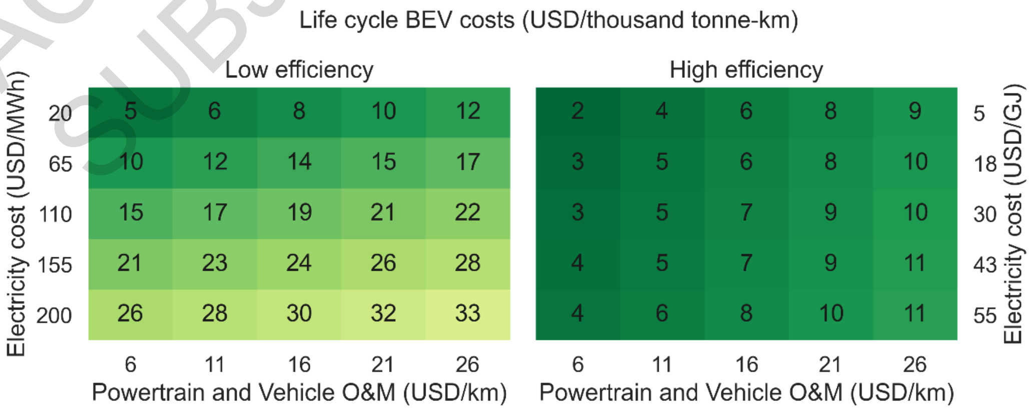
Figure 10.9 shows the results of a parametric analysis of the LCC of trucks and freight rail technologies with the highest potential for deep GHG reductions. As with Figure 10.8, the vehicle efficiency ranges are the same as those from the LCA estimates (80% payload for trucks; effective payload as reported by original studies for rail). Vehicle, fuel and maintenance costs represent ranges in the literature (Moultak et al. 2017; Eudy and Post 2018b; IEA 2019e; Argonne National Laboratory 2020; BNEF

2020; IRENA 2020; Burnham et al. 2021; IEA 2021c), and the discount rate is 3% where applicable (details are in Appendix 10.2). The panels for the ICEV can represent trucks and freight trains powered with any form of diesel, whether derived from petroleum, synthetic hydrocarbons, or biofuels. See discussion preceding Figure 10.7 for additional details about current global fuel costs. Under most parameter combinations, rail is the more cost-effective option, but the high efficiency case for trucks (representing fuel efficient vehicles, favourable drive cycles and high payload) can be more cost-effective than the low efficiency case for rail (representing systems with higher fuel consumption and lower payload). For BEV trucks, cost ranges are driven by vehicle purchase price due to the large batteries required and the associated wide range between their current high costs and anticipated future cost reductions. For all other truck and rail technologies, fuel cost ranges play a larger role. Similar to transit technologies, the current state of freight ICEV technologies is best represented by cheap vehicles and low fuel costs for diesel (top left of each panel), and the current status of alternative fuels is better represented by high capital costs and mid-to-high fuel costs (right side of each panel; mid-to-bottom rows), with expected future increases in ICEV LCC and decreases in alternative fuel vehicle LCC. Electric and Hydrogen freight rail are potentially already competitive with diesel rail (especially electric catenary (IEA 2019e)), but low data availability (especially for Hydrogen efficiency ranges) and wide ranges for reported diesel rail efficiency (likely encompassing low capacity utilization) makes this comparison challenging. Alternative fuel trucks are currently more expensive than diesel trucks, but future increases in diesel costs or a respective decrease in Hydrogen costs or in BEV capital costs (especially the battery) would enable either alternative fuel technology to become financially attractive. These results are largely consistent with raw results reported in existing literature, which suggest ambiguity over whether BEV trucks are already competitive, but more consistency that Hydrogen is not yet competitive, but could be in future (Zhao et al. 2016; White and Sintov 2017; Moultak et al. 2017; Sen et al. 2017; Zhou et al. 2017; Mareev et al. 2018; Yang et al. 2018a; El Hannach et al. 2019; S. Mojtaba et al. 2019; Tanco et al. 2019; Burke and Sinha 2020; Jones et al. 2020). There is limited data available on the LCC for freight rail, but at least one study IEA (2019g) suggests that electric catenary rail is likely to have similar costs as diesel rail, while battery electric trains remain more expensive and Hydrogen rail could become cheaper under forward-looking cost reduction scenarios.


Life cycle ICEV costs (USD/thousand tonne-km)
Low efficiency
High efficiency
Diesel cost (USD/L)
0.5
1.0
1.5
2.0
2.5
26 28 30 32 34
39 41 43 45 47
52 54 56 58 60
65 67 69 71 73
78 80 82 84 86
18 20 22 24 26
24 26 28 30 32
29 31 33 35 37
34 36 38 40 42
40 42 43 45 47
Diesel cost (USD/GJ)
13
27
41
55
69
90 130 170 210 250
Vehicle purchase price (thousand USD)
90 130 170 210 250
Vehicle purchase price (thousand USD)


Life cycle ICEV costs (USD/thousand tonne-km)
Low efficiency
High efficiency
Diesel cost (USD/L)
0.5
1.0
1.5
2.0
2.5
11
22
33
44
55
2
3
5
6
8
Diesel cost (USD/GJ)
13
27
41
55
69
1 1
Powertrain and Vehicle O&M (USD/km)


Life cycle BEV costs (USD/thousand tonne-km)
Low efficiency
High efficiency
Electricity cost (USD/MWh)
20
65
110
155
200
13 21 29 37 45
17 25 33 41 49
21 29 37 45 53
25 33 41 49 58
29 37 45 53 62
12 20 28 36 44
13 21 29 37 46
14 22 31 39 47
16 24 32 40 48
17 25 33 41 50
Electricity cost (USD/GJ)
5
18
30
43
55
120 285 450 615 780
Vehicle purchase price (thousand USD)
120 285 450 615 780
Vehicle purchase price (thousand USD)


Life cycle BEV costs (USD/thousand tonne-km)
Low efficiency
High efficiency
Electricity cost (USD/MWh)
20
65
110
155
200
5 6 8 10 12
10 12 14 15 17
15 17 19 21 22
21 23 24 26 28
26 28 30 32 33
2 4 6 8 9
3 5 6 8 10
3 5 7 9 10
4 5 7 9 11
4 6 8 10 11
Electricity cost (USD/GJ)
5
18
30
43
55
6 11 16 21 26
Powertrain and Vehicle O&M (USD/km)
6 11 16 21 26
Powertrain and Vehicle O&M (USD/km)

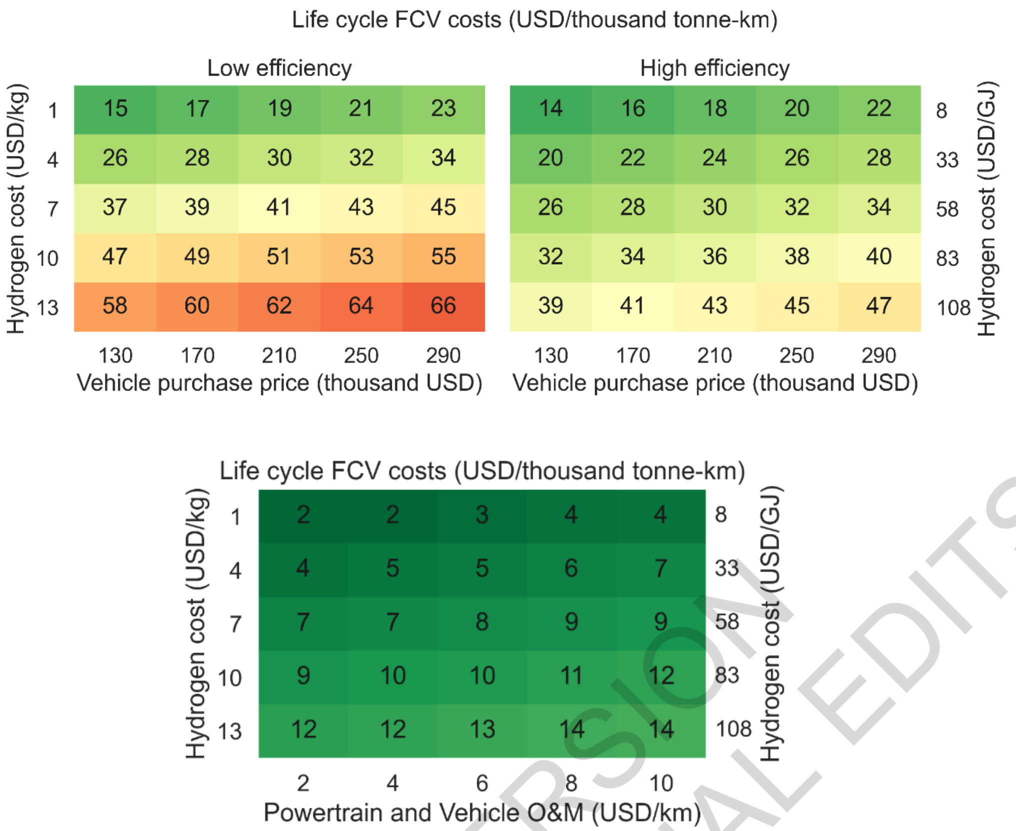


Figure 10.9 Life cycle costs for ICEV, BEV, and HFCV for heavy-duty trucks and freight rail. The range of efficiencies for each vehicle type are consistent with the range of efficiencies in Figure 10.8. The results for the ICEV can be used to evaluate the life cycle costs of ICE trucks and freight rail operated with any form of diesel, whether from petroleum, synthetic hydrocarbons, or biofuels, as the range of efficiencies of vehicles operating with all these fuels is similar. The secondary y-axis depicts the cost of the different of the energy carriers normalized in USD/GJ for easier cross-comparability.

10.4.4 Abatement costs

Taken together, the results in this section suggest a range of cost-effective opportunities to reduce GHG emissions from land-based transport. Mode shift from cars to passenger transit (bus or rail) can reduce GHG emissions while also reducing LCCs, resulting in a negative abatement cost. Likewise, increasing the utilization of vehicles (i.e., % occupancy for passenger vehicles or % payload for freight vehicles) simultaneously decreases emissions and costs per pkm or per tkm, respectively. Within a given mode, alternative fuel sources also show strong potential to reduce emissions at minimal added costs. For LDVs, BEVs can offer emission reductions with LCCs that are already approaching that for conventional ICEVs. For transit and freight, near-term abatement costs for the low-carbon BEV and FCV options relative to their diesel counterparts range from near 0 USD/tonne CO_2-eq (e.g., BEV buses and BEV passenger rail) into the hundreds or even low thousands of dollars per tonne CO_2-eq (e.g., for heavy duty BEV and FCV trucks at current vehicle and fuel costs). With projected future declines in storage, fuel cell, and low-carbon Hydrogen fuel costs, however, both BEV and FCV technologies can likewise offer GHG reductions at negative abatement costs across all land-transport modes in 2030 and beyond. Further information about costs and potentials is available in Chapter 12.

10.5 Decarbonisation of aviation

This section addresses the potential for reducing GHG emissions from aviation. The overriding constraint on developments in technology and energy efficiency for this sector is safety. Governance is complex in that international aviation comes under the International Civil Aviation Organization (ICAO), a specialised UN agency. The measures to reduce GHG emissions that are considered include both in-sector (technology, operations, fuels) and out of sector (market-based measures, high-speed rail modal shift/substitution). Demand management is not explicitly considered in this section, as it was discussed in 10.2. A limited range of scenarios to 2050 and beyond are available and assessed at the end of the section.

10.5.1 Historical and current emissions from aviation

Aviation is widely recognised as a 'hard-to-decarbonise' sector (Gota et al. 2019) having a strong dependency on liquid fossil fuels and an infrastructure that has long 'lock-in' timescales, resulting in slow fleet turnover times. The principal GHG emitted is CO_2 from the combustion of fossil fuel aviation kerosene ('JET-A'), although its non-CO_2 emissions can also affect climate (see section 10.5.2). International emissions of CO_2 are about 65% of the total emissions from aviation (Fleming and de Lépinay 2019), which totalled approximately 1 Gt of CO_2 in 2018. Emissions from this segment of the transport sector have been steadily increasing at rates of around 2.5% per year over the last two decades (see Figure 10.10), although for the period 2010 to 2018 the rate increased to roughly 4% per year. The latest available data (2018) indicate that aviation is responsible for approximately 2.4% of total anthropogenic emissions of CO_2 (including land use change) on an annual basis (using IEA data, IATA data and global emissions data of Le Quéré et al., 2018).

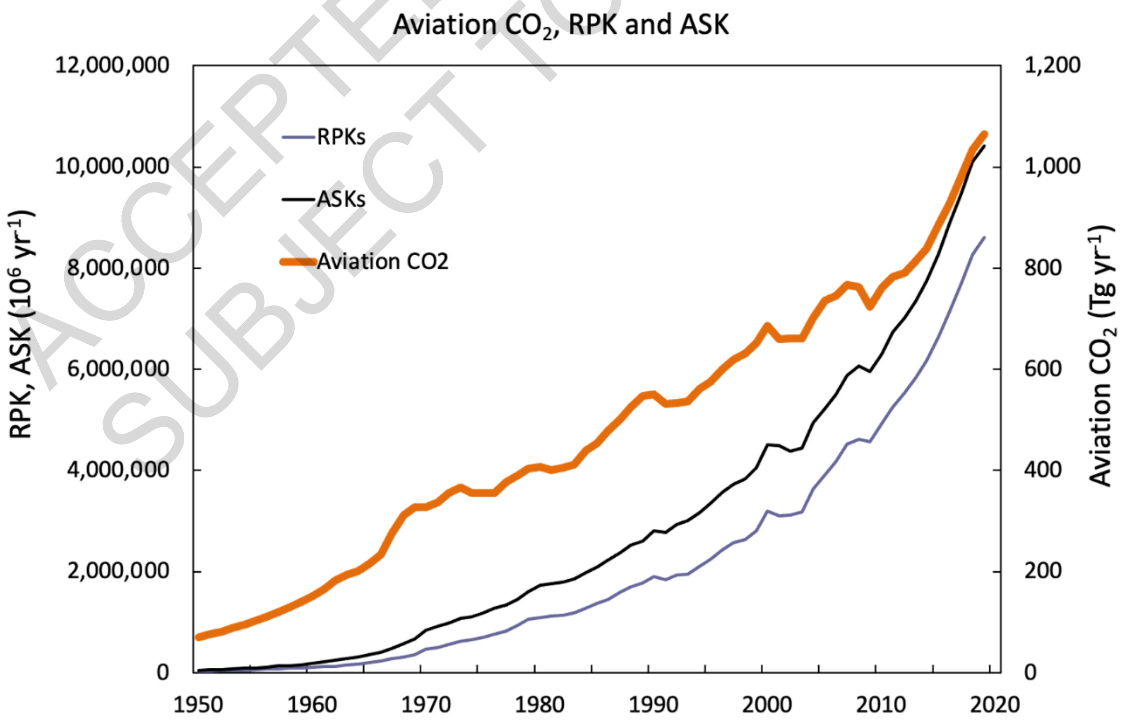


Figure 10.10 Historical global emissions of CO_2 from aviation, along with capacity and transport work (given in available seat kilometres, ASK; revenue passenger kilometres, RPK), Adapted from Lee et al. (2021) using IEA and other data

10.5.2 Short lived climate forcers and aviation

Aviation's net warming effect results from its historical and current emissions of CO_2, and non-CO_2 emissions of water vapour, soot, sulphur dioxide (from sulphur in the fuel), and nitrogen oxides (NO_x, = NO + NO_2) (Penner et al. 1999; Lee et al. 2021; Naik et al. 2021). Although the effective radiative forcing (ERF) of CO_2 from historic aviation emissions is not currently the largest forcing term, it is difficult to address because of the sector's current dependency on fossil-based hydrocarbon fuels and the longevity of CO_2. A residual of emissions of CO_2 today will still have a warming effect in many thousands of years (Archer et al. 2009; Canadell et al. 2021) whereas water vapour, soot, and NO_x emissions will have long ceased to contribute to warming after some decades. As a result, CO_2 mitigation of aviation to 'net zero' levels, as required in 1.5 ºC emission scenarios, requires fundamental shifts in technology, fuel types, or changes of behaviour or demand.

The non-CO_2 effects of aviation on climate fall into the category of short-lived climate forcers (SLCFs). Emissions of NO_x currently result in net positive warming from the formation of short-term ozone (warming) and the destruction of ambient methane (cooling). If the conditions are suitable, emissions of soot and water vapour can trigger the formation of contrails (Kärcher 2018), which can spread to form extensive contrail-cirrus cloud coverage. Such cloud coverage is estimated to have a combined ERF that is ~57% of the current net ERF of global aviation (Lee et al. 2021), although a comparison of cirrus cloud observations under pre- and post-COVID-19 pandemic conditions suggest that this forcing could be smaller (Digby et al. 2021). Additional effects from aviation from aerosol-cloud interactions on high-level ice clouds through soot (Chen and Gettelman 2013; Zhou and Penner 2014; Penner et al. 2018), and lower-level warm clouds through Sulphur (Righi et al. 2013; Kapadia et al. 2016) are highly uncertain, with no best estimates available (Lee et al. 2021). In total, the net ERF from aviation's non-CO_2 SLCFs is estimated to be approximately 66% of aviation's current total forcing. It is important to note that the fraction of non-CO_2 forcing to total forcing is not a fixed quantity and is dependent on the recent history of growth (or otherwise) of CO_2 emissions (Klöwer et al. 2021) The non-CO_2 effects from aviation are the subject of discussion for mitigation options (e.g., (Arrowsmith et al. 2020)). However, the issues are complex, potentially involving technological and operational trade-offs with $CO_{2.}$

10.5.3 Mitigation potential of fuels, operations, energy efficiency, and market-based measures

Technology options for engine and airframe: For every kg of jet fuel combusted, 3.16 kg CO_2 is emitted. Engine and airframe manufacturers' primary objective, after safety issues, is to reduce direct operating costs, which are highly dependent on fuel burn. Large investments have gone into engine technology and aircraft aerodynamics to improve fuel burn per km (Cumpsty et al. 2019). There have been major step changes in engine technology over time, from early turbojet engines, to larger turbofan engines. However, the basic configuration of an aircraft has remained more or less the same for decades and will likely remain at least to 2037 (Cumpsty et al. 2019). Airframes performance has improved over the years with better wing design, but large incremental gains have become much harder as the technology has matured. For twin-aisle aircraft, generally used for long ranges, fuel-burn is a pressing concern and there have been several all-new aircraft designs with improvements in their lift-to-drag ratio (Cumpsty et al. 2019). The principal opportunities for fuel reduction come from improvements in aerodynamic efficiency, aircraft mass reduction, and propulsion system improvements. In the future, Cumpsty et al. (2019) suggest that the highest rate of fuel burn reduction achievable for new aircraft is likely to be no more than about 1.3% per year, which is well short of ICAO's aspirational goal of 2% global annual average fuel efficiency improvement. Radically different aircraft shapes, like the blended wing body (where the wings are not distinct from the fuselage) are likely to use about 10% less fuel than future advanced aircraft of conventional form (Cumpsty et al. 2019). Such improvements would be "one-off" gains, do not compensate for growth in emissions of CO_2 expected to be in excess of 2% per annum, and would take a decade or more to penetrate the fleet completely. Thus, the literature does not support the idea that there are large improvements to be made in the energy efficiency of aviation that keep pace with the projected growth in air transport.

Operational improvements for navigation: From a global perspective, aircraft navigation is relatively efficient, with many long-haul routes travelling close to great circle trajectories, and avoiding headwinds that increase fuel consumption. The ICAO estimates that flight inefficiencies on a global basis are currently of the order 2–6% (ICAO 2019), while (Fleming and de Lépinay 2019) project operational improvements (air traffic management) of up to 13% on a regional basis by 2050. 'Intermediate stop operations' have been suggested, whereby longer-distance travel is broken into flight legs, obviating the need to carry fuel for the whole mission. (Linke et al. 2017) modelled this operational behaviour on a global basis and calculated a fuel savings of 4.8% over a base case in which normal fuel loads were carried. However, this approach increases the number of landing/take-off cycles at airports. 'Formation flying', which has the potential to reduce fuel burn on feasible routes has also been proposed (Xu et al. 2014; Marks et al. 2021).

Alternative biofuels, synthetic fuels, and liquid Hydrogen: As noted above, the scope for reducing CO_2 emissions from aviation through improved airplane technology or operations is limited and unable to keep up with the projected growth, let alone reduce beyond the present emission rate at projected levels of demand (assuming post-pandemic recovery of traffic). Thus, the literature outlined here suggests that the only way for demand for aviation to continue to grow without increasing CO_2 emissions is to employ alternative lower-carbon bio- or synthetic aviation fuels (Klöwer et al. 2021). For shorter ranges, flights of light planes carrying up to 50 passengers may be able to use electric power (Sahoo et al. 2020) but these planes are a small proportion of the global aviation fleet (Epstein and O'Flarity 2019; Langford and Hall 2020) and account for less than 12% of current aviation CO_2 emissions. Alternative lower-carbon footprint fuels have been certified for use over recent years, principally from bio-feedstocks, but are not yet widely available at economic prices (Kandaramath Hari et al. 2015; Capaz et al. 2021a). In addition, alternative fuels from bio-feedstocks have variable carbon footprints because of different life cycle emissions associated with various production methods and associated land-use change (de Jong et al. 2017; Staples et al. 2018; Capaz et al. 2021b; Zhao et al. 2021).

The development of 'sustainable aviation fuels' (referred to as 'SAFs') that can reduce aviation's carbon footprint is a growing area of interest and research. Alternative aviation fuels to replace fossil-based kerosene have to be certified to an equivalent standard as Jet-A for a variety of parameters associated with safety issues. Currently, the organisation responsible for aviation fuel standards, ASTM International, has certified seven different types of sustainable aviation fuels with maximum blends ranging from 10% to 50% (Chiaramonti 2019). Effectively, these blend requirements limit the amount of non-hydrocarbon fuel (e.g., Methanol) that can be added at present. While there currently is a minimum level of aromatic hydrocarbon contained in jet fuel to prevent 'O-ring' shrinkage in the fuel seals (Khandelwal et al. 2018), this minimum level can likely be lower in the medium- to long- term, with the added benefits of reduced soot formation and reduced contrail cirrus formation (Bier et al. 2017; Bier and Burkhardt 2019).

Bio-based fuels can be produced using a variety of feedstocks including cultivated feedstock crops, crop residues, municipal solid waste, waste fats, oils and greases, wood products and forestry residues (Staples et al. 2018). Each of these different sources can have different associated life cycle emissions, such that they are not net zero-CO_2 emissions but have associated emissions of CO_2 or other GHGs from their production and distribution (see Section 10.3 and Box 10.2). In addition, associated land use change emissions of CO_2 represent a constraint in climate change mitigation potential with biofuel

(Staples et al. 2017) and has inherent large uncertainties (Plevin et al. 2010). Other sustainability issues include food vs. fuel arguments, water resource use, and impacts on biodiversity. Cost-effective production, feedstock availability, and certification costs are also relevant (Kandaramath Hari et al. 2015). Nonetheless, bio-based SAFs have been estimated to achieve life cycle emissions reductions ranging between approximately 2% and 70% under a wide range of scenarios (Staples et al. 2018). For a set of European aviation demand scenarios, Kousoulidou and Lonza (2016) estimated that the fuel demand in 2030 would be ~100 Mtoe and biokerosene (HEFA/HVO) penetration would provide around 2% of the total fuel demand at that date. Several issues limit the expansion of biokerosene for aviation, the primary one being the current cost of fossil fuel compared to the costs SAF production (Capaz et al. 2021a). Other hybrid pathways e.g., the Hydrogenation of biofuels (the Hydrogen assumed to be generated with low carbon energy), could increase the output and improve the economic feasibility of bio-based SAF (Hannula 2016; Albrecht et al. 2017).

Costs remain a major barrier for bio-SAF, which cost around three times the price of kerosene by (Kandaramath Hari et al. 2015). Clearly, for SAFs to be economically competitive, large adjustments in prices of fossil fuels or the introduction of policies is required. Staples et al. (2018) estimated that in order to introduce bio-SAFs that reduce life cycle GHG emissions by at least 50% by 2050, prices and policies were necessary for incentivization. They estimate the need for 268 new biorefineries per year and capital investments of approximately USD 22 to 88 billion (2015 prices) per year between 2020 and 2050. Wise et al. (2017) suggest that carbon prices would help leverage production and availability.

Various pathways have been discussed for the production of non-bio SAFs such as power-to-liquid pathways (Schmidt et al. 2018), sometimes termed 'electro-fuels' (Goldmann et al. 2018), or more generalised power to 'x' pathways (Kober and Bauer 2019). This process would involve the use of low carbon energy electricity, CO_2, and water to synthesise jet fuel through the Fischer-Tropsch process or Methanol synthesis. Hydrogen would be produced via an electrochemical process, powered by low carbon energy and combined with CO_2 captured directly from the atmosphere or through BECCS. The energy requirement from photovoltaics has been estimated to be of the order 14 – 20 EJ to phase out aviation fossil fuel by 2050 (Gössling et al. 2021a). These synthetic fuels have potential for large life cycle emission reductions (Schmidt et al. 2016). In comparison to bio-SAF production, the implementation of the processes is in its infancy. However, assuming availability of low carbon energy electricity, these fuels have much smaller land and water requirements than bio-SAF. Low carbon energy supply, scalable technology, and therefore costs represent barriers. (Scheelhaase et al. 2019) review current estimates of costs, which are estimated to be approximately 4 to 6 times the price of fossil kerosene.

Liquid Hydrogen (LH_2) as a fuel has been discussed for aeronautical applications since the 1950s (Brewer 1991) and a few experimental aircraft have flown using such a fuel. Experimental, small aircraft have also flown using Hydrogen fuel cells. Although the fuel has an energy density per unit mass about 3 times greater than kerosene, it has a much lower energy density per unit volume (approximately factor 4, (McKinsey 2020)). The increased volume requirement makes the fuel less attractive for aviation since it would require the wings to be thickened or else fuel to take up space in the fuselage. Bicer and Dincer (2017) found that LH_2-powered aircraft compared favourably to conventional kerosene-powered aircraft on a life cycle basis, providing that the LH_2 was generated from low carbon energy sources (0.014 kg CO_2 per tonne km *cf* 1.03 kg CO_2 per tonne km, unspecified passenger aircraft). However, Ramos Pereira et al. (2014) also made a life cycle comparison and found much smaller benefits of LH_2-powered aircraft (manufactured from low carbon energy) compared with conventional fossil-kerosene. The two studies expose the sensitivities of boundaries and assumptions in the analyses. (Shreyas Harsha 2014; Rondinelli et al. 2017) conclude that there are many infrastructural barriers but that the environmental benefits of low carbon-based LH_2 could be considerable. Khandelwal et al. (2013) take a more optimistic view of the prospect of LH_2-powered aircraft but envisage them within a Hydrogen-oriented energy economy. A recently commissioned study by the European Union (EU)'s 'Clean Sky' (McKinsey 2020) addresses many of the aspects of the opportunities and obstacles in developing LH_2 powered aircrafts. The report provides an optimistic view of the feasibility of developing such aircraft for short to medium haul but makes clear that new aircraft designs (such as blended-wing body aircraft) would be needed for longer distances.

The non-CO_2 impacts of LH_2-powered aircrafts remain poorly understood. The emission index of water vapour would be much larger (estimated to be 2.6 times greater by Ström and Gierens (2002)) than for conventional fuels, and the occurrence of contrails may increase but have lower ERF because of the lower optical depth (Marquart et al. 2005). Moreover, contrails primarily form on soot particles from kerosene-powered aircraft, which would be absent from LH_2 exhaust (Kärcher 2018). The overall effect is currently unknown as there are no measurements. Potentially, NO_x emissions could be lower with combustor redesign (Khandelwal et al. 2013).

In conclusion, there are favourable arguments for LH_2-powered aircraft both on an efficiency basis (Verstraete 2013) and an overall reduction in GHG emissions, even on an life cycle basis. However, LH_2 requires redesign of the aircraft, particularly for long-haul operations. Similarly, there would be a need for expanded infrastructure for fuel manufacture, storage, and distribution at airports, which is likely to be more easily overcome if there is a more general move towards a Hydrogen-based energy economy.

Technological and operational trade-offs between CO_2 and non-CO_2 effects: Since aviation has additional non-CO_2 warming effects, there has been some discussion as to whether these can be addressed by either technological or operational means. For example, improved fuel efficiency has resulted from high overall pressure ratio engines with large bypass ratios. This improvement has increased pressure and temperature at the combustor inlet, with a resultant tendency to increase thermal NO_x formation in the combustor. Combustor technology aims to reduce this increase, but it represents a potential technology trade-off whereby NO_x control may be at the expense of extra fuel efficiency. Estimating the benefits or disbenefits of CO_2 (proportional to fuel burned) vs. NO_x in terms of climate is complex (Freeman et al. 2018).

Any GWP/GTP type emissions equivalency calculation always involves the user selection of a time horizon over which the calculation is made, which is a *subjective* choice (Fuglestvedt et al. 2010). In general, the longer the time horizon, the more important CO_2 becomes in comparison with a short-lived climate forcing agent. So, for example, a net (overall) aviation GWP for a 20-year time horizon is 4.0 times that of CO_2 alone, but only 1.7 over a 100-year time horizon. Correspondingly, a GTP for a 20-year time horizon is 1.3, but it is 1.1 for 100 years (Lee et al. 2021).

A widely discussed opportunity mitigation of non-CO_2 emissions from aviation is the avoidance of persistent contrails that can form contrail cirrus. Contrails only form in ice-supersaturated air below a critical temperature threshold (Kärcher 2018). It is therefore feasible to alter flight trajectories to avoid such areas conducive to contrail formation, since ice-supersaturated areas tend to be 10s to 100s of km in the horizontal and only a few 100 metres in the vertical extent (Gierens et al. 1997). Theoretical approaches show that avoidance is possible on a flight-by-flight basis (Matthes et al. 2017; Teoh et al. 2020). Case studies have shown that flight planning according to trajectories with minimal climate impact can substantially (up to 50%) reduce the aircraft net climate impacts despite small additional CO_2 emissions (e.g., (Niklaß et al. 2019)). However, any estimate of the net benefit or disbenefit depends firstly on the assumed magnitude of the contrail cirrus ERF effect (itself rather uncertain, assessed with a low confidence level;) and upon the choice of metric and time-horizon applied. While this is a potentially feasible mitigation option, notwithstanding the CO_2 percontrail trade-off question, meteorological models cannot currently predict the formation of persistent contrails with sufficient accuracy in time and space (Gierens et al. 2020) such that this mitigation option is speculated to take of the order of up to a decade to mature (Arrowsmith et al. 2020)

Market-based offsetting measures: The EU introduced aviation into its CO_2 emissions trading scheme (ETS) in 2012. Currently, the EU-ETS for aviation includes all flights within the EU as well as to and from EEA states. Globally, ICAO agreed in 2016 to commence, in 2020, the 'Carbon Offsetting and Reduction Scheme for International Aviation' (CORSIA). The pandemic subsequently resulted in the baseline being changed to 2019.

CORSIA has a phased implementation, with an initial pilot phase (2021–2023) and a first phase (2024–2026) in which states will participate voluntarily. The second phase will then start in 2026–2035, and all states will participate unless exempted. States may be exempted if they have lower aviation activity levels or based on their UN development status. As of September 2021, 109 ICAO Member States will voluntarily be participating in CORSIA starting in 2022. In terms of routes, only those where both States are participating are included. There will be a special review of CORSIA by the end of 2032 to determine the termination of the scheme, its extension, or any other changes to the scheme beyond 2035.

By its nature, CORSIA does not lead to a reduction in in-sector emissions from aviation since the program deals mostly in approved offsets. At its best, CORSIA is a transition arrangement to allow aviation to reduce its impact in a more meaningful way later. From 2021 onwards, operators can reduce their CORSIA offsetting requirements by claiming emissions reductions from 'CORSIA Eligible Fuels' that have demonstrably reduced life cycle emissions. These fuels are currently available at greater costs than the offsets (Capaz et al. 2021a). As a result, most currently approved CORSIA offsets are avoided emissions, which raises the issue of additionality (Warnecke et al. 2019) The nature of 'avoided emissions' is to prevent an emission that was otherwise considered to be going to occur, e.g. prevented deforestation. Avoided emissions are 'reductions' (over a counterfactual) and purchased from other sectors that withhold from an intended emission (Becken and Mackey 2017), such that if additionality were established, a maximum of 50% of the intended emissions are avoided. Some researchers suggest that avoided deforestation offsets are not a meaningful reduction, since deforestation continues to be a net source of CO_2 emissions (Mackey et al. 2013; Friedlingstein et al. 2020).

Modal shift to High-Speed Rail: Due to the limitations of the current suite of aviation mitigation strategies, the potential for high-speed rail (HSR) is of increasing interest (Givoni and Banister 2006; Chen 2017; Bi et al. 2019). The IEA's Net Zero by 2050 roadmap suggests significant behavioural change with more regional flights shifting to HSR in the NZE pathway (IEA 2021e). For HSR services to be highly competitive with air travel, the optimal distance between the departure and arrival points has been found to be in the approximate range of 400-800 km (Bows et al. 2008; Rothengatter 2010), although in the case of China's HSR operations, this range can be extended out to 1,000 km with corresponding air services having experienced significant demand reduction upon HSR service commencement (Lawrence et al. 2019). In some instances, negative effects on air traffic, air fare, and flight frequency have occurred at medium-haul distances such as HSR services in China on the Wuhan-Guangzhou route (1,069 km) and the Beijing-Shanghai route (1,318 km) (Fu et al. 2015; Zhang and Zhang 2016; Chen 2017; Li et al. 2019; Ma et al. 2019). This competition at medium-haul distances is contrary to that which has been experienced in European and other markets and may be attributable to China having developed a comprehensive network with hub stations, higher average speeds, and an integrated domestic market with strong patronage (Zhang et al. 2019a).

The LCA literature suggests that the GHG emissions associated with HSR vary depending on spatial, temporal, and operational specifics (Åkerman 2011; Baron et al. 2011; Chester and Horvath 2012; Yue et al. 2015; Hoyos et al. 2016; Jones et al. 2017; Robertson 2016, 2018; Lin et al. 2019). These studies found a wide range of approximately 10 - 110 grams CO_2 per pkm for HSR. This range is principally attributable to the sensitivity of operational parameters such as the HSR passenger seating capacity, load factor, composition of renewable and non-renewable energy sources in electricity production, rolling stock energy efficiency and patronage (i.e. ridership both actual and forecast), and line-haul infrastructure specifics (e.g. tunnelling and aerial structure requirements for a particular corridor) (Åkerman 2011; Chester and Horvath 2012; Yue et al. 2015; Newman et al. 2018; Robertson 2018) The prospect for HSR services providing freight carriage (especially on-line purchases) is also growing rapidly (Strale 2016; Bi et al. 2019; Liang and Tan 2019) with a demonstrated emission reduction potential from such operations (Hoffrichter et al. 2012). However, additional supportive policies will most likely be required (Strale 2016; Watson et al. 2019). Limiting emissions avoidance assessments for HSR modal substitution to account only for CO_2 emissions ignores aviation's non-CO_2 effects (see Section 10.5.2), and likely results in an under-representation of the climate benefits of HSR replacing flights.

HSR modal substitution can generate a contra-effect if the air traffic departure and arrival slots that become available as the result of the modal shift are simply reallocated to additional air services (Givoni and Banister 2006; Givoni and Dobruszkes 2013; Jiang and Zhang 2016; Cornet et al. 2018; Zhang et al. 2019a). Furthermore, HSR services have the potential to increase air traffic at a hub airport through improved networks but this effect can vary based on the distance of the HSR stations to airports (Jiang and Zhang 2014; Xia and Zhang 2016; Zhang et al. 2019b; Liu et al. 2019). Such rebound effects could be managed through policy interventions. For example, in 2021 the French government regulated that all airlines operating in France suspend domestic airline flights on routes if a direct rail alternative with a travel time of less than 2.5 hours is available. Other air travel demand reduction measures that have been proposed include regulations to ban frequent flyer reward schemes, mandates that all marketing of air travel declare flight emissions information to the prospective consumer (i.e., the carbon footprint of the nominated flight), the introduction of a progressive 'Air Miles Levy' as well as the inclusion of all taxes and duties that are presently exempt from air ticketing (Carmichael 2019). Moreover, China has the highest use of HSR in the world in part due to its network and competitive speeds and in part due to heavy regulation of the airline industry, in particular restrictions imposed on low-cost air carrier entry and subsidisation of HSR (Li et al. 2019). These air travel demand reduction strategies in addition to stimulating HSR ridership may induce shifts to other alternative modes.

Despite the risk of a rebound effect, and due to the probable reality of an incremental adoption of sustainable aviation fuel technology in the coming decades, the commencement of appropriate HSR services has the potential to provide, particularly in the short to medium-term, additional means of aviation emissions mitigation.

10.5.4 Assessment of aviation-specific projections and scenarios

The most recent projection from ICAO (prior to the COVID-19 pandemic) for international traffic (mid-range growth) is shown in Figure 10.11 (Fleming and de Lépinay 2019). This projection shows the different contributions of mitigation measures from two levels of improved technology, as well as improvements in air traffic management (ATM) and infrastructure use. The projections indicate an increase of CO_2 emissions by a factor of 2.2 in 2050 over 2020 levels for the most optimistic set of mitigation assumptions. The high/low traffic growth assumptions would indicate increases by factors of 2.8 and 1.1, respectively in 2050, over 2020 levels (again, for the most optimistic mitigation assumptions).

The International Energy Agency has published several long-term aviation scenarios since the AR5 within a broader scope of energy projections. Their first set of aviation scenarios include a 'reference technology scenario' (RTS), a '2° Scenario' (2DS) and a 'Beyond 2° Scenario' (B2DS). The scenarios are simplified in assuming a range of growth rates and technological/operational improvements (IEA 2017b) Mitigation measures brought about by policy and regulation are treated in a broad-brush manner, noting possible uses of taxes, carbon pricing, price and regulatory signals to promote innovation.

The IEA has more recently presented aviation scenarios to 2070 in their 'Sustainable Development Scenario' that assume some limited reduced post-COVID-19 pandemic demand, and potential technology improvements in addition to direct reductions in fossil kerosene usage from substitution of biofuels and synthetic fuels (IEA 2021b). There is much uncertainty in how aviation will recover from the COVID-19 pandemic but, in this scenario, air travel returns to 2019 levels in three years, and then continues to expand, driven by income. Government policies could dampen demand (12% lower by 2040 than the IEA 'Stated Policies Scenario,' which envisages growth at 3.4% per year, which in turn is lower than ICAO at 4.3%). Mitigation takes place largely by fuel substitution – lower-carbon biofuels and synthetic fuels, with a smaller contribution from technology. Approximately 85% of the actual cumulative CO_2 emissions (to 2070) are attributed to use of fuel at their lowest Technology Readiness Level of 'Prototype,' which is largely made up of biofuels and synthetic fuels, as shown in Figure 10.12. Details of the technological scenarios and the fuel availability/uptake assumptions are given in (IEA 2021b), which also makes clear that the relevant policies are not currently in place to make any such scenario happen.

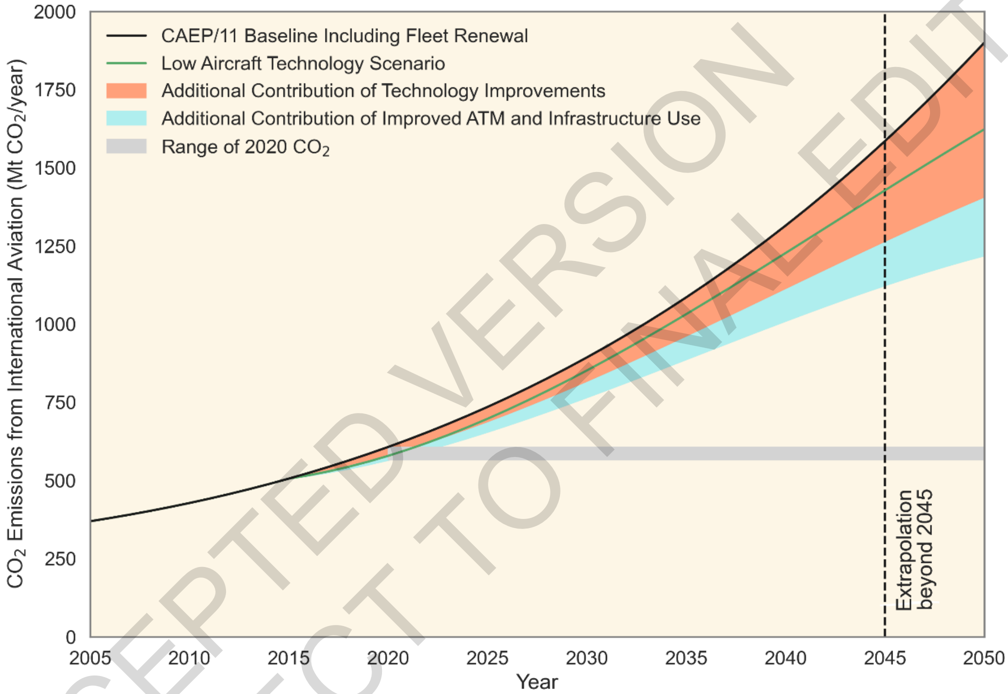


Figure 10.11 Projections of international aviation emissions of CO_2. Data in Mt yr-1, to 2050, showing contributions of improved technology, and air traffic management and infrastructure to emissions reductions to 2050.

Data from Fleming and de Lépinay (2019); projections made pre-COVID-19 global pandemic

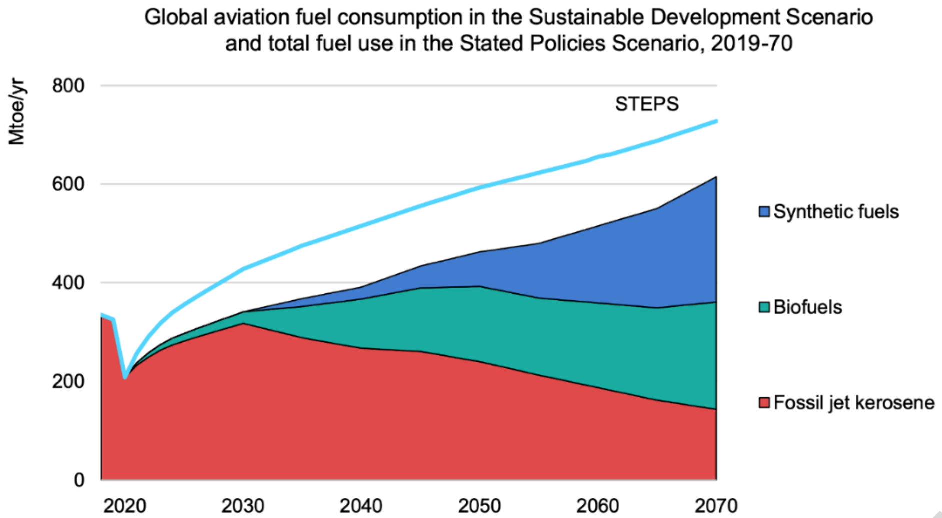


Figure 10.12 The International Energy Agency's scenario of future aviation fuel consumption for the States Policies Scenario ('STEPS') and composition of the Sustainable Development Scenario (from (IEA 2021b))

Within the Coupled Model Intercomparison Project Phase 6 (CMIP6) emissions database, a range of aviation emission scenarios for a range of SSP scenarios are available (see Figure 10.13). This figure suggests that by 2050, direct emissions from aviation could be 1.5 to 6.5 (5-95th percentile) times higher than in the 2020 model year under the scenarios without firm commitments to meet a long-term temperature target (i.e., C7-8 scenarios with temperature change above 2.5°C by 2100). In the C1-2 scenario group, which limit temperature change below 1.5°C, aviation emissions could still be up to 2.5 times higher in 2050 than emissions in the 2020 model year (95th percentile) but may need to decrease by 10% by 2050 (5th percentile).

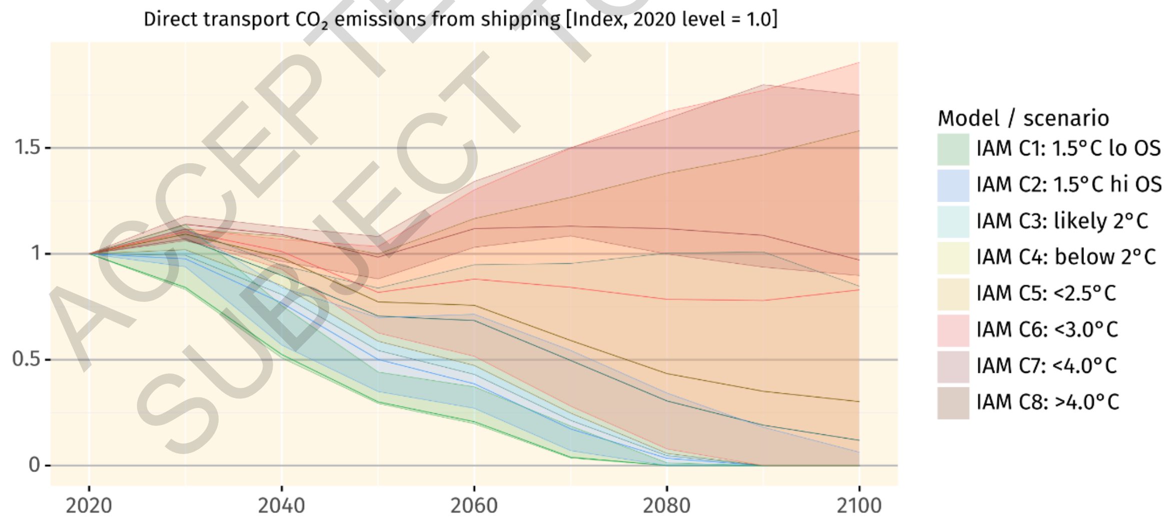


Figure 10.13 CO_2 emission from AR6 aviation scenarios indexed to 2020 modelled year. Data from the AR6 scenario database.

The COVID-19 pandemic of 2020 has changed many activities and consequentially, associated emissions quite dramatically (Le Quéré et al. 2018; Friedlingstein et al. 2020; Liu et al. 2020c; UNEP 2020). Aviation was particularly affected, with a reduction in commercial flights in April 2020 of ~74%

over 2019 levels, with some recovery over the following months, remaining at 42% lower as of October 2020 (Petchenik 2021). The industry is considering a range of potential recovery scenarios, with the International Air Transport Association (IATA) speculating that recovery to 2019 levels may take up until 2024 (see Box on COVID-19 and (Early and Newman 2021). Others suggest, however, that the COVID-19 pandemic and increased costs as a result of feed-in quotas or carbon taxes, could slow down the rate of growth of air travel demand, though global demand in 2050 would still grow 57%–187% between 2018 and 2050 (instead of 250% in a baseline recovery scenario) (Gössling et al. 2021a).

10.5.5 Accountability and governance options

Under Article 2.2 of the Kyoto Protocol, Annex I countries were called to *"...pursue limitation or reduction of emissions of GHGs not controlled by the Montreal Protocol from aviation and marine bunker fuels, working through the International Civil Aviation Organization and the International Maritime Organization, respectively.*" The Paris Agreement is different, in that ICAO (and the IMO) are not named. As a result, the Paris Agreement, through the NDCs, seemingly covers CO_2 emissions from domestic aviation (currently 35% of the global total) but does not cover international emissions. A number of states and regions, including the UK, France, Sweden, and Norway, have declared their intentions to include international aviation in their net zero commitments, while the EU, New Zealand, California, and Denmark are considering doing the same (Committee on Climate Change 2019). The Paris Agreement describes temperature-based goals, such that it is unclear how emissions of GHGs from international aviation would be accounted for. Clearly, this is a less than ideal situation for clarity of governance of international GHG emissions from both aviation and shipping. At its 40th General Assembly (October 2019) the ICAO requested its Council to "*...continue to explore the feasibility of a long-term global aspirational goal for international aviation, through conducting detailed studies assessing the attainability and impacts of any goals proposed, including the impact on growth as well as costs in all countries, especially developing countries, for the progress of the work to be presented to the 41st Session of the ICAO Assembly*". What form this goal will take is unclear until work is presented to the 41st Assembly (Autumn, 2022). It is likely, however, that new accountability and governance structures will be needed to support decarbonisation of the aviation sector.

10.6 Decarbonisation of Shipping

Maritime transport is considered one of the key cornerstones enabling globalisation (Kumar and Hoffmann 2002). But as for aviation, shipping has its challenges in decarbonisation, with a strong dependency on fossil fuels without major changes since AR5. At the same time, the sector has a range of opportunities that could help reduce emissions through not only changing fuels, but also by increasing the energy efficiency, optimising operations and ship design, reducing demand, improving regulations, as well as other options that will be reviewed in this section.

10.6.1 Historical and current emissions from shipping

Maritime transport volume has increased by 250% over the past 40 years, reaching an all-time high of 11 billion tons of transported goods in 2018 (UNCTAD 2019). This growth in transport volumes has resulted in continued growth in GHG emissions from the shipping sector, despite an improvement in the carbon intensity of ship operations, especially since 2014. The estimated total emissions from maritime transport can vary depending on data set and calculation method, but range over 600 – 1,100 Mt CO_2 per year over the past decade (Figure 10. 14), corresponding to 2 - 3% of total anthropogenic emissions. The legend in Figure 10.14 refers to the following data sources: (Endresen et al. 2003), (Eyring et al. 2005), (Dalsøren et al. 2009), DNV-GL (DNV GL 2019), CAMS-GLOB-SHIP (Jalkanen et al. 2014; Granier et al. 2019), EDGAR (Crippa et al. 2019), (Hoesly et al. 2018), (Johansson et al. 2017), ICCT (Olmer et al. 2017), the IMO GHG Studies; IMO 2nd (Buhaug et al. 2009), IMO 3rd (Smith et al. 2014), IMO 4th-vessel and IMO 4th-voyage (Faber et al. 2020), and (Kramel et al. 2021).

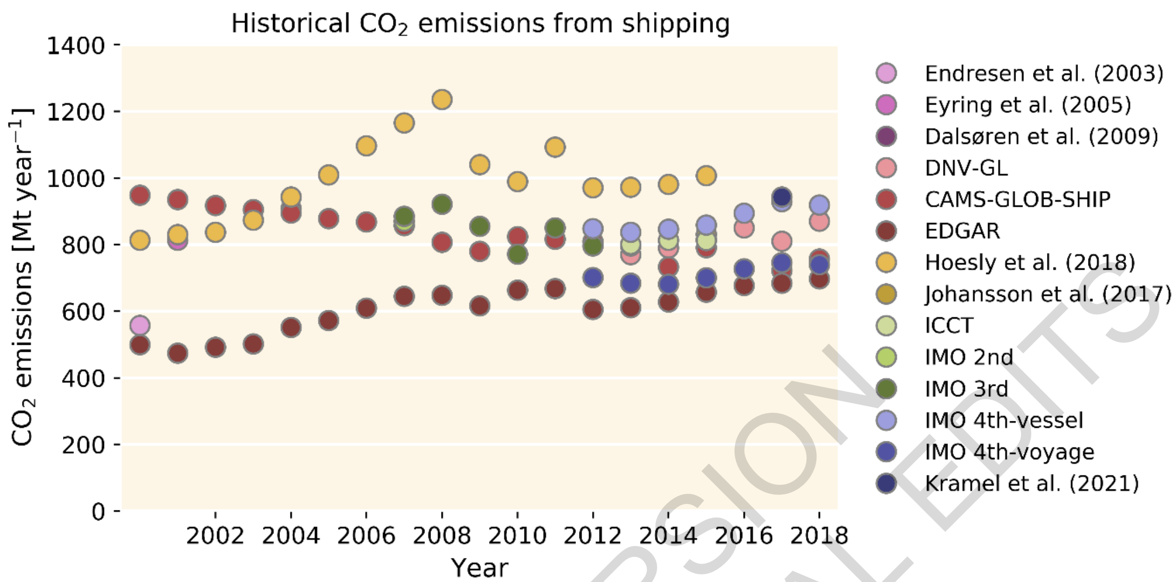


Figure 10.14 CO_2 emissions (Mt year-1) from shipping 2000 – 2018. Data from various inventories as shown in the label.

10.6.2 Short lived climate forcers and shipping

Like aviation, shipping is also a source of emissions of the SLCFs described in Section 10.5, including nitrogen oxides (NO_x), sulphur oxides (SO_2 and SO_4), carbon monoxide (CO), black carbon (BC), and non-methane volatile organic carbons (NMVOCs) (Naik et al. 2021). Though SLCF have a shorter lifetime than the associated CO_2 emissions, these short-lived forcers can have both a cooling effect (e.g., SO_x) or a warming effect (e.g., ozone from NO_x). The cooling from the SLCF from a pulse emission will decay rapidly and diminish after a couple of decades, whilst the warming from the long-lived substances lasts for centuries (Naik et al. 2021).

Emissions of SLCF from shipping not only affects the climate, but also the environment, air quality, and human health. Maritime transport has been shown to be a major contributor to coastal air quality degradation (Viana et al. 2014; Zhao et al. 2013; Jalkanen et al. 2014; Goldsworthy and Goldsworthy 2015; Goldsworthy 2017). Sulphur emissions may contribute towards acidification of the ocean (Hassellöv et al. 2013). Furthermore, increases in sulphur deposition on the oceans has also been shown to increase the flux of CO_2 from the oceans to the atmosphere (Hassellöv et al. 2013). To address the risks of SO_x emissions from shipping, there is now a cap on the on the amount of sulphur content permissible in marine fuels (IMO 2013). There is also significant uncertainty about the impacts of pollutants emitted from ships on the marine environment (Blasco et al. 2014).

Pollution control is implemented to varying degrees in the modelling of the SSP scenarios (Rao et al. 2017); for example, SSPs 1 and 5 assume that increasing concern for health and the environment result in more stringent air pollution policies than today (Naik et al. 2021). There is a downward trend in SO_x and NO_x emissions from shipping in all the SSPs, in compliance with regulations. The SLCF emission reduction efforts, within the maritime sector, are also contributing towards achieving the UN SDGs. In essence, while long lived GHGs are important for long term mitigation targets, accounting for short lived climate forcers is important both for current and near-term forcing levels as well as broader air pollution and SDG implications.

10.6.3 Shipping in the Arctic

Shipping in the Arctic is a topic of increasing interest. The reduction of Arctic summer sea ice increases the access to the northern sea routes (Melia et al. 2016; Smith and Stephenson 2013; Aksenov et al. 2017; Fox-Kemper et al. 2021). Literature and public discourse on the increased access sometimes has portrayed this trend as positive (Zhang et al. 2016b), as it allows for shorter shipping routes, e.g. between Asia and Europe with estimated travel time savings of 25 – 40% (Aksenov et al. 2017). However, the acceleration of Arctic cryosphere melt and reduced sea ice that enable Arcitc shipping reduce surface albedo and amplify climate warming (Eyring et al. 2021). Furthermore, local air pollutants can play different roles in the Arctic. For example, Black Carbon (BC) emissions reduce albedo and absorb heat in air, on snow and ice (Messner 2020; Browse et al. 2013; Kang et al. 2020; Eyring et al. 2021). Finally, changing routing from Suez to the north-eastern sea route may reduce total emissions for a voyage, but also shift emissions from low to high latitudes. Changing the location of the emissions adds complexity to the assessment of the climatic impacts of Arctic shipping, as the local conditions are different and the SLCF may have a different impact on clouds, precipitation, albedo and local environment (Marelle et al. 2016; Fuglestvedt et al. 2014; Dalsøren et al. 2013). Observations have shown that 5-25% of air pollution in the Arctic stem from shipping activity within the Arctic itself (Aliabadi et al. 2015). Emissions outside of the Arctic can affect Arctic climate, and changes within the Arctic may have global climate impacts. Both modelling and observations have shown that aerosol emissions from shipping can have a significant effect on air pollution, and shortwave radiative forcing (Peters et al. 2012; Roiger et al. 2014; Marelle et al. 2016; Dalsøren et al. 2013; Ødemark et al. 2012; Righi et al. 2015).

Increased Arctic shipping activity may also impose increased risks to local marine ecosystems and coastal communities from invasive species, underwater noise, and pollution (Halliday et al. 2017; IPCC 2019). Greater levels of Arctic maritime transport and tourism have political, as well as socio-economic implications for trade, and nations and economies reliant on the traditional shipping corridors. There has been an increase in activity from cargo, tankers, supply, and fishing vessels in particular (Zhao et al. 2015; Winther et al. 2014). Projections indicate more navigable Arctic waters in the coming decades (Smith and Stephenson 2013; Melia et al. 2016) and continued increases in transport volumes through the northern sea routes (Winther et al. 2014; Corbett et al. 2010; Lasserre and Pelletier 2011). Emission patterns and quantities, however, are also likely to change with future regulations from IMO, and depend on technology developments, and activity levels which may depend upon geopolitics, commodity pricing, trade, natural resource extractions, insurance costs, taxes, and tourism demand (Johnston et al. 2017). The need to include indigenous peoples' voices when shaping policies and governance of shipping activities in the high north is increasing (Dawson et al. 2020).

The Arctic climate and environment pose unique hazards and challenges with regards to safe and efficient shipping operations: low temperature challenges, implications for vessel design, evacuation and rescue systems, communications, oil spills, variable sea ice, and meteorological conditions (Buixadé Farré et al. 2014). To understand the total implications of shipping in the Arctic, including its climate impacts, a holistic view of synergies, trade-offs, and co-benefits is needed, with assessments of impacts on not only the physical climate, but also the local environment and ecosystems. To furthermore ensure safe operations in the Arctic waters, close monitoring of activities may be valuable.

10.6.4 Mitigation potential of fuels, operations and energy efficiency

A range of vessel mitigation options for the international fleet exist and are presented in this section. A variety of feedstocks and energy carriers can be considered for shipping. As feedstocks, fuels from biomass (advanced biofuels), fuels produced from renewable electricity and CO_2 capture from flue gas or the air (electro-, e-, or power-fuels), and fuels produced via thermochemical processes (solar fuels) can be considered. As energy carriers, synthetic fuels and the direct use of electricity (stored in batteries) are of relevance. The most prominent synthetic fuels discussed in literature are Hydrogen, Ammonia, Methane, Methanol, and synthetic hydrocarbon diesel. Figure 10.15 shows the emissions reductions potential for alternative energy carriers that have been identified as having the highest potential to mitigate operational emissions from the sector (Psaraftis 2015; DNV GL 2017; Hansson et al. 2019; Gilbert et al. 2018; Balcombe et al. 2019; Brynolf et al. 2014; Winebrake et al. 2019; Perčić et al. 2020; Bongartz et al. 2018; Biernacki et al. 2018; Faber et al. 2020; Sharafian et al. 2019; Seddiek 2015; ITF 2018b; Seithe et al. 2020; Xing et al. 2020; Czermański et al. 2020; Hua et al. 2018; Bicer and Dincer 2018a; Kim et al. 2020; Liu et al. 2020a; Hansson et al. 2020; Singh et al. 2018; Valente et al. 2021; Sadeghi et al. 2020; Nguyen et al. 2020; Stolz et al. 2021; Winkel et al. 2016; Chatzinikolaou and Ventikos 2013; Lindstad et al. 2015; Tillig et al. 2015; Traut et al. 2014; Teeter and Cleary 2014).

Low-carbon Hydrogen and Ammonia are seen to have a positive potential as a decarbonised shipping fuel. Hydrogen and Ammonia when produced from renewables or coupled to CCS, as opposed to mainly by fossil fuels with high life-cycle emissions (Bhandari et al. 2014), may contribute to significant CO_2-eq reductions of up to 70 - 80% compared to low-sulphur heavy fuel oil (Bicer and Dincer 2018b; Gilbert et al. 2018). These fuels have their own unique transport and storage challenges as Ammonia requires a pilot fuel due to difficulty in combustion, and Ammonia combustion could lead to elevated levels of NO_x, N_2O, or NH_3 emissions depending on engine technology used (DNV GL 2020). There is a need for the further development of technology and procedures for safe storage and handling of fuels such as Hydrogen and Ammonia both onboard and onshore for a faster rate of uptake of such shipping fuels (Hoegh-Guldberg et al. 2019), but they remain an encouraging decarbonisation option for shipping in the next decade.

While Methanol produced from fossil sources induces an emission increase of +7.5% (+44%), e-Methanol (via Hydrogen from electrolysis based on renewable energy and carbon from direct air capture) reduces emission by 80% (82%). In general, several synthetic fuels, such as synthetic diesel, methane, Methanol, ethanol, and dimethyl ether (DME) could in principle be used for shipping (Horvath et al. 2018). The mitigation potential of these is though fully dependent on the sourcing of the Hydrogen and carbon required for their synthesis.

As noted in Section 10.3, LNG has been found to have a relatively limited mitigation potential and may not be viewed as a low-carbon alternative, but has a higher availability than other fuel options (Gilbert et al. 2018). Emission reductions across the full fuel life cycle are found in the order of 10%, with ranges reported from -30% (reduction) to +8% (increase), if switching from heavy fuel oil to LNG, as indicated in Figure 10.15 (Bengtsson et al. 2011). Regardless of the production pathway, the literature points to the risk of methane slip (emissions of unburnt methane especially at low engine loads and from transport to ports) from LNG fuelled vessels, with no current regulation on emission caps (Ushakov et al. 2019; Anderson et al. 2015; Peng et al. 2020). Leakage rates are a critical point for the total climate impact of LNG as a fuel, where high pressure engines remedy this more than low pressure ones. As discussed in 10.3, some consider LNG as a transition fuel, whilst some literature point to the risk of stranded assets due to the increasing decarbonisation regulation from IMO and the challenge of meeting IMO's 2030 emissions reductions targets using this fuel.

In addition to fossil and e-fuels, advanced biofuels might play a role to provide the energy demand for future shipping. Biomass is presently used to produce alcohol fuels (such as ethanol and Methanol), liquid biogas, or biodiesel that can be used for shipping and could reduce CO_2 emissions from this segment. As explained in Box 10.2 and Chapter 7, the GHG footprint associated with biofuels is strongly dependent on the incurred land us and land use change emissions. Advanced biofuels from processing cellulose rather than sugar are likely to be more attractive in terms of the quantities required but are not commercially available Section 10.3. The estimates of emissions reductions from biofuels shown in Figure 10.15 rely on data from the Integrated Assessment Models –Energy Modelling Forum 33 (IAM EMF33), partial models assuming constant land cover (CLC), and partial models using natural growth (NRG). Box 10.2 and Section 10.4 include a more detailed description of the assumptions underlying these models and their estimates. The results based on IAM EMF33 and CLC suggests median mitigation potential of around 73% for advanced biofuels in shipping, while the NRG based results suggest increased emissions from biofuels. The EMF33 and CLC results rely on modelling approaches compatible with the scenarios in the AR6 database (see Chapters 6 and Box 7.7 for a discussion about emissions from bioenergy systems).

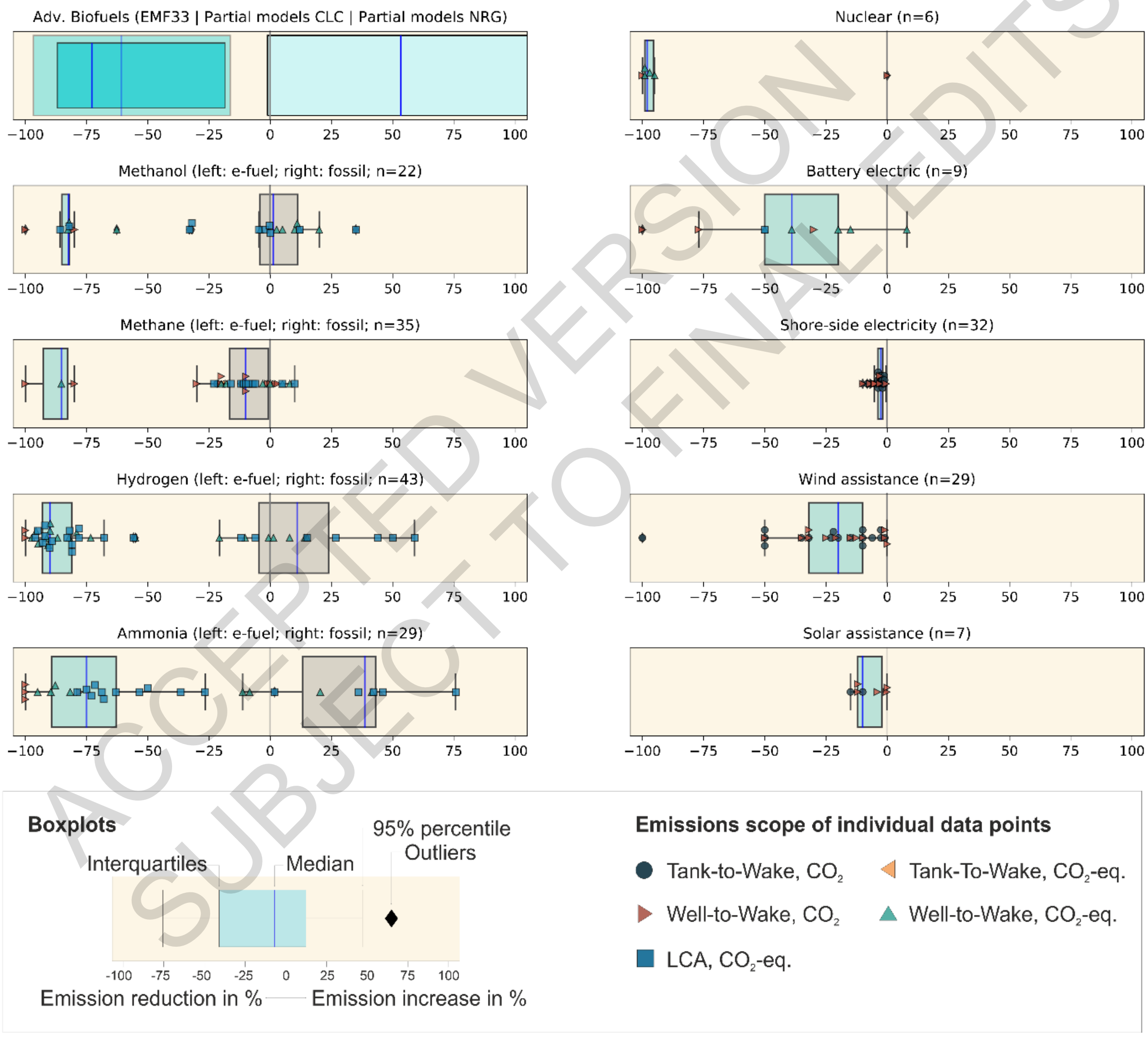


Figure 10.15 Boxplot of emission reductions potential compared to conventional fuels in the shipping sector. The x-axis is reported in %. Each individual marker represents a data point from the literature, where the blue square indicates a full LCA CO_2-eq value; light orange triangles tank – to – wake CO_2-eq.; light blue triangles well – to – wake CO_2-eq; dark orange triangles well – to – wake CO_2; and dark blue circle tank – to – wake CO_2 emission reduction potentials. The values in the figure rely on the 100-year GWP value embedded in the source data, which may differ slightly with the updated 100-year GWP values from WGI. 'n' indicates the number of data points per sub-panel. Grey shaded boxes represent

data where the energy comes from fossil resources, and turquoise from low carbon renewable energy sources. Advanced Biofuels EMF33 refers to emissions factors derived from simulation results from the integrated assessment models EMF33 scenarios (darkest coloured box in top left panel). Biofuels partial models CLC refers to partial models with constant land cover. Biofuels partial models NRG refers to partial models with natural regrowth. For ammonia and Hydrogen, low-carbon electricity is produced via electrolysis using low-carbon electricity, and 'fossil' refers to fuels produced via steam methane reforming of natural gas.

In addition to the fuels, there are other measures that may aid the low-carbon transition shipping. The amounts and speed of uptake of alternative low- or zero-carbon fuels in ports depend upon investments in infrastructure – including bunkering infrastructure, refinery readiness, reliable supply of the fuels, as well as sustainable production. The ship lifetime and age also play a role, whereupon retrofitting ships to accommodate engines and fuel systems for new fuel types may not be an option for older vessels. As such, operational efficiency becomes more important (Bullock et al. 2020). There is some potential to continue to improve the energy efficiency of vessels through operational changes (e.g., Traut et al. 2018), reducing the speed or 'slow steaming' (Bullock et al. 2020), and improved efficiency in port operations (Viktorelius and Lundh 2019; Poulsen and Sampson 2020). There is also a growing interest in onboard technologies for capturing carbon, with prototype ships underway showing 65-90% potential reduction in CO_2 emissions (Japan Ship Technology Reserach Association et al. 2020; Luo and Wang 2017; Awoyomi et al. 2020). Challenges identified include CO_2 capture efficiency (Zhou and Wang 2014), increased operating costs, and limited onboard power supply (Fang et al. 2019). Furthermore, designing CO_2 storage tanks for transport to shore may pose a challenge, as the volume and weight of captured CO_2 could be up to four times more than standard oil (Decarre et al. 2010).

Changes in design and engineering provide potential for reducing emissions from shipping through a range of measures, e.g., by optimizing hull design and vessel shape, power and propulsion systems that include wind or solar assisted propulsion, and through improved operations of vessels and ports. Figure 10.15 shows that such measures may decrease emissions by 5 - 40%, though with a broad range in potential (Bouman et al. 2017). Nuclear propulsion could decrease emissions from individual vessels by 98%. Battery- or hybrid-electric ships have been identified as a means to reduce emissions in short-sea shipping such as ferries and inland waterways (Gagatsi et al., 2016), which may also importantly reduce near-shore SLCF pollution (Nguyen et al. 2020). Figure 10.15 shows that the median emission from electric ships can be ~40% lower than equivalent fossil-based vessels but can vary widely. The wide reduction potential of battery-electric propulsion is due to different assumptions about the CO_2 intensity of the electricity used and the levels of CO_2 footprints associated with battery production.

Although projections indicate continued increase in freight demand in the future, demand-side reductions could contribute to mitigation. The development of autonomous systems may play a role (Colling and Hekkenberg 2020; Liu et al. 2021) while 3-D printing can reduce all forms of freight as parts and products can be printed instead of shipped (UNCTAD 2018). As more than 40% of transported freight is fossil fuels, a lessened demand for such products in low emission scenarios should contribute to reduce the overall maritime transport needs and hence emissions in the future (Sharmina et al. 2017). An increase in alternative fuels on the other hand, may increase freight demand (Mander et al. 2012). Potentials for demand-side reduction in shipping emissions may arise from improving processes around logistics and packaging, and further taxes and charges could serve as leverage for reducing demand and emissions.

The coming decade is projected to be costly for the shipping sector, as it is preparing to meet the 2030 and 2050 emission reduction targets set by the IMO (UNCTAD 2018). With enough investments, incentives, and regulation, substantial reductions of CO_2 emissions from shipping could be achieved through alternative energy carriers. The literature suggests that their cost could be manyfold higher than for conventional fuels, which in itself could reduce demand for shipping, and hence its emissions, but make the transition difficult. Hence R&D may help reduce these costs. The literature points to the need for developing technology roadmaps for enabling the maritime transport sector to get on to pathways for decarbonisation early enough to reach global goals (Kuramochi et al. 2018). Accounting for the full life cycle of emissions of the vessels and the fuels is required to meet the overall long-term objectives of cutting GHG and SLCF emissions. The urgency of implementing measures for reducing emissions is considered to be high, considering the lifetime of vessels is typically 20 years, if not more.

10.6.5 Accountability and governance options

Regulatory frameworks for the shipping sector have been developed over time and will continue to do so through bodies such as the IMO, which was established by the UN to manage international shipping. The IMO strategy involves a 50% reduction in GHG emissions from international shipping by 2050 compared to 2008 (IMO 2018). The strategy includes a reduction in carbon intensity of international shipping by at least 40% by 2030, and 70% by 2050, compared to 2008. IMO furthermore aims for the sectoral phase out of GHG emissions as soon as possible this century.

In 2020, the IMO approved the short-term goal-based measure to reduce the carbon intensity of existing international vessels. This measure addresses both technical and operational strategies. The operational element is represented by a Carbon Intensity Indicator (CII), and the technical element is represented by the Energy Efficiency Existing Ship Index (EEXI), which will apply to ships from 2023. The EEXI builds upon the Energy Efficiency Design Index (EEDI), which is a legally binding mitigation regulation for newbuild ships, established as a series of baselines for the amount of fuel ships may burn for a particular cargo-carrying capacity. The EEDI differs per ship segment. E.g., ships built in 2022 and beyond should be 50% more energy efficient than in 2013. This legislation aims to reduce GHG emissions in particular. Energy efficiency may be improved by several of the mitigation options outlined above. The ship energy efficiency management plan (SEEMP) is seen as the international governance instrument to improve energy efficiency and hence emissions from ships. SEEMP is a measure to enable changes to operational measures and retrofits (see Johnson et al., 2013). The combination of EEXI, EEDI, and SEEMP may reduce emissions by 23% by 2030 compared to a ‘no policy’ scenario (Sims et al. 2014). With regards to accountability, it is mandatory for ships of ≥5,000 gross tonnage to collect fuel consumption data, as well as specified data for e.g. transport work. Similarly, the EU MRV (Monitoring, Reporting, Verification) requires mandatory reporting of a vessel’s fuel consumption when operating in European waters.

Policy choices may enable or hinder changes, and gaps in governance structures may, to some degree, hinder the objectives of mechanisms like SEEMP to improve energy efficiency and emissions. Policies may be developed to incentivize investments in necessary changes to the global fleet and related infrastructures. The literature argues that regulations and incentives that motivates mitigation through speed optimisation, ship efficiency improvements, and retrofits with lower-carbon technologies at a sub-global scale may contribute to immediate reductions in CO_2 emissions from the sector (Bows-Larkin 2015). The role of the financial sector through initiatives such as the Poseidon Principle, whereupon financial institutions limit lending to companies that fail to uphold environmental standards, could also become increasingly important (Sumaila et al. 2021).

It has been proposed to make shipping corporations accountable for their emissions by making it mandatory to disclose their vessel’s emissions reductions (Rahim et al. 2016). Market based mechanisms may increasingly encourage ship operators to comply with IMO GHG regulations. Development of policies such as carbon pricing / taxing to enable a business case for adopting low carbon fuels could be a near term priority for acceleration of transformation of the sector (Hoegh-Guldberg et al. 2019). The EU is considering including shipping in its carbon trading system, with the details still to be agreed upon but expected to come into force in 2023, along with the CII. The proposition is that shipowners who conduct voyages within Europe, or start or end at an EU port, will have to pay for carbon permits to cover the CO_2 emitted by their vessel.

Regulations exist also to limit emissions of air pollution from shipping with the aim to improve environment and health impacts from shipping in ports and coastal communities. In sulphur emission control areas (SECAS), the maximum permissible sulphur content in marine fuels is 0.10% m/m (mass/mass). These are further tightened by the IMO legislation on reducing marine fuel sulphur content to a maximum of 0.5% in 2020 outside of SECAS, compared to 3.5% permissible since 2012 (MARPOL Convention). The MARPOL Annex VI also limits the emissions of ozone depleting substances and ozone precursors; NO_x, and VOCs from tankers (Mertens et al. 2018). The implementation of the emission control areas have been shown to reduce the impacts on health and the environment (Viana et al. 2015).

While there are many governance and regulatory initiatives that help reduce emissions from the shipping sector, few are transformative on their own, unless zero carbon fuels can become available at a reasonable cost as suggested in 10.3 and in scenarios outlined next.

10.6.6 Transformation trajectories for the maritime sector

Figure 10.16 shows CO_2 emissions from shipping in scenarios from the AR6 database and the 4th GHG study by the IMO (Faber et al., 2020). Panel (a) shows that CO_2 emissions from shipping go down by 33-70% (5-95% percentile) by 2050 in the scenarios limiting warming to 1.5°C (C1-C2). By 2080, median values for the same set of scenarios reach net zero CO_2 emissions. IAMs often do not report emission pathways for shipping transport and the sector is underrepresented in most IAMs (Esmeijer et al. 2020). Hence pathways established outside of IAMs can be different for the sector. Indeed, the IMO projections for growth in transport demand (Faber et al. 2020) indicate increases by 40 - 100 % by 2050 for the global fleet. Faber and et al. (2020), at the same time predict, reductions in trade for fossil fuels dependent on decarbonisation trajectories. The energy efficiency improvements of the vessels in these scenarios are typically of 20 - 30%. This offsets some of the increases from higher demand in the future scenarios. Fuels assessed by the 4th IMO GHG study were limited to HFO, MGO, LNG, and Methanol, with a fuels mix ranging from 91 - 98% conventional fuel use and a small remainder of alternative fuels (primarily LNG, and some Methanol). Panel (b) in Figure 10.16 shows average fleetwide emissions of CO_2 emissions based on these aggregate growth and emission trajectories from the IMO scenarios. In these scenarios, CO2 emissions from shipping remain stable or grow compared to 2020 modelled levels. These results contrast with the low emission trajectories in the C1-C2 bin in panel (a) of Figure 10.16. It seems evident that the scenarios in the AR6 database explore a broader solutions space for the sector, than the 4th GHG study by IMO. However, the 1.5°C - 2°C warming goal has led to an IMO 2050 target of 40% reductions in carbon intensity by 2030, which would require emission reduction efforts to begin immediately. Results from global models, suggest the solutions space for deep emission reductions in shipping is available.

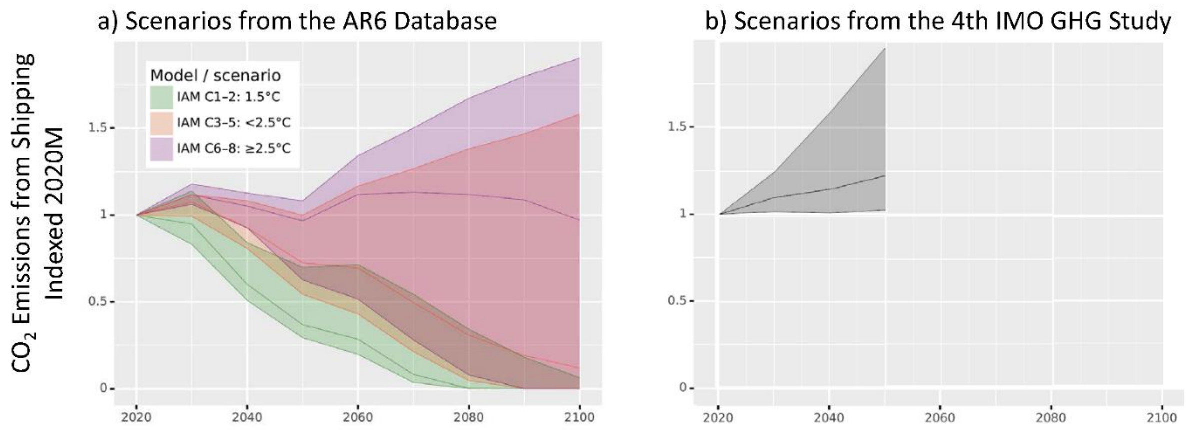


Figure 10.16 CO_2 emission from shipping scenarios indexed to 2020 Modelled year. Panel a) Scenarios from the AR6 database. Panel b) Scenarios from the 4th IMO GHG Study (Faber et al., 2020). Figures show median, 5th and 95th percentile (shaded area) for each scenario group.

Combinations of measures are likely needed for transformative transitioning of the shipping sector to a low-carbon future, particularly if an expected increase in demand for shipping services is realised (Smith et al. 2014; Faber et al. 2020). Both GHG and SLCF emissions decrease significantly in SSP1-1.9, where mitigation is achieved in the most sustainable way (Rao et al. 2017). Conversely, there are no emissions reductions in the scenarios presented by the IMO 4th GHG study, even though these scenarios incorporate some efficiency improvements and a slight increase in the use of LNG.

Options outlined in this chapter suggest a combination of policies to reduce demand, increase investments by private actors and governments, and develop the TRL of alternative fuels and related infrastructure (especially synthetic fuels). Some literature suggests that battery electric-powered short distance sea shipping could yield emission reductions given access to low carbon electricity. For deep sea shipping, advanced biofuels, Hydrogen, Ammonia, and synthetic fuels hold potential for significant emission reductions, depending on GHG characteristics of the fuel chain and resource base. Other options, such optimisation of speed and hull design and wind-assisted ships could also combine to make significant contributions in 2050 to further bring emissions down. In total a suite of mitigation options exists or is on the horizon for the maritime sector.

10.7 Scenarios from integrated, sectoral, and regional models

10.7.1 Transport scenario modelling

This section reviews the results of three types of models that systemically combine options to assess different approaches to generate decarbonisation pathways for the transport system: (1) integrated assessment models (IAMs); (2) global transport energy sectoral models (GTEM); and (3) national transport/energy models (NTEMs) (Yeh et al. 2017; Edelenbosch et al. 2017). Common assumptions across the three model types include trajectories of socioeconomic development, technological development, resource availability, policy, and behavioural change. The key differences underlying these models are their depth of technological and behavioural detail versus scope in terms of sectoral and regional coverage. In very general terms, the narrower the scope in terms of sectors and regions, the more depth on spatial, technological, and behavioural detail. A large set of scenarios from these models were collected in a joint effort led by Chapter 3 and supported by Chapter 10 and others. The outcomes from over 100 models have been analysed for this chapter with the methodologies set out in Annex III for the whole report.

GHG emissions from transport are a function of travel demand, travel mode, transport technology, GHG intensity of fuels, and energy efficiency. These drivers can be organized around a group of levers that can advance the decarbonisation of the transport system. The levers thus include reducing travel activity, increasing use of lower-carbon modes, and reducing modal energy intensity and fuel carbon content. This section explores each lever's contributions to the decarbonisation of the transport sector by reviewing the results from the three model types IAM and G-/NTEMs.

IAMs integrate factors from other sectors that interact with the transport system endogenously, such as fuel availability and costs. IAMs minimize mitigation costs to achieve a temperature goal *across all sectors of the economy* over a long-time horizon (typically to 2100). IAMs typically capture mitigation options for energy and carbon intensity changes with greater technology/fuel details and endogeneity linked to the other sectors. In the scenarios with very large-scale electrification of the transport sector, the coupling with the other sectors in fuel production, storage, and utilization becomes more important. G-/NTEMs and related regional transport sectoral models have more details in transport demand, technology, behaviours, and policies than IAMs, but treat the interactions with the other sectors exogenously, potentially missing some critical interactions, such as the fuel prices and carbon intensity of electricity. National models have detailed representation of national policies related to transport and energy, sometimes with greater spatial resolution. Compared with IAMs, G-/NTEMs typically have greater detailed representation to explore mitigation options along the activity and mode dimensions where spatial, cultural, and behavioural details can be more explicitly represented. The appendix in Annex III provides more details about these types of models. Scenarios for shipping and aviation are handled in more detail in sections 10.5 and 10.6, respectively.

This section applies the following categorization of scenarios (see table 3.1 in Chapter 3 for more details): C1 (1.5°C with no or limited Overshoot (OS)), C2 (1.5°C with high OS), C3 (>67% below 2°C), C4 (>50% below 2°C), C5 (below 2.5°C), C6 (below 3°C), C7 (above 3°C). A large share of the scenarios was developed prior to 2020. Results from such the scenario are indexed to a modelled (non-covid) year 2020, referred to as 2020Mod.

10.7.2 Global emission trajectories

In 2018, transport emitted 8.5 Gt CO_2eq, reaching a near doubling from 1990 levels after two decades of 2% per year emissions growth (see Section 10.1). Assessing future trajectories, Figure 10.17 provides an overview of direct CO_2 emissions estimates from the transport sector across IAMs (colour bars) and selected global transport models (grey bars). The results from the IAMs are grouped in bins by different temperature goal. Global energy transport models (GTEMs) are grouped into reference and policy bins, since the transport sector cannot by itself achieve fixed global temperature goals. The policy scenarios in G-/NTEMs cover a wide range of "non-reference" scenarios, which include, for example, assumptions based on the "fair share action" principles. In these scenarios, transport emissions reach emissions reductions consistent with the overall emission trajectories aligning with warming levels of 2°C. These scenarios may also consider strengthening existing transport policies such as increasing fuel economy standards or large-scale deployments of electric vehicles. In most cases, these Policy scenarios are not necessarily in line with the temperature goals explored by the IAMs.

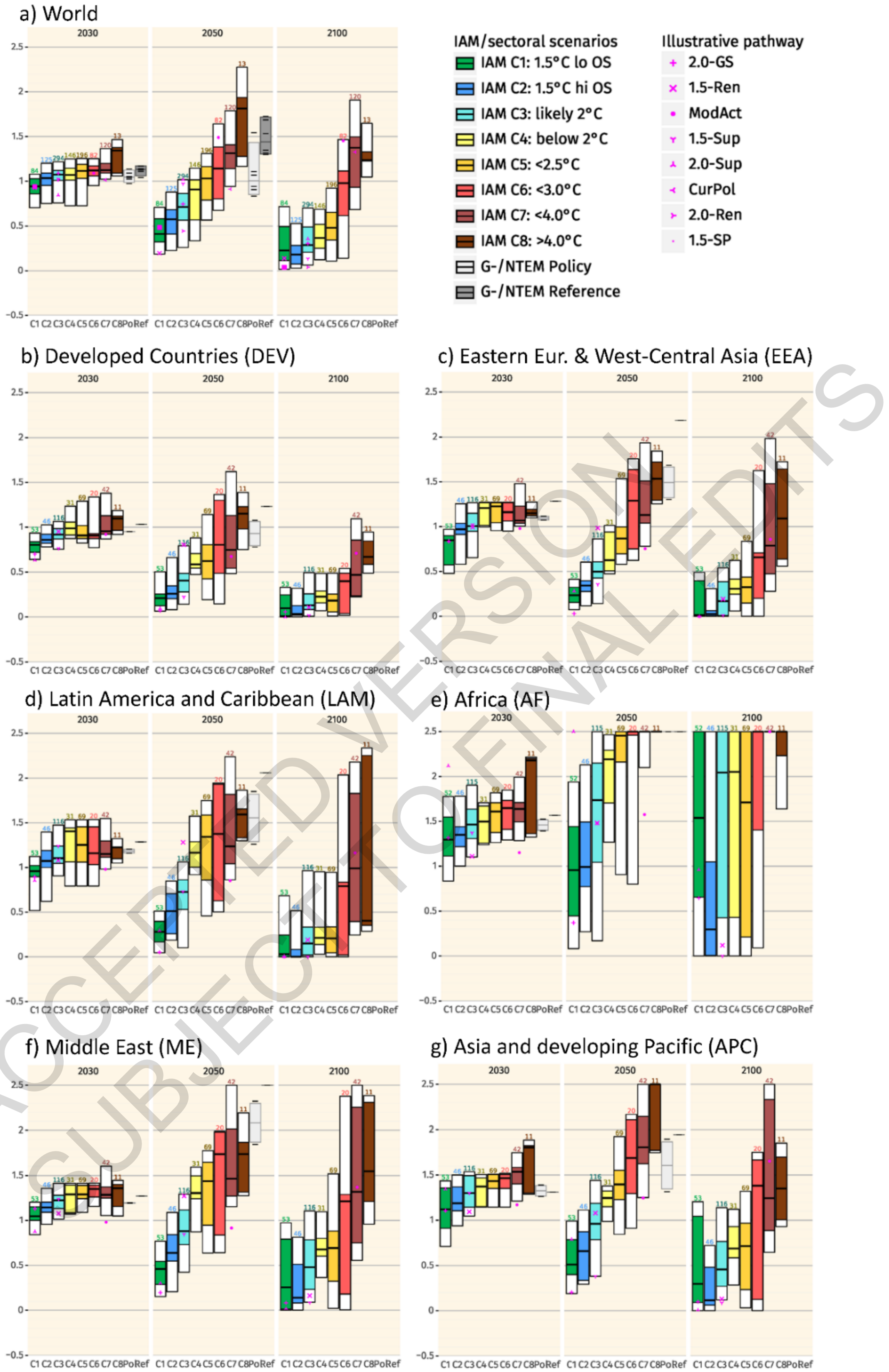


Figure 10.17 Direct CO_2 emissions in 2030, 2050, and 2100 indexed to 2020 modelled year across R6 Regions and World. IAM results are grouped by temperature targets. Sectoral studies are grouped by reference and policy categories. Plots show 5th/95th percentile, 25th/75th percentile, and median. Numbers above the bars indicate the number of scenarios. Data from the AR6 scenario database.

According to the collection of simulations from the IAM and GTEM models shown in Figure 10.17, global transport emissions could grow up to 2–47% (5–95th percentile) by 2030 and -6–130% by 2050 under the scenarios without firm commitments to meet a long-term temperature goal (i.e., C7-8 scenarios with temperature change above 3.0°C by 2100). Population and GDP growth and the secondary effects, including higher travel service demand per capita and increased freight activities per GDP, drive the growth in emissions in these scenarios (see Section 10.7.3). Though transport efficiencies (energy use per pkm travelled and per ton-km of delivery) are expected to continue to improve in line with the historical trends (see Section 10.7.4), total transport emissions would grow due to roughly constant carbon intensity (Section 10.7.5) under the C7-8 (>3.0°C) scenarios. Significant increases in emissions (> 150% for the medium values by 2050) would come from Asia and developing Pacific (APC), the Middle East and (ME), and Africa (AF), whereas Developed Countries (DEV) would have lower transport emissions (medium value -25% for C7 and 15% for C8) than the estimated 2020 level in 2050.

To meet temperature goals, global transport emissions would need to decrease by 17% (67–+23% for the 5–95th percentile) below 2020Mod levels in the C3-5 scenario group (1.5 - 2.5°C, orange bars), and 47% (14–80% for the 5–95th percentile) in the C1-2 scenario group (below 1.5°C, green bars) by 2050. However, transport-related emission reductions may not happen uniformly across regions. For example, transport emissions from the Developed Countries (DEV), and Eastern Europe and West-Central Asia (EEA) would decrease from 2020 levels by 2050 across all C1-2 scenarios, but could increase in Africa (AF), Asia and developing Pacific (APC), Latin America and Caribbean (LAM) and the Middle East (ME), in some of these scenarios. In particular, the median transport emissions in India and Africa could increase by 2050 in C1-2 scenarios, while the 95th percentile emissions in Asia and developing Pacific (APC), Latin America and Caribbean (LAM), and the Middle East (ME), could be higher in 2050 than in 2020.

The Reference scenario emission pathways from GTEMs described in Figure 10.17 have similar ranges as C7-8 scenario groups in 2050. The Policy scenarios are roughly in line with C6-7 scenarios for the world region. The results suggest that the majority of the Policy scenarios examined by the GTEMS reviewed here are in the range of the 2-3°C temperature goal scenarios examined by the IAMs (Gota et al. 2016; Yeh et al. 2017; IEA 2017b; Fisch-Romito and Guivarch 2019). The NDCs in the transport sector include a mix of measures targeting efficiency improvements of vehicles and trucks; improving public transit services; decarbonising fuels with alternative fuels and technologies including biofuels, fossil- or bio-based natural gas, and electrification; intelligent transport systems; and vehicle restrictions (Gota et al. 2016). Because of the long lag-time for technology turnover, these measures are not expected to change 2030 emissions significantly. However, they could have greater impacts on 2050 emissions.

Several GTEMs not included in AR6 scenario database have examined ambitious CO_2 mitigation scenarios. For example, a meta-analysis of scenarios suggests that global transport emissions consistent with warming levels of 2°C, would peak in 2020 at around 7-8 $GtCO_2$ and decrease to 2.5-9.2 Gt for 2°C with an average of 5.4 Gt by 2050 (Gota et al. 2019). For comparison, the IEA's Sustainable Development Scenario (SDS) suggests global transport emissions decrease to 3.3 Gt (or 55% reduction from 2020 level) by 2050 (IEA 2021f). In the latest IEA Net Zero by 2050 report proposes transport emissions to be close to zero by 2050 (IEA 2021e). The latter is lower than the interquartile ranges of the C1 group of scenarios from the AR6 database analysed here.

Low carbon scenarios are also available from national models (Latin America, Brazil, Canada, China, France, Germany, Indonesia, India, Italy, Japan, Mexico, South Africa, UK, US) with a good representation of the transport sector. The low carbon scenarios are either defined with respect to a global climate stabilization level of e.g., 2°C /1.5°C Scenario (Dhar et al. 2018), or a CO_2 target that is more stringent than what has been considered in the NDCs, such as the net zero emissions pathways (Bataille et al. 2020; IEA 2021e). These studies have generally used bottom-up models (see Annex III) for the analysis, but in some cases, they are run by national teams using global models (e.g., GCAM for China and India). National studies show that transport CO_2 emissions could decline significantly in low-carbon scenarios in all the developed countries reviewed (Bataille et al. 2015; Kainuma et al. 205AD; Virdis et al. 2015; Pye et al. 2015; Criqui et al. 2015; Kemfert et al.; Williams et al. 2015; Zhang et al. 2016a) in 2050 from the emissions in 2010 and reductions vary from 65% to 95%. However, in developing countries reviewed (Altieri et al. 2015; Buira and Tovilla 2015; Teng et al. 2015; Rovere et al. 2015; Siagian et al. 2015; Shukla et al. 2015; Di Sbroiavacca et al. 2014; Dhar et al. 2018), emissions could increase in 2050 in the range of 35% - 83% relative to 2010 levels. Transport CO_2 emissions per capita in the developing countries were much lower in 2010 (vary from 0.15 to 1.39 tCO_2 per capita) relative to developed countries (vary from 1.76 to 5.95 tCO_2 per capita). However, results from national modelling efforts suggest that, by 2050, the CO_2 emissions per capita in developed countries (vary from 0.19 to 1.04 tCO_2 per capita) could be much lower than in developing countries (vary from 0.21 to 1.7 tCO_2 per capita).

The transport scenario literature's mean outcomes suggest that the transport sector may take a less steep emission reduction trajectory than the cross-sectoral average and still be consistent with the 2°C goal. For example, most of the 1.5°C pathway scenarios (C1-2) reach zero-emission by 2060, whereas transport sector emissions are estimated in the range of 20% of the 2020Mod level (4-65% for the 10th – 90th percentiles) by 2100. This finding is in line with perspectives in the literature suggesting that transport is one of the most difficult sectors to decarbonise (Davis et al. 2018). There is, however, quite a spread in the results for 2050. Since temperature warming levels relate to global emissions from all sectors, modelling results from IAMs tend to suggest that in the short and medium-term, there might be lower cost mitigation options outside the transport sector. On the other hand, compared with G-/NTEMs, some IAMs may have limited mitigation options available including technology, behavioural changes, and policy tools especially for aviation and shipping. The models therefore rely on other sectors and/or negative emissions elsewhere to achieve the overall desired warming levels. This potential shortcoming should be kept in mind when interpreting the sectoral results from IAMs.

10.7.3 Transport activity trajectories

Growth in passenger and freight travel demand is strongly dependent on population growth and GDP. In 2015, transport activities were estimated at around 35-50 trillion pkm or 5,000-7,000 pkm per person per year, with significant variations among studies (IEA 2017b; ITF 2019). The number of passenger cars in use has grown 45% globally between 2005-2015, with the most significant growth occurring in the developing countries of Asia and the Middle East (119%), Africa (79%) and, South and Central America (80%), while the growth in Europe and North America is the slowest (21% and 4% respectively) (IOMVM 2021). On the other hand, car ownership levels in terms of vehicles per 1,000 people in 2015 were low in developing countries of Asia and the Middle East (141), Africa (42), South and Central America (176), while in Europe and North America they are relatively high (581 and 670 respectively) (IOMVM 2021). The growth rate in commercial vehicles (freight and passenger) was 41% between 2005 and 2015, with a somewhat more even growth across developed and developing countries (IOMVM 2021).

Figure 10.18 shows activity trajectories for both freight and passenger transport based on the AR6 database for IAMs. According to demand projections from the IAMs, global passenger and freight transport demand could increase relative to a modelled year 2020 across temperature goals. The median transport demand from IAMs for all the scenarios in line with warming levels below 2.5°C (C1-C5) suggests the global passenger transport demand could grow by 1.14-1.3 times in 2030 and by 1.5-1.8 times in 2050 (1.27-2.33 for the 5th – 95th percentile across C1-C5 scenarios) relative to modelled 2020 level. Developed regions including North America and Europe exhibit lower growth in passenger demand in 2050 compared to developing countries across all the scenarios. In 2030, most of the global passenger demand growth happens in Africa (AF) (44%% growth relative to 2020), and Asia and developing Pacific (APC) (57%% growth in China and 59% growth in India relative to 2020) in the below 2.5 scenario (C5). These regions start from a low level of per capita demand. For example, in India, demand may grow by 84%. However, the per capita demand in 2010 was under 7,000 km per person per year (Dhar and Shukla 2015). Similarly, in China, demand may grow by 52%, starting from per capita demand of 8,000 km per person per year in 2010 (Pan et al. 2018). The per capita passenger demand in these regions was lower than in developed countries in 2010, but it converges towards the per capita passenger transport demand of advanced economies in less stringent climate scenarios (C6-7). Demand for passenger travel would grow at a slower rate in the stricter temperature stabilization scenarios (< 2.5 and 1.5 scenarios, C1-C5) compared to the scenarios with higher warming levels (C7-C8). The median global passenger demand in the scenarios with warming levels below 1.5°C scenarios (C1-C2) are 27% lower in 2050 relative to C8.

Due to limited data availability, globally consistent freight data is difficult to obtain. In 2015, global freight demand was estimated to be 108 trillion tkm, most of which was transported by sea (ITF 2019). The growth rates of freight service demand vary dramatically among different regions: over the 1975–2015 period, road freight activity in India increased more than 9-fold, 30-fold in China, and 2.5-fold in the US (Mulholland et al. 2018). Global freight demand continues to grow but at a slower rate compared to passenger demand across all the scenarios in 2050 compared to modelled 2020 values. Global median freight demand could increase by 1.17 -1.28 times in 2030 and 1.18-1.7 times in 2050 in all the scenarios with warming level below 2.5°C (C1-C5). Like passenger transport, the models suggest that a large share of growth occurs in Africa (AF) and Asian regions (59% growth in India and 50% growth in China in 2030 relative to a modelled year 2020) in C5 scenario. Global median freight demand grows slower in the stringent temperature stabilization scenarios, and is 40% and 22% lower in 2050 in the below 1.5°C scenarios (C1-C2) and below 2.5°C scenarios (C3-C4), respectively, compared to scenarios with warming levels of above 4°C (C8).

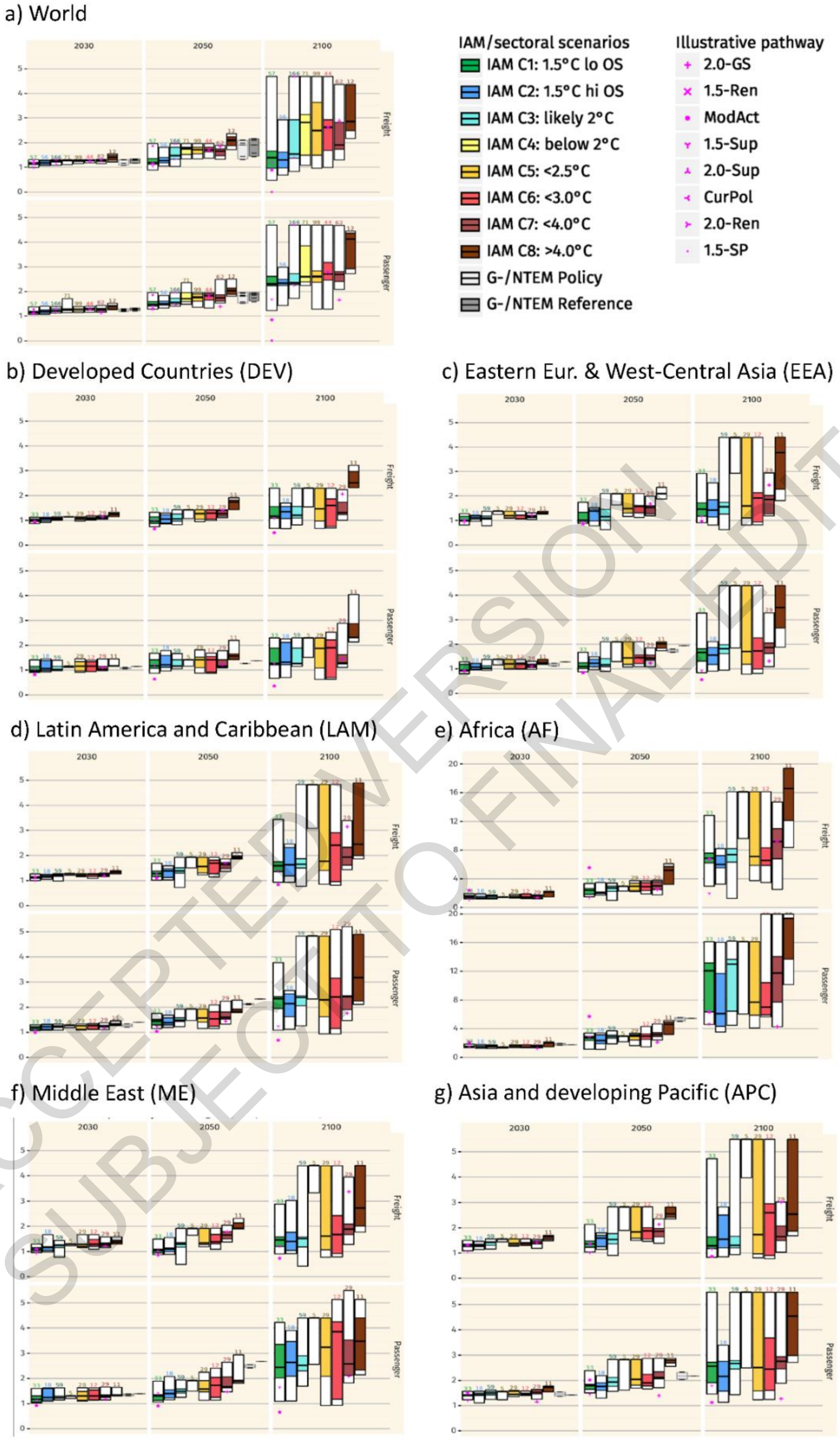


Figure 10.18 Transport activity trajectories for passenger (bottom panel) and freight (top panel) in 2030, 2050, and 2100 indexed to 2020 modelled year across R6 Regions and World. Plots show 5-95% percentile, 25th/75th percentile, and median. Numbers above the bars indicate the number of scenarios. Data from the AR6 scenario database.

GTEMs show broad ranges for future travel demand, particularly for the freight sector. These results show more dependency on models than on baseline or policy scenarios. According to ITF Transport Outlook (ITF 2019) , global passenger transport and freight demand could more than double by 2050 in a business-as-usual (BAU) scenario. Mulholland et al. (2018) suggest the freight sector could grow by 2.4-fold over 2015–2050 in the reference scenario, with the majority of growth attributable to developing countries. The IEA suggests a more modest increase in passenger transport, from 51 trillion pkm in 2014 to 110 trillion pkm in 2060, in a reference scenario without climate policies and a climate scenario that would limit emissions below 2ºC. The demand for land-based freight transport in 2060 is, however, slightly lower in the climate scenario (116 trillion tkm) compared to the reference scenario (130 trillion tkm) (IEA 2017b)The ITF, however, suggests that ambitious decarbonisation policies could reduce global demand for passenger transport by 13-20% in 2050, compared to the business-as-usual scenario (ITF 2019, 2021). The reduction in vehicle travel through shared mobility could reduce emissions from urban passenger transport by 30% compared to the BAU scenario. Others suggest reductions larger than 25%, on average, for both passenger and freight in 2030 and 2050 may be needed to achieve very low carbon emission pathways (Fisch-Romito and Guivarch 2019). In absence of large-scale carbon dioxide removal, few global studies highlight the need for significant demand reduction in critical sectors (aviation, shipping and road freight) in well below 2ºC scenarios (van Vuuren et al. 2018; Grant et al. 2021; Sharmina et al. 2021).

Many models find small differences in passenger transport demand across temperature goals because IAM models rely on historical relationships between population, GDP, and demand for services to estimate future demand. This assumption poses a limitation to the modelling efforts, as mitigation efforts would likely increase travel costs that could result in lower transport demand (Zhang et al. 2018). In most models, demand is typically an exogenous input. These models often assume mode shifts of activities from the most carbon-intensive modes (driving and flying for passenger travel and trucking for freight) to less carbon-intensive modes (public transit and passenger rails, and freight rail) to reduce emissions.

Traditionally there is a disconnection between IAM models and bottom-up sectoral or city-based models due to the different scale (both spatial and temporal) and focus (climate mitigation vs. urban pollutions, safety (Creutzig 2016)). The proliferation of shared and on-demand mobility solutions are leading to rebound effects for travel demand (Chen and Kockelman 2016; Coulombel et al. 2019) and this is a new challenge for modelling. Some IAM studies have recently begun to explore demand-side solutions for reducing transport demand to achieve very low-carbon scenarios through a combination of culture and low-carbon lifestyle (Creutzig et al. 2018; van Vuuren et al. 2018); urban development (Creutzig et al. 2015a); increased vehicle occupancy (Grubler et al. 2018); improved logistics and streamline supply chains for the freight sector (Mulholland et al. 2018); and disruptive low-carbon innovation, described as technological and business model innovations offering "novel value propositions to consumers and which can reduce GHG emissions if adopted at scale" (Wilson et al. 2019). In the literature from national models, demand has been differentiated between conventional and sustainable development scenarios through narratives built around policies, projects, and programs envisaged at the national level (Shukla et al. 2015; Dhar and Shukla 2015) and price elasticities of travel demand (Dhar et al. 2018). However, a greater understanding of the mechanisms underlying energy-relevant decisions and behaviours (Brosch et al. 2016), and the motivations for sustainable behaviour (Steg et al. 2015) are critically needed to realize these solutions in reality.

Overall, passenger and freight activity are likely to continue to grow rapidly under the C7 (>3.0°C) scenarios, but most growth would occur in developing countries. Most models treat travel demand exogenously following the growth of population and GDP, but they have limited representation of responses to price changes, policy incentives, behavioural shifts, nor innovative mobility solutions that can be expected to occur in more stringent mitigation scenarios Chapter 5 provides a more detailed discussion of the opportunities for demand changes that may results from social and behavioural interventions.

10.7.4 Transport modes trajectories

Globally over the last century, shares of faster transport modes have generally increased with increasing passenger travel demand (Schafer and Victor 2000; Schäfer 2017). For short- to medium-distance travel, private cars have displaced public transit, particularly in OECD countries, due to a variety of factors, including faster travel times in many circumstances (Liao et al. 2020); increasing consumers' value of time and convenience with GDP growth; and broader transport policies, e.g. provision of road versus public transit infrastructure (Mattioli et al. 2020). For long-distance travel, travel via aviation for leisure and business has increased (Lee et al. 2021). These trends do not hold in all countries and cities, as many now have rail transit that is faster than driving (Newman et al. 2015a). For instance, public transport demand rose from 1990 through 2016 in France, Denmark, and Finland (eurostat 2019). In general, smaller and denser countries and cities with higher or increasing urbanization rates tend to have greater success in increasing public transport share. However, other factors, like privatisation of public transit (Bayliss and Mattioli 2018) and urban form (ITF 2021), also play a role. Different transport modes can provide passenger and freight services, affecting the emissions trajectories for the sector.

Figure 10.19 shows activity trajectories for freight and passenger transport through 2100 relative to a modelled year 2020 across different modes based on the AR6 database for IAMs and global transport models. Globally, climate scenarios from IAMs, and policy and reference scenarios from global transport models indicate increasing demand for freight and passenger transport via most modes through 2100 (Yeh et al. 2017; Zhang et al. 2018; Mulholland et al. 2018; Khalili et al. 2019). Road passenger transport exhibits a similar increase (roughly tripling) through 2100 across scenarios. For road passenger transport, scenarios that limit warming to 1.5 °C (C1-C2) have a smaller increase from modelled 2020 levels (median increase of 2.4 times modelled 2020 levels) than do scenarios with higher warming levels (C3-C8) (median increase of 2.7-2.8 times modelled 2020 levels). There are similar patterns for passenger road transport via light-duty vehicle, for which median increases from modelled 2020 levels are smaller for C1-2 (3 times larger) than for C3-5 (3.1 times larger) or C6-7 (3.2 times larger). Passenger transport via aviation exhibits a 2.2 times median increase relative to modelled 2020 levels under C1-2 and C3-5 scenarios but exhibits a 6.2 times increase under C6-C8. The only passenger travel mode that exhibits a decline in its median value through 2100 according to IAMs is walking/bicycling, in C3-5 and C6-8 scenarios. However, in C1-2 scenarios, walking/bicycling increases by 1.4 times relative to modelled 2020 levels. At the 5th percentile of IAM solutions (lower edge of bands in Figure 10.19), buses and walking/bicycling for passenger travel both exhibit significant declines.

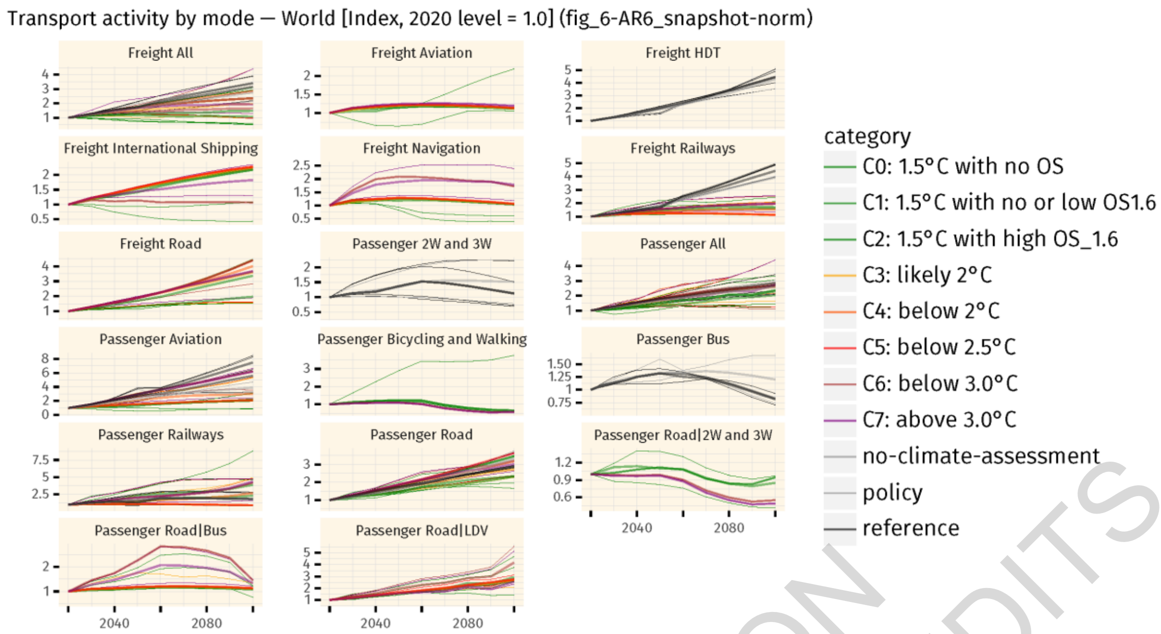


Figure 10.19 Transport activity trajectories for passenger and freight across different modes. Global passenger (billion pkm per year) and freight (billion tkm per year) demand projections relative to a modelled year 2020 index. Results for IAM for selected stabilization temperatures by 2100. Also included are global transport models Ref and Policy scenarios. Data from the AR6 scenario database. Trajectories span the 5th/95th percentiles across models with a solid line indicating the median value across models.

For freight, Figure 10.19 shows that the largest growth occurs in transport via road (Mulholland et al. 2018). By 2100, global transport models suggest a roughly 4 times increase in median- heavy-duty trucking levels relative to modelled 2020 levels, while IAMs suggest a 2-4 times increase in freight transport by road by 2100. Notably, the 95th percentile of IAM solutions see up to a 4.7 times increase in road transport through 2100 relative to modelled 2020 levels, regardless of warming level. Other freight transport modes – aviation, international shipping, navigation, and railways – exhibit less growth than road transport. In scenarios that limit warming to 1.5 °C (C1-C2), navigation and railway remain largely unchanged and international shipping roughly doubles by 2100. Scenarios with higher warming (i.e., moving from C1-2 to C6-8) generally lead to more freight by rail and less freight by international shipping.

Relative to global trajectories, upper-income regions – including North America, Europe, and the Pacific OECD – generally see less growth in passenger road via light-duty vehicle and passenger aviation, given more saturated demand for both. Other regions like China exhibit similar modal trends as the global average, whereas regions such as the African continent and Indian subcontinent exhibit significantly larger shifts, proportionally, in modal transport than the globe. In particular, the African continent represents the starkest departure from global results. Freight and passenger transport modes exhibit significantly greater growth across Africa than globally in all available scenarios. Across Africa, median freight and passenger transport via road from IAMs increases by 5-16 times and 4-28 times, respectively, across warming levels by 2100 relative to modelled 2020 levels. Even C1 has considerable growth in Africa via both modes (3-16 times increase for freight and 4-29 times increase for passenger travel at 5th and 95th percentiles of IAM solutions by 2100).

As noted in Section 10.2, commonly explored mitigation options related to mode change include a shift to public transit, shared mobility, and demand reductions through various means, including improved urban form, teleconferences that replace passenger travel (Creutzig et al. 2018; Grubler et al. 2018;

Wilson et al. 2019), improved logistics efficiency, green logistics, and streamlined supply chains for the freight sector (Mulholland et al. 2018). NDCs often prioritize options like bus improvements and enhanced mobility that yield pollution, congestion, and urban development co-benefits, especially in medium and lower-income countries (Fulton et al. 2017). Conversely, high-income countries, most of which have saturated and entrenched private vehicle ownership, typically focus more on technology options, e.g., electrification and fuel efficiency standards (Gota et al. 2016). Available IAM and regional models are limited in their ability to represent modal shift strategies. As a result, mode shifts alone do not differentiate climate scenarios. While this lack of representation is a limitation of the models, it is unlikely that such interventions would completely negate the increases in demand the models suggest. Therefore, transport via light-duty vehicle and aviation, freight transport via road, and other modes will likely continue to increase through end-of-century. Consequently, fuel and carbon efficiency and fuel energy and technology will probably play crucial roles in differentiating climate scenarios, as discussed in the following sub-sections.

10.7.5 Energy and Carbon efficiency trajectories

This section explores what vehicle energy efficiencies and fuel carbon intensity trajectories, from the data available in AR6 database from IAMs and GTEMs, could be compatible with different temperature goals. Figure 10.20 shows passenger and freight energy intensity, and fuel carbon intensity indexed relative to 2020Mod values. The top panel shows passenger energy intensity across all modes. LDVs constitute a major share of this segment. (Yeh et al. 2017) report 2.5-2.75 MJ vkm^{-1} in 2020 across models for the LDV segment, which is also very close to the IEA estimate of 2.5 MJ vkm^{-1} for the global average fuel consumption for LDVs in 2017 (IEA 2020d). For reference, these numbers correspond to 1.6-1.7 MJ pkm^{-1} for an occupancy rate of 1.5. The following results of the AR6 database are conditional on the corresponding reductions in fuel carbon intensity. Figure 10.20 shows that the scenarios suggest that passenger transport's energy intensity drops to between 10%-23% (interquartile ranges across C1-C4) in 2030 for the scenarios in line with warming levels below 2°C. In 2050, the medians across the group of 1.5°C scenarios (C1-C2) and 2°C scenarios (C2-C3) suggest energy intensity reductions of 51% and 45-46% respectively. These values correspond to annual average energy efficiency improvement rates of 2.3-2.4% and 2.0-2.1%, respectively, from 2020 to 2050. For reference, the IEA reports an annual energy efficiency improvement rate of 1.85% per year in 2005-16 (IEA 2020d). In contrast, the results from GTEMs suggest lower energy efficiency improvement, with median values for policy scenarios of 39% reduction in 2050, corresponding to annual energy efficiency improvement rates close to 1.6%. The IAM scenarios suggest median energy intensity reductions of passenger transport of 57-61% by the end of the century would align with warming levels of both 1.5°C and 2°C (C1-C4) given the corresponding decarbonisation of the fuels.

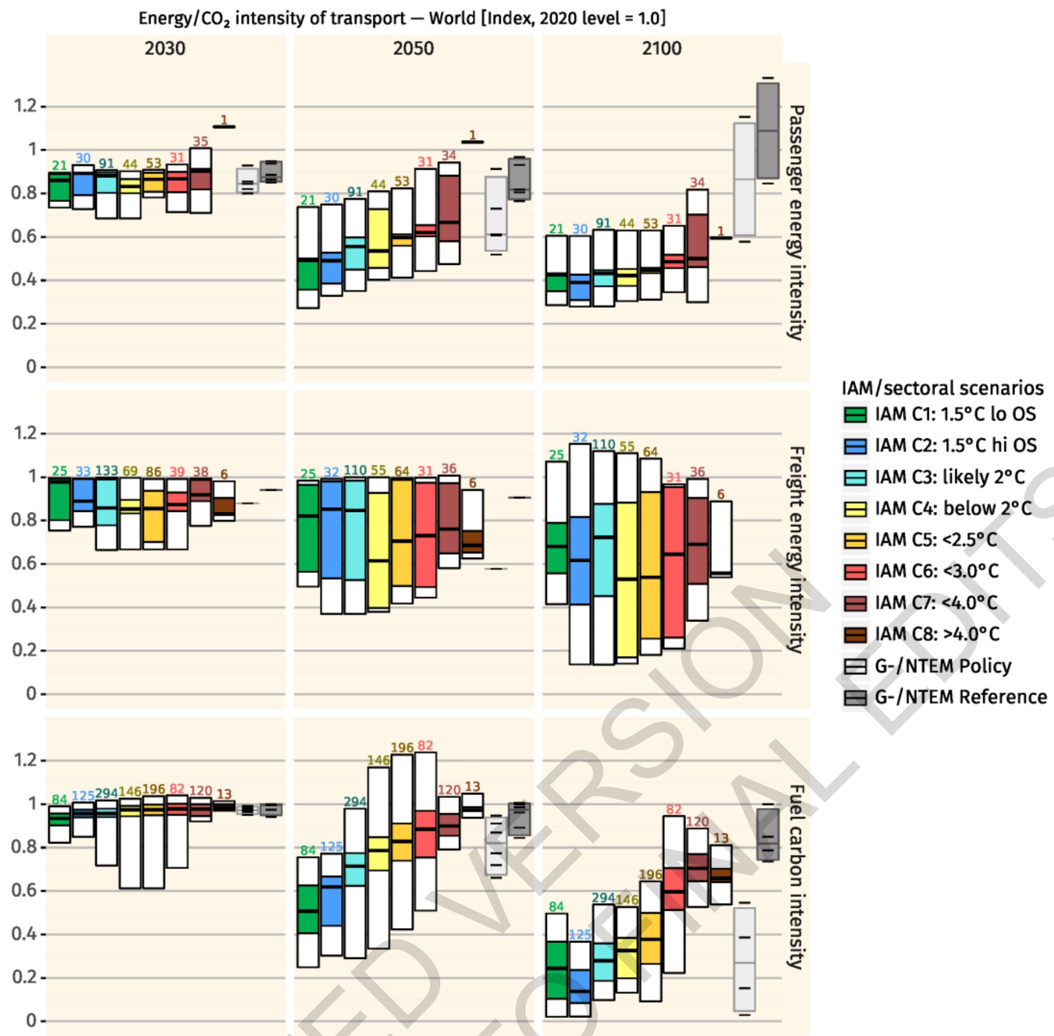


Figure 10.20 Energy efficiency and carbon intensity in 2030, 2050, and 2100 indexed to 2020 modelled year across scenarios. Plots show 5th/95th percentile, 25th/75th percentile, and median. Numbers above the bars indicate the number of scenarios. Data from the AR6 scenario database.

The scenarios in line with warming levels of 1.5°C or 2°C goals show different trends for freight's energy intensity. The amount of overshoot and differences in demand for freight services and, to some extent, fuel carbon intensities contribute to these differences. For the two scenarios aligning with the warming levels of 1.5°C, the trajectories in 2030 and 2050 are quite different. The median scenario in the high overshoot bin (C2) takes a trajectory with lower energy intensity improvements in the first half of the century. In contrast, the limited overshoot scenario (C1) takes on a more steadily declining trajectory across the means. The IAMs provide a less clear picture of required energy intensity improvements for freight than for passenger associated with different temperature targets. As for the carbon intensity of direct energy used across both passenger and freight, the modelling scenarios suggest very moderate reductions by 2030. The interquartile ranges for the C1 scenarios suggest global average reductions in carbon intensity of 5%-10%. Across the other scenarios compatible with warming levels of 1.5°C or 2°C (C2-4), the interquartile ranges span from 1%-6% reductions in carbon intensity of direct energy used for transport. For 2050 the scenarios suggest that dependence on fuel decarbonisation increases with more stringent temperature targets. For the 1.5°C scenarios (C1), global carbon intensity of energy used for transport decreases by 37%-60% (interquartile range) by 2050 with a mean of 50% reduction. The IAM scenarios in the AR6 database do not suggest full decarbonisation of transport fuels by 2100. The interquartile ranges across the C1-C4 set of scenarios, compatible with warming levels of 2°C and less, span from 61%-91% reduction from 2020Mod levels.

Increasing occupancy rate of passenger transport (Grubler et al. 2018) and reducing empty miles or increasing payload in freight deliveries (Gucwa and Schäfer 2013; McKinnon 2018) via improved logistics efficiency or streamlined supply chains (Mulholland et al. 2018), can present significant opportunities to effectively improve energy efficiency and decrease GHG emissions in transport. However, the recent trends of consumer behaviours have shown a declining occupancy rate of light-duty vehicles in industrialized countries (Schäfer and Yeh 2020), and the accelerating growing preference for SUVs challenges emissions reductions in the passenger car market (IEA 2019d). These trends motivate a strong focus on demand-side options.

Based on the scenario literature, a 51% reduction in median energy intensity of passenger transport and a corresponding reduction of 38%-50% reduction in median carbon intensity by 2050 would be aligned with transition trajectories yielding warming levels below 1.5°C by the end of the century. For comparison, the LCA literature suggests a switch from current ICEs to current BEVs would yield a reduction in energy intensity well beyond 45% and up to 70%, for a mid-sized vehicle (see Sections 10.4). Correspondingly, a switch from diesel or gasoline to low-carbon electricity or low-carbon Hydrogen would yield carbon intensity reduction beyond the median scenario value. Thus, the LCA literature suggests technologies exist today that would already match and exceed the median energy and carbon intensities values that might be needed by 2050 for low warming levels.

10.7.6 Fuel energy and technology trajectories

Two mechanisms for reducing carbon emissions from the transport sector are fuel switching for current vehicle technologies and transitioning to low carbon vehicle technologies. Figure 10.21 combines data from IAMs and GTEMs on shares of transport final energy by fuel. These shares account for fuels uses across modes - road, aviation, rail, and shipping- and both passenger and freight transport. Since the technologies have different conversion efficiencies, these shares of final energy by fuel are necessarily different from the shares of service (passenger- or ton-km) by fuel and shares of vehicle stock by fuel. For example, a current battery-electric LDV powertrain is roughly 3 times more energy-efficient than a comparable ICE powertrain (see Section 10.3, and Table 10.9 in Appendix 10.1); thus, fuel shares of 0.25 for electricity and 0.75 for oil could correspond to vehicle stock shares of 0.5 and 0.5, respectively. In general, while models may project that EVs constitute a greater share of road vehicle stock, and provide a greater share of road passenger-kilometres, their share of transport final energy (shown in Figure 10.21) can still remain lower than the final energy share of fuels used in less-efficient (e.g. ICE) vehicles. Thus, the shares of transport final energy by fuel presented in Figure 10.21 should be interpreted with care.

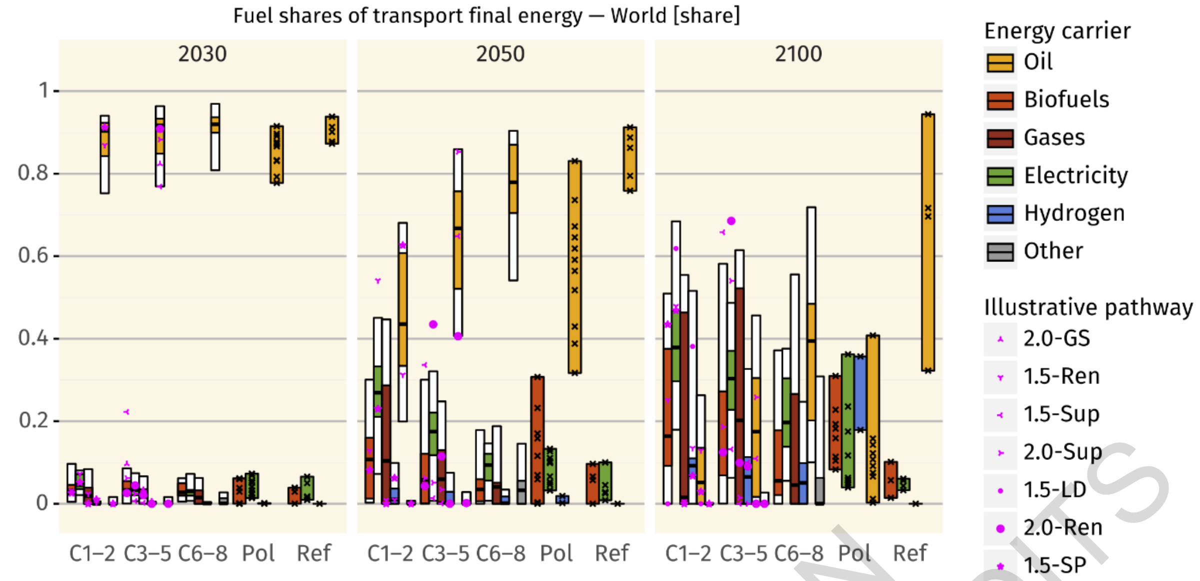


Figure 10.21 Global shares of final fuel energy in the transport sector in 2030, 2050, and 2100 for freight and passenger vehicles. Plots show 10th/90th percentile, 25th/75th percentile, and median. Data from the AR6 scenario database.

IAM and GTEM scenarios indicate that fuel and technology shifts are crucial to reduce carbon emissions to achieve lower levels of warming (Edelenbosch et al. 2017; IEA 2017b). Across the transport sector, a technology shift towards advanced fuel vehicles is the dominant driver of decarbonisation in model projections. This trend is consistent across climate scenarios, with larger decreases in the final energy share of oil in scenarios that achieve progressively lower levels of warming. Due to efficiency improvements; the higher efficiency of advanced fuel vehicles; and slower progress in the freight sector, the final energy share of oil decreases more rapidly after 2030. By 2050, the final energy shares of electricity, biofuels, and alternative gaseous fuels increase, with shares from electricity generally about twice as high (median values from 10%–30% across warming levels) as the shares from biofuels and gases (median values from 5%–10%). While IAMs suggest that the final energy share of hydrogen will remain low in 2050, by 2100 the median projections include 5%–10% hydrogen in transport final energy.

While only few IAMs report final energy shares by transport mode or passenger/freight, several relevant studies provide insights into fuel share trends in passenger LDVs and freight. The IEA suggests that full LDV electrification would be the most promising low-carbon pathway to meet a 1.75°C goal (IEA 2017b). The MIT Economic Projection and Policy Analysis (EPPA) model focuses on the future deployment of gasoline versus EV technologies in the global LDV stock (Ghandi and Paltsev 2019). These authors estimate that the global stock of vehicles could increase from 1.1 billion vehicles in 2015 up to 1.8 billion by 2050, with a growth in EVs from about 1 million vehicles in 2015 up to 500 million in 2050. These changes are driven primarily by cost projections (mostly in battery cost reductions). Similarly, the International Council on Clean Transport (ICCT) indicates that EV technology adoption in the light-duty sector can lead to considerable climate benefits. Their scenarios reach nearly 100% electrification of LDVs globally, leading to global GHG emissions ranging from 0% to -50% of 2010 LDV levels in 2050 (Lutsey 2015). Khalili *et al* (2019) estimate transport stocks through 2050 under aggressive climate mitigation scenarios that nearly eliminate road transport emissions. They find the demand for passenger transport could triple through 2050, but emissions targets could be met through widespread adoption of BEVs (80% of LDVs) and, to a lesser extent, fuel cell and plug-in hybrid electric vehicles. Contrary to these estimates, the US Energy Information Administration (EIA) finds small adoption of electrification for LDVs and instead identifies diffusion of natural gas-fuelled LDVs in OECD and, to a greater extent, non-OECD countries through 2040. This trend occurs in a reference and a "low liquids" case, which lowers LDV ownership growth rates and increases preferences for alternative fuel vehicles. A comprehensive overview of regional technology adoption models across many methodological approaches can be found in (Jochem et al. 2018).

In freight transport, studies indicate a shift toward alternative fuels would need to be supplemented by efficiency improvements. The IEA suggests efficiency improvements would be essential for decarbonisation of trucks, aviation, and shipping in the short-to-medium term. At the same time, the IEA suggests that fuel switching to advanced biofuels would be needed to decarbonise freight in the long-term (IEA 2019d). Mulholland et al. (2018) investigated the impacts of decarbonising road freight in two scenarios: countries complying with COP21 pledges and a second more ambitious reduction scenario in line with limiting global temperature rise to 1.75ºC. Despite the deployment of logistics improvements, high-efficiency technologies, and low carbon fuels, activity growth leads to a 47% increase in energy demand for road freight while overall GHG emissions from freight increase by 55% (4.8 $GtCO_2eq$) in 2050 (relative to 2015) in the COP21 scenario. In the 1.75ºC scenario, decarbonisation happens primarily through a switch to alternative fuels (hybrid electric and full battery-electric trucks), which leads to a 60% reduction in GHG emissions from freight in 2050 relative to 2015. Khalili et al. (2019) also find substantial shifts to alternative fuels in HDVs under aggressive climate mitigation scenarios. Battery electricity, Hydrogen fuel cell, and plug-in hybrid electric vehicles constitute 50%, 30%, and 15% of heavy-duty vehicles, respectively, in 2050. They also find 90% of buses would be electrified by 2050.

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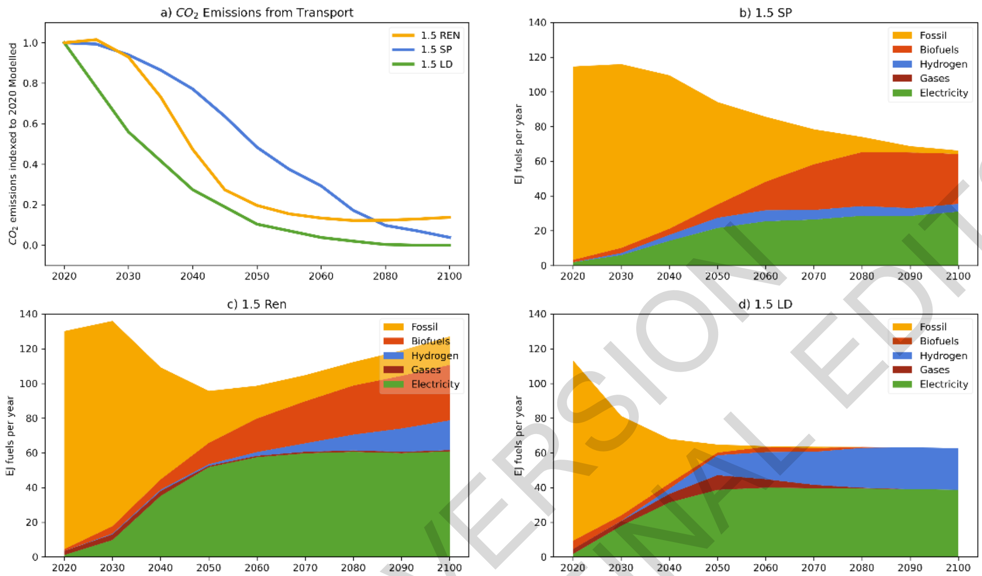
Box 10.4 Three Illustrative Mitigation Pathways.

Section 10.7 presents the full set of scenarios in the AR6 database and highlight the broader trends of how the transport sector may transform in order to be compliant with different warming levels. This box elaborates on three illustrative mitigation pathways (IMPs) to exemplify a few different ways the sector may transform. A total of 7 illustrative pathways are introduced in section 3.2.5 of chapter 3. In this box we focus on three of the IMPs: (1) focus on deep renewable energy penetration and electrification (IMP-Ren), (2) low demand (IMP-LD) and (3) pathways that align with both sustainable development goals as well as climate policies (IMP-SP). In particular, the variants of these three scenarios limit warming to 1.5°C with no or limited overshoot (C1). All of the three selected pathways reach global net zero CO_2 emissions across all sectors between 2060 and 2070, but not all reach net zero GHG emissions (see Figure 3.4 Chapter 3). Panel (a) in Box 10.4, Figure 1 below shows the CO_2 trajectories for the transport sector for the selected IMPs. Please note that the year 2020 is modelled in these scenarios. Therefore, the scenarios do not reflect the effects of the COVID-19 pandemic. For the low demand scenarios IMP-LD and renewables pathway IMP-Ren, CO_2 emissions from the transport sectors decrease to 10% and 20% of modelled 2020 levels by 2050, respectively. In contrast, the IMP-SP has a steady decline of transport sector CO_2 emissions over the century. By 2050, this scenario has a 50% reduction in emissions compared to modelled 2020 levels. Panels (b), (c) and (d) show energy by different fuels for the three selected IMPs. The IMPs-SP yields a drop in energy for transport of about 40% by the end of the century. CO_2 emission reductions are obtained through a phase-out of fossil fuels with electricity and biofuels, complemented by a minor share of Hydrogen by the end of the century. In IMP Ren, the fuel energy demand at the end of the century is in par with the 2020 levels, but the fuel mix has shifted towards a larger share of electricity complimented by biofuels and a minor share of Hydrogen. For the IMP-LD scenario, the overall fuel demand decreases by 45% compared to 2020 levels by the end of the century. Oil is largely phased out by mid-century, with electricity and Hydrogen becoming the major fuels in the second half of the century. Across the three IMPs, electricity plays a major role, in combination with biofuels, Hydrogen, or both.



Box 10.4, Figure 1 Three Illustrative mitigation pathways for the Transport sector. Panel (a) shows CO_2 emissions from the transport sector indexed to simulated non-COVID 2020 levels. Panels (b), (c), and (c) show fuels mix for 1.5 (IMP-SP), 1.5 REN (IMP-Ren) and 1.5 LD (IMP-LD), respectively. All data from IPCC AR6 Scenario database.

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10.7.7 Insights from the modelling literature

This section provides an updated, detailed assessment of future transport scenarios from IAM and G-/NTEMs given a wide range of assumptions and under a set of policy targets and conditions. The scenario modelling tools are necessary to aggregate individual options and understand how they fit into mitigation pathways from a systems perspective. The scenarios suggest that 43% (30-63% for the inter quartile ranges) reductions in CO_2 emissions from the transport emissions CO_2 (below modelled 2020 levels) by 2050 would be compatible with warming levels of 1.5°C (C1-C2 group). While the global scenarios suggest emissions reductions in energy supply sectors at large precede those in the demand sectors (see section 3.4.1), a subset of the scenarios also demonstrate that more stringent emission reductions in the transport sector are feasible. For example, the illustrative mitigation pathways IMP-REN and IMP-LD suggest emission reductions of respectively 80% and 90% are feasible by 2050 en-route to warming levels of 1.5°C (C1-C2) with low or no overshoot by the end of the century.

The scenarios from the different models project continued growth in demand for freight and passenger services, particularly in developing countries. The potential of demand reductions is evident, but the specifics of demand reduction measures remain less explored by the scenario literature. This limitation not-withstanding, the IAM and GTEMs suggest interventions that reduce the energy and fuel carbon intensity are likely crucial to successful mitigation strategies.

The scenario literature suggests that serious attempts at carbon mitigation in the transport sector must examine the uptake of alternative fuels. The scenarios described in the IAMs and GTEMs literature decarbonise through a combination of fuels. Across the scenarios, electrification plays a key role, complemented by biofuels and Hydrogen. In general terms, electrification tends to play the key role in passenger transport while biofuels and Hydrogen are more prominent in the freight segment. The three illustrative mitigation pathways in Box 10.4 exemplify different ways these technologies may be combined and still be compatible with warming levels of 1.5°C with low or no overshoot. Shifts towards alternative fuels must occur alongside shifts towards clean technologies in other sectors, as all alternative fuels have upstream impacts. Without considering other sectors, fuel shifts would not yield their full mitigation potentials. These collective efforts are particularly important for the electrification of transport, as the transformative mitigation potential is strongly dependent on the decarbonisation of the power sector. In this regard, the scenario literature is well aligned with the LCA literature reviewed in Section 10.4.

The models reviewed in this section would all generally be considered to have a good representation of fuels, technologies, and costs, but they often better represent land transport modes than shipping and aviation. While these models have their strengths in some areas, they have some limitations in other areas, like behavioural aspects. Analogously, these models are also limited in their ability to account for unexpected technological innovation such as a breakthrough in heavy vehicle fuels, AI, autonomy and big data, even the extent of digital communications replacing travel (see Section 10.2). As a result of these type of limitations, the models cannot yet provide a fully exhaustive set of options for decarbonising the transport sectors. These limitations not-withstanding, the models can find solutions encompassing the transport sector and its interactions with other sectors that are compatible with stringent emissions mitigation efforts. The solution space of transportation technology trajectories is therefore wider than explored by the models, so there is still a need to better understand how all options in combination may support the transformative mitigation targets.

10.8 Enabling conditions

10.8.1 Conclusions across the chapter

This final section draws some conclusions from the chapter, provides an overview-based feasibility assessment of the major transport mitigation options, as well as a description of emerging issues. The section ends by outlining an integrated framework for enabling the transformative changes that are emerging and required to meet the potential transformative scenarios from Section 10.7.

Transport is becoming a major focus for mitigation as its GHG emissions are large and growing faster than for other sectors, especially in aviation and shipping. The scenarios literature suggests that without mitigation actions, transport emissions could grow by up to 65% by 2050. Alternatively, successful deployment of mitigation strategies could reduce sectoral emissions by 68%, which would be consistent with the goal of limiting temperature change to 1.5°C above pre-industrial levels. This chapter has reviewed the literature on all aspects of transport and has featured three special points of focus: (1) A survey of life cycle analysis from the academic and industry community that uses these tools; (2) A similar exercise of surveying the modelling community for top-down and bottom-up approaches to identify decarbonisation pathways for the transport sector, and (3) For the first time in the IPCC, separate sections on shipping and aviation. The analysis of the literature suggests three crucial components for the decarbonisation of the transport sector: demand and efficiency strategies, electromobility, and alternative fuels for shipping and aviation.

The challenge of decarbonisation requires a transition of the socio-technical system, which in turn depends on the combination of technological innovation and societal change (Geels et al. 2017). A socio-technical system includes technology, regulation, user practices and markets, cultural meaning, infrastructure, maintenance networks, and supply networks (Geels 2005) (see Cross Chapter Box 12 in Chapter 16). The multi-level perspective (MLP) is a framework that provides insights to assist policymakers when devising transformative transition policies (Rip and Kemp 1998; Geels 2002). Under the MLP framework, strategies are grouped into three different categories. The Micro level (niche) category includes strategies where innovation differs radically to that of the incumbent socio-technical system. The niche provides technological innovations a protected space during development and usually requires considerable R&D and demonstrations. In the Meso level (regime) state, demonstrations begin to emerge as options that can be adopted by leading groups who begin to overcome lock-in barriers from previous technological dependence. Finally, in the Macro level (Landscape) stage, main-streaming happens, and the socio-technical system enables innovations to breakthrough. Figure 10.22 maps the MLP stage for the major mitigation strategies identified in this chapter.

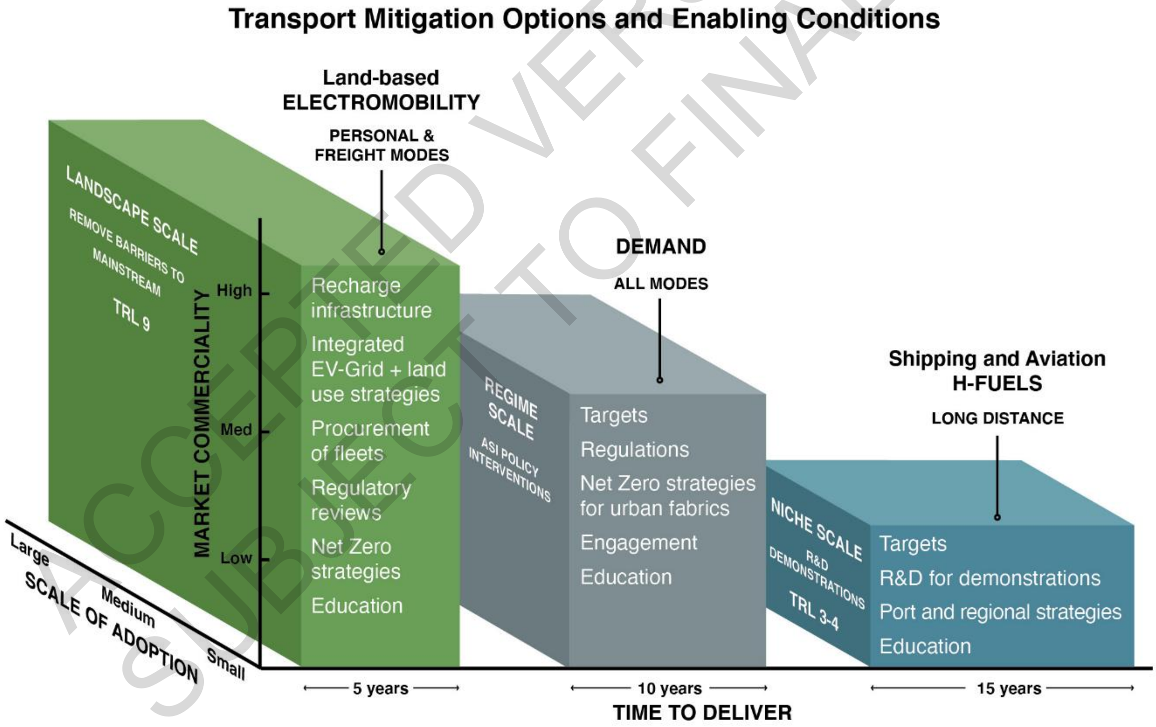

Figure 10.22 Mitigation Options and Enabling Conditions for Transport. Niche scale includes strategies that still require innovation.

Demand and behaviour. While technology options receive substantial attention in this chapter, there are many social and equity issues that cannot be neglected in any transformative change to mitigate climate change. Transport systems are socio-economic systems that include systemic factors that are developing into potentially transformative drivers of emissions from the sector. These systemic drivers include, for example, changes in urban form that minimises automobile dependence and reduces stranded assets; behaviour change programs that emphasise shared values and economies; smart technologies that enable better and more equitable options for transit and active transport as well as integrated approaches to using autonomous vehicles; new ways of enabling electric charging systems to fit into electricity grids creating synergistic benefits to grids, improving the value of electric transit, and reducing range anxiety for EV users; and, new concepts for the future economy such as circular economy, dematerialisation, shared economy that have the potential to affect the structure of the transport sector. The efficacy of demand reductions and efficiency opportunities depends on the degree of prioritisation and focus by government policy. Figure 10.22 suggests that innovative demand and efficiency strategies are at the regime scales. While these strategies are moving beyond R&D, they are not mainstreamed yet and have been shown to work much more effectively if combined with technology changes as has been outlined in the transformative scenarios from Section 10.7 and in Chapter 5.

Electromobility in Land-based Transport. Since AR5, there has been a significant breakthrough in the opportunities to reduce transport GHG emissions in an economically efficient way due to electrification of land-based vehicle systems, which are now commercially available. EV technologies are particularly well-established for light duty passenger vehicles, including micro mobility. Furthermore, there are positive developments to enable EV technologies for buses, light and medium-duty trucks, and some rail applications (though advanced biofuels and hydrogen may also contribute to the decarbonisation of these vehicles in some contexts). In developing countries, where micro mobility and public transit account for a large share of travel, EVs are ideal to support mitigation of emissions. Finally, demand from critical materials needed for batteries has become a focus of attention, as described in Box 10.6.

Electromobility options are moving from regime to landscape levels. This transition is evident in the trend of incumbent automobile manufacturers producing an increasing range of EVs in response to demand, policy, and regulatory signals. EVs for light-duty passenger travel are largely commercial and likely to become competitive with ICE vehicles in the early 2020's (Dia 2019; Bond et al. 2020; Koasidis et al. 2020). As these adopted technologies increase throughout cities and regions, governments and energy suppliers will have to deploy new supporting infrastructure to support them, including reliable low-carbon grids and charging stations (Sierzchula et al. 2014). In addition, regulatory reviews will be necessary to ensure equitable transition and achievement of SDG's, addressing the multitude of possible barriers that may be present due to the incumbency of traditional automotive manufacturers and associated supporting elements of the socio-technical system (Newman 2020b); and Chapter 6). Similarly, new partnership between government, industry, and communities will be needed to support the transition to electromobility. These partnerships could be particularly effective at supporting engagement and education programs ((Newman 2020b); and Chapter 8).

Deployment of electromobility is not limited to developed countries. The transportation sector in low- and middle-income countries includes millions of gas-powered motorcycles within cities across Africa, Southeast Asia, and South America (Ampersand 2020; Ehebrecht et al. 2018; Posada et al. 2011). Many of these motorcycles function as taxis. In Kampala, Uganda, estimates place the number of motorcycle taxis, known locally as boda-bodas, at around 40,000 (Ehebrecht et al. 2018). The popularity of the motorcycle for personal and taxi use is due to many factors including lower upfront costs, lack of regulation, and mobility in highly congested urban contexts (UNECE 2018; Posada et al. 2011). While motorcycles are often seen as a more fuel-efficient alternative, emissions can be worse from 2-wheelers than cars, particularly nitrogen oxides (NOx), carbon monoxide (CO), and hydrocarbon (HC) emissions (Vasic and Weilenmann 2006; Ehebrecht et al. 2018). These 2-wheeler emissions contribute to dangerous levels of air pollution across many cities in low- and middle-income countries. In Kampala, for example, air pollution levels frequently exceed levels deemed safe for humans by the World Health Organization (WHO) (Airqo 2020; World Health Organization 2018; Kampala Capital City Authority 2018). To mitigate local and environmental impacts, electric boda boda providers are emerging in many cities, including Zembo in Kampala and Ampersand in Kigali, Rwanda.

Bulawayo, the capital city of Zimbabwe, is also looking at opportunities for deploying electromobility solutions. The city is now growing again after a difficult recent history, and there is a new emphasis on achieving the Sustainable Development Goals (City of Bulawayo 2020a,b). With this goal in mind, Bulawayo is seeking opportunities for investment that can enable leapfrogging private, fossil fuel vehicle ownership. In particular, trackless trams, paired with solar energy, have emerged as a potential pathway forward (Kazunga 2019). Trackless trams are a new battery-based mid-tier transit system that could enable urban development around stations that use solar energy for powering both transit and the surrounding buildings (Newman et al. 2019). The new trams are rail-like in their capacities and speed, providing a vastly better mobility system that is decarbonised and enable low transport costs (Ndlovu and Newman 2020). While this concept is only under consideration in Bulawayo, climate funding could enable the wider deployment of such projects in developing countries.

Fuels for Aviation and Shipping. Despite technology improvements for land-based transport, equivalent technologies for long distance aviation and shipping remain elusive. Alternative fuels for use in long range aviation and shipping are restricted to the niche level. The aviation sector is increasingly looking towards synthetic fuels using low-carbon combined with CO_2 from direct air capture, while shipping is moving towards Ammonia produced using low-carbon Hydrogen. Biofuels are also of interest for these segments. To move out of the niche level, there is a need to set deployment targets to support breakthroughs in these fuels. Similarly, there is a need for regulatory changes to remove barriers in new procurement systems that accommodate uncertainty and risks inherent in the early adoption new technologies and infrastructure (Borén 2019; Sclar et al. 2019; Marinaro et al. 2020). R&D programs and demonstration trials are the best focus for achieving fuels for such systems. Finally, there is a need for regulatory changes. Such regulatory changes need to be coordinated through ICAO and IMO as well as with national implementation tools related to the Paris Agreement (see Box 10.5). Long-term visions, including creative exercises for cities and regions will be required providing a protected space for the purpose of trialling new technologies (Borén 2019; Geels 2019).

10.8.2 Feasibility Assessment

Figure 10.23 sets out the feasibility of the core mitigation options using the six criteria created for the cross-sectoral analysis. This feasibility assessment outlines how the conclusions outlined in Section 10.8.1 fit into the broader criteria created for feasibility in the whole AR6 report and that emphasise the SDGs. Figure 10.23 highlights that there is high confidence that demand reductions and mode shift can be feasible as the basis of a GHG emissions mitigation strategy for the transport sector. However, demand-side interventions work best when integrated with technology changes. The technologies that can support such changes have a range of potential limitations as well as opportunities. EV have a reliance on renewable resources (wind, solar, and hydro) for power generation, which could pose constraints on geophysical resources, land use, water use. Furthermore, expanding the deployment of EVs requires a rapid deployment of new power generation capacity and charging infrastructure. The overall feasibility of electric vehicles for land transport is likely high and their adoption is accelerating. HFCVs for land transport would also have constraints related to land geophysical resource needs, land use, and water use. These constraints are likely higher than for EVs, since producing Hydrogen with electricity reduces the overall efficiency of meeting travel demand. Furthermore, the infrastructure to produce, transport, and deliver Hydrogen is under-developed and would require significant R&D and a rapid scale-up. Thus, the feasibility of HFCV is likely lower than for EVs. Biofuels could be used in all segments of the transport sector, but there may be some concerns about their feasibility. Specifically, there are concerns about land use, water use, impacts on water quality and eutrophication, and biodiversity impacts. Advanced biofuels could mitigate some concerns and the feasibility of using these fuels likely varies by world region. The feasibility assessment for alternative fuels for shipping and aviation suggests that Hydrogen-based fuels like Ammonia and synthetic fuels have the lowest technology readiness of all mitigation options considered in this chapter. Reliance on electrolytic Hydrogen for the production of these fuels poses concerns about land and water use. Using Ammonia for shipping could pose risks for air quality and toxic discharges to the environment. The DAC/BECCS infrastructure that would be needed to produce synthetic fuel does not yet exist. Thus, the feasibility suggests that the technologies for producing and using these Hydrogen-based fuels for transport are in their infancy.

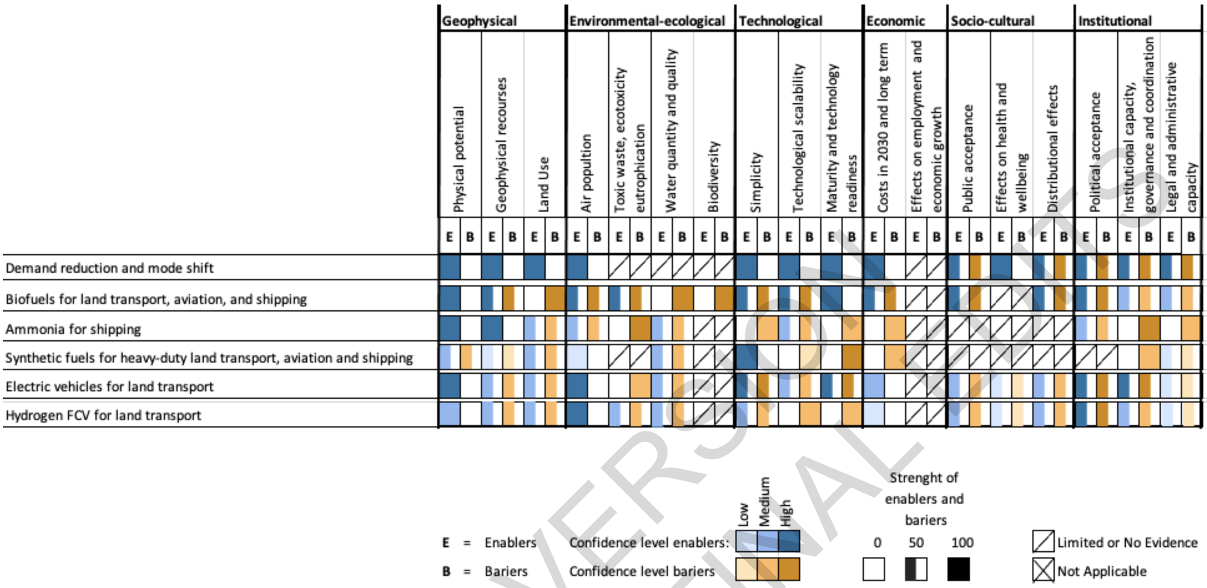

Figure 10.23 Summary of the extent to which different factors would enable or inhibit the deployment of mitigation options in Transport. Blue bars indicate the extent to which the indicator enables the implementation of the option (E) and orange bars indicate the extent to which an indicator is a barrier (B) to the deployment of the option, relative to the maximum possible barriers and enablers assessed. An 'X' signifies the indicator is not applicable or does not affect the feasibility of the option, while a forward slash indicates that there is no or limited evidence whether the indicator affects the feasibility of the option. The shading indicates the level of confidence, with darker shading signifying higher levels of confidence. Appendix 10.3 provides an overview of the extent to which the feasibility of options may differ across context (e.g., region), time (e.g., 2030 versus 2050), and scale (e.g., small versus large), and includes a line of sight on which the assessment is based. The assessment method is explained in Annex II.11.

10.8.3 Emerging Transport Issues

Planning for integration with the power sector: Decarbonising the transport sector will require significant growth in low-carbon electricity to power EVs, and more so for producing energy-intensive fuels, such as Hydrogen, Ammonia and synthetic fuels. Higher electricity demand will necessitate greater expansion of the power sector and increase land use. The strategic use of energy-intensive fuels, focussed on harder-to-decarbonise transport segments, can minimise the increase in electricity demand. Additionally, integrated planning of transport and power infrastructure could enable sectoral synergies and reduce the environmental, social, and economic impacts of decarbonising transport and energy. For example, smart charging of EVs could support more efficient grid operations. Hydrogen production, which is likely crucial for the decarbonisation of shipping and aviation, could also serve as storage for electricity produced during low-demand periods. Integrated planning of transport and power infrastructure would be particularly useful in developing countries where "greenfield" development doesn't suffer from constraints imposed by legacy systems.

Shipping and aviation governance: Strategies to deliver fuels in sufficient quantity for aviation and shipping to achieve transformative targets are growing in intensity and often feature the need to review international and national governance. Some literature suggests that the governance of the international transport systems could be included the Paris Agreement process (Gençsü and Hino 2015; Traut et al. 2018; Lee 2018). Box 10.6 sets out these issues.

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Box 10.5 Governance Options for shipping and aviation

Whenever borders are crossed, the aviation and shipping sector creates international emissions that are not assigned to states' Nationally Declared Contributions in the Paris Agreement. Emissions from these segments are rapidly growing (apart from COVID affecting aviation) and are projected to grow between 60% to 220% by 2050 (IPCC 2018; UNEP 2020). Currently, the International Civil Aviation Organization (ICAO) and the International Marine Organization (IMO), specialised UN Agencies, are responsible for accounting and suggesting options for managing these emissions.

Transformational goals?

ICAO has two global aspirational goals for the international aviation sector: 2% annual fuel efficiency improvement through 2050; and carbon neutral growth from 2020 onwards. To achieve these goals, ICAO has established CORSIA – Carbon Offsetting and Reduction Scheme for International Aviation, a market-based program.

In 2018, IMO adopted an 'Initial Strategy' on the reduction of GHG emissions from ships. This strategy calls for a reduction of the carbon intensity of new ships through implementation of further phases of the energy efficiency design index (EEDI). Similarly, the IMO calls for a 40% reduction of the carbon intensity of international shipping by 2030, and is striving for a 70% reduction by 2050. Such reductions in carbon intensity would result in an overall decline in emissions of 50% in 2050 (relative to 2008).

These goals are likely insufficiently transformative for the decarbonisation of aviation or shipping, though they are moving towards a start of decarbonisation at a period in history where the options are still not clear, as set out in Sections 10.5 and 10.6.

Regulations?

The ICAO is not a regulatory agency, but rather produces standards and recommended practices that are adopted in national/international legislation. IMO does publish 'regulations' but does not have power of enforcement. Non-compliance can be regulated by nation states if they so desire, as a ship's 'MARPOL' certificate, issued by the flag state of the ship, means there is some responsibility for states with global shipping fleets.

Paris?

Some commentators have suggested that emissions from international aviation and shipping should be part of the Paris Agreement (Gençsü and Hino 2015; Traut et al. 2018; Lee 2018; Rayner 2021) argue that the shipping and aviation industries would prefer emissions to be treated under an international regime rather than a national-oriented regime. If international aviation and shipping emissions were a part of the Paris Agreement, it may remove something of the present ambiguity of responsibilities. However, inclusion in the Paris agreement is unlikely to fundamentally change emissions trends unless targets and enforcement mechanisms are developed either by ICAO and IMO or by nation states through global processes.

Individual nations?

If international regulations do not occur, then the transformation of aviation and shipping will be left to individual nations like Switzerland. In 2020, Switzerland approved a new CO_2 tax on flights (The Swiss Parliament 2020) with part of its revenues earmarked for the development of synthetic aviation fuels, to cover up to 80% of their additional costs compared to fossil jet fuel (Energieradar 2020). Hence, appropriate financing frameworks will be a key to the large-scale market adoption of these fuels. Egli et al. (2019) suggest that the successful design of renewable energy investment policies for solar and wind power over the past 20 years could serve as a model for future synthetic aviation fuels production projects "attracting a broad spectrum of investors in order to create competition that drives down financing cost", and with state investment banks building "investor confidence in new technologies." These national investment policies would provide the key enablers for successful deployments.

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Managing critical minerals: Critical minerals are required to manufacture LIB's and other renewable power technologies. There has been growing awareness that critical minerals may face challenges related to resource availability, labour rights, and costs. Box 10.6, below, sets out the issues showing how emerging national strategies on critical minerals, along with requirements from major vehicle manufacturers, are addressing the need for rapid development of new mines with a more balanced geography, less use of cobalt through continuing LIB innovations, and a focus on recycling batteries. The standardisation of battery modules and packaging within and across vehicle platforms, as well as increased focus on design for recyclability are important. Given the high degree of potential recyclability of LIBs, a near closed-loop system in the future would be a feasible opportunity to minimise critical mineral issues.

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Box 10.6 Critical Minerals and The Future of Electro-Mobility and Renewables

The global transition towards renewable energy technologies and battery systems necessarily involves materials, markets, and supply chains on a hitherto unknown scale and scope. This has raised concerns regarding mineral requirements central to the feasibility of the energy transition. Constituent materials required for the development of these low carbon technologies are regarded as "critical" materials (US Geological Survey 2018; Commonwealth of Australia 2019; Lee et al. 2020; Marinaro et al. 2020; Sovacool et al. 2020). 'Critical materials' are critical because of their economic or national security importance, or high risk of supply disruption (UK Government 2019). describes many of these materials and rare earth elements (REEs) as "technologically critical" not only due to their strategic or economic importance but the risk of short supply or price volatility (Marinaro et al. 2020). In addition to these indicators, production growth and market dynamics are also incorporated into screening tools to assess emerging trends in material commodities that are deemed as fundamental to the well-being of the nation (NSTC 2018).

The critical materials identified by most nations are: REEs Neodymium and Dysprosium for permanent magnets in wind turbines and electric motors; Lithium and Cobalt, primarily for batteries though many other metals are involved (see figure below); and, Cadmium, Telluriam, Selenium, Gallium and Indium for solar PV manufacture (Valero et al. 2018; Giurco et al. 2019). Predictions are that the transition to a clean energy world will be significantly energy intensive (World Bank Group 2017; Sovacool et al. 2020) putting pressure on the supply chain for many of the metals and materials required.

Governance of the sustainability of mining and processing of many of these materials, in areas generally known for their variable environmental stewardship, remains inadequate and often a source for conflict. (Sovacool et al. 2020) propose four holistic recommendations for improvement to make these industries more efficient and resilient: diversification of mining enterprises for local ownership and livelihood benefit; improve the traceability of material sources and transparency of mining enterprise; exploration of alternative resources; and the incorporation of minerals into climate and energy planning by connecting to the NDCs under the Paris Accord.

Resource Constraints?

Valero et al. (2018) highlights that the demand for many of the REEs and other critical minerals will, at the current rate of RE infrastructure growth, increase a multiple of 3,000 times or more by 2050. Some believe this growth may reach constraints in supply (Giurco et al. 2019). Others suggest that the minerals involved are not likely to physically run out (Sovacool et al. 2020) if well managed, especially as markets are found in other parts of the world (for example the transition away from Lithium in brine lakes to hard rock sources). Lithium hydroxide, more suitable for batteries, now competes well, in terms of cost, when extracted from rock sources (Azevedo et al. 2018) due to the ability to more easily create high quality Lithium Hydroxide from rock sources, even though brines provide a cheaper source of Lithium *per se* (Kavanagh et al. 2018). Australia has proven resources for all the Li-ion battery minerals and has a strategy for their ethical and transparent production (Commonwealth of Australia 2019). Changes in the technology have also been used to create less need for certain critical minerals (Månberger and Stenqvist 2018). Recycling of all the minerals is not yet well developed but is likely to be increasingly important (Habib and Wenzel 2014; Golroudbary et al. 2019; World Bank Group 2017; Giurco et al. 2019).

International Collaboration

There have been many instances since the 1950's when the supply of essential minerals has been restricted by nations in times of conflict and world tensions, but international trade has continued under the framework of the World Trade Organization. Keeping access open to critical minerals needed for a low-carbon transition will be an essential role of the international community as the need for local manufacture of such renewable and electro-mobility technologies will be necessary for local economies. shows that the trend over the past 30 years has been for the US to move from being self-sufficient in REEs to being 100% reliant on imports, predominantly from China, Japan, and France. In terms of heavy REEs, essential for permanent magnets for wind turbines, China has a near-monopoly on REE processing though other mines and manufacturing facilities are now responding to these constrained markets (Stegen 2015; Gulley et al. 2018, 2019; Yan et al. 2020). China, on the other hand, is reliant on other nations for the supply of other critical metals, particularly cobalt and lithium for batteries.

A number of Critical Materials Strategies have now been developed by nations developing the manufacturing-base of new power and transport technologies. Some of these strategies pay particular attention to the supply of lithium (Martin et al. 2017; Hache et al. 2019). For example, Horizon 2020, a substantial EU Research and Innovation program, couples research and innovation in science, industry, and society to foster a circular economy in Europe thus reducing these bottlenecks in the EU nations. Similarly CREEN (Canada Rare Earth Elements Network) is supporting the US-EU-Japan resource partnership with Australia (Klossek et al. 2016).

As renewables and electromobility-based development leapfrogs into the developing world it will be important to ensure the critical minerals issues are managed for local security of supply as well as participation in the mining and processing of such minerals to develop their own employment around renewables and electro-mobility (Sovacool et al. 2020).

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Enabling creative foresight: Human culture has always had a creative instinct that enables the future to be better dealt with through imagination (Montgomery 2017). Science and engineering have often been preceded by artistic expressions such as Jules Verne, who first dreamed of the Hydrogen future in 1874 in his novel The Mysterious Island. Autonomous vehicles have regularly occupied the minds of science fiction authors and filmmakers (Braun 2019). Such narratives, scenario building, and foresighting are increasingly seen as a part of the climate change mitigation process (Lennon et al. 2015; Muiderman et al. 2020) and can 'liberate oppressed imaginaries' (Luque-Ayala 2018). (Barber 2021) have emphasised the important role of positive images about the future instead of dystopian visions and the impossibility of business-as-usual futures.

Transport visions can be a part of this cultural change as well as the more frequently presented visions of renewable energy (Wentland 2016; Breyer et al. 2017). There are some emerging technologies like Maglev, Hyperloop, and Drones that are likely to continue the electrification of transport even further (Daim 2021) and which are only recently at the imagination stage. Decarbonised visions for heavy vehicle systems appear to be a core need from the assessment of technologies in this chapter. Such visioning or foresighting requires deliberative processes and the literature contains a growing list of transport success stories based on such processes (Weymouth and Hartz-Karp 2015). Ultimately, reducing GHG emissions from the transport sector would benefit from creative visions that integrate a broad set of ideas about technologies, urban and infrastructure planning (including transport, electricity, and telecommunication infrastructure), and human behaviour and at the same time can create opportunities to achieve the SDGs.

Enabling transport climate emergency plans, local pledges and net zero strategies: National, regional and local governments are now producing transport plans with a climate emergency focus (e.g. (Jaeger et al. 2015; Pollard 2019)). Such plans are often grounded in the goals of the Paris Agreement, based around Local Low Carbon Transport Roadmaps that contain targets for and involve commitments or pledges from local stakeholders, such as workplaces, local community groups, and civil society organisations. Pledges often include phasing out fossil-fuel based cars, buses, and trucks (Plötz et al. 2020), strategies to meet the targets through infrastructure, urban regeneration and incentives, and detailed programs to help citizens adopt change. These institution-led mechanisms could include bike-to-work campaigns, free transport passes, parking charges, or eliminating car benefits. Community-based solutions like solar sharing, community charging, and mobility as a service can generate new opportunities to facilitate low-carbon transport futures. Cities in India and China have established these transport roadmaps, which are also supported by the UNCRD's Environmentally Sustainable Transport program (Baeumler et al. 2012; Pathak and Shukla 2016; UNCRD 2020). There have been concerns raised that these pledges may be used to delay climate action in some cases (Lamb et al. 2020) but but such pledges can be calculated at a personal level and applied through every level of activity from individual, household, neighbourhood, business, city, nation or groups of nations (Meyer and Newman 2020) and are increasingly being demonstrated through shared communities and local activism (Bloomberg and Pope 2017; Sharp 2018; Figueres and Rivett-Carnac 2020). Finally, the world's major financing institutions are also engaging in decarbonisation efforts by requiring their recipients to commit to Net Zero Strategies before they can receive their funding (COVID Box, Chapter 1; Chapter 15; (Robins 2018; Newman 2020a)). As a result, transparent methods are emerging for calculating what these financing requirements mean for transport by companies, cities, regions, and infrastructure projects (see Chapters 8, 15). The continued engagement of financial institutions may, like in other sectors, become a major factor in enabling transformative futures for transport as long as governance and communities continue to express the need for such change.

10.8.4 Tools and Strategies to Enable Decarbonisation of the Transport Sector

Using the right tools and strategies is crucial for the successful deployment of mitigation options. Table 10.7 summarises the tools and strategies to enable electromobility, new fuels for aviation and shipping, and the more social aspects of demand efficiency.

Table 10.7 Tools and Strategies for enabling mitigation options to achieve transformative scenarios

Tools and Strategies	Travel Demand Reductions and Fuel/Vehicle Efficiency	Light Vehicle Electromobility Systems	Alternative Fuel Systems for Shipping and Aviation
Education and R&D	TDR can be assisted with digitalisation, connected autonomous vehicle, EVs and Mobility as a Service (Marsden et al. 2018; Shaheen et al. 2018). Knowledge gaps on TDR exist for longer distance travel (intercity); non-mandatory trips (leisure; social trips), and travel by elder people. Travel demand foresighting tools can be open source (Marsden 2018).	Behaviour change programs help EV's become more mainstream. R&D will help on the socio-economic structures that impede adoption of EV's and the urban structures that enable reduced car dependence and how EV's can assist grids (Newman 2010; Taiebat and Xu 2019; Seto et al. 2021).	R&D is critical for new fuels and to test the full life cycle costs of various heavy vehicle options (Marinaro et al. 2020).
Access and Equity	TDR programs in cities can be inequitable. To avoid such inequities, there is a need for better links to spatial and economic development (Marsden et al, 2018), mindful of diverse local priorities, personal freedom and personal data (See Box on Smart Technologies in Section 10.2)	Significant equity issues with EV's in the transition period can be overcome with programs that enable affordable electric mobility, especially transit. (IRENA 2016)	Shipping is mostly freight and is less of a problem but aviation has big equity issues (Bows-Larkin 2015)
Financing Economic Incentives and Partnerships	Carbon budget implications of different demand futures should be published and used to help incentivize net zero projects (Marsden 2018). Business and community pledges for net zero can be set up in partnership agreements (see Section 10.8.3).	Multiple opportunities for financing, economic incentives, and partnerships with clear economic benefits can be assured especially using the role of value capture in enabling such benefits. The nexus between EV's and the electricity grid needs opportunities to demonstrate positive partnership projects (Zhang et al. 2014; Mahmud et al. 2018; Newman et al. 2018; Sovacool et al. 2018; Sharma and Newman 2020)	Taking R&D into demonstration projects is the main stage for heavy vehicle options and these are best done as partnerships. Government assistance will greatly assist in such projects as well as an R&D levy. Abolishing fossil fuel subsidies and imposing carbon taxes are likely to help in the early stages of heavy vehicle transitions (Sclar et al. 2019)
Co-benefits and Overcoming Fragmentation	A focus on people-centred solutions for future mobility with more pluralistic and feasible sets of outcomes for all people can be achieved	The SDG benefits in zero carbon light vehicle transport systems are being demonstrated and can now be quantified as nations	Heavy vehicle systems can also demonstrate SDG co-benefits if formulated with this in mind. Demonstrations of how innovations can also help

	when they focus on more than simple benefit cost ratios but include well-being and livelihoods, considering transport as a system, rather than loosely connected modes as well as behaviour change programs (Barter and Raad 2000; Newman 2010; Martens 2020).	mainstream this transition. Projects with transit and sustainable housing are more able to show such benefits. New Benefit Cost Ratio methods that focus on health benefits in productivity are now favouring transit and active transport (Buonocore et al. 2019; UK DoT 2019; Hamilton et al. 2021).	SDGs will attract more funding. Such projects need cross-government consideration (Pradhan et al. 2017).
Regulation and Assessment	Implementing a flexible regulatory framework is needed for most TDR (Li and Pye 2018). Regulatory assessment can help with potential additional (cyber) security risk due to digitalization, AVs, IoT, and big data (Shaheen and Cohen 2019). Assessment tools and methods need to take account of greater diversity of population, regions, blurring of modes, and distinct spatial characteristics (Newman and Kenworthy 2015).	With zero carbon light vehicle systems rapidly growing the need for a regulated target and assessment of regulatory barriers can assist each city and region to transition more effectively. Regulating EV's for government fleets and recharge infrastructure can establish incentives (Bocken et al. 2016).	Zero carbon heavy vehicle systems need to have regulatory barrier assessments as they are being evaluated in R&D demonstrations (Sclar et al. 2019).
Governance and Institutional Capacity	TDR works better if adaptive decision-making approaches focus on more inclusive and whole of system benefit-cost ratios (Yang et al. 2020; Marsden 2018)	Governance and institutional capacity can now provide international exchanges and education programs based on successful cities and nations enabling light vehicle decarbonisation to create more efficient and effective policy mechanisms towards self-sustaining markets (Greene et al. 2014; Skjølsvold and Ryghaug 2019)..	Governance and institutional capacity can help make significant progress if targets with levies for not complying. Carbon taxes would also affect these segments. A review of international transport governance is likely (Makan and Heyns 2018)
Enabling infrastructure	Ensuring space for active transport and urban activities is taken from road space where necessary (Gössling et al. 2021b). Increasing the proportion infrastructure that supports walking in urban areas will structurally enable reductions in car use (Section 10.2 and	Large-scale electrification of LDVs requires expansion of low-carbon power systems, while charging or battery swapping infrastructure is needed for some segments (Gnann et al. 2018; Ahmand et al. 2020)	In addition to increasing the capabilities to produce low or zero-carbon fuels for shipping and aviation, there is a need to invest in supporting infrastructure including low carbon power generation. New Hydrogen delivery and refuelling infrastructure may be needed (Maggio et al. 2019). For zero-carbon

	(Newman and Kenworthy 2015). Creating transit activated corridors of TOD-based rail or mid-tier transit using value capture for financing will create inherently less car dependence (McIntosh et al. 2017; Newman et al. 2019)		synthetic fuels, infrastructure is needed to support carbon capture and CO_2 transport to fuel production facilities (Edwards and Celia 2018).

Frequently Asked Questions (FAQs)

FAQ 10.1 -How important is electro-mobility in decarbonising transport and are there major constraints in battery minerals?

Electromobility is the biggest change in transport since AR5. When powered with low-carbon electricity, electric vehicles (EVs) provide a mechanism for major GHG emissions reductions from the largest sources in the transport sectors, including cars, motor-bikes, tuk tuks, buses and trucks. The mitigation potential of EVs depends on the decarbonization of the power system. EVs can be charged by home or business renewable power before or in parallel to the transition to grid-based low-carbon power.

Electromobility is happening rapidly in micro-mobility (e-autorickshaws, e-scooters, e-bikes) and in transit systems, especially buses. EV adoption is also accelerating for personal cars. EVs can be used in grid stabilization through smart charging applications.

The state-of-the-art Lithium-Ion Batteries (LIBs) available in 2020 are superior to alternative cell technologies in terms of battery life, energy density, specific energy, and cost. The expected further improvements in LIBs suggest these chemistries will remain superior to alternative battery technologies in the medium-term, and therefore LIBs will continue to dominate the electric vehicle market.

Dependence on LIB metals will remain, which may be a concern from the perspective of resource availability and costs. However, the demand for such metals is much lower than the reserves available, with many new mines starting up in response to the new market particularly in a diversity of places.

Recycling batteries will significantly reduce long-term resource requirements. The standardisation of battery modules and packaging within and across vehicle platforms, as well as increased focus on design for recyclability are important. Many mobility manufacturers and governments are considering battery recycling issues to ensure the process is mainstreamed.

The most significant enabling condition in electro-mobility is to provide electric recharging opportunities and a strategy to show they can be helping the grid.

FAQ 10.2 - How hard is it to decarbonise heavy vehicles in transport like long haul trucks, ships and planes?

Unlike for land transport vehicles, there are few obvious solutions to decarbonizing heavy vehicles like international ships and planes. The main focus has been increased efficiency, which so far has not prevented these large vehicles from becoming the fastest growing source of GHG globally. These vehicles likely need alternative fuels that can be fitted to the present propulsion systems. Emerging demonstrations suggest that ammonia, advanced biofuels, or synthetic fuels could become commercial.

Electric propulsion using hydrogen fuel cells or Li-ion batteries could work with short-haul aviation and shipping, but the large long-lived vessels and aircraft likely need alternative liquid fuels for most major long-distance functions.

Advanced biofuels, if sourced from resources with low GHG footprints, offer decarbonisation opportunities. As shown in Chapters 2, 6, and 12, there are multiple issues constraining traditional biofuels. Sustainable land management and feedstocks, as well as R&D efforts to improve lignocellulosic conversion routes are key to maximise the mitigation potential from advanced biofuels.

Synthetic fuels made using CO_2 captured with DAC/BECCS and low-carbon hydrogen can subsequently be refined to a net zero jet fuel or marine fuel. These fuels may also have less contrails-based climate impacts and low emissions of local air pollution. However, these fuels still require significant R&D and demonstration.

The deployment of low-carbon aviation and shipping fuels that support decarbonisation of the transport sector will likely require changes to national and international governance structures

FAQ 10.3 - How can governments, communities and individuals reduce demand and be more efficient in consuming transport energy?

Cities can reduce their transport-related fuel consumption by around 25% through combinations of more compact land use and less car dependent transport infrastructure.

More traditional programs for reducing unnecessary high-energy travel through behaviour change programs (i.e., taxes on fuel, parking, and vehicles or subsidies for alternative low-carbon modes), continue to be evaluated with mixed results due to the dominance of time savings in an individual's decision-making.

The circular economy, the shared economy, and digitalisation trends can support systemic changes that lead to reductions in demand for transport services or expands the use of more efficient transport modes

COVID-19-based lockdowns have confirmed the transformative value of telecommuting replacing significant numbers of work and personal journeys as well as promoting local active transport. These changes may not last and impacts on productivity and health are still to be fully evaluated.

Solutions for individual households and businesses involving pledges and shared communities that set new cultural means of reducing fossil fuel consumption, especially in transport, are setting out new approaches for how climate change mitigation can be achieved.

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Appendix 10.1: Data and methods for life cycle assessment

IPCC LCA Data Collection Effort

In mid-2020, the IPCC, in collaboration with the Norwegian University of Science and Technology, released a request for data from the life cycle assessment community, to estimate the life cycle greenhouse (GHG) emissions of various passenger and freight transport pathways. The data requested included information about vehicle and fuel types, vintages, vehicle efficiency, payload, emissions from vehicle and battery manufacturing, and fuel cycle emissions factors, among others.

Data submissions were received from approximately 20 research groups, referencing around 30 unique publications. These submissions were supplemented by an additional 20 studies from the literature. While much of this literature was focused on LDVs and trucks, relatively few studies referenced bus and rail pathways.

Harmonization method

First, the datapoints were separated into categories based on the approximate classification (e.g., heavy-duty vs medium-duty trucks), powertrain (i.e., ICEV, HEV, BEV, FCV), and fuel combination. For each category of vehicle/powertrain/fuel, a simplified LCA that harmonizes values from across the reviewed studies was constructed, using the following basic equation:

$$Life\ cycle\ GHG\ intensity = \frac{FC}{P} * EF + \frac{VC}{P * LVKT}$$

Where:

- Life cycle GHG intensity represents the normalized life cycle GHG emissions associated with each transportation mode, measured in g CO_2-eq/passenger-km or g CO_2-eq/tonne-km
- FC is the fuel consumption of the vehicle in MJ or kWh per km
- P represents the payload (measured in tonnes of cargo) or number of passengers, at a specified utilization capacity (e.g., 50% payload or 80% occupancy)
- EF is an emissions factor representing the life cycle GHG intensity of the fuel used, measured in g CO_2-eq/MJ or g CO_2-eq/kWh. A single representative EF value is selected for each fuel type. When a given fuel type can be generated in different ways with substantially different upstream emissions factors (e.g., H_2 from methane steam reforming vs H_2 from water electrolysis), these are treated as two different fuel categories. The fuel emissions factors that were used are presented in Table 10.8
- VC are the vehicle cycle emissions of the vehicle, measured in g CO_2-eq /vehicle. This may include vehicle manufacturing, maintenance and end-of-life, or just manufacturing.
- LVKT is the lifetime vehicle kilometres travelled

Note: for PHEVs, the value of FC/P*EF is a weighted sum of this aggregate term for each of battery and diesel/gasoline operation.

Fuel emissions factors used are presented in Table 10.8. Note that the fuel emissions factors were compiled from several studies that used different global warming potential (GWP) values in their underlying assumptions, and therefore the numbers reported here may be slightly different if GWP_{100} from the AR6 had been used. This difference would be small given the small contribution from non-CO_2 gases to the total life cycle emissions. For example, methane emissions exist in the life cycle of natural gas supply chains or natural gas dependent supply chains such as Hydrogen from SMR. Recent data from the U.S. suggests emissions of approximately 0.2-0.3 g CH_4/MJ natural gas (Littlefield et al. 2017, 2019), which would range by no more than 1-2 g CO_2-eq/MJ natural gas (<3% of natural gas life cycle emissions) when converting from a GWP_{100} of 25 (AR4) or 36 (AR5) to the current (AR6) GWP_{100} of 29.8.

For LDVs, the entire distribution of estimated life cycle emissions is presented for each vehicle/powertrain/fuel category (as a boxplot). For trucks, rail and buses, only the low and high estimates are presented (as solid bars) since the number of datapoints were not sufficient to present as a distribution. Table 10.9 presents the low and high estimates of fuel efficiency for each category. The references used are reported in the main text.

Table 10.8 Fuel emissions factors used to estimate life cycle greenhouse gas (GHG) emissions of passenger and freight transport pathways

Fuel	Emissions factor	Units	Source
Gasoline	92	g CO_2-eq MJ^{-1}	Submissions to IPCC data call (median)
Diesel	92	g CO_2-eq MJ^{-1}	Submissions to IPCC data call (median)
Diesel, high	110	g CO_2-eq MJ^{-1}	Diesel from oil sands: average of in-situ pathways (Guo et al. 2020)
Biofuels, IAM EMF33	25	g CO_2-eq MJ^{-1}	From Chapter 7
Biofuels, partial models CLC	36	g CO_2-eq MJ^{-1}	From Chapter 7
Biofuels, partial models NG	141	g CO_2-eq MJ^{-1}	From Chapter 7
Compressed natural gas	71	g CO_2-eq MJ^{-1}	Submissions to IPCC data call (median)
Liquefied natural gas	76	g CO_2-eq MJ^{-1}	Submissions to IPCC data call (median)
Liquefied petroleum gas	78	g CO_2-eq MJ^{-1}	Submissions to IPCC data call (median)
DAC FT-Diesel, wind electricity	12	g CO_2-eq MJ^{-1}	From electrolytic Hydrogen produced using low-carbon electricity (Liu et al. 2020a)
DAC FT-Diesel, natural gas electricity	370	g CO_2-eq MJ^{-1}	From electrolytic Hydrogen produced using natural gas electricity; extrapolated from (Liu et al. 2020a)
Ammonia, low carbon renewable	3.2	g CO_2-eq MJ^{-1}	From electrolytic Hydrogen produced using low-carbon electricity via Haber-Bosch (Gray et al. 2021)
Ammonia, natural gas SMR	110	g CO_2-eq MJ^{-1}	From H_2 derived from natural gas steam methane reforming; via Haber-Bosch (Frattini et al. 2016)
Hydrogen, low carbon renewable	10	g CO_2-eq MJ^{-1}	From electrolysis with low-carbon electricity (Valente et al. 2021)
Hydrogen, natural gas SMR	95	g CO_2-eq MJ^{-1}	From steam-methane reforming (SMR) of fossil fuels (Valente et al. 2021)
Wind electricity	9.3	g CO_2-eq kWh^{-1}	Submissions to IPCC data call (median)
Natural gas electricity	537	g CO_2-eq kWh^{-1}	Submissions to IPCC data call (median)
Coal electricity	965	g CO_2-eq kWh^{-1}	Submissions to IPCC data call (median)

For transit and freight, the life cycle harmonization exercise allows two aggregate parameters to vary from the low to high among submitted values within each category: FC/P and VC/P. Aggregate parameters are used to capture internal correlations (e.g., fuel consumption and payload both depend heavily on vehicle size) and are presented in Table 10.10 to Table 10.14. The references used are reported in the main text.

Table 10.9 Range of fuel efficiencies for light duty vehicles by fuel and powertrain category, per vehicle kilometre

Fuel	Powertrain	Fuel efficiency (MJ/vehicle-km)		Electric efficiency (kWh/vehicle-km)	
		Low	High	Low	High
Compression ignition	ICEV	1.34	2.6		
Spark ignition	ICEV	1.37	2.88		
Spark ignition	HEV	1.22	2.05		
Compression ignition	HEV	1.15	1.51		
Electricity	BEV			0.12	0.242
Hydrogen	FCV	1.14	1.39		

Table 10.10 Range of fuel efficiencies for buses by fuel and powertrain category, at 80% occupancy

Fuel	Powertrain	Fuel efficiency (MJ/passenger-km)		Electric efficiency (kWh/passenger-km)	
		Low	High	Low	High
Diesel	ICEV	0.16	0.52		
CNG	ICEV	0.25	0.61		
LNG	ICEV	0.27	0.37		
Biodiesel	ICEV	0.16	0.52		
DAC FT-Diesel	ICEV	0.16	0.52		
Diesel	HEV	0.11	0.37		
Electricity	BEV			0.01	0.04
Hydrogen	FCV	0.11	0.31		

Table 10.11 Range of fuel efficiencies for passenger rail by fuel and powertrain category, at 80% occupancy

Fuel	Powertrain	Fuel efficiency (MJ/passenger-km)		Electric efficiency (kWh/passenger-km)	
		Low	High	Low	High
Diesel	ICEV	0.36	0.40		
Biofuels	ICEV	0.36	0.40		

DAC FT-Diesel	ICEV	0.36	0.40		
Diesel	HEV	0.33	0.33		
Electricity	BEV			0.03	0.03
Hydrogen[a]	FCV	0.18	0.18		

[a] *Occupancy corresponds to average European occupancy rates* (IEA 2019e)

Table 10.12 Range of fuel efficiencies for heavy-duty truck by fuel and powertrain category, at 100% payload

Fuel	Powertrain	Fuel efficiency (MJ/tonne-km)		Electric efficiency (kWh/tonne-km)	
		Low	High	Low	High
Diesel	ICEV	0.38	0.93		
CNG	ICEV	0.48	1.45		
LNG	ICEV	0.43	1.00		
Biofuels	ICEV	0.38	0.93		
Ammonia[a]	ICEV	0.38	0.93		
DAC FT-Diesel	ICEV	0.38	0.93		
Diesel	HEV	0.34	0.59		
LNG	HEV	0.46	0.51		
Electricity	BEV			0.03	0.09
Hydrogen	FCV	0.25	0.43		
Ammonia[b]	FCV	0.25	0.43		

[a]*Ammonia ICEV trucks are assumed to have the same fuel economy as diesel ICEVs due to lack of data.*

[b]*Ammonia FCV trucks are assumed to have the same fuel economy as Hydrogen FCVs due to lack of data.*

Table 10.13 Range of fuel efficiencies for medium-duty truck by fuel and powertrain category, at 100% payload

Fuel	Powertrain	Fuel efficiency (MJ/tonne-km)		Electric efficiency (kWh/tonne-km)	
		Low	High	Low	High
Diesel	ICEV	0.85	2.30		
CNG	ICEV	1.08	2.54		
LNG	ICEV	1.05	1.41		
Biofuels	ICEV	0.85	2.30		
Ammonia[a]	ICEV	0.85	2.30		
DAC FT-Diesel	ICEV	0.85	2.30		
Diesel	HEV	0.81	1.54		

Electricity	BEV			0.12	0.22
Hydrogen	FCV	0.65	0.99		
Ammonia[b]	FCV	0.65	0.99		

[a]Ammonia ICEV trucks are assumed to have the same fuel economy as diesel ICEVs due to lack of data.

[b]Ammonia FCV trucks are assumed to have the same fuel economy as Hydrogen FCVs due to lack of data.

Table 10.14 Range of fuel efficiencies for freight rail by fuel and powertrain category, at an average payload

Fuel	Powertrain	Fuel efficiency (MJ/tonne-km)		Electric efficiency (kWh/tonne-km)	
		Low	High	Low	High
Diesel	ICEV	0.11	0.78		
Biodiesel	ICEV	0.11	0.78		
DAC FT-Diesel	ICEV	0.11	0.78		
Electricity	BEV			0.01	0.12
Hydrogen	FCV	0.10	0.10		

Appendix 10.2: Data and assumptions for life cycle cost analysis

Fuel cost ranges

For diesel, a range of 0.5-2.5 USD/L is used based on historic diesel costs across all OECD countries reported in the IEA Energy Prices and Taxes Statistics database (IEA 2021c) since 2010. The lower end of this range is consistent with the minimum projected value from the 2021 U.S. Annual Energy Outlook (low oil price scenario, 0.55 USD/L) (U.S. Energy Information Administration 2021). The upper end of the range encompasses both the maximum diesel price observed in the 2021 U.S. Annual Energy Outlook projections (high oil price scenario, 1.5 USD/L) (U.S. Energy Information Administration 2021), and the diesel price that would correspond to the 2020 IEA World Energy Outlook crude oil price projections (Stated Policies scenario) (IEA 2020b), assuming the historical price relationship between crude oil and diesel is maintained (1.5 USD/L). For reference, the IEA reports current world-average automotive diesel costs to be around 1 USD/L (IEA 2021d). The selected range also captures the current range of production costs for values for bio-based and synthetic diesels (51-144 Eur/MWh, corresponding to 0.6-1.70 USD/L), which are generally still higher than wholesale petroleum diesel costs (30-50 Eur/MWh corresponding to 0.35-0.6 USD/L), as reported by IEA (IEA 2020c). This range also encompasses costs for synthesized electro-fuels from electrolytic Hydrogen as reported in Chapter 6 (1.6 USD/L).

The range of electricity costs used here are consistent with the range of levelized cost of electricity estimates presented in Chapter 6 (20-200 USD/MWh).

For Hydrogen, a range of 1-13 USD/kg is used. The upper end of this range corresponds approximately to reported retail costs in the US (Burnham et al. 2021; Eudy and Post 2018b; Argonne National Laboratory 2020). Despite the high upper bound, lower costs (6-7 USD/kg) are already consistent with recent cost estimates of Hydrogen produced via electrolysis from Chapter 6 and current production cost estimates from IRENA (IRENA 2020). The lower end of the range (1 USD/kg) corresponds to projected future price decreases for electrolytic Hydrogen (BNEF 2020; Hydrogen Council 2020; IRENA 2020), and is consistent with projections from Chapter 6 for the low end of long-term future prices for fossil Hydrogen with CCS.

Vehicle efficiencies

The vehicle efficiencies used in developing the life cycle cost estimates were derived from the harmonized ranges used to develop life cycle GHG estimates and are presented in Table 10.9 to Table 10.14.

Other inputs to bus cost model

For buses, a 40-ft North American transit bus with a passenger capacity of 50, lifetime of 15 years, and an annual mileage of 72,400 km based on data in the ANL AFLEET model (Argonne National Laboratory 2020) is assumed. Maintenance costs were assumed to be 1 USD/mile for ICEV buses and 0.6 USD/mile for BEV and ICEV buses, also based on data from the AFLEET model (Argonne National Laboratory 2020). For ICEV and BEV purchase costs, data from the National Renewable Energy Laboratory (Johnson et al. 2020) is used for bounding ranges (430,000 to 500,000 USD for ICEV and 579,000 to 1,200,000 USD for BEV), which encompass the default values from AFLEET model (Argonne National Laboratory 2020). Note that wider ranges are available in the literature (e.g., as low as USD120,000 per bus in (Burnham et al. 2021) and (Harris et al. 2020)); but these are not included in the sensitivity analysis to avoid conflating disparate vehicles. For FCV buses, the upper bound of the purchase price range (1,200,000 USD) represents current costs in the U.S. (Argonne National Laboratory 2020; Eudy and Post 2020), and the lower bound represents the target future value from the U.S Department of Energy (Eudy and Post 2020).

Other inputs to rail cost model

For freight and passenger rail, powertrain and vehicle O&M costs in USD/km from the IEA Future of Rail report (IEA 2019e) (IEA Figure 2.14 for passenger rail and IEA Figure 2.15 for freight rail) are used as a proxy for non-fuel costs. The ranges span conservative and forward-looking cases. In addition, the range for BEV rail ranges encompass short and long-distance trains – corresponding to 100-200 km for passenger rail, and 400-750 km for freight rail. Note that all values exclude the base vehicle costs, but they are expected not to be significant as they are amortized over the lifetime-km travelled. For freight rail, a network that is representative of North America is assumed, with a payload of 2800 tonnes per train (IEA Figure 1.17), assumed to be utilized at 100%, with a lifetime of 10 years, and an average mileage of 120,000 km/year. For BEV freight rail, the range in powertrain costs are driven by battery costs of 250-600 USD/kWh, while for FCV freight rail, the range in powertrain costs are driven by fuel cell stack costs of 50-1000 USD/kW. For passenger rail, a network that is representative of Europe is assumed, with an average occupancy of 180 passengers per train (IEA Figure 1.14), with a lifetime of 10 years, and an average mileage of 115,000 km/year.

Other inputs to truck cost model

Capital cost ranges vary widely in the literature depending on the exact truck model, size and other assumptions. For ICEVs in this analysis, the lower bound (90,000 USD) corresponds to the 2020 estimate for China from (Moultak et al. 2017), and the upper bound (250,000 USD) corresponds to the 2030 projection for the US from the same study. These values encompass the full range reported by Argonne (Burnham et al. 2021). The lower bound BEV cost (120,000 USD) is taken from 2030 projections for China (Moultak et al. 2017) and the upper bound (780,000 USD) is taken from 2020 cost estimates in the US (class 8 sleeper cab tractor) (Burnham et al. 2021). The lower bound for FCV trucks (130,000 USD) corresponds to the 2050 estimate for class 8 sleeper cab tractors from Argonne National Laboratory and the upper bound (290,000 USD) corresponds the 2020 estimate from the same study (Burnham et al. 2021). These values span the full range reported by (Moultak et al. 2017) for the US, Europe and China from 2020-2030.

The analysis uses a truck lifetime of 10 years and annual mileage of 140,000 km based on (Burnham et al. 2021). An effective payload of 17 tonnes (80% of maximum payload of 21 tonnes) is assumed based on reported average effective payload submitted by Argonne National Laboratory in response to the IPCC LCA data collection call. A discount rate of 3% is used, based on (Burnham et al. 2021) and consistent with the social discount rate from Chapter 3. Maintenance costs are assumed to be 0.15 USD/km for ICEV trucks and 0.09 USD/km for BEV and FCV trucks, as reported in (Burnham et al. 2021).

Appendix 10.3: Line of sight for feasibility assessment

	Geophysical		
	Physical potential	**Geophysical recourses**	**Land Use**
Demand reduction and mode shift	+	+	+
Role of contexts	Adoption of Avoid Shift Improve approach along with improving fuel efficiency will have negligible physical constraints; they can be implemented across the countries.	Reduction in demand, fuel efficiency and demand management measures such as Clean Air Zones/ Parking Policy will reduce negative impact on land use and resource consumption - without any constraints in terms of available resources	Reduction in demand, increase in fuel efficiency and demand management measures will have a positive impact on land use as compared to 'without' them - no likely adverse constraints in terms of limited land use (such decline in biofuel)
Line of sight	Holguín-Veras, J., & Sánchez-Díaz, I. (2016). Freight demand management and the potential of receiver-led consolidation programs. Transportation Research Part A: Policy and Practice, 84, 109-130. Creutzig, F., Roy, J., Lamb, W. F., Azevedo, I. M., De Bruin, W. B., Dalkmann, H., ... & Hertwich, E. G. (2018). Towards demand-side solutions for mitigating climate change. Nature Climate Change, 8(4), 260. Rajé, F. (2017). Transport, demand management and social inclusion: The need for ethnic perspectives. Routledge. Dumortier, J., Carriquiry, M., & Elobeid, A. Where does all the biofuel go? Fuel efficiency gains and its effects on global agricultural production. Energy Policy, 148, 111909.		
Biofuels for land transport, aviation, and shipping	+	±	-
Role of contexts	Climate conditions are an important factor for bioenergy viability. Land availability constrains might be expected for bioenergy deployment	Land and synthetic fertilizers are examples of limited resources to deploy large-scale biofuels, however the extent of this restrictions will depend on local and context specific conditions	Implementing biofuels may require additional land use. However, it will depend on context and local specific conditions.
Line of sight	Daioglou, Vassilis, Jonathan C. Doelman, Birka Wicke, Andre Faaij, and Detlef P. van Vuuren. "Integrated assessment of biomass supply and demand in climate change mitigation scenarios." Global Environmental Change 54 (2019): 88-101. Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V., Deppermann, A., Doelman, J., Emmet-Booth, J., Engelmann, J. and Fricko, O., 2021. Land-based measures to mitigate climate change: Potential and feasibility by country. Global Change Biology.		
Ammonia for shipping	+	+	±
Role of contexts	A global ammonia supply chain is already established; the primary requirement for delivering greater carbon emission reductions will be through the production of ammonia using green hydrogen or CCS.	The use of ammonia would reduce reliance of fossil fuels for shipping and is expected to reduce reliance on natural resources when produced using green hydrogen. The primary resource requirements will be the supply of renewable electricity and clean water to produce green hydrogen, from which ammonia can be produced.	No major changes in land use for the vehicle. Increases may occur if the hydrogen is produced through electrolysis and renewable energy sources or hydrogen production with CCS.
Line of sight	Bicer, Y., and I. Dincer, 2018: Clean fuel options with hydrogen for sea transportation: A life cycle approach. International Journal of Hydrogen Energy, 43, 1179–1193, https://doi.org/https://doi.org/10.1016/j.ijhydene.2017.10.157 Gilbert, P., C. Walsh, M. Traut, U. Kesieme, K. Pazouki, and A. Murphy, 2018: Assessment of full life-cycle air emissions of alternative shipping fuels. Journal of Cleaner Production, 172, 855–866, https://doi.org/10.1016/j.jclepro.2017.10.165.		

Synthetic fuels for heavy-duty land transport, aviation, and shipping (e.g., DAC-FT)	±	±	±
Role of contexts	Fischer Tropsch chemistry is well established; pilot scale direct air capture (DAC) plants are already in operation; - does not qualify as a mitigation option except in regions with very low carbon electricity	+ Gasification can use a wide range of feedstocks; DAC can be applied in wide range of locations - Limited information available on potential limits related to large input energy requirements, or water use and required sorbents for DAC	No major changes in land use for the vehicle. Potential increases in land use for electricity generation (especially solar, wind or hydropower) for CO2 capture and fuel production; likely lower land use than crop-based biofuels
Line of sight	Realmonte, G., Drouet, L., Gambhir, A. et al. An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nat Commun 10, 3277 (2019). https://doi.org/10.1038/s41467-019-10842-5 Liu, C. M., N. K. Sandhu, S. T. McCoy, and J. A. Bergerson, 2020: A life cycle assessment of greenhouse gas emissions from direct air capture and Fischer-Tropsch fuel production. Sustain. Energy Fuels, https://doi.org/10.1039/c9se00479c. Ueckerdt, F., C. Bauer, A. Dirnaichner, J. Everall, R. Sacchi, and G. Luderer, 2021: Potential and risks of hydrogen-based e-fuels in climate change mitigation. Nat. Clim. Chang., https://doi.org/10.1038/s41558-021-01032-7.	Realmonte, G., Drouet, L., Gambhir, A. et al. An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nat Commun 10, 3277 (2019). https://doi.org/10.1038/s41467-019-10842-5	
Electric vehicles for land transport	+	±	±
Role of contexts	Electromobility is being adopted across a range of land transport options including light-duty vehicles, trains and some heavy-duty vehicles, suggesting no physical constraints	Current dominant battery chemistry relies on minerals that may face supply constraints, including lithium, cobalt, and nickel. Regional supply/availability varies. Alternative chemistries exist; recycling may likewise alleviate critical material concerns. Similar supply constraints may exist for some renewable electricity sources (e.g., solar) required to support EVs. May reduce critical materials required for catalytic converters in ICEVs (e.g., platinum, palladium, rhodium)	No major changes in land use for the vehicle. Potential increases in land use for electricity generation (especially solar, wind or hydropower) and mineral extraction, but may be partially offset by a decrease in land use for fossil fuel production; likely lower land use than crop-based biofuels, or technologies with higher electricity use (e.g., those based electrolytic hydrogen)

Line of sight	IEA (2021), Global EV Outlook 2021, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2021	Jones, B., R. J. R. Elliott, and V. Nguyen-Tien, 2020: The EV revolution: The road ahead for critical raw materials demand. Appl. Energy, 280, 115072, https://doi.org/10.1016/J.APENERGY.2020.115072., Xu, C., Q. Dai, L. Gaines, M. Hu, A. Tukker, and B. Steubing, 2020: Future material demand for automotive lithium-based batteries. Commun. Mater. 2020 11, 1, 1–10, https://doi.org/10.1038/s43246-020-00095-x. IEA, 2021: The Role of Critical Minerals in Clean Energy Transitions – Analysis. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions (Accessed October 20, 2021). Zhang, J., M. P. Everson, T. J. Wallington, I. Frank R. Field, R. Roth, and R. E. Kirchain, 2016: Assessing Economic Modulation of Future Critical Materials Use: The Case of Automotive-Related Platinum Group Metals. Environ. Sci. Technol., 50, 7687–7695, https://doi.org/10.1021/ACS.EST.5B04654 Milovanoff, A., I. D. Posen, and H. L. MacLean, 2020: Electrification of light-duty vehicle fleet alone will not meet mitigation targets. Nat. Clim. Chang., https://doi.org/10.1038/s41558-020-00921-7.	Arent et al, Implications of high renewable electricity penetration in the U.S. for water use, greenhouse gas emissions, land-use, and materials supply. Applied Energy. 2014, 123: 368-377 https://doi.org/10.1016/j.apenergy.2013.12.022 Orsi, F., 2021: On the sustainability of electric vehicles: What about their impacts on land use? Sustain. Cities Soc., 66, 102680, https://doi.org/10.1016/J.SCS.2020.102680.
Hydrogen FCV for land transport	+	±	±
Role of contexts	The use of fuel cells in the transport sector is growing, and will potentially be important in heavy-duty land transport applications	FCVs are reliant on critical minerals for manufacturing fuel cells, electric motors and supporting batteries. Platinum is the primary potential resource constraint for fuel cells; however, its use may decrease as the technology develops, and platinum is highly recyclable.	
Line of sight	Global EV Outlook 2020 https://www.iea.org/reports/global-ev-outlook-2020	Hao, H., and Coauthors, 2019: Securing Platinum-Group Metals for Transport Low-Carbon Transition. One Earth, https://doi.org/10.1016/j.oneear.2019.08.012. Rasmussen, K. D., H. Wenzel, C. Bangs, E. Petavratzi, and G. Liu, 2019: Platinum Demand and Potential Bottlenecks in the Global Green Transition: A Dynamic Material Flow Analysis. Environmental Science & Technology, https://doi.org/10.1021/ACS.EST.9B01912.	Orsi, F., 2021: On the sustainability of electric vehicles: What about their impacts on land use? Sustainable Cities and Society, 66, 102680, https://doi.org/10.1016/J.SCS.2020.102680.

	Evoronmental-ecological			
	Air pollution	Toxic waste, ecotoxicity eutrophication	Water quantity and quality	Biodiversity
Demand reduction and mode shift	+	0	0	0
Role of contexts	Reduction in demand, increase in fuel efficiency and demand management measures will improve Air Quality			Reduction in demand, fuel efficiency and demand management measures such as Clean Air Zones/ Parking Policy will reduce road supply and protect the biodiversity
Line of sight	Creutzig, F., Roy, J., Lamb, W. F., Azevedo, I. M., De Bruin, W. B., Dalkmann, H., ... & Hertwich, E. G. (2018). Towards demand-side solutions for mitigating climate change. Nature Climate Change, 8(4), 260. Dumortier, J., Carriquiry, M., & Elobeid, A. Where does all the biofuel go? Fuel efficiency gains and its effects on global agricultural production. Energy Policy, 148, 111909. Ambarwati, L., Verhaeghe, R., van Arem, B., & Pel, A. J. (2016). The influence of integrated space–transport development strategies on air pollution in urban areas. Transportation Research Part D: Transport and Environment, 44, 134-146. Clean Air Zone Framework. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/863730/clean-air-zone-framework-feb2020.pdf			
Biofuels for land transport, aviation, and shipping	±	±	-	-
Role of contexts	Biofuels may improve air quality due reduction in the emission of some pollutants, such as SOx and particulate matter, in relation to fossil fuels. Evidence is mixed for other pollutants such as NOx. The biofuels supply chain (e.g., due to increased fertilizer use) may negatively impact air quality.	Increased use of fertilizers and agrochemicals due the biofuel production may increase impacts in ecotoxicity and eutrophication; some biofuels may be less toxic than fossil fuel counterparts	Increasing production of biofuels may increase pressure in water resources due to the need of irrigation. However, some biofuel options may also improve these aspects in respect to conventional agriculture. These impacts will depend on specific local conditions.	Additional land use for biofuels may increase pressure on biodiversity. However, biofuel can also increase biodiversity depending on the previous land use. These impacts will depend on specific local conditions and previous land uses.
Line of sight	Robertson et al., Science 356, 1349 (2017); Humpenöder, Florian, Alexander Popp, Benjamin Leon Bodirsky, Isabelle Weindl, Anne Biewald, Hermann Lotze-Campen, Jan Philipp Dietrich, David Klein, Ulrich Kreidenweis, and Christoph Müller. 2018. “Large-Scale Bioenergy Production: How to Resolve Sustainability Trade-Offs?” Environmental Research Letters 13 (2): 24011. Ai, Zhipin, Naota Hanasaki, Vera Heck, Tomoko Hasegawa, and Shinichiro Fujimori. "Global bioenergy with carbon capture and storage potential is largely constrained by sustainable irrigation." Nature Sustainability (2021): 1-8.			
Ammonia for shipping	±	-	±	LE

Role of contexts	If produced from green hydrogen or coupled with CCS, ammonia could reduce short lived climate forcers and particulate matter precursors including black carbon and SO2. However, the combustion of ammonia could lead to elevated levels of nitrogen oxides and ammonia emissions	Ammonia is highly toxic, and therefore requires special handling procedures to avoid potential catastrophic leaks into the environment. That said, large volumes of ammonia are already safely transported internationally due to a high level of understanding of safe handling procedures. Additionally, the use of ammonia in shipping presents an additional risk to eutrophication and ecotoxicity from the release of ammonia in the water system - either via a fuel leak, or via unburnt ammonia emissions.	May increase or decrease water footprint depending on the upstream energy source	Lack of studies assessing the potential impacts of the technology on biodiversity.
Line of sight	Bicer, Y., and I. Dincer, 2018: Clean fuel options with hydrogen for sea transportation: A life cycle approach. International Journal of Hydrogen Energy, 43, 1179–1193, https://doi.org/https://doi.org/10.1016/j.ijhydene.2017.10.157 Gilbert, P., C. Walsh, M. Traut, U. Kesieme, K. Pazouki, and A. Murphy, 2018: Assessment of full life-cycle air emissions of alternative shipping fuels. Journal of Cleaner Production, 172, 855–866, https://doi.org/10.1016/j.jclepro.2017.10.165; DNV GL, 2019: Maritime Forecast To 2050. 118 pp. https://eto.dnvgl.com/2019. ——, 2020: Ammonia as a marine fuel. 1–28.			
Synthetic fuels for heavy-duty land transport, aviation, and shipping (e.g., DAC-FT)	+	NE	±	LE
Role of contexts	Potential reductions in air pollutants related to reduced presence of sulphur, metals, and other contaminants; improvements likely smaller than for electric vehicles or hydrogen fuel cell vehicles		DAC requires significant amounts of water, which may be a limitation in water stressed areas; typically uses less water than crop-based biofuels	Potential biodiversity issues related to electricity generation; however fossil fuel supply chains also adversely impact biodiversity; net effect is unknown
Line of sight	Beyersdorf, A. J., and Coauthors, 2014: Reductions in aircraft particulate emissions due to the use of Fischer-Tropsch fuels. Atmos. Chem. Phys., https://doi.org/10.5194/acp-14-11-2014; Lobo, P., D. E. Hagen, and P. D. Whitefield, 2011: Comparison of PM emissions from a commercial jet engine burning conventional, biomass, and fischer-tropsch fuels. Environ. Sci. Technol., https://doi.org/10.1021/es201902e; Gill, S. S., A. Tsolakis, K. D. Dearn, and J. Rodríguez-Fernández, 2011: Combustion characteristics and emissions of Fischer-Tropsch diesel fuels in IC engines. Prog. Energy Combust. Sci., https://doi.org/10.1016/j.pecs.2010.09.001		Realmonte, G., Drouet, L., Gambhir, A. et al. An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nat Commun 10, 3277 (2019). https://doi.org/10.1038/s41467-019-10842-5 Byers, E. A., J. W. Hall, J. M. Amezaga, G. M. O'Donnell, and A. Leathard, 2016: Water and climate risks to power generation with carbon capture and storage. Environ. Res. Lett., https://doi.org/10.1088/1748-9326/11/2/024011.	
Electric vehicles for land transport	+	-	±	LE

Role of contexts	Elimination of tailpipe emissions. If powered by nuclear or renewables, large overall improvements in air pollution. Even if powered partially by fossil fuel electricity, tailpipe emissions tend to occur closer to population and thus typically have larger impact on human health than powerplant emissions; negative air quality impacts may occur, but only in fossil fuel heavy grids	Some toxic waste associated with mining and processing of metals for battery and some renewable electricity supply chains (production and disposal)	May increase or decrease water footprint depending on the upstream electricity source	Potential biodiversity issues related to electricity generation; however fossil fuel supply chains also adversely impact biodiversity; net effect is unknown
Line of sight	Requia, W. J., M. Mohamed, C. D. Higgins, A. Arain, and M. Ferguson, 2018: How clean are electric vehicles? Evidence-based review of the effects of electric mobility on air pollutants, greenhouse gas emissions and human health. Atmos. Environ., 185, 64–77, https://doi.org/10.1016/J.ATMOSENV.2018.04.040 Horton, D. E., J. L. Schnell, D. R. Peters, D. C. Wong, X. Lu, H. Gao, H. Zhang, and P. L. Kinney, 2021: Effect of adoption of electric vehicles on public health and air pollution in China: a modelling study. Lancet Planet. Heal., https://doi.org/10.1016/s2542-5196(21)00092-9; Gai, Y., L. Minet, I. D. Posen, A. Smargiassi, L. F. Tétreault, and M. Hatzopoulou, 2020: Health and climate benefits of Electric Vehicle Deployment in the Greater Toronto and Hamilton Area. Environ. Pollut., https://doi.org/10.1016/j.envpol.2020.114983; Choma, E. F., J. S. Evans, J. K. Hammitt, J. A. Gómez-Ibáñez, and J. D. Spengler, 2020: Assessing the health impacts of electric vehicles through air pollution in the United States. Environ. Int., https://doi.org/10.1016/j.envint.2020.106015; Schnell, J. L., V. Naik, L. W. Horowitz, F. Paulot, P. Ginoux, M. Zhao, and D. E. Horton, 2019: Air quality impacts from the electrification of light-duty passenger vehicles in the United States. Atmos. Environ., https://doi.org/10.1016/j.atmosenv.2019.04.003; Air quality impacts from light-duty transportation Christopher W. Tessum, Jason D. Hill, Julian D. Marshall Proceedings of the National Academy of Sciences Dec 2014, 111 (52) 18490-18495; DOI: 10.1073/pnas.1406853111	Lattanzio, R. K., and C. E. Clark, 2020: Environmental Effects of Battery Electric and Internal Combustion Engine Vehicles. Congr. Res. Serv.; Puig-Samper Naranjo, G., D. Bolonio, M. F. Ortega, and M. J. García-Martínez, 2021: Comparative life cycle assessment of conventional, electric and hybrid passenger vehicles in Spain. J. Clean. Prod., https://doi.org/10.1016/j.jclepro.2021.125883; Bicer, Y., and I. Dincer, 2017: Comparative life cycle assessment of hydrogen, methanol and electric vehicles from well to wheel. Int. J. Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2016.07.252; Hawkins, T. R., B. Singh, G. Majeau-Bettez, and A. H. Strømman, 2013: Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. J. Ind. Ecol., https://doi.org/10.1111/j.1530-9290.2012.00532.x.	Onat, N. C., M. Kucukvar, and O. Tatari, 2018: Well-to-wheel water footprints of conventional versus electric vehicles in the United States: A state-based comparative analysis. J. Clean. Prod., https://doi.org/10.1016/j.jclepro.2018.09.010; Kim, H. C., T. J. Wallington, S. A. Mueller, B. Bras, T. Guldberg, and F. Tejada, 2016: Life Cycle Water Use of Ford Focus Gasoline and Ford Focus Electric Vehicles. J. Ind. Ecol., https://doi.org/10.1111/jiec.12329; Wang, L., W. Shen, H. C. Kim, T. J. Wallington, Q. Zhang, and W. Han, 2020: Life cycle water use of gasoline and electric light-duty vehicles in China. Resour. Conserv. Recycl., https://doi.org/10.1016/j.resconrec.2019.104628	

Hydrogen FCV for land transport	+	±	±	LE
Role of contexts	Fuel cells' only tailpipe emission is water vapour. However, blue hydrogen production pathways may generate air pollutants nearby the production sites. Overall, FCV would reduce emissions of criteria air pollutants.	Mining of Platinum Group Metals may generate additional stress on the environment, compared to conventional technologies. Furthermore, the recycling of fuel cell stacks can generate additional impacts.	May increase or decrease water footprint depending on the upstream energy source	Lack of studies assessing the potential impacts of the technology on biodiversity.
Line of sight	Wang, Q., M. Xue, B. Le Lin, Z. Lei, and Z. Zhang, 2020: Well-to-wheel analysis of energy consumption, greenhouse gas and air pollutants emissions of hydrogen fuel cell vehicle in China. Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2020.123061.	Velandia Vargas, J. E., and J. E. A. Seabra, 2021: Fuel-cell technologies for private vehicles in Brazil: Environmental mirage or prospective romance? A comparative life cycle assessment of PEMFC and SOFC light-duty vehicles. Science of the Total Environment, 798, 149265, https://doi.org/10.1016/j.scitotenv.2021.149265. Bohnes, F. A., J. S. Gregg, and A. Laurent, 2017: Environmental Impacts of Future Urban Deployment of Electric Vehicles: Assessment Framework and Case Study of Copenhagen for 2016-2030. Environmental Science and Technology, 51, 13995–14005, https://doi.org/10.1021/acs.est.7b01780.		

	Technological		
	Simplicity	Technological scalability	Maturity and technology readiness
Demand reduction and mode shift	+	+	+
Role of contexts	Application of Demand and Fuel efficiency measures can be scaled and developing countries can leapfrog to most advanced technology. India skipped Euro V, and implemented Euro VI from IV, but this shift will require investment in the short-term	Technology to deliver Demand and Fuel efficiency is readily available	Significant economic benefit in short and long term
Line of sight	Vashist, D., Kumar, N., & Bindra, M. (2017). Technical Challenges in Shifting from BS IV to BS-VI Automotive Emissions Norms by 2020 in India: A Review. Archives of Current Research International, 1-8; Clean Air Zone Framework. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/863730/clean-air-zone-framework-feb2020.pdf		
Biofuels for land transport, aviation, and shipping	±	±	+
Role of contexts	Typically based on internal combustion engines, similar to fossil fuels, however, may require engine recalibration	Biofuels are scalable up to and may benefit from economies of scale; potential for scale up of sustainable crop production may be limited	There are many biofuels technologies that are already at commercial scale, while some technologies for advanced biofuels are still under development.

Line of sight	Mawhood, Rebecca, Evangelos Gazis, Sierk de Jong, Ric Hoefnagels, and Raphael Slade. 2016. "Production Pathways for Renewable Jet Fuel: A Review of Commercialization Status and Future Prospects." *Biofuels, Bioproducts and Biorefining* 10 (4): 462–84. Puricelli, Stefano, Giuseppe Cardellini, S. Casadei, D. Faedo, A. E. M. Van den Oever, and M. Grosso. "A review on biofuels for light-duty vehicles in Europe." Renewable and Sustainable Energy Reviews (2020): 110398.		
Ammonia for shipping	-	±	±
Role of contexts	Requires either new engines or retrofits for existing engines. It is likely some ammonia will need to be mixed with a secondary fuel due its relatively low burning velocity and high ignition temperature. This would likely require existing powertrains to be modified to accept dual fuel mixes, including ammonia. Exhaust treatment systems are also required to deal with the release of unburnt ammonia emissions.	Ammonia supply chains are well established; transport and storage more feasible than hydrogen; scalability of electrolytic production routes remain a challenge for producing low GHG ammonia	The production, transport and storage of ammonia is mature based on existing international supply chains. The use of ammonia in ships is still the early stages of research and development. Further research and development will be required for ammonia to be widely used in shipping, including improving the efficiency of combustion, and treatment of exhaust emissions. Ammonia could also potentially be used in fuel cell powertrains in the future, but the development of this technology is even less mature at present.
Line of sight	Frigo, S., Gentili, R., and De Angelis, F., "Further Insight into the Possibility to Fuel a SI Engine with Ammonia plus Hydrogen," SAE Technical Paper 2014-32-0082, 2014, https://doi.org/10.4271/2014-32-0082. Dimitriou, Pavlos & Javaid, Rahat. (2020). A review of ammonia as a compression ignition engine fuel. International Journal of Hydrogen Energy. 45. 10.1016/j.ijhydene.2019.12.209; Man ES, 2019. "Engineering the future two-stroke green-ammonia engine". Available at: https://www.ammoniaenergy.org/wp-content/uploads/2020/01/engineeringthefuturetwostrokegreenammoniaengine1589339239488-1.pdf		
Synthetic fuels for heavy-duty land transport, aviation, and shipping (e.g., DAC-FT)	+	-	-
Role of contexts	Can produce drop-in fuels, which use existing engine technologies	Rate at which DAC or other carbon capture can be scaled-up is likely a limiting factor; large energy inputs (requiring substantial new low carbon energy resources), and sorbent requirements likely to be a challenge	Some processes (e.g., Fischer Tropsch) are well established, but DAC and BECCS are stlil at demonstration stage
Line of sight	Sutter, D., M. van der Spek, and M. Mazzotti, 2019: 110th Anniversary: Evaluation of CO2-Based and CO2-Free Synthetic Fuel Systems Using a Net Zero-CO2-Emission Framework. Ind. Eng. Chem. Res., 58, 19958–19972, https://doi.org/10.1021/acs.iecr.9b00880., The Royal Society, 2019, Sustainable synthetic carbon-based fuels for transport: Policy briefing	The Royal Society, 2019, Sustainable synthetic carbon based fuels for transport: Policy briefing; Realmonte, G., Drouet, L., Gambhir, A. et al. An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nat Commun 10, 3277 (2019). https://doi.org/10.1038/s41467-019-10842-5	Liu, C. M., N. K. Sandhu, S. T. McCoy, and J. A. Bergerson, 2020: A life cycle assessment of greenhouse gas emissions from direct air capture and Fischer-Tropsch fuel production. Sustain. Energy Fuels, 4, 3129–3142, https://doi.org/10.1039/c9se00479c.
Electric vehicles for land transport	±	±	±

Role of contexts	Fewer engine components; lower maintenance requirements than conventional vehicles; potential concerns surrounding battery size/weight, charging time, and battery life	Widespread application already feasible; some limits to adoption in remote communities or long-haul freight; at large scale, may positively or negatively impact electric grid functioning depending on charging behaviour and grid integration strategy	+ Technology is mature for light duty vehicles; - Improvements in battery capacity and density as well as charging speed required for heavy duty applications
Line of sight	Burnham, A., et al, 2021: Comprehensive total cost of ownership quantification for vehicles with different size classes and powertrains., Argonne National Laboratory	IEA (2021), Global EV Outlook 2021, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2021, Milovanoff, A., I. D. Posen, and H. L. MacLean, 2020: Electrification of light-duty vehicle fleet alone will not meet mitigation targets. Nat. Clim. Chang., https://doi.org/10.1038/s41558-020-00921-7., Constance Crozier, Thomas Morstyn, Malcolm McCulloch, The opportunity for smart charging to mitigate the impact of electric vehicles on transmission and distribution systems, Applied Energy, Volume 268, 2020, 114973, ISSN 0306-2619; Kapustin, N. O., and D. A. Grushevenko, 2020: Long-term electric vehicles outlook and their potential impact on electric grid. Energy Policy, https://doi.org/10.1016/j.enpol.2019.111103; Das, H. S., M. M. Rahman, S. Li, and C. W. Tan, 2020: Electric vehicles standards, charging infrastructure, and impact on grid integration: A technological review. Renew. Sustain. Energy Rev., https://doi.org/10.1016/j.rser.2019.109618; Liimatainen, H., O. van Vliet, and D. Aplyn, 2019: The potential of electric trucks – An international commodity-level analysis. Appl. Energy, https://doi.org/10.1016/j.apenergy.2018.12.017; Forrest, K., M. Mac Kinnon, B. Tarroja, and S. Samuelsen, 2020: Estimating the technical feasibility of fuel cell and battery electric vehicles for the medium and heavy duty sectors in California. Appl. Energy, https://doi.org/10.1016/j.apenergy.2020.115439	IEA (2021), Global EV Outlook 2021, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2021; Smith, D., and Coauthors, 2019: Medium-and Heavy-Duty Vehicle Electrification: An Assessment of Technology and Knowledge Gaps. Oak Ridge Natl. Lab. Natl. Renew. Energy Lab.; Forrest, K., M. Mac Kinnon, B. Tarroja, and S. Samuelsen, 2020: Estimating the technical feasibility of fuel cell and battery electric vehicles for the medium and heavy duty sectors in California. Appl. Energy, https://doi.org/10.1016/j.apenergy.2020.115439.
Hydrogen FCV for land transport	±	-	-

Role of contexts	Lower maintenance requirements compared to conventional technologies; potential issues with on-vehicle hydrogen storage, fuel cell degradation and lifetime; fewer weight and refuelling time barriers compared to electric vehicles	Currently the refuelling infrastructure is limited, but it is growing at the pace of the technology deployment. Challenges exist with transport and distribution of hydrogen. Electrolytic hydrogen not currently produced at scale.	The technology is already available to users for light duty vehicle applications and buses, but further improvements in fuel cell technology are needed. Use in heavy duty applications is currently constrained. Maturity and technology readiness level can vary for different parts of the supply chain, and is lower than for EVs
Line of sight	Trencher, G., A. Taeihagh, and M. Yarime, 2020: Overcoming barriers to developing and diffusing fuel-cell vehicles: Governance strategies and experiences in Japan. Energy Policy, 142, 111533 https://doi.org/10.1016/j.enpol.2020.111533.	Pollet, B. G., S. S. Kocha, and I. Staffell, 2019: Current status of automotive fuel cells for sustainable transport. Current Opinion in Electrochemistry, 16, 90–95, https://doi.org/10.1016/j.coelec.2019.04.021.	Wang, J., H. Wang, and Y. Fan, 2018: Techno-Economic Challenges of Fuel Cell Commercialization. Engineering, 4, 352–360, https://doi.org/10.1016/j.eng.2018.05.007. Kampker, A., P. Ayvaz, C. Schön, J. Karstedt, R. Förstmann, and F. Welker, 2020: Challenges towards large-scale fuel cell production: Results of an expert assessment study. International Journal of Hydrogen Energy, 45, 29288–29296, https://doi.org/10.1016/j.ijhydene.2020.07.180.

	4. Economic	
	Costs in 2030 and long term	Employment effects and economic growth
Demand reduction and mode shift	+	LE
Role of contexts	Significant economic benefit in short and long term	
Line of sight	Creutzig, F., Roy, J., Lamb, W. F., Azevedo, I. M., De Bruin, W. B., Dalkmann, H., ... & Hertwich, E. G. (2018). Towards demand-side solutions for mitigating climate change. Nature Climate Change, 8(4), 260.; The UK, The Green Book (2020; https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent/the-green-book-2020)	
Biofuels for land transport, aviation, and shipping	±	LE
Role of contexts	Some biofuels are already cost competitive with fossil fuels. In the future, reduction of costs for advanced biofuels may be a challenge	Biofuels are expected to increase job creation in comparison to fossil fuel alternatives. This is still to be further demonstrated.

Line of sight	Daioglou, V., Rose, S.K., Bauer, N., Kitous, A., Muratori, M., Sano, F., Fujimori, S., Gidden, M.J., Kato, E., Keramidas, K. and Klein, D., 2020. Bioenergy technologies in long-run climate change mitigation: results from the EMF-33 study. Climatic Change, 163(3), pp.1603-1620. Brown, A., Waldheim, L., Landälv, I., Saddler, J., Ebadian, M., McMillan, J.D., Bonomi, A. and Klein, B., 2020. Advanced Biofuels—Potential for Cost Reduction. IEA Bioenergy, 88.	
Ammonia for shipping	-	NE
Role of contexts	Green ammonia is likely to be significantly more expensive than conventional fuels for the coming decades.	
Line of sight	Energy Transitions Commission, 2021. Making the hydrogen economy possible. Available at: https://energy-transitions.org/wp-content/uploads/2021/04/ETC-Global-Hydrogen-Report.pdf; Energy Transitions Commission, 2020. The First Wave: A blueprint for commercial-scale zero-emission shipping pilots. Available at: https://www.energy-transitions.org/wp-content/uploads/2020/11/The-first-wave.pdf	
Synthetic fuels for heavy-duty land transport, aviation, and shipping (e.g., DAC-FT)	-	NE
Role of contexts	Large uncertainty on future costs but expected to remain higher than conventional fuels for the coming decades	-
Line of sight	Ueckerdt, F., C. Bauer, A. Dirnaichner, J. Everall, R. Sacchi, and G. Luderer, 2021: Potential and risks of hydrogen-based e-fuels in climate change mitigation. Nat. Clim. Chang., https://doi.org/10.1038/s41558-021-01032-7., Zang, G., P. Sun, E. Yoo, A. Elgowainy, A. Bafana, U. Lee, M. Wang, and S. Supekar, 2021: Synthetic Methanol/Fischer–Tropsch Fuel Production Capacity, Cost, and Carbon Intensity Utilizing CO2 from Industrial and Power Plants in the United States. Environ. Sci. Technol., 55, 7595–7604, https://doi.org/10.1021/acs.est.0c08674., Scheelhaase, J., S. Maertens, and W. Grimme, 2019: Synthetic fuels in aviation - Current barriers and potential political measures. Transportation Research Procedia.	
Electric vehicles for land transport	+	LE
Role of contexts	Life cycle costs for electric vehicles are anticipated to be lower than conventional vehicles by 2030; high confidence for light duty vehicles; lower confidence for heavy duty applications	Some grey studies exist on employment effects of electric vehicles; however, the peer-reviewed literature is not well developed
Line of sight	IEA (2021), Global EV Outlook 2021, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2021, Liimatainen, H., O. van Vliet, and D. Aplyn, 2019: The potential of electric trucks – An international commodity-	

	level analysis. Appl. Energy, https://doi.org/10.1016/j.apenergy.2018.12.017 Kapustin, N. O., and D. A. Grushevenko, 2020: Long-term electric vehicles outlook and their potential impact on electric grid. Energy Policy, https://doi.org/10.1016/j.enpol.2019.111103; Forrest, K., M. Mac Kinnon, B. Tarroja, and S. Samuelsen, 2020: Estimating the technical feasibility of fuel cell and battery electric vehicles for the medium and heavy duty sectors in California. Appl. Energy, https://doi.org/10.1016/j.apenergy.2020.115439	
Hydrogen FCV for land transport	+	LE
Role of contexts	Life cycle costs for hydrogen fuel cell vehicles projected to be competitive with conventional vehicles in future, however high uncertainty remains.	Some studies exist on employment effects of hydrogen economy; however, the literature is not well developed and does not apply directly to FCVs.
Line of sight	Miotti, M., J. Hofer, and C. Bauer, 2017: Integrated environmental and economic assessment of current and future fuel cell vehicles. International Journal of Life Cycle Assessment, 22, 94–110, https://doi.org/10.1007/s11367-015-0986-4. Ruffini, E., and M. Wei, 2018: Future costs of fuel cell electric vehicles in California using a learning rate approach. Energy, 150, 329–341, https://doi.org/10.1016/j.energy.2018.02.071. Olabi, A. G., T. Wilberforce, and M. A. Abdelkareem, 2021: Fuel cell application in the automotive industry and future perspective. Energy, 214, https://doi.org/10.1016/j.energy.2020.118955.	

	Socio-cultural		
	Public acceptance	Effects on health & wellbeing	Distributional effects
Demand reduction and mode shift	±	+	±

Role of contexts	Public support for some measures such as emission charging schemes can be mixed initially, it is likely to again acceptance as benefits are realised and/or focused. Such as recent COVID-19 road network changes in London	Significant economic health and wellbeing benefits	Some measures such as travel restriction, emission charging schemes and others can have mixed distributional effects initially (e.g. accessibility)
Line of sight	Winter, A. K., & Le, H. (2020). Mediating an invisible policy problem: Nottingham's rejection of congestion charging. Local Environment, 1-9.. TfL (2020) London Streetspace changes. content.tfl.gov.uk/doctors-and-health-professionals-support-london-streetspace-changes.pdf. Creutzig, F., Roy, J., Lamb, W. F., Azevedo, I. M., De Bruin, W. B., Dalkmann, H., ... & Hertwich, E. G. (2018). Towards demand-side solutions for mitigating climate change. Nature Climate Change, 8(4), 260.; Clean Air Zone Framework. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/863730/clean-air-zone-framework-feb2020.pdf; Adhikari, M., L. P. Ghimire, Y. Kim, P. Aryal, and S. B. Khadka, 2020: Identification and analysis of barriers against electric vehicle use. Sustain., https://doi.org/10.3390/SU12124850.		
Biofuels for land transport, aviation, and shipping	±	LE	±
Role of contexts	Varied public acceptance of biofuel options is observed in different regions of the world	No known impacts	Food secutiry but agricultural economies
Line of sight	Løkke, S., Aramendia, E. and Malskær, J., 2021. A review of public opinion on liquid biofuels in the EU: Current knowledge and future challenges. *Biomass and Bioenergy*, *150*, p.106094. Taufik, D. and Dagevos, H., 2021. Driving public acceptance (instead of skepticism) of technologies enabling bioenergy production: A corporate social responsibility perspective. Journal of Cleaner Production, p.129273.		
Ammonia for shipping	LE	LE	LE
Role of contexts	Some concerns in industry regarding handling of hazardous fuel; limited evidence overall		
Line of sight	N/A		
Synthetic fuels for heavy-duty land transport, aviation, and shipping (e.g., DAC-FT)	LE	LE	NE
Role of contexts	Currently low public awareness of the technology and little evidence regarding associated perceptions	No known impacts	
Line of sight	N.A.		
Electric vehicles for land transport	±	±	±

Role of contexts	Growing public acceptance, especially in some jurisdictions (e.g., majority of light duty vehicle sales in Norway are electric), but wide differences across regions; range anxiety remains a barrier among some groups	No major impacts; some potential for reduced noise, which can improve wellbeing of city residents but may adversely affect pedestrian safety	Higher vehicle purchase price and access to off-road parking limits access to some disadvantaged groups; potentially insufficient infrastructure for adoption in rural communities (initially); air quality improvements may disproportionately benefit disadvantaged groups, but may also shift some impacts onto communities in close proximity to electricity generators
Line of sight	Coffman, M., P. Bernstein, and S. Wee, 2017: Electric vehicles revisited: a review of factors that affect adoption. Transp. Rev., https://doi.org/10.1080/01441647.2016.1217282, Burkert, A.; Fechtner, H.; Schmuelling, B. Interdisciplinary Analysis of Social Acceptance Regarding Electric Vehicles with a Focus on Charging Infrastructure and Driving Range in Germany. World Electr. Veh. J. 2021, 12, 25; Wang, N., L. Tang, and H. Pan, 2018: Analysis of public acceptance of electric vehicles: An empirical study in Shanghai. Technol. Forecast. Soc. Change, https://doi.org/10.1016/j.techfore.2017.09.011	Campello-Vicente, H., R. Peral-Orts, N. Campillo-Davo, and E. Velasco-Sanchez, 2017: The effect of electric vehicles on urban noise maps. Appl. Acoust., https://doi.org/10.1016/j.apacoust.2016.09.018	Canepa, K., S. Hardman, and G. Tal, 2019: An early look at plug-in electric vehicle adoption in disadvantaged communities in California. Transp. Policy, https://doi.org/10.1016/j.tranpol.2019.03.009., Brown, M. A., A. Soni, M. V Lapsa, K. Southworth, and M. Cox, 2020: High energy burden and low-income energy affordability: conclusions from a literature review. Progress in Energy, 2, 042003, https://doi.org/10.1088/2516-1083/abb954.
Hydrogen FCV for land transport	±	±	±
Role of contexts	Public acceptance is growing in countries where the technology is being promoted and subsidized. However, sparse infrastructure, high costs and perceived safety concerns are currently barriers to a widespread deployment of the technology	No major impacts: some potential for reduced noise, which can improve wellbeing of city residents but may adversely affect pedestrian safety	Higher vehicle purchase price limits access to some disadvantaged groups; potentially insufficient infrastructure for adoption in rural communities (initially); air quality improvements may disproportionately benefit disadvantaged groups
Line of sight	Itaoka, K., A. Saito, and K. Sasaki, 2017: Public perception on hydrogen infrastructure in Japan: Influence of rollout of commercial fuel cell vehicles. International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2016.10.123. Canepa, K., S. Hardman, and G. Tal, 2019: An early look at plug-in electric vehicle adoption in disadvantaged communities in California. Transp. Policy, https://doi.org/10.1016/j.tranpol.2019.03.009., Brown, M. A., A. Soni, M. V Lapsa, K. Southworth, and M. Cox, 2020: High energy burden and low-income energy affordability: conclusions from a literature review. Progress in Energy, 2, 042003, https://doi.org/10.1088/2516-1083/abb954. Trencher, G., 2020: Strategies to accelerate the production and diffusion of fuel cell electric vehicles: Experiences from California. Energy Reports, https://doi.org/10.1016/j.egyr.2020.09.008.		

	Institutional		
	Political acceptance	Institutional capacity & governance, cross-sectoral coordination	Legal and administrative feasibility
Demand reduction and mode shift	±	±	±
Role of contexts	Public support for some measures such as emission charging schemes can be mixed initially, it is likely to again acceptance as benefits are realised and/or focused. Such as recent COVID-19 road network changes in London	Some local authorities have limited capacity to deliver demand management measures as compared to other developed authorities. However, this can be mitigated to optioneering processes to selected the preferred measures in the local context	Legal Air Quality limits is forcing cities and countries to implement travel demand and fuel efficiency measures such in the UK and Europe. However, there be legal and administrative changes in delivery of measures.
Line of sight	Winter, A. K., & Le, H. (2020). Mediating an invisible policy problem: Nottingham's rejection of congestion charging. Local Environment, 1-9. TfL (2020) London Streetspace changes. content.tfl.gov.uk/doctors-and-health-professionals-support-london-streetspace-changes.pdf Creutzig, F., Roy, J., Lamb, W. F., Azevedo, I. M., De Bruin, W. B., Dalkmann, H., ... & Hertwich, E. G. (2018). Towards demand-side solutions for mitigating climate change. Nature Climate Change, 8(4), 260.; Clean Air Zone Framework. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/863730/clean-air-zone-framework-feb2020.pdf		
Biofuels for land transport, aviation, and shipping	±	±	±
Role of contexts	Varied political support for biofuel deployment in different regions of the world	There is varied institutional capacity to coordinate biofuel deployment in the different regions of the world	There is different legal contexts and barriers for biofuel implementation on the different regions of the world
Line of sight	Lynd, L.R., 2017. The grand challenge of cellulosic biofuels. Nature biotechnology, 35(10), pp.912-915.Markel, E., Sims, C. and English, B.C., 2018. Policy uncertainty and the optimal investment decisions of second-generation biofuel producers. Energy Economics, 76, pp.89-100.		
Ammonia for shipping	±	-	-
Role of contexts	Varied political support for deployment in different regions of the world	The major contributor to marine emissions is international shipping which falls under the jurisdiction of the IMO. Coordination with international governments will be required.	Potential challenges related to emission regulations
Line of sight	Hoegh-Guldberg, O., and Coauthors, 2019: The Ocean as a Solution to Climate Change: Five Opportunities for Action. 116; Energy Transitions Commission, 2021. Making the hydrogen economy possible. Available at: https://energy-transitions.org/wp-content/uploads/2021/04/ETC-Global-Hydrogen-Report.pdf;		

	Energy Transitions Commission, 2020. The First Wave: A blueprint for commercial-scale zero-emission shipping pilots. Available at: https://www.energy-transitions.org/wp-content/uploads/2020/11/The-first-wave.pdf		
Synthetic fuels for heavy-duty land transport, aviation, and shipping (e.g., DAC-FT)	LE	-	±
Role of contexts	Plans for adoption of technology remain at early stage; political acceptance not known	Synthetic fuel use in aviation and marine shipping requires international coordination; challenges exist related to carbon accounting frameworks for utilization of CO2; likely fewer barriers for use of fuel in land transport applications	legal barriers exist for synthetic fuel use in aviation; need for development of CO2 capture markets; drop-in fuels are compatible with existing fuel standards in many jurisdictions
Line of sight	Scheelhaase, J., S. Maertens, and W. Grimme, 2019: Synthetic fuels in aviation - Current barriers and potential political measures. Transportation Research Procedia.		
Electric vehicles for land transport	±	±	±
Role of contexts	Varied political support for deployment in different regions of the world	Coordination needed between transport sector (including vehicle manufacturers; charging infrastructure) and power sector (including increased generation and transmission; capacity to handle demand peaks). Institutional capacity is variable;	Compatible with urban low emission zones; grid integration may require market and regulatory changes
Line of sight	Milovanoff, A., I. D. Posen, and H. L. MacLean, 2020: Electrification of light-duty vehicle fleet alone will not meet mitigation targets. Nat. Clim. Chang., https://doi.org/10.1038/s41558-020-00921-7; IEA (2021), Global EV Outlook 2021, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2021		
Hydrogen FCV for land transport	±	±	±
Role of contexts	Varied political support for deployment in different regions of the world	Coordination needed across sector (including vehicle manufacturers, hydrogen producers and refuelling infrastructure); Institutional capacity is variable;	Compatible with urban low emission zones; fuel distribution network may require market and regulatory changes
Line of sight	Itaoka, K., A. Saito, and K. Sasaki, 2017: Public perception on hydrogen infrastructure in Japan: Influence of rollout of commercial fuel cell vehicles. International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2016.10.123.		