Chapter 10: Transport

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Executive summary

Transport GHG had a three-fold increase from 1970 and grew 29% between 2010 and 2016. This is now needing to be a bigger area of focus if climate change goals are to be met. It is an area that relates to almost all the SDG's and is a big part of government economic planning in the developed and developing world. 75% of transport emissions came from on road, 3% from rail and this need to shift the load further remains a theme from AR5. But 22% of emissions come from aviation and shipping (split evenly), and are the fastest growth areas, so for the first time this Chapter has a strong focus on decarbonizing aviation and shipping. Since AR5 there has been a developing split between the decarbonization options for light vehicle systems such as bikes, autorickshaws, cars, buses and trains that lend themselves to electrification, and heavy vehicle systems like trucks, ships and planes that have only complex options that all require R&D.

The Chapter has reviewed the recent literature on the systemic parts of transport that can help with Avoid-Shift-Improve strategies, such as urban form, behaviour, smart systems that influence transport choice and electric recharging that shapes the roll-out of electric vehicles. It then examines the new technology options for vehicles and fuels with electrification now well ahead of other decarbonization opportunities followed by hydrogen, biofuels, synthetic hydrocarbons and advanced ICE. The application to Land-Transport, Aviation and Shipping presents detailed Life Cycle Analysis and Readiness Levels that confirm the mainstreaming of electrification on land transport and the complexity of options for sea and air.

Scenarios using bottom-up models and top-down models are joined into the perspectives generated from the scientific overview to shape transport outcomes into Business-As Usual, Incremental and Transformative. In order to enable the better decarbonization scenarios a Multi-Level Perspective shows that: heavy vehicle systems remain at the micro-level (where governments mostly can only set long term targets and facilitate R&D with trials); light vehicle systems are moving from meso to macro-level (where mainstreaming requires facilitating markets and especially recharge facilities). Governance of international shipping and aviation will need continual evaluation and considerably more ability to provide R&D. The Chapter ends by surveying literature on the value of people-based programs that enable creative inputs to scenarios, building shared economy approaches to behaviour, and climate pledges (including transport) at various levels of human activity.

10.1 Introduction and overview

This Chapter will examine the context for transport's increasingly significant role in climate change mitigation, the systemic aspects of transport that go beyond the technology of vehicles and fuels, before an understanding is provided of how these technologies are providing options for decarbonizing transport. The Chapter will then focus on new trends and developments in the systems of land-based transport, aviation and shipping to show their decarbonization potentials, before bringing these together into scenarios for the future and how they can be enabled.

This first section (10.1) will look at the context for how transport relates to virtually all the SDG's, the trends and drivers making transport a big player in greenhouse gas emissions, the impacts climate is having on transport that can be addressed as part of mitigation, and the emerging transport disruptions of electrification, shared transport and autonomous transport that are shaping the future.

10.1.1 Transport and the sustainable development goals

The adoption of the 2030 Agenda for Sustainable Development by the United Nations has renewed international efforts to pursue and accurately measure global actions towards sustainable development (United Nations, 2015). The 17 Sustainable Development Goals (SDGs) set out the overall goals which are further specified by 169 targets. To monitor progress at national and regional levels, one up to three SDG indicators have been developed per target, summing up to 232 indicators (United Nations, 2017). To monitor the sustainable development actions of companies, the Global Reporting Initiative and the UN Global Compact have developed a "Business Reporting on the SDGs" containing 800 business disclosures (GRI & UN Global Compact, 2017).

Sustainable transport is a cross-cutting theme and supports the achievement of several of the 17 SDGs. According to an analysis of Voluntary National Reviews (VNRs) and global stakeholder consultations, transport is particularly linked to SDGs 3, 7, 8, 9, 11, 12, and 13 (WBA, 2019) (SLoCaT, 2019) (Move Humanity, 2018) (ITF International Transport Forum, 2019a). This matches quite well with an analysis of corporate sustainability reports (Corporate Social Responsibility (CSR) reports) of the largest automotive manufacturers, container shipping companies, airlines, and aircraft manufacturers. Table 10.1 summarizes transport-related topics for these SDGs and corresponding research.

Table 10.1 Main transport-related SDGs

SDG	Transport-related topics	Exemplary references
SDG 3: "Good Health and Well-Being"	• Access to healthcare • Diseases from air pollution • Injuries and deaths from traffic accidents	(Peden & Puvanachandra, 2019); (Cheng et al., 2018); (SLoCaT, 2019); (Grant, Goldsmith, Gracy, & Johnson, 2016); (Haines et al., 2017); (Nieuwenhuijsen, 2018); (Sofiev et al., 2018)
SDG 7 "Affordable and Clean Energy"	• Share of renewable energy use • Energy efficiency of vehicles	(SLoCaT, 2019); see particularly following Chapters
SDG 8 „Decent Work and Economic Growth"	• Role of transport for economic and human development	(Grzelakowski, 2018); (ICAO, 2019); (ATAG, 2018)
SDG 9 "Industry, Innovation, and	• Sustainable transport infrastructure	(S. Jones, Lidbe, & Hainen, 2019); (SLoCaT, 2019); (Weiss

Infrastructure”	- Affordable transport access for all	et al., 2018); (Xu, Bai, & Chen, 2019)
SDG 11 “Sustainable Cities and Communities“	- Sustainable transport systems for cities - Universal access to public transport	(Peden & Puvanachandra, 2019); (Brussel, Zuidgeest, Pfeffer, & van Maarseveen, 2019); (SLoCaT, 2019); (Bruun & Givoni, 2015); (Mohammadi, Elsaid, & Amador-Jiminez, 2019)
SDG 12 “Responsible Consumption and Production”	- Material consumption during production of vehicles and their operations	(Stephan & Crawford, 2016); (G. Harper et al., 2019); (Onat, Kucukvar, & Tatari, 2018); (Sen, Onat, Kucukvar, & Tatari, 2019); (Hao, Qiao, Liu, & Zhao, 2017); (F. E. K. Sato, Furubayashi, & Nakata, 2019)
SDG 13 “Climate Action”	- Reduction of GHG emissions	(Farzaneh, de Oliveira, McLellan, & Ohgaki, 2019); see particularly following Chapters

Besides these major contributions of sustainable transport towards achieving the SDG targets, it has also strong indirect effects regarding poverty reduction (SDG 1): by improving access to education (SDG Targets 4.2, 4.3), safe drinking water (6.1.), financial services (8.3), and by increasing agricultural productivity (2.3) (S. Jones et al., 2019) (SLoCaT, 2019).

Sustainable transport can promote gender equality (SDG 5), by proper design “of costs and access to transport, as women and girls make more trips and change more frequently than men“ (Reckien et al., 2017). Access to green transport technologies such as electric vehicles or vehicle-to-grid is gendered, along with preferences and values concerning public transport and sustainable mobility (Sovacool, Kester, Noel, & Zarazua de Rubens, 2019).

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

The transport sector is a fundamental part of global GHG mitigation strategies as it is the fastest growing emitting sector in the world and, represents the third-largest source of CO_2 emissions after the power and industry sectors. Transport sector carbon dioxide (CO_2) direct emissions increased 29% (from 5.8 Gt to 7.5 gigatonnes (Gt)) between 2000 and 2016, at which point transport produced about 23% of global energy-related CO_2 emissions, and (as of 2014) 14% of GHG emissions (Hasan, Frame, Chapman, & Archie, 2019) (Shah, Dawood, Jalil, & Adnan, 2019) (Xie, Huang, Tian, & Fang, 2019) (Avetisyan, 2018) (Halim, Kirstein, Merk, & Martinez, 2018) (Sudhir Gota, Huizenga, Peet, Medimorec, & Bakker, 2019a) (Makan & Heyns, 2018).

75% of transport emissions came from on road, 3% from rail and this need to shift the load further remains a theme from AR5. But 22% of emissions come from aviation and shipping (split evenly), and are the fastest growth areas, so for the first time this Chapter has a strong focus on decarbonizing aviation and shipping.

Passenger and freight transport emissions increased by 36% and 75%, respectively, between 2000 and 2015. Freight transport industries are the major causes for increasing the CO_2 emissions within the supply chain (Makan & Heyns, 2018). Freight emissions are now growing much faster than passenger transport emissions, and the freight emission share in total transport CO_2 emissions increased from 35% in 2000 to 41% in 2015. Road transport is the largest contributor to global CO_2 emissions from transport, accounting for three quarters of transport emissions in 2015 (Yeh et al., 2017a). Passenger cars, two-and-three wheelers and mini buses contribute about 75% of passenger transport CO_2 emissions, while public transport (bus and railways) generates about 7% of the passenger transport CO_2 emissions despite covering a fifth of passenger transport globally (SLoCaT, 2018) (Sudhir Gota et al., 2019a) (Halim et al., 2018) (Sheng, Shi, & Su, 2018a) (Rodrigue, 2017).

Available evidence suggests that transport 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 targets set in the Paris Agreement (Sudhir Gota et al., 2019a) (IPCC, 2018). Mitigation from passenger and freight show similar potential, while the road sector offers the largest magnitude of mitigation potential (Halim et al., 2018) (Taptich, Horvath, & Chester, 2016a).

A low carbon scenario for the transport sector should ideally be a balanced combination of ‘Avoid-Shift-Improve’ strategies applicable uniformly across passenger and freight movement, including: policies that avoid (or reduce) the need for transport trips; avoiding unnecessary motorized trips; promoting a shift towards more efficient and low-carbon travel modes; reducing the lengths of trips; improving the carbon intensity of modes of transport; and increasing performance of vehicles and fuels (S. Gota, Huizenga, Peet, & Kaar, 2015) (Lutsey and Speling, 2008). These will all be pursued in the Chapter though the Chapter has found a growing split between options for heavy vehicle and light vehicle systems.

10.1.3 Climate impacts on the transport sector

Climate changes such as extreme high temperatures, intense rainfall leading to flooding, more intense winds and/or storms and sea level rise (SLR), can seriously impact transport infrastructure, operations, mobility and carbon emissions for subsectors of road, rail, shipping and aviation. Studies since AR5 confirm that serious challenges to transport infrastructure are increasing, with consequent delays or derailing (Miao, Feeney, Zhang, Welch, & Sriraj, 2018) (Pérez-Morales, Gomariz-Castillo, & Pardo-Zaragoza, 2019) (Moretti & Loprencipe, 2018). Roads are directly exposed to the environment and are, as such, environmentally sensitive infrastructure. Flexible pavements are particularly vulnerable to extreme high temperatures that can cause permanent deformation (Qiao, Santos, Stoner, & Flinstch, 2019) (Underwood, Guido, Gudipudi, & Feinberg, 2017).

Most countries are examining what to do, for example the UK (Wang et al., 2019), but few are using the need to mitigate climate change through transport emissions reductions, as the basis for adaptation action also (Thornbush et al, 2013). For example, greater use of rail passengers and freight will reduce road pressures and reducing urban sprawl will reduce impacts on new infrastructure, often in more vulnerable areas (IPCC, 2019; Newman, Beatley, & Boyer, 2017).

Global sea level rise, due to climate change, may exceed 24 cm in 2050 and 48 cm in 2100, even if global temperatures are stabilized at 1.5 °C (Rasmussen et al., 2018) (Noland, Wang, Kulp, & Strauss, 2019). Noland et al. (2019) with worst-case scenarios of more than six ft (1.8 m) of global mean sea level rise by end of century, progressively making coastal flood events more frequent and severe with large impacts on people and the economy. Where retreat is attempted the opportunity is there to rebuild with lower emissions options.

Shipping and aviation are being impacted through coastal flooding (Yang et al, 2018; Pérez-Morales et al. 2019). The main climate change threats to port operations are due to both sea level rise and extreme storms, high waves and high winds damaging port facilities and leading to coastal erosion. Aviation is impacted by more frequent heat waves that can affect runways (heat buckling) and aircraft lift, resulting in payload restrictions and disruptions (Coffel, Thompson, & Horton, 2017) Monioudi et al. 2018). Burbidge (2018) discussed how additional potential climate impacts may affect airport operations and infrastructure in Europe and other areas of the world, and suggests that is important to think about “cascading effects” e.g. if one element in the system or actor is impacted how does that impact the rest of the system or other actors, both in-sector and between sectors. Adaptations can again be used to build new low emissions aviation systems at airports.

In developing countries, such as Small Island Developing States (SIDS), transport infrastructure and related operations that are situated at the coast are likely to be seriously affected by the impacts of climate variability and climate change (Monioudi et al., 2018).

10.1.4 Transport disruption

Sprei (2018) suggests there are three converging disruptions in transport: electrification of vehicles, shared mobility and autonomous vehicles. All three are discussed in this Chapter as options that are likely to be transformative and hence can be labelled as disruptive due to their rapid adoption and impacts on the whole transport system.

The biggest disruption in transport since AR5 has been the rapid adoption of Lithium Ion batteries as a cost-effective way to produce electric vehicles (Brown, 2017) (Perry, Kredell, Perry, & Leonard, 2018) Arbib & Seba, 2017) ;International Energy Agency, 2017b). The production of EV's is now occurring very rapidly, though mostly China is the leader (Gao & Newman, 2018). This growth means that battery production is also increasing exponentially and is expected to continue (SLoCaT, 2018) (Sheng, Shi, & Su, 2018b) (Sun, Zhang, & Wandelt, 2017) (Bachmann, 2017) (Tanabe, SHIBASAKI, & Kato, 2016). Electrification of passenger transport is therefore well underway but the detailed adoption and mainstreaming of this process will be needed for transport to achieve the necessary shift away from petroleum fuels as outlined in Chapter 3 and detailed further below.

Shared mobility is another potential transport disruption; it is expanding but literature is still very unsure how much it will contribute to decarbonization or make it worse as it may take from transit (ITF, 2018). Asia represents the largest carsharing region (58% of worldwide membership and 43% of global fleets deployed) followed by Europe, the world's second largest carsharing market which accounts for 29% of worldwide members and 37% of vehicle fleets (Shaheen, Cohen, & Jaffee, 2018).

Smart city technologies are a disruption moving into transport with autonomous vehicles and the digitalization of transport (presented in Section 10.2). Intelligent transport systems (ITS's), are expected to be one of the major building blocks of future cities, but there is no guarantee this will include zero CO_2 emissions (Angelidou et al., 2018) (Menouar et al., 2017) (Komninos, 2016) (Newman & Kenworthy, 2015b).

These issues will be further explored in the Chapter as they are all part of systems that may be disrupted positively or negatively in terms of the climate agenda.

10.2 Systemic changes in the transport sector

This section will focus on system level trends that affect the demand, operation, and emissions from the transport sector. Systems impacting on transport emissions can be defined as drivers that influence the use of vehicles and fuels rather than the isolated vehicle technologies and fuels that are outlined in section 10.3 without any specific context. These systemic drivers are set out below in four overlapping components: physical geography and urban form; behaviour and modal choice; smart systems that influence transport choice and electric recharging that shapes the roll-out of electric vehicles. As will be elaborated in section 10.8 on the policy enabling conditions for transport emissions, these four factors can be changed for each of the potential technology systems (set out in section 10.3) in three stages or levels (Micro niches, Meso regimes and Macro landscapes) as defined by Geels et al 2017 and set out in general in Chapter 1.

10.2.1 Physical geography and urban form

Transport is needed to move people and goods between origins and destinations defined by physical geography, both intercity and intracity movements.

Intercity. Transport for freight and people can be generally predicted using gravity models based on the size of populations but beneath is a rationale for why certain locations have higher densities of people. The geography of agriculture and industry and mining determine where settlements have grown and their ports, generally at the mouths of rivers, are linked across the world in an increasingly global market (Berry, 2010). Both time and economic cost determine the modes of transport for both freight and people, called the generalised cost of transport (Scafer, 2009; ICMF, 2003; Koopmans et al, 2013). The most recent data (Sun et al, 2017) suggest these have increasingly favoured:

- aviation for light loads plus increasingly competitive high-speed rail (K. Sato & Chen, 2018) (Jiang & Zhang, 2014) (Prussi & Lonza, 2018) (D'Alfonso, Jiang, & Bracaglia, 2016).
- trucks, trains and ships for heavy loads (ERTRAC, 2019).

Intracity. Time and cost also influence movement within cities and over time create the physical urban form around the modes (Ausubel and Marchetti 2004) (Newman & Kenworthy, 2015a). As outlined in Chapter 8 cities developed three main urban fabrics that were based on a fixed travel time budget of around one hour (Schafer et al, 2009) and which also shapes their transport outcomes thereafter:

- High density walking fabric over the past several millenia with time and space favouring walking and active transport but travelling only a few kms in any direction;
- Medium density transit fabric since the mid-19th century with time and space favouring trains and trams over 20-30 kms of corridors;
- Low density automobile fabric since the mid-20th century with time and space favouring cars over 50-60 kms distances.

The systemic effect of city form and transport emissions is shown in Table 10.2 where the three fabrics are outlined along with their associated transport emissions and other co-benefits (Newman et al. 2016) (Thomson & Newman, 2018).

Table 10.2 The systemic effect of city form and transport emissions

Transport Emissions and Co-Benefits	Walking Urban Fabric	Transit Urban Fabric	Automobile Urban Fabric
Transport Emissions	Low	Medium	High
Health benefits from walkability	High	Medium	Low
Equity of location	High	Medium	Low
Waste generated in construction	Low	Medium	High
Water consumption	Low	Medium	High
Economics of infrastructure and transport operations	High	Medium	Low

Source: (Newman et al. 2016) Thomson & Newman, 2018)

Urban design is increasingly seen as a major way to influence the structural dependence on cars (automobile dependence also known as automobility) thus influencing the lock-in or path dependency of transport options with their greenhouse emissions (Newman and Kenworthy, 1989; 1999; 2015; Haas, 2012; Urry, 2016).

The reported trend to peak car in AR5 showing a revival of walking and transit fabric (Salvo et al., 2017) (Colenbrander et al., 2017) (Sudhir Gota, Huizenga, Peet, Medimorec, & Bakker, 2019b) (P Newman, Beatley, & Boyer, 2017) is now more highly contested as new data on cities shows some cities reaching peak car use per capita with new ones emerging such as Shanghai and Beijing (Gao & Newman, 2018) but others in the USA again increasing in personal vehicle use due to use of smart systems (see below) that favour car-based fabric and reduced transit (Florida, 2017). Infrastructure investments can favour automobile fabric or walking/transit fabric, depending on the infrastructure and urban planning outcomes prioritized (Heinen, Harshfield, Panter, Mackett, & Ogilvie, 2017a) (Sudarmanto Budi Nugroho et al., 2018).

10.2.2 Behavior and new demand factors

Behaviour continues to be a major source of interest in the decarbonization of transport as it directly addresses demand, but there are also some new concepts that impact indirectly on demand including circular economy, dematerialization and decoupling.

10.2.2.1 Behaviour

Behaviour is about people's actions and there is much new literature suggesting that primarily time and cost continue to dominate in transport behaviour as measured by elasticities of demand for transport services (Ahmad & Oliveira Puppim de, 2016; Capurso, Hess, & Dekker, 2019; He, Zhao, & Gou, 2020). However, there is also evidence of a role for personal values, and in particular environmental values, shaping choices within these structural limitations (Bouman & Steg, 2019). For example, individuals are more likely to drive less when they care about the environment (De Groot, Steg & Dicke, 2008; Abrahamse, Steg, Gifford & Vlek, 2009; Jakovcevic & Steg, 2013; Hiratsuka, Perlaviciute & Steg, 2018; Unal, Steg & Granskaya, 2019). Moreover, emotional and symbolic factors affect the level of car use (Steg, 2005) (Steg, 2007). Differences in behaviour may also result due to differences in gender, age, norms, values and social status. For example, women are more sensitive to parking pricing than men (Simićević et al., 2019). A survey in Nanjing found women had more diverse travel purposes than men resulting in a higher acceptance of electric bikes (Lin, Wells, & Sovacool, 2017). Individuals are more likely to adopt an electric vehicle when they think this benefits the environment, and when they think this says something positive about them to self and others (Noppers et al., 2014; 2015).

Choice of modes for urban transport

Choice modelling and elasticities of demand for transport services show that household income and price have a strong influence on the demand for transport fuels (Bakhat, Labandeira, Labeaga, & López-Otero, 2017) (Wadud, 2017). Income elasticities for transport for typical households in the UK was 1.2 (Bergantino, Capurso, & Toner, 2018). Recent studies for the Scandinavian transport sector estimated long-term elasticities of cars, mopeds and motorbikes were 1.28, while those for buses were lower (1.1) (Salvucci et al., 2019). These also vary by income, between urban and rural households and in the case of external factors such as recession (Bergantino et al., 2018). Transit elasticities depend on a number of factors including the type of users, nature of the trip, mode route, type of transit, type and direction of price change, geography of the city and time period (Litman, 2019). A survey in 98 Indian cities showed income as the main factor influencing travel demand and mode choice with only the top income quintile showing positive elasticity of transport with income (Ahmad & de Oliveira, 2016). In response to the changing climate, people may enhance thermal comfort with more cooling or heating or change travel behaviour through more travel or no travel at all (van Ruijven, De Cian, & Sue Wing, 2019).

Intercity travel

There is significant interest in understanding public behaviour regarding mode choice for intercity travel, especially between high speed rail and aviation. Literature on mode competition reveals the influence of various factors. While cost of travel is a significant factor (Zhang, Yao, & Sun, 2017), sensitivity decreases with increasing income as well as when the cost of the trip was paid by someone else (Capurso et al., 2019). 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). Price reduction strategies such as discounted fares could enhance the share of high speed rail (He et al., 2020). Both air fares and frequency impact HSR ridership (Rui Zhang, Johnson, Zhao, & Nash, 2019). Airline companies reduce fares on routes which are directly competing with HSR (Bergantino, Capozza, & Capurso, 2015) and charge excessively high fares on non HSR routes(Xia & 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 & Croccolo, 2018). In addition to fares, choice modelling studies show travel time to be a significant influencing factor as people prefer faster modes over slower ones (Capurso et al., 2019). A choice modelling study comparing air travel with hypothetical HSR on the Seoul-Jeju route showed business travellers were more likely to opt for a safer transport while for leisure passengers other factors such as availability of duty free shops was important (Lee, Yoo, & Song, 2016). In Turkey, where the share of HSR trips has grown sizeably since its introduction in 2009, for short to medium distances HSR trips have replaced road based modes including buses and private cars (Celikkol-Kocak, Dalkic, & Tuydes-Yaman, 2017). Socio-economic profiles of travellers influence the choice of modes. In China, older and wealthier populations continued to show preference for car travel (Yang, Feng, Dijst, & Ettema, 2019) while younger and low-income travellers sought variety in transport modes (Song, Hess, & Dekker, 2018). A higher number of subway lines and diversity of land use around HSR stations is associated with less car use for business travellers (Yang, Tsai, & Chang, 2015).

10.2.2.2 New demand concepts

Demand, as covered by Chapter 5's framework of 'Avoid, shift and improve', suggests that structural and behavioural choices which are driving transport emissions such as time and cost based on geography of freight and urban fabric, are likely to continue as 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. There are some new demand values that are possibly shaping transport emissions since AR5, including the shift to a circular economy, to dematerialization and to a shared economy all of which lead to decoupling (transport choices change without economic activity suffering).

Circular Economy. The problem of resources and their environmental impacts is driving the move to a circular economy (Van der Voet, Van Oers, Verboon, & Kuipers, 2018). Circular economy principles including light weighting (use of less material for the same level of service), re-using or extending product lifetimes can reduce the demand for steel and aluminium bringing about substantial emission reduction opportunities (Dhar, Pathak, & Shukla, 2019). For the transport systems this means there is increased political pressure to create a greater proportion of recycled materials saving natural resources and energy. LCA's that demonstrate how a whole transport system impacts on greenhouse emissions are the main tool in enabling circular economy actions (Ma, Rong, Mangalagiu, Thornton, & Zhu, 2018). Recycling end-of-life vehicles, re-using spare parts and recycling materials save natural resources, energy and related GHG. There is a connection between circular economy and transport efficiency due to optimization in freight managing vehicle loading, avoiding empty return journeys and reducing the weight and volume of packaging (Akeb, Moncef, & Durand, 2018) (Wiercx, van Kalmthout, & Wiegmans, 2019).

Dematerialization. Dematerialization is where technology is created that incorporates a range of functions previously taken up by several different products. The best example is a smart phone. This process is also enabled by the move to declutter lifestyles instead of consuming more and more (Kondo, 2016) (Whitmarsh, Capstick, & Nash, 2017). McKinnon (2007) applied the idea to freight transport and an assessment for the transport sector in EU-27, showed higher materialization (increasing energy consumption) until 2007 followed by a reversing trend with higher dematerialization between 2008 to 2010 (Ziolkowska & Ziolkowski, 2015). In the UK, transition to a service economy resulted in dematerializing some freight transport (Alises, Vassallo, & Guzmán, 2014) but new evidence is showing that freight can increase due to on-line shopping deliveries (Fix 2019; Laghaei et al. 2016); Visser et al. 2014)). Whether or not such practices achieve dematerialization could be ascertained only through a full lifecycle emissions accounting, including supply chains, energy of ICT, travel behaviour and the overall macro structure of global production and consumption (Coroama, Moberg, & Hilty, 2015; Van Loon, McKinnon, Deketele, & Dewaele, 2014). Strategies to reduce these emissions include improving efficiency of freight operations through better routes, type of packaging and enhancing awareness of customers (Patricia Van Loon, Deketele, Dewaele, McKinnon, & Rutherford, 2015). A literature review of LCA on e-commerce so far shows it is saving energy in the total process (Palsson et al, 2017). However, this is not yet a significant enough process to achieve the kind of decoupling of economic growth rates from escalating use of natural resources (Bringezu, 2015). For sustainable use of global resources by 2050, the average material intensity of consumption per capita needs to be reduced from the forecasted 8–17 tonnes to 6–8 tonnes per capita per year (RP (2018).

Shared Economy. The values of creating a more shared economy are related to both of the above values as well as the notion of community well-being associated with the act of sharing instead of simply owning for oneself (Sharp, 2018) (Maginn, Burton, & Legacy, 2018). Shared mobility is arguably the most rapidly growing and evolving sector of the sharing economy. Bike sharing, carsharing, on-demand mobility (the use of a car, bike or transport mode as needed) (Greenblatt & Shaheen, 2015). 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 in recent years has enhanced the possibility of upscaling (Alonso-González, Liu, Cats, Van Oort, & Hoogendoorn, 2018). Car sharing could provide the same level of service as taxis, however the taxis could be three times more expensive (Cuevas, Estrada, & Salanova, 2016). The sharing economy, as an emerging economic-technological phenomenon (Kaplan & Haenlein, 2010) (Wang & Zhang, 2012) is likely to be a key driver of demand for transport of goods though data shows increasing container movement due to on line shopping (Suel & Polak, 2018).

There is growing evidence that this more structured form of behaviour change through shared economy practices, supported by a larger group than a single family, has a much higher potential to save transport emissions especially when complemented with decarbonised grid electricity (Greenblatt & Shaheen, 2015; Sharp, 2018). 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, 2018; Schaller 2018). Successful providers compete by optimising personal comfort and convenience rather than enabling a sharing culture (Bardhi & Eckhardt, 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). Concerns have appeared about the financial viability of demand responsive transport systems (Ryley, Stanley, Enoch, Zanni, & Quddus, 2014), how the mainstreaming of shared mobility systems can be institutionalized equitably, and the operation and governance of existing systems that are only mode and operator-focused (Akyelken, Banister, & Givoni, 2018; Jittrapirom, Marchau, van der Heijden, & Meurs, 2018; Pangbourne, Mladenović, Stead, & Milakis, 2019).

Decoupling. Decoupling is a concept examined through UNEP processes that enables environmental improvements to happen without loss of economic activity (UNEP, 2011; 2013). Demand has been seen in the past as inherently connected to growth in fossil fuels so decoupling has emerged as the concept to show that economic activity can be positive while decarbonization accelerates (Newman, 2017). As set out in Figure 10.1 the G20 nations have shown decoupling in a range of indicators about greenhouse emissions.

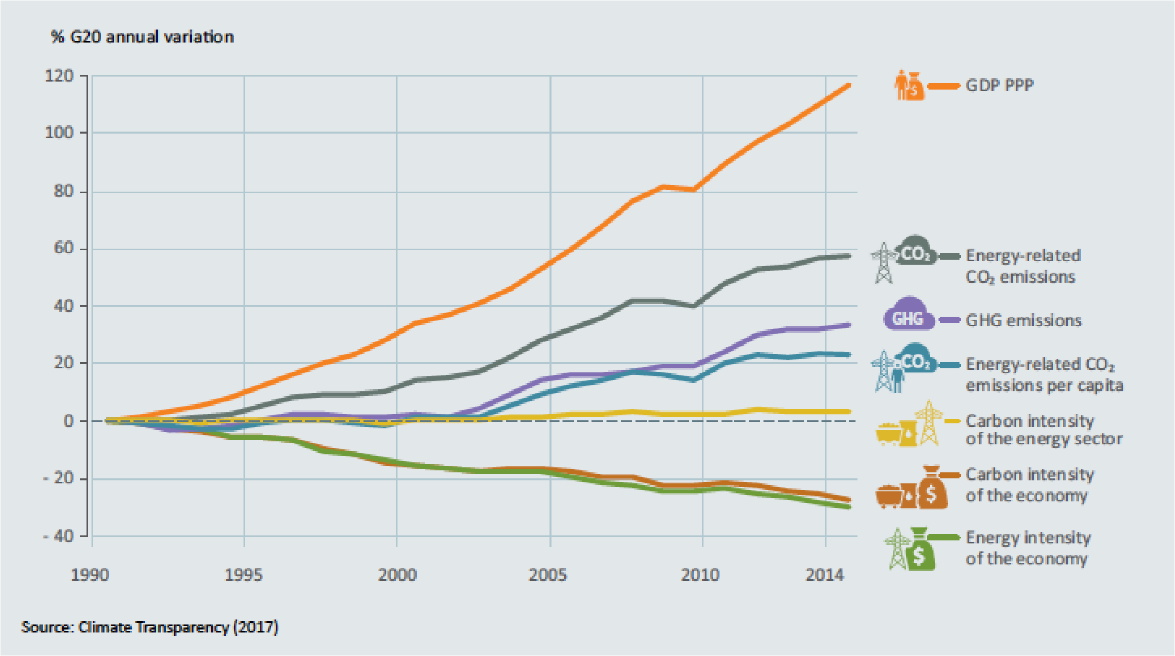


Figure 10.1 Key Indicators on the G20 transition to a low-carbon economy: trends between 1990 and 2014

Source: Climate Transparency (2017)

There are many aspects of policy and behaviour choices that can lead to decoupling including the three demand factors outlined above. There is evidence of decoupling for both developed and developing countries with many cities demonstrating decoupling of transport-related emissions from urban economic activity (Newman, Beatley and Boyer, 2017; Loo and Banister 2016).

10.2.3 Smart city technology and autonomous transport

The process and practices of assimilation of ICTs and other sophisticated hi-technology innovations into transport are increasingly referred to as the Smart Mobility paradigm (Noy and Givoni, 2018). Smart mobility can be used to influence transport behaviour and hence can be seen as a systemic factor (Benevolo, Dameri, & D'Auria, 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 such as EVs (Taiebat & Xu, 2019) (Chen et al., 2016a) (Weiss et al., 2018) (Marletto, 2014).

In Box 10.1 the main smart technologies being adopted rapidly by cities across the world are outlined.

Box 10.1 Smart city technologies and transport

Information and Communication Technology (ICT): The use of ICT can help cities by providing real time information on mobility options for cars or for transit users or those using bikes and pedestrians. ICT can help with ticketing and payment for transit or for road user charges (Gossling 2017; Tafidis et al, 2017).

Internet of Things (IoT) Sensors: These sensors can be used for road safety along roads to ensure cars do not lose their direction and smart tyres equipped with sensors helps to slightly improve fuel efficiency and reduce CO_2 emissions (Kubba and Jiang, 2014; Kavitha et al, 2018). Or, the IoT can be used to create safety for a fast-moving Trackless Tram and its associated last mile connectivity shuttles as part of a Transit Activated Corridor (Newman et al, 2019).

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 easily navigate from A to B based on what modes are most efficient and all necessary bookings or payments can be made through the one service. With smart city planning, these platforms can steer more 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. 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, 2017).

Artificial Intelligence (AI) and Big Data Analytics: 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 along with advanced shared transit scheduling can provide value to new and existing transit systems Toole, et al, 2015; Anda et al, 2017; Milne and Whatling, 2019).

Blockchain or Distributed Ledger Technology: Blockchain can be the basis of MaaS or any local shared mobility as it facilitates shared activity. As the future city is going to have distributed solar energy it can be applied to that and to how urban regeneration along a TAC can be sharing mobility opportunities, especially the payments for tickets on a transit system and its last mile connectivity shuttles. This technology can also be used for road user charging along any corridor and by businesses accessing any services and in managing freight (Green and Newman, 2016; Jin et al, 2019; Charter and Koh, 2018; Nguyen, et al, 2019).

Smart technologies can improve competitiveness of transit and active transport, and reverse logistics in trucking can lead to GHG savings as set out below; smart technologies also provide transport efficiency as optimizing traffic by providing more competitive opportunities for transit and active transport over personal vehicle usage, and in freight by managing vehicle loading, avoiding empty return journeys and reducing the weight and volume of packaging. Evaluations of actual GHG savings from such applications include Palsson et al (2017).

Autonomous vehicles are the other emerging transport technology that has the potential to significantly improve the value of each mode of transport. Planes and high-speed trains are already largely autonomous as they are guided in all their movements, especially coming into stations and airports, however that does not mean they are driverless. This principle is also being used in new on-road transit systems like Trackless Trams (Newman et al, 2019). Private vehicles are being fitted out with more and more levels of autonomy and many are being trialled as driverless in cities though with mixed results (Aria, Olstam, & Schwietering, 2016) (Skeete, 2018).

There is a growing body of literature about the effect of smart city technology (including sensors guiding vehicles) on demand for transport services as it is unclear what is the direction of the effect (Lenz and Heinrichs, 2017; Debnath et al, 2014). Smart city technologies can be used to improve competitiveness of transit and active transport or favour even more private vehicle movement, even when it is being shared. Some work suggests that shared vehicles such as Uber and Lyft and also vehicle autonomy is leading to increased vehicle kms travelled (Schaller, 2018) (Tirachini & Gomez-Lobo, 2019).

Heavy haulage trucks in the mining industry are already autonomous (Price et al, 2019) and long-haul trucks may happen sooner than automation of LDVs though how they will be allowed to move through cities is yet to be worked out as they will be an impenetrable barrier (Hancok et al, 2019). Drones are being presented as a potential major freight device in cities for light parcels and even people, however the implications for disturbance of neighbourhoods and airspace are likely to limit this application (Stolaroff et al., 2018).

The impact of these new technologies will be determined by how they are managed in terms of demand. It is likely that different parts of the city will be enabled to use autonomous vehicles more than others – automobile city fabric for example will be more able to accommodate AV's than in transit city fabric and walking city fabric where fast-moving autonomous vehicles would not be economically and socially acceptable due to pedestrian priority. There are also going to be some parts of society who will find it very helpful, eg marginal groups such as the elderly, people with disabilities, and those who cannot drive, stakeholders who have expressed concerns over being excluded already in the transition to battery electric vehicles (Sovacool, Kester, Noel, & de Rubens, 2019). Local shared mobility systems can be used to integrate with fast transit corridors and local shopping and services centres, enabling much reduced demand for private vehicles overall (Hancock et al 2019; Newman et al, 2020).

Some commentators are optimistic that smart and autonomous technologies can transform the greenhouse emissions from the transport sector (Rivkin, 2019) (Seba, 2014). Others are more sanguine unless policy interventions can enable the technologies to be used for purposes that include zero carbon and the SDG's (Hancock et al, 2019).

10.2.4 Integrating electric mobility and grid management with V2G

Recharge of EV's has been an issue often discussed as 'range anxiety' concerning drivers and also grid destabilization for utility management (Pearre & Ribberink, 2019) (Zheng, Niu, Shang, Shao, & Jian, 2019). As this is also a behavioural issue it has been classified here as a systemic factor. Since AR5 there has been a growing literature on how to intelligently integrate electric utility grid operations with electric vehicles to both reduce range anxiety and also to manage electric grids. They have termed this integration vehicle-to-grid (V2G) (Noel, Kester, Rubens, & Sovacool, 2019) (Ercan, Noori, Zhao, & Tatari, 2016), grid-integrated vehicles (GIV) (Sovacool, Noel, Axsen, & Kempton, 2018), and vehicle-grid-integration (VGI) (California Independent System Operator, 2014). These connected concepts describe efforts to link transport and electricity systems in ways that may provide synergetic benefits to both. V2G and VGI has more recently developed as a sort of umbrella term to encompass unidirectional integration efforts, such as "smart" or "controlled" charging (now sometimes called V1G), as well as bidirectional integration, namely V2G (Sovacool, Axsen, & Kempton, 2017) and even V2X or vehicle-to-everything (Wang, 2019).

For electric utilities, V2G can provide back-up power, support load balancing, reduce peak-loads (Noel et al., 2019), reduce the uncertainty in forecasts of daily and hourly electrical load (Peng, Liu, & Jiang, 2012), allow greater utilization of existing generation capacity (Hajimiragha, Canizares, Fowler, & Elkamel, 2010) (Madzharov, Delarue, & D'haeseleer, 2014) and of distribution infrastructure (Bedir, Ogden, Yang, & Ogden, 2015). V2G has been characterized as a comparatively advantageous means of peak load shaving, assuming peak shaving events lasted one hour or less per day (Zhuk, Zeigarnik, Buzoverov, & Sheindlin, 2016). Another specific application is spinning reserves, noting that such an application outweighed the cost of additional load from PEV charging (Mirmoradi & Ghasemi, 2016).

In terms of climate benefits, V2G-capable PEVs can result in lower total emissions, particularly when compared to other alternatives (Reddy, Panwar, Kumar, & Panigrahi, 2016). Climate change benefits can accrue via the general electrification of transport, controlled charging to avoid high carbon electricity sources, decarbonisation of the ancillary service markets, or peak shaving of high carbon electricity sources. Noel et al. analyze V2G pathways in Denmark, and note that at an optimal penetration rate of 75% by 2030, $34 billion in social benefits would be accrued (through things like displaced pollution) or a cost savings of $1200 per vehicle (XIV). V2G-capable PEVs had the potential to reduce carbon emissions compared to a conventional gasoline vehicle by up to 59%, assuming optimized charging schedules (Hoehne & Chester, 2016). However, these benefits are not a given. In some electricity grids with higher CO_2-intensity electricity and no climate policy, V2G providing load shaving services might actually increase total carbon emissions (Hoehne & Chester, 2016).

Despite these uncertainties, projections suggest V2G will come to play a significant role in future transport systems. One assessment simulated the future penetration of decentralized, flexible power systems (including renewable energy and storage) and concluded that V2G offered the *most storage* potential in Europe compared to other options such as standalone batteries, compressed air energy storage, or pumped hydro (see Figure 10.2) (Després et al., 2017). Another study calculated that V2G-enabled PEVs could provide much needed assistance to transmission operators in the United States as they maintain reliability and operating standards, and it estimated the value of those electric services at up to $12 billion per year, some of which would flow to PEV owners (Kempton & Tomić, 2005). A 2016 study by the Transport Research Board reported that vehicle-to-infrastructure (V2I) systems, where vehicles utilize communication devices to share information with the components that support a country's highway system, could be utilized by about 460 million vehicles globally by 2030; vehicle-to-retail (V2R) systems, where cars communicate directly with fuel or automotive parts retailers, by another 406 million vehicles by 2030 globally; and another 50 million vehicles globally offering active V2G services by 2030 (Mohaddes & Sweatman, 2016). For perhaps reasons such as these, the Parker-Project (2018) documented at least 50 V2G projects across 14 countries, although most of these are still only at the pilot stage (Parker-Project, 2018).

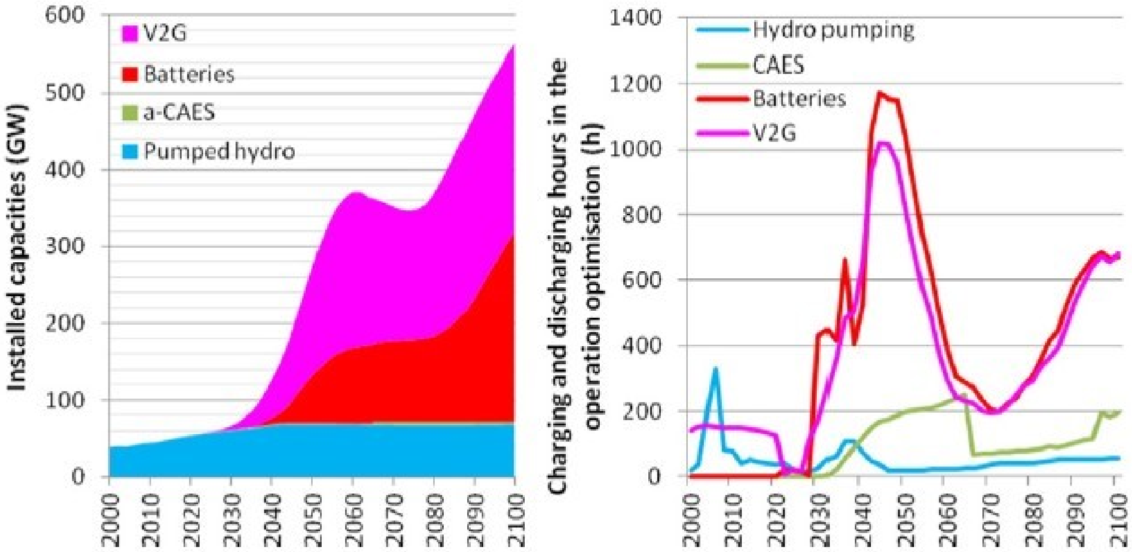


Figure 10.2 Installed capacities (left) and hours of utilization (right) in the operation of different optimized energy storage technologies for Europe, 2000-2100

Source: (Després et al., 2017)

Note: V2G = vehicle-to-grid. CAES = Compressed Air Energy Storage.

10.3 Transport technology innovations for decarbonisation

This section will focus on technology innovations in four key technologies - batteries, hydrogen fuel-cells, biofuels and advanced ICE. They can be applied for land-based transport, shipping and aviation and have the potential for decarbonization of the transport system. The development of these technologies will affect other sectors such as energy, industry, buildings but the review is more from the perspective of their application in the transport sector. The trends in these technologies will contribute to the later discussions on alternative technologies within sections on land-based transport, aviation and shipping.

10.3.1 Battery-electric technologies

Battery technologies can be divided into primary and rechargeable batteries. Rechargeable batteries are of interest for applications within the transport sector, with a range of mature and emerging chemistries able to support the electrification of vehicles.

10.3.1.1 Development of battery technology

Lithium-ion batteries (LIB) were discovered in the 1980s and have since become the default choice for providing driving power for automotive vehicles (Placke et al. 2017) and are expected to play a dominant role in the near term (International Energy Agency 2019a). A large-scale diffusion of batteries will, however, depend on improvements in energy density (energy stored per unit volume), specific energy (energy stored per unit weight) and the costs of batteries (Cano et al. 2018). These improvements will occur in LIBs, as well as battery chemistries which go beyond LIBs - also referred to as post-LIBs (Placke et al. 2017).

10.3.1.1.1 Pre-LIB batteries

The pre-LIB phase occurred prior to the 1990s before the large-scale diffusion of LIBs. Four types of rechargeable batteries were available during this phase: lead-acid batteries, nickel batteries, high-temperature sodium batteries and redox flow batteries (Placke et al. 2017). Lead-acid batteries were the most common batteries used for automotive auxiliary power applications, however, their low specific energy (Andwari et al. 2017) limited their application for providing driving power in automobiles - though they have been used in smaller automotive vehicles e.g. e-scooters and e-rickshaws (Dhar et al. 2017) due to their low cost. Nickel-metal hydride (NiMH) has a better energy density than lead-acid batteries. For this reason, they were the battery of choice for hybrid EVs and are well-optimised for regenerative braking (Cano et al. 2018), however, due to a rapid cost reduction they are now being replaced by LIBs. Ni-Cadmium (NiCd) batteries have energy densities lower than NiMH batteries (Table 10.3) and cost around ten times more than lead-acid batteries. For this reason, they do not have major prospects within automotive applications. There are no examples of high-temperature sodium batteries being used within automotive applications.

10.3.1.1.2 Lithium-ion batteries (LIB)

LIBs came into existence in 1980s (Placke, et al. 2017) and were initially used within electronics applications. By 2010 the cumulative capacity of LIBs in electronics was 98 GWh (Schmidt et al. 2017). This large-scale diffusion in electronics resulted in significant innovations within LIB chemistries. Commercial application of LIBs in automotive applications started around 2000 when the price of LIBs was more than 1000 USD per kWh (Schmidt et al. 2017). By 2017 the cumulative battery capacity for automotive applications was around 60 GWh and in 2018 the cost had come down to around 176 USD per Kwh (Goldie Scot, 2019). Further improvements in LIBs, with respect to specific energy, energy density (Placke et al. 2017) (Nykvist and Nilsson 2015) and cost (Schmidt et al. 2017) is expected when LIB design is further optimised (Table 10.3) see LIB energy optimised). These advancements are expected to lead to electric vehicles with even longer driving ranges, further supporting the uptake of LIBs for transport applications (Cano et al. 2018). Schmidt et al. (2017), using experience learning curves, project that the cost of LIBs will be close to 100 USD per kWh in 2030 (Table 10.3), however, given the rapid rate at which LIB prices have fallen in recent years some estimates are putting prices at closer to 80 USD per kWh by 2030 (International Energy Agency 2019a). Price parity between EVs and equivalent combustion engine vehicles is expected at LIB prices of around 100 USD per kWh.

The state-of-the-art LIBs available in 2019 are superior to alternative cell technologies in terms of battery life, energy density, specific energy and cost (Table 10.3). The expected further improvements in LIBs (optimised) suggest these chemistries will remain superior to alternative battery technologies in the medium-term, and therefore LIBs will continue to dominate the automotive market.

For EVs sold in 2018, the material demand was about 11 kilotonnes (kt) of lithium, 15 kt of cobalt, 11 kt of manganese and 34 kt of nickel (International Energy Agency 2019a). 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. Concerns about these widespread crustal elements have been addressed by International Resources Panel (2019), World Bank (2018) and Sovacool (2020).

A wide variety of materials or material combinations can be used in LIBs (Placke et al. 2017). In terms of cathodic materials being used currently, these are based on a combination of nickel, manganese and cobalt and in short are referred to as NMC. In the future, LIBs will increasingly use chemistries that are less dependent on cobalt, such as NMC 622, NMC 532, NMC 811 instead of NMC 111 in the NMC family (International Energy Agency 2019a) or move on to alternative chemistries (Placke et al. 2017). These changes in cathodic materials will also contribute towards the reduction of costs for LIBs (International Energy Agency 2019a). However, dependence on lithium will remain and this is a cause of concern for some (You & Manthiram, 2018; Oliveti et. al., 2017). At the same time, lithium demand from electric vehicles was only around 11 ktons in 2018 (International Energy Agency 2019a); much lower than reserves of 14,000 ktons globally (IBRD & World Bank, 2017). This suggests that resource concerns may be overstated.

Externalities from resource extraction is another concern, however, other metals (steel, aluminium, etc) - for which production was around 900 million tonnes in 2017 - is a greater concern. Lithium was not even mentioned in the global resource outlook of UNEP (UNEP, 2019). Nonetheless, it is important to manage demand and limit externalities. since demand for Lithium is going to increase many fold in future. Reuse of LIB used in EVs for stationary applications can help in reducing the demand of LIBs however the main challenges are the difficulty in accessing information on health of batteries to be recycled and technical difficulties in remanufacturing the batteries for their second life (Ahmadi et. al., 2017). Recycling of lithium from used batteries could be a possible supply source (Winslow et al. 2018), however, most of the efforts to recycle lithium are currently at a laboratory scale and with further effort required for commercialisation (Ling et. al., 2018). The main challenges to recycling is a lack of standardisation of battery designs and no focus on recyclability (Harper et. al., 2019) which make it difficult and expensive to recycle LIBs.

10.3.1.1.3 Post-LIB batteries

There are several next-generation battery chemistries which are often referred to as post-LIBs (Placke et al. 2017). These chemistries include metal sulfur, metal-air, metal ion (besides Li) and All-Solid-StateBatteries (ASSB). The long development cycles of the automotive industry (Cano et. al., 2018) and the advantages of LIBs in terms of energy density, cycle life, etc, mean that it is unlikely that post-LIB technologies will replace LIBs in the next decade, however, Lithium-sulfur, Lithium-air and Zinc-air have emerged as potential alternatives for LIBs (Cano et al. 2018).

10.3.1.1.3.1 Lithium-sulphur batteries

These batteries have a lithium metal anode which has a higher theoretical capacity compared to Lithium-ion anodes and much lower cost sulfur cathodes relative to typical Li-ion insertion cathodes (Manthiram et al. 2014). Due to these factors, these batteries are much cheaper than LIB to manufacture and have a higher energy density (Table 1.3). Conversely, these batteries face several challenges from sulfur cathodes which affect the cycle life of the battery (Cano et al. 2018).

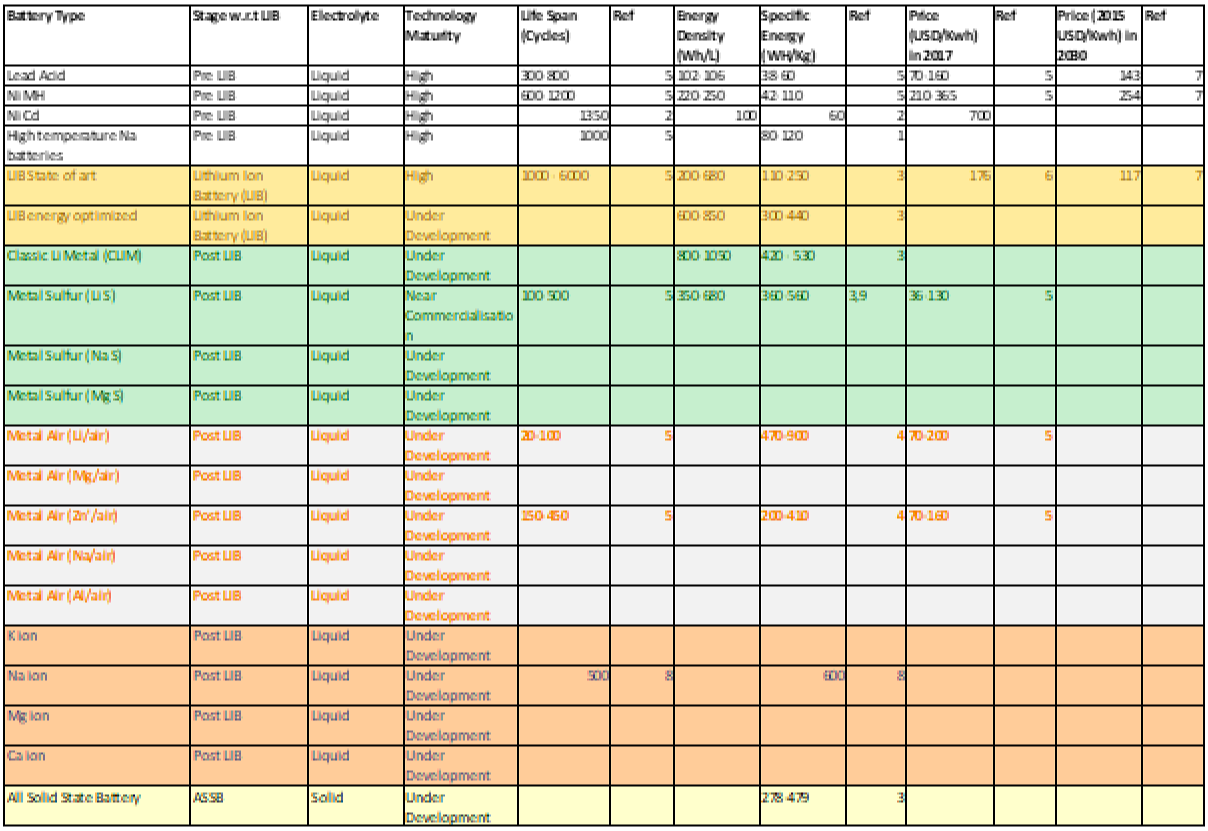
10.3.1.1.3.2 Lithium-air batteries

These 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 sulfur. However, their demonstrated cycle-life is much lower (Table 1.3). The Lithium-air have a low specific power which means they require a complimentary battery for practical purposes (Cano et al. 2018).

10.3.1.1.3.3 Zinc-air batteries

Zinc–air batteries seem more likely to 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 them from being used as a primary energy source for EVs; however, they could be promising when used in a dual-battery configuration (Cano et al. 2018).

Table 10.3 Overview of technologies for rechargeable batteries



Battery Type	Stage w.r.t LIB	Electrolyte	Technology Maturity	Life Span (Cycles)	Ref	Energy Density (Wh/L)	Specific Energy (WH/Kg)	Ref	Price (USD/Kwh) in 2017	Ref	Price (2015 USD/Kwh) in 2030	Ref
Lead Acid	Pre-LIB	Liquid	High	300-800	5	102-106	38-60	5	70-160	5	143	7
Ni-MH	Pre-LIB	Liquid	High	600-1200	5	220-250	42-110	5	210-365	5	254	7
Ni-Cd	Pre-LIB	Liquid	High	1350	2	100	60	2	700			
High temperature Na batteries	Pre-LIB	Liquid	High	1000	5		80-120	1				
LIB State of art	Lithium Ion Battery (LIB)	Liquid	High	1000 - 6000	5	200-680	110-250	3	176	6	117	7
LIB energy optimized	Lithium Ion Battery (LIB)	Liquid	Under Development			600-850	300-440	3				
Classic Li Metal (CLIM)	Post LIB	Liquid	Under Development			800-1050	420 - 530	3				
Metal Sulfur (Li-S)	Post LIB	Liquid	Near Commercialisation	100-500	5	350-680	360-560	3,9	36-130	5		
Metal Sulfur (Na-S)	Post LIB	Liquid	Under Development									
Metal Sulfur (Mg-S)	Post LIB	Liquid	Under Development									
Metal Air (Li/air)	Post LIB	Liquid	Under Development	20-100	5		470-900	4	70-200	5		
Metal Air (Mg/air)	Post LIB	Liquid	Under Development									
Metal Air (Zn'/air)	Post LIB	Liquid	Under Development	150-450	5		200-410	4	70-160	5		
Metal Air (Na/air)	Post LIB	Liquid	Under Development									
Metal Air (Al/air)	Post LIB	Liquid	Under Development									
K ion	Post LIB	Liquid	Under Development									
Na ion	Post LIB	Liquid	Under Development	500	8		600	8				
Mg ion	Post LIB	Liquid	Under Development									
Ca ion	Post LIB	Liquid	Under Development									
All Solid State Battery	ASSB	Solid	Under Development				278-479	3				

Source : 1. Andwari et. al., 2018; 2. Manzetti & Mariasiu, 2015; 3. Placke et. al., 2017; 4. Nykvist & Nilsson, 2015; 5. Cano et. al., 2018; 6. Blomberg Energy Finance, 2019; 7. Schmidt et. al.,2017; 8. You & Manthiram, 2018; 9. Fotouhi et. al., 2017

10.3.1.2 Technology readiness of batteries

The technological readiness of a battery is adjudged as a crucial parameter in the advancement of Battery Electric Vehicles (BEVs) (Manzetti and Mariasiu 2015). Energy density, power density, cycle life, calendar life, and the cost per kWh are considered as the pertinent parameters for comparing the technological readiness of various battery technologies (Andwari et al. 2017) (Manzetti and Mariasiu 2015) (Lajunen et al. 2018). A summary of alternative battery technologies has been presented in Table 1.3 in terms of these parameters.

LIBs dominate the other battery types in a comprehensive manner and are at a readiness level where they can be applied for most transport applications except medium-long haul aviation, ocean going ships and heavy-duty trucks. LIBs will not, however, significantly replace the lead acid batteries which have been used extensively till now for auxiliary power applications and in some low-cost electric vehicles (e.g., e-rickshaws, e-scooters, etc) (Cano et. al., 2018). In fact, the cumulative capacity of lead-acid batteries is expected to increase from 8,867 GWh in 2010 to 10,630 GWh in 2030 (Schmidt et al. 2017). There are many innovations underway with LIBs which are likely to improve their energy density, specific energy and also bring down the costs (Placke et. al., 2017).

There are a number of battery technologies under development (Table 1.3) however Li-S, Li-air and Zn-air are three battery chemistries hold the highest potential (Cano et. al., 2017). All three of these technologies rely on making use of elements that are relatively inexpensive. This can help in bringing down battery costs (Cano et. al., 2017). 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 within unmanned aerial vehicles (Fotouhi et. al., 2017) due to relatively high specific energy (almost double of state of art LIBs). Even with low cycle life Li-air and Zn-air hold good prospects for commercialisation as range extender batteries for long-range road transport (Cano et. al., 2017) for vehicles that are normally used for in the city driving.

10.3.1.3 Infrastructure for charging

In order to accelerate the uptake of EVs globally, 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 electric vehicle will be capable of meeting their driving range requirements. As a consequence, the provision of public charging infrastructure is seen as one avenue for alleviating range anxiety and facilitating longer distance travel in electric vehicles. While there is some level of variation in the expected required ratio of public charging infrastructure points to electric vehicles - see Figure 10.3- a comprehensive network of public charging infrastructure - with good coverage - will be required to support the transition to an electric vehicle fleet (Gnann et al. 2018).

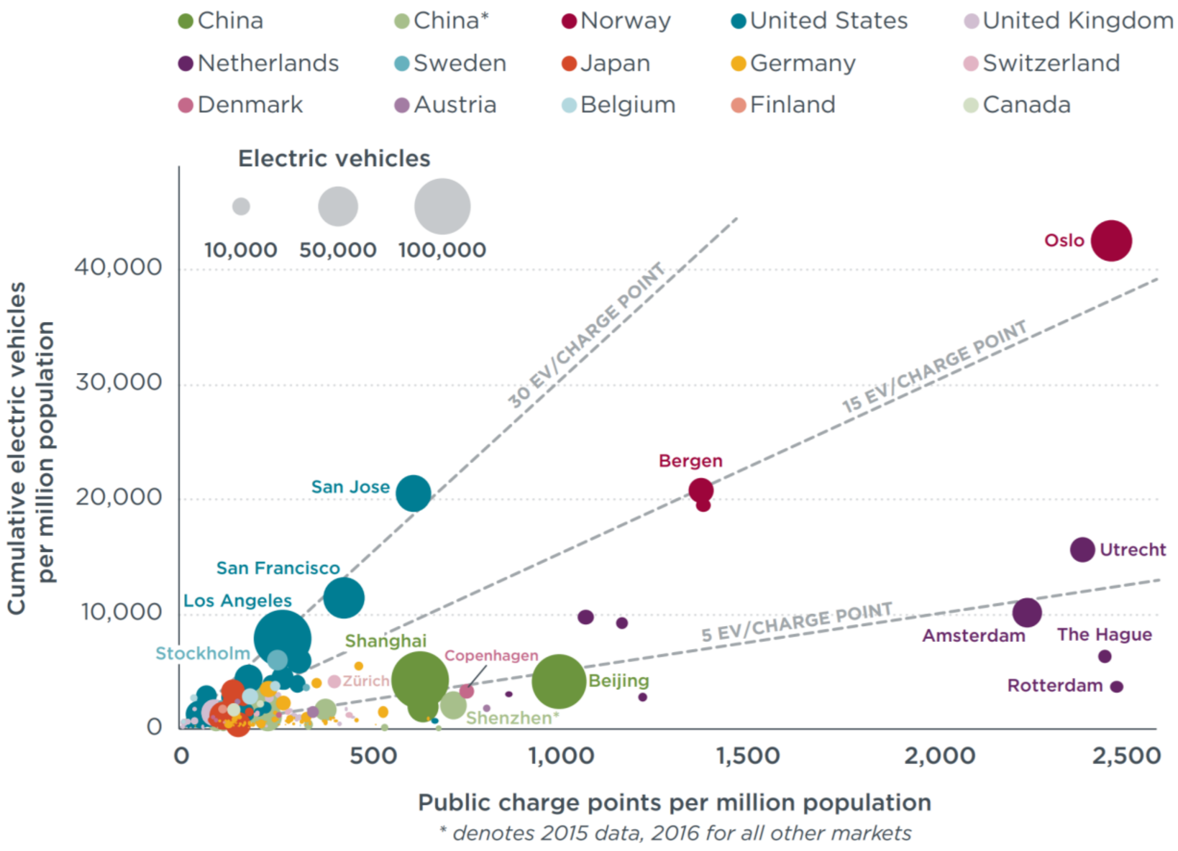


Figure 10.3 Public charging infrastructure and electric vehicle registrations per million population by metropolitan area, with size of circles indicating total electric vehicles

Source: (Hall and Lutsey 2017b)

Beyond simply the number of EV chargers, this infrastructure must be fit-for-purpose, and meet the needs of consumers. In particular, it must be: accessible, close to amenities, safe, and affordable (Hardman et al. 2018). In order to deliver ‘fit-for-purpose’ public charging infrastructure, many stakeholders must coordinate efforts including: charging station operators, charging station manufacturers, automakers, electricity utilities, landowners, and policy makers. Policy makers, in particular, can play a central role in ensuring that charging infrastructure is not only deployed in high demand locations, but is also spread broadly to enable a comprehensive network that supports long-distance electric driving, and adoption of this technology in regional and rural communities. Proactive planning of charging infrastructure can also drive down costs.

10.3.1.3.1 Charing infrastructure levels and types

Electric vehicles can charge at different speeds depending on both the external charging hardware capabilities, and the on-board vehicle charging capabilities. Different charging speeds are often referred to as charging ‘Levels’. Charging infrstructures can be differentiated on the basis of their level (power output range of charger), the type of socket and connenctor and the mode of cooomunication protocol between the vehicle and charger (International Energy Agency 2019a).

There are three levels of charging, Level 1 charging having an conventional AC plug with a power output up to 3.7 kW, Level 2 charging having a dedicated AC wall charger with a power output between 3.7 kW and 22 kW and a Level 3 charger that can have a AC 3 phase plug with a power output between 22 kW and 43.5 kW or DC plug and till now the maximum power output installed is 400 kW (International Energy Agency 2019a). Level 1 chargers are basically electrical wall socket at homes, Level 2 are referred as slow charger and Level 3 as the fast chargers.

Each charging level has different implications for the electricity grid. Level 1 and 2 charging requires a lower electricity load, compared to Level 3, however, it tends to be uncontrolled, adhoc, and unplanned - particularly at the residential level - making it hard for utilities to safeguard the stability of low voltage networks. Conversely, while Level 3 charges require much higher loads, they tend to be more planned - given the approvals required to connect to the electricity grid - and as such, utilities can more easily plan for and manage this infrastructure.

In addition to standard plug-in charging infrastructure, wireless charging technologies are also emerging, allowing vehicles to be charged autonomously while parked and/or in-motion - if wireless charging is built into the road pavement (IRENA, 2019). Other forms of road electrification also may have potentially, particularly for heavy freight where load demand is higher. Road electrification can take the form of a charging rail built into the road pavement, running along the side the road, or overhead through catenary power lines - similar to electrical infrastructure used for light and/or heavy rail.

Seperate to charging levels, there are also several types of charging connectors, differing for AC (Level 1/2) and DC (Level 3) charging. While initially several connectors were deployed in each market, in recent years there has been a level of standardisation occur across most markets - similar to charging plugs for other electrical appliances. Europe/Australia has converged on the Type 2 (AC) and CCS-2 (DC) charging standard; North America has converged on the Type 1 (AC) and CCS-1 (DC) charging standard (with the exception of Tesla which use a proprietary connector in North America), Japan has converged on the Type 1 (AC) and CHAdeMO (DC), while China has converged on its own standard for AC/DC charging, known as GB/T (International Energy Agency 2019a).

10.3.1.3.2 Charging locations

Electric vehicle charging occurs at four primary locations:

1. At or near home
2. Workplace or commuter carpark
3. Public destinations e.g. shopping centres, tourist attractions.
4. Along travel corridors during long-distance travel.

In terms of the current electric vehicle market, the majority of charging (75-90%) has been reported to be carried out at or near homes (Figenbaum 2017) (Webb et al. 2019) (Wenig et al. 2019). It has been found that access to charging at home is a significant factor in the adoption of EVs, with consumers less willing to purchase an EV without home charging (Nicholas, Tal & Hybrid, 2017; (Funke and Plötz 2017) (Bailey et al. 2017) (Bailey et al. 2017). Consumers can be supported in installing home charging infrastructure by automakers, utilities and/or policy-makers (Hardman et al. 2018). Apartment dwellers may face specific challenges in installing charging infrastructure, highlighting the need for supporting planning policy, and availability of charging infrastructure nearby these forms of residential developments.

Combined, these efforts will be particularly important for encouraging the uptake of electric vehicles in a timeframe that is congruent with required emission reduction targets. Charging infrastructure at workplaces and commuter car parks is also important, particularly given many vehicles are parked at these locations, for many hours, during peak renewable energy generation periods i.e. the middle of the day. Around 15-30% of EV charging occurs at these locations (Figenbaum 2017) (Webb et al. 2019) (Wenig et al. 2019). Ideally, this would be increased further through policy support in order to absorb excess solar energy generated during the day (Hardman et al. 2018).

Of the remaining approximately 10% of charging, this occurs at public locations, is roughly spil equally between AC (slower) and DC (fast) charging (Figenbaum 2017) (Webb et al. 2019) (Wenig et al. 2019). Slower AC charging is available at destinations when EV owners are expected to spend a number of hours, and would like to get a top-up charge during this time. This form of charging is largely discretionary, and is not generally relied upon for daily or long-distance travel. Conversely, DC fast charging is essential for extending the range of EVs, particular for long-distance travel along highway corridors. DC fast charging allows consumers to get a quick recharge during rest stops (15-45 mins), and be able to drive for several hundred miles/kilometres before having to charge again. This form of charging, however, is not the primary form of charging given it is generally more expensive than home/work/destination charging, and is also not as convenient as charging at locations when vehicles are already parked for several hours at a time. Nonetheless, this form of charging infrastructure is critical for addressing range anxiety.

It should also be noted that while the current charging profile of EV owners is skewed towards slower AC charging at home/work, this may change as EV technology continues to evolve, and market preferences shift. Particularly for those consumers who do not have regular access to a parking space with EV charging e.g. apartment dwellers, they will become increasingly reliant on using DC fast-chargers in cities to recharge as required, at quicker, more convenient speeds. There are also potential synergies between the siting of this type of infrastructure in cities, and establishment of e-Mobility hubs near/at public transport interchanges, to encourage multi-modal transport, including the use of EVs by ride- and car-sharing providers.

Placeholder-Para on capacitors will be added in SOD.

10.3.2 Hydrogen fuel cell-electric technologies

Low carbon hydrogen in fuel cells (and associated synthetic fuels) are an emerging option to power heavy duty-transport that are 'battery-challenged' (Intergovernmental Panel on Climate Change 2018). Hydrogen can also directly be used as a substitute for diesel. Hydrogen is therefore seen as one of the important potential fuels to solve decarbonization for the heavy vehicle transport system

(International Energy Agency 2019b) (Tokimatsu et al. 2016) (International Energy Agency, n.d.-a) (Tokimatsu et al., 2016). However, significant advancements in technological and economic maturity will be required in order for hydrogen fuel cells to play more than a niche role.

10.3.2.1 Technology development and demonstration

During the last decade, fuel cell vehicles (FCVs) have attracted growing attention and have made significant technological progress. The power density of the internationally advanced electric reactor has reached 3.1kW/L, the service life of passenger vehicle systems has generally reached 5000 hours, and that of commercial vehicles has reached 20,000 hours.

Vehicle fuel cell system engines cost 80 to 95 percent less than they did in the early 2000s and cost $49 per kW (based on 500,000 units per year), which is getting close to $30 per kW for internal combustion engines (White paper:H2 and FCV in China (2019) P5~6, International Energy Agency 2019b). By 2018, there were 369 hydrogen stations in operation worldwide, 273 of which were open to the public, and the rest belonged to the internal hydrogen stations of the institute/enterprise who manages them. Europe currently has 152, Asia 136 and North America 78 (LBST, 2019, H2stations.org). The global installed capacity of hydrogen fuel cells had exceeded 2091 MW, however, the sales of passenger vehicles totalled only about 9,900 – 0.0005% of the global fleet. Fuel cell buses have been used in demonstration projects in various countries, such as the Clean Hydrogen in European Cities project and the fuel cell bus project for the 2022 Winter Olympics in China (Annual Report on the Development of Automotive Hydrogen Industry in China 2019). Hydrogen applications in aircraft, ships and trains have progressed on the technology R&D stage in the last decade (van Biert et al. 2016; Hydrogen Roadmap Europe, 2019).

The number of countries with polices that directly support investment in hydrogen technologies is increasing, along with the number of sectors they target. By mid-2019 the total number of targets, mandates and policy incentives in place globally to directly support hydrogen was around 50 (International Energy Agency 2019b).

10.3.2.2 Technology readiness

Fuel cell technology is still relatively immature with low reliability and significant R&D still required but the first attempt to estimate readiness is set out in Table 10.4. The Table shows that the future competitiveness of hydrogen fuel cell cars depends on fuel cell costs, hydrogen fuel costs and hydrogen refuelling stations while for trucks the priority is to reduce the delivered price of hydrogen. While battery electric alternatives are starting to emerge in the short-haul shipping and aviation sectors, long-haul shipping and aviation have limited low-carbon fuel options available. These sectors represent key opportunities for hydrogen-based fuels in an effort to reduce transport emissions but remain firmly in the non-commercial arena, unlikely to cost effective until 2030 while others argue that in the EU it may be possible to achieve serial production of fuel cell heavy-duty trucks by the mid-2020s, and comparable costs to diesel vehicles by 2030. Fundamental to this is the recharging facilities which remain a major issue (see below). For air and sea transport, hydrogen-based synthetic fuels hold some promise, but on a longer time horizon (beyond 2030).

Table 10.4 Current performance of key technologies of H2

Application	*Power or capacity*	*Efficiency **	*Initial investment cost*	*Life time*	*Maturity*
Part 1: Key technologies of H2 conversion, T&D, storage					
Alkaline FC	Up to 250 kW	~50% (HHV)	USD 200-700/kW	5 000-8 000 hours	Early market
PEMFC stationary	0.5-400 kW	32%-49% (HHV)	USD 3 000-4 000/kW	~60 000 hours	Early market
PEMFC mobile	80-100 kW	Up to 60%	USD ~500/kW	<5 000 hours	Early market

		(HHV)			
SOFC	Up to 200 kW	50%-70% (HHV)	USD 3 000-4 000/kW	Up to 90 000 hours	Demonstration
PAFC	Up to 11 MW	30%-40% (HHV)	USD 4 000-5 000/kW	30 000-60 000 hours	Mature
MCFC	KW to several MW	More than 60% (HHV)	USD 4 000-6 000/kW	20 000-30 000 hours	Early market
Compressor, 18 MPa	-	88%-95%	USD ~70 /kWH2	20 years	Mature
Compressor, 70 MPa	-	80%-91%	USD 200-400/kWH2	20 years	Early market
Liquefier	15-80 MW	~70%	USD 900-2 000/kW	30 years	Mature
FCEV on-board storage tank, 70 MPa	5 to 6 kg H2	Almost 100% (without compression)	USD 33-17/kWh (10 000 and 500 000 units produced per year)	15 years	Early market
Pressurised tank	0.1-10 MWh	Almost 100% (without compression)	USD 6 000-10 000/MWh	20 years	Mature
Liquid storage	0.1-100 GWh	Boil-off stream: 0.3% loss per day	USD 800-10 000/MWh	20 years	Mature
Pipeline	-	95%, incl. compression	Rural: USD 300 000-1.2 million/ km Urban: USD 700 000-1.5 million / km (dependent on diameter)	40 years	Mature
Part 2: Key technologies of H2 conversion, T&D, storage					
Fuel cell vehicles	80 - 120 kW	Tank-to-wheel efficiency 43-60% (HHV)	USD 60 000-100 000	150 000 km	Early market introduction
Hydrogen retail stations	200 kg/day	~80%, incl. compression to 70 MPa	USD 1.5 million-2.5 million	-	Early market introduction
Tube trailer (gaseous) for hydrogen delivery	Up to 1 000 kg	~100% (without compression)	USD 1 000 000 (USD 1 000 per kg payload)	-	Mature
Liquid tankers for hydrogen delivery	Up to 4 000 kg	Boil-off stream: 0.3% loss per day	USD 750 000	-	Mature

* Unless otherwise stated, efficiencies are based on lower heating values (LHV).

** All power-specific investment costs refer to the energy output.

Notes: HHV = higher heating value; kg = kilogram; kW = kilowatt.

Source: For part 1: IEA data; Decourt et al. (2014), *Hydrogen-Based Energy Conversion, More than Storage: System Flexibility*; Elgowainy (2014), "Hydrogen infrastructure analysis in early markets of FCEVs", IEA Hydrogen Roadmap North America Workshop; ETSAP (2014), *Hydrogen Production and Distribution*; Iiyama et al. (2014), "FCEV Development at Nissan", ECS Transactions, Vol. 3, pp. 11-17; Nexant (2007), "Liquefaction and pipeline costs", Hydrogen Delivery Analysis Meeting, 8-9 May; NREL (2014), *Hydrogen Station Compression, Storage and Dispensing - Technical Status and Costs*; NREL (2012a), *National Fuel Cell Electric Vehicle Learning Demonstration Final Report*; US DOE (2010a), *Hydrogen Program 2010 Annual Progress Report - Innovative Hydrogen Liquefaction Cycle*; US DOE (2010b), *DOE Hydrogen Program 2010 Annual Progress Report - Technology Validation Sub-Program Overview*; Yang and Ogden (2007), "Determining the lowest-cost hydrogen delivery mode", *International Journal of Hydrogen Energy*, pp. 268-286.

For part 2: IEA data; Blum et al. (2014), "Overview on the Jülich SOFC development status", 11th European SOFC & SOE Forum, Lucerne; Decourt et al. (2014), *Hydrogen-Based Energy Conversion, More Than Storage: System Flexibility*; ETSAP (2014), *Hydrogen Production and Distribution*; IEA AFC IA (2015), *International Status of Molten Carbonate Fuel Cells Technology*; NREL (2009a), "Scenario development and analysis of hydrogen as a large-scale energy storage medium", RMEL Meeting; NREL (2010), *Molten Carbonate and Phosphoric Acid Stationary Fuel Cells: Overview and Gap Analysis*; NREL (2009b), *Scenario Development and Analysis of Hydrogen as a Large-Scale Energy Storage Medium*; Saur (2008), *Wind-To-Hydrogen Project: Electrolyzer Capital Cost Study*; Schaber, Steinke and Hamacher (2013), "Managing temporary oversupply from renewables efficiently: electricity storage versus energy sector coupling in Germany"; Stolzenburg et al. (2014), *Integration von Wind-Wasserstoff-Systemen in das Energiesystem – Abschlussbericht*; US DOE (2014b), *Hydrogen and Fuel Cells Program Record*; US DOE (2014d), *DOE Fuel Cell Technologies Office Record – Fuel Cell System Costs*; US DOE (2013), *Fuel Cell Technology Office Record - Onboard Type IV Compressed Hydrogen Storage Systems – Current Performance and Cost*.

10.3.2.3 Hydrogen refuelling infrastructure

Hydrogen fuel cell vehicles (FCVs) are reliant on the development of widespread and convenient refuelling infrastructure if they are to play more than a niche role in the transport sector. There are four main components of hydrogen refuelling infrastructure (see Figure 10.4):

1. Supply & Delivery: on-site hydrogen production versus off-site production
2. Compression: to achieve pressure required for economic stationery and vehicle storage
3. Storage: liquid versus gaseous
4. Dispensing: connection between hydrogen refueling station (HRS) and vehicle.

The technological and economic development of each of these components continues to be developed.

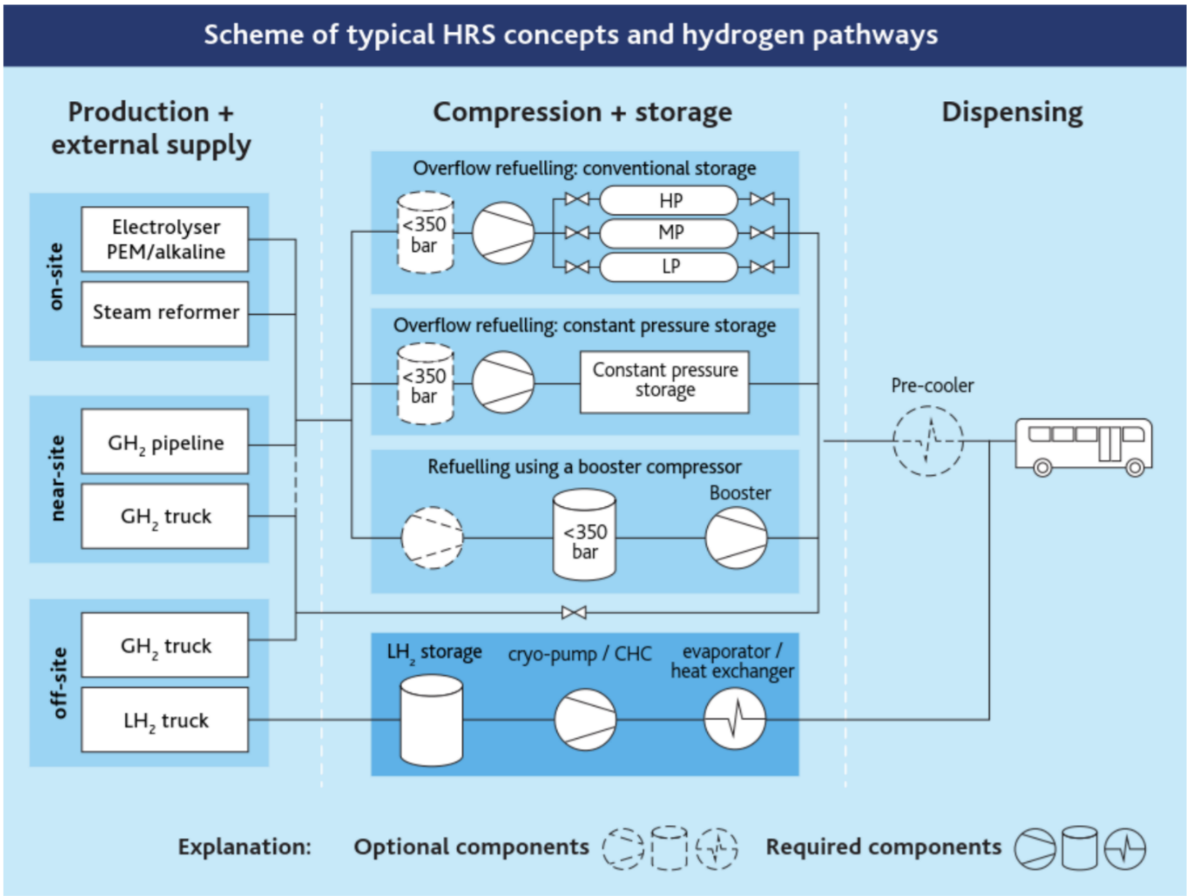


Figure 10.4 Schematic overview of typical hydrogen refuelling station components

Source: (FCHJU, 2017).

Most existing HRS globally today have been designed to refuel less than 250 kilograms of hydrogen per day, on average. This would be enough to support up to approximately 15 city buses. For FCVs to be a viable option in the future, HRS need to support the refuelling of several hundreds of vehicles per day, implying a fuel requirement of more than 1,500 kilograms per day.

A summary of HRS costs, compiled by ICCT, 2017, suggests that at a capacity of 600 kilograms of hydrogen per day, the capital cost (excluding on-site production capital costs) of a single HRS would be approximately $US1.8 million. An HRS producing 1,000 kg of hydrogen per day (100,000 kilometres in a light FCV), including on-site hydrogen generation, is expected to cost approximately EUR 16 million to construct (FCHJU, 2017) – see Figure 10.5. These costs do not include the maintenance and operating costs associated with a HRS of this capacity. Some argue that while HRS costs are high today, through improvements and an increase in production volumes, these costs may fall.

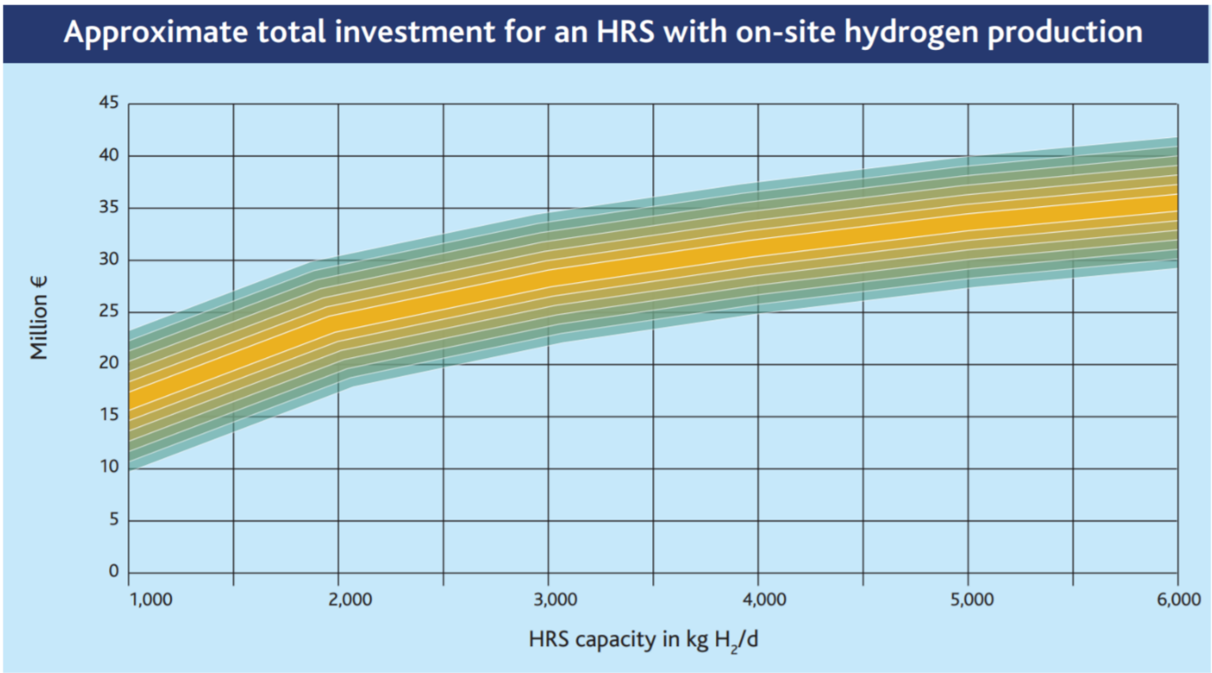


Figure 10.5 - Forecast of HRS costs, including on-site hydrogen production

(Source: FCHJU, 2017).

The dispensed cost of hydrogen is highly correlated with scale of production and the cost of electricity, when produced using water electrolysis. As outlined, and again shown in Figure 10.6, the economic competitiveness of hydrogen fuel cell vehicles is highly dependent on increased volume of production, as well as securing low-cost, ideally renewable electricity.

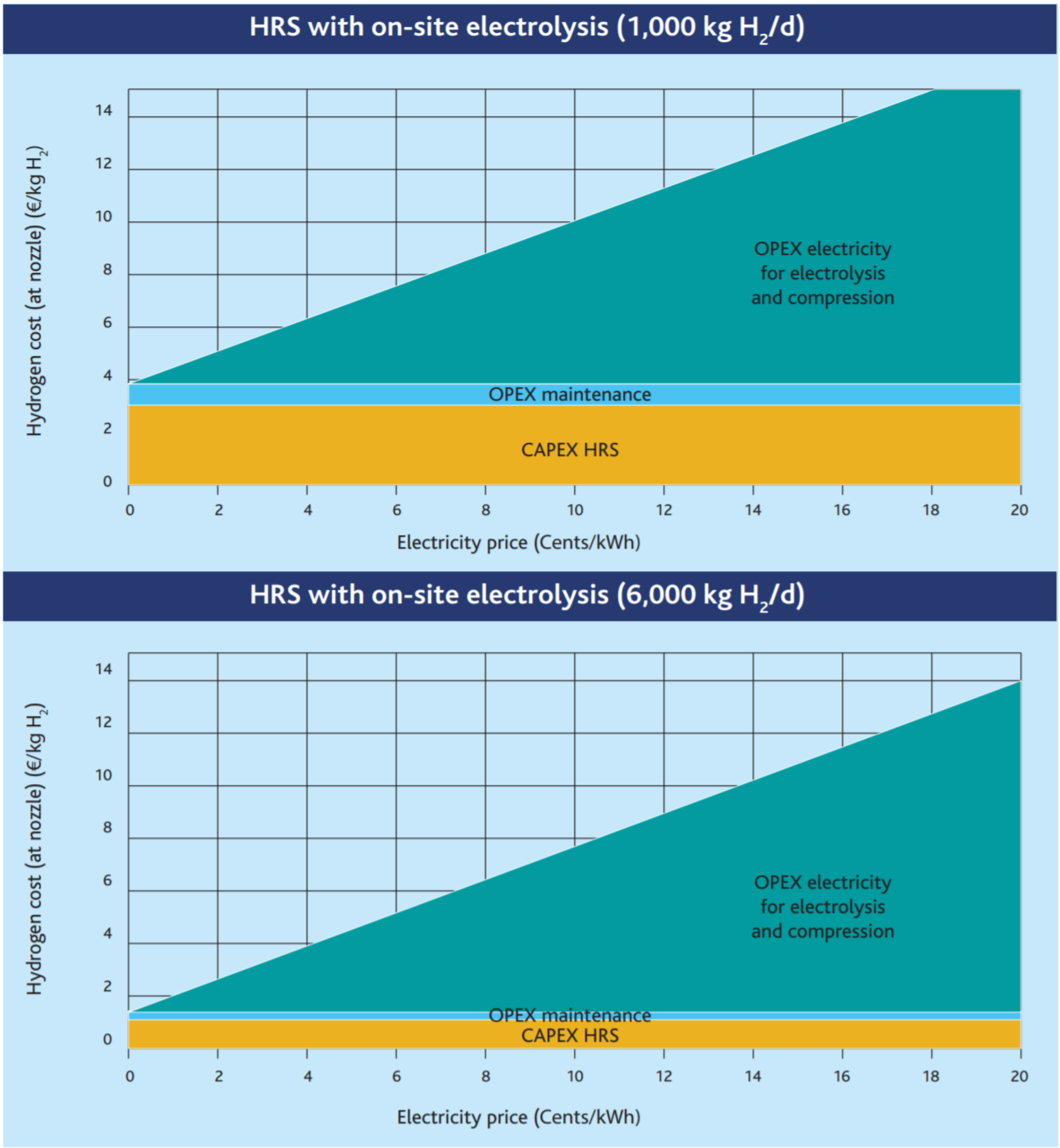


Figure 10.6 Modelled HRS capital, maintenance and operating costs when including on-site hydrogen production.

(Source: FCHJU, 2017).

Even with optimistic improvements in the future, the required capital investment in HRS for FCVs to become economically competitive, and convenient, will remain significant and will require strategic planning.

10.3.2.4 Future perspectives including key batteries

There are currently many barriers, including technology uncertainty, infrastructure system construction, public acceptance, to be overcome before hydrogen-powered transport can be realized in a commercial market (International Energy Agency 2019b).

How low-carbon hydrogen will compete in the future is unclear. This makes it difficult to compare potential future hydrogen prices with those of alternatives. In the case of fuel cells, the speed of cost reduction is a key factor, yet experts disagree on the relationship between the scale of fuel cell demand, cost and performance improvements (Cano et al, 2018).

Infrastructure, such as pipeline and delivery networks (which has higher capacity and longer transport distance than trailer pathways, see Table 10.5) is of particular importance for a new energy carrier such as hydrogen. In the case of hydrogen use for road transport, where a network of refuelling stations will be a precondition for widespread adoption of FCVs, the current pace of infrastructure development is one of the barriers to adoption. In some cases, these investments will also need to be co-ordinated across borders, requiring international collaboration at a level not yet seen for hydrogen.

Table 10.5 Qualitative overview of hydrogen T&D technologies for hydrogen delivery in the transport sector

	Capacity	***Transport 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

Source: Adapted from (International Energy Agency 2015)

Public acceptance must also be secured in order to create demand for FCV technology. Deployment of large-scale hydrogen infrastructure with carbon capture & storage (CCS) technology would be premature, as some of the key technical issues that are still being worked on, such as fuel cell operating conditions, hydrogen on-board storage options, and the safety risks of hydrogen usage may have a considerable impact on the choice of hydrogen production, distribution and refuelling (International Energy Agency, 2015) (Cristina Galassi et al., 2012) (van Biert, Godjevac, Visser, & Aravind, 2016).

There are also other challenges preventing the large-scale application of hydrogen in the transport sector. Issues include: the significant quantity of renewable energy that would be required for hydrogen production, being diverted away from other uses where emissions reductions maybe higher; water scarcity as hydrogen electrolysis, paired with renewables could deliver emissions reductions, but is both energy and water intensive and therefore will need to be used strategically; the significant volumes of energy also required to support the compression or liquefaction of hydrogen for delivery; and the environmental impacts of hydrogen fuel cells, in particular, the use of platinum as a catalyst in fuel cells, as well as carbon fibre in the hydrogen storage tanks (Elgowainy et al., 2018a) (Simons & Bauer, 2015a) (Lee, Elgowainy, Kotz, Vijayagopal, & Marcinkoski, 2018).

10.3.3 Biofuels

10.3.3.1 Climate mitigation potentials of biofuels

A broad understanding of the impacts on the climate associated with global biofuel deployment scenarios warrants the combination of a set of comprehensive modelling approaches (Andrews, Betts, Booth, Jones, & Jones, 2017; Davies-Barnard, Valdes, Singarayer, Pacifico, & Jones, 2014; Monier et al., 2018). There is broad agreement in the literature that the most important factors in determining the mitigation potential of biofuels are the land use and land use change characteristics associated with biofuel deployment scenarios, in addition to the life-cycle greenhouse gases emissions (e.g., Daioglou et al. 2017; Elshout et al. 2015). The land use characteristics can be separated into two main elements: i) what type of land use and land use change is associated with the different biofuel deployment scenarios, and ii) what are the climate forcings associated with these land use transitions, typically associated with biogeochemical and biogeophysical feedbacks.

From the Earth system model and regional climate modelling literature, we know that in order to understand the climate impacts of land use and land use change, we need models that encompass the full suite of biogeophysical and biogeochemical feedbacks associated with the land use and land use change as an interactive part of the climate system. Examples of such models include CESM (the Community Earth System Model of global resolution) Hurrel et.al. 2013, Gettelman et.al 2012)) and WRF (Weather Research and Forecasting regional model) (Skamarock.et al 2008; Warrach-Sagi et al. 2019). See Chapter 7 and 12 WGIII and Chapter 3,5,7 in WGI as well as the SRL for details.

The combination of land use models with integrated assessment modelling approaches provides insights that allows for comprehensive analysis ensuring consistency between land use to support scenarios for future demands of food, fibres and energy across the economic sectors (Daioglou, Doelman, Wicke, Faaij, & van Vuuren, 2019; Hanssen et al., 2019; Humpenöder et al., 2018; Popp et al., 2017; Roe et al., 2019; Stehfest et al., 2019; van Vuuren et al., 2017; Van Vuuren et al., 2018). A smaller segment of the literature concerns the unique combination of the latter type modelling with Earth system or reduced climate models (Monier et al. 2018; Hallgren et al. 2013; Davies-Barnard et al. 2014; Jones et al. 2015). This allows for state-of-the-art integrated analysis that captures both the full suite of climate forcings as well as cross sectoral demands for food, fibre and bioenergy and the related land use and land use change. This literature alert to the fact that biogeochemical and biogeophysical components of large-scale land use changes may have contrasted contribution to temperature and climate; and these effects may even compensate each other at global level. For example, the CO_2-induced (biogeochemical) temperature increase associated with historical land-use change is found to have the same order of magnitude to the globally-averaged biogeophysical cooling resultant from the same land-use change (Simmons & Matthews, 2016). Similarly, the impacts of large-scale biofuels expansion scenarios on climate are found to be negligible at the global scale (Hallgren et al., 2013) or even for some specific value chains when considering the combinations of biogeophysical and biogeochemical effects, e.g. (Caiazzo et al., 2014). However, these impacts are region dependent, and spatially differentiated mitigation strategies may therefore be advantageous. (Andrews et al., 2017; Davies-Barnard et al., 2014; Muri, 2018). For example, global land use strategies that protect tropical forests could dramatically reduce warming (Hallgren et al. 2013; Muri 2018, Sonntag et.al 2016), while middle latitude afforestation may lead to net warming due the large biogeophysical effect of decreasing albedo (Davies-Barnard et al., 2014). However, these climate implications from climate mitigation strategies should certainly be balanced against the other important co-benefits of forest for ecosystems and humans, including biodiversity, income generation, flood control, and improving soil, air and water quality must be considered (Gilroy et al., 2014; Griscom et al., 2017; A. B. Harper et al., 2018).

The outcomes of scenarios obtained using integrated assessment models (IAMs) indicate that non-negligible amounts of biofuels will be needed considering the different climate mitigation targets. Earth System Model Inter-comparison studies (Coupled Model Intercomparison Project, CMIP6), including for a range of anthropogenic and natural climate forcings as well as feedbacks for selected SSP reference scenarios will be discussed here.

The projected amounts of biofuels to be used in the transport sector vary across the future scenarios. However, since many biofuel options are easy to adapt and implement with existing technologies, they appear as an attractive climate mitigation option. The question how to prioritize, whatever amounts that may be produced in a sustainable manner towards different mitigation targets, is therefore in any case of relevance. In the following section we review the bottom up studies to see what insights the scientific literature offers in this regard.

10.3.3.2 Prioritization of biofuel use in transport sector

Projections form the oil industry indicate that the largest portion (about 90%) of the grow in the biofuels use at global level in the period up to 2040 will be used for road transport, followed by an small increase in the biofuel use in the aviation sector (BP, 2019). The literature evaluating the avoided life-cycle greenhouse gas emissions of biofuels substituting fossil fuel also identified road passenger transport as the use with highest mitigation potential. For example, an analysis addressing the optimal use of global bioenergy resources to offset fossil fuels has shown that biofuel offsetting light distillate liquid fossil fuels (e.g. gasoline, naphtha) have higher climate mitigation potential at global level in comparison to biofuels offsetting middle (e.g. kerosene, jet fuel, diesel) and heavy (e.g. heavy fuel oil) liquid distillate fossil fuels for different scenarios of biomass availability (Staples, Malina, & Barrett, 2017a). However, these results are subject of many methodological assumptions regarding biomass availability and readiness of conversion technologies. The authors indicate that an optimal deployment of bioenergy resources to maximize greenhouse gases reductions requires a mix of bioenergy end-uses and, notably, this mix consists of uses that are not necessarily the most effective, initially or on average, including drop-in middle distillate fuels such as aviation biofuels. Therefore, there is low agreement and low confidence in the optimal biomass allocation to substitute light distillate fossil fuels will deliver highest climate mitigation potential at global level, considering the energy demands from all the economic sectors.

When specific targets of climate change stabilization at low levels are considered, the use of biofuels for heavy transport, aviation and marine gain more prominence. For example, IEA stablished a set of global scenarios with different energy technology and policy pathways for a low-carbon energy system in the period up to 2060 (IEA, 2017). These scenarios consider the existing and planned energy and climate-related commitments by countries as well as the feasibility of accelerating clean energy technology deployment in pursuit of more ambitious climate goals, among other factors. Results indicate that biofuels will play a key role in the decarbonisation of long-haul transport modals, complementing measures aimed at constraining the sector's energy needs and the enhanced role of electrification and other measures in urban and other shorter-haul transport applications. Biofuels are expected to provide about 40% of aviation transport fuel in 2060, and 30% of fuel for shipping. However, the lack of a supportive regulatory environment for biofuels is identified as one of the barriers to their adoption in both aviation and marine transport (IEA, 2017). The new emission reduction targets stablished by aviation and shipping sectoral organizations may help to accelerate the adoption of biofuels in these transport modals (Hsieh & Felby, 2017; Scheelhaase, Maertens, Grimme, & Jung, 2018). Likewise, some oil industry scenarios for future energy demands aiming at achieving the Paris Agreement also project a rapid electrification of passenger vehicle fleet with increased biofuel use for shipping and aviation (Shell, 2018). Analyses addressing the future biofuel use projections of the energy demands under more stringent climate mitigation targets show high agreement and high confidence that biofuels will likely have key role for decarbonizing aviation, marine and heavy-duty transport.

The top-town analyses of SSP scenarios calculated using integrated assessment models (IAM) o indicate increasing importance in the use of biofuels for heavy road transport and aviation (van Vuuren et al., 2017). The projection for the transport system in the SSP scenarios shows a dominant position of electric and hydrogen-fuelled drive-trains in SSP1 in road transport. For aviation and heavy road transport, biofuels are the most important fuel option. Similar trends occur in the SSP2 and SSP3, but a smaller scale due relatively slower technology development is these scenarios (van Vuuren et al., 2017). In another example, (Rochedo et al., 2018) used an IAM developed for Brazil to explore different 2 °C compliant carbon emission scenarios related to alternative environmental governance in the country. Their finding support that a more stringent decarbonization scenario will require rapid electrification in the road passenger transport, complemented to higher use of biofuels to decarbonize freight transport and aviation, for which there are fewer alternatives available. Energy-dense liquid fuels are likely to remain the preferred energy source for long-distance transport services (Davis, Lewis, Shaner, Aggarwal, Arent, Azevedo, Benson, Bradley, Brouwer, & Chiang, 2018). Literature using IAMs to illustrate societal changes needed to achieve specific temperature stabilization targets have high agreement and high confidence that use of biofuels will be mostly needed for heavy transport and aviation. However, most of the policies regarding renewable liquid transport fuels have been geared towards the road transport sector, while mandates promoting the use of renewables for shipping and aviation transport have been lagging (Hsieh & Felby, 2017).

10.3.3.3 Biofuel conversion technologies and readiness levels

Many studies have addressed the life-cycle emission of biofuel conversion pathways for road, aviation and marine applications, e.g. (Robert Edwards et al., 2017; Staples, Malina, Suresh, Hileman, & Barrett, 2018a; Tanzer, Posada, Geraedts, & Ramírez, 2019). While some biofuels options such as ethanol from fermentation of sugars and biodiesel from oil crops have already achieved commercial scale in many countries, there has been slow technology development to produce biofuels derived from lignocellulosic feedstocks (Table 10.6).

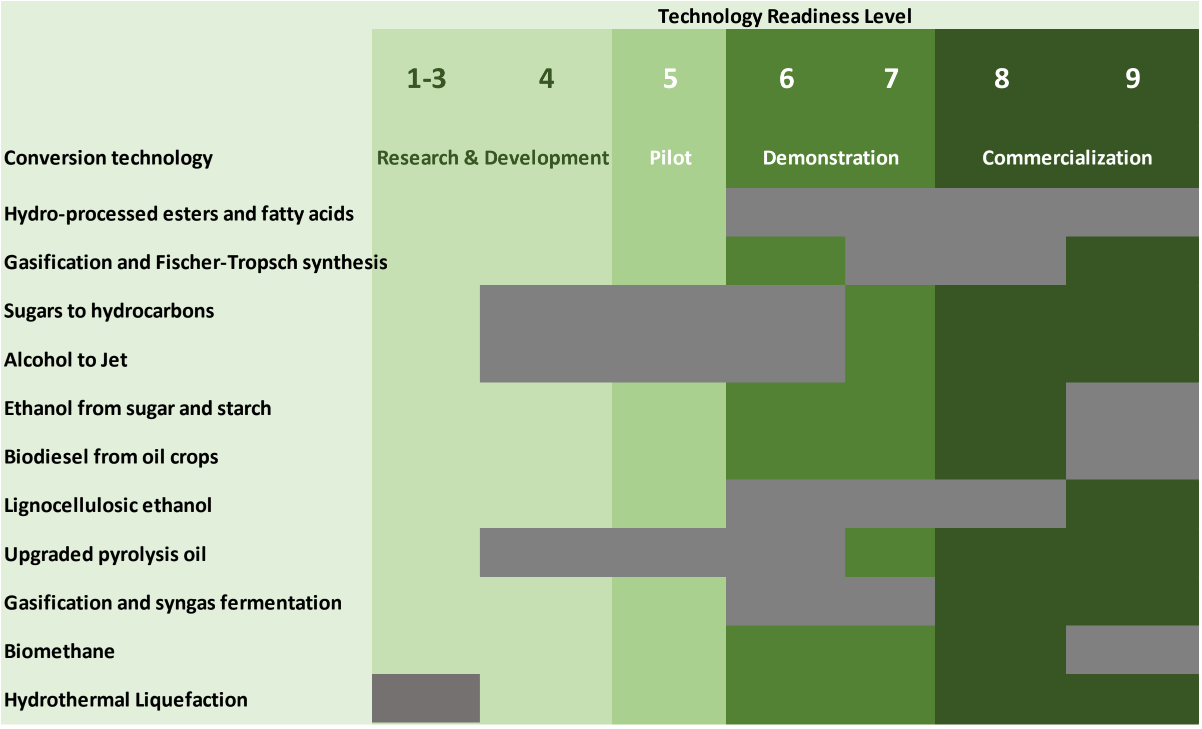
Table 10.6 Ranges of efficiency, GHG emissions and relative costs of selected biofuel conversion technologies for road, marine and aviation biofuels.

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

Source: [a]Calculated as liquid fuels output divided by energy in feedstock entering the conversion plant; [b](Olofsson, Barta, Börjesson, & Wallberg, 2017); [c](Robert Edwards et al., 2017); [d](Simell et al., 2014); [e](de Souza Dias et al., 2015); [f](Castanheira, Grisoli, Coelho, Anderi Da Silva, & Freire, 2015); [g](Tanzer et al., 2019); [h](Klein et al., 2018); [i](Narula, Davison, & Keller, 2017); [j](de Jong et al., 2017a); [k](Salman, Schwede, Thorin, & Yan, 2017); [l](Moreira, Gurgel, & Seabra, 2014).

Within the aviation sector there is optimism that jet fuels produced from biomass resources could offer a viable means to reduce emissions under the right policy circumstances. Despite the growing interest in aviation biofuels, both demand and production volumes remain negligible compared to conventional fossil aviation fuels. Nearly all flights powered by biofuels have been using fuels derived from vegetable oils and fats (Mawhood, Gazis, de Jong, Hoefnagels, & Slade, 2016). Although many technology routes for these biofuels are consolidated, the potential to scale-up of aviation biofuel volumes is severely restricted by the lack of low cost and sustainable feedstocks. Lignocellulosic feedstocks, however, are considered to have greater potential for production of sustainable and financially competitive RJF in many regions. In addition, production facilities involve significant capital investment and estimated levelized costs are typically more than twice the selling-price of conventional petroleum jet fuel, and in some cases (notably for vegetable oils), the price of the raw feedstock is already greater than that of the fossil jet fuel (Mawhood et al., 2016). Some promising technological routes for producing RJF from lignocellulosic feedstocks are below TRL 6 (pilot scale) with just a few players involved in the development of these technologies (Figure 10.7).

In comparison to the aviation sector, advances in technology deployment are not far behind for 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 extensive refining processes as road and aviation fuels. However, the use of biofuels in marine engines has only been tested at an experimental stage or in small-scale applications, leaving doubts about the scalability of the operations. In addition, having an abundant feedstock supply and reliable processing technologies to produce price-competitive biofuel at a large scale remains a challenge for the maritime sector (Hsieh & 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 maritime sector in large quantities, a wider initial introduction of biofuels in the sector is likely to depend upon increased environmental regulation of particulate and greenhouse gases emissions. 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-midterm future seems unlikely. Thus, much of the effort has been placed to develop biofuels compatible with diesel engines. So far, biodiesel blends of up to 20% look promising as it has been done in the road transport sector. Hydrotreated vegetable oil (HVO) is also a technically good alternative and is compatible with current engines and supply chain, but the introduction of multifuel engines may open market for ethanol fuels (Hsieh & Felby, 2017).



Technology Readiness Level	1-3	4	5	6	7	8	9
Conversion technology	Research & Development		Pilot	Demonstration		Commercialization	
Hydro-processed esters and fatty acids				▨	▨	▨	▨
Gasification and Fischer-Tropsch synthesis					▨	▨	
Sugars to hydrocarbons		▨	▨	▨			
Alcohol to Jet		▨	▨	▨			
Ethanol from sugar and starch							▨
Biodiesel from oil crops							▨
Lignocellulosic ethanol				▨	▨	▨	
Upgraded pyrolysis oil		▨	▨	▨			
Gasification and syngas fermentation				▨	▨		
Biomethane							▨
Hydrothermal Liquefaction	▨						

Figure 10.7 Commercialisation status of selected biofuels conversion technologies.

Source: Based on (IEA, 2017; Mawhood et al., 2016; Skeer, Boshell, & Ayuso, 2016)

10.3.4 Advanced internal combustion engines

Internal combustion engines (ICE) remain the dominant vehicle technology used for transport. In the medium-term, it is likely these engines will continue to account for a significant share of vehicles used worldwide. Research is thus ongoing to identify opportunities improve efficiency and reduce carbon emissions from ICE.

Two types of ICE are widely used around the world. Spark ignition engines, which typically run on gasoline, operate at break thermal efficiencies of 30-36% (Liu et al., 2018). Compression ignition engines, which typically run with diesel, can reach break thermal efficiencies of 40-47% (Liu et al., 2018). Current efficiencies represent improvements in ICE technologies. Indeed, a recent report suggests that the average fuel economy of new vehicles sold globally decreased by 2% between 2005 and 2017 (International Energy Agency (IEA), 2019). Figure 10.8 shows the average fuel economy of new registered light-duty vehicles (LDV) in select countries for which data are available between 2005 and 2017. The figure shows that the fuel economy has increased in all countries. However, the efficiency improvements diverged between countries and regions. Furthermore, these observed improvements in fuel economy of LDV fall short of the efficiency improvements required to reach a target fuel economy of 4.4 liters of gasoline equivalent (Lge) per 100 kilometers (km) set through the Global Fuel Economy Initiative (International Energy Agency (IEA), 2019).

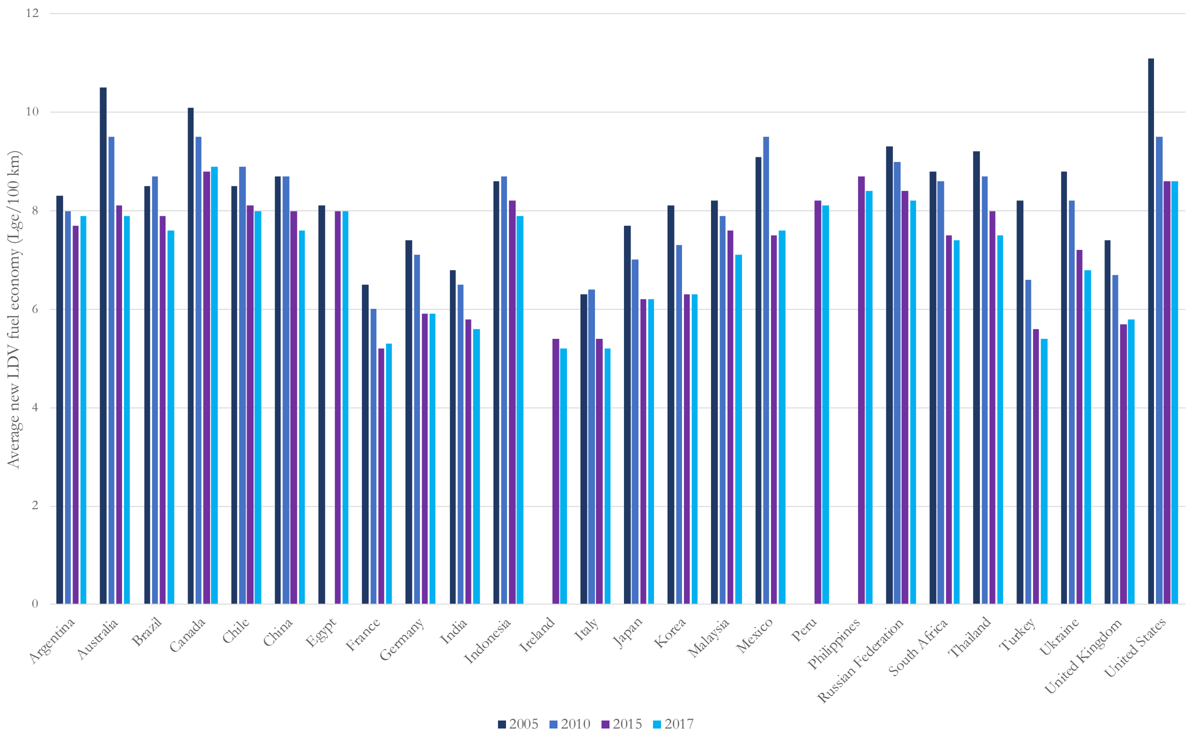


Figure 10.8 Average fuel economy of new LDV in 2005, 2010, 2015, and 2017

Source: (International Energy Agency (IEA), 2019)

Efficiency improvements in ICE for all vehicle applications (light-duty, heavy-duty, and rail) can be obtained via several strategies that include improvements in engines and transmission technologies, as well as changes in weight, aerodynamics, tires, and auxiliary power systems. 1.7 shows the efficiency gains of strategies available to improve the efficiency of a mid-size gasoline car and a mid-size diesel car. The figure also shows the direct costs associated with the deployment of these technologies. The figure highlights that existing technologies are available to increase the fuel efficiency of a mid-size ICE vehicle by up to 50% at costs below US$5,000 (National Research Council, 2015). Additional efficiency gains are possible through the use of improved transmission technologies (using a shift optimizer, for example), the use of electrified accessories technologies (electric power steering, for example), and hybridization technologies. Finally, mass reductions can also lead to fuel economy improvements. For example, a 25% reduction in the mass of a mid-size car could result in a 15% incremental fuel consumption reduction (National Research Council, 2015).

In addition to improving the efficiency of ICE, the use of alternative fuels in these engines could result in reduced carbon emissions. Alternative fuels to replace gasoline in spark ignition engines include liquified petroleum gases (LPG), compressed natural gas (CNG), liquified natural gas, alcohol fuels like methanol and ethanol produced from natural gas or biomass, or hydrogen produced from fossil fuels or through electrolysis (Bae & Kim, 2017; Brynolf, Taljegard, Grahn, & Hansson, 2018; Davis, Lewis, Shaner, Aggarwal, Arent, Azevedo, Benson, Bradley, Brouwer, Chiang, et al., 2018). Biodiesel and biomass-based alcohols could be used in compression ignition engines to replace diesel (Bae & Kim, 2017). Finally, synthetic hydrocarbons with characteristics similar to those of oil-based gasoline and diesel can be produced through the Fischer-Tropsch process using coal, natural gas, captured CO_2, or biomass (Brynolf et al., 2018; Chen et al., 2016b). Figure 10.9 shows the different production pathways for fuels that can be used in ICE. The carbon mitigation potential of these fuels varies significantly. Coal-based fuels, for example, would not provide emission reductions compared to petroleum-based fuels (Hao, Liu, Zhao, Du, & Chen, 2017; Kong, Dong, & Jiang, 2018; H. Zhou, Qian, Kraslawski, Yang, & Yang, 2017). The carbon reduction potential of natural gas-based fuels for use in ICEs is also limited (F. Tong, Jaramillo, & Azevedo, 2015; Fan Tong, Jaramillo, & Azevedo, 2015). Finally, there is significant variability in the emission reduction potential of bio-based fuels used in ICE depending on the feedstock used and production process. Section 10.4 includes a review of emission abatement potential and costs of different fuels.

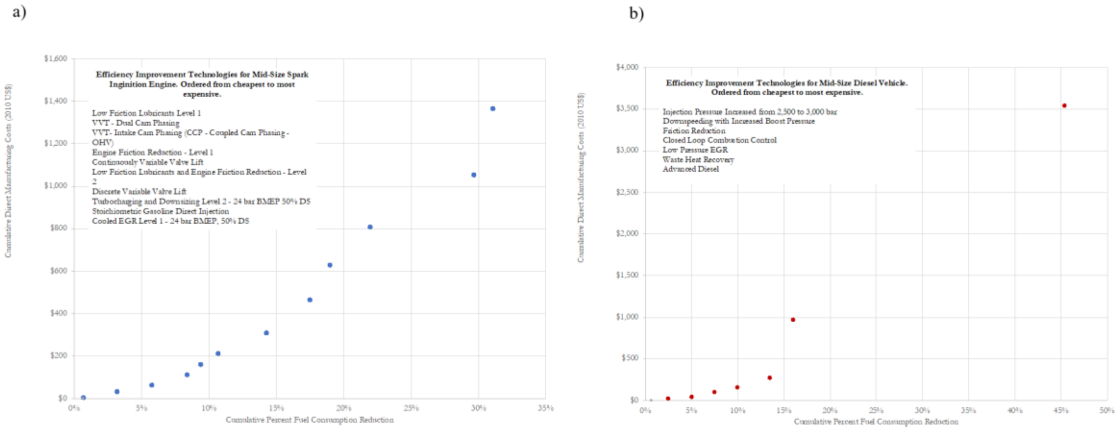


Figure 10.9 Cumulative fuel consumption reductions versus cumulative direct manufacturing costs of technologies to improve efficiency of an example mid-size gasoline vehicle (a) and an example mid-class diesel vehicle (b).

Source: : (National Research Council, 2015)

10.4 Decarbonization of land-based transport

Land-based transport is a crucial component of the global transport system. Land-based transport includes the movement of people (passenger transport) as well as the movement of goods (freight transport), as shown in Figure 10.10. Historically, petroleum-based fuels have been the primary source of energy for land-based transport. Gasoline and diesel, in particular, have been the major fuel used in light-duty vehicles, buses that provide passenger mobility, as well as medium-and-heavy duty truck and rail that provide freight services. Low carbon technologies for land-based transport of people and goods will be increasingly important to meet decarbonization goals, as demand for these services will continue to grow in the future. This section summarizes the state of the knowledge about low-carbon technologies for land-based transport. Specifically, this section includes information about the greenhouse gas emissions abatement potential, abatement cost, and feasibility of deploying these low-carbon technologies for land-based transport of people and goods.

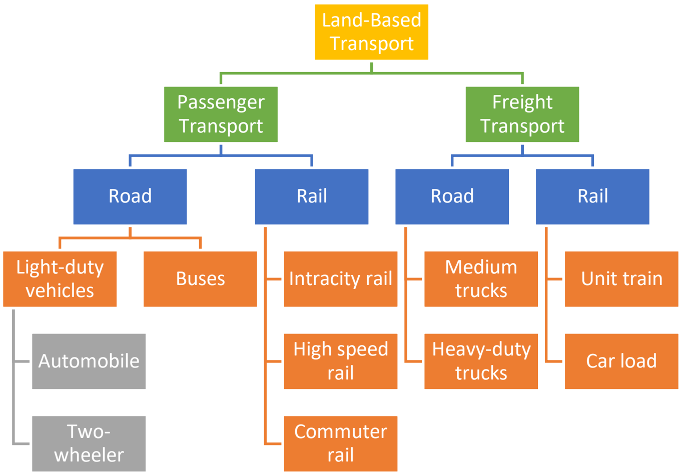


Figure 10.10 Motorized land-based transport options

10.4.1 Light-duty vehicles for passenger transport

Light duty vehicles (LDVs) represent the main mode of transport for private citizens, and currently represent the largest share of transport emissions globally (International Energy Agency, 2019b). Currently, powertrains depending on gasoline and diesel fuels remain the dominant technology in the LDV segment (International Energy Agency, 2019a). Hybrid electric and fully battery electric vehicles (BEVs), however, have become increasingly popular in recent years (IEA, Global EV Outlook 2019). Correspondingly, the number of life cycle assessment (LCA) studies investigating these and fuel cell electric 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 value chain, particularly for alternative powertrain technologies. LCAs also reveal the trade-offs of different types of environmental impacts. However, studies examining prospective climate performance of vehicles remains somewhat sparse.

Furthermore, a significant bulk of the studies reviewed rely on a select few studies that are based on primary data (Ellingsen, et.al 2016; Miotti et.al 2017; Evangelisti et al. 2017; Dai et al. 2018; Zackrisson, Avellán, and Orlenius 2010; Majeau-Bettez et.al 2011; Notter et al. 2015, 2010; Bauer et al. 2015; Kim et al. 2016; Simons and Bauer 2015).

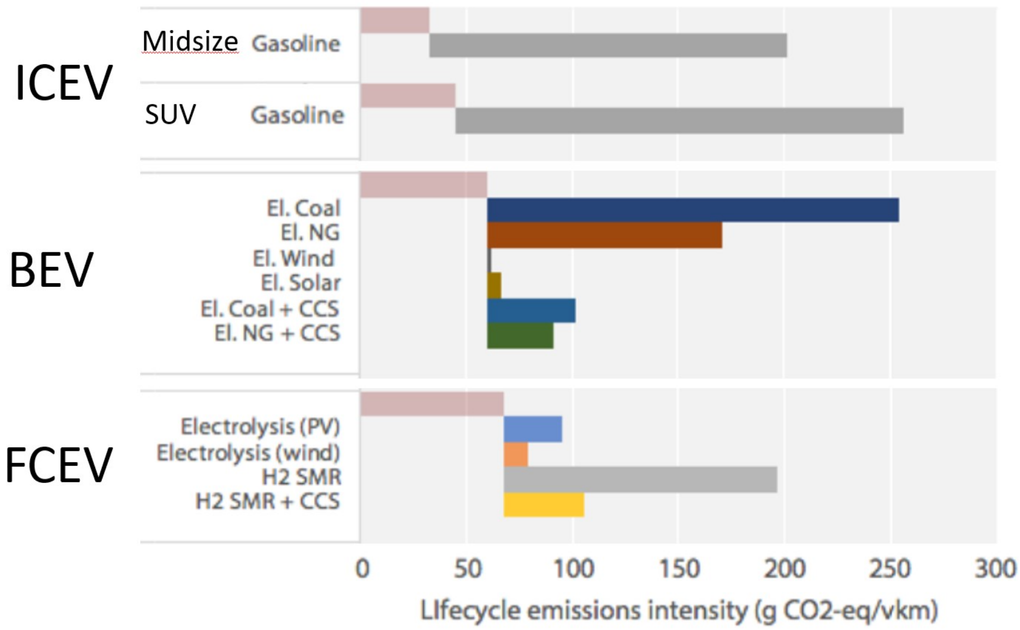


Figure 10.11 Life cycle greenhouse emissions for light-duty vehicle and fuel technologies. All emissions are presented in g CO_2-eq/vkm. Bars represent the median of the reviewed values. GHG life-cycle emissions are measured as intensity per vehicle-km driven, normalized over 180 000 km for LDVs

Figure 10.11 presents the life cycle emissions and mitigation costs for selected powertrain technologies and fuel chain combinations for light duty vehicles. The figures in the table and the section below are gathered from the academic literature and grey literature reviewed thus far (Bauer et al., 2015; Benajes, García, Monsalve-Serrano, & Martínez-Boggio, 2020; Cox & Mutel, 2018; Cusenza, Bobba, Ardente, Cellura, & Persio, 2019; de Souza et al., 2018; Elgowainy et al., 2018b; L. A. W. Ellingsen et al., 2016; Evangelisti et al., 2017; Hawkins, Singh, Majeau-Bettez, & Strømman, 2013; Hoque, Biswas, Mazhar, & Howard, 2019; Kim et al., 2016; Lombardi, Tribioli, Cozzolino, & Bella, 2017; Mercedes-Benz, 2013, 2015, 2018, 2019; Messagie, Boureima, Coosemans, Macharis, & Mierlo, 2014; Miotti et al., 2017; Rosenfeld, Lindorfer, & Fazeni-Fraisl, 2019; Wu et al., 2019). The vehicle manufacturing emissions (including disposal emissions for some studies) are presented separately from the fuel chain and tailpipe emissions (operation emissions). The tailpipe emissions and fuel consumption reported in the literature generally do not use empirical emissions data, nor the relatively newly developed World-harmonised Light Vehicles Test Cycles (WLTC), which is intended to more realistically represent actual driving conditions (Tsiakmakis et al., n.d.). Rather, they tend to report fuel efficiency from the New European Driving Cycle (NEDC) or analogous testing cycles. As a result, the operating emissions reported in literature are therefore likely somewhat underestimated in comparison to actual emissions (Tsiakmakis et al., n.d.). The extent of these underestimations, however, vary between powertrain types and engine sizes. Emissions from fossil fuel, hydrogen and electricity production in the operation phase are derived from (Acar & Dincer, 2014; Bhandari Ramchandra A4 - Trudewind, Clemens A. A4 - Zapp, Petra, 2014; Bicer & Dincer, 2017, 2018; Bruckner et al., 2014; Burmistrz, Chmielniak, Czepirski, & Gazda-Grzywacz, 2016; R Edwards, Larive, Rickeard, & Weindorf, 2013; Hake et al., 2017; Khojasteh Salkuyeh, Saville, & MacLean, 2017; Mehmeti, Angelis-Dimakis, Arampatzis, McPhail, & Ulgiati, 2018; Ozbilen, Dincer, & Rosen, 2013; Suleman, Dincer, & Agelin-Chaab, 2015).

Current average life cycle impacts of midsize ICEVs span from approximately 145 to 255 g CO_2-eq/vkm, while sport utility vehicles (SUVs) have life cycle emissions in the range of 180 – 370 g CO_2-eq/vkm. Regardless of the size, fuel consumption dominates the life cycle emissions of ICEVs, with approximately 80% of these emissions arising from the tailpipe and fuel chain. However, the trend towards increasing vehicle size and engine power within segments, and consumer preferences towards the larger SUV classes, would result in higher overall emissions from the LDV fleet (International Energy Agency, n.d.-b). On a global scale, SUV sales have been constantly growing in the last decade, with 39% of the vehicles sold in 2018 being SUVs (International Energy Agency, n.d.-b). The transition from smaller vehicles to SUVs, in turn, may lead to increases in the emissions intensity of LDV fleet due to the higher life cycle emissions of SUVs compared to smaller vehicles (International Energy Agency, n.d.-b). However, the trend towards bigger and heavier vehicles, with consequently higher use phase emissions, can be offset by improvements in powertrain design, fuel efficiency, light weighting and aerodynamics (Gargoloff et al., 2018). Alternative fuels such as those described in 10.3.7 may also provide some mitigation potential for ICEVs.

There is an increasing trend for light weighting using advanced materials such as high-strength steel, aluminium, carbon fibre and polymer composites (Hottle, Caffrey, McDonald, & Dodder, 2017). These materials reduce the mass of the vehicle and thereby the fuel or energy consumption required to drive. Light weighted components often have higher production emissions than the components they replace due to these advanced materials, however, the reduced fuel consumption over the life cycle of the light weighted vehicle provides a net mitigation effect in comparison to the non-light weighted vehicle (Hottle et al., 2017; Kim & Wallington, 2013). In addition, these advanced materials may be challenging to recycle while maintaining their high technical performance (Meng, McKechnie, Turner, Wong, & Pickering, 2017).

Hybrid (HEVs) and plug-in hybrid electric vehicles (PHEVs) vary in terms of degree of powertrain electrification. HEVs mainly rely on regenerative braking for charging the battery. On the other hand, 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-dependent, and for PHEVs, on the source of the electricity for charging. Generally, life cycle emissions intensity will lie somewhat between that of equivalently sized ICEVs and BEVs charged with the same electricity mix, although their production impacts are comparable to the emissions generated for producing ICEVs. Current HEVs may help reducing the emissions of ICEVs of about 9-20%, yielding life cycle intensities varying between 115 and 235 g CO_2-eq/vkm. The GHG emissions of PHEVs, on the other hand, range between 25 and 315g CO_2-eq/vkm with 100% electric driving and electricity produced from wind and coal, respectively. 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. HEVs and PHEVs are the most sold class of electric vehicles, due to life cycle costs comparable to equivalently sized ICEVs (International Energy Agency, 2019a). Because HEVs cannot harness low-carbon energy carriers, they offer limited mitigation opportunities. In contrast, PHEVs have greater opportunities to reduce the use phase emissions, due to the possibility of charging the battery with low-carbon electricity and the ability to drive in full-electric mode for longer distances. However, driving patterns, consumer behaviour and access to renewable electricity for charging strongly affect the total operational impacts (Wu et al., 2019).

Currently, BEVs have higher manufacturing emissions than equivalently sized ICEVs, with 7 – 16 t CO_2-eq/vkm against approximately 3.5 - 7 t CO_2-eq/vkm of their mid-sized fossil-fuelled counterparts. The higher current-day production emissions of BEVs are largely attributed to the battery cell manufacture, which is currently performed in countries with relatively carbon-intensive electricity (L. A.-W. Ellingsen et al., 2014; Kim et al., 2016). As a result, the production emissions of BEVs are sensitive to the energy capacity of the battery, as illustrated by the larger range of production emissions intensity over ICEVs. 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 wide variety of energy sources available today, BEVs have a wide range of potential life cycle impacts, ranging roughly between 20 to 355 g CO_2-eq/vkm with electricity generated from wind and coal, respectively. The highest mitigation effects are achieved when charging the battery with electricity generated through low-carbon energy sources. Operational phase impacts of BEVs charged with low-carbon technologies can range from 2 to 10 g CO_2-eq/vkm, for wind and solar respectively. Due to the lack of tailpipe emissions, BEVs reduce the amount of local air pollutants that are responsible for human health complications, particularly in densely populated areas (Hawkins, Singh, Majeau-Bettez, et al., 2013; Ke, Zhang, He, Wu, & Hao, 2017). State-of-the-art lithium ion batteries contain graphite and cobalt, which are listed as EU critical materials and may have associated supply risks (EC—European Commission, 2017). Of the materials in traction batteries, only cobalt, copper, aluminum and nickel are actively recovered in the recycling process (as of today), whereas lithium is not always recovered due to lacking economic incentives under current conditions (Hache, Seck, Simoen, Bonnet, & Carcanague, 2019; Zeng, Li, & Singh, 2014). Future battery chemistries may achieve lower costs, higher power and energy densities, leading to decreased battery mass, making vehicles lighter and consequently decrease the energy required for driving (Cano et al., 2018). Furthermore, potential cobalt-free technologies might reduce production cost and the mass of critical materials employed in BEVs. Additionally, as the technology develops, the lifetime of batteries, and consequentially BEVs, may increase. This in turn, would reduce the life cycle emissions intensity (g CO_2-eq/vkm).

As with BEVs, current fuel cell electric vehicles (FCEVs) have higher production emissions than similarly sized ICEVs and BEVs, generating approximately 6.5 – 16 t CO_2-eq/vkm. Since water vapour is the only tailpipe emission generated during the FCEV use phase, the hydrogen fuel chain is the only factor influencing the operational phase impacts of the technology. FCEVs can therefore reduce the local air pollution issues caused by ICEVs. To date, the most common method of hydrogen production is steam methane reforming from natural gas, which is relatively carbon intensive, producing approximately 130 g CO_2-eq/vkm. Current literature covering life cycle impacts of the FCEVs 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 production pathways for hydrogen are the use of electrolysis with electricity either produced with solar (27 g CO_2-eq/vkm) or wind (12 g CO_2-eq/vkm). Compared to ICEVs and BEVs, FCEVs are at a lower technology readiness level. Current R&D efforts aim to reduce platinum usage to the same levels as ICEVs (approximately 12 g/car), longevity of the vehicles and cost reduction (Pollet, Kocha, & Staffell, 2019).

Two-wheelers, consisting mainly of lower-powered mopeds and higher-powered motorcycles, are popular for personal transport in densely populated cities. Studies performing LCAs for this class of vehicles are uncommon in contrast to LDVs. We see, however, that the results available for two-wheelers exhibit similar trends for the different powertrain technologies as the LDVs, with electric powertrains having higher production emissions, but generally lower operating emissions, depending on the fuel chain. Life cycle emissions intensity for two-wheelers is also generally lower than LDVs on a vehicle-kilometer basis, however, generally have less carrying capabilities than LDVs, so this may change on a passenger-kilometer basis.

Current policies focus on reducing tailpipe emissions, however as alternative powertrains gain popularity, considering the emissions from the entire life cycle, including vehicle manufacturing and fuel production, will become increasingly important. Advanced ICEV, HEV and PHEV technologies powered by fossil fuels have limited potential for further reduction of GHG emissions. The mitigation potential of battery- and fuel cell vehicles is strongly dependent on the carbon intensity of their production and the energy sources fueling operation. Consequently, BEVs and FCEVs have no or low climate mitigation effects when carbon intensive energy is used in production and operation phases. In contrast, using low-carbon energy sources in manufacturing and operation maximizes the high climate mitigation potentials of these powertrain technologies.

10.4.2 Transit technologies for passenger transport

Buses provide urban and peri-urban transport services to millions of people around the world. Historically, buses have been powered with diesel fuel. However, a growing number of transport agencies around the world are exploring alternative-fueled buses. Alternative technologies to conventional diesel-powered buses include diesel hybrid-electric buses; buses powered with compressed natural gas (CNG), biodiesel, ethanol, dimethyl ether, and propane; battery electric buses; hydrogen fuel cell electric buses; and hydrogen fuel cell hybrid buses.

Passenger rail is another alternative mode of passenger transport that could support decarbonization of land-based passenger mobility consistent with strong climate mitigation targets. Rail systems can provide urban services (metro systems), as well as longer distance transport. Rapid increases in metro rail have occurred in Asian cities (Asian Development Bank, 2018) (Asian Development Bank, 2019) following Japanese and European robust inter-city and intra-city railway networks (Glazebrook & Newman, 2018). Metro systems around the world typically use electric regenerative braking for greater efficiency. Recent work suggests alternative propulsion systems like electric battery multiple units and fuel cell multiple units could become more useful in intra-urban connector services (Peter Newman et al., 2019). Intercity rail transport is increasingly powered with electricity, however, diesel is still prevalent for long-distance rail freight transport.

The carbon abatement potential, abatement costs, and technology readiness for these buses and passenger rail differ. For example, buses powered with compressed natural gas would have higher life cycle carbon emissions than battery electric vehicles charged with low carbon electricity. However, the life cycle cost of CNG buses is currently lower than the life cycle costs of battery electric buses. Future changes in technology readiness and economies of scale could change the cost differential of these bus types. Similarly, robust inter-city rail networks could offer opportunities to replace long-distance bus transport with electric locomotives.

Placeholder- In the second order draft, this section will include a summary of the life cycle greenhouse gas emissions, mitigation costs, and feasibility of motorized options for passenger transit.

10.4.3 Land-based freight transport

Medium and heavy-duty trucks are a crucial mode for the inland movement of goods. Diesel fuel has been the traditional fuel used to power these trucks, but there is growing interest in alternative fuels that could reduce greenhouse gas emissions. In the U.S. for example, there has been growing interest in using natural gas-based fuels for medium and heavy-duty trucks. Specifically, natural gas could be used directly as CNG or liquified natural gas, or it could be used to generate electricity or to produce hydrogen that could then fuel the trucks. However, natural gas-based fuels may not lead to drastic reductions in greenhouse gas emissions compared to diesel. Decarbonization of medium and heavy-duty trucks would likely require the use of low-carbon electricity in battery-electric trucks, low-carbon hydrogen in fuel-cell trucks, or bio-based fuels used in trucks with internal combustion engines(Fan Tong et al., 2015).

Freight rail is also a major mode for the inland movement of goods. Trains are more energy efficient (on the basis of tonne-km) than trucks, so expanded use of rail system (particularly in developing countries where demand for goods could explode) could provide carbon abatement opportunities. While diesel-based locomotives are still the major propulsion used in freight rail, interest in low-carbon propulsion technologies is growing. Such technologies may include biofuels, natural gas, electricity, or hydrogen.

Figure 10.12 presents a review of life cycle greenhouse gas (GHG) emissions from land-based freight technologies (heavy and medium-duty truck, and rail), as reported in recent literature (since 2015). Each panel within the figure represents data in GHG emissions per ton-km 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 (Cai, Burnham, Chen, & Wang, 2017; Cooper, Hawkes, & Balcombe, 2019; Lajevardi, Axsen, & Crawford, 2018; Mojtaba Lajevardi, Axsen, & Crawford, 2019; Nahlik, Kaehr, Chester, Horvath, & Taptich, 2016; Otten, Hoen, & Boer, 2016; Quiros, Smith, Thiruvengadam, Huai, & Hu, 2017; Quiros et al., 2016; Rupp et al., 2018; H. Song, Ou, Yuan, Yu, & Wang, 2017; Taptich, Horvath, & Chester, 2016b). The black square markers correspond to data from studies that only report deterministic life cycle GHG emissions for different technology/fuel categories, while the red bars represent similar data from studies that report a range (minimum and maximum) instead of a single value. Results from multiple studies are reported in each panel causing some overlap of the ranges (i.e. bars) reported for a single technology/fuel type. The dark red areas on the bars represent this overlap. Placeholder-*In the second order draft, we will expand Figure 10.12 to include information about mitigation costs and feasibility indicators for each of these vehicle/fuel technologies.*

There are some caveats to the life cycle greenhouse gas emissions values reported in this figure. Some of the values in the figure were taken directly from the papers reviewed. Other papers did not include final values in the appropriate functional unit (tonne-km). We thus made some conversions based on other values obtained from the paper. Finally, none of the values reported in the figure have been harmonized for consistency in assumptions. To address biases resulting from different assumptions, 10.12 shows percentage reductions in emissions for each vehicle/fuel combination. These reductions were calculated separately for each value from the literature based on the baseline emissions reported in the corresponding paper for conventional diesel technologies. The figure only includes data for medium and heavy-duty trucks as there wasn’t enough data available in the papers reviewed for freight rail. As in Figure 10.12, the black square markers correspond to data from studies that only report deterministic life cycle GHG emissions for different technology/fuel categories, while the red bars represent similar data from studies that report a range (minimum and maximum) instead of a single value. Results from multiple studies are reported in each panel causing some overlap of the ranges (i.e. bars) reported for a single technology/fuel type. Not surprisingly, the literature suggests that electric vehicles and hydrogen vehicles would provide the greatest reductions in the life cycle greenhouse gas emissions of land-based freight compared to freight vehicles powered with conventional diesel today.

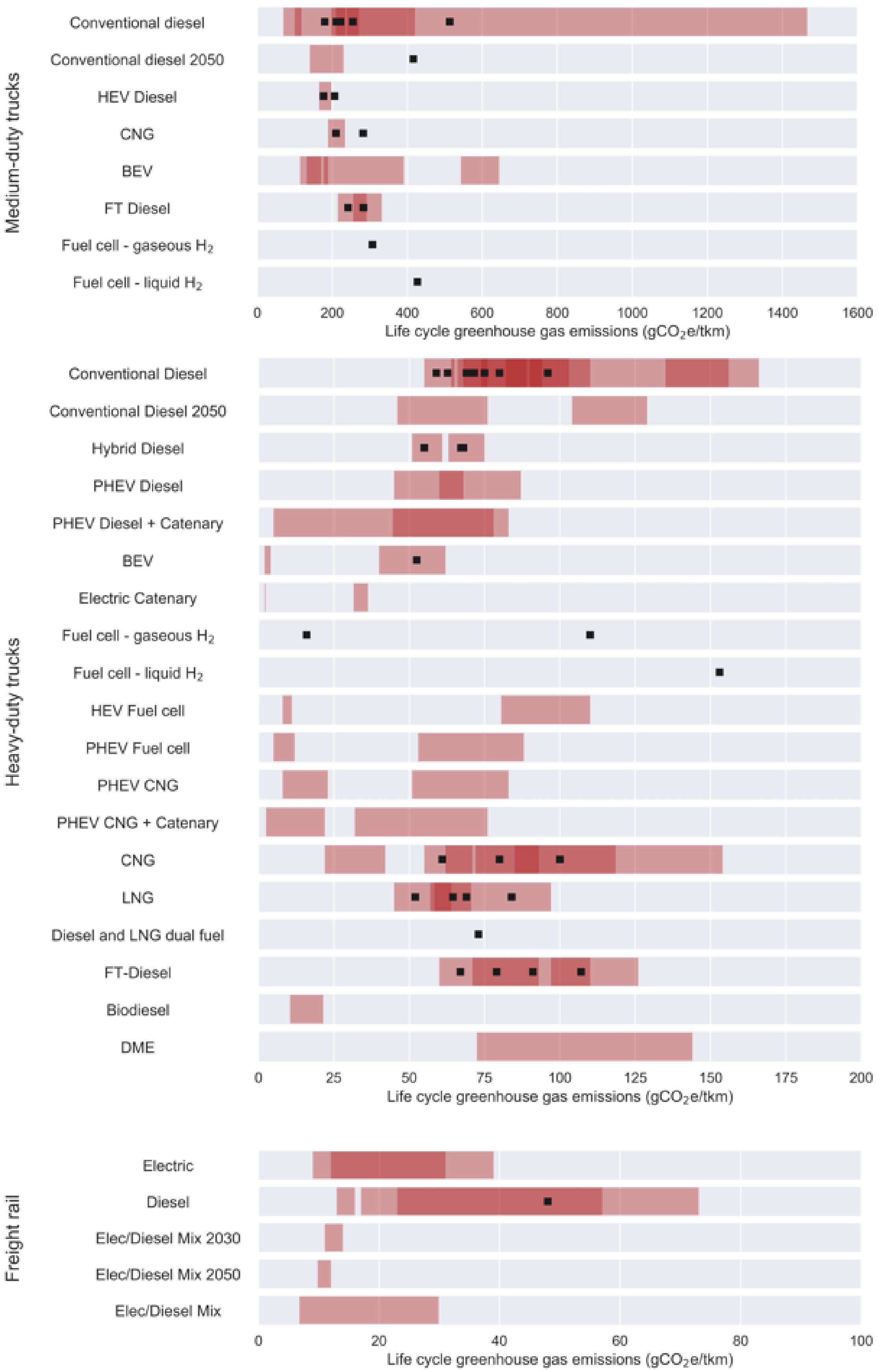


Figure 10.12 Life cycle greenhouse emissions for land-based freight technologies from the literature. Each panel within the figure represents data in GHG emissions per ton-km of freight transported by different

technology and/or fuel types, as indicated by the labels to the left. Note that the scale in the x-axis in the three panels is different.

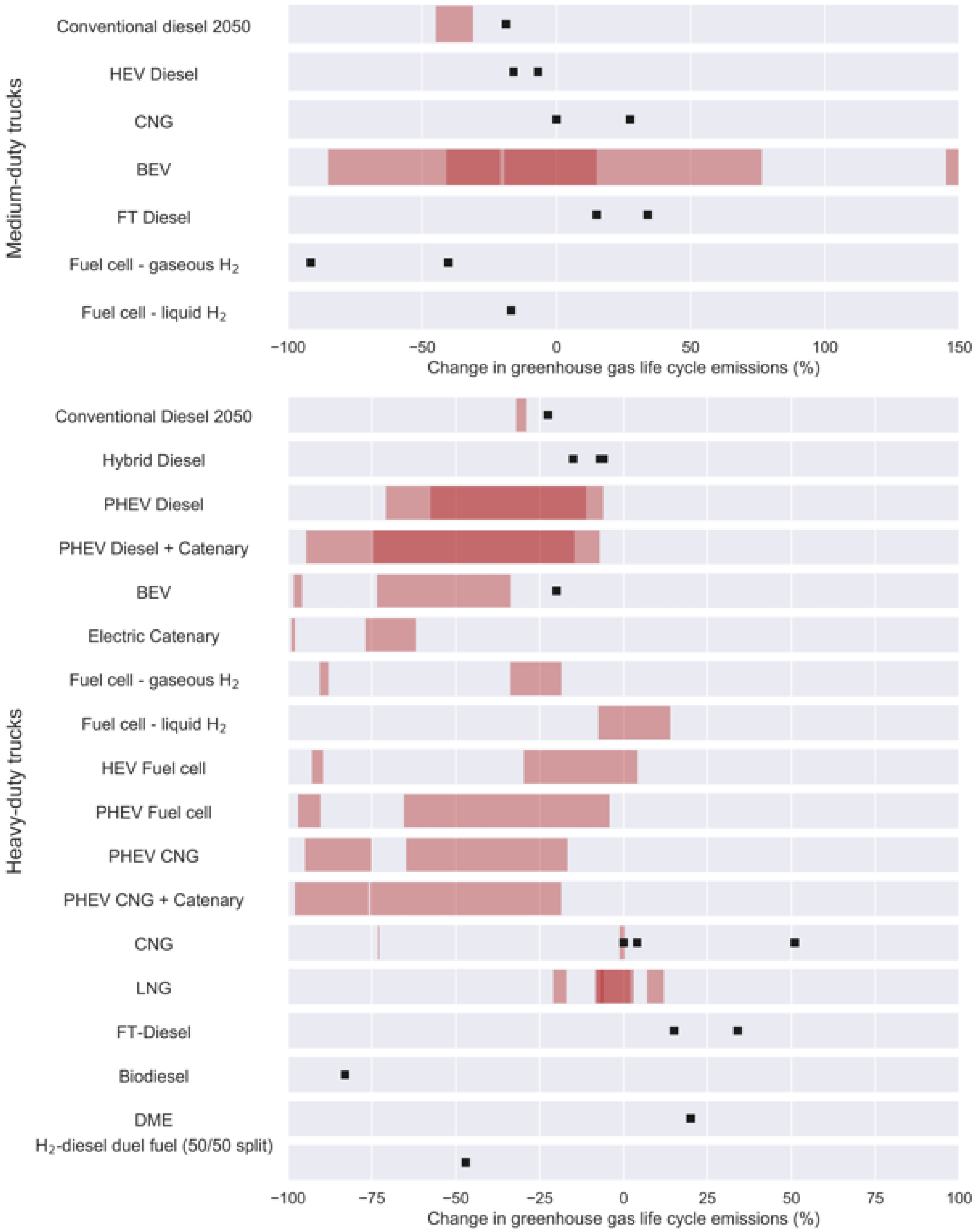


Figure 10.13 Life cycle greenhouse gas (GHG) emissions reduction potential from land-based freight technologies and fuel types, as reported in recent literature (since 2015). Each panel within the figure represents data in % reduction in GHG emissions compared to conventional diesel, per ton-km of freight transported by different technology and/or fuel types, as indicated by the labels to the left.

10.4.4 Conclusions

This section summarized the state-of-the-knowledge about the life cycle greenhouse gas emissions of such vehicle technology and fuels for light-duty passenger transport, transit technologies for passenger transport, and land-based freight. There is a relatively large variety of low-carbon technologies and fuels for light-duty vehicles, which have been widely documents in the life cycle analysis (LCA) literature. Of the available technologies and fuels, vehicle electrification offered the greatest opportunity for decarbonization of personal passenger transport. Indeed, as noted in section 10.3, electric light-duty vehicles are gaining market share. Furthermore, the integrated assessment models and global transport models reviewed in section 10.7 also show the market share of electric vehicles growing in the most ambitious climate stabilization scenarios. However, vehicle electrification will only provide carbon mitigation benefits in so far electricity generation transitions to low-carbon technologies.

As noted earlier in the Chapter, modal shifts from passenger vehicles to transit systems could improve the efficiency of passenger mobility and support decarbonization efforts. Diesel fuel has been the dominant fuel used in buses. Increasingly, municipalities throughout the world are showing interest in hybrid-electric or battery-electric buses. Natural gas-based fuels could also provide some carbon benefits relative to diesel-powered buses, but these technologies will not lead to deep decarbonization of the bus fleets. Urban and peri-urban rail can also benefit from electrification.

The technological choices for decarbonizing freight transport are more limited than for passenger transport. Electrification of medium and heavy-duty trucks is an option, but there are still challenges associate with technology and infrastructure (Çabukoglu, Georges, Küng, Pareschi, & Boulouchos, 2018). Electrolytic hydrogen could also support decarbonization of truck-based freight transport. Hydrogen as a fuel is likely more viable for freight applications than for passenger vehicles (Moriarty & Honnery., 2019). Rail transport is an important mode for the movement of goods and less research about low-carbon technologies is available in the LCA literature for freight rail. Some of the work reviewed in this section suggests electrification of freight rail may be an option, but some of the technical challenges for electric trucks are also a concern for electric freight rail. Technological innovations are likely needed to enable deep decarbonization of freight transport.

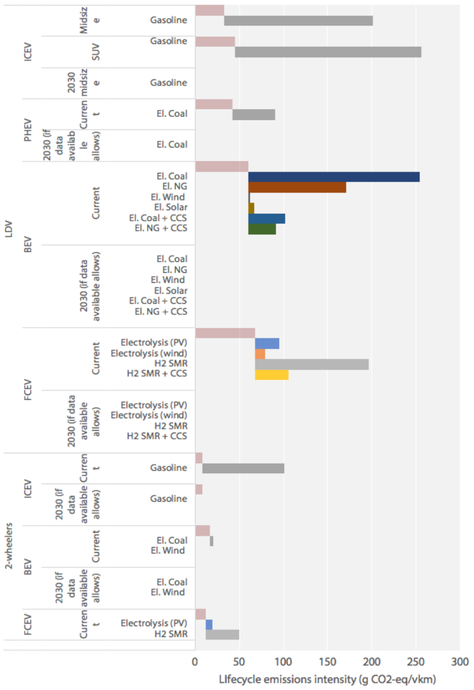
Finally, the LCA literature reviewed in this section focused on technologies that can support decarbonization of land-based transport. Other, non-technical strategies may also support efficiency gains and decarbonization of this transport sector. Section 10.2, for example, includes a discussion of systemic changes that would affect the carbon intensity of land-based transport. Other strategies not discussed in section 10.2 that may be of particular relevance for land-based transport include logistic optimization of freight as well as shared transport of passengers and goods (Beirigo, Schulte, & Negenborn, 2018; Gatta, Marcucci, Nigro, Patella, & Serafini, 2018; Masson et al., 2017; Pimentel & Alvelos, 2018; Serafini, Nigro, Gatta, & Marcucci, 2018). Placeholder-*In the SOD we will aim to include mitigation potential, abatement costs, and feasibility of these strategies.*

Placeholder-In the SOD this summary will also include a discussion about abatement costs and feasibility for low-carbon technologies for freight transport.

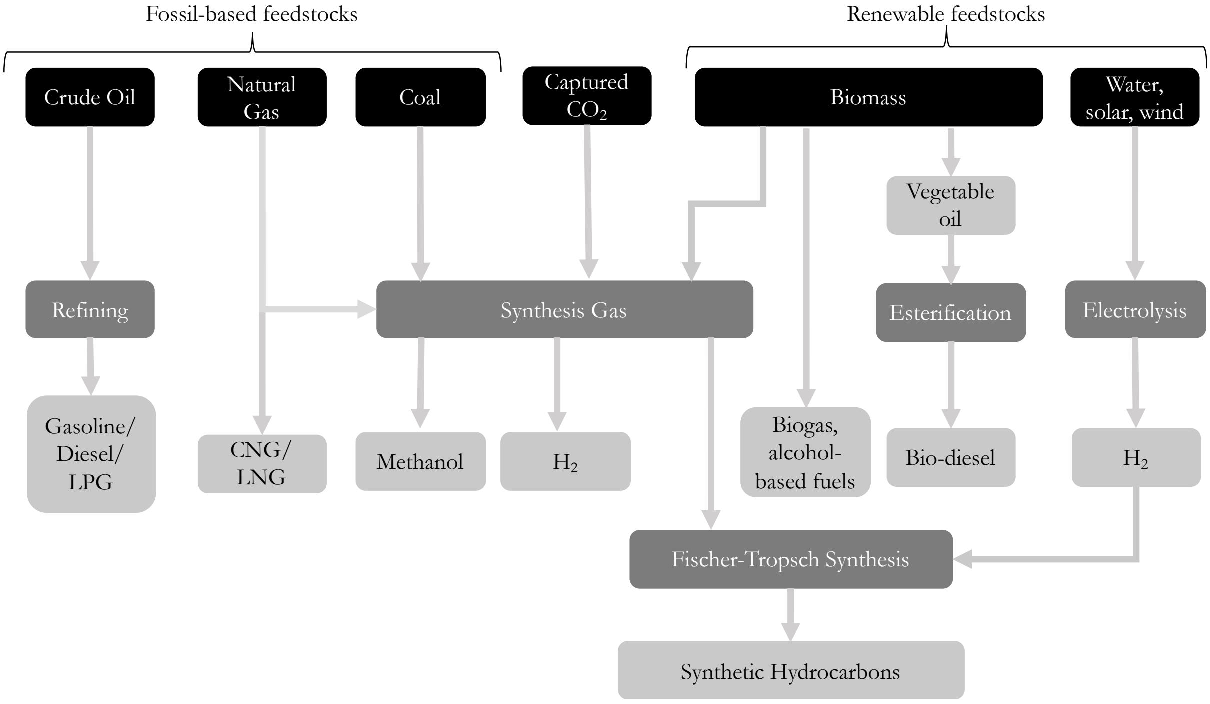
-Throughout the text for this section we have pointed out additional text we will add for the SOD. In particular, we aim to include a detailed review of the carbon abatement costs of the technologies/fuels included in the section. Additionally, the SOD will include a detailed discussion about the feasibility of these technologies. To synthetize such information, we propose to modify the figures included in this FOD following the example Table 10.7 below.

1 **Placeholder for SOD-Table 100.7 WGIII contribution to AR6 cycle Caption above the table**

2 **Placeholder for SOD-Table 10.7 Proposed structure for summarizing carbon intensity, mitigation cost,**
3 **and feasibility of land-based transport technologies in SOD**

Life Cycle Carbon Intensity (g CO_2-eq/vkm)	**Mitigation cost (US\$2015/t CO_2)**	**Feasibility (Work in progress)**	
		Adaptation indicators	**Mitigation indicators**
		**ICEVs (diesel and gasoline):** ↑ Micro- and Macro-economic viability; Technical resource availability ↓ Risks mitigation potential; Social co-benefits **HEVs:** ↑ Micro- and Macro-economic viability; Technical resource availability ↓ Risks mitigation potential; **BEVs:** ↑ Micro- and Macro-economic viability; Technical resource availability ↓ Technical resource availability; **FCEVs:** ↑ Social co-benefits; Physical feasibility; Risks mitigation potential; Social co-benefits ↓ Technical resource availability; Micro- and Macro- economic viability	**ICEVs (diesel and gasoline):** ↑ Cost-effectiveness; Technical scalability; Maturity; Global spread ↓ Social co-benefits, Reduction of air pollution, Improved biodiversity **HEVs:** ↑ Maturity; Technical scalability; ↓ Risks mitigation potential; Social co-benefits **BEVs:** ↑ Maturity; Technical scalability; Legal & administrative feasibility; Social co-benefits; Reduction of air pollution ↓ Limited use of scarce (geo)physical resources **FCEVs:** ↑ Reduction of air pollution; Technical scalability; Social co-benefits ↓ Cost-effectiveness; Maturity;

4



5

6 **Figure 10.14 Alternative fuel pathways for Internal Combustion Engines**

7 *Notes: Black boxes represent feedstocks. Dark grey boxes represent production processes. Light grey*
8 *boxes represent final products.*

10.5 Decarbonization of aviation

Aviation is widely recognized as a 'hard-to-decarbonize' sector (Sudhir Gota, Huizenga, Peet, Medimorec, & Bakker, 2019c) (Committee on Climate Change, 2019) having a high dependency on liquid fossil fuels and an operational and technology infrastructure that has long 'lock-in' timescales, resulting in slow fleet turnover times and long technology development timescales. Alternative lower-carbon footprint fuels have been certified for usage over recent years, principally from bio-feedstocks but are not yet widely available at economic prices yet (Kandaramath Hari, Yaakob, & Binitha, 2015). In addition, alternative fuels from bio-feedstocks have variable carbon footprints because of different life-cycle emissions associated with different production methods and associated land-use change (de Jong et al., 2017b) (Staples, Malina, Suresh, Hileman, & Barrett, 2018b) (Witcover, Yeh, & Sperling, 2013) (Staples, Malina, & Barrett, 2017b) – see section 10.3.3. The complex options emerging will be reviewed.

10.5.1 Historical and current emissions from aviation

The principal greenhouse gas from aviation is CO_2, although aviation has a number of other effects on climate through its non-CO_2 emissions (see section xx). Emissions of CO_2 are calculated under UNFCCC reporting requirements as being either domestic or international; however, a number of methodologies are used by states according to facilities and data availability such that the global data are less reliable for assessment purposes. The International Civil Aviation Organization (ICAO) emissions estimation uses more complex greenhouse gas emissions models (tier 3 models, IPCC, 2006) and datasets of real aircraft movements, where available, and probably represents the best inventory available for spot years (e.g. 2006, 2013). However, ICAO focusses on international emissions and there are some known sources of underestimation. Historical data are required for assessment of CO_2 impacts and this has been estimated from International Energy Agency (IEA) statistics of aviation fuel (Jet-A1, AvGas) production and usage (Sausen & Schumann, 2000) (Lee et al., 2009) (Lee et al., 2020).

Domestic aviation emissions are attributable to states and are included under their NDCs towards the Paris Agreement goals, whereas international emissions are non-attributable to states (similar to international shipping emissions). International emissions of CO_2 from aviation are not specified under the Paris Agreement (unlike the Kyoto Protocol), however, the respective UN agencies of ICAO and the International Maritime Organization are still pursuing measures for limiting and reducing emissions of greenhouse gases.

In 2018, emissions of CO_2 from global aviation were just over 1 Gt of CO_2 and have been steadily increasing at rates of around 2.5% yr^{-1} over the last two decades although the period 2010 to 2018 saw a sharper increase of +27% in total. International emissions of aviation are calculated by ICAO to be 65% of global emissions and projected to increase both in absolute terms and as a relative proportion to total aviation (Fleming & Lepinay, 2019). Current (2018) total CO_2 emissions from aviation represent 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, Le Quéré et al., 2018).

10.5.2 Short lived climate forcers and aviation

Aviation emits a number of gases and aerosol particles that contribute towards its total fraction of anthropogenic climate forcing of approximately 3%, from its historical emissions of CO_2 and other emissions of water vapour, particles from soot and sulphate (from S in the fuel), and nitrogen oxides ($NOx, =NO + NO_2$), with its 2018 total being ~98 mW m^{-2} (Lee et al., 2020). The non-CO_2 effects of aviation on climate fall into the category of short-lived climate forcers (SLCFs). Emissions of water vapour and soot particles can trigger the formation of contrails, if the atmosphere is supersaturated with respect to ice, and below a critical threshold temperature condition (Kärcher, 2018). These linear contrails can spread to form extensive contrail cirrus cloud coverage, which is estimated to have a combined effective radiative forcing (ERF) of around 50 mW m^{-2} (Lee et al., 2020), some 51% of the current ERF of global aviation. Emissions of NO_x result in an enhancement of short-lived O_3 (a positive ERF) and a reduction of ambient CH_4, which represents a negative ERF; the CH_4 reduction also results in negative ERFs from reductions in stratospheric water vapour (Myhre et al., 2007) and background O_3 (Holmes, Tang, & Prather, 2011), which together results in a net NO_x ERF of ~18 mW m^{-2} (Lee et al., 2020).

Additional effects from aviation from aerosol-cloud interactions are thought to exist but the magnitude of these are highly uncertain, with no best estimates available. Soot emissions from aircraft, either deposited directly in the atmosphere or sublimed from contrail cirrus may increase cloudiness, and the forcing from this cloudiness may be strongly negative or positive, depending on critical atmospheric parameters (C. Zhou & Penner, 2014) (C. Zhou, Penner, Lin, Liu, & Wang, 2016), or possibly closer to a zero net effect (Gettelman & Chen, 2013) (Pitari et al., 2015). Sulphur from the fuel is largely emitted as SO_2 with a small fraction (~3%) emitted as H_2SO_4 (Petzold et al., 2005). The SO_2 oxidises in the background atmosphere to form sulphate particles, and these particles are thought to contribute to the secondary indirect effect on warmer low-level liquid clouds, resulting in a net negative forcing of uncertain magnitude (Righi, Hendricks, & Sausen, 2013) (Kapadia et al., 2016).

The net warming from aviation's non-CO_2 SLCFs is ~64% of aviation's total warming and as such is the subject of discussion for reducing its impacts. However, the issues are complex, potentially involving technological, operational and atmospheric trade-offs with CO_2 (see section X). Moreover, the impacts of aviation NO_x emissions perturbing the chemical composition of the atmosphere are not independent of background emissions from surface sources (ozone precursor emissions of NO_x, CO, CH_4 and NMHCs) and need to be accounted for in assessing future changes in ERF and mitigation potential (Skowron et al., 2020).

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

Technology options (engine/airframe)

The principal GHG of importance from aviation is CO_2, emitted at a ratio of 3.16 kg CO_2 for every kg of fuel combusted. Other emissions that impact on aviation's non-CO_2 effects on climate are water vapour, particles, and NO_x (10.5.1). Engine and airframe manufacturers primary objective after safety issues is to reduce direct operating costs, i.e. fuel burn so much investment has gone into engine technology and aerodynamics to improve fuel burn per km. there have been major step changes in emgine technology over time, e.g. from early 'jet' (turbojet) engines, to larger turbofan engines, and second-generation turbofans. Airframes have had improved performance over the years with wing design and incorporation of 'winglets' on the wing-tips. However, the basic configuration of an aircraft has remained more or less the same for decades.

As a result of this continuous improvement, large incremental gains have become much harder as the technology has matured, although twin-aisle aircraft have seen greater improvement rates in their lift to drag ratio than those of single-aisle aircraft (Cumpsty et al., 2018). The principal opportunities for fuel reduction come from improvements in aerodynamic efficiency, aircraft mass reduction, and propulsion system improvements. In terms of the future, Cumpsty et al.'s (2018) comprehensive assessment suggested that the highest rate of fuel burn reduction achievable for new aircraft was about 1.3% per year, which short of ICAO's aspirational goal of 2% global annual average fuel efficiency improvement. Hence, the case established in the technology assessment of the IPCC (1999) report on Aviation and the Global Atmosphere is that growth continues to greatly outpace emission reductions from improved efficiency, which is why alternative approaches have been sought to reduce aviation's climate impact by, e.g. alternative lower-carbon fuels on a life cycle basis (next section). More radical solutions have been suggested to modify the current air traffic system, e.g. by 'formation flying' (Xu et al., 2014), which has the potential to reduce fuel burn by up to ~8%. However, this would require increased capability onboard safety systems for wake sensing (Hemati et al., 2014) and ground-based air traffic control.

Operational improvements (navigation)

Aircraft navigation, from a global perspective is relatively efficient, with many long-haul routes travelling along great circle trajectories, or as close to possible, avoiding headwinds that increase fuel consumption (e.g. the north Atlantic flight corridor). In more densely populated and trafficked regions, aviation is more constrained; often by military airspace, congestion or adverse weather (e.g. Europe, North America). Few independent assessments are available of the potential for operational improvements. The ICAO 'trends assessment' exercise (Fleming & Lepinay, 2019), projects global improvements introduced by operational improvements (air traffic management) by an unspecified amount by 2050[1]. In contrast, such projections have to be balanced against detailed assessments of the challenges of operating in more congested airspace: for example, EUROCONTROL (2018) projected in their 'most likely' growth scenario, 'Regulation and Growth', that the majority of en-route airspace will face an increase of demand over 2017 levels by between 50% and 80% by 2040.

Fuels (alternative biofuels, synthetic fuels and liquid hydrogen)

The development of bio-based 'sustainable alternative fuels' has been widely addressed in recent years as a 'drop in' alternative fuel to reduce aviation's carbon footprint. This obviates difficulties over developing radical new or alternative technologies in terms of engines and airframes, which would still utilize fossil-based kerosene aviation fuel. The cost of replacing the 2012 global aviation fleet was estimated at a trillion dollars, taking at least 14 years highlighting the difficulties associated with fleet replacement for new technologies (Hileman and Stratton, 2014). Thus, alternative fuels that can be utilized with current technologies, is an attractive proposition for CO_2 mitigation. Alternative aviation fuels to fossil-based kerosene have to be certified to the same standard as Jet-A for a variety of parameters associated with safety issues. Currently, the American Society for Testing and Materials (ASTM International) has certified five different types of sustainable aviation fuels with maximum blends ranging from 50% to 10% (Chiaramonti, 2019).

Bio-based fuels can be created by a number 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 but have associated emissions of CO_2 or other GHGs from their production and distribution. There are many challenges and barriers to widespread development of sustainable alternative fuels (SAF), the primary one being the current cost of fossil fuel vs SAF production (SAF is currently around three times the price of kerosene, Hari et al., 2015), which is a constraint on commercial development and viability. Other factors include cost effective production, feedstock availability, and certification costs (Hari et al., 2015). In addition, associated land use change emissions can be as large, or larger than the other life cycle emissions, depending upon crop type and location and represent a constraint in biofuel mitigation potential (Staples et al., 2017) and have inherent large uncertainties (Plevin et al., 2009). Other sustainability issues include food vs fuel arguments, water resource usage, and impacts on biodiversity.

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 demand in

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[1] Estimated from their Figure 4 as a saving of approximately 7% fuel over a baseline, by 2050.

2030 would be ~100 Mtoe in 2030 and biokerosene (HERFA/HVO) penetration would be just over 2% of the total fuel demand at that date.

Clearly, for bio-based SAFs to be economically competitive, large adjustments in prices of fossil fuels or introduction of policies are required. Staples et al. (2018) estimated that in order to introduce bio-based SAFS that reduced LCA emissions by >50% by 2050, prices and policies were necessary for incentivization and require 268 new biorefineries per years and capital investment of approximately 22 to 88 billion US$ (2015 prices) per year between 2020 and 2050.

Other pathways have been discussed for the production of SAFs such as power-to-liquid pathways (Schmidt et al., 2018), sometimes termed 'electro-fuels' (Goldmann et al., 2018), or more generalized power to 'x' pathways (Kober et al., 2019). This process would involve the utilization of renewable electricity, CO_2 and water to synthesize jet fuel. Hydrogen is produced via an electrochemical process, powered by renewable energy and combined with CO_2 captured directly from the atmosphere and combined either by the Fischer-Tropsch or methanol synthesis. In comparison to bio-SAF production, the process is in its infancy but in terms of environmental performance, assuming availability of renewable electricity, it has much smaller land and water requirements, and potential for large life cycle emission reductions (Schmidt et al., 2016). No trials have yet been achieved.

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. Although the fuel has an energy density ~3 times greater than kerosene, it has a much lower energy density per unit volume. Experimental small aircraft have also flown using hydrogen fuel cells. LH_2 is a viable fuel source for commercial civil aviation passenger aircraft albeit with altered airframe structures to accommodate the fuel in the fuselage (Klug and Faass, 2001). Bicer and Dincer (2017) found that LH_2-powered aircraft compared favourably to conventional kerosene-powered aircraft on a life cycle analysis (LCA) basis, providing that the LH_2 was generated from renewable energy sources (0.014 kg CO_2 tonne km^{-1} cf 1.03 kg CO_2 tonne km^{-1}, unspecified passenger aircraft). However, Pereria et al. (2014) also made a LCA comparison, and found much smaller benefits of LH_2-powered aircraft (manufactured from renewable energy) compared with conventional fossil-kerosene, the two studies exposing the sensitivities of boundaries and assumptions in the analyses. Harsha (2014) and Rondinelli et al. (2017) conclude that there are many infrastructural barriers but that the environmental benefits of renewably-sourced LH_2 would 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.

In conclusion, there are many favourable arguments for LH_2-powered aircraft both on an efficiency basis (Verstraete, 2013) and an overall reduction in GHG emissions, even on an LCA basis, but the major constraint is the infrastructural issues associated with fuel storage and distribution at airports, which is unlikely to be overcome unless there was a more general move towards a hydrogen-based energy economy. This is a conclusion for most heavy vehicle systems and the hydrogen option.

Technological and operational trade-offs of non-CO_2 emissions and effects with CO_2

Since aviation has significant non-CO_2 warming impacts, there has been some discussion as to whether these can be addressed by either technological or operational means. For example, as aircraft engines have improved their fuel efficiency, with widescale usage of large high overall pressure ratio engines with large bypass ratios from large fan-bladed engines, this has tended to increase pressures and temperatures at the combustor inlet, with a resultant increase in tendency for thermal NO_x formation in the absence of combustor technology to reduce this. This 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 fuel and therefore CO_2 vs NO_x is complex (Freeman, Lee, Lim, Skowron, & De León, 2018), requiring climate/chemistry model calculations and usage of emissions-equivalency metrics, such as the Global Warming Potential (GWP) or Global Temperature change Potential (GTP) (see (Dalsøren et al., 2013) for an overview). 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 SCLF.

A widely discussed opportunity for aviation non-CO_2 mitigation is the avoidance of contrails. Contrails only form with the emission of water vapour and soot particles from aircraft into 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 these ‘moist lenses’ tend to be 10s of km in the horizontal and only a few 100 metres in the vertical extent (Gierens, Schumann, Smit, Helten, & Zängl, 1997). Theoretical approaches in the literature show that avoidance is possible on a flight-by-flight basis (Matthes et al., 2017). In case studies, it has been demonstrated that flight planning according to *trajectories with minimal climate impact* can substantially (up to 50%) reduce the aircraft net climate impacts despite additional CO_2 emissions (e.g., (Niklaß et al., 2019)). However, such a conclusion of the net benefit or disbenefit depends upon the choice of metric and time-horizon applied. As for the above example of technological trade-offs, there is a tendency for additional CO_2 to cause a net disbenefit for all metrics when longer time horizons are considered.

Market-based measures – EU-ETS, other ETS, ICAO-CORSIA offsetting measure

Market-based measures have been introduced in various regions of the world, based on emissions trading of CO_2, notably in Europe but also for domestic aviation in New Zealand. The other major initiative is within ICAO, the ‘Carbon Offset and Reduction Scheme for International Aviation’ (CORSIA), agreed in 2016 to commence in 2020.

The European Union (EU) introduced aviation into its CO_2 emissions trading scheme (ETS) in 2012. This initially included flights between the European Economic Area (EEA) states and non-EEA states. However, the extension of the scheme to non-EEA states was highly controversial and in 2014 the EU deferred the inclusion these flights under the so-called ‘stop-the-clock’ derogation. Currently, the EU-ETS for aviation includes all flights within and to and from EEA states. At around the same time, the International Civil Aviation Organization (ICAO) proposed to develop a global offsetting scheme, which was agreed in 2016 to commence in 2020, the ‘Carbon Offset and Reduction Scheme for International Aviation’.

CORSIA has a phased implementation, with 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 (2026–2035) in which 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 16 July 2019, 81 States, representing ~77% of international aviation activity, intend to voluntarily participate in CORSIA from its outset. In terms of routes, only those where both States are participating are included. There is currently no “third phase” described and the fate of the CORSIA beyond 2035 is unclear.

The fate of the EU-ETS running concurrently with CORSIA is unclear at the moment. The EU-ETS is different to CORSIA in that the former is a cap-and-trade scheme, with airlines purchasing allowances, whereas CORSIA relies on verified offsetting, and exempts some biofuels. The nature of offsetting means that reductions are purchased from other sectors that either withhold from an intended emission, or reforest (Becken & Mackey, 2017), which is unclear that this represents a real reduction in CO_2 emissions.

10.5.4 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 rather different, in that ICAO (and the IMO) are not named, so that international aviation emissions of CO_2 do not appear to be covered, in that the Paris Agreement deals with states, and their Nationally Determined Contributions (NDCs). This would imply that domestic aviation emissions of CO_2 (currently 35% of the global total) are covered by NDCs but international emissions are not. A number of states and regions have declared their intentions to include international aviation in their net-zero commitments including the UK, France, Sweden, and Norway, with the intentions of the European Union, New Zealand, California and Denmark being as yet unclear but under consideration (Committee on Climate Change, 2019). The Paris Agreement is a temperature-based target, such that it is unclear how emissions of GHGs and other climate forcers that are not included, including those 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.

The ICAO CORSIA is a part of ICAO's aspirational 'carbon-neutral growth goal, 2020', such that through CORSIA and technological and operational improvements, ICAO aims that international aviation emissions of CO_2 should not grow above 2020 levels. In addition, ICAO has a goal of global annual average fuel efficiency improvements of 2 percent until 2020 and an aspirational global fuel efficiency improvement rate of 2 percent per annum from 2021 to 2050. ICAO also regulates emissions, including those of NO_x, CO, hydrocarbons (HCs) and non-volatile particulate emissions (nvPM) from engines, and recently (2017) adopted a whole-aircraft emissions standard for CO_2. The emissions regulations of NO_x, HCs, CO and nvPM are primarily targeted at protecting air quality in and around airports. However, there has been a working assumption that reducing NO_x will reduce its impacts on tropospheric O_3 formation and its subsequent radiative forcing. In addition, emissions of nvPM or 'soot' are part of the early process of contrail formation and reducing the emissions (number) will reduce the initial number of ice crystal particles in the plume at altitude and reduce the propensity for contrail and subsequent contrail cirrus formation (Kärcher, 2018).

More recently, ICAO has at its 40th General Assembly (October, 2019) requested ICAO's 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).

10.5.5 Synthesis: transformation trajectories for the aviation sector

Here, three basic trajectories of development are envisaged that have differing degrees of response to reductions in GHG emissions. Some of the developments are encompassed by global or regional goals while some are more speculative.

A '**business as usual**' (BAU) scenario largely reflects current and projected rates of technology development and policies currently in place. So, for aviation, global fleet fuel efficiency improves at around 1-2% per annum, with operational improvement delivering smaller improvements (since the system is relatively efficient). Market-based measures continue to operate through to at least 2030 in the case of the EU-ETS and 2035 in the case of CORSIA. Nonetheless, demand for aviation continues to increase at rates of somewhere between 5-7% yr^{-1} in terms of RPK. Biofuel continues to make small contributions to aviation energy demand, of somewhere between 2 and 10% by 2050.

An '**incremental scenario'** might be envisaged that sees technology developments similar to BAU, but with somewhat improved fuel efficiencies achieved from technology development with greater R&D development but a higher penetration of biofuels and zero-C synthetic fuels from renewables, resulting from greater private and governmental investment and the widening of 'net-zero CO_2 ambitions' by individual countries.

A '**transformational scenario**' is one that works towards a target of net-zero CO_2 emissions from the aviation sector. This would be driven by active policies that mandated phase-out of fossil fuel usage by 2050, considerable private and governmental investment in technologies for zero-C synthetic fuels produced from widely deployed new fuel production facilities, powered by renewable energy as part of a wider system promotion and mandating of renewable energy sources, with decommissioning of the fossil-fuel energy supply system. Short haul aviation would also be potentially powered by all- or semi-electric powered propulsion systems. Bio-based lower carbon fuels are regarded as an integral part of such a scenario in the short to medium term, gradually being replaced by zero-C synthetic fuels from renewable resources. The cost of flying may become considerably higher and subsequent demand reduced over a BAU scenario. An alternative to widespread usage of zero-C paraffinic fuels which would equally fall under a transformative scenario is that of LH_2 as a fuel for aviation. This would equally require the H_2 to be generated from renewable energy sources. However, it could be likely that such widespread usage is less likely, as this would require complete fleet renewal and design of airframes and to a lesser degree, the engines, as current airframes could not be converted to take LH_2 fuel. Moreover, this would also require renewal of fuel supply infrastructure to airports. Even if the CO_2 impact could be made to be zero under this scenario, the non-CO_2 impacts remain poorly understood, since the emission index of water vapour would be much higher (×2.6, Ström and Gierens, 2002) than for conventional paraffinic fuels, and contrail and contrail cirrus formation may be of a greater incidence although with possibly lower optical thickness with estimates of RF ranging from ×1.3 to ×0.7 when compared with conventional contrail cirrus RF (Marquart et al., 2005). Potentially, NO_x emissions would be lower, since combustion temperatures may be lower (Khandelwal et al., 2013).

10.6 Decarbonization of shipping

10.6.1 Historical and current emissions from shipping

Maritime transport volume has increased by 250% over the past 40 years, reaching all time high of 11 billion tons of transported good in 2018 (UNCTAD, 2019). Shipping (international combined with domestic and fishing) emitted 938 Mt CO_2 in 2012, accounting for 2.6% of global anthropogenic CO_2 emissions (3rd IMO GHG Study, Smith et al., 2014). International shipping alone accounted for 805 Mt CO_2 in 2012. The estimated total emissions from maritime transport vary (Fig 10.15) depending on data set, and converge on 700 – 850 Mt CO_2 per year over the past decade, corresponding to 2-3% of total anthropogenic emissions, as found by Buhaug et al. (2009), Smith et al. (2014), Olmer et al. (2017), Johansson et al. (2017), DNV-GL (2019), the EDGAR data by Crippa et al. (2019), and the CAMS-GLOB-SHIP inventory by Jalkanen et al. (2014) and Granier et al. (2019). The emissions from international shipping are typically based on AIS data on ship traffic activity. There are a number of challenges in calculating emissions from the global fleet, explaining the range in the estimates in Figure 10.15. Such factors include coverage of AIS satellite data, especially further back in time, neglecting to account weather drag on vessels, in addition to hull fouling, as well as lack of information on vessels, such as technological specifications.

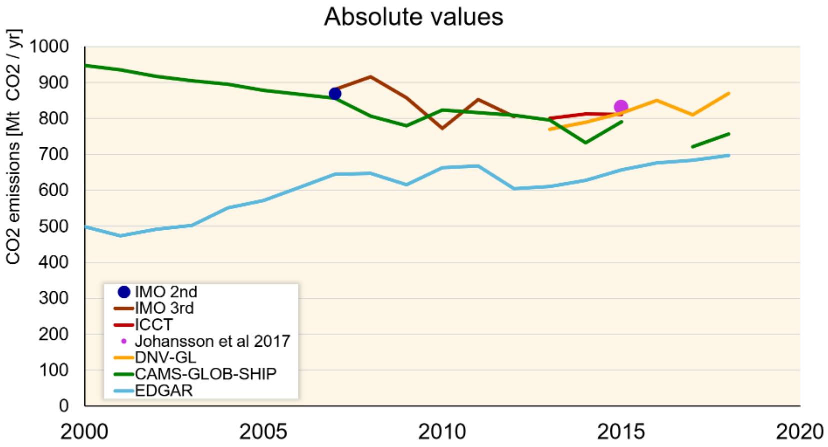

Figure 10.15 CO_2 emissions (Mt / year) from shipping from year 2000 - 2018. Source: Authors

From anticipated increases in transport demand, emissions have been projected to increase significantly in the coming decades, by 50 – 250 % (Smith et al., 2014). Maritime transport demands increase with international trade and economic activity. Decoupling demand growth and emissions will require very high reduction in fleetwide average emission intensities per ton km. This would be achievable through increasing energy efficiency, improving operations, as well as alternative fuels (See section 10.6.3).

10.6.2 Short lived climate forcers and shipping

The short-lived climate forcers (SLCF) like sulphur in fossil maritime fuels, have a fraction of the life time of the warming from the associated CO_2 emissions. The cooling from the SLCF from a pulse emission will be insignificant after a couple of decades, whilst the warming from the long-lived substances lasts for centuries (see WG1 Ch6). Sulphur emissions contribute towards acidification of the oceans (Hassellöv et al., 2013), and this effect has been shown to be equal to acidification from CO_2 in the major shipping lanes, though the evidence is limited as this stage. Increase in sulphur deposition on the oceans has also been shown to increase the flux of CO2 from the oceans to the atmosphere. More studies are required to establish confidence in this.

Emissions of SLCF from shipping not only affects the climate, but also the environment and air quality. Maritime transport has been shown to be a major contributor to coastal air quality degradation (e.g. Viana et al., 2014, Zhao et al., 2013, Jalkanen et al., 2013. Goldsworthy et al., 2015, Goldsworthy, 2017). Uncertain impacts of pollutants emitted from ships on the marine environment have been identified as a gap in knowledge and understanding (Blasco et al., 2014). Given this, to fully understand the climatic implications of emissions from shipping, both GHGs and SLCFs should be taken into account.

Pollution control is implemented to varying degrees in the SSPs (Rao et al., 2017), with SSP 1 and 5 assume that increasing concern for health and environment results in more stringent air pollution policies than today. There is a downward trend in SOx and NOx emissions from shipping in all the SSPs, in compliance with regulations. The SLCF emission reduction efforts, also within the maritime sector, are contributing towards achieving the UN SDGs as well as climate mitigation.

10.6.3 Shipping in the Artic

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, 2015, Smith et al., 2013, Aksenov et al., 2016). This is in parts of the literature and public discourse portrayed as positive (e.g Zhang et al., 2016), as it allows for shorter shipping routes, e.g. between Asia and Europe with estimated travel time savings of 25 – 40% (Aksenov et al., 2016).

GHG emissions accelerate Arctic cryosphere melt (cf. WG1 Ch 3.1) and reduced sea ice reduces surface albedo and amplifies climate warming. Air pollutants on the other hand play different roles regionally. Arctic particularly sensitive region. Some aerosols, like SOx, contributed to offset some of this effect. Black Carbon (BC) emissions reduce albedo and absorb heat in air, snow and ice (also link to WG1 Ch 6) (Messner, 2020, Browse et al., 2013), and may pose a threat to local ecosystems (link to WG2 Ch 3).

Changing routing from going through e.g. Suez to the northeastern sea route shifts emissions from low to high latitudes. This adds complexity to the assessment of the climatic impacts, 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 local air pollution stems from shipping in Canadian Arctic (Aliabadi et al, 2015). Both modelling and observations have shown that aerosol emissions from shipping can have a significant affect in air pollution, and shortwave radiative forcing (Roiger et al., 2015, Marelle et al., 2016, Dalsøren et al., 2013, Ødemark et al., 2012).

More open waters has invited increased maritime activities in the Arctic over the past two decades (Pizzolato et al., 2016). This poses increased risks to local marine ecosystems and coastal communities from invasive species and pollution (IPCC SROCC, 2019). Greater levels of Arctic maritime transport and tourism have political, as wells as socio-economic implications for trade, and nations and economies reliant on the traditional shipping corridors. There has been activity increase from cargo, tankers, supply and fishing vessels in particular (Zhang et al., 2016, Winther et al., 2014). New trades are also from growing Asian economies, as well as increasing Russian exports. Projections indicate more navigable Arctic waters in the coming decades (Smith et al., 2013, Melia et al., 2016) and continued increases in transport volumes through the northern sea routes (Winther et al., 2014, Corbett et al., 2010), with a particular increase from destinational and not transit traffic (Lasserre and Pelletier, 2011). Emission patterns and quantities, however, are likely to change with future regulations from e.g. IMO, and depend on technology developments, and activity levels may depend upon among other; geopolitics, commodity pricing, trade, natural resource extractions, insurance costs, taxes and tourism demand (Johnston et al, 2017). Arctic environment poses unique hazards challenges with regards to safe and efficient operations; low temperature challenges, implications for vessel design, evacuation and rescue systems, communications, oil spills, variable sea ice and meteorological conditions (e.g. Buixade-Farre et al., 2014).

To understand the total implications of shipping in the Arctic a holistic view 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.

The figure 10.16 is illustrating the northern sea routes, along the lines of the figure 10.16 below from Mélia et al. (2015). We propose to include September sea ice edges, based on historical observations, and RCP projections of sea ice extent (Stephenson et al., 2013).

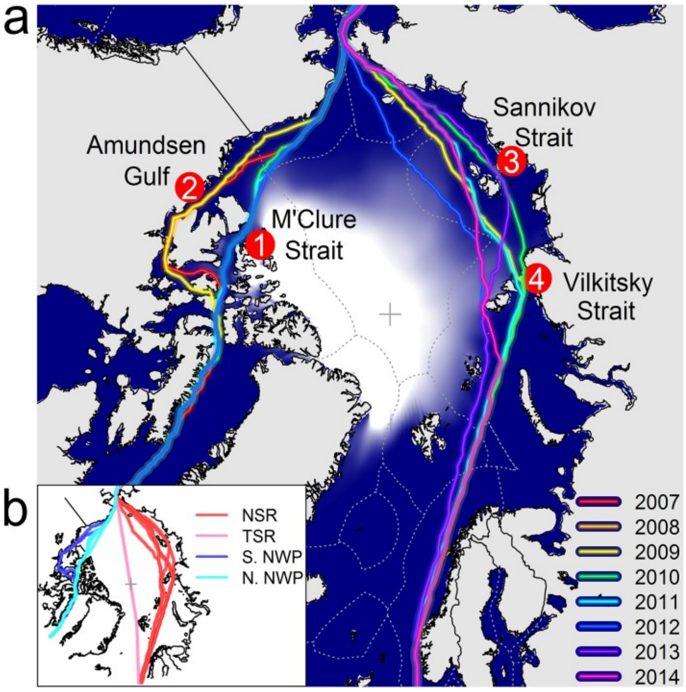

Figure 10.16 Northern sea routes

10.6.4 Mitigation potential of fuels, operations and energy efficiency

A range of vessel mitigation options for the international fleet exist and include:

- Hull design options: vessel size, hull shape, lightweight materials, air lubrication, resistance reduction devices, anti-fouling hull coatings, and ballast water management.
- Operations: weather routing, slow steaming (Psaraftis et al., 2013), capacity utilization.
- Power and propulsion system options: hybrid power /propulsion, power system / machinery, propulsion efficiency devices, on-board power demand, and waste heat recovery systems.
- Alternative fuels (e.g., Brynolf et al., 2014) and energy: biofuels, methanol (Connolly et al., 2014), LNG (Burel et al., 2013), wind power, solar power, cold ironing, fuel cells (van Biert et al., 2016).

The literature describes potentials for reducing emissions from shipping through a number of such measures, typically by optimizing e.g. hull design and vessel shape, power and propulsion systems, and through improved operations. Such measures may decrease emissions by 15 - 40%, though with a broad range in potential found in the literature, as assessed by Bouman et al. (2017). A broad range of measures was reviewed, and it was found an upper bound of 39% emission reductions in 2030, and 73% in 2050, compared to the BAU scenario of the 2nd IMO GHG study (Smith et al., 2014).

Alternative fuels, and alternative energy sources, and in the case of switching to sustainable biofuels; as much as 80% of CO_2 emissions may be cut, though such numbers are associated with large uncertainties. Biomass may be used to produce alcohol fuels, such as ethanol, methanol, liquified bio-gas or biodiesel. Though there are concerns regarding large-scale production (see Section 10.3 on biofuels), hence it is questioned whether biofuels will become available at the scales required to decarbonize the shipping and aviation sectors (SSI, 2019, Gilbert et al., 2018). It is projected that the primary energy supply from sustainably sourced biofuels might be of 50-100 EJ / year in 2050 (SSI, 2019), whilst there might be a potential shipping demand of 26 – 60 EJ / year, compared to 10 EJ in 2018. LNG has been found to have a more limited mitigation potential in comparison and may not be considered as a low-carbon alternative, but has a higher availability than biofuels (Gilbert et al., 2018).

Decarbonizing primary energy supply may enable the production of fuels, such as hydrogen and ammonia, with zero emissions. Unless energy supply is renewable or coupled to CCS, there might be an upstream shift in emissions in the fuel value chains. Hence a full life cycle perspective of the decarbonization measure will give a more complete picture of the total emissions from the sector (Gilbert et al., 2018). Hydrogen and ammonia when produced from renewables or couple to CCS, as opposed to mainly by fossil fuels today with high life-cycle CO_2 emissions (Bhandari et al., 2014), may contribute to significant emissions reductions of up to 33 - 80% compared to low-sulfur heavy fuel oil (Bicer and Dincer, 2018, Gilbert et al., 2018), though have their own unique transport and storage challenges.

Literature shows there is a potential for improving the energy efficiency of vessels and by such reducing fuel consumption (e.g. Traut et al., 2018). Improved efficiency in port operations and training of crew to handle new technologies may also provide further to the mitigation potentials for the sector (Viktorelius and Lundh, 2019). The development of autonomy within the sector may also play a role in mitigation in the future.

Considering that more than 40% of transported freight is fossil fuels, a lessened demand for such products, as well as coal, in low emission scenarios may contribute to reduce the overall maritime transport needs and hence emissions in the future (Sharmina et al., 2017). An increase in biofuels and biomass, on the other hand, may increase freight demand (Mander et al., 2014).

Literature points to the need for developing technology roadmaps for enabling the maritime transport sector to get on to pathways for decarbonization early enough to reach the Paris Agreements temperature goals (Kuramochi et al., 2018). Accounting for the full life-cycle of emissions 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 and the IMO target of halving emissions by 2050 (see Section 10.6.3 on governance options).

10.6.5 Accountability and governance options

Research has indicated that market forces alone are not enough to drive down emissions from the sector (e.g. Cullinane and Cullinane, 2013). Regulatory frameworks have hence been developed over time and will continue to do so through bodies such as the IMO. Recent IMO regulations target a 50% reduction in emissions from the sector by 2050 compared to 2008 (IMO, 2018). An initial strategy with implementation of policies is to be developed. It furthermore aims for the sector to become carbon neutral by the end of the century, in line with the Paris Agreement. The initial strategy for implementation is to be revised in 2023. As a step towards this goal, the initial strategy is to reduce CO_2 emissions per transport work by 40% by 2030 (IMO, 2018).

The Energy Efficiency Design Index (EEDI) by IMO is a legally binding mitigation regulation, 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. Ships built in 2025 should be 30% more energy efficient than in 2014. This legislation aims to reduce GHG emissions in particular. Energy efficiency may be improved by several of the mitigation options outlined in Section 10.6.3 on mitigation options. The ship energy efficiency management plan (SEEMP) as the international governance instrument to improve energy efficiency and hence emissions from ships, is a measure to enable changes to operational measures and retrofits (e.g. Johnson et al., 2013). This was implemented in 2013 and each vessel develop their individual plan. The combination of EEDI and SEEMP may reduce emissions by 23% by 2030, cf. ‘no policy’ (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.

In SECAS (sulphur emission control areas), the sulphur cap is 0.10% m/m (mass/mass), as implemented in 2015 by IMO. This is also in place for particulate matter (PM). The Sulphur emissions regulations are further tightened by the IMO legislation on reducing marine fuel sulphur content to a maximum of 0.5% by 2020 outside of SECAS, compared to 3.5% permissible since 2012 (Decided at MEPC 70 in 2016, included in Annex VI to the International Convention for the prevention of Pollution from ships (MARPOL Convention)). The cap on permissible sulphur aims to improve environment and health impacts from shipping in ports and coastal communities, in particular. Ships may meet the SOx requirements by using pre-approved measures, such as exhaust gas cleaning through the use of scrubbers, or indeed low Sulphur fuel options, with fuel switching being identified as most cost effective for vessels mostly operating outside of ECAs (Carr et al., 2015). MARPOL Annex VI furthermore prohibits the emissions of other ozone depleting substance; NOx, and VOCs from tankers. NOx Tier III: more stringent regulation on diesel engines on ships constructed since 2016. ECAs have been shown to reduce the impacts of ship emission on health and environment (Viana et al., 2015). Speed optimisation and rerouting has been projected as a consequence of ECAs, considering the higher cost low-sulfur fuels (Fagerholt et al., 2015).

Policy choices may enable or hinder changes, e.g. the EEDI (e.g.) literature shows there is a gap between the SEEMP requirements to the shipping companies and the requirements to management systems, monitoring, and reviews. These gaps in the governance structure may somewhat hinder the objectives of SEEMP to improve energy efficiency and emissions. Stevens et al. (2015) point out that the EEDI is encouraging makes shipping companies order vessels with reduced design speeds, rather than stimulate the use of alternative fuels or new lower-carbon ship engine technologies. Policies may incentivize investments in necessary changes to the global feet and related infrastructures. Literature argues that regulations and incentives that motivates mitigation through slow-steaming, improves ship efficiency, 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).

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 encourage ship operators to comply with IMO GHG regulations.

10.6.6 Synthesis: transformation trajectories for the maritime sector

As indicated in Figure 10.17, CO_2 emissions from shipping go substantially down in the two shared socio-economic pathways that align with the Paris Agreement's temperature targets, SSP1-1.9 and SSP1-2.6 (Gidden et al., 2019). By 2050, the emissions are reduced to 30% of the 2015 emissions in the scenario closest to 1.5°C (SSP1-1.9). On the other hand, 2.0°C (SSP1-2.6) takes a leaner reduction trajectory with emissions down to 60% of 2015 by 2050. By the end of the century, emissions are down to 1-40% in 4 of the 8 scenarios considered by ScenarioMIP in CMIP6 (cf. AR6, WG1). The IMO projections for growth in transport demand (Smith et al., 2014) indicate increases by 3 - 6 times 2015 levels by 2050 for unitized cargo and 2-3 times for non-coal dry bulk. Smith et al. (2014) at the same time predicts reductions in trade for fossil fuels dependent on decarbonization trajectories. Based on these aggregate growth and emission trajectories, average fleet wide reductions in GHG emission per unit transport work in an order of 70% by 2050 may be well aligned with an RCP 2.6 based 2.0°C target. While an RCP 1.9 based 1.5°C target would require further reductions.

This points to the scale of change needed in terms of technological transformation of the maritime sector. Moreover, combinations of measures are likely needed for sustainable transitioning of the sector to a low-carbon future. From the section above, we see that not one measure alone may enable low carbon – shipping, as the availability of some solutions and technology is still limited, and there may be competition for sustainable biofuels from other sectors with unique challenges to mitigate, such as aviation. The further expected increase in demand for shipping services (Smith et al., 2014), offers an additional requirement for shipping to increase its energy efficiency and shift to cleaner fuels in order reduce its overall impact on the climate. Both GHG and SLCF emissions are reduced significantly in SSP1-1.9 (Rao et al., 2017), where the Paris Agreement goal of limiting global warming to 1.5°C compared to the pre-industrial is aimed for in the most sustainable way.

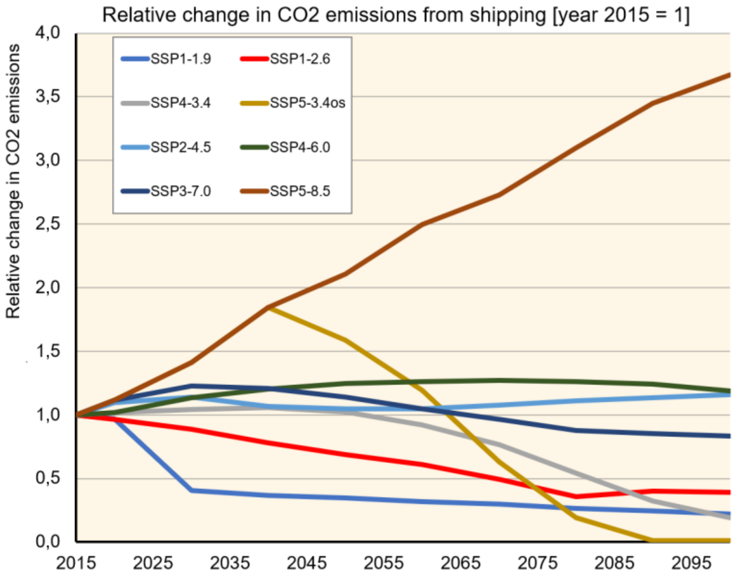

Figure 10.17 CO_2 emission changes from shipping according to the SSPs, relative to year 2015

Placeholder-Scenarios for BAU, Incremental and Transformative options will be developed for SOD as with Aviation.

10.7 Transformation pathways for the transport sector

The engineering and LCA literatures have identified numerous options for reducing GHG emissions from the transport sector. These options would be embedded within and interact with larger systems. To understand the total decarbonization potential of these options, we must capture the larger system features and constraints within which the options would be embedded.

In this section, we review results of three types of models that combine these options in a systemic manner to assess different approaches to generate decarbonization pathways for the transport system: i) integrated assessment models (IAMs), ii) global transport sectoral models (GTM), and iii) national transport/energy models (Yeh. et al 2017, Edelenbosh 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 difference underlying these models is their depth versus scope.

IAMs integrate factors from other sectors that interact with the transport system endogenously, such as fuel availability and cost. IAMs minimize mitigation costs to achieve a temperature target *across all sectors of the economy* over a long-time horizon (typically to 2100). GTMs 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 important 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. In this section we will synthesize findings across model types with varying assumptions to understand what decarbonization pathways exist for the transport system.

Greenhouse gas emissions from transport are a function of travel demand, travel mode, transport technology, fuel consumption, and energy efficiency. Each emissions driver is a lever that can advance decarbonization of the transport system. Our section explores each lever in turn below, but begins with an overview of global transport emission trajectories needed to meet varying climate targets.

10.7.1 Global emission trajectories

The transport sector accounts for a quarter of global CO_2 emissions. In 2017, transport emitted 8.0 $GtCO_2$ (Joint Research Center, n.d.), a three-fold increase from 1970 (Figure 10.18). Of those emissions, 75% came from on road, 22% from aviation and shipping (split evenly), and 3% from rail. Emissions are expected to grow 20% to 9-10 $GtCO_2$ by 2030 and 50% to 12-13 $GtCO_2$ by 2050 under the BAU scenarios without efforts to meet long-term stabilization targets. Growth will be driven by the growth in population and GDP and the secondary effects including higher travel service demand per capita and increased freight activities per GDP. Though transport efficiencies (energy use per passenger-km travelled and per ton-km of delivery) are expected to continue to improve in line with the historical trends (see Section 7.4), total transport emissions are expected to grow due to roughly constant carbon intensity (Section 7.5) under the BAU.

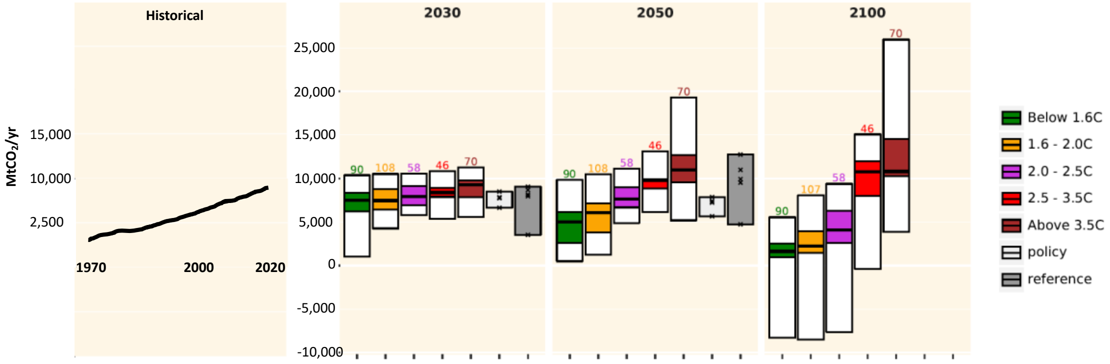

Figure 10.18 Direct CO_2 emissions from global transport scenarios

Sources: IAMs —IPCC WGIII AR6 Scenario Database (Annex II.10). Sectoral models: MoMo (IEA), EPPA5 (MIT), Roadmap (ICCT), GCAM (PNNL), and MESSAGE (IIASA). The policy scenarios in global transport models (GTMs) cover a wide range of "non-BAU" scenarios (to be defined) that are not necessarily designed to achieve the targets set in the Paris Agreements.

Notes: IAM results are grouped by temperature targets. Sectoral studies are grouped by baseline and policy categories because they don't track global emissions so cannot solve for achieving temperature targets. Numbers above the bars indicate the number of scenarios.

Figure 10.18 provides an overview of direct CO_2 emissions from the transport sector across IAMs (colour bars) and selected global transport models (grey bars). The results from the IAMs are grouped in bins in accordance with different temperature targets. See Chapter 3 for further detail on the definition of these. The transport sector models are generally single sector models and does therefore not keep account of total global emissions. This in turn makes it difficult for them to endogenously solve for outcomes in terms of global temperature targets. These are therefore grouped into reference and policy bins. The results show that in the below 1.6°C and 1.6°C – 2.0°C scenarios, IAMs curb transport emissions back down to 2017 levels (median values across scenarios) in 2030 and down by 22% to 37% (median values across scenarios) of 2017 level in 2050. In comparisons the low overshoot 1.5 degree scenarios warranted global cuts in CO_2 emissions in the range of 40 to 58% across all sectors in 2030 and 94% to 107% in 2050 relative to 2010.

The scenarios from the GTMs shown in Figure 10.18 and elsewhere suggest that emissions could increase to 6.4 to 8.4 $GtCO_2$ in 2030 for both the Reference and Policy scenarios, and could reach 9-

12 Gt CO_2 or higher in 2050 in the Reference scenario and 6 to 7.8 $GtCO_2$ in the Policy scenario. The Reference scenario emission pathways from GTMs fall outside of the bound of the above 3.5°C scenarios from the IAMs and the Policy scenarios are roughly in line with the above 3.5°C emission pathways. *This suggests that without an explicit temperature target, the transport policy scenarios examined by the GTMs can only bring transport emissions down to a pathway that is consistent with the above 3.5°C increase* (Fisch-Romito & Guivarch, 2019; Sudhir Gota, Huizenaga, Peet, & Kaar, 2016; International Energy Agency, 2017a; Yeh et al., 2017b). The NDCs in the transport sector include a mix of measures targeting efficiency improvements of vehicles and trucks; improving public transits services; decarbonizing fuels with alternative fuels and technologies including biofuels, fossil- or bio-based natural gas, and electrification; intelligent transport systems; vehicle restrictions; etc (Sudhir Gota et al., 2016). Taken all together, because of the long lag-time for technology turnover, these measures are not expected to significantly change 2030 emissions but could bring down 2050 emissions to 2030 levels.

Several GTMs not *(yet)* included in Figure 10.18 have examined ambitious CO_2 mitigation scenarios. For example, emissions from transport in the beyond 2°C scenario by the IEA would decrease by 90% compared to the IEA's BAU scenario. Global transport emissions consistent with 2°C target is estimated to reach peak transport emissions in 2020 at around 8 $GtCO_2$ (Sudhir Gota, Huizenga, Peet, Medimorec, & Bakker, 2019d; International Energy Agency, n.d.-b) and decrease to 5 Gt for 2°C or below 2.5 Gt for the 1.5°C scenarios by 2050.

Low carbon scenarios are also available from national models (Argentina, Brazil, Canada, China, France, Germany, Indonesia, India, Italy, Japan, Mexico, South Africa, UK, USA) with good coverage of the transport sector. The low carbon scenarios are either defined with respect to a global climate stabilization target 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. These studies have generally used bottom-up models (TIMES, ANSWER MARKAL, LEAP) for analysis, but in some cases, they are run by national teams using global models (e.g., GCAM for China, India, etc). National studies show that transport CO_2 emissions are expected to decline significantly in low carbon scenarios in all the developed countries reviewed (Bataille et. al., 2015; Kainuma et. al., 2015; Virdis et. al., 2015; Pye et. al., 2015; Criqui et. al., 2015; Kemfert et. al., 2015; Williams et. al., 2015 & Zhang et. al., 2016) in 2050 from the emissions in 2010 and reductions vary from 65% to 95%. However, in developing countries reviewed (Altieri et. al., 2015; Buira et. al., 2015; Dhar et. al., 2018; Teng et. al., 2015; Lebre La Reovere et. al., 2015; Siagian et. al., 2015; Shukla et. al., 2015; Di Sbroiavacca et. al., 2015), the emissions are expected to increase in 2050 in the range of 35% - 83% relative to 2010 levels. Transport CO_2 emissions per capita in the developing countries are 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, by 2050, the CO_2 emissions per capita in developed countries (vary from 0.19 to 1.04 tCO_2 per capita) are much lower than developing countries (vary from 0.21 to 1.7 tCO_2 per capita).

The mean outcomes of the transport scenario literature 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 target. This is in line with perspectives in the literature suggesting that transport is one of the most difficult sectors to decarbonize (Davis et al. 2018). There is, however, quite a spread in the results for 2030 and 2050. For 2100, the median results suggest cuts down to -80% for a 1.5^0 trajectory.

10.7.2 Transport demand and activity

Transport demand for services, generally broken into passenger (in passenger-km or passenger-km per capita) and freight (in ton-km or ton-km per GDP), is reviewed in this section. Growth in passenger and freight travel demand are generally dependent on population and GDP and the secondary effect of increased demand for travel and good consumptions and transport as country GDPs grow.

In 2015, transport activities were estimated around 35-50 trillion passenger kilometers (pkm) or 5,000-7,000 pkm per person per year with significant variations among studies (International Energy Agency, 2017a; ITF International Transport Forum, 2019b). The number of vehicles in use has grown 45% globally from 2005-2015 with the largest growth occurring in Asia and the Middle East (120%, in which China alone has grown 540% during such period and 200% in India), Africa (80%), South and Central America (80%) and Russia (78%), while the growth in Europe and North America are the slowest (21% and 4% respectively) (International Organization of Motor Vehicle Manufacturers, n.d.). Passenger transport demand is expected to double (relative to 2015) in 2030 and close to tripling in 2050 for the above 2 degrees scenarios. The median 2 °C scenario also show a doubling by 2030 but closer to a factor of 2.5 in growth by 2050. The 1.5 scenarios show much lower demand growth. Closer to a factor of 1.5 in 2050 and a factor of 2 in 2050.

Globally consistent freight data are difficult to obtain (Mulholland, Teter, Cazzola, McDonald, & Ó Gallachóir, 2018) and regional growth rates vary dramatically: over the period 1975–2015, road freight activity in India increased by more than 9-fold, 30-fold in China, and 2.5-fold in the US (Mulholland, Teter, Cazzola, McDonald, & Ó Gallachóir, 2018). The growth rates for commercial vehicles between 2005-2015 are similar to passenger cars (global average of 41%), with slower growth in China (160%) and faster growth in North America (36%).freight sector could grow by 2.4-fold over the period 2015–2050 in the reference scenario with the majority of growth attributable to developing countries. Among the IAM models reviewed, the median scenarios indicate a growth of about 30% in 2030 and 15% for the above and 2°C scenarios in 2050. While the median 1.5°C scenarios indicate a no growth in 2030 and a reduction of 50% by 2050 (all number relative to 2015).

Figure 10.19 shows demand trajectories for freight and passenger transport from the IAMs and GTMs reviewed.

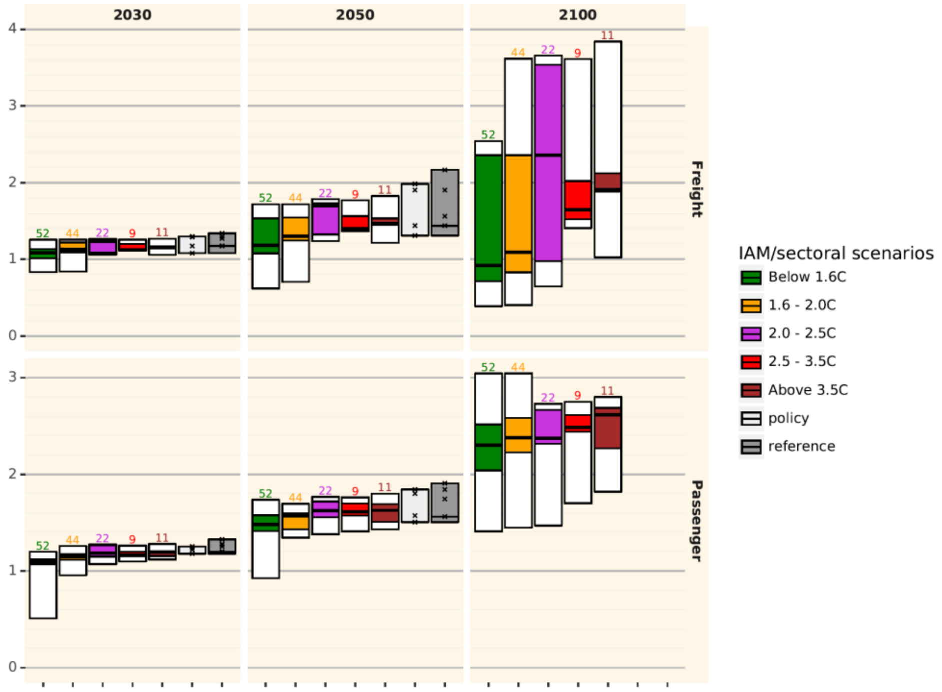

Figure 10.19 Transport activity trajectories for passenger (bottom panel) and freight (top panel)

Source: IPCC AR6 database

Notes: Global passenger (billion p-km/yr) and freight (billion t-km/yr) demand projections, 2020 index, based on integrated models for selected stabilization temperatures by 2100. Also included are global transport models Ref and Policy scenarios.

IAMs indicate passenger transport demand is expected to increase relative to 2015 across temperature targets. For instance, passenger transport demand doubles (relative to 2015) by 2030 and nearly triples by 2050 for the above 2°C scenarios. The median 1.5°C and 2 °C scenarios show a doubling or greater of passenger transport demand by 2050. Unlike passenger demand, freight transport demand decreases through 2050 relative to 2015 under the median 1.5°C and 2°C scenarios. In all other temperature targets, freight transport demand grows by 2050.

GTMs show broad ranges with respect to future travel demand, particularly for the freight sector. These results show more dependency on model than on baseline or policy scenario. According to the most recent ITF Transport Outlook (ITF International Transport Forum, 2019b), global demand for passenger transport and freight could each triple by 2050 in a business-as-usual (BAU) scenario. Mulholland et al., (2018) suggest the freight sector could grow by 2.4-fold over the period 2015–2050 in the reference scenario with the majority of growth attributable to developing countries. The International Energy Agency’s Energy Technology Perspectives (International Energy Agency, 2017a) suggests more modest growth in passenger transport, from 51 trillion pkm in 2014 to 110 trillion pkm in 2060, in a reference scenario without climate policies. Furthermore, the IEA estimates that final energy demand for freight transport could double by 2050 (from 45 EJ in 2014) in their reference scenario. Under IEA’s most ambitious carbon policy, the beyond 2°C scenario, demand for passenger travel remains similar to the reference scenario (around 110 trillion passenger-kms by 2050), while demand for land-based freight transport in 2050 is slightly lower in this scenario (116 trillion ton-km) compared to the reference scenario (130 trillion ton-km. In the IEA beyond 2°C scenario, reductions in emissions would result from efficiency gains and a transition to lower-carbon fuels. The ITF, however, suggests that an ambitious decarbonization policies could reduce global demand for passenger transport by 2050, compared to the business-as-usual scenario. This in turn could reduce emissions from passenger transport by 70% compared to the BAU scenario. Similarly, under strict carbon policy, the ITF suggests that emissions from freight transport could decrease by 45% compared to the BAU scenario, even though demand would be similar in both scenarios. Others suggest contributions greater than 25% in average for both passenger and freight in 2030 and 2050 may be needed to achieve very low carbon emission pathways (Fisch-Romito & Guivarch, 2019).

The reason many models find small differences in passenger transport demand across temperature targets is that IAM models treat demand growth exogenously despite the fact that mitigation efforts would likely increase travel costs and lower transport demand (Runsen Zhang, Fujimori, Dai, & Hanaoka, 2018). Sectoral models often assume mode shift 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 lower emissions.

Studies have recently begun to explore demand-side solutions to reducing transport demand to achieve very low carbon scenarios through a combination of culture and low-carbon lifestyle (Creutzig et al., 2018); urban development and increased vehicle occupancy through mobility-as-a-service (Grubler et al., 2018); improved logistics and streamline supply chains for the freight sector (Mulholland et al., 2018); and disruptive innovation (Wilson, Pettifor, Cassar, Kerr, & Wilson, 2019). However, greater understanding of the mechanisms underlying energy-relevant decisions and behaviors (Brosch, Sander, & Patel, 2016) and the motivations for sustainable behavior (Steg, Perlaviciute, & van der Werff, 2015) are critically needed in order to realize these solutions in reality.

Overall, we find passenger and freight activity will continue to grow rapidly under BAU, but most growth will occur in developing countries. Most models indicate reducing travel activity will play little role in meeting mitigation scenarios, but this is an area of growing and critical research.

Transport mode trajectories

Globally, as the demands of passenger travel grow, the shares of faster modes have continued to increase since the last century (Schafer & Victor, 2000; Schäfer, 2017). This pattern is mainly driven by two separate trends. First, for the short to medium distance travel, private cars displace public transit, particularly in non-OECD countries as consumers' value of time and the aspirations for comfort, status symbols, and convenience increase with GDP growth. Secondly, there is a growing demand for the long-distance travel with aviation for both leisure and business travel. There are, however, also significant variations among countries and cities. For example, even though the share of public transport in UK has dropped from 7% in 1990 to 4.6% in 2016, the opposite trend has been observed in countries such as France, Denmark, and Finland during the same period (eurostat, 2019). In general, smaller and denser countries/cities with higher/increasing urbanization rate tend to have higher success rate in increasing the share of public transport.

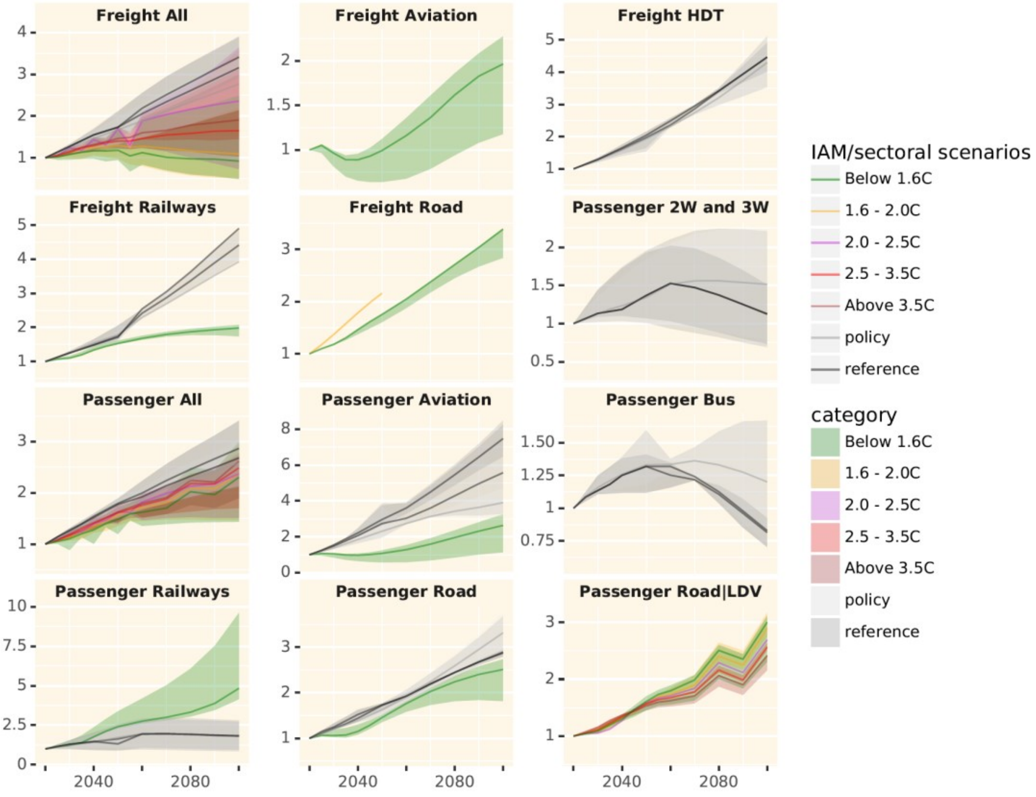

Figure 10.20 Transport activity trajectories for passenger and freight across different modes. Global passenger (billion p-km/yr) and freight (billion t-km/yr) demand projections, 2020 index, based on IAM for selected stabilization temperatures by 2100. Also included are global transport models Ref and Policy scenarios.

Source: IPCC AR6 database.

Figure 10.20 shows activity trajectories for both freight and passenger transport across different modes based on the AR6 database for both IAMs and global transport models. The database is under development with data being collected from modelling teams. The following paragraphs reflect the data currently collected. With respect to road passenger transport in total, both the median from the 1.6°C scenarios of the IAMs and the policy and reference scenario from the global transport models suggest an increase by a factor of around 1.5 to 2 by 2050. In 2100, the spread between the median of the scenarios spans from an increase of 2.5 to 3.5. In terms of the different modes, the median across the broad set of IAM scenarios project fairly similar trajectories with around a 1.5 - 2 fold increase by 2050 towards an increase by a factor of 2-3 in 2100. The global transport models yield a much larger span in their scenarios for 2 and 3 wheelers with the policy scenario spanning from mild decline towards a factor of 2.5 by the end of the century. With respect to bus, we observe a mild increase and decline, as rail transport increases significantly. For the below 1.6°C set of scenarios, the median yield a growth in passenger rail transport by a factor of 5 by the end of the century. For aviation, the reference scenario of the transport models indicates 4-fold median growth relative to 2020, by the middle of the century, towards an 8-fold growth by the end of the century. The below 1.6°C scenarios of the IAMs on the other hand suggests a median increase in passenger aviation of a factor of 1.5 by 2050 and up towards 3 fold by the end of the century.

The overall demand for freight is also expected to grow significantly. In terms of the land transport modes, trucking is expected to grow the most (Mulholland et al., 2018). In Figure 10.20 we can observe that the IAMs predict a growth of around a factor for 2 in 2050 for the below 1.6°C scenarios while the global transport models expect a somewhat higher growth, closer to around factor of 2.5 for the same year. International shipping is also expected to grow by a factor of 3 by 2050. As the heavy-duty truck demand grows the fastest compared to the other modes, trucks gradually become the largest mode used for freight transport. In terms of freight by aviation, the median of the below 1.6°C scenarios is around 30% growth by 2050 and 100% growth by 2100.

The global transport model yields almost overlapping trajectories for both the policy and reference scenario with a factor of 2.5 increase by 2050 and around 4 by 2100. The below 1.6°C scenarios all yield rail freight increase by a factor of 1.6 2050 and around 2 by 2100.

Commonly explored mitigation options related to mode change include shift to public transit, shared mobility, demand reduction through land use and teleconferences for passenger travel (Creutzig et al., 2018; Grubler et al., 2018; Wilson et al., 2019) and improve logistics efficiency, green logistics and streamline supply chains (Mulholland et al., 2018) for the freight sector. Options that induce significant co-benefits in addressing air pollution, congestion, and urban development such as bus improvement or BRTS, metro rail, mobility plan and urban form are commonly the preferred choices in the NDCs proposed especially from developing countries. Whereas developed countries, given saturation in demand growth, focus more on technology options such as E-mobility and fuel economy standards (Sudhir Gota et al., 2016).

Driving remains the fastest growing mode for passenger travel giving the significant growth rate in developing counties. Similarly, trucking is expected to grow the most for the freight. Commonly explored mitigation options related to mode change include shift to public transit, shared mobility, demand reduction through land use and teleconferences for passenger travel and improvements within modes including improve logistics efficiency, green logistics, and streamline supply chains for the freight sector.

Energy intensity

The following section summarizes current data available in AR6 database from IAMs and GTMs on energy intensities and efficiencies for transport. From this data, across different models and scenarios, we observe that light-duty vehicles energy efficiency are expected to evolve at 0.5-2% reduction per year from today’s 2.8-3.1 MJ/vkm (1.5-2 MJ/pkm) by 15-50% by 2050 under the Reference scenario, and steeper reductions to 55-70% percent below today’s level to 0.8-2.0 MJ/vkm (or 0.4-1.0 MJ/pkm) for the mitigation scenarios. Slower magnitudes of reductions are expected for buses (from the current 0.25-0.48 MJ/pkm to 0.2-0.4 MJ/pkm in Reference scenario and 0.19-0.37 MJ/pkm in the mitigation scenarios by 2050) and airplanes (1.8-2.2 MJ/pkm to 1.0-1.8 MJ/pkm in Reference scenario and 0.8-1.8 MJ/pkm in the mitigation scenarios by 2050). The energy efficiency reductions are smaller compared with LDVs for the freight sector in the IAMs and GTMs, from today’s 2.1-2.3 MJ/tkm for heavy-duty trucks to 2 MJ/tkm in Reference scenario and 1.1-1.9 MJ/tkm in the mitigation scenarios by 2050, and 0.15-0.25 MJ/tkm for freight rail to 0.11-0.25 MJ/tkm in Reference scenario and 0.10-0.25 MJ/tkm in the mitigation scenarios by 2050.

Three key trends insufficiently addressed in existing models could increase the uncertainties of the estimates presented in this section: behavioral aspects of passenger transport and freight logistics, rapid and unexpected technological innovation; and the rise of automation, big data and AI (see Section 10.2).

Increasing occupancy rate of passenger transport (Grubler et al., 2018) and reducing empty miles or increasing payload in freight deliveries (Gucwa & Schäfer, 2013; McKinnon, 2018) can present significant opportunities to effectively improve energy efficiency hence lowering GHG emissions in transport. The recent trends of consumer behaviors, however, have shown declining occupancy rate of light-duty vehicles in industrialized countries (Schafer and Yeh, 2020) and the accelerating growing preference for SUVs, challenges emissions reductions in passenger car market (International Energy Agency, n.d.-b).

While the models reviewed in this section include a representation of technologies for decarbonization, these models can fail to capture, sudden and unexpected technological breakthroughs. For example, electrification has progressed faster than previously expected just a few years ago, in other non-LDV mode, including electric scooters, electric buses, electric ferries (Thongam, Tarbouchi, Okou, Bouchard, & Beguenane, 2013), or even electric airplanes for domestic trips (Schäfer et al., 2019) are receiving increasing attention. A sudden and unexpected breakthrough in the electrification of heavy vehicle systems could also provide opportunities to further improve energy efficiencies and reduce GHG beyond what the models suggested that we reviewed here.

Fuel energy and technology

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 GTMs on fuel shares that reflect technology shares across road, aviation, rail and shipping. Oil (fossil), biofuels and gas imply the use of internal combustion engines, electricity implies battery electric for road vehicles and direct electric for trains, and hydrogen implies a fuel cell-based technology. Since the technologies have different conversion efficiencies, the fuel shares do not reflect the share of different technologies among transport services. For example, a current battery electric driveline would be 3 or greater times more energy efficient than current comparable ICE driveline (see section 10.2 for more details).

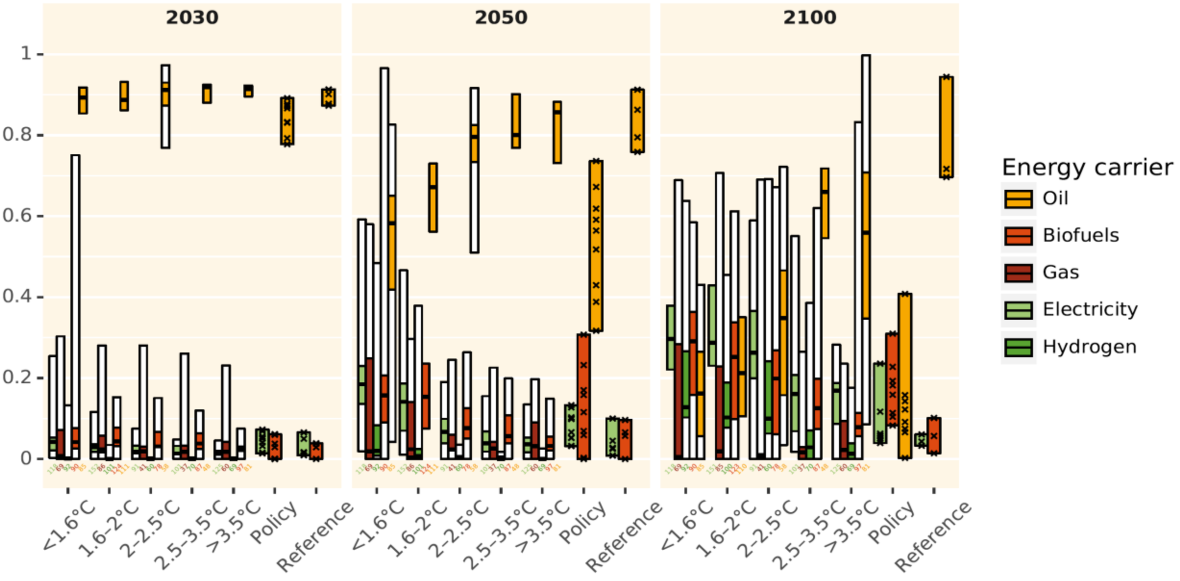

Figure 10.21 Global shares of final fuel energy in the transport sector in 2030, and 2050 Based on integrated models grouped by CO_2eq concentration levels by 2100 and compared with sectoral models (grouped by baseline and policies) in 2050. Box plots show minimum/maximum, 25th/75th percentile and median. Numbers above each bar represent the # of scenarios.

Source: IPCC WGIII AR6 Database

Across model types, Figure 10.21 indicates fuel and technology shifts will be crucial to meet carbon emission reduction targets (IEA-ETP 2017, Edelenbosh et.al 2017). IAMs and sector models maintain high shares of fossil fuels in 2030 across emission trajectories. By 2050, the median share of fossil fuels in IAM trajectories at or below 2.0°C decline to 58-67% of total energy consumption. Driving this decline, electricity and biofuels increases to 14-18% and 15-16%, respectively. Taking energy conversion efficiencies into account, in scenarios below 1.6°C, electricity is on average fueling a similar volume of transport services as fossil fuels in 2050. For the below 1.6°C and 1.6°C-2.0°C scenarios, we observe a continued decrease of the use of fossil fuels yielding median energy shares of respectively 16% and 21% in 2100. The residual fuel mix across the median of these scenarios is covered by a steady increase in electrification and biofuels at about equal levels, while energy from hydrogen is a bit less than half of that from electricity.

In passenger transport, a technology shift towards alternative fuel vehicles, particularly electric and hydrogen fuel cell vehicles, is the dominant driver of decarbonization. Electrifying passenger transport leverages decarbonization efforts in the power sector. In many studies, electrification of light-duty vehicles plays an essential role in meeting carbon targets, so the share of final energy for electric LDVs increases significantly through 2100. Moreover, due to the higher efficiency of electric drive, total transport energy consumption can decrease but transport consumption of electricity can increase. The IEA (ETP 2017) suggests that full LDV electrification would be the most promising low-carbon pathway to meet the 1.75^0 target. The MIT Economic Projection and Policy Analysis (EPPA) model focuses on the future deployment of gasoline versus electric vehicle technologies in the global LDV stock (Ghandi & Paltsev, 2019). Ghandi and Paltsev forecast that the global stock of vehicles will increase from 1.1 billion vehicles in 105 up to 1.8 billion by 2050, with a growth in electric vehicles from about 1 million vehicles in 2015 up to 500 million in 2050. These changes are driven primarily by cost projections (primarily in battery cost reductions). Similarly, the International Council on Clean Transport (ICCT) indicates that the technology adoption of electric vehicles in the light-duty sector can lead to large climate benefits. Their projections 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) forecast transport stocks through 2050 under aggressive climate mitigation scenarios that nearly eliminate road transport emissions. They find demand for passenger transport triples through 2050, but emission targets are met through widespread adoption of battery electric vehicles (80% of LDVs) and, to a lesser extent, fuel cell and plug-in hybrid electric vehicles. Contrary to these forecasts, the 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, Gómez Vilchez, Ensslen, Schäuble, & Fichtner, 2018).

In non-passenger transport, studies indicate a shift toward alternative fuels will need to be supplemented by efficiency improvements. The IEA suggests efficiency improvements will be key for decarbonization of trucks, aviation, and shipping in the short-to-medium term, while fuel switching to advanced biofuels will be needed for decarbonization of freight in the long-term. (Mulholland et al., 2018) investigated the impacts of decarbonizing 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 1.75 °C. Despite deployment of logistics improvements, high efficiency technologies, and low carbon fuels, activity growth leads to increase in energy demand for road freight of 47% and overall GHG increases by 55% (4.8 GTons CO_2e) from 2015 to 2050 in COP21 scenario. In the 1.75 °C scenario, decarbonization happens primarily through a switch to alternative fuels (hybrid electric and full battery electric trucks), which leads to overall reductions in GHG emissions by 60% in 2050 relative to 2015. Khalili et al. (2019) also find substantial shifts to alternative fuels in heavy-duty vehicles under aggressive climate mitigation scenarios, such that 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 will be electrified by 2050.

It is clear that any serious attempt at carbon mitigation in the transport sector must examine the uptake of alternative fuels from fossil gasoline and diesel. Most scenarios we observe in the IAMs and GTMs decarbonize through electrification, but other fuels such as hydrogen and biofuels may also play a significant role in decarbonization—particularly in more aggressive climate scenarios that require near-zero or zero carbon in transport. Shifts towards alternative fuels must occur alongside shifts towards clean technologies in other sectors as all of the alternative fuels have upstream impacts. Without considering other sectors, fuel shifts would not yield their full mitigation potentials.

10.7.3 Scenario summary

This section provides an updated, detailed assessment of futures transport scenarios given a wide range of assumptions and under a set policy targets and conditions. The scenario modelling tools are necessary to aggregate individual options identified in the engineering and LCA literature and understand how they fit into mitigation pathways from a systems perspective. To meet aggressive climate targets, transport is a key sector to decarbonize. It accounts for a quarter of global CO_2 emissions in 2017 and could grow by nearly 50% by 2050 under BAU. To stay below 1.5°C, IAMs reduce transport systems by 80% in 2100. Such These emission reductions can come from addressing transport activity, energy intensity (at the technological or system level), or fuel carbon intensity. IAMs, GTMs, and national transport models generally indicate electrification will be the dominant driver of decarbonization, followed by biofuels and hydrogen. Adoption of these technologies, though, will vary across sectors, transport modes, and regions.

Finally, these models do not account for the systemic changes discussed in section 10.2, that may result from such things as increased automation, the use of big data for planning and operations of the transport system, or the use of blockchain and AI technologies. All of these could affect the variables that determine the carbon intensity of the sector.

Placeholder-This summary will be completed for SOD after bringing together the three decarbonization sections (based on the approach in Aviation) and this section on bottom up and top down modelling.

10.8 Enabling conditions

This final section draws some conclusions from the Chapter, and the outlines an integrated framework for enabling the changes that are emerging, also seeing the broader co-benefits with an SDG lens. It will end with the emerging evidence associated with what people can do as individuals at home, at work or in their communities.

10.8.1 Conclusions

1. Transport is becoming a major focus as its GHG is large and growing faster than other sectors, especially in aviation and shipping.

2. Since AR5 there has been a significant breakthrough in the opportunities to remove transport GHG in an economically efficient way due to electrification of light vehicle systems. This is mostly in light duty passenger vehicles but is moving to buses and trucks.

3. At the same time an equivalent set of technologies for heavy vehicle systems, especially for aviation and shipping, remains elusive. However, options are being trialled and breakthroughs may occur in hydrogen, biofuels, synthetic hydrocarbons or electrification based on different batteries.

4. Transport systems are also socio-economic not just technology systems and there are a range of systemic factors that are developing into potentially important change factors: urban form that minimises automobile dependence; behaviour change programs that emphasize shared values and economies; smart technologies that enable better options for transit and active transport as well as integrated approaches to using autonomous vehicles; new ways of enabling electric recharge systems to fit into electricity grids that balance grids and reduce range anxiety in EV's; and new concepts for the future economy such as circular economy, dematerialization, shared economy and decoupling, that are beginning to change transport GHG.

5. Scenarios using bottom-up models and top-down models are joined into the perspectives generated from the scientific overview to shape transport outcomes into Business-As Usual, Incremental and Transformative options for the future.

10.8.2 Policy framework

The Multi-Level Perspective (MLP) of transition theory have become a major way of understanding how to do effective policy work in complex issues like climate change (Geels, Sovacool, Schwanen, & Sorrell, 2017) Grubb et al (2014); (Frantzeskaki, Broto, Coenen, & Loorbach, 2017) (Wolfram & Frantzeskaki, 2016). The MLP proponents have set out a framework and tools for enabling technological changes that are facing significant cost and systemic barriers but usually can be seen to offer solutions to broader sustainability concerns that can help achieve other development objectives (SDGs) (Bulkeley et al., 2011). While the challenge is that climate change is a "wicked problem" wherein considerable uncertainty prevents easy solutions, a related quandary is that complexity necessitates combining evidence-based decision-making with experiential knowledge to ensure solutions are transparent, forward-looking and context-appropriate (Friend et al., 2014).

The MLP Framework has three levels:

1. Micro level where there are technological niches requiring small scale tools relevant to R&D in organizations and communities.
2. Meso level where there are a patchwork of socio-technical regimes that influence markets and pricing and the tools are needed to show how the system can change for the better.
3. Macro level where the whole landscape or governance system needs to be transformed mainly involving public authorities resetting the regulations and recreating appropriate institutions.

Figure 10.22 and 10.23 set out the three Multi Level Phases and where the two groups of transport technologies and their associated fuels presently can be located.

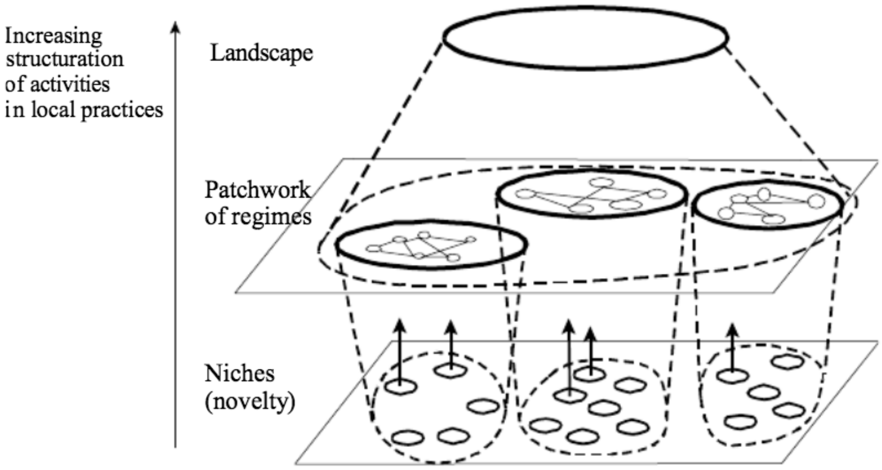

Figure 10.22 Multi-Level Phases of Transition Theory (Geels, 2018)

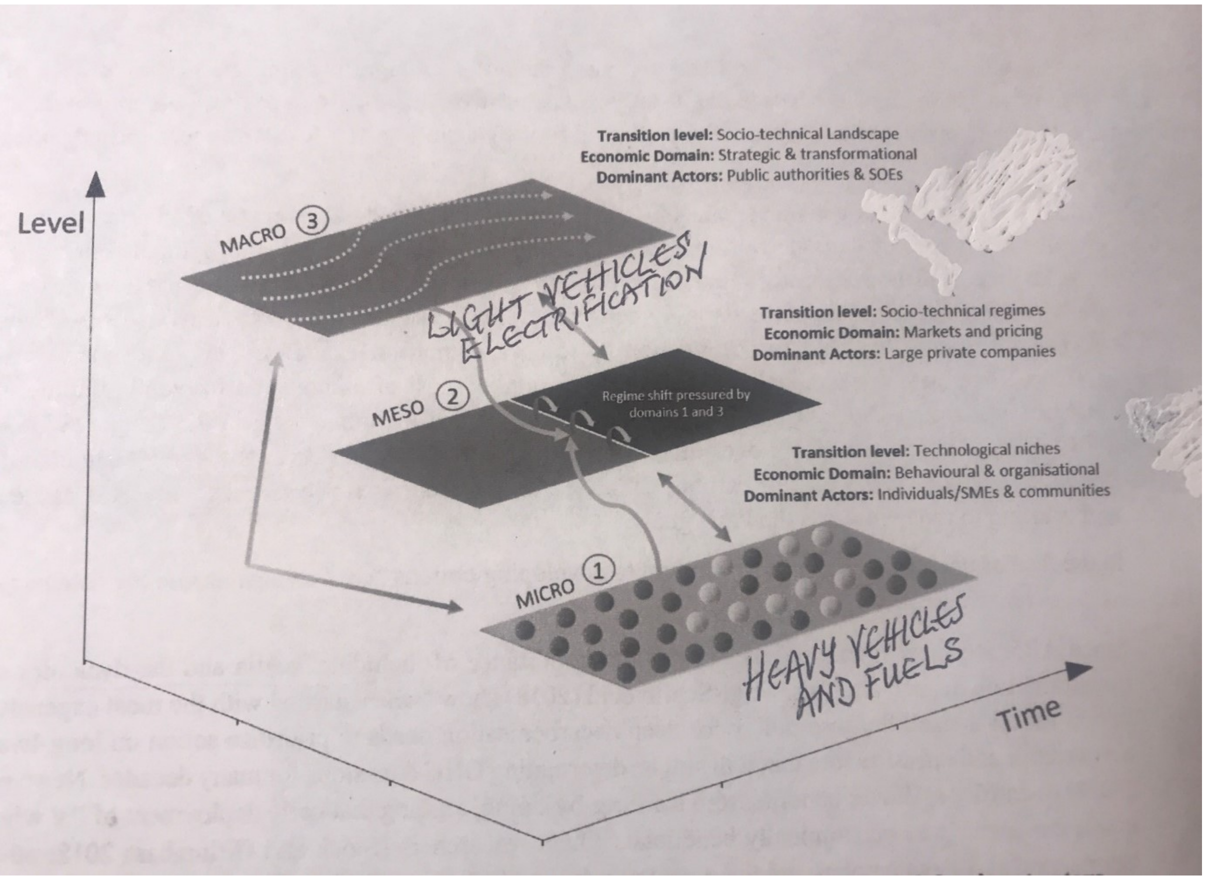

Figure 10.23 The MLP levels as set out in Chapter 1 with the Heavy and Light Vehicle Systems.

The two groups of transport technologies are in different stages in the Multi Level Phases of transition as set out Figure 10.23. The light vehicles, usually just for passengers in cities, and heavy vehicles for passengers and freight, especially planes and ships, will be discussed separately using the tools suggested by Grubb et al, (2014) and elaborated in Chapter 1.

Light Vehicle and Transit Electrification. Light vehicle electric mobility is at the Meso and Macro level with technologies that are rapidly maturing as they are brought into cities and regions but there are tools such as LCA that can help show the benefits to particular places and tools such as subsidies that will enable electric light vehicles to be rapidly adopted. At the Macro level transformational change will need to resolve the issues of recharging and grid stabilization as well as many issues from barriers imposed by present markets threatened by the changes. There is a necessity to create more efficient and effective policy mechanisms that aim to establish self-sustaining markets (Green et al, 2014). Regulatory changes are increasingly barriers that need to be removed as the new grid systems emerge with batteries and other storage systems for grid stabilization; the role of electric vehicles in enabling a stable, smart system for recharge and grid enhancement still needs some large-scale testing and assessment of barriers (Sierzchula, Bakker, Maat, & Van Wee, 2014). The synergies between emerging technologies and the shared economy applied to transport, can help address some of the challenges facing EV adoption and the combination of all can offer even greater benefits for EVs, especially with new public transport systems (Taiebat & Xu, 2019) (G. Wang et al., 2019) (Newman et al, 2020).

Heavy Vehicles and Fuels. Heavy vehicle mobility able to achieve major decarbonization is still at the micro level with complex options and major issues to be resolved over the best options to be adopted (section 10.4, 5 and 6). R&D programs and trials are the best focus for achieving fuels for such systems as well as how best to reduce the need for such mobility and to shift to better modes. There will need to be education about why such changes are needed and how particular solutions can help with demand (section 10.2, 3, 4 and 5). Small trials of electric trucks in mining as well as urban parcel delivery and electric buses in several cities, for example, are helping establish a demand and show the benefits that will enable electric heavy vehicles to be more rapidly adopted (Yang et al., 2018) (Lajunen & Lipman, 2016) (Lee, Thomas, & Brown, 2013). Regulatory changes need to be made to ensure barriers are removed in new procurement systems that accommodate uncertainty and risks inherent in the early adoption of e-buses, e-airport and e-shipping port systems and their corresponding infrastructures (European Commission, 2017; Sclar et al, 2019; Boren, 2019). Long-term visions, including creative exercises (see 10.8.4) of cities and regions are needed that begin to trial the new technologies (Sclar, Gorguinpour, Castellanos, & Li, 2019) (Geels, 2019).

Grubb et al (2014) suggest that the economic tools needed are also at three levels based on individuals or communities, private companies and public authorities with some overlap on the Geels multi-level perspective. They suggest that the tools of behavioural economics which set up demand patterns can influence the micro level (as well as the macro level) and the key actors will be small entrepreneurial organizations, especially if they are funded or financed to do the R&D with demonstrations. This applies very clearly to heavy vehicles and their potential fuels. The next level needs neoclassical and welfare economics at the meso scale to enable markets to be generated through mass production. This is happening to light vehicles as they are being electrified in mass production now and need to go up to the next level quickly. At the macro level there is a need for evolutionary economics that enables the transformations to fully mainstream the system of transport in cities and regions for people. This is likely to be the need for governments and large companies to enable the integration of public and private goals into a fully developed carbon zero system for light vehicles over the next few years (Geels, 2019; IEA, 2019).

Finding the right level and appropriate tools depends a lot on the level of economic maturity in the city, region and nation. Developing economies are better placed to leave the micro level R&D-based work on heavy vehicle mobility to more developed economies but it is possible that lighter vehicle systems can rapidly be adopted in emerging economies where large growth and lower mobility provide opportunities to leap frog into the new electric systems (IEA, 2019; European Commission, 2017). China has already shown it can leapfrog developed nations by its rapid development of electric transport in e-bikes, e-cars, e-buses, e-trains and the new Trackless Trams which are a cross-over innovation from High Speed Rail (Dans, 2019; Gao and Newman, 2019; Newman et al 2019).

10.8.3 Tools and strategies

All economies will need to find the right tools and strategies to use for both mobility systems. Tools and strategies are set out in Table 10.9 for both Light Vehicle Systems and Heavy Vehicle Systems.

Table 10.8

Tools and Strategies	Light Vehicle Systems	Heavy Vehicle Systems
1. Education and R&D	Behaviour change programs are needed as EV's become more mainstream. R&D is mostly needed 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 (Taiebat and Xu, 2019; Newman, et al, 2020)	Less emphasis on education and more on R&D to test the full life cycle costs of various heavy vehicle options (European Commission, 2017)
2. Access and Equity	Significant equity issues with EV's in the transition period require programs to address (IRENA, 2016)	Shipping less a problem but aviation looking heavily to demand management with big equity issues (Bows-Larkin, 2015).
3. Financing Economic Incentives and Partnerships	Multiple opportunities for financing, economic incentives and partnerships with clear economic benefits. The role of value capture in enabling such benefit is being demonstrated. The nexus between EV's and the electricity grid needs demonstration partnership projects (Sierczhula, 2014; Zhang et al, 2014; Mahmud et al, 2018; Newman Davies-Slate and Jones, 2018)	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 on all international transport. Abolishing fossil fuel subsidies and providing carbon taxes are likely to help in the early stages of heavy vehicle transitions (Sclar et al, 2019)
4. Co-benefits and Overcoming Fragmentation	The SDG benefits in zero carbon light vehicle transport systems are being demonstrated and these can now be quantified as nations mainstream this transition. Holistic projects are clearly more able to demonstrate such benefits. New methods for doing Benefit Cost Ratios that make more of health benefits in productivity are now favouring transit and active transport (UK DoT, 2019; Buonocore et al, 2019).	Heavy vehicle systems can also demonstrate SDG co-benefits if formulated with this in mind. Demonstrations of how SDG's can benefit are needed for all options being studied. Such projects need cross-government consideration (Pradhan et al, 2017).
5. Regulation and Assessment	With zero carbon light vehicle systems rapidly growing the need for a full assessment of regulatory barriers needs to be assessed in each city and region as well as different economic opportunities and a sustainable business model (SBM) (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)

6. Governance and Institutional Capacity	Governance and institutional capacity can now be provided, international exchanges and education programs based on successful cities and nations enabling light vehicle decarbonisation to create more efficient and effective policy mechanism towards self-sustaining markets (Green, 2014; Skjolsvold and Ryghaug, 2019)	Governance and institutional capacity will require significant interventions such as levies or carbon taxes to enable heavy vehicle system transitions away from fossil fuels. Unless a global system of transparent accounting for international transport can be accomplished this part of the transport market will continue to fail in its decarbonization (Makan and Heyns, 2018)

10.8.4 What can people do?

IPCC reports have increasingly shown that there is a role for programs and policies that can better involve people in helping bring about change. Transport is something that everyone can relate to on a daily basis. This final section will therefore focus on how people-oriented programs and policies can help to decarbonize transport for the future.

Creative foresight

Human culture has always had a creative instinct that enables the future to be better dealt with through imagination (Lent, 2016). Science and engineering have often been preceded by artistic expressions such as Jules Verne who first dreamed of the hydrogen future in 1874 in a novel The Mysterious Island. Autonomous vehicles have regularly occupied the minds of science fiction authors and film-makers (Braun, 2019). Such narratives, scenario building and foresighting are increasingly being seen as a part of the climate change mitigation process (Baer, 2015; Vervoort et al, 2018) and to even 'liberate oppressed imaginaries' as suggested by Luque-Ayala (2018). McPherson et al (2016) have emphasized the important role of positive images about the future instead of dystopian visions that are simply based around the science of climate change and the impossibility of business-usual futures. Transport visions need to be a part of this cultural change as well as the more frequently presented visions of renewable energy (Ruotsolainen, 2017; Wentand, 2016). There are some emerging technologies (discussed in s10.3.5) like Maglev, Hyperloop, and Drones that are likely to continue the electrification of transport even further (Kasliwal et al., 2019) and which only recently at the imagination stage. Decarbonized visions for heavy vehicle systems appear to be a core need from the assessment of technologies in this Chapter.

Initiatives to induce behavioural change

This Chapter has shown there is a growing significance to behaviour change (Creutzig, et al, 2018). There is emerging evidence on the effectiveness of 'nudging' strategies to induce behaviour change which are set out in Table 10.10. Nudge tools for sustainable transport behaviour could include changes in physical environment such as infrastructure, clear and simplified information on available choices, improving existing options and use of descriptive social norms (Lehner, Mont, & Heiskanen, 2016). Shifting to active transport and public transport is enabled by a combination approach including 'carrots' that incentivise a shift away from private transport and 'sticks' that disincentivise car ownership and use (Petrunoff, Rissel, & Wen, 2017) Gao and Newman, 2019).

Options to facilitate a switch to public transport could include measures that reduce vehicle ownership such as high taxes on cars or which reduce vehicle use such as congestion charges, and high parking fees (Ahmad et al., 2016). Parking management is one key to reducing private transport growth, however it is difficult to manage unless it is part of a package of other options that are made better by parking fees (Richardson, 2017). New transport infrastructure such as busway/trackless tram systems complimented by biking and walking infrastructure could lead to behaviour change, especially if they involve attractive new walking environments involving biophilic design, walkable urban design and behaviour change programs (Soderlund, 2019; Gehl, 2012; (Heinen, Harshfield, Panter, Mackett, & Ogilvie, 2017b). Evidence suggests a high potential for bikeshare programs especially if they involve an enabling environment which includes other complementary pro-cycling measures (Ricci, 2015).

Incentives such as free public transport fares can enhance mobility of low income households (Cats, Susilo, & Reimal, 2017). Hourly parking pricing could complement road pricing and other strategies to reduce demand, however, when the parking space demand is inelastic, demand may not respond directly to the increase in parking price. Recent experiments using mobile phones to generate travel behaviour and personal profiles to nudge users to change their mobility behaviour on a personalized level have shown positive results (Anagnostopoulou et al., 2018).

Recent studies emphasize the need to shift from interventions focusing in the narrower 'personal choice' space towards a more systems perspective focusing on institutional responsibility (Spotswood et al., 2015). This suggests that individuals will respond more if they are part of a group whether this is a local community group or neighbourhood (Brog et al, 2007), or at work where their organizational culture assists people to make choices that help their active travel arrangements; such support has been shown to greatly improve worker productivity (Sallis, 2016). Institutions can facilitate change by adopting an organisation culture that motivates sustainable behaviour. Leadership support and pro-environment behaviour, initiatives to make walking and cycling options attractive by imposing speed limits for motorized vehicles, campaigns such as bike to work and free transport passes can influence employee behaviour positively (Blok, Wesselink, Studynka, & Kemp, 2015). Similarly, parallel initiatives such as parking charges and eliminating car benefits at workplaces could be effective in reducing car use (Christiansen, Engebretsen, Fearnley, & Usterud Hanssen, 2017; Metzler, Humpe, & Gössling, 2019).

Transport interventions to enable active and transit improvements offer co-benefits (Lecompte & Juan Pablo, 2017; Priya Uteng & Turner, 2019; De Vos, Mokhtarian, Schwanen, Van Acker, & Witlox, 2016; Petrunoff et al., 2017). Lack of methodologies to calculate these benefits often results in an undervaluation of health benefits in transport policy evaluations (Brown, Diomedi, Moodie, Veerman, & Carter, 2016) and new approaches such as the UK Department of Transport 'Active Transport Appraisal' are showing dramatic changes in Benefit Cost Ratios towards modes that increase transit, walking and cycling.

Table 10.9 Initiatives that facilitate transport behaviour change and their impact on mitigation and SDGs

Category	Intervention	Behaviour change	SDG impacts	References
IT	User behaviour data to nudge behaviour	■		(Anagnostopoulou et al., 2018; Klecha & Gianni, 2018; Smidfelt Rosqvist & Hiselius, 2016)
	Transforming travel behaviour related to shopping	□		
	Smart phone apps to encourage physical activity			
Incentives	Free public transport fares	▣	+++	(Cats et al., 2017)
Pricing	Congestion charging	□	- -	(Christiansen et al., 2017)
	Workplace parking charges	■		

	Intercity pricing	▓		
	Hourly parking pricing	▒		
	Taxes on cars	▓		
Restrictions	Reducing parking	▒		(Kammerlander et al., 2015)(Mohan, Tiwari, Goel, & Lahkar, 2017)
	Driving restrictions, Odd-even policy	░	-	(W. Zhang, Chen, Wang, Huang, & Wang, 2017)
Awareness and advocacy	Promotions through campaigns, training and education on cycling, providing information on impacts of car use	▒	++	(Savan et al. 2017; Kammerlander et al. 2015; Nugroho, 2020)
New Transport Infrastructure	Bike sharing, network of bike routes, separate bicycle lanes, safe parking for bicycles, integration of bikes with public transport	▓	+++	(Heinen et al., 2017b; Nematchoua, Roshan, Tchinda, Nasrabadi, & Ricciardi, 2015; Otero, Nieuwenhuijsen, & Rojas-Rueda, 2018; Ricci, 2015)
	Busway systems	▓		
Organisational culture	Campaigns such as Bike to work	░	++	(Petrunoff et al., 2017; Young et al., 2015)
	Managing parking the at workplace	▓		
	Leadership and organizational commitment	░	++	
	Management support and training	░		

Behaviour change

Large	Moderate	Minor
▓	▒	░

SDG impact

Direction/scale	Large	Moderate	Small
Positive	+++	++	+
Negative	- - -	--	-

Transport Climate Emergency Plans and Local Pledges

The above literature suggests that national, regional and local governments could produce transport plans with a climate emergency focus that involve commitments or pledges from institutions such as work places, local community groups and civil society organizations that involve behaviour change towards more active and low carbon transport. It could also involve pledges from major freight companies, airlines and shipping companies with attempts to link their customers to the need for action on climate change. Such pledges are increasingly part of climate change legislation including the Paris Agreement and at other levels of government such as how regional/provincial governments involve local government (e.g. Victorian Government, 2019; Jaeger et al, 2019). These are based often around Local Low Carbon Transport Roadmaps which are now happening in India and China as well as through the UNCRD's Environmental Sustainable Transport program (Pathak and Shukla, 2016; Baeumler et al, 2012; UNCRD, 2010; 2019). Such pledges can be calculated at a personal level and applied through multiples at every level of activity (Meyer and Newman, 2019, 2020).

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