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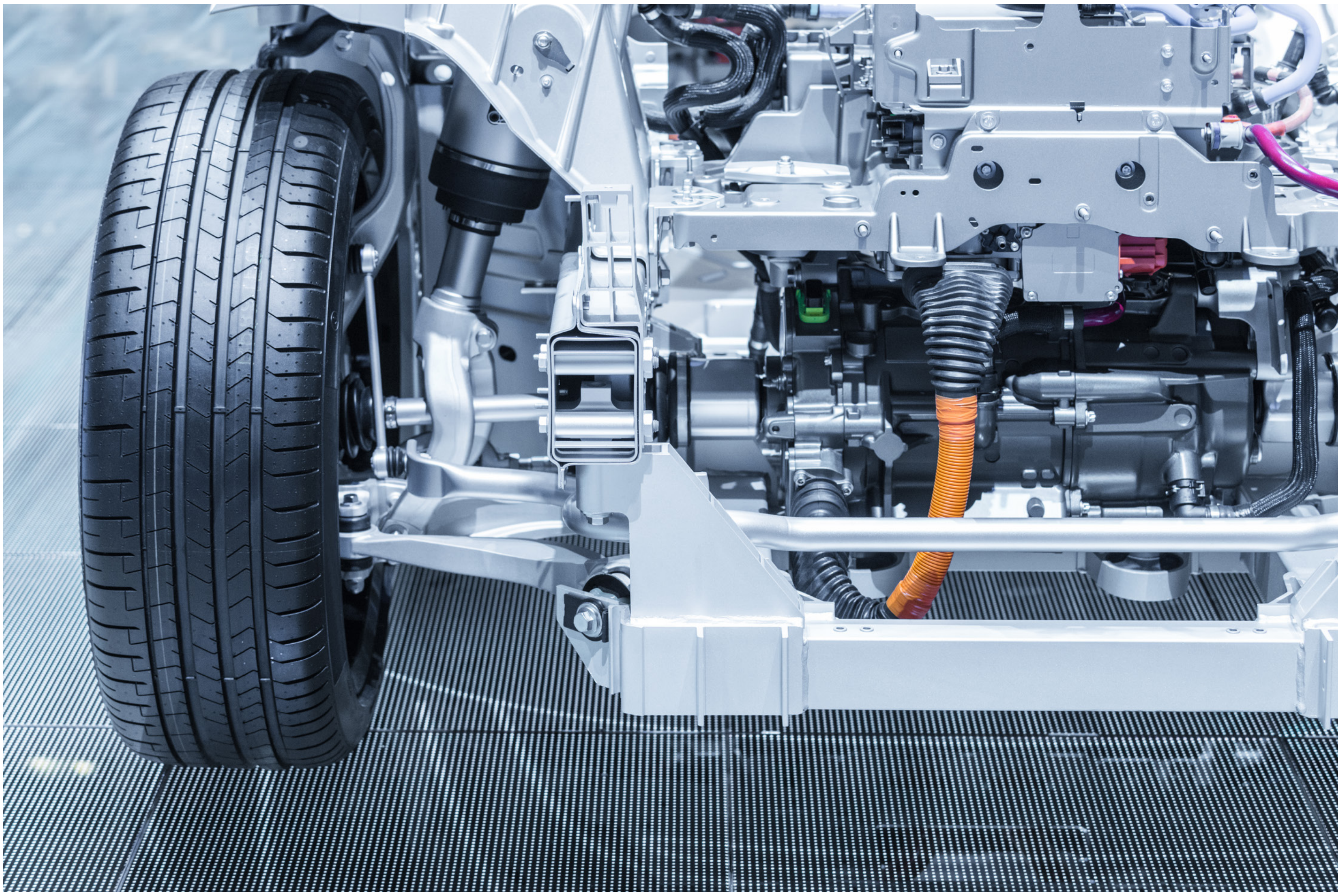
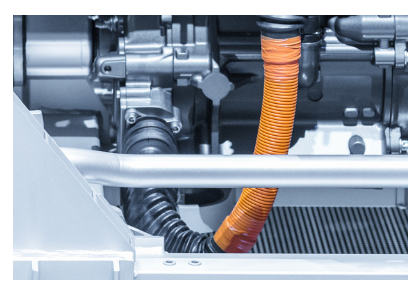


Cleaner Vehicles

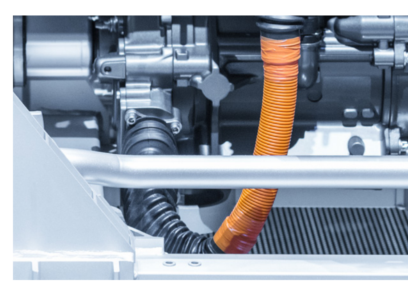
Achieving a Resilient Technology Transition



Decarbonising Transport

Decarbonising Transport • Initiative •

Cleaner Vehicles
Achieving a Resilient Technology Transition



Decarbonising Transport

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The International Transport Forum is an intergovernmental organisation with 63 member countries. It acts as a think tank for transport policy and organises the Annual Summit of transport ministers. ITF is the only global body that covers all transport modes. The ITF is politically autonomous and administratively integrated with the OECD.

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International Transport Forum
2 rue André Pascal
F-75775 Paris Cedex 16
contact@itf-oecd.org
www.itf-oecd.org

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- tracks progress to evaluate how current mitigation measures contribute to reaching objectives for reducing greenhouse gas (GHG) emissions from transport
- develops in-depth sectoral and focus studies to identify effective policies in specific modes (e.g. road transport) and thematic areas (e.g. cities)
- brings policies together to form a catalogue of effective measures, to support countries in developing their GHG emissions mitigation strategy in transport
- supports the policy dialogue, leveraging on extensive engagement with the United Nations Framework Convention on Climate Change (UNFCCC), including the ITF's designation as a focal point for transport of the Marrakech Partnership for Global Climate Action (MP-GCA).

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Abbreviations and acronyms

BEPS	Base Erosion and Profit Shifting
BEV	Battery Electric Vehicle
CCS	Carbon Capture and Storage
C-ITS	Cooperative-intelligent Transport Systems
DAC	Direct Air Capture
DSRC	Dedicated Short-range Communications
ERS	Electric Road System
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas
GNSS	Global Navigation Satellite System
HDV	Heavy-duty Vehicle
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
IoT	Internet of Things
ITS	Intelligent Transport Systems
LZEV	Low- or Zero-emission Vehicle
OEM	Original Equipment Manufacturer
PEMS	Portable Emission Measurement Systems
PHEV	Plug-in Hybrid Electric Vehicle
REE	Rare Earth Element
SMR	Steam Methane Reformation
SUV	Sport Utility Vehicle
TTW	Tank-to-Wheel
UNFCCC	United Nations Framework Convention on Climate Change
Vkm	Vehicle Kilometre
WTT	Well-to-Tank
WTW	Well-to-Wheel

Executive summary

What we did

This report identifies technologies capable to help transition road transport to clean vehicles in a cost-effective manner. It covers passenger cars, light commercial vehicles, buses and trucks and focuses on large vehicle markets and major economies, namely China, Europe, Japan, Korea and the United States. The study assesses how policies can promote this transition in a way that can also foster inclusive economic growth and sustainable development, and how the transport and energy sectors will likely respond to these. The report also highlights policy challenges for the transition to clean vehicles and proposes ways to address them. Particular attention is paid to electric and electrified vehicles.

What we found

A combination of factors has increased interest in, and the deployment of, clean vehicles. First, policies have stimulated innovation in clean vehicle and clean energy technologies. Second, recent developments allow cost reductions and productivity improvements, especially in battery and renewable energy technology. Third, policy makers have become increasingly aware of these dynamics.

These factors have significantly impacted the market capitalisation of automakers and energy companies. New competitors have entered these markets, driven by prospects for market growth and spurred by technological advantages over incumbents. Covid-19 has further accelerated the deployment of clean vehicles, especially electric vehicles, as many governments put in place economic stimuli aiming to drive a recovery subject to lower financial, climate and sustainability risks.

The ambitious decarbonisation targets announced by an increasing number of governments and non-state actors include a complete transition to low- and zero-emission vehicles new buses by 2030, passenger cars by 2035 and trucks by 2040. This heralds a significant acceleration in the pace of adoption of clean mobility. Announcements and investment decisions by vehicle manufacturers, battery producers, energy companies, fleet operators and technology companies also indicate a change in pace along the low- and zero-emission vehicles value chain.

Digital technologies increase competitiveness and consumer attractiveness for existing products, help developing new products and create new markets. Financial markets value digital technology companies because of these characteristics. Governments increasingly seek integrated policies to maximise benefits and address challenges of digital technologies, given their pervasiveness, importance and likely role as a pillar of the future economy. This is also the case for transport, which sees substantial development and deployment of digital technology, notably in the areas of connectivity and automation.

Policy action encouraging the adoption of clean, connected and autonomous vehicles will likely accelerate due to falling costs and opportunities from continued technological improvements. Increasingly, governments will also need to manage the resulting changes to ensure a just transition. Some are already moving towards an integrated, whole-of-government approach to maximise the benefits from clean vehicles while addressing the challenges of the transition.

Some significant implications of the transition are already discernible. First, the change in powertrain technologies and a switch to renewable electricity will increase the demand for new materials and the pressure on related supply chains. Second, the shift towards alternative vehicle fuels will rapidly reduce government revenues from fossil fuel duties. Third, and perhaps most importantly, the shift to clean and digital technologies in the automotive and energy sectors will impact jobs and required skill sets. Government action to tackle these challenges will need to avoid missing opportunities to stimulate economic development compatible with sustainability goals.

What we recommend

Support the adoption of clean vehicles with targeted policy action and by increasing transparency of their carbon footprint

A policy framework for supporting the uptake of clean vehicles will include several elements: a clear vision with medium- to long-term targets; technical standards and regulations; energy prices and taxes that favour clean vehicles; ambitious public procurement programmes for clean vehicles; economic incentives that enable cost reductions for new technologies and foster industrial transformations; regulatory requirements for the market penetration of clean vehicles and energy based on their lifecycle impacts; the reinforcement of networks for the distribution of low-carbon energy vectors; and the deployment of charging and refuelling infrastructure for clean mobility.

Prioritise a transition to direct electrification of vehicles and renewable energy

Direct electrification of vehicles and renewable electricity are best placed to deliver timely and significant environmental benefits and energy efficiency for road transport vehicles. They also reduce costs and increase economic productivity and therefore should be prioritised in industrial strategies. Regulatory frameworks should allow electric vehicles to help stabilise the electricity network and optimise its use, leveraging digital technologies to better align electricity demand and supply. This will also be important for creating synergies between developing electric mobility and the renewable energy sources they need, in particular wind and solar, which are inherently subject to variable supply patterns.

Address challenges in resource efficiency and sustainable supply chains

Regulations that extend the life of batteries into second-life applications and ensure adequate end-of-life treatment through recycling will improve resource efficiency. Solutions that help to avoid oversizing vehicles and batteries will enhance material efficiency further. These include plug-in hybrid electric vehicles if mainly used in all-electric mode. Electric road systems can enable large shares of all-electric driving with smaller batteries. Reaching a consensus on their wide adoption and limiting risks for their deployment is essential. Measures to integrate electric vehicles and renewable electricity into the power sector also save resources. Traceability of materials helps to minimise the carbon footprint of batteries and enhance recycling rates. It supports the establishment of sustainable supply and value chains if combined with sustainable labour and environmental practices in resource extraction and processing.

Prepare for a transition from fuel duties by seizing opportunities arising from increased connectivity and accelerating enabling regulatory actions

Clean vehicles need to pay for the road transport infrastructure they require. They may also need to contribute to avoiding shortfalls in government revenue from fossil fuel taxes. Taxing carbon and distances driven instead of fuel can prevent conflicts between environmental and fiscal objectives. Regulations for connected vehicles and intelligent transport systems should require manufacturers to make on-board telematics systems capable for digital road-use charging. Regulations should ensure these systems can be interoperable across borders, future-proof and backward-compatible. Additional opportunities to address congestion effectively can come from ensuring that user charging can be location- and time-specific.

Include infrastructure for easy access to clean energy and digital connectivity of road transport in Covid-19 recovery packages

Covid-19 recovery packages should support the roll-out of charging infrastructure and the strengthening of electricity transport networks. Electric vehicles will become increasingly cost-competitive and prevalent, and providing charging points aligns well with the post-pandemic focus on publically-funded infrastructure. Public investment is also vital for electric road systems and could support hydrogen refuelling solutions, provided that prospects for cost reductions and low-carbon production improve. Covid-19 recovery funds for connected transport infrastructure to enable smart road user charging, geo-fencing and other applications can also support a resilient transition to low-carbon vehicles and energy.

Prepare for the impact of the sustainable mobility transition on jobs, required skill sets and social equity

Governments need to strengthen their ability to assess the wider impacts of the concurrent shift towards electrification, renewable energy, digitalisation and automation. Improving their foresight capacity will also give them a better understanding of socio-economic consequences and, for instance, help to anticipate the impact on jobs and required skills. Developing policies and programmes for training and up-skilling will be crucial to ensuring that affected workers are adequately supported and that the benefits of the transition to sustainable mobility are shared among all citizens. This is a vast challenge. Addressing it is likely to require significant budget allocations. Funding could come from tax reforms, such as the OECD/G20 Inclusive Framework on Base Erosion and Profit Shifting (BEPS) and the introduction of a global minimum corporate income tax for multinational enterprises.

Accelerate the development of other low-carbon technologies

Technological progress for low-carbon technologies other than direct electrification is still in need of a boost to reach greater readiness levels. Accelerating progress for bringing low-carbon hydrogen, synthetic fuels and other forms of carbon-neutral fuels as well as some low-carbon sustainable biofuels to market can help to decarbonise legacy vehicles. They are also crucial to help cutting the carbon footprint of hard-to-decarbonise transport modes such as aviation and shipping and may be necessary in cases that are most challenging to electrify in long-haul trucking. Support efforts should focus on the low-carbon technologies with the strongest sustainability impact and the highest potential to compete on cost with direct electrification. This support is important to mitigate asset and job stranding as well as geopolitical impacts on sectors like oil and gas that are particularly exposed to the shift to electrification and renewable energy.

Introduction

Road vehicles are crucial enablers of a wide range of passenger and freight services, and therefore a vital instrument serving our economy and our society. Road vehicles account for about 70% of all passenger kilometres globally, and about 20% of all tonne-kilometres (ITF, 2021a). The automotive industry, which is responsible for road vehicle production, is also a major industrial and economic force in several economies. Its annual turnover is equivalent to the size of the sixth-largest economy in the world (ILO, 2021). Its GDP share is high in developed countries (more than 10%), and its contribution is also rising in emerging economies. The industry is capital-intensive, a key driver of innovation (Grosso et al., 2020; IEA, 2020a), and capable of mobilising billions of dollars in investment.

Additional indirect impacts on socio-economic development come from the facts that road vehicles require extensive road infrastructure to operate, that road vehicle production is an important driver of demand of metals and other materials (e.g. rubber) (Cooper, Doody and Allwood, 2017), and that the automotive industry is also a major consumer of energy. Both vehicle and energy production, along with the construction and maintenance of the infrastructure they require, are also important sources of direct and indirect employment (ILO, 2018).

Given their major importance in the global economy and nearly complete dependence on fossil fuels, it is unsurprising to see that road transport vehicles represent a large fraction of total energy use (direct and indirect) globally. For the same reasons, road transport vehicles also account for most direct greenhouse gas (GHG) emissions from transport. Before the pandemic, three-quarters of global transport emissions came from the road sector (IEA, 2021a); of this, passenger transport accounted for about two-thirds.

Taking all these aspects into consideration, in conjunction with growing global interest in mitigating environmental impacts (starting from climate change), this report looks into ways road transport can continue to help foster inclusive economic growth and development while also helping governments and industry reach sustainable development goals. Although there are good reasons for doing so in a way that integrates aspects related to travel demand management (e.g. reducing discretionary trips, chaining trips to reduce overall vehicle kilometres, and avoiding unnecessary travel thanks to better urban and transport planning and solutions), the focus of this analysis is on the role of vehicle powertrain technologies and the energy vectors they need to improve energy and resource efficiency while mitigating GHG emissions. The scope of this analysis covers vehicles serving all road transport modes, except for two- and three-wheelers.

The aim of this work is to help governments chart a way forward for supporting and accompanying the move towards sustainable mobility and clean energy. It emphasises not only policies that can stimulate change, but also instruments that can help manage upcoming challenges and ensure a resilient and just transition to low-carbon mobility. The analysis first examines the technical characteristics of different options, with a focus on energy efficiency and GHG emissions. This is followed by an analysis of costs, a brief assessment of the status of the market, and a review of key policy and market drivers that have led to important changes in the recent past. The report then turns towards challenges governments will need to consider while making policy choices and concludes with a set of recommendations for upcoming policy priorities.

Clean vehicle technologies

The amount of GHG emissions produced by vehicles varies significantly based on the type of vehicle and its usage profile, as well as the powertrain technologies and sources of energy that are used. These characteristics also affect air pollutant emissions, vehicle costs and energy and material requirements.

This report identifies the most promising technological options for the main vehicle market segments, taking into consideration their capacity to reduce GHG emissions, maximise energy and resource efficiency, and offer the best economic competitiveness, while also paying attention to emissions of local air pollutants. The report focuses on the potential for 'clean' vehicle technologies to reduce environmental and health impacts, especially GHG and air pollutant emissions, on a lifecycle basis.

This section begins by comparing potential clean vehicle technologies to conventional combustion engines powered by fossil energy. The analysis combines insights available from lifecycle assessments, considerations on the thermodynamic efficiency of different processes, and insights related to the availability of alternative transport fuels. The assessment also considers the importance of minimising and optimising the use of resources required to manufacture vehicles and their powertrains, in addition to the production, transport and distribution of fuels.

Particular attention is paid to electric vehicles (EVs), including battery electric vehicles (BEVs) and plug-in hybrid EVs (PHEVs). Hydrogen fuel cell vehicles are also analysed in greater detail than combustion technologies in this assessment. Alternative fuels for internal combustion engine (ICE) and hybrid vehicles are assessed at the end of this section.

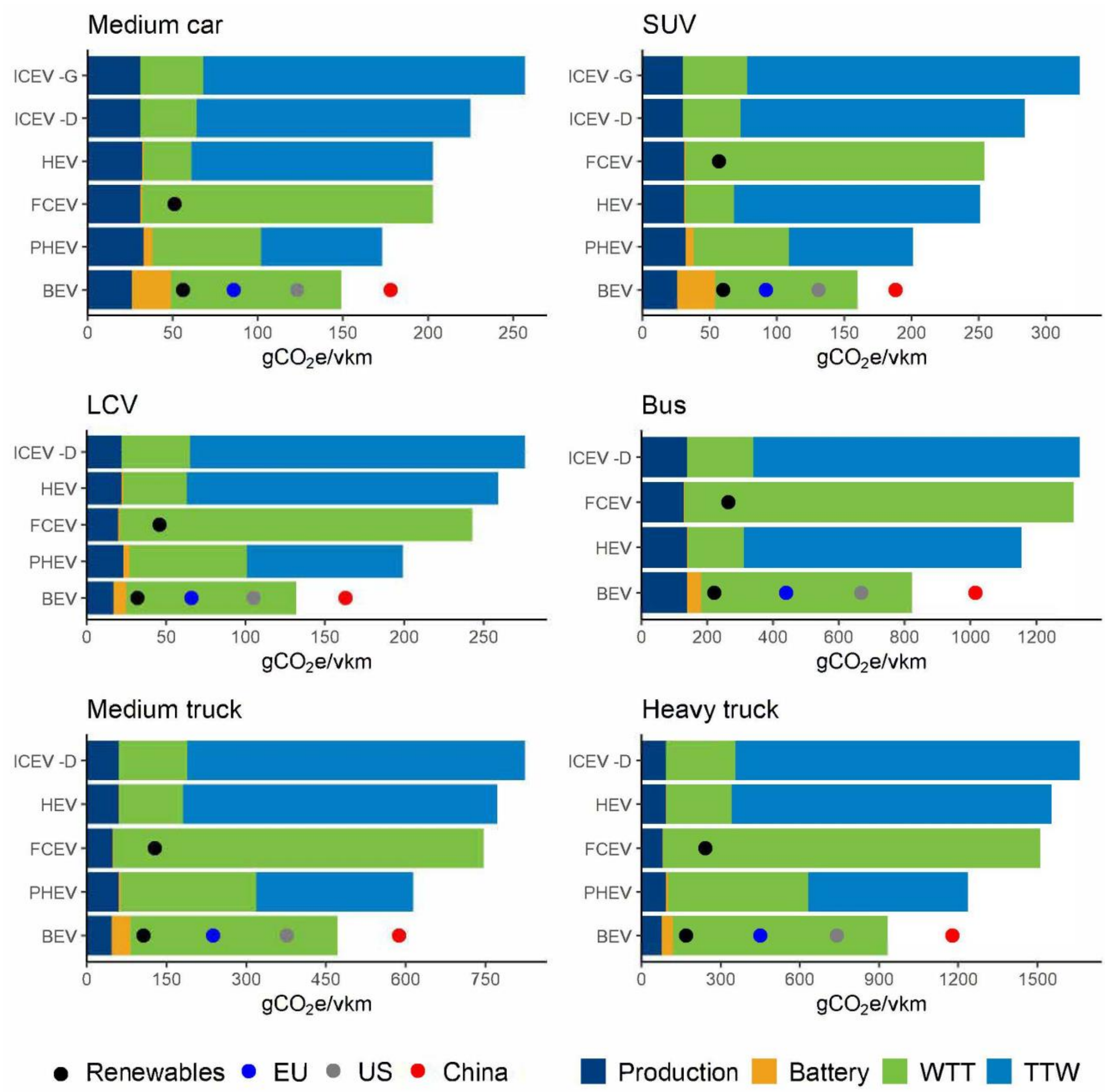
Lifecycle emissions

Figure 1 presents estimates of lifecycle GHG emissions over the lifetime mileage in vehicle kilometres (vkm) of a selection of technologies and vehicle types, using global average values for each case (further details in appendix A). The technologies considered include: internal combustion engine vehicles (ICEV), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), fuel cell electric vehicles (FCEV) and battery electric vehicles (BEV). The results shown in Figure 1 account for vehicle and component manufacturing (including replacement parts, and operational aspects related to material extraction and processing[1]), as well as emissions produced during use (tank-to-wheel, or TTW) and from energy production (well-to-tank, or WTT).[2]

Figure 1 points to the following core insights:

- The relative importance of vehicle manufacturing emissions is lower for vehicles with high lifetime mileages such as buses and trucks; in these cases, WTT and TTW emissions account for a larger share of lifecycle emissions.
- Increasing levels of powertrain electrification reduces emissions intensities for vehicles in all market segments. This is true even with the global average electricity mix in 2021. Electric vehicles have even lower emissions in regions with lower carbon electricity and with stated ambitions of promoting renewable energy (such as Europe and US).

Figure 1. Lifecycle GHG emissions intensity of new vehicles in 2020, by vehicle type and technology



Note: Emissions intensities expressed per vehicle kilometre (vkm) with global averages. ICEV = conventional internal combustion engine vehicle; ICEV-G for gasoline; ICEV-D for diesel; HEV = hybrid electric vehicle; PHEV = plug-in hybrid electric vehicle; BEV = battery electric vehicle; FCEV = fuel cell electric vehicle; SUV = sport utility vehicle; LCV = light commercial vehicle; EU = European Union; US = United States; TTW = tank to wheel; WTT = well-to-tank. Average FCEVs use hydrogen produced by steam methane reformation. Points represent regional differences in electricity carbon intensity in China, the European Union and the United States and electricity and hydrogen produced purely with renewables. More details are in Appendix A.

- A shift to low-carbon electricity significantly reduces GHG emissions for BEVs during their use (TTW). These benefits more than offset any additional manufacturing emissions associated with BEVs. A further reduction in manufacturing emissions can be achieved through a transition to low-carbon industrial processes related to material extraction, refinement, processing and assembly.

- Similarly to using BEVs with low-carbon electricity, a shift to low-carbon hydrogen (produced with renewable electricity) in FCEVs could lead to significant GHG emission reductions in all vehicle types. The emissions intensity of FCEVs using hydrogen produced by steam methane reformation (SMR) and carbon capture and storage would be similar in magnitude to hydrogen produced from renewables, provided high capture rates are achieved.
- FCEVs using hydrogen derived from steam methane reforming of natural gas – the dominant technology for hydrogen production today (IEA, 2019c) – leads to GHG emissions that are significantly higher than those of BEVs (with the global average electricity generation mix) and much closer to the emissions of ICE vehicles using conventional fuels today.

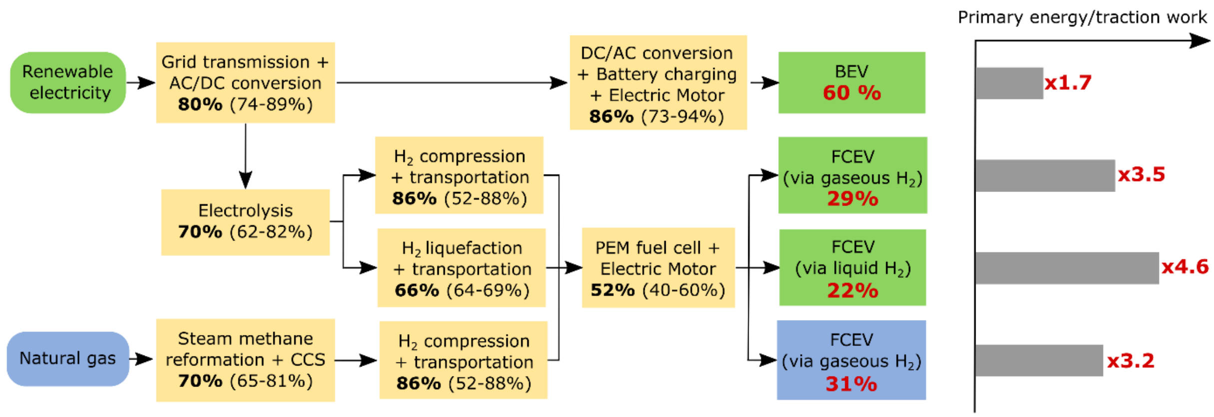
In summary, the results of Figure 1 indicate that the rapid uptake of electrified vehicles, along with a transition towards low-carbon sources of energy, can be highly effective at decarbonising transport.

Energy efficiency

The lowest GHG emissions technologies shown in Figure 1 have significant differences in their energy and resource requirements. Supplying a unit of energy to the wheels of a BEV requires approximately 1.7 units of electricity and results in a roundtrip efficiency of approximately 60% (Figure 2). Conversely, delivering a unit of energy to the wheels of a FCEV requires approximately 3.5 units of renewable electricity to produce the hydrogen, compress and distribute it, and then convert it into electricity in a fuel cell and mechanical traction in an electric motor (Haugen *et al.*, 2020). The lower energy efficiency of the hydrogen route (roughly 29% of the renewable electricity is converted into mechanical traction, with the remainder wasted) means that greater electricity generation resources are required. To limit the additional costs associated with these additional primary energy inputs, hydrogen could potentially be produced in locations with particularly cheap and abundant renewable energy resources. Transporting hydrogen from these sources of production to destinations of high demand would require either liquefaction or conversion to a hydrogen carrying molecule such as ammonia (to increase its energy density). These additional steps entail even higher energy losses than compression, meaning approximately 4.6 units of renewable electricity would be needed for each unit of mechanical traction supplied to the wheels of a fuel cell vehicle (a round-trip efficiency of 22%) (Haugen *et al.*, 2020). Finally, hydrogen could potentially be used in pathways with an internal combustion engine rather than a fuel cell (not included in Figure 2); these would have even lower round-trip efficiencies than FCEV routes, but could have lower H_2 purity requirements and potential flexibility from dual-fuel engines (which could also use diesel). For comparison, the round-trip efficiency of conventional gasoline or diesel routes would be between 18% and 45%, depending on the type of vehicle, powertrain hybridisation and usage conditions.

Figure 1 showed that using hydrogen produced by SMR delivers only marginal emissions reductions compared with conventional ICEVs. The CO_2 emissions from this process could potentially be captured and stored underground (using carbon capture and storage, CCS), thereby reducing the GHG intensity of the hydrogen. However, this would entail higher energy losses to capture, compress and store the waste CO_2 (pathway efficiency 31%) and would involve storing large quantities of waste CO_2. For example, an average FCEV passenger car using hydrogen produced with CCS would produce 21 tonnes of CO_2 each year, a liability that would need to be stored permanently underground.

Figure 2. Energy chains to power vehicles from different sources



Note: This figure shows the source of primary energy on the left and the series of transformations required to produce, transport and convert hydrogen and electricity into motive traction at the wheels of vehicles. The range of energy efficiencies for each process is included in brackets with the average in bold. The product of each of these efficiencies for each pathway is highlighted in red. Also included is the primary energy required to deliver a unit of traction energy at the wheels for each pathway; BEVs, for example, require 1.7 MJ of renewable electricity to produce 1 MJ of traction. AC = alternating current; DC = direct current; CCS = carbon capture and storage; FCEV = fuel cell electric vehicle; PEM = proton exchange membrane.

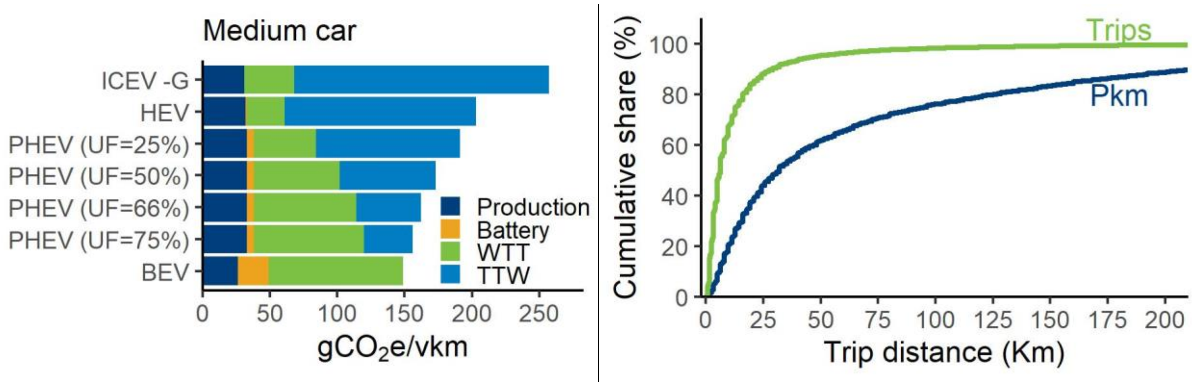
Source: Adapted from Haugen et al. (2020).

As Figure 2 shows, maximising the use of direct electrification in road transport using BEVs brings advantages from an energy efficiency perspective in comparison with hydrogen-based pathways, and avoids the need to store large amounts of waste CO_2 using CCS technologies. In addition to energy, other resources required for EVs and renewable-electricity generation technologies include significant quantities of critical materials and rare earth elements in their construction; these are explored later in this report. The resource efficiency of EVs can be further improved by maximising the utilisation of charging infrastructure and available battery capacity and recycling their materials at end of life.

A focus on plug-in hybrid vehicles

The emissions of passenger cars can vary based on their real-world usage patterns. Plug-in hybrid electric vehicles (PHEVs) in particular can operate by using electrical power from a battery or power from an internal combustion engine. The emissions-saving potential of PHEVs compared with conventional ICE vehicles is therefore highly dependent upon the share of kilometres driven in electric mode, also known as the *utility factor*. Recent analysis (Plötz *et al.*, 2021) focused on cars, highlights that during real-world driving, the utility factors of passenger cars are consistently lower (approximately 50% on average) than reference values used for vehicle testing procedures (used to assign fuel economy ratings to new vehicles). This means that fuel economy and vehicle CO_2 ratings given to vehicles overstate the environmental benefits of PHEVs – as shown in Figure 3 (left), which presents the sensitivity of vehicle lifecycle emissions of PHEVs with different utility factors. When PHEVs are only driven 25% of the time in electric mode, their emissions become comparable with HEVs, though they remain better than similarly-sized conventional ICE vehicles.

Figure 3. Sensitivity of gasoline PHEV cars with respect to share of electric driving (left) and cumulative share of car trips and passenger kilometres by trip distance (right)



Note: ICEV = conventional internal combustion engine vehicle; ICEV-G for gasoline; HEV = hybrid electric vehicle; PHEV = plug-in hybrid electric vehicle; UF = utility factor; TTW = tank to wheel; WTT = well-to-tank. Sensitivity of lifecycle emissions to PHEV utility factor (UF) is at left; further details are in appendix A. On the (right) cumulative share of passenger car trips and passenger kilometres (pkm) by trip distance from the UK National Travel Survey (Craglia, 2020), values are likely to be roughly representative of trips in other OECD countries.

In principle, PHEVs offer the potential for relatively resource-efficient travel in comparison with BEVs. The majority of passenger car trips are for short distances; in the UK, for example, 90% of car trips are below 30 km. However, these account for only 50% of passenger kilometres travelled, as shown in Figure 3 (right). For vehicles that are rarely used for longer distance journeys, the electric range of PHEV batteries could be sized to deliver the majority of passenger kilometres in electric mode, with fewer embodied emissions from battery production than a long-range BEV (though lifecycle emissions of BEVs would likely still be lower). However, the range of PHEVs available for sale today mostly targets large vehicles that tend to be driven longer distances than average. The average advertised electric range of PHEVs today is approximately 52 km, according to the Worldwide Harmonised Light Vehicle Test Procedure (WLTP) (EV Volumes, 2021b), with real-world values likely lower for non-urban, longer-distance trips. This means large PHEVs, while potentially less GHG-intensive than comparable ICEV or HEV vehicles, would require longer range batteries (e.g. with a range 100 km) to electrify a large share of the distance they travel, or be switched for a full BEV.

The real-world utility factor of PHEVs tends to be higher for vehicles with longer electric range and differs by country; for example, utility factors for plug-in hybrid cars have been found to be higher in Norway than in China (Plötz *et al.*, 2021). Potential reasons include that fuel is relatively expensive compared with electricity in Norway and vehicles tend to have easier access to charging infrastructure – with charging occurring most frequently at home or at the workplace (IEA, 2018b). Conversely, the dense urban environments and low availability of private parking in China mean PHEV owners may have less potential for overnight charging. Company cars in the Netherlands and Germany were found to have a particularly low utility factors, potentially caused by companies paying for employee's fuel (via fuel cards) while not covering their electricity charging costs at home.

The real-world emissions outcomes of PHEVs are also worsened by the fact that half of PHEVs sold globally in 2020 were sport utility vehicles (SUVs) (EV Volumes, 2021b). SUVs have much higher lifecycle emissions than sedans due to both higher fuel consumption and higher embodied emissions from manufacture. The continuing rise in popularity of SUVs and other large vehicles risks offsetting a large share of energy efficiency gains, as has been the case in the past two decades (Craglia, 2020).

Electric vehicles

In addition to advantages in terms of energy efficiency and a high capacity to reduce GHG emissions, several analyses also show that, when produced at scale, electric road vehicles can be cost-competitive with ICE vehicles powered with fossil fuels on a total-cost-of-ownership basis[3] (IEA, 2018a; BNEF, 2020a; ITF, 2020c; Nykvist and Olsson, 2021; Phadke *et al.*, 2021; Transport & Environment, 2021b). The upfront purchase prices of electric vehicles remain higher than conventional ICE vehicles; however, technological development and increasing economies of scale mean upfront purchase price parity of passenger cars may be achieved in the 2020s (ICCT, 2019b, 2021a). Furthermore, the lower operational costs of EVs can more than offset higher upfront purchase prices, particularly in cases where battery capacity can be optimised to fit with usage profiles.

The two main factors leading to relatively low operational costs are: the high end-use energy efficiency benefits of systems based on batteries and electric motors, in comparison with ICE equivalents (also true when comparing BEV and HEV efficiencies); and the lower number of moving parts, which reduces maintenance costs. Additional structural reasons point to continuing improvements in the cost-competitiveness of EVs in the future. These include:

- continuously reducing the cost of renewable electricity through technological improvements – especially for solar PV modules (IRENA, 2019a; IEA, 2020f; NREL, 2021) – along with learning effects and scale increases in production capacity and installation – most relevant for wind electricity (IRENA, 2019b; IEA, 2020f)
- cost reductions in vehicle charging infrastructure, as well as increasing its utilisation with further adoption of electric vehicles (ICCT, 2019a)
- cost reductions in batteries, thanks to improvements in battery chemistries (increasing energy and power densities and battery longevity), in addition to technology learning effects and scale increases in production capacity (BNEF, 2020b). This is in line with continuous progress in cost reduction over the past decade, thanks to a surge in battery demand that originated first in the consumer electronic sector (IEA, 2018a) and then included transport, and that is most recently reaching also large-scale stationary energy storage applications (Tesla, 2019)
- growing interest in, and additional opportunities to generate value from, the integration of batteries available on EVs with the wider electricity system (IEA, 2019a, 2020d; Matthes and Menzel, 2021; Menzel, 2021)
- increasingly stringent air-pollutant emission requirements for ICE vehicles, leading to additional costs to ensure compliance.

When looking at specific market segments, techno-economic cost assessments indicate that, for BEVs, the best conditions allowing for cost parity with ICE vehicles are achieved in global regions applying high fossil-fuel taxes (comparable to the level seen in Europe), for vehicles that have predictable daily mileage (allowing for smaller battery packs) and also high annual mileage (allowing for the maximisation of operational cost savings). These conditions are often best fulfilled by buses, urban delivery vehicles and taxis or ridesourcing vehicles, provided that they have access to daily charging (ideally taking place at times of low electricity prices – e.g. overnight or, in electricity systems allowing time-of-use pricing, at times when there are high amounts of renewable electricity available). For PHEV passenger cars, the greatest opportunities for cost parity with internal combustion engine vehicles (ICEVs) are found in cases where they can maximise the portion of driving in electric mode, due to lower operational costs.

Key uncertainties include a lack of transparency about likely residual values of vehicles at end of life, given their limited adoption to date (particularly for buses and trucks), and the rapidly changing technological environment. A recent study from the United States showed that premium long-range EVs had higher residual values than even ICE vehicles, though short-range, early-model EVs had poor second-hand market value (Guo and Zhou, 2019). Additional uncertainties include battery lifetime degradation, although preliminary evidence from the passenger car market shows battery degradation is unlikely to be a significant issue (NimbleFins, 2020; Geotab, 2021). A final important factor affecting the cost-competitiveness of all alternative powertrain vehicles involves future road taxation policy, discussed in detail later in this report. Revenues from fuel duties could be maintained by transferring additional tax burdens to electric vehicles and other alternative fuels, but this would add further barriers to their adoption and cost-competitiveness.

A focus on heavy-duty vehicles

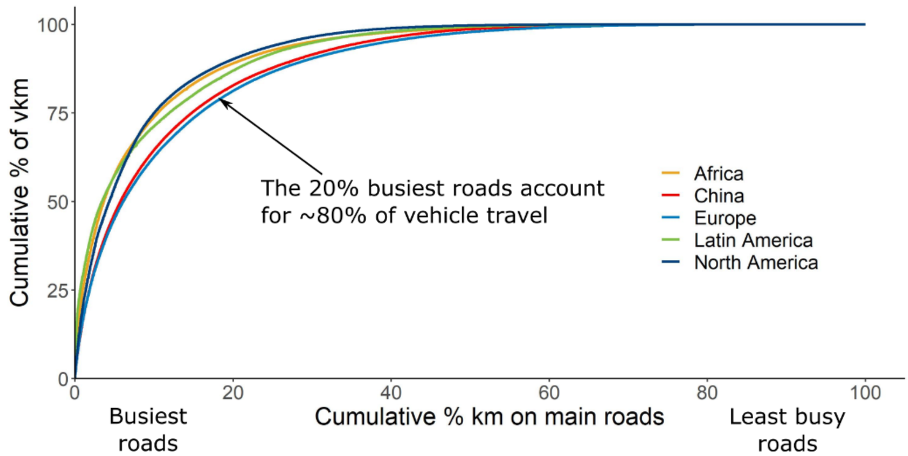
Key elements in the assessment of the breakeven costs for trucks include the price differential between diesel and electricity, the annual mileage (which varies between trucks used for urban delivery, regional missions and long-haul duty cycles) and the all-electric range (IEA, 2018a; Nykvist and Olsson, 2021; Phadke *et al.*, 2021; Transport & Environment, 2021b). As battery costs continue to decline, some of the initial trucking segments that become cost-competitive are vehicles in urban environments, which are used frequently and can charge overnight. Further cost reductions and technical improvements will extend the scope of cost-effective electrification of trucks. Nevertheless, due to their operational requirements, long-haul trucks remain a relatively challenging mode of transport to decarbonise in comparison with lighter vehicles. Three factors explain this:

- Long-haul ranges increase both battery-capacity requirements and the associated upfront purchase costs, even if the share of battery costs per unit of freight is lower.
- Because long-haul electric trucks cannot completely rely on overnight depot charging, they require the deployment of capital-intensive, high-power charging and grid infrastructure to have access to low-carbon energy (ITF, 2018; Nykvist and Olsson, 2021; Phadke *et al.*, 2021). Regular high-power charging may also reduce battery longevity.
- In turn, to be economically viable, capital-intensive charging infrastructure requires a solid business model to recover costs and reduce investment risks.

On the other hand, electric long-haul trucks have a number of possible advantages in comparison with light vehicles. They are heavily used capital goods that are much more expensive to fuel than they are to acquire, meaning they are well placed to benefit from technologies that have low operational costs. This is likely the case for direct electrification, if the utilisation levels of chargers can be maximised.[4]

Long-haul trucks have a higher share of travel on main roads with high vehicle traffic than light vehicles. Figure 4 shows the share of vehicle travel (in vehicle kilometres) by heavy-duty vehicles (HDVs) in different regions by the amount of traffic (busyness) on main roads. In most regions, the busiest 20% of main roads account for approximately 80% of HDV travel; this means that a smaller number of vehicle charging stations would be needed to service long-haul heavy-vehicle requirements – though they would have to be larger in size, requiring consideration to local electricity grids.[5]

Figure 4. Cumulative share of truck travel (vkm) by road traffic



Note: Estimates from the ITF Freight model of the share of total travel by medium and heavy-duty vehicles (expressed in vehicle kilometres), by cumulative length of main (non-urban) roads and ordered by annual traffic (vehicles/year).

As with other BEVs, the adoption of BEV long-haul trucks requires the roll-out of charging infrastructure – the nature of which depends on the technical characteristics and operational requirements of long-haul trucks. Long-distance journeys may require charging en-route, potentially increasing journey times due to recharging. However, in Europe, legal requirements related to labour conditions and road safety dictate that drivers of long-haul trucks have a rest period after 4.5 hours of driving, and drive a maximum of 9 hours per day, then take an 11-hour rest period (Siemens, 2020; Gründler and Kammel, 2021). In the United States, for example, regional-haul and long-haul trucks have been estimated to travel approximately 240 km and 300 km, respectively, between 30-minute driver breaks (Phadke *et al.*, 2021); delivering a further 300 km of range in 30 minutes would require a 1 MW charger.[6] Integrating periods of vehicle charging with driver rest periods (perhaps assisted via digital planning technologies) can therefore be a potential solution for managing long-range requirements with limited increases in journey time (even if some may be inevitable) (Nykvist and Olsson, 2021; Phadke *et al.*, 2021). Other potential solutions include battery swapping, which may help to tackle a number of the challenges outlined above.

High power chargers would be important in this context to minimise recharging times (Phadke *et al.*, 2021), with ongoing work on standardisation for solutions rated at 1 MW or more (ITF, 2020d), Alternatively, vehicles could be recharged using lower power (comparable with fast chargers for cars), overnight chargers in vehicle depots or along motorways. High-power chargers are more expensive than low-power options, requiring significant grid upgrades; this could lead to higher electricity costs (depending on the utilisation and the potential for time-of-use fee structures). High-power charging costs are estimated at approximately USD 350 000 per charging point, though they have the potential to drop considerably for each additional charge point per site (ICCT, 2019a). Overnight, low-power charging would likely need to be the default,[7] with vehicle deployment and range limitations jointly dictating the amount of high-power chargers needed.

As explained in Box 1, electric road systems (ERSs) also offer opportunities to address the range concerns of electric trucks while limiting their required battery capacity (thereby lowering BEV truck purchase costs) (Transport & Environment, 2021b). High rates of utilisation of ERS infrastructure could therefore help ensure heavy-duty road-freight electrification takes place in a way that is less dependent on battery materials, while maintaining high energy efficiency.

Box 1. Electric road systems

Electric road systems (ERS) enable a transfer of electricity between vehicles in motion and the road transport infrastructure. The most advanced, and likely the most viable, ERS solution existing today requires building overhead contact lines, transmitting electricity to a truck using a pantograph.[8] Similar to any other system requiring a switch in energy distribution infrastructure, an ERS has the challenge of being capital intensive[9] and requires high utilisation rates; it is therefore subject to a relatively high risk profile, likely requiring public investment.[10] It may also encounter public opposition if it is perceived to visually disrupt landscapes more than existing roads.

However, similar to other EV-charging solutions, a number of features help ERS mitigate risks related to capital intensiveness. First, only a relatively small share of roads would need to be electrified to cover the majority of HDV vehicle travel, as shown earlier in Figure 4.[11] Second, ERS can be built in a way that adapts to changes in electricity demand on the system. In particular, ERS infrastructure costs can be reduced by installing an intermittent overhead line system.[12] Spacing between the substations that are needed to transfer electricity to the system can also be adjusted – starting with longer distances initially, and then reducing spacing and increasing the number of substations step-wise, until the load expected for a fully utilised system is reached.[13]

The ERS concept can operate with a range of electrified powertrains (including FCEVs, BEVs and HEVs), which adds flexibility. A share of truck journeys could be initially electrified using diesel hybrids, with the final portions of journeys progressively decarbonised with the adoption of BEVs or FCEVs. The roll-out of retrofit-ready solutions for trucks that are already equipped with electric motors may also facilitate the scaling-up the utilisation of ERS, accelerating its cost recovery timeline.[14] BEVs using an ERS would require only small, low-range batteries (around 50 km) for the final miles of journeys, which would limit manufacturing emissions and the quantities of battery materials needed (sEEnergies, 2021). Furthermore, ERS solutions would reduce the time needed for battery recharging and have a number of future synergies with the potential adoption of autonomous vehicles.

The lower variable costs of using electricity compared with diesel (principally due to the higher efficiency of electric motors) means that there is potential for ERS operators to apply additional user charges. A recent analysis (Ainalis, Thorne and Cebon, 2020) suggests that if a surcharge were applied to electricity sold through the system, a payback period for infrastructure costs of 15-20 years could be feasible.[15]

Hydrogen vehicles

Hydrogen vehicles potentially require fewer behavioural changes from consumers, because their refuelling times and vehicle ranges are similar to those of conventional vehicles. However, compared with BEVs and ERS vehicles which make direct use of electricity, FCEVs using low-carbon hydrogen face greater long-term challenges when assessed from a cost perspective. This is for three fundamental reasons:

- First, FCEVs face challenges in achieving the economies of scale needed to drive costs down with learning curves. FCEVs require fuel cells, hydrogen storage tanks, and batteries similar to those used on EVs. The fuel cell is one of the most expensive components of FCEVs (Yumiya, 2015a), and its price could be reduced with sufficiently large production volumes (Wilson and Kleen, G. Papageorgopoulos, 2017). However, sales of FCEVs in the car market are proceeding at a slow pace, due to the relative advantages of BEVs. Remaining transport modes that could make use of hydrogen, such as trucks, are relatively small in terms of annual vehicle production volumes, meaning they face challenges in achieving significant scale alone. Furthermore, hydrogen storage tanks are expected to have slower rates of cost reductions.[16]

- Second, due to the low thermodynamic efficiencies shown in Figure 2, hydrogen needs to be produced from primary forms of energy available at very low cost (and with acceptable margins for producers) to enable operational costs for transport applications to be lower than for ICE vehicles, even if greater cost differences are possible in countries that apply high road-fuel taxes.
- Third, the need for low-cost hydrogen is further exacerbated by the complexity of handling the transportation and distribution of hydrogen to small end-use applications such as transport vehicles, which adds energy losses, complexity and costs to the process. This is clearly shown by the fact that hydrogen demand is located entirely in large industrial complexes as of 2021, with hydrogen production often taking place on site – even when produced as "green" hydrogen from offshore wind, as shown by a recent project announcement, aiming to feed a refinery in Germany (BP, 2020).

These considerations apply to both light and heavy road vehicles. In the case of cars, where capital costs account for a higher share of the total cost of ownership due to lower lifetime mileages, reductions in fuel cell system costs are most important to improving cost-competitiveness. In heavy vehicles such as buses and trucks, where lifetime travel is higher, reductions in hydrogen costs delivered at the refuelling stations are also important, in addition to those required for the fuel cell and storage tank.

All cases are also affected by a certain degree of path dependency in the build-up of hydrogen refuelling infrastructure. This is because small refuelling stations make more economic sense in the initial deployment phase (as they are more likely to secure higher capacity-utilisation rates when demand for hydrogen from transport vehicles is limited), but they come at higher cost per unit of hydrogen delivered. Large stations are better once sufficient demand exists, but high capital costs and low capacity utilisation at low volumes of demand mean that they are unlikely to be prioritised in the initial deployment phase. This is further complicated by the significant differences in refuelling station size and pressure requirements that could serve passenger cars and trucks (Rose, 2020),[17] in addition to standardisation work that still needs to be completed for heavy vehicles.[18]

Similarly to BEVs, hydrogen refuelling costs are also highly dependent upon the frequency of use of the distribution infrastructure; this is related both to the size of refuelling stations built and to the diffusion of FCEVs in the fleet. This can be partly mitigated by starting FCEV deployment in captive fleets and near existing sources of hydrogen demand. These cases could allow some FCEV trucks to be cost-effective. However, for FCEVs to be scaled to the wider market, hydrogen distribution infrastructure would need to be widely available – initially without FCEV deployment to ensure its initial utilisation (unlike electricity, which is already widely available and used in a range of end-uses). With low shares of FCEV deployment, the costs (per unit of fuel delivered) increase. Recent estimates suggest that the cost per unit of hydrogen delivered would be 25% higher with a 40% FCEV share in the vehicle fleet compared with a 60% share (Rose, 2020). This makes it more difficult to scale up organically without large-scale government investment and long payback periods.

These challenges illustrate some of the main barriers to rapid hydrogen uptake in road transport. Although some could eventually be bridged by public funding, a compelling business case remains elusive – meaning it is likely that financing projects using hydrogen as an energy vector in road transport will face greater challenges with respect to direct electrification.

Alternative fuels

In addition to the technology options shown in Figure 1, other options being considered for transport decarbonisation are largely focused on the use of alternative fuels for ICE vehicles. These include liquid biofuel and biogas production pathways (especially fuels reliant on waste feedstocks) and low-carbon synthetic fuels that can be obtained from the chemical synthesis of low-carbon hydrogen and carbon (from different biological and non-biological origins).

Biofuels and synthetic fuels have the potential to be low-carbon energy vectors if, and only if, the CO_2 produced during their combustion is balanced by the carbon sink effect of their feedstocks (from the growth of biomass or the absorption of CO_2 from the atmosphere by mechanical means). The advantage of these alternative hydrocarbon fuels is that they can be blended with fossil fuels and are largely compatible with existing vehicles and fuel storage and distribution infrastructure with relatively minor modifications. This has the advantage of limiting the costs and risks associated with the build-up of a new refuelling infrastructure. They can also potentially play a role in reducing emissions from older vehicles within the existing vehicle fleet. However, they face a number of barriers hindering their ability to fully decarbonise road transport energy use.

Biofuels

The well-to-wheel (WTW) GHG emissions reductions of the various liquid biofuels pathways can differ widely, with the best-performing pathways generally relying on waste oils or lignocellulosic feedstocks, in addition to sugar cane ethanol (JEC, 2020). However, the large-scale potential of waste-based biofuels is limited by the availability of low-carbon feedstocks,[19] biochemical pathways face risks of adverse consequences for food supply, and land-use change and pathways based on lignocellulosic feedstocks face significant challenges in terms of cost-competitiveness with fossil-based alternatives (IEA Bioenergy, 2014, 2019).

The use of biogas in ICEs could also potentially reduce WTW GHG emissions compared with fossil-based liquid fuels (JEC, 2020) and be cost-competitive compared with other advanced biofuels (Bracmort, 2020). Challenges related to the use of biogas are cost-competitiveness with fossil fuels, fugitive methane emissions (despite the existence of technologies partially mitigating this) and, similarly to liquid biofuels, constraints on the availability of low-carbon feedstocks at scale. Biogas also faces lower initial cost barriers to distribution for existing end-uses of methane today. Recent work by (IEA, 2021d) shows a transitional role for biofuels in road transport up to 2030 before biofuels are then used predominantly in non-road transport modes.

Synfuels

The main limiting factor for synthetic fuels is the large thermodynamic losses that occur across their production and use, leading to round-trip efficiencies of less than 13% (Transport & Environment, 2020).[20] A first source of these losses relates to the production of low-carbon hydrogen, mentioned previously. A second source of thermodynamic losses relates to the need to combine low-carbon hydrogen with carbon molecules sourced from the atmosphere. This includes carbon derived from either biomass (where atmospheric carbon is absorbed while plants grow) or the "direct air capture" (DAC) of CO_2 (consisting of processes that separate atmospheric CO_2). In both cases, thermodynamic losses arise from the need to capture the primary source of carbon (biomass or CO_2) and convert it into the carbon monoxide required for the chemical synthesis process of synthetic fuels. A third source of thermodynamic losses (in common with biofuels) stems from the fact that synthetic fuels are used in internal combustion engines, which are inherently limited with respect to thermodynamic efficiency (Paoli and Cullen, 2019).

The significant thermodynamic losses and the multiple conversions required to produce synthetic fuels at scale would require large amounts of low-cost and low-carbon electricity, far beyond those needed in systems where electricity is stored in batteries and used in electric motors (Transport & Environment, 2021a). Additionally, DAC has a low technology readiness and is still far from being applicable at large scale (Napp *et al.*, 2017; IEA, 2020b; Kearns, Liu and Consoli, 2021).

There will be some specific situations that allow low-carbon synfuels and biofuels to have a lower cost in road transport than other low-carbon alternatives. An example is the case of synthetic fuel production in locations with very high solar and wind energy endowments or abundant sustainable biomass. However, the limitations outlined above mean they are likely to play a relatively minor role in reducing GHG emissions from road transport globally compared with electrification and hydrogen. The desirable chemical properties of bio- and synthetic fuels (high energy density, ability to use existing infrastructure), mean they are likely better suited to sectors like shipping and aviation, where there is far less scope for direct electrification in comparison with road transport (IEA, 2020c; Ueckerdt *et al.*, 2021).[21] It is for these reasons that the main focus of this report is on vehicle electrification.

Priorities for the remainder of this analysis

As this chapter has shown, decarbonising road transport through the direct use of electricity has a number of significant advantages over competing alternatives when assessed from a technical perspective that accounts for GHG emissions intensity, energy and resource efficiency, and costs. Although opportunities exist to produce low-carbon hydrogen at low cost, the specific case of hydrogen use for road transport vehicles faces unique challenges due to the difficulty of transporting and distributing a gaseous fuel, exacerbated by the challenge of scaling-up demand and the dependence on very-low-cost energy supply in order to reduce the operational costs of moving road vehicles.

Based on these considerations, the focus of the discussion in the following sections will be on electric and electrified vehicles, in particular BEVs and PHEVs. Other options – in particular FCEVs and, to a lesser extent, low-carbon fuels for ICE vehicles – will be taken into consideration as a complement to BEVs and PHEVs.

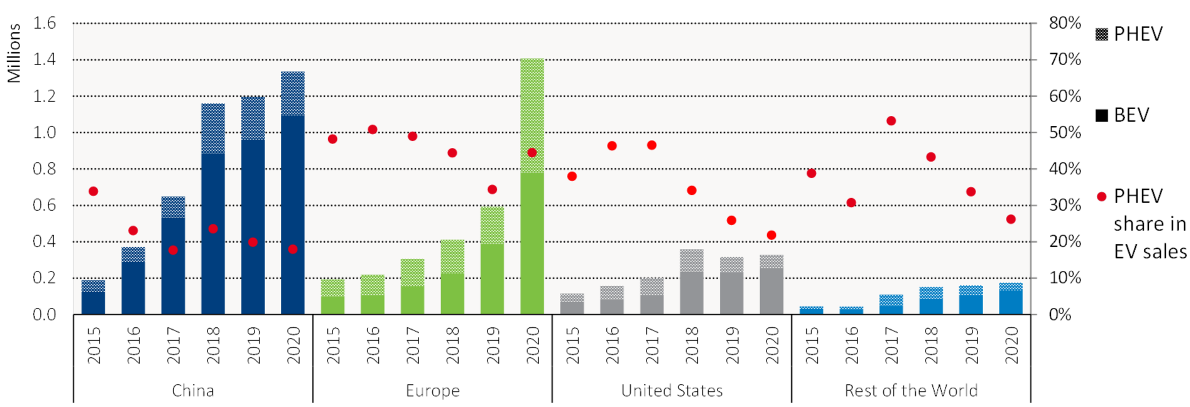
Clean vehicle adoption

BEVs are the clean vehicle technology with the greatest market share today. Aside from electric two-wheelers, whose sales are close to 25 million units (IEA, 2021b), electrification developments have been concentrated in the passenger car segment. PHEVs also play an important role in leading car markets and sales volumes of FCEVs increase. Buses are another large segment for clean vehicle technologies, spearheading their application in heavy-duty vehicles, with dynamic development set to take place also in the truck segment. The following sections review the market status of available zero-emissions vehicle technologies in different vehicle segments.

By the end of 2020 there were 10 million EVs (including BEVs and PHEVs) on the road. In 2020, global sales reached 3.2 million vehicles, up 41% from 2.3 million vehicles sold in 2019 (IEA, 2021b). This increase took place despite the Covid-19 crisis, which depressed the overall car market by 16%, from 64 million to 54 million cars sold globally in 2019 (OICA, 2021).

The increased policy support for EVs under economic recovery packages helped to boost sales, especially in the second half of 2020 in Europe. As a result, the European EV market grew the strongest in 2020 and, with 1.4 million units sold, led Europe to become the largest EV market, ahead of China (Figure 5). Europe also remains the EV market with the highest market share of PHEVs. Their share increased to 45% in 2020, breaking with a trend of decreasing PHEV share in previous years. PHEVs shares are lower in other major global markets: 18% in China and 22% in the United States.

Figure 5. Battery-electric and annual battery-electric and plug-in hybrid electric car sales by region, 2015-20



Note: PHEV = plug-in hybrid electric vehicle; BEV = battery electric vehicle.

Source: EV Volumes (2021a); IEA (2021b).

Although electrification of light commercial vehicles trails that of passenger cars, it is gaining momentum as large operators pledge to electrify their fleets. Sales of electric LCVs in 2020 reached 112 000 units, with most sold in China (64 000 Units) and Europe (33 000 units). Another emerging market is Korea, with 14 000 registrations in 2020 (EV Volumes, 2021a).

The market for electric heavy-duty vehicles is strongest in China, with registrations in 2020 of over 80 000 electric buses and over 7 000 electric trucks, accounting for almost all the global total. Europe is the second-largest market for electric buses, with more than 2 000 registrations in 2020. Together with the

United States, Europe is also seeing growing sales of electric trucks. Truck sales in these markets in 2020 (450 units sold in Europe and 780 in the United States) were, however, still a fraction of those seen in China (ICCT, 2021b; IEA, 2021b).

Installations of publicly accessible EV chargers in 2020 were estimated at 922 000 units for slow chargers (up to 22 kW) and 386 000 for fast chargers, increasing from 626 000 and 269 000 in 2019, respectively (IEA, 2021b). Their regional distribution approximates that of the global EV fleet, with most public chargers being installed in China (62%), Europe (22%) and the United States (8%). However, the ratio of vehicles per charger varies across these regions, with a lower ratio of EV per publicly accessible charger in China (8 EVs per public charger), followed by Europe (11) and the United States (18). The high availability of public chargers in China reflects a lower reliance on private chargers than in other major markets, as predominant housing types in urban areas do not always allow the installation of private chargers (Bloomberg, 2021a).

The market size for FCEVs reached 8 000 units in 2020, representing only a tiny fraction (0.2%) of the entire EV market. By early 2021, the global FCEV car stock reached 28 000 units (EV Volumes, 2021a). The FCEV car market consists largely of two models, the Toyota Mirai and Hyundai NEXO. Sales are concentrated in Korea, Japan, the United States and Germany (E4tech, 2020). Very few fuel-cell cars are sold in China; however, China hosts more than 95% of the heavy-duty vehicle fleet powered by fuel cells, with 4 300 buses and 1 800 trucks in 2019 (Samsun, Antoni and Rex, 2020). Heavy-duty fuel-cell vehicles grew fast in China in 2020, with 3 600 additional FCEV buses (E4tech, 2020), despite a wide gap that remains wide when FCEVs are benchmarked with BEVs. The market for heavy-duty FCEVs is starting to emerge also in other markets, but it is still very small, ranging in the thousands of vehicles worldwide. Hyundai Motor in 2020 delivered its first ten units of the Xcient fuel-cell heavy-duty truck in Switzerland, where the company has plans to sell 1 600 units by 2025 (E4tech, 2020).

The stock of FCEVs had access to 540 hydrogen refuelling stations by the end of 2020. These are concentrated in the leading FCEV markets of Japan (25% of all stations), Germany (17%), China (16%), the United States (12%) and Korea (9%) (IEA, 2021b). Given FCEVs' slow market uptake, many stations have low rates of utilisation: 8 FCEVs per station in Germany and 150 in Korea (Samsun, Antoni and Rex, 2020).

Policy drivers

Increased interest in clean vehicles and their growing deployment is the result of a combination of factors. Policy increasingly aims to take action to improve air quality, reduce GHG emissions, increase energy security (through enhanced energy efficiency and diversification), and stimulate innovation and economic growth. The adoption of new clean-vehicle technologies has been identified as an important means of tackling many of these issues.

Recent technological developments have been able to reduce costs and increase the competitiveness of key components of clean vehicles, in particular batteries and renewable electricity, in comparison with incumbent technologies. Awareness of these dynamics has increased among policy makers, resulting in strengthened action and technology policies that aim to foster innovation while stimulating technology deployment and industrial development. These, in turn, have stimulated significant changes in the market capitalisation of automakers and energy companies. New competitors in the market have arisen, driven by prospects for significant markets for their products and by technological advantages over incumbents that have been reluctant to make significant investments in the technology transition to cleaner vehicles.

The growing momentum in the deployment of clean vehicles has been further accelerated by Covid-19 as governments make plans for economic stimulus spending to drive a recovery that is subject to lower financial, climate, sustainability and energy price volatility risks.

Policies promoting the adoption of cleaner vehicles were first developed in the 1970s in the United States and have since been adopted in some form in the majority of advanced vehicle markets. Their aim is to create demand for technologies that can provide greater environmental and societal benefits at competitive costs (once they have been scaled up) and, in parallel, to mobilise capital to ensure adequate supply of clean vehicles and the energy vectors that they need.

Clean vehicle policies require a series of actions at different administrative levels, beyond the central (and even the single) government level. It involves supra-national (e.g. at the level of the European Union, and even the United Nations, on specific topics), national and local/city authorities at once. An example of the complexity of this process is the "whole of government" approach recently adopted by the United States to tackle climate change, which includes policies promoting clean vehicles and related energy distribution systems as two important pillars of a broader articulation of policy instruments.

Due to their vast economic impact and cross-sectoral nature (touching on industry, transport and energy), the development of clean vehicle policies also requires a high degree of coordination between public authorities and a wide range of stakeholders. These include industry, energy companies, financial institutions, trade unions and civil society.

Crucial pieces of a successful policy framework to stimulate the deployment of clean vehicle and energy technology include:

- The development of technical standards[22] and regulations[23] to ensure (a) the safe operation of vehicles and the infrastructure needed to provide them with energy and (b) the parallel development of technical texts to ensure that the environmental characteristics of vehicles and their energy sources can be clearly defined and objectively measured.
- The presence (or the establishment) of a conducive energy pricing and taxation environment, where energy sources that have a poorer performance with respect to environmental targets (in particular climate change) are subject to higher taxes than alternative forms of energy.
- The adoption of ambitious public procurement programmes to reduce investment risks in early phases of the technology deployment, when learning and scale effects are not yet strong enough to ensure lower costs. These measures are also instrumental for the early roll-out of charging/refuelling infrastructure.
- The use of economic incentives to reduce the costs of clean vehicle technologies, to ease investment risks associated with low initial frequency of use of charging/refuelling infrastructure.
- The deployment of regulatory requirements for clean vehicles, such as pollutant emissions and/or fuel economy standards integrating low- and zero-emission vehicle (LZEV)[24] market shares and energy vectors (such as low-carbon fuel standards and renewable electricity quotas), along with instruments focusing on the deployment of charging/refuelling infrastructure.
- The clear definition of sustainable finance thresholds for clean vehicles and energy vectors, to ensure that investors influencing the decisions taken by corporations and other entities are aligned with the vision identified for clean vehicle and energy technology deployment while also ensuring the stewardship of the capital invested, minimising the risk of stranded assets in the presence of climate and environmental policy action.

Several considerations (summarised in Box 2) also underpin the choice of many governments to engage with stakeholders to seek consensus for a move into industrial development policies that go beyond the concept of technology neutrality to endorse specific technologies.

Box 2. Clean vehicle policies in the context of technology neutrality

A common principle in technology policy is that of ‘technological neutrality’ – that is, setting a policy goal, such as meeting a desired GHG emissions reduction target, without being prescriptive about the technology used to attain the goal. The advantage of technological neutrality is that it allows policy goals to be met with the least-cost technology solutions driven by unencumbered market forces.

Nevertheless, technology neutral policies are unlikely to work effectively for technologies that have a lower technology readiness level, since spending in knowledge development for these solutions is far less likely to generate commercial profit within a timeline that is aligned with the requirements of investors. This is also the case for technologies that are closer to market but need a scale increase to achieve cost reductions and systemic changes (like a shift in energy vector) to deliver net benefits and bridge the so-called “valley-of-death” of technology deployment, since bridging these barriers comes with higher investment risks.

Technology neutrality is also openly challenged in cases where different options rely on very different infrastructure (e.g. for energy distribution). This is for two reasons: policies that can foster the infrastructure roll-out will likely have technology-specific requirements (e.g. safety standards), and the budgets available to bridge initial transitional investment barriers are limited.

Technology-specific, market-oriented policies are therefore best suited to technology options with the potential for market entry, subject to rapid declines in costs with increased cumulative production, and structurally well placed to help achieve multiple policy goals (such as safety, connectivity, equity, environmental goals or enhanced socio-economic development) and to outcompete alternative options.

The need for clear prospects for a steep technology learning curve is essential to ensure that the technology can effectively remain commercially competitive once supportive policies are removed. The need to ensure that technologies are aligned with multiple policy goals is crucial, especially for technological solutions that require investments in new infrastructure deployment (for which payback times are measured in decades, often requiring public investments). The need for structural capacity to outcompete alternatives is essential to ensure resilience.

Once and if these key conditions are fulfilled, it is in the interest of governments to steer investments that will shift their industries towards technology options that have better chances of ensuring they can be effectively met. This is especially relevant in cases where there is widespread consensus on the relevance of these goals, as this is a further element helping with risk mitigation.

In the case of clean vehicles, these are key reasons why it is important to evaluate different technology options against their capacity to fulfil relevant policy objectives – such as better air quality, greater energy and resource efficiency, and low GHG emissions.

Where the capacity to outcompete alternatives remains an open question (potentially also because of factors that are external to the characteristics of the vehicles and energy technologies alone), technology policy needs to factor in elements allowing for the support of a range of competing options that could all deliver. Due to resource constraints, governments should still develop analytical capacity to identify what to prioritise and what not. The risk of not doing so is not only to waste resources (e.g.

paying the high cost of developing of a different set of policies, including technical standards and regulations, which are inherently very technology-specific), but also to lock-in solutions that are not fit for purpose, increasing stranded-asset risks – with important negative consequences for the economy, and the need for corrective policy instruments later on.

These considerations matter even more in a global context, where major economies are also beginning to use their market scale to drive technological development for a particular technological solution and enable their industry to acquire a competitive advantage (e.g. by moving early on supply chains whose importance is fostered by specific technological developments, including for transport vehicles).

Rolling out technical standards and regulations

Technical regulations and standards are important prerequisites for deploying safe and reliable vehicles at scale. Their establishment is a crucial step when introducing new technologies, and clean vehicles are no exception. Technical standards and regulations also play an important role in removing barriers to international trade.

Technical regulations and standards are essential to set and meet common performance criteria and design requirements, reducing risks due to uncertainty. They are best conceived when ensuring a level playing field in technology development. This suggests that internationally agreed standards are best suited to avoiding barriers to trade and the use of these technical instruments for protectionist practices. An important principle in the definition of technical standards is that they do not disproportionately favour any one country or company; it is therefore essential to ensure surveillance and engagement of other countries' standards and promote international co-operation and compliance (Cory and Atkinson, 2020).

Significant work on the international harmonisation of technical regulations and standards has been developed within the framework of the United Nations as well as other international standardisation organisations, such as the International Organization for Standardisation (ISO), the International Electrotechnical Commission (IEC), the Society of Automotive Engineers (SAE), and ASTM International (originally the American Society for Testing and Materials).

A comprehensive review of technical standards and regulations that apply to light and heavy road vehicles relying on electricity and hydrogen as energy vectors was recently been carried out by the ITF (ITF, 2020d). The report's summary of key findings and recommendations related to technical standards on clean vehicle and charging/refuelling safety is included in Table 1.

In addition, it is important to mention that a set of technical standards for safety and interoperability is also being developed by the IEC for battery swapping for electric vehicles, a solution emerging rather prominently in China. While the first large commercial applications focused on electric two-wheelers, several Chinese car OEMs (original equipment manufacturers) have started to invest in domestic battery-swapping stations and to offer EVs using this technology; these include NIO, Geely and Beijing New Energy Vehicles (a subsidiary of BAIC) (Shepherd, 2021). The Chinese government also offers targeted subsidies for vehicles using this technology.

In the European Union, additional standardisation requirements have been identified to achieve full interoperability across all parts of the EV recharging ecosystem. These are crucial for the deployment of emerging technologies such as smart recharging and vehicle-to-grid (V2G) services. They include standardised communication interfaces among vehicle manufacturers, recharging point operators, mobility service providers, e-roaming platforms and distribution system operators. They also include new data models to integrate EVs into the grid and to develop EU-wide e-roaming networks (EC, 2021b).

Table 1. The most advanced clean-vehicle and charging/refuelling safety standards and regulations

Subject	Status	Remaining gaps
Electric vehicles	International safety standards that apply to electric vehicles and batteries tend to cover cars, light commercial vehicles and heavy vehicles like buses and trucks under a single framework.	Differences in technical requirements and duty cycles between light and heavy vehicles require further differentiation in regulations and standards. The most pressing issues to be addressed by regulations and standards on BEVs relate to batteries, in particular thermal runaway, propagation and electrolyte leakage. Given the increasing competition in this crucial technology for EVs, ensuring that there is international harmonisation of technical standards on batteries is crucial, since it facilitates the creation of a level playing field for competing companies.
Electric vehicle charging	Technical standards for safe and interoperable electric vehicle charging cover conductive and wireless systems. So far, their focus has been on passenger cars, but recent developments for conductive systems cover higher power, which is more suitable for heavy-duty vehicles. Other recent developments include bi-directional power flow control, multiple DC outputs, updates on communication and charging processes, and charging with liquid cooling.	DC charging has seen important developments and is now looking beyond electric cars to larger-vehicles charging (with up to 450 kW) and DC-charging of 1 MW or more. This work has yet to be finalised. Ensuring that high-power (megawatt) charging for commercial vehicles is available is a key priority.[25] Standards related to communications between the vehicle or the charger and the rest of the electricity system are also being developed. Electric Road Systems (ERSs) are also subject to technical regulations and standardisation challenges, in particular on interoperability and metering of electricity consumed, along with safety specifications.[26]
Fuel cell electric vehicles (FCEVs)	FCEVs use electrical components, including batteries, meaning many of the vehicle safety regulations and standards related to electric vehicles also apply to FCEVs. In addition, standards and regulations specific to FCEVs focus on compressed gaseous on-board storage. Standardisation is ready for tanks using a nominal working pressure of 35 and 70 megapascals (MPa) on light vehicles.	Regulatory priorities include making heavy vehicle tanks ready for gaseous hydrogen at 70 MPa nominal working pressure and developing targeted improvement of safety requirements to account for higher lifetime travel of heavy vehicles, test procedures and periodic inspections for high-pressure vessels, along with crash-related safety provisions (especially for roll-over). Future developments will need to cover other forms of on-board hydrogen storage, in particular liquid hydrogen.
Hydrogen refuelling	The focus of existing standards for hydrogen refuelling is on gaseous systems (with nominal working pressures of 35 MPa and 70 MPa) and light vehicles. For heavy-vehicle refuelling, the historical focus has been on 35-MPa tanks. This was due to a focus on urban buses (which are not subject to strong time constraints, as refuelling can take place overnight). Standards are not in place for systems that use chemical bonding of hydrogen and swappable solutions.	Key priorities are the development of refuelling protocols for medium and heavy vehicles (especially for 70 MPa compressed-hydrogen storage systems and more than 10 kg of storage capacity) and the development of a hydrogen-refuelling nozzle for 70 MPa and high refuelling flows. Regulatory developments also need to focus on hydrogen quality. Future developments will need to cover other forms of refuelling, in particular for liquid hydrogen.

Source: ITF (2020d).

Technical standards on energy/resource efficiency, environment and health are also covered in the comprehensive review of international safety standards recently released by the ITF (ITF, 2020d). Key findings and recommendations for transport vehicles are included in Table 2, which also contains additional considerations specifically related to fuel quality.

Table 2. The most advanced technical standards and regulations on energy/resource efficiency, environment and health for road transport vehicles and energy vectors

Subject	Status	Remaining gaps
Energy consumption and tailpipe (tank-to-wheel) CO_2 emissions	Measurement procedures developed for both cars and trucks, in regulatory texts that cover different stages. For heavy vehicles, these procedures are not internationally harmonised. The most advanced regulatory frameworks in this field rely on simulations developed with dedicated software tools (not covering PHEVs, BEVs and FCEVs). Test cycles are also different across jurisdictions.	Need to extend the scope of simulation tools developed for the most advanced regulatory frameworks to include PHEVs, BEVs and FCEVs. In the case of PHEVs, the focus should be on determining the real share of electric driving, which can vary significantly depending on vehicle types and mission profiles. Test procedures also need to consider extreme ambient temperatures and mobile AC systems.
Tailpipe emissions of local pollutants	For heavy vehicles, technical regulations on tailpipe emissions of pollutants apply to their engines, rather than the whole vehicle – with the exception of on-road vehicle tests, which rely on portable emission measurement systems (PEMS). Requirements for off-cycle tailpipe emission of pollutants are also in place.	Need to update utility factors, outlining the share of electric driving (subject to wide variations across vehicle types and mission profiles) for PHEVs. Need to target the development of testing for pollutant emissions (especially CO and NOx) for heavy-duty vehicles burning hydrogen-in internal combustion engines. Need to finalise more-stringent air pollutant emissions standards for combustion-engine vehicles (beyond Euro 6d and US Tier 3 Bin 5).
Well-to-tank energy, GHG and pollutant emissions of energy vectors	Measurement and/or estimation procedures, based on lifecycle assessments, are available – in selected global regions – for a wide (but not complete) range of energy carriers.	Approaches developed for assessing well-to-tank characteristics (guarantees of origin) are limited to selected global regions (Europe, North America) and therefore require expansion in geographical coverage. Continuous development and updates of different fuel production pathways are needed: hydrogen and hydrogen-based fuels (plus hybrid “power and biomass to liquids”, as well as electrofuels) are not yet covered. Parallel refinement of sustainability criteria (most relevant for the production of biofuels) also needed. This is a vast task and prioritisation is needed to manage costs.
Other quality requirements for energy vectors	Minimum fuel quality requirements for different vehicle pollutant emission standards are integrated into United Nation’s WP.29 Resolutions (construction of vehicles and common definitions of vehicle categories, masses and dimensions) and industry recommendations.	Tightening of fuel quality requirements to minimise real driving emissions from combustion engines, to enable better NOx and particulate matter after-treatment technologies, and to support energy efficiency improvements. Further optimisation of engines and fuels (including synfuels) and development of related technical standards, with the same objectives.
Energy, GHG and pollutant emissions occurring in vehicle and parts manufacturing	Developments mostly taking place in Europe, aimed at making batteries’ carbon footprint more transparent and clarifying rules for product differentiation for major components (like batteries). These cover aspects related to design, in-service verification, traceability of materials, recyclability characteristics, carbon footprint and end-of-life treatment of batteries and vehicles.	Expansion of geographical coverage and integration with policies on supply chain sustainability (which may also require technical standards/specifications for better traceability), to enable a scale-up of responsible sourcing practices for battery materials.

Sources: ACEA (2019); ITF (2020d); US DOE (2021b).

Box 3 discusses other aspects of environment and health impacts from road transport vehicles, with a focus on non-exhaust emissions. These also have implications for technical standards and/or regulations, given the possibility of integrating them into the most advanced legislation on pollutant emission limits under discussion.

Box 3. Non-exhaust emissions

A recent OECD report noted that, while emission standards for exhaust particles from motor vehicles are becoming more stringent worldwide, non-exhaust emissions of particulate matter (PM, generated by the wearing down of brakes, tyres and road surfaces, as well as by the suspension of road dust) are still largely unregulated (OECD, 2020b).

The report finds that electric vehicles emit levels of non-exhaust emissions similar to those of well-maintained ICE vehicles.[27] Accordingly, it suggests governments reconsider their policy approaches on emissions of particulate matter. Rather than provide blanket support for electric vehicles, they should develop more-sophisticated policy instruments that consider a vehicle's non-exhaust emissions rather than its drivetrain only. Considering that PM emissions also vary based on vehicle size, with higher non-exhaust emissions from road dust for large vehicles, the report also calls for a differentiated approach that accounts for differences across vehicle categories and the development of a standardised measurement methodology for the processes that generate non-exhaust emissions.

This recommendation is likely most relevant for brake and tyre wear, because (a) emissions from particle resuspension largely depend on the presence of dust on the road (and cannot therefore be easily controlled via regulations regarding vehicle characteristics) and (b) road wear is also often merged with road dust resuspension in studies that analyse this subject.

Due to the far worse performance of ICE vehicles not subject to the most stringent tailpipe emission standards (along with challenges related to the need for effective maintenance), this recommendation is also most relevant to the subset of countries that are working on norms aiming to tighten further (i.e. beyond the most stringent tailpipe emission standards) the impact of vehicle operations on local air quality.

Since the negative health impacts of PM are stronger for small particles (Maher *et al.*, 2016), it will also be important that future development of technical standards for pollutant emissions integrate particle number thresholds, no matter if the origin is brake wear, tyre wear or combustion. Doing this will require a better understanding of particle number emissions from brake and tyre wear, especially for tyres for which there are more unknowns.

The World Forum for Harmonization of Vehicle Regulations' Working Party on Pollution and Energy (GRPE) has initiated the development of a rigorous test procedure to measure brake particle emissions under standardised conditions. This would be based on a the WLTP test cycle and also consider effects of regenerative braking used to recharge vehicle batteries in the case of HEVs and EVs (UNECE, 2021a).

The health impacts of the different sources of PM should also be assessed, so that greater stringency can be devoted to those with the highest health impacts. While a very high impact is known for exhaust particles, brake particles seem to mainly produce negative effects in the lungs (Park *et al.*, 2018), while the lungs are not the main transfer route for nanoparticles to the brain (Cunha *et al.*, 2017; Costa *et al.*, 2019).

The development of technical standards and regulations for clean vehicles is typically led by countries whose automotive and/or energy industries have important stakes in the economy and the global automotive and/or energy market. These are often also export-oriented industrial economies. Key examples traditionally include Canada, Europe, Korea, Japan and the United States, as well as China, more recently. Other countries actively involved in the development of international standards for vehicles and charging/refuelling infrastructure include emerging economies like India and Russia. They are followed by countries with a strong automotive sector in Latin America (Argentina and Brazil) and in the ASEAN region (Indonesia, Malaysia and Thailand).

Technical standards and regulations in low- and middle-income countries have generally followed developments in the most developed markets. However, this paradigm has changed in recent times. This can be attributed to a greater awareness among policy makers about (a) the need to respond to worsening air-quality conditions and climate-related concerns (and risks) and (b) opportunities for enhanced economic competitiveness, export opportunities and job creation from developments in clean energy and sustainable mobility technology.

While region-specific standards have been used in emerging economies to support the development of new industries (without the same quality requirements applied in developed economies), a tendency towards greater harmonisation emerges in conjunction with a subsequent consolidation of industrial players, enabling the best performers to gain market share and flourish. This was the case in China for the developments related to technologies – in particular batteries – that play a central role in clean energy and sustainable mobility (including through the integration of digital connectivity in transport) (Jin *et al.*, 2021). A quicker alignment to international standards can also be associated with the more recent desire to attract foreign investment and seize leapfrogging opportunities. The case of electric mobility in India could be seen as a relevant example (NITI Aayog and Rocky Mountain Institute, 2017).

All these developments are supplementing the strong signals emerging (a) in Europe, especially in the framework of the Green Deal (EC, 2021d; European Committee of the Regions, 2021), in combination with its long-standing engagement in international regulatory activities for the vehicle market (EC, 2021f); and, more recently, (b) in the United States, as demonstrated by the White House Executive orders on Tackling the Climate Crisis at Home and Abroad (White House, 2021c) and on America's Supply Chains (White House, 2021a).

Establishing a clear vision and integrating key targets

Due to the significant complexity (and therefore cost) of their development, technical standards and regulations come with important prioritisation requirements. These are due to the need to optimise available public and private sector resources for policy interventions to serve clearly identified and motivated policy goals, and to be effective in producing benefits that outweigh costs.

This is why resources dedicated to the development of these key prerequisites for technological transition are best invested when they fit with a clear vision. The latter is generally sketched out at a high level in policy documents that have a long-term horizon and outline key policy priorities, along with a range of specific and quantified objectives. Key examples include the recent set of net-zero pledges made by the leaders of several major economies.[28]

Visions are then detailed further in sectorial documents, outlining ways in which these high-level objectives are expected to materialise and specifying the policy instruments that governments plan to develop for that purpose.

For clean road-transport vehicles, vision documents and targets often focus on the central objective of fostering the industrial and socio-economic development associated with vehicle construction and activity, while reducing its harmful impacts. This includes reducing emissions of local air pollutants and GHGs while improving energy efficiency. The targets integrate increases in the market shares of low- and/or zero-emission vehicles (LZEVs). Selected examples that integrate specific objectives on clean vehicles are summarised in Table 3.

Table 3. Clean vehicle deployment targets in major automotive markets

Market	Targets
China	The "New Energy Automobile Industry Development Plan (2021-2035)" released by the State Council in China confirms market-share targets for 'New Energy Vehicles' (BEVs, PHEVs and FCEVs) of 20% by 2025 and 50% 2035, when non-hybridised ICE vehicles will no longer be permitted (Government of China, 2020b).[29]
European Economic Area	The European Sustainable and Smart Mobility Strategy (EC, 2020e) outlines key milestones for all transport modes as well as specific ones for clean vehicles. At least 30 million zero- (tailpipe) emission cars will be in operation on European roads by 2030, and nearly all cars, vans, buses and new heavy-duty vehicles are to be zero-emission by 2050.
Japan	Japan has targeted a market share below 50% for ICE vehicles in 2030 (Morimoto, 2021), recently followed by a commitment, outlined in Japan's "Green Growth Strategy Through Achieving Carbon Neutrality in 2050" of December 2020, to take comprehensive measures to make electrified vehicles (including HEVs, PHEVs, BEVs and FCEVs) account for 100% of new passenger vehicles sales by the mid-2030s and to consider similar measures for commercial vehicles during 2021 (METI, 2020a). FCEVs have been a traditional focus for Japan, with specific targets of 200 000 cars on the road by 2025 and 800 000 cars plus 1 200 fuel cell buses by 2030 (METI, 2019; MFAT, 2020). However, the Green Growth Strategy makes explicit reference to an ambitious push to introduce electric vehicles and build world-leading industrial supply chains – including for batteries, which are seen as key to promoting vehicle electrification and renewable energy (METI, 2020a).
Korea	Korea has targets of 350 000 EVs in 2022, 1.13 million EVs (including passenger cars, buses, and freight vehicles) by 2025 and 3 million by 2030; for hydrogen, 0.2 million FCEVs by 2025. One-third of all vehicles shall also be "eco-friendly" by 2030 (Government of Korea, 2020; IEA, 2020e; Ministry of Land Infrastructure and Transport, 2021).
United States	The American Jobs Plan includes specific goals of electrifying 50 000 public transport buses and 20% of all school buses by 2030 (White House, 2021e). Goals also exist at the state level; in particular, California has a goal of 5 million "zero-emission vehicles" on the roads by 2030 (CPUC, 2021).

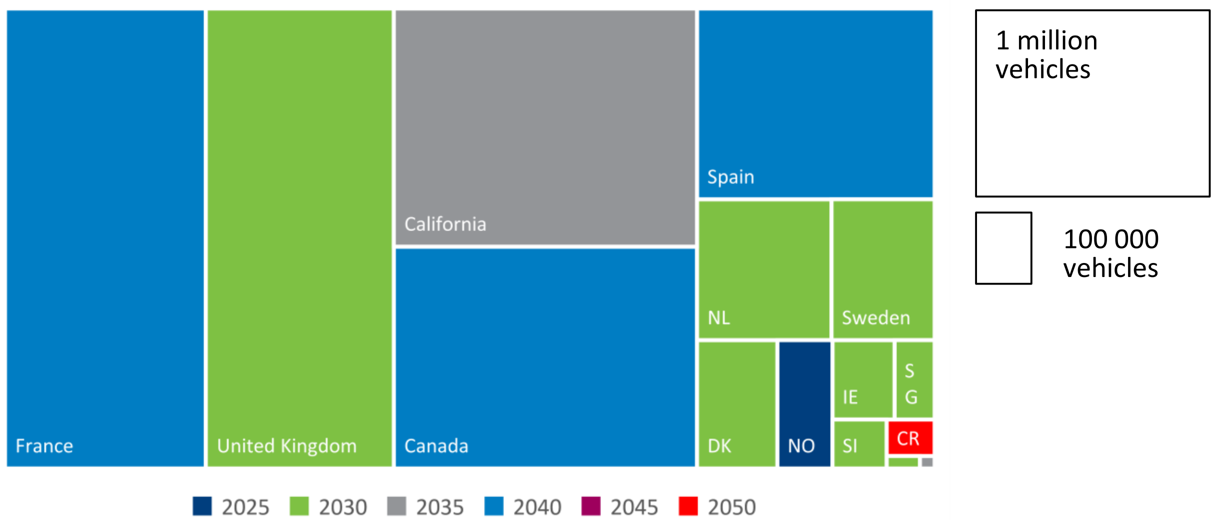
A growing number of pledges also include complete bans on the sale of ICE cars (or market-share targets of 100% LZEVs) and cover markets that represent over 10% of vehicle sales (Figure 6). The most ambitious announcements target a phase-out by 2025 (passenger cars, light commercial vehicles and urban buses in Norway, and urban delivery vehicles in the Netherlands) and by 2030 (passenger cars in Denmark, Iceland, Ireland, Israel, the Netherlands, Singapore, Slovenia, Sweden and the United Kingdom).

In Europe, a recent letter by Austria, Belgium, Denmark, Greece, Malta, Ireland, Lithuania, Luxembourg and the Netherlands also called for a phase-out date for the sale of new ICE passenger cars and ICE light commercial vehicles with combustion engines across the entire European Union (Gewessler *et al.*, 2020), facing opposition from Germany (Nijhuis, 2020). Following this, the "Fit for 55" policy package revised the CO_2 emission standards for new cars and vans. It proposed regulatory requirements for a full transition to vehicles with zero CO_2 tailpipe emissions by 2035, across the European Union (EC, 2021n). This proposal needs clearance from the European Council and Parliament as of July 2021.

Other pledges have also been announced at sub-national level. The most ambitious and iconic include a ban on all ICE vehicles by 2030 in Hainan (China) and a ban on passenger ICE cars and ICE light-duty trucks in California (United States) by 2035 (Wappelhorst and Cui, 2020). Similar to the case of European governments calling for an ICE ban, two Senators from California also recently called for the federal government to follow California's lead and set a date by which all new cars and passenger trucks must be zero-emission vehicles and to restore California's authority to set clean car standards (Shepardson, 2021).

Several municipalities also pledged to restrict areas for LZEVs and procure LZEVs for their public transport fleets, along with other mobility-related initiatives (C40, 2019b, 2021).

Figure 6. Car markets requiring the ICE phase out or the full transition to LZEVs, by size (sales in 2019)



Source: Government of the United Kingdom (2020a); Wappelhorst and Cui (2020), Wappelhorst (2021); ACEA (2021b); OICA (2021); Posaner and Oroschakoff (2021).

Notes: CR=Costa Rica, DK=Denmark, IE=Ireland NL= Netherlands, NO=Norway, SG=Singapore, SI=Slovenia. Panel sizes represent 2020 share in global light-duty vehicle sales. Markets without label in figure are (with respective phase out year and listed by market size): Iceland (2030) and Cabo Verde (2035). In addition, China's province of Hainan has announced an ICE phase out from 2030 and the Canadian province of Quebec has confirmed to phase out ICEs by 2035. Markets with ICE phase out announcements represent more than 10% of global market size (derived from 2019 sales). Figure only includes phase-out targets that are stated in official policy documents. It excludes unconfirmed ICE phase-out initiatives in Hong Kong, the U.S. states of Massachusetts, Washington and New York, as well as in the European Union (Wappelhorst, 2021; Posaner and Oroschakoff, 2021).

The availability of charging and refuelling infrastructure is a key requirement to ensure access to energy for clean vehicles running on electricity or hydrogen and reinforce consumer confidence in choosing them. These vehicles are also a high-priority area for government responding to the economic downturn brought by the Covid-19 crisis.[30] Additional objectives have been set through location-specific planning activities to ensure sufficient charging installations at the city/municipal level, starting from "EV capitals" (Hall *et al.*, 2020).

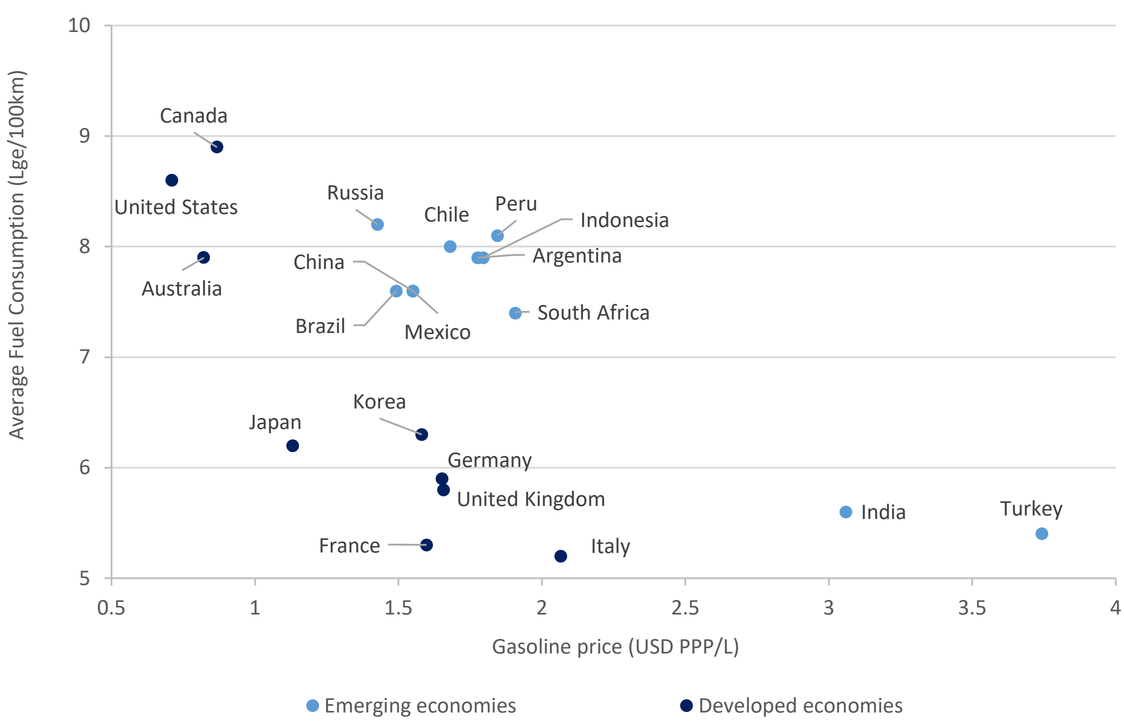
Ensuring that there is an enabling environment on energy and carbon taxes

In addition to the key prerequisite of available technical regulations and standards and the need for a clear vision to reassure investors regarding technology shifts, making sure that taxation of GHG-intensive forms of energy is sufficient to encourage citizens and investors to favour clean over polluting energy sources is an important step to enable a transition to clean vehicles and energy vectors, especially (but not only) when more targeted policy instruments are not feasible.

Recent work by the Organisation for Economic Co-operation and Development (OECD) pointed to good reasons to tax different forms of energy use differently. This is because different forms of energy lead to different external costs on society, due to different levels of emissions (of greenhouse gases and local pollutants) (OECD, 2019a). This can explain, at least partly, why road transport fuels tend to be taxed at far higher rates (primarily through fuel excise taxes and, to a lower extent, through explicit carbon taxes) than energy use in other sectors.[31] Other justifications for fuel taxes include the need to raise funds for the general budget, cover the costs of energy security, reduce oil import bills, and improve access at affordable cost to all – for instance, through reallocating revenues to public transport services (IEA, 2021f).

Analyses by the OECD and the International Energy Agency (IEA) also show that energy use tends to be less carbon-intensive in countries that tax road transport fuels at higher rates. This is because higher energy prices encourage citizens to consume less energy, inducing them to opt for more energy-efficient choices, technologies and behaviours. In the case of road transport, country-level data with a focus on cars shows that declining fuel consumption levels are related to increasing fuel prices (Figure 7), while increasing distances are travelled in countries with lower fuel prices and similar income levels (IEA, 2017b).

Figure 7. Fuel consumption of cars as a function of gasoline prices (2017)



Note: Lge = litres of gasoline equivalent; PPP = purchasing power parity; USD = United States dollars.

Source: ITF elaboration based on IEA and ICCT (2019).

Taxation is also used in a few administrations as an instrument for supporting the adoption of low-carbon fuels, taking a lifecycle-GHG-emissions accounting perspective. This is the case in jurisdictions that adopt carbon pricing mechanisms like low-carbon fuel standards (used in the U.S. states of California and Oregon and the Canadian province of British Columbia). Technically, this could be the case for countries that have established carbon pricing through cap-and-trade schemes. This is the direction envisaged by the proposals made in the EC "Fit for 55" policy package, July 2021. Revision of the EU Emission Trading

System, in particular, includes a separate new emissions trading system for road transport and buildings, complemented by the an increase in funding to accelerate innovation and support the modernisation of the European energy system. This new trading system includes the integration of shipping and revision of the policy framework applying to aviation and other transport sectors (EC, 2021j).

Countries also tax the consumption of electricity through electricity excise taxes, mainly applied to residential and commercial uses (OECD, 2019a). Additionally, electricity is also subject to indirect carbon taxes in countries that apply market-based mechanisms for carbon pricing like emissions trading schemes; however, due to the diversity and cost-competitiveness of the various primary forms of energy used to produce electricity, these indirect electricity taxes have only weak impacts on end-user prices.[32]

On the other hand, consumption taxes on electricity are applied in a way that not only fails to differentiate between primary energy sources, but is even detrimental for some forms of renewable energy (OECD, 2019a). This is because such taxes apply a lower burden, per unit of primary energy, on electricity generation processes that are subject to higher losses in the conversion process. This is the case in thermal power generation, as opposed to hydro, solar and wind electricity.

As hydrogen is primarily used within industrial processes and has only recently emerged as a potentially tradeable commodity (S&P Global Platts, 2019), it is not subject to direct end-use taxation. Like electricity, though, it is subject to indirect signals from carbon taxes in countries that include facilities producing hydrogen for the synthesis of transport fuels (such as chemical plants and refineries). As with electricity, consumption taxes on hydrogen would be comparatively detrimental for renewable energy sources, as primary renewables would be subject to similar or higher taxation (per unit of primary energy) in comparison with fossil natural gas (the actual balance depends on the production pathway).[33]

In Europe, the “Fit for 55” policy proposal to revise the European Energy Taxation Directive addresses some of these challenges. This better reflects the impact that the taxation of motor fuels, heating fuels and electricity have on the environment and health. It suggests that electricity should always be among the least-taxed energy sources to encourage its use, notably in the transport sector, and removes exemptions and reduced rates still applicable to fossil fuels – e.g. due to distinctions between commercial and non-commercial diesel fuel in road transport (EC, 2021i).

Adopting ambitious public procurement programmes

Public procurement programmes are important in creating market demand and reducing investment risks for businesses that support clean vehicles. They incentivise vehicle manufacturers to invest in production and spur the initial deployment of charging points and/or refuelling stations for vehicles running on electricity and hydrogen. These programmes also increase awareness and visibility for emerging clean-vehicle technologies while they are not yet familiar to the general public. Public procurement also supports the emergence of businesses (and related expertise) supplying complimentary services, including vehicle parts and component manufacturers and vehicle maintenance and after-sale services.

To maximise benefits and minimise costs, public procurement programmes for clean and energy-efficient vehicles are best conceived when they first target vehicles with the highest usage levels, as these are the cases where clean technologies offer clear economic advantages. Prime candidates include BEVs used in cases with predictable daily ranges (allowing battery capacity to be optimised for a specific usage profile) and regular access to overnight charging (which is better suited to helping with electricity demand management). Key examples of these cases include urban buses, taxis, ridesourcing and service vehicles (such as garbage trucks), for which public authorities often have regulatory oversight. Urban delivery vehicles are another promising segment for electrification.

Public procurement policies typically take the form of minimum thresholds for low- and zero-emission vehicles for the renewal of vehicles that are directly purchased or whose purchase is funded (e.g. through public service contacts) by different levels of the public administration. To the extent that public procurement policies focus on vehicles using electricity and energy vectors that cannot be blended with petroleum gasoline and diesel, they have direct implicit implications for the deployment of charging/refuelling infrastructure.

Procured vehicles and charging/refuelling infrastructure can both benefit from centralised bulk purchases to reduce purchase costs (thanks to lower transaction costs and risk mitigation for manufacturers aiming to scale up production). The public sector also has access to capital at low cost, which is also effective in minimising financing costs.

Following the initial phase of ensuring vehicle and infrastructure supply availability and stimulating vehicle demand, public procurement programmes are also crucial to ensuring continued technology cost reductions. Key mechanisms enabling this are technology learning and economies of scale.

An overview of policy frameworks on public procurement for clean vehicles deployed in major automotive markets[34] points to the fact that China, the European Union and, more recently, the United States are the markets where procurement action has been or is bound to be broadest in scope – i.e. it involves a range of different vehicle categories, from light duty to heavy duty.

Providing economic incentives

Economic incentives are crucial to scale up the deployment of clean vehicles. The nature of the economic incentives that have been used is far from uniform. Gaining a better understanding of the role and the timeline of economic incentives needed to boost supply and demand for clean vehicles is possible when looking more closely at markets that have been particularly successful in kick-starting the roll-out of electric vehicles. This is certainly the case for China, Europe (in particular the Nordic region) and parts of the United States (namely California).

Table 4 shows the lessons resulting from these experiences, summarising information on economic measures that have proved effective in supporting clean-vehicle deployment from low technology readiness to mainstream market development.

Table 4. Economic incentives to support deployment of clean vehicles and fuel solutions

Phase of market development	Area of intervention	Type of economic incentive
Low technology readiness (pre-standardisation)	Supply-side technology push	• Support for technological developments through grants, research funds and tax exemptions for R&D spending.
	Demand-side market pull	• Targeted budgetary allocations for public procurement programmes.
	Supply-side technology push	• Economic instruments aimed at bringing technologies to the market (while stimulating cost reductions through scale increases and technology learning) by mobilising private capital by reducing investment risks. These include grants,[35] co-investment by public entities,[36] debt service reserves,[37] government-held subordinated debt,[38] credit insurance products for bond financing,[39] and loan guarantees.[40]

Phase of market development	Area of intervention	Type of economic incentive
Initial deployment (accompanying the availability of technical safety standards and regulations)	Demand-side market pull	• Budgetary allocations for public procurement programmes focused on purchases of clean vehicles and energy for the public administration and entities receiving public funding for public service contracts (e.g. for public transport). • Contracts for difference, which commit the government to paying part or all of the cost difference between clean and conventional vehicle or energy technologies. • Taxation on vehicle purchase and/or circulation, differentiated on the basis of environmental performance of vehicles (e.g. via bonus/malus schemes or incremental rates per g CO_2/km).[41] • Differentiated parking, access and infrastructure-use fees, based on the environmental performance of vehicles.
Consolidation (accompanying the emergence of environmental standards and regulations)	Supply-side technology push	• Research funding, tax rebates and financial instruments aiming to reduce investment risks, conditional on the achievement of specific performance goals (e.g. energy and/or power density, durability of EV batteries, focus on zero-emission enabling technologies), integrating enforcement provisions (e.g. proof of sale and use of clean vehicles and energy). • Progressive reductions in budgetary allocation (and shift to regulatory requirements) for procurement programmes. • Green/climate bonds, conditional on specific attributes (performance based on environmental parameters such as GHG emissions per km) for the type of investment made, paired with tax advantages on revenues realised by investors. • Economic incentives from export credit or investment insurance agencies for projects facilitating the development of supply/value chains for materials and components needed for clean vehicle production and/or clean energy supply.
	Demand-side market pull	• Taxation on vehicle purchase and/or circulation differentiated on the basis of environmental performance of vehicles (e.g. via bonus/malus schemes or incremental rates, e.g. per g CO_2/km), with advantages subject to tighter requirements (e.g. with a focus on zero-emission enabling technologies), combined with regulatory requirements (e.g. low/zero-emission vehicle mandates, fuel economy standards). • Differentiated parking, access and infrastructure-use fees, based on the environmental performance of vehicles, with advantages subject to tighter requirements (e.g. with a focus on zero-emission enabling technologies). • Export credit agencies can also support infrastructure deployment to increase consumer confidence on clean vehicle purchases in emerging markets.
Mainstream market development (accompanying the tightening of environmental regulations)	Supply-side technology push	• Progressive phase-out of tax rebates and financial incentives for manufacturers and phase-in of taxation. • Economic incentives from export credit or investment insurance agencies for projects facilitating the scale-up of clean vehicle/energy supply/value chains. • Green/climate bonds, conditional on specific attributes (performance based on environmental parameters, e.g. GHG emissions/km) for the type of investment made.
	Demand-side market pull	• Progressive phase-out of economic incentives for vehicle purchases and shift to regulatory requirements (e.g. low/zero-tailpipe-emission vehicle mandates and fuel economy standards). Continued relevance of export credit agencies in supporting infrastructure deployment in emerging markets, thereby increasing consumer confidence on clean vehicle purchases.

Source: This summary is informed by information available from IEA (2018b, 2018a); Runkel and Mahler (2018); IEA (2019a); Wappelhorst and Cui (2020); Goldie-Scot (2021); Jin *et al.* (2021); US DOE (2021a).

Important insights from the table indicate the following:

- Economic incentives can be broadly categorised in two groups. The first consists of supply-side or "technology push" measures that promote investments in clean vehicle production and/or technology progress to cut costs. The second consists of demand-side or "market pull" measures that stimulate consumer demand for clean vehicles.
- Public support for research and innovation is the supply-side measure with the greatest relevance in the early phase of technology development, when budgetary allocations to stimulate demand are likely best placed in targeted procurement programmes, allowing for the early commercialisation of innovative forms of clean vehicles. Support for R&D through tax incentives can take the form of advantageous tax treatment of R&D expenditures, as well as preferential treatment of incomes attributable to R&D or patents (OECD, 2018).
- In the initial phase of technology deployment, public support on the supply side needs to shift towards the mobilisation of private investment as the market demand for clean vehicles increases. On the demand side, this needs to be matched by increased budgetary allocations for public procurement and other economic instruments capable of increasing the value proposition for clean vehicles – beginning with vehicles that are used intensively, such as urban buses and other fleets.
- As vehicles with high utilisation rates move towards cost parity, economic incentives shift to vehicles that have lower intensities of use. On the supply side, financial instruments like green bonds gain relevance (over other forms of public support) in the mobilisation of capital for investment for market scale-up. On the demand, side, the focus can start to shift to larger portions of the market, going beyond vehicles with heavy usage profiles alone. This is the phase when differentiated taxation on vehicle purchase or circulation (including for company cars), based on the environmental characteristics of the vehicles, can make a significant difference (IEA, 2018b; Runkel and Mahler, 2018; IEA, 2019a; Wappelhorst and Cui, 2020). As budgetary requirements increase in this phase, market pull measures need to be focused on a narrower range of technologies – and accompanied by instruments that allow the necessary budget to be raised, such as bonus/malus approaches or increases in taxes applied to vehicles with poor performances.
- As market demand and vehicle supply reach maturity, supply and demand incentives need to transition towards revenue-generating solutions to ensure resilience and sustainability for the market transformation.

In addition to the considerations contained in Table 4, it is also important to flag elements that increase the complexity of the challenge of setting these economic incentives effectively:

- Market developments are not uniform for all road transport modes. Some modes (e.g. buses, urban delivery vehicles and two wheelers) are better placed to transition towards clean vehicle technologies (in particular electrification) first (ITF, 2020b, 2020c). Others (e.g. heavy-duty vehicles) are likely to be a better fit for a later transition, benefiting from cost reductions resulting from earlier market deployment in the car segment (i.e. the market segment with the largest volume of sales), even if differences in mission profiles (e.g. urban vs. non-urban use) are also important to consider.
- The deployment of clean vehicle technologies does not happen in isolation, and needs to take into account the dynamics that influence technology cost that are taking place beyond the transport sector. A crucial example is the case of batteries, whose cost has fallen thanks to large-scale

demand in a high-value market like consumer electronics (IEA, 2018a), before reaching passenger cars, and even there started from high-margin vehicles (ITF, 2020c).

- Clean vehicle technologies showing clear potential to compete on costs against incumbent solutions are in a far better position to succeed than technologies that do not come with compelling expectations to offer lower operational costs.
- Clean vehicle technologies are also favoured significantly if they can offer the prospect of lower transitional cost for their access to energy. This is more likely in cases where the energy vector is also used in buildings and industry, not only by transport vehicles, since this allows the sharing of energy transportation and/or transmission costs across different end-uses. The availability of the energy distribution infrastructure is also important in this context.

The last three points (in addition to differences in the likelihood of contributing to net savings in energy and GHG emissions once large-scale deployment is achieved) largely explain the stark difference in market uptake between direct electrification technologies (PHEVs and BEVs) and FCEVs.

An overview of economic incentives in place for clean vehicle supply and demand, as well as charging and refuelling infrastructure,[42] points to a number of observations:

- Governments have a tendency to take stronger actions for plug-in vehicles requiring electricity as an energy vector (BEVs and PHEVs) than for FCEVs and hydrogen. This reflects a higher level of technology readiness, and lower economic barriers for the availability of the fuel the vehicles need, for the former than for the latter, thanks to the already widespread role of electricity as an energy end-use vector.
- Economic incentives have historically focused on cars and urban buses, though they are being expanded to include other heavy vehicles.
- For more than a decade, China has used a series of economic incentives to stimulate both demand for and supply of “new energy vehicles” (in particular BEVs and PHEVs, but also FCEVs); this includes the supply of key components, such as batteries (Jin *et al.*, 2021, Goldie-Scot, 2021). China is also the automotive market that, to date, has placed the greatest emphasis on the deployment of charging infrastructure (The People’s Republic of China, 2020, Bloomberg, 2021c, 2021d).
- The European Economic Area also emerges as a region with an important series of policy decisions on economic incentives (ACEA, 2020b, 2020a; EC, 2021p) and a strong tradition of investments in automotive research and development (Grosso *et al.*, 2020; ACEA, 2021d), especially for EVs (BEVs and PHEVs). This global market also has scope for greater coherence and more-effective action in the case of infrastructure deployment for charging and refuelling (EAFO, 2021; ECA, 2021). This reflects each government’s considerable autonomy on topics requiring specific budgetary allocations (such as those influencing the roll-out of charging/refuelling infrastructure and taxation applied to vehicles, which may or may not be framed by European Union directives) with respect to regulatory requirements.[43]
- The United States has used economic instruments to encourage both clean-vehicle research and development and the manufacturing of clean vehicles and related energy infrastructure (US DOE, 2021d, US DOE, 2021e), sometimes with heterogeneous choices across states (US DOE, 2021a). Recent decisions have shifted the focus towards the scale-up of EV manufacturing, battery production, battery material supply chains, and charging infrastructure deployment, despite a remaining interest in FCEV technologies and other clean vehicle and alternative energy technologies (White House, 2021e).

- Japan and Korea – whose domestic market size is smaller, but whose industries are major global exporters of transport vehicles – are increasingly considering economic incentives and budgetary allocations aimed at supporting their export capacity, both for vehicles and for key components such as batteries (METI, 2020a; IEA, 2019a; Seo, Oh and Lee, 2021). Because they face potential limitations in terms of availability of low-carbon electricity supply, they are also showing a stronger interest in FCEVs (which may benefit from imports of low-carbon hydrogen).

In some cases, decisions taken by local authorities have also complemented national and state-level action on economic incentives. For example, in London and Milan, electric vehicles are exempt from congestion and urban access charges (IEA, 2018a). Other examples include licence tag lotteries and quotas on new registrations in Chinese cities (Jin *et al.*, 2021).

Equity impacts also deserve greater attention when looking at the economic measures being implemented to accelerate the shift to low-carbon mobility. Studies have shown that subsidies are often used more widely by higher-income groups (Bansal, Kockelman and Wang, 2015; Turrentine, Tal and Rapson, 2018). It is therefore crucial that these incentives and programmes be designed in a way that is inclusive and allows all income groups to benefit. Examples of good practice already exist. In 2016, California's Clean Vehicle Rebate Project introduced income-eligibility requirements to ensure more-equitable distribution of the incentive (Clean Vehicle Rebate Project, 2016).

Similarly, tax credits can help reduce the sum owed in taxes by a specific amount or a range of amounts. However, a low-income household whose tax liability is lower than the amount of credit does not benefit from this incentive to the same extent as a high-income household. Hence, considering the distributional impacts, tax credits are a less attractive incentive option unless they are targeted towards low-income households and work like a tax refund, without requiring a certain threshold of tax liability (Greenlining, 2016).

Studies have shown also that targeting incentives at low-income groups not only makes them more equitable, but can also make the programme more cost-effective, since higher-income households are more likely to buy an EV without incentives (DeShazo, Sheldon and Carson, 2017; Muehlegger and Rapson, 2018; Jenn et al., 2019). Policies that ensure equitable distribution of incentives are key enablers of a just transition.

Enforcing regulatory requirements

Regulatory requirements on clean vehicles and the energy they use have been introduced in major automotive markets with the aim of managing impacts of transport vehicles on local air quality, ensuring that vehicles contribute to energy efficiency improvements and GHG emission reductions, and facilitating energy diversification in a sector that is still largely reliant on fossil oil. Additionally, regulatory action has been justified by desires to enhance economic productivity, given that cost-effective energy savings can help foster both economic and industrial development. This is especially important in cases where the automotive industry has a central role in the economy and where its competitiveness is crucial to ensuring that economic development is based on strong foundations. Table 5 provides a brief overview of different types of regulatory measures in place or about to be adopted in major global automotive and energy markets, targeting both vehicles and energy vectors.

Table 5. Regulatory measures framing clean vehicle (and related energy) deployment

Area of intervention	Type of regulatory measure
Vehicle	• Pollutant emission regulations/standards • Fuel economy/GHG emission regulations/standards • LZEV emission mandates • Access/registration/use restrictions (and waivers) in portions of the road network • Carbon content and sustainability requirements for key components (batteries)
Energy	• Carbon intensity and sustainability requirements of energy vectors • Charging/refuelling infrastructure deployment requirements

A recent review of energy- and environment-related regulations was released in September 2020 by the ITF (ITF, 2020d). With regard to regulations on clean vehicles (and related energy requirements), the review found that:

- California, China and Europe adopted regulatory texts with specific LZEV requirements and/or incentives. These include California's Zero-Emission Vehicle mandate, China's New Energy Vehicle (NEV) credit mandate and the European Regulation on GHG emission limits for cars and vans. The latter has been revised in the July 2021 "Fit for 55" policy package. This proposal tightens the 2030 reduction requirements. Cars from 37.5% to 55%, and vans from 31% to 50% relevant to a 2021 benchmark based on the Worldwide Harmonised Light-duty Vehicles Test Procedures (WLTP). It adds also a requirement for a full transition to vehicles with zero CO2 tailpipe emissions by 2035 (EC, 2021m).
- California's recent major regulatory development is relevant for both NO_X and GHG emissions and requires manufacturers to transition from diesel to electric trucks and vans beginning in 2024; it requires a full market transformation by 2045 (including existing vehicles). All other major markets, except Korea, have also established GHG emission regulations for heavy vehicles. In the United States, a recent executive order also foresees a review of federal legislation on fuel economy standards and an increase in their ambition (White House, 2021b).
- All major markets regulate vehicle tailpipe pollutant emissions. Significant developments on this subject are taking place in Europe, tightening existing emission thresholds and including the integration of on-board monitoring (OBM) to ensure lifetime compliance (Dilara, 2021). As OBM requires solutions for reading data from the vehicles and communicating with infrastructure, this could open up opportunities to integrate technologies that, combined with geofencing, could also enable the enforcement of all-electric driving in zero-emission zones.
- Market developments in global regions that have introduced regulatory requirements for clean vehicles – such as California (and the United States more broadly), China and Europe – clearly indicate that regulatory measures play an important role in converting vision statements into concrete market transformations.

The 2020 ITF analysis also reviews regulations on batteries, which are a central technology pillar for all types of LZEVs (they are essential in BEVs, instrumental for PHEVs, and critical to ensuring that the energy efficiency of FCEVs is optimised). Batteries are the subject of significant regulatory innovations (ITF, 2020d), an observation strengthened by recent policy proposals released in China, Europe and Korea as well as policies being developed in the United States.[44] This subject is important not only in terms of environmental sustainability (see Box 4), but also in terms of the international harmonisation of safety and environmental standards, a subject that is gaining relevance for efforts to encourage competition on a level playing field.

Batteries can also be framed in a broader set of emerging regulatory developments related with GHG emissions that aim to limit effects from carbon leakage. Such a risk is the transfer of productive activities from one global area to another (with laxer carbon pricing requirements) for reasons of costs related to climate policies. The most prominent of these is the proposed Regulation establishing a carbon border adjustment mechanism in Europe (EC, 2021l). This Regulation seeks to address the risk of carbon leakage by ensuring that imported products are subject to equivalent carbon pricing as domestic products, but it does not gives credit for non-tax measures (such as technical regulatory requirements on safety and environmental impacts). There will be a progressive approach to replace carbon leakage avoidance measures, which are mainly based on a system of free allowances within the European Emission Trading Scheme (EC, 2021l). The relevance that this type of policy has for clean vehicles is that its scope includes steel and aluminium. These are materials and products that are widely used in the manufacturing of transport vehicles and parts/components. However, the EC "Fit for 55" Regulation proposal made in July 2021 does not include complex final products such as transport vehicles and many of their complex components. This is because they are likely to require a higher carbon price in the future to gain relevance for the risk of carbon leakage (EC, 2021l).[45]

Box 4. Government action on sustainable battery supply chains

Promoting sustainable battery supply chains has become a priority for regulators and industry, the goal being to reduce the environmental and social impacts of vehicle batteries at all product stages, from the mining of raw materials to the recycling of end-of-life batteries.

Vehicle batteries are a new product about which existing electronic waste legislation can be ambiguous. China, Europe and Korea have proposed new legislation in the areas of battery production, second life and end-of-life disposal. In China and Korea, the focus is on battery reuse and recycling. In Europe, proposals address safety, durability, circular-economy responses (including second life and recycling) and the sustainability of battery supply chains. Europe is also addressing the carbon footprint of batteries within the framework of the European Green Deal, an initiative that may have relevance for policy developments in carbon border adjustments (European Commission, 2020). The United States also aims to promote recycling of vehicle batteries, and an advisory group in California is working to establish practices for 100% reuse or recycling (IEA, 2020d).

Cobalt production is also a priority for due diligence of battery supply chains. Over 60% of global extraction takes place in the Democratic Republic of the Congo, some of it from artisanal mining (IEA, 2019a). The OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas is a global framework that helps companies mitigate the risks of contributing to human rights violation, conflict or financial crimes through their sourcing practices; it applies to all minerals and metals (OECD, 2021d). In Europe, the proposed Battery Regulation requires that due diligence policies be established for rechargeable industrial batteries and electric vehicle batteries sold on the single market (EC, 2020b).

Regulations governing urban access have also gained significant attention in recent years. As with the access charges mentioned earlier for London and Milan, this has been driven largely by the desire of local authorities to mitigate local pollution. Many cities have committed to creating zero-emission urban environments by 2030 (C40, 2019b, 2019a; Sadler, 2020).

Because OEMs can find it difficult to comply with various locally determined restrictions, several countries are trying to better co-ordinate the development of access regulations and road charges for both light and heavy vehicles. Some examples are the development of country-specific labels on LZEVs (e.g. in France) or differentiated number plates (e.g. in Germany, Norway and recently the United Kingdom) (ITF, 2020d; Sadler, 2020). The Netherlands pioneers the use of regulations on access restrictions to urban freight delivery vehicles (C40, 2020). Since the early 2010s, China has also used a quota system for new car registrations, with different allocations for conventional and "new energy vehicles" (largely consisting of PHEVs and BEVs); this has been accompanied by traffic control policies that integrate waivers for new energy vehicles (Jin *et al.*, 2021).[46]

Box 5. Integrating EVs into the grid through unidirectional and bidirectional controlled charging

Equipping electric vehicles and grid infrastructure for unidirectional controlled charging (V1G) or the more advanced bidirectional controlled charging (V2G) can help integrate intermittent renewables (e.g. PV, wind power) into the power system. In markets that allow electricity prices to vary according to the time of the day and where network tariffs are adjusted to enable EVs to become an asset rather than a liability for the electricity networks (favouring charging choices capable of contributing to demand response), this can also allow EV owners to access electricity at more convenient rates.

V1G optimises charging time, duration and rate according to power system needs, while V2G enables EVs to feed electricity back into the grid to become distributed electricity resources. Both entail communication between vehicles and the power system and require digitalisation of vehicles and the grid (IRENA, 2019c). V1G and V2G can help the power system to reduce the need for peak generation capacity. These flexible generation units typically represent a 15-25% addition on top of what is needed to meet demand 90% of the time (IEA, 2020d). Peak generation capacity is typically provided by gas-powered power plants with high costs and limited decarbonisation potential.

Average electricity demand in key EV markets like China and Europe is highest in the four-hour interval from 18h to 22h and coincides with typical charging times of EVs that rely on home charging. V1G can shift EV charging away from daily demand peaks to night hours, thereby avoiding the need to expand peak generation capacity to accommodate a growing EV fleet. More benefits are expected from the more advanced V2G, which can not only prevent EVs from contributing to peak demand, but can reduce it by feeding power back to the grid during peak hours. This could enable a strong growth of intermittent renewables while reducing the need for additional peak generation capacity.

As of 2021, there is no large commercial application of V1G nor V2G, yet car manufacturers as well as energy companies have expressed interest (Matthes and Menzel, 2021). Tesla in 2020 announced that its vehicles will be V2G-ready in the future and Volkswagen will equip all EVs produced on its Modular Electrification Toolkit (MEB) platform with a V2G function from 2022 onwards (Tesla, 2020; Menzel, 2021). Hyundai-Kia has also announced that EVs on its E-GMP platform can be used as a power resource (Hyundai Motor, 2020b). The charging standard association CHAdeMO, together with selected OEMs and utilities, has completed projects to demonstrate that V2G is ready for commercial application (CHAdeMO Association, 2018).

Regulatory requirements have also been rolled out to ensure that electric mobility can play an active role in increasing the flexibility of electricity systems. The European Union has been at the forefront of legislative work on the topic, with the update of the Directive on common rules for the internal market in electricity, adopted in March 2019. As explained in Box 5, this allows EV owners and other energy consumers to get access – via intermediary entities capable of pooling demand from different end-users – to electricity markets and to perform demand response activities, increasing opportunities for integrating variable renewable energy resources into the generation mix, as well as reducing the cost of electricity for EV owners (IEA, 2019a). Recently, the Federal Energy Regulatory Commission of the United States started to move in this direction, seeking comment on whether to revise related regulations (FERC, 2021).

Regulatory instruments have not frequently been used to facilitate EV charging and/or FCEV refuelling infrastructure, but the use of regulatory requirements in this field is gaining momentum. The main example of this is the proposal of a Regulation to replace the Alternative Fuels Infrastructure Directive in Europe, released in the broader context of the "Fit for 55" policy package, as discussed in Box 6 (EC, 2021o). Quantitative indicators were already integrated into infrastructure-related targets and plans in the Alternative Fuels Infrastructure Directive of 2014, but these did not include detailed and binding methodologies to calculate targets and adopt measures. Regulatory requirements have now been introduced for parking spots in buildings to be ready for EV charging installations. This is the case for both Europe and also and specific jurisdictions in North America. Korea is also considering mandatory requirements in regulations for new buildings (IEA, 2019a; Kang, 2020).[47]

Box 6. European regulatory instruments for alternative fuel charging/refuelling infrastructure

The proposed European Regulation on alternative fuel infrastructure encourages the availability and usability of a dense, widespread network of alternative fuels infrastructure throughout the European Union (EC, 2021o). Its specific objectives are: (i) ensuring minimum infrastructure to support the required uptake of alternative fuel vehicles; (ii) ensuring the infrastructure's full interoperability; and (iii) ensuring full user information and adequate payment options.

The proposed Regulation for electric road vehicles introduces minimum requirements for light and heavy vehicles.

- *Light vehicles*: minimum requirements for publicly accessible recharging stations (i.e. physical installations for the recharging of electric vehicles) are expressed in terms of power output per vehicle, with thresholds set at 1 kW for BEVs and 0.66 kW for PHEVs.
- *Both light and heavy vehicles*: the proposed Regulation also includes geographical availability requirements. These are expressed both in terms of maximum distance (60 km) and power output per recharging pool (i.e. one or more recharging stations at a specific location), at different points in time (2025, 2030 and 2035). These requirements apply to the main European roads, according to the definitions available in the trans-European transport network (TEN-T), also differentiating between the "core" and "comprehensive" network links.

Electric Road Systems are considered as an emerging technology. Their integration is therefore limited to a recognition as alternative fuel infrastructure, and does not include regulatory requirements.

Requirements for road vehicles using hydrogen focus heavily vehicles to the year 2030. They have been identified as the most likely segment for early mass deployment in the European Commission's "A hydrogen strategy for a climate-neutral Europe"). Requirements label minimum station capacity (2 t/day) and geographical availability, expressed in terms of maximum distances between refuelling points, differentiating between gaseous hydrogen at 70 MPa (150 km) and liquid hydrogen (450 km) on the core and TEN-T comprehensive TEN-T networks. The proposed Regulation also requires that publicly accessible hydrogen refuelling stations are deployed in each urban node by 2030.

Fossil gaseous or liquid fuels for road transport are not the main focus of the proposal. Their use is considered possible only if clearly embedded into an obvious decarbonisation pathway in line with the long-term objective of climate neutrality.

Using regulatory requirements sets binding and directly applicable obligations. It is a healthy contrast from the overly wide variety of target setting and supporting policy ambitions that existed from the 2014 Directive. The use of Regulation is expected to be significantly more effective to deliver a geographically coherent deployment of infrastructure according to clear timelines. It will also instil robust governance and progress tracking mechanisms, as monitoring will rely on indicators for the physical rollout of recharging and refuelling infrastructure. The Regulation is also expected to more effectively mitigate risks from uneven deployment of infrastructure for vehicle producers, leading to the establishment of an effective level-playing field.

The proposed Regulation is consistent with the EU Sustainable and Smart Mobility Strategy and has the option to consider more-ambitious binding targets for the roll-out of infrastructure and a set of other measures included in the “Fit for 55” policy package. For road transport, these include:

- updating the regulation setting CO_2 emission performance standards for new passenger cars and light commercial vehicles
- updating the Renewable Energy Directive – requiring that 50 % of the hydrogen used in 2030 is from renewable electricity (EC, 2021i)
- a proposal to revise the Regulation on the Guidelines for the Trans-European Transport Network, the revision of the Emissions Trading System
- the revision of the EU Energy Taxation Directive.

Synergies for the Regulation also exist with the Energy Performance of Buildings Directive, the Clean Vehicles Directive, measures designed to ensure alignment with the necessary grid investments in the context of the Commission’s energy system integration and hydrogen strategies. The proposal works in conjunction with the Intelligent Transport Systems Directive, in particular on the subject of the fast-evolving data environment for alternative fuels. The proposed Regulation is also in line with measures to ensure full interoperability of infrastructure and infrastructure-use services for all alternatively fuelled vehicles.

The proposal follows calls from both original equipment manufacturers (OEMs) and non-governmental organisations (NGOs) for greater political commitment, indeed suggesting a switch towards a Regulation (rather than a Directive), and the integration of binding targets, for passenger cars and heavy-duty vehicles, per each EU Member State (ACEA, BEUC and T&E, 2021). Prior to the proposal, OEMs had called for the establishment of conditionality clauses linking EV charging infrastructure deployment with regulatory targets for reducing GHG emissions per km for cars and vans, and had also shown openness to even more ambitious targets (ACEA, 2021c, 2021a). The car industry and the main European environmental NGO working on transport, had also recently made a similar call in the case of trucks (ACEA and T&E, 2021). Both initiatives contain considerations for EV chargers and hydrogen refuelling, and a call for the harmonisation of the common market for zero-emission road transport across Europe. Recharging and refuelling standards to payment methods, tariff transparency and maintenance are some examples of this. Similar suggestions (accompanied by a call for a standalone regulation on EV charging infrastructure) have also come, prior to the release of the “Fit for 55” policy package, from the European association of the charging infrastructure industry (ChargeUp Europe, 2021).

Clearly define sustainable finance thresholds for clean vehicles and clean energy

The definition of sustainable finance thresholds for clean vehicles and energy vectors can be framed in the context of regulatory developments aiming to align the decisions taken by investors, corporations and other entities with governments' visions for developing the energy and the transport systems in alignment with the Paris Agreement. Details defining the relevant technologies (in particular those defining clean vehicles) can have important implications for choices made by major actors in the capital markets.

These developments, which are intended to increase the transparency of climate-related financial risks, were initiated by the Financial Stability Board (FSB)[48] with the creation, in 2015, of the Task Force on Climate-Related Financial Disclosures (TCFD) and the ensuing release, in 2017, of its climate-related financial disclosure recommendations.[49]

Due to the large contribution of road transport to global oil demand and related GHG emissions, clean vehicle and energy technologies play an important role in stewarding the capital invested by economic actors trying to minimise the risk of having their assets stranded as a result of climate (and innovation) policy.[50, 51]

The European Union is the global market that has made the most progress in terms of defining instruments (such as green bonds) to direct investments towards sustainable projects and activities. A key initiative in this regard was the creation of a common classification system, or a "taxonomy", for environmentally sustainable economic activities. The Taxonomy Regulation, which entered into force in July 2020, establishes this framework in the European Union (EC, 2020d). Its delegated acts, not yet finalised in July 2021, include screening criteria for low-carbon transport technologies (EC, 2021r).

Economic activities classified as sustainable include cars with up to 50 g CO_2/km of tailpipe emissions (therefore including PHEVs) until 2025, and zero tailpipe emissions of CO_2 after that (therefore excluding PHEVs). They also include buses, two-wheelers, three-wheelers and LCVs with zero tailpipe emissions of CO_2 and heavy trucks that emit less than half of the average CO_2 emissions/km of all vehicles in the same vehicle category (EC, 2021r).

On energy vector distribution for road transport, the economic activities include infrastructure dedicated to the operation of vehicles with zero tailpipe CO_2 emissions. In particular, these include electric charging points, electricity grid connection upgrades, hydrogen fuelling stations and electric road systems (ERSs). They also include infrastructure and installations dedicated to public passenger transport (EC, 2021r).

On energy vectors used or suitable for road transport vehicles, the activities cover electricity and hydrogen as well as biofuels. For electricity (and heat), they include (a) generation from renewable solar, wind, hydro, geothermal energy, and gaseous and liquid fuels leading to less than 100 g CO_2e/kWh and (b) biomass fulfilling the sustainability criteria defined in the recast of the Renewable Energy Directive (EC, 2021r). However, decisions regarding the way to consider electricity produced from natural gas and nuclear energy are the subject of a significant debate and will likely be dealt with in upcoming discussions (Simon, 2021). Economic activities included in the draft formulation also include (a) electricity transmission and distribution infrastructure – for cases where newly connected generation capacity is primarily serving generation capacity below the threshold value of 100 g CO_2e/kWh measured on a lifecycle basis – and (b) electricity storage in closed-loop pumped hydropower storage (EC, 2021r).

For hydrogen, they include construction of hydrogen storage facilities, development of transmission and distribution networks, manufacturing of technologies for producing hydrogen and hydrogen-based synthetic fuels, as well as production of hydrogen and hydrogen-based synthetic fuels, provided that they have lifecycle GHG emissions savings requirement of 73.4% for hydrogen and 70% for hydrogen-based synthetic fuels, relative to a fossil fuel benchmark of 94 g CO2-eq/MJ (EC, 2021r).

In addition, seven European countries (Denmark, France, Germany, the Netherlands, Spain, Sweden and the United Kingdom) have committed to halting export finance for fossil fuels (Thomas and Potter, 2021).

Beyond Europe, Korea also plans to build up a taxonomy for green finance to channel financial flows into businesses delivering environmental benefits (UNFCCC, 2020a) and the Japanese government has announced it will take measures to attract private investment into green, transition and innovation initiatives, while formulating basic principles and roadmaps for industries with large CO_2 emissions (METI, 2020a). In this context, Japan will also co-operate with financial institutions in defining criteria for investments that contribute to a carbon-neutral economy. The Japanese government also plans to lead international discussions on taxonomy and transition finance in G7 and G20 meetings (METI, 2020a).

The United States Treasury is also supporting international efforts to better identify climate-aligned investments and encourage financial institutions to credibly align their portfolios and strategies with the objectives of the Paris Agreement (Shalal *et al.*, 2021) and instructed federal agencies to measure, mitigate and disclose climate risks (White House, 2021g).

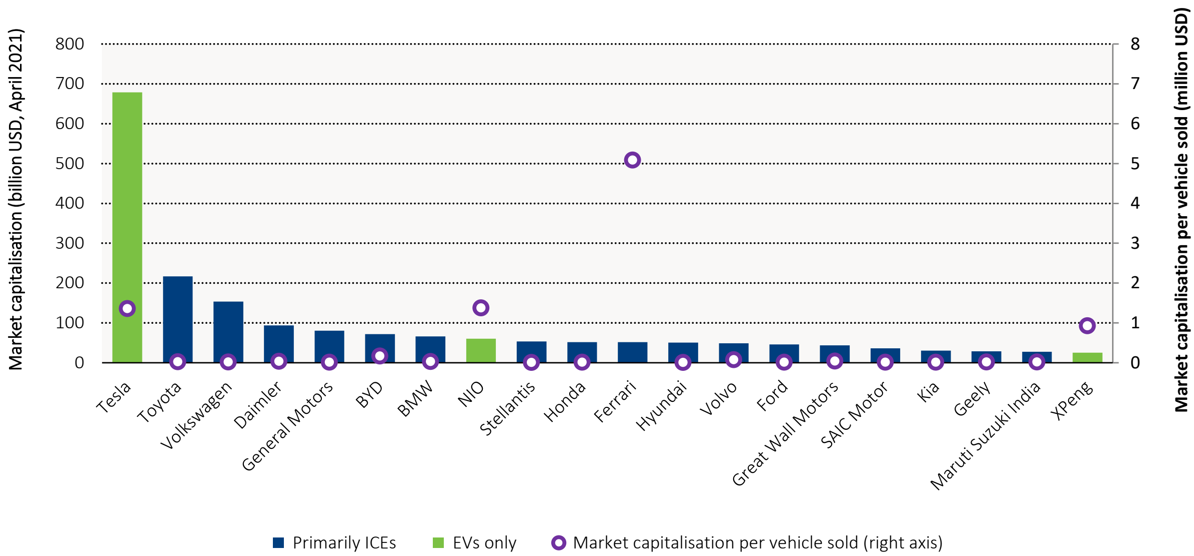
Market response

Financial risks associated with technologies reliant on fossil energy and business opportunities (especially for early movers) associated with clean energy and transport technologies are leading to major shifts in the market and in private sector responses to climate and sustainable development policy imperatives. Major signs – especially shifts in the market capitalisation of private companies – point towards a migration of investments away from companies that have been reluctant to make investments into a technology transition. In the area of clean vehicles and energy vectors, this shift has direct large-scale implications for two major sectors: automotive and energy.

For automotive companies (and more specifically the car market), capital markets are attaching far greater value per unit of vehicle sold for emerging companies focusing on electric car production, even if other factors (in particular expectations for market-share increases for these manufacturers) may also be a driver of these differences. As Figure 8 shows, car makers producing exclusively EVs are valued in the capital market 45 to 70 times more than the average of the two main car manufacturers by number of vehicles sold in 2020. Figure 8 also shows that one of these factors (especially relevant in the specific case of Ferrari) relates to consumer perception of the vehicles and their identification as luxury goods. The integration of digital technologies on vehicles could also be another factor influencing the ratio of market capitalisation per vehicle sold, since this is perceived as adding competitiveness and consumer attractiveness (and therefore strong growth prospects) – as demonstrated by the high values attributed by financial markets to tech companies.

Even if some analysts are warning that the differences in market capitalisation may be overdone (due to limitations in the scope of EV producers available), Figure 8 illustrates that they are undoubtedly exerting pressure on legacy automakers to move towards greater electrification. Delaying decisions to embrace this transition risks hindering their capacity to raise funds, as recently flagged by Herbert Diess, the CEO of Volkswagen (Rauwald, 2021).

Figure 8. Market capitalisation and ratio of market capitalisation per vehicle sold, top 20 car makers



Note: Market capitalisation values refer to April 2021.

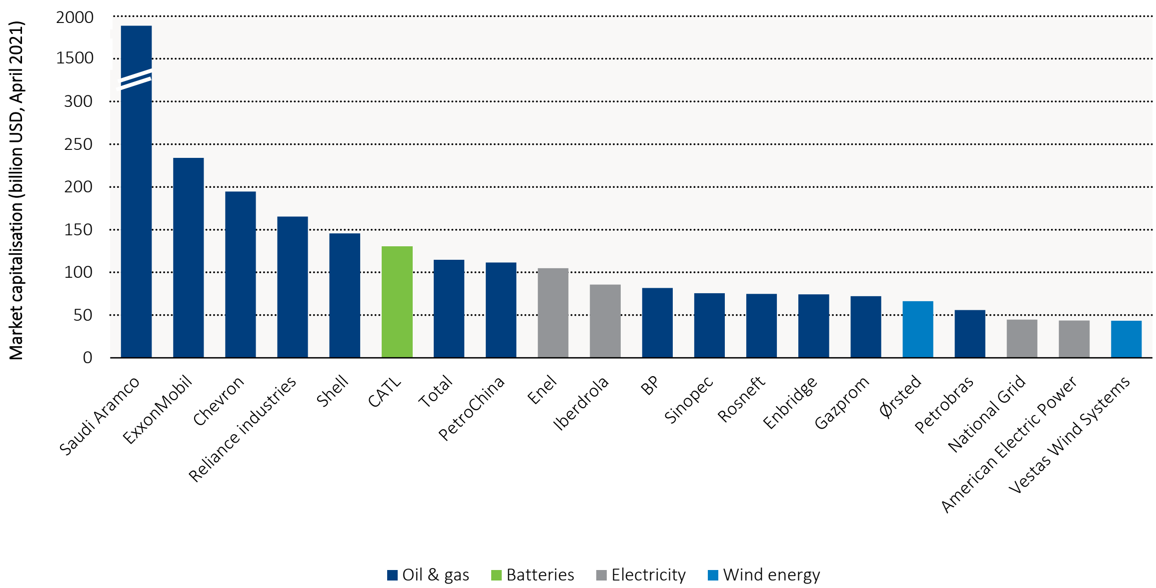
Source: ITF elaboration based on data from Yahoo Finance (https://finance.yahoo.com) and company reports on vehicle sales.

For energy companies, changes in market capitalisation values are also exerting pressures for investments to shift towards assets that will be subject to lower financial risks from climate policy imperatives. This is visible from a number of parallel developments:

- the fact that companies focused on battery production (e.g. CATL) or electricity generation\ with a significant focus on renewables (e.g. Enel, Iberdrola, Ørsted), and even wind turbine manufacturers (e.g. Vestas) have market values that now rival major international oil companies, as shown in Figure 9 (Blunt and McFarlane, 2020; Cowan, 2021)
- the increasing frequency of announced decisions by major oil and gas companies to decarbonise their portfolio mix of production and reserves of hydrocarbons, including through investments in renewable energy and battery storage (Pickl, 2019; Storrow, 2020; Jus and Dobson, 2021)
- the fact that oil majors, and not only electricity companies, are increasing their investments in EV charging infrastructure (including through targeted acquisitions) – not only to hedge risks of declining demand for oil products, but also as a way to leverage their experience in the energy retail sector, ultimately facilitating the electrification of transport (Jus and Dobson, 2021).

The impact of Covid-19 on the economy is pushing the world towards investments in solutions that can be subject to strong growth dynamics. This is due to the need for debt to re-start the economy and the need to ensure that spending for this purpose is future-proof (and therefore capable of meeting sustainability requirements). Quantitative indications of this come from strong increases in investments by mutual funds and exchange-traded funds (almost a doubling in 2020, vs. 2019) in sustainable assets, likely reflecting the beginning of a long but rapidly accelerating transition – one that will unfold over many years and reshape asset prices of every type (Fink, 2021). Looking at these dynamics from the perspective of clean vehicles and clean energy points toward an acceleration of the transition towards e-mobility and renewable electricity (both identified as enablers of what can be an affordable and effective transition, reliant on technologies that are ready to scale up and also well aligned with the digital transition) with respect to pre-Covid-19 conditions, affecting both the automotive and energy sectors (Kramarchuk *et al.*, 2020; Cowan, 2021; Rauwald, 2021).

Figure 9. Market capitalisation of top-20 oil and gas, energy, battery and electricity companies



Note: market capitalisation values refer to April 2021.

Source: ITF elaboration based on data from CompaniesMarketCap.com (https://companiesmarketcap.com) and Bloomberg (https://www.bloomberg.com).

An indicator that helps to reveal a tendency towards an acceleration in the pace of adoption of clean energy and sustainable mobility technologies is the comprehensive set of ambitious decarbonisation targets for coalitions of non-state actors which is summarised in the UN Race-to-Zero Emissions Breakthroughs, launched in January 2021 at the World Economic Forum meeting in Davos (UNFCCC, 2021), building on the UNFCCC Climate Action Pathways established in 2020 (UNFCCC, 2020b). This is focused on the mobilisation of climate action for businesses and investors, and also involving civil society and local public authorities. Seen from a road transport perspective, as of July 2021, these targets include a full transition, in leading markets, to LZEV for buses by 2030, passenger cars by 2035 and trucks by 2040; the availability of fully decarbonised electricity by 2040; the full reliance on renewable energy for mining activities; and a full transition, for fuels from oil and gas (whose extraction is declining), to net zero greenhouse gas emissions by 2050.

The break from past trends is also evident from announcements and investment decisions made by market players located at different points across the LZEV value chain. These include carmakers, bus and truck manufacturers, battery manufacturers, energy companies and fleet managers/operators. The following sections include a review of actions and decisions that illustrate the materiality of these signals.

Leading car manufacturers’ strategies point to a shift to electric cars

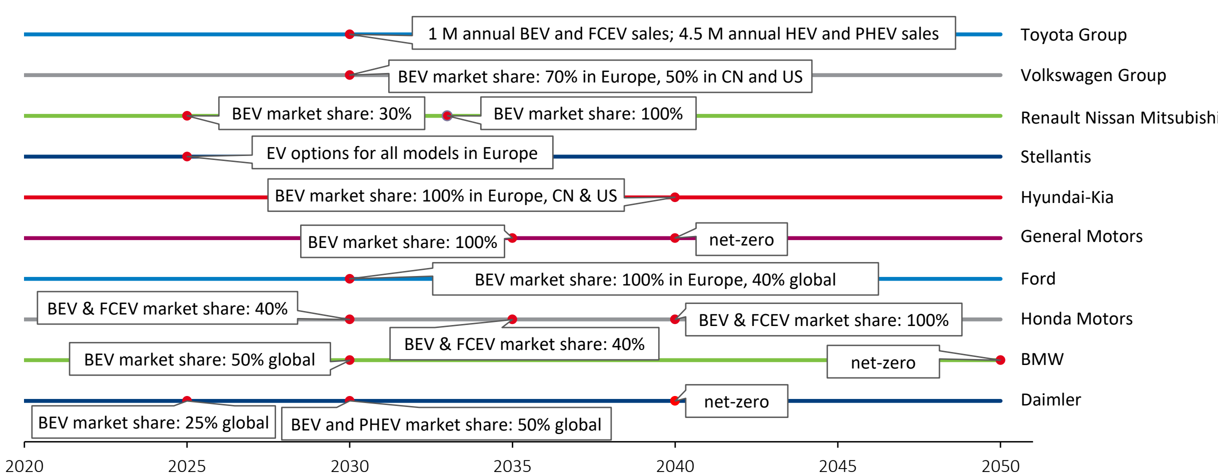
Although the speed of adopting electric vehicles and other zero-emission technologies differs among leading car manufacturers, there is a market-wide trend to scale up production of electric vehicles. Nevertheless, the analysis of announced milestones in the electrification strategies of leading car manufacturers (which together represent about half of the global car market) reflects a gradual shift towards vehicle electrification.

Eight of the largest car manufacturing groups or alliances (by number of vehicles sold) project that EVs will outsell conventional cars in key markets by 2040, with four expecting this milestone as early as 2030 and another three by 2035 (Figure 10). PHEVs make up a large share of today's electric vehicle sales, especially in Europe, yet take a less visible role than BEVs in car manufacturers' long-term announcements. This consideration also applies to FCEVs: only few major car manufacturers, including Honda, Hyundai-Kia and Toyota, explicitly include FCEVs in their announced strategy to scale up sales of LZEVs.

Toyota, which sold 10.7 million cars in 2019 and 9.6 million in 2020, explicitly includes HEVs in its strategy and by 2030 targets annual sales of 4.5 million HEVs and PHEVs, in addition to 1 million BEVs and FCEVs. These targets indicate that HEVs and PHEVs combined could account for 40% of the company's sales volumes, while the target for BEVs and FCEVs represents about 10% (Toyota, 2021).

Volkswagen's strategy has a stronger focus on BEVs and aims to reach large BEV sales shares in the world's largest car markets by 2030 – 70% in Europe and 50% in China and the United States. In 2019 the Volkswagen Group sold 10.2 million cars worldwide, for which the three key markets represent 86% (41% in Europe, 6% in US, 39% in China) (Volkswagen, 2020). In 2020, sales were 9.3 million cars (Volkswagen, 2020). Applied to 2019 sales, Volkswagen's electrification goals represent 5.6 million BEVs by 2030. For its Volkswagen brand, the Volkswagen Group further announced to end ICE sales in Europe by 2035 and in China and the United States soon after (Schmidtutz and Prem, 2021a). The group's Audi brand will only sell BEVs from 2026 onwards (Merkur, 2021),

Figure 10. EV market announcements by leading car manufacturers, 2021



Note: Figure reflects situation in spring 2021 to the best knowledge of the authors. Figure focuses on 10 leading OEMs by vehicle sales in Q1 2021(Focus2move, 2021). Does not include smaller manufacturers with ambitious electrification programmes (especially Tesla and Chinese OEMs) which together have a strong impact on the overall market. Honda Motors' target includes average sales in its key markets of China, Japan and the United States. Figure focuses on EVs and excludes HEVs where possible.

Sources: Toyota (2019); Hyundai Motor (2020a); Autovista Group (2021); BMW (2021); Volkswagen (2021b); Volvo (2021); Daimler (2021); Campbell and Keohane (2021); Ford (2021a); GM (2021a); Honda (2021); Klayman (2021); Piovaccari, Guillaume, and Carey (2021).

Manufacturers are also starting to use vehicle platforms that are designed and optimised for electric powertrains – allowing, for example, for a better integration of vehicle batteries or electric motors into the chassis. The launch of Volkswagen's Modular Electrification Toolkit (MEB) as well as Hyundai's Electric Global Modular Platform (E-GMP) and GM's Ultium in 2020 are examples for vehicle platforms designed for electric drivetrains, offering lower costs and better performance than platforms that can accommodate electric drivetrains but are not exclusively designed for this powertrain type (Volkswagen, 2017; GM, 2020c; Hyundai Motor, 2020b). Other examples come from collaborations between manufacturers to jointly use EV platforms. Ford and Volkswagen in 2020 announced an alliance for the development and construction of a range of vehicles, which includes Ford's use of Volkswagen's MEB platform for an electric Ford model to enter the European market in 2023 (Ford, 2020). Honda and GM in 2020 announced that Honda will launch two EV models for the US market that will use GM's Ultium platform (GM, 2020b). Parallel developments point to OEMs also scrapping platforms that are not fit for electrification, as shown by the recent mention of a shift away from Alfa Romeo's Giorgio platform by Stellantis (CCFA, 2021).

Automotive groups with smaller production volumes than those included in Figure 10 have also adopted ambitious electrification strategies. This applies especially to producers in China, the world's largest car market, where car manufacturers are less consolidated than in other regions. The Chinese companies with most EV sales are BYD, BAIC, Geely and SAIC. Geely fell short of its 2015 pledge to reach a 90% sales share for "new energy" vehicles by 2020, with new energy vehicles (NEVs) representing only 5% of sales in the target year (BNN Bloomberg, 2021; Geely, 2021). BAIC in 2017 announced it would reach 100% NEV sales by 2025 (Reuters, 2017). SAIC outsold Tesla's Model 3 in the first few months of 2021 with its Hong Guang Mini EV model (The Verge, 2021).

Heavy-duty vehicle manufacturers are set to expand product lines with low or zero tailpipe emissions

China leads this development and is home to the world's largest electric bus manufacturer – BYD – from Shenzhen, the city with the world largest electric bus fleet, with about 17 000 vehicles (Berlin, Zhang and Chen, 2020). Chinese bus manufacturers have expanded to other markets including Europe, the United States and Latin America. European producers now also offer electric buses.

Although electrification of heavy-duty trucks trails that of buses, major manufacturers are scaling up programmes and investments for zero-emission vehicles. The 2020 pledge from European manufacturers Daimler, Scania, Man, Volvo, DAF, Iveco and Ford to phase out sales of conventional diesel trucks by 2040 demonstrates their commitment to decarbonising freight transport (Campbell, 2020). Truck manufacturer's investments in LZEV technologies encompass BEVs, PHEVs as well as FCEVs. The latter have a focus on long-distance transport and are considered for longer timescales than BEV and PHEV trucks.

Some OEMs – in particular Traton, the parent company of Scania and MAN, of which the latter will start series production of electric trucks by 2024 (MAN, 2021) – clearly favour direct electrification, stressing the high well-to-tank energy needs of FCEVs and pointing to the same cost challenges discussed in the second chapter. Others, like Daimler Trucks, announced they will start series production of both battery electric and fuel cell electric long-haul trucks in the 2020s and aim to offer only new vehicles that are CO_2-neutral in driving operation ("tank-to-wheel") in Europe, Japan and North America by 2039 (Daimler Trucks, 2021; Traton, 2021). Manufacturers that invested in fuel cell technology also include Hino (Toyota group) and Navistar, in co-operation with GM (Toyota, 2020; GM, 2021c).

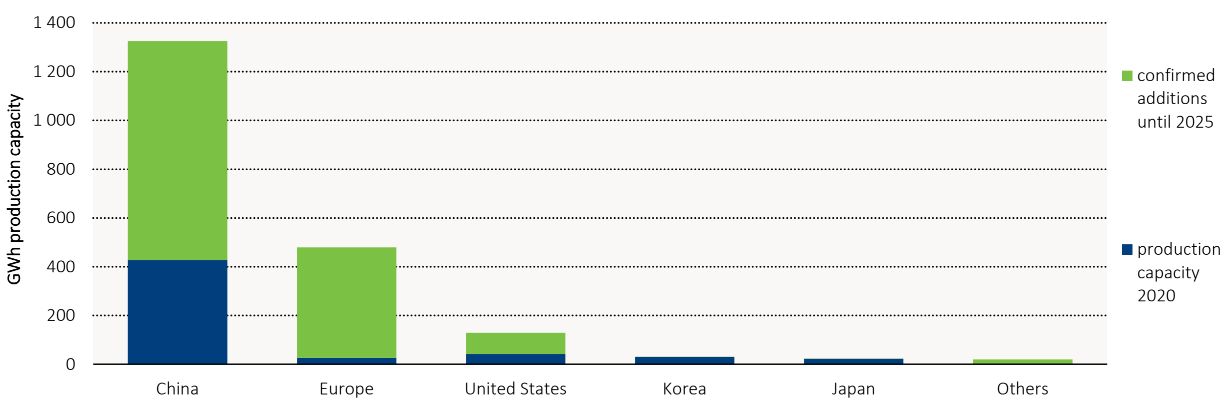
Electrification ambitions support a strong growth of battery production

Battery costs, a key determinant of the production cost of EVs, have experienced impressive reductions in recent years. The average global price for vehicle battery packs in 2020 was an estimated USD 137 per kWh, nearly one-tenth of what it was 10 years earlier; further cost reductions to USD 105 per kWh are expected by 2023 (BNEF, 2020b). Several car manufacturers have confirmed these expectations with pledges to bring down battery costs by more than 50% and/or below USD 100 per kWh in the coming years (GM, 2020c; Tesla, 2020; Volkswagen, 2021a). These price declines are made possible through increasing production scales as well as through advancing battery technologies.

Investments by car manufacturers to produce electric vehicles at large volumes have been accompanied by parallel decisions to scale up production of electric batteries, which are still used mainly for consumer electronics. As of late 2020, the global battery-cell production capacity for purposes other than consumer electronics, such as electric cars or stationary electricity storage, was nearly 550 GWh. This capacity is set to exceed 2 000 GWh by 2025 (BNEF, 2021). These factories are expected to supply not only EVs, but also other applications such as stationary electricity storage. Their production capacity could cover demand for 37 million BEVs with 55 kWh battery capacity per year by 2030. This is 12 times larger than the 2020 EV market size.

Today most battery cell production capacity is in China, followed by the United States, Europe, Korea and Japan. Announced additions until 2025 project the strongest growth in Europe (Figure 11). This strong outlook reflects the ambitious electrification plans of European governments and car manufacturers, as factories for vehicle batteries are usually planned close to vehicle production sites to optimise supply chains. Announcements made up to July 2021 do not project notable production capacity additions in Korea and Japan, but major battery producers with headquarters in these countries (Samsung SDI, SK Innovation and LG Chem from Korea, Panasonic from Japan) plan to expand production in other regions, often in collaboration with car manufacturers.

Figure 11. Global battery cell manufacturing capacity by region, 2020-25



Note: Excludes battery manufacturing for consumer electronics.

Source: BNEF (2021).

As car manufacturers scale up production of electric vehicles, they are also moving towards a closer integration of battery-cell and car production. This includes alliances between car manufacturers and battery producers, as well as car manufacturers announcing plans to produce battery cells in-house. For example, Volkswagen has announced it will expand its battery production capacity to 240 GWh in six European plants by 2030 to meet demand for its electrification programme and has entered a joint venture with battery manufacturer Northvolt (Volkswagen, 2019). In the United States, GM is building a battery plant in a joint venture with LG Chem (with an initial production capacity of 30 GWh per year) and has announced plans for a second production site (GM, 2020d, 2021b). Tesla, together with Panasonic, has started in-house battery production at its Gigafactory 1 plant in Nevada, with a 54 GWh capacity target for

2020 (Yamazaki and Panchadar, 2019); it is also building additional integrated electric car production plants near Shanghai and Berlin, the latter with a planned capacity of up to 100 GWh per year (Franke, 2020). Ford and SK Innovation have announced their BlueOvalSK joint venture to produce vehicle battery cells starting mid-decade with an initial annual volume of 60 GWh (Ford, 2021b).

In addition to scaling up their in-house production capacity, car manufacturers are continuing to buy vehicle batteries from incumbent producers such as Samsung SDI, LG Chem (both headquartered in Korea), Panasonic (Japan) and CATL (China). Further, some announced expansions of battery production are earmarked for purposes other than electric cars. For example, CATL in 2021 announced investment in additional battery production capacity for stationary storage of electricity (BJX, 2021).

Private sector engagement in the scale up of EV chargers

Many EV owners charge their car at home or at their workplace, and commercial fleets often charge at their vehicle depot. However, drivers without access to private chargers at their home or workplace rely on public charging stations. Longer trips that cannot be covered by a single charge are only possible with access to publicly accessible fast chargers en-route.[52] To promote easy access, several car manufacturers have set up programmes to roll out public vehicle chargers, which is a prerequisite for their electrification plans to become reality. The programmes listed in Table 6 focus on fast chargers along motorways, thus enabling long-distance trips with electric vehicles. They complement the charger networks in cities, whose private and public chargers are typically slower.

Table 6. Private sector announcements to scale up charging networks

Operator	Details
BP	BP's pulse subsidiary aims to operate 16 000 charging points in the United Kingdom by 2030, with focus on ultra-fast chargers.
GM	Pledged to add 2 700 fast chargers together with charging company EVgo in the United States.
Ionity	Joint venture of the BMW Group, Mercedes Benz AG, Ford Motor Company, Hyundai Motor Group and the Volkswagen Group with 1 200 fast chargers along motorways in 24 European countries.
NIO	Aims to operate 1 000 battery swapping stations for electric cars in China by end of 2021.
Ola Electric	Announced the construction of 100 000 charging stations for two-wheelers in 400 Indian cities.
Tesla	Operates over 2 000 Supercharger stations worldwide, with 20 000 proprietary fast chargers, half of them in North America.
Total	Aims to operate 150 000 vehicle chargers by 2025. In 2020 acquired the Blue Point London charging network (> 1 600 chargers in the United Kingdom) and won concessions to operate Paris' Bélib' charger network for ten years – with planned expansion to 2 300 charging points and addition of 20 000 chargers for the network Metropolitan Region Amsterdam Electric in the Netherlands. Total also operates chargers in the Brussels area.
Traton, Daimler Truck and Volvo	Announced in 2021 a plan for the development of a public charging network for battery-electric heavy trucks and long-distance coaches, with at least 1 700 high-capacity charging points powered by green electricity to be installed by 2027.
VW	Europe: Pledged to invest EUR 400 million between 2021 and 2025 to expand fast chargers, including installation of 8 000, 150 kW fast chargers at BP service stations, mostly in DE and UK. Programme also aims to expand charger access along motorways in Italy together with Enel, and along main traffic routes in Spain together with Iberdrola. These investments are additional to Ionity activities. United States: Will complete installation of 3 500 public fast chargers through Electrify America subsidiary. China: Pledges to complete installation of 17 000 fast chargers through CAMS joint venture.

Sources: bp pulse (2021); Status Tracker for Ionity HPC (2021); Total (2020a, 2020b, 2021); Crothers (2020); GM (2020a); Shell (2020, 2021); Bloomberg (2021b); Tesla (2021); Volkswagen (2021a); Cordon (2021); Ionity (2021); Ola (2021a), Traton (2021).

These programmes from car manufacturers are in addition to the expansion plans of other actors in the private sector, including energy companies and charging companies. Despite initial low frequency of use, which hinders the development of a healthy business case, these choices point to a growing confidence in EV deployment and a willingness to enter the EV charging market in an early phase, as a strategic investment enabling a business with an increasing user base in the future.

The roll-out of public charging infrastructure for trucks is in its infancy, as deployment of these vehicles is low as of 2021 and pilot fleets often operate and charge at depots. Demand for truck charging infrastructure along transport corridors will emerge with increasing deployment. Existing infrastructure for trucks is typically at a pilot stage. Germany is home to important pilot projects in this context. These include two 10 km highway segments in Hesse and Schleswig-Holstein, Germany, which are electrified with catenary lines (Siemens, 2021). Another 6 km project on a federal road in Baden-Württemberg is set to start operation in 2021. The German Association of the Automotive Industry recently announced it is seeking funding for a project to equip a demonstration route between Berlin and the Ruhr area with charging infrastructure for long-haul trucks (VDA, 2021).

Fleet operators at the forefront of vehicle electrification

The market growth of electric vehicles since the early 2010s has been largely concentrated in premium passenger cars, the segment in which OEMs tend to launch new technologies. Nevertheless, electrification of commercial vehicles has picked up speed in the past two years – especially for light-commercial vehicle fleets, used for example for urban deliveries or as service vehicles (ITF, 2020c).

The segment of urban delivery vans is an early candidate for electrification of commercial vehicles because its driving profile is a good fit for EVs. These vehicles have a high annual mileage, so savings from lower fuel costs offsets the price premium of electric models relatively quickly. Their daily driving distance is typically below 200 km and does not vary between days, which makes it possible to optimise battery capacity and does not require recharging during operation. Vehicles can charge overnight using slow chargers in the vehicle depot – reducing overall costs, thanks to low electricity costs at night and lower equipment costs for slow chargers than for fast chargers. Leading logistic companies have pledged to electrify their last-mile operations in the coming years and have already started to procure electric vans.

The attractiveness of EVs for logistics is clearly shown also by the willingness of major logistic operators to enter into alliances (including through investments) with manufacturers to design and build EVs for freight deliveries. Examples include Amazon and UPS, which have ordered large numbers of customised electric vans from vehicle manufacturer start-ups Rivian and Arrival and invested in these companies, respectively.[53] A broader discussion on actions undertaken by major logistics companies on the electrification of urban delivery vehicles can also be found in ITF (2020c).

Programmes to electrify fleet vehicles are not limited to the light commercial vehicle segment. Company-owned passenger car fleets also offer electrification benefits that can exceed those of private passenger cars, due to above-average mileages that maximise the saving potential and environmental benefits of electrification, as well as opportunities to use centralised charging infrastructure, depending on the use case. Examples of ongoing initiatives can be found among the 108 members of the Climate Group's EV100 campaign, which have collectively committed to electrifying over 4.8 million light-duty vehicles globally by 2030 (Climate Group, 2021).

Electrifying company fleets also has support from the World Business Council for Sustainable Development (WBCSD), a business association that advocates for sustainable development, as well as the Zero Emissions Urban Fleets (ZEUF) network of the World Economic Forum, a non-profit that seeks to foster public-private co-operation (WBCSD, 2021; World Economic Forum, 2021). Another programme that advocates for fleet electrification in the private sector is the Corporate Electric Vehicle Alliance of Ceres, an initiative for sustainability-oriented investors with a focus on the United States (Ceres, 2021).

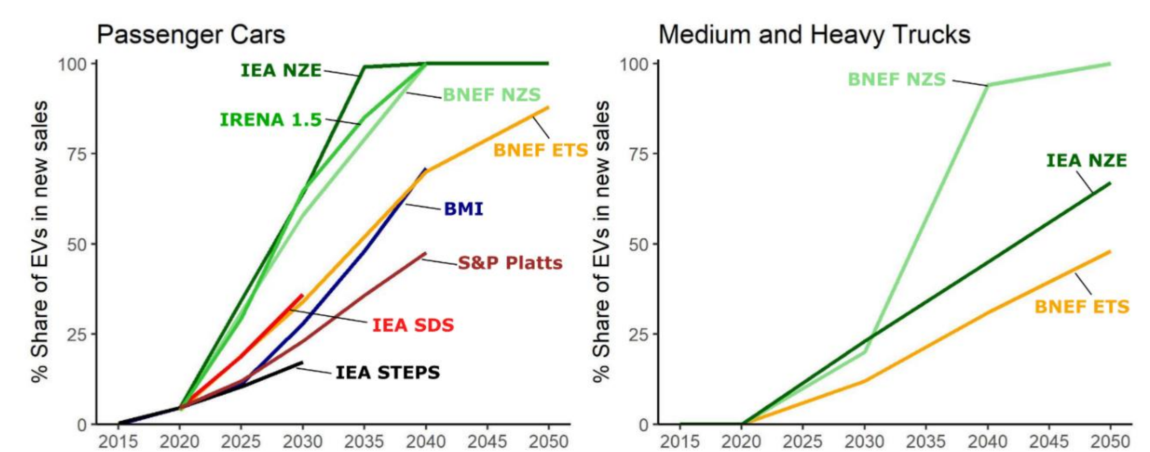
Ridesourcing or transport network companies (TNCs) typically do not own the vehicles that operate through their platform, yet have adopted programmes to accelerate uptake of electric vehicles towards ambitious electrification goals. Uber has pledged to reach 100% share of electric rides on its platform in Canada, Europe and the United States by 2030 and elsewhere by 2040 (Uber, 2021). Lyft also supports its drivers in adopting electric cars and anticipates a full switch to electric rides by 2030 (Lyft, 2021). Ola Electric, which is mostly active in the Indian market (where small vehicles, including two- and three-wheelers, play a larger role than passenger cars), pledges to put 1 million electric vehicles on the road by the end of 2021 (Ola, 2021b). Like vans in last-mile delivery, traffic from ridesourcing cars is concentrated in cities and is responsible for an increasing share of all transport activity. Targeting these vehicles in electrification programmes can thus maximise benefits in terms of cost savings and reduced environmental impacts.

Projections for future market uptake

The marked potential for GHG emissions reductions and increasing cost-competitiveness of electric vehicles has drawn the attention of policy makers and markets. The strong actions by policy makers to promote the adoption of electric vehicles, and the resulting improvement in market conditions, mean that the rapid penetration of electrified passenger vehicles into the global vehicle fleet is now considered inevitable, with the main questions no longer being *if* electric vehicles will be adopted but rather *how quickly* they will enter the market.

Figure 12 shows a number of projections of the share of electric vehicles in global new vehicle sales by a range of institutions tracking their adoption. The IEA's Stated Policy Scenario (STEPS) aims to assess the impacts of existing policy commitments and stated policy intentions on the energy sector. The IEA expects existing commitments alone will lead to a rapidly accelerating adoption of electric vehicles, reaching 17% market share globally by 2030. However, this would not be sufficient to meet climate commitments. The IEA Sustainable Development Scenario (SDS) provides a higher-ambition pathway to the level of commitment required to meet climate change goals, requiring at least 36% of global new car sales in 2030 to be electric. There is a consensus among the scenarios shown in Figure 12 below that the most ambitious climate goals, targeting 'net zero' emissions or a 1.5 degrees of warming, require a massive deployment of EVs globally between 2020 and 2040.

Figure 12. Share of electric vehicles in global vehicle sales



Note/Source: BMI= Benchmark Mineral Intelligence forecast data from Benchmark Week 2020. BNEF= Bloomberg New Energy Finance data from BNEF EVO 2021 for Economic Transition Scenario (ETS) and Net Zero Scenario (NZS). S&P Platts forecast data from London Energy Forum 2021. IEA= International Energy Agency data for Sustainable Development Scenario (SDS) and Stated Policy Scenario (STEPS) from GEVO 2021 and Net Zero scenario (NZE) from (IEA, 2021c). IRENA= International Renewable Energy Agency data for 1.5 degree scenario from World Energy Transition Outlook 2021 report. Includes both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs).

Expectations for EV sales shares continue to be regularly revised upwards, particularly in light of recent spending commitments and stimulus packages promoting the adoption of electrification. Whereas the majority of policy and market activity to date has focussed on passenger cars, given the relatively low barriers to entry, recent attention has also turned to trucks and other freight vehicles, as shown in Figure 12 (right). The BNEF Economic Transition Scenario (ETS) suggests that purely economic forces will already lead to a significant uptake of electrified trucks, but further policy action is needed to reach levels compatible with net zero emissions goals. Differences between the BNEF ETS and IEA Net zero (NZE) primarily reflect uncertainties about the role of FCEVs.

Beyond clean vehicles: Digital technologies, connectivity, sharing and automation

Digital technologies have demonstrated a major capacity to change how people, firms and governments live, interact and work. Key trends – such as the exponential growth of internet traffic and data centre workloads (IEA, 2019b) and the diffusion of consumer electronic devices like smartphones and their applications (IMF, 2020) – demonstrate that the changes brought by digital technologies are taking place at a fast pace. Looking forward, the increased penetration of digital technologies on a wide range of everyday objects – driven by the "Internet of Things" (IoT), cloud computing, big data and analytics, and broadband connectivity – suggests that the shift towards a digital economy will continue to be a defining trend for the overall global economy (Gartner, 2019).

The capacity of digital technologies to continue to provide greater competitiveness and consumer attractiveness for existing products, as well as the possibility of developing new products (and markets), are key reasons why financial markets are also placing great value on technology companies. By April 2021, seven (eight, counting Tesla) of the largest ten global companies by market capitalisation were in the digital technology sector (CompaniesMarketCap.com, 2021). As with transport electrification, governments have played a crucial role as enablers of many these developments by creating ecosystems that provided a fertile basis for private capital investments, leading to major business opportunities (Mazzucato, 2011).

The pervasive nature of digital technologies, their implications for society and the economy, and expectations that they will remain a key pillar of the future economic system – a feature that has been exacerbated by the Covid-19 pandemic, which amplified all aspects of the digital transformation (OECD, 2020c) – are also major reasons why governments are increasingly looking for an integrated policy framework capable of maximising their benefits while also addressing their challenges (OECD, 2021b).

Transport and mobility are no exception in this context. In recent years, the application of digital technologies has been substantial across the transport systems and subsystems. Similar considerations apply in the case of connectivity and automation, which come with a highly disruptive potential to significantly reshape passenger and freight mobility – and, as with clean vehicle technologies, have recently been high on the priority list of government investments and private sector research.

Intelligent transport systems, vehicle connectivity and automation

The concept of intelligent transportation systems (ITS) goes a long way towards the definition of digital connectivity technologies in transport. It encompasses integrated communications and data processing technologies that, when combined and managed, improve the operating capabilities of the overall transport system (US DOT, 2016; Baranzelli *et al.*, 2019). Key pillars of the ITS concept include in-road traffic detectors to control traffic lights, radio-frequency identification (RFID), automatic number-plate recognition, the global navigation satellite system (GNSS) and telecommunication technologies (including dedicated short-range communications [DSRC] services and cellular and dedicated short-range communications, like C-ITS (V2X) technology), as well as other means of remote sensing.

The same set of technologies, broadly applicable to the whole transport sector, is also a crucial enabler of increased vehicle connectivity. Combined with big data, improvements in computational power, machine learning and artificial intelligence, digital connectivity is also a key prerequisite for autonomous driving, which has long been an area driving major attention and mobilising significant investments within the future-of-mobility space (Möller et al., 2019; Benedikt Kloss *et al.*, 2020).

Wireless networks and digital connectivity for transport vehicles

Many of the ITS technologies are already commercially available. Some have been used by governments (which invested heavily in the deployment of devices like GNSS satellite networks) to deploy new policy instruments and by companies to deploy novel applications. Examples of policies enabled by the combined use of satellite networks and on-board units (or smartphones) recording position, navigation and timing include smart tachographs,[54] dangerous-goods tracking, smart road-use charges (further discussed in Box 7) and the automatic emergency eCall system for road traffic accidents (UNECE, 2017; GSA, 2019).

Box 7. Selected experiences in the use of ITS technologies to collect road charges

Several countries in the European Union (initially Germany, Slovakia, Belgium and Hungary, followed by Czech Republic, Poland and Bulgaria in 2020) have adopted electronic tolling technologies, based on the GNSS, for distance-based tolling for heavy-duty vehicles (Fernández Wyttenbach, 2021). The choice of the GNSS is driven by considerations that reduce environmental impacts and installation costs, since the system requires approximately 80% less roadside infrastructure (GSA, 2015). The legislative framework for the use of distance-based tolls in Europe is provided by the recast of the European Electronic Tolling Directive (EETD) (EC, 2019) and Eurovignette Directive, which, following a political agreement reached in late 2020, extends the scope of application of road charges to buses, vans or passenger cars and allows the introduction for differentiations of heavy-duty vehicles charges based on tailpipe CO2 emissions (European Council, 2020).[55]

Singapore also has plans to implement GNSS-based Electronic Road Pricing (ERP) during 2021-23. This follows a long-standing road-pricing tradition in the country. Its approach is also based on GNSS but, due to issues with the technology system selected, it needs to be supplemented by road-side units that use legacy Dedicated Short Range Communications (V2I) or GNSS signal boosters (Theseira, 2021).

In the United States, Oregon and Utah operate permanent programmes allowing the collection of road use charges intended to provide a replacement option for the gasoline tax in the case of electric vehicles. Both programmes allow the opt-in for GPS-enabled solutions. In Oregon, these are supported by smartphone applications or dedicated on-board devices (OReGo, 2021). In Utah, the focus is solely on smartphone applications (UTDOT, 2021). Two state-wide pilot programmes developed in the states of Washington and California have also tested GPS-enabled solutions supported by smartphone applications or dedicated on-board devices.[56]

Being instrumental for system optimisation (at many levels), digital technologies have the technical capacity to maximise energy and resource efficiency, and therefore also to contribute to mitigating the environmental impact of mobility. ITS- and GNSS-enabled solutions can effectively complement this, offering opportunities for both targeted and systemic improvements.[57] On the other hand, they may also result in significant increases in vehicle kilometres travelled, for both passenger and freight, especially if they enable autonomous driving. In the absence of changes in powertrain technology, behavioural shifts (e.g. to increase loads) and policy action, this would also lead to increases in energy use as well as GHG and pollutant emissions (Wadud, MacKenzie and Leiby, 2016; IEA, 2017a; Sperling, 2018).

Some concrete examples have also start to emerge of the use of GNSS-enabled technologies to mitigate environmental impacts, but they remain rather marginal. These include on-board monitoring (OBM) to ensure lifetime compliance with pollutant emission regulations, as discussed earlier, as well as other applications enabled by geofencing (e.g. compliance monitoring for all-electric driving in environmental zones)[58] (Dilara, 2021).

On the commercial side, a prominent example of GNSS-enabled technological solutions for transport (not having a specific focus on environmental action, but potentially interesting for future applications) is the case of pay-as-you-drive auto insurance (III, 2020).Cooperative intelligent transport systems (C-ITS) include more-advanced ITS technologies – based on vehicle-to-vehicle (V2V), vehicle to infrastructure (V2I), up to vehicle to everything (V2X) communication – that enhance the benefits of the ITS concept.

C-ITS can rely on different interoperable networking technologies and requires the allocation of a radio frequency spectrum to enable vehicles to communicate directly, in a secure and ad-hoc basis. Governments and stakeholders worked to allocate this spectrum, nationally and internationally. Different technological solutions compete in this context, including Dedicated Short-Range Communications (DSRC) services, based on wireless communication local area network (Wi-Fi), cellular based C-V2X and future upgrades. C-ITS pilot projects are being promoted prominently by governmental action in all major automotive markets. Key examples of C-ITS deployment are detailed in Table 7.

The deployment of the fifth-generation technology standard for broadband cellular networks (5G), which comes with greater bandwidth and faster data exchange speeds, is adding a layer of opportunities to what earlier generations of cellular communication technologies were already offering.

5G is seen as a key enabling factor in the development not only of connected and automated mobility, but also of other IoT applications. Nevertheless, expectations are that the automotive industry will become the largest market for IoT solutions (Gartner, 2019; ABI Research, 2020). Considering the advantages pointed out by industrial players on C-V2X, the expectation is that 5G is expected to accompany DSRC services in the C-ITS ecosystem (EC, 2021c).

Table 7. Main strategic plans and policies for C-ITS development across countries and regions

Country/region	Key strategic plans and policies for C-ITS development
China	China has been focusing on C-ITS to develop smart highways, automated driving systems, intelligent transport infrastructure and intelligent and connected vehicles (ICVs). In 2017, the government established the National Innovation Platform for the Acceleration of ICV Development (Dezao, 2019). The platform addresses obstacles in the development of ICVs and ensures the effective implementation of national strategies. China's Strategy for Innovation and Development of Intelligent Vehicles, issued in 2020, foresees its C-ITS environment in place by 2025. China has also opted to make use of C-V2X mandatory on its highways (Canis, 2021).
European Union	The European Commission in 2016 published a Master Plan for the Interoperable Cooperative Intelligent Transport Systems in the EU with the aim of increasing the continuity and interoperability of C-ITS, through co-ordinated development and deployment across Member States and industries (EC, 2016b). Later that year, the European Commission adopted a European Strategy on Cooperative Intelligent Transport Systems, a milestone initiative towards c-ooperative, connected and automated mobility, with the objective of facilitating the convergence of investments and regulatory frameworks across the EU, in order to see deployment of mature C-ITS services in 2019 and beyond (EC, 2016a). Follow-up actions led to the roll-out of pilot programmes for C-ITS on European roads, with 6 000 km equipped with DSRC/WiFi connectivity and 10 000 km covered with cellular communications by 2019. A major automotive OEM already serialises C-ITS in its compact class, introducing the technology into mass markets (Ollinger, 2018). The C-Roads Platform is a joint initiative promoting harmonised profiles for the roll-out of C-ITS services. Projects are aiming to promote interoperability and cross-border functionality, as well as integration of connected and automated driving technologies (C-Roads, 2020). The C-ITS development includes a joint corridor from Rotterdam through Frankfurt to Vienna (Canis, 2021).
Korea	Korea's long-term C-ITS plan has already led to the implementation of C-ITS at the Daejeon-Sejong National Highway (87.8 km) in 2016 (Lim, 2017). In 2020, the Korean New Deal (announced in the context of Korea's post Covid-19 economic recovery package) introduced the Digital New Deal and the Green New Deal (Government of Korea, 2020). The roll-out of C-ITS infrastructure on major highways is included under the Digital New Deal, along with the installation of other measures for rail transport infrastructure.[59] The aim is to cover 51.2% of the national highways by 2022 and 100% by 2025.
United States	Over the past two decades, industry, the Department of Transport and other government agencies have collaborated to develop, test, and deploy DSRC/WiFi technologies for C-ITS. States have invested in DSRC/WiFi-based improvements, and this technology is operating in pilot tests in several states and cities. Several automakers have also installed DSRC/WiFi communication devices in new vehicles. The emergence of C-V2X led to a decision, in November 2020, to allocate radio frequency spectrum to C-V2X, effectively eliminating spectrum for DSRC (Canis, 2021). The same decision also reduced the spectrum available for intelligent transport systems by more than half (Federal Communications Commission, 2021a).

While a global vision for 5G has been agreed at the International Telecommunication Union (ITU) (EC, 2021g), the 5G technology deployment is an area of significant international competition, in part because of the implications that it may carry in the area of vehicle automation. Governments are actively mobilising to enable investment for 5G deployment, and not only for automotive applications. Table 8 lists key examples of this from China, Korea, Japan, Europe and the United States.

Table 8. Key 5G deployment plans across different countries and regions

Country/region	Activities
China	In its post-Covid-19 development goals, China has prioritised the development of next-generation information networks, expansion of 5G applications and development of data centres (State Council of the People's Republic of China, 2020; The People's Republic of China, 2020). This includes the integration of digital connectivity into EV charging infrastructure.
European Union	The European Commission's 5G Action Plan outlines a clear vision of the crucial role that 5G plays for Europe's digital single market and transport (EC, 2016c). The European Sustainable and Smart Mobility Strategy makes explicit reference to the need to ensure the highest level and performance of digital infrastructure, notably through 5G, which offers a wide range of services and helps to reach higher levels of automation across different mobility applications. The strategy also mentions that further efforts are needed to achieve the objective of uninterrupted coverage across the major transport corridors across Europe with 5G connectivity infrastructure (EC, 2020e). The European Commission's 5G Public Private Partnership also supports three 5G cross-border projects for large-scale testing of connected and automated mobility, adding to demonstration projects led by the telecom and automotive industries.[60]
Japan	All mobile service providers in Japan launched 5G services in 2020, and two of them set up a joint venture to speed up 5G roll-out in rural areas (European 5G observatory, 2020). The Beyond 5G Promotion Strategy was published in June 2020 by the Japanese Ministry of Internal Affairs and Communications. This strategy has three pillars: research and development (R&D), standardisation of intellectual property and 5G proliferation strategy. R&D, which will be conducted over the next five years, aims to develop the basic technologies. It is referred to as "Beyond 5G" since the aim is to achieve 10 to 100 times the speed and bandwidth of 5G – while reducing network power consumption, which is expected to increase in line with the growth of 5G (Japanese Ministry of Internal Affairs and Communications, 2020).
Korea	Korea's Digital New Deal also comprises a strong component related to the integration of 5G and AI throughout all the sectors (Government of Korea, 2020).
United States	The United States announced in August 2020 its intention to move swiftly to lead the world in 5G wireless connectivity, along with major investments in high-speed broadband networks nationwide (Federal Communications Commission, 2021b).

Connected and autonomous vehicles

Improvements in digital connectivity like those discussed in the previous section enable a range of new features on vehicles – thanks to the collection, recording and processing of digitalised information, as well as exchange with other vehicles (V2V), road infrastructure (V2I) and other devices (V2X). Connectivity has already enabled the large-scale deployment of navigation services. Improved connectivity makes it possible to offer new features related to enhancement of passenger/driver experiences (infotainment). Depending on rebound effects and other framing conditions (including policy-driven requirements), improved digital connectivity for road vehicles can also lead to improvements for road safety and traffic efficiency as well as energy and emission savings (Heineke *et al.*, 2019; ITU, 2020a).

The combination of connectivity and progress in digital technologies (e.g. computational capacity, data storage capacity, machine learning and artificial intelligence) is also a key enabler of vehicle automation, i.e. the capacity of a vehicle to drive, on an open road, without the intervention of a driver. The autonomous vehicle concept integrates itinerary planning, real-time decision capacity and implementation with command methods inspired by those developed for mobile robots. Highly automated driving also requires wireless vehicle communication for many reasons, including access to road data, traffic conditions, vehicle interactions and software updates (ITU, 2020a).

Expectations that vehicle automation will provide greater competitiveness and consumer attractiveness for existing and new products (and markets) are so high that pursuing it is having enormous financial and economic and social implications (IEA, 2017a; OECD, 2021b). They have also led to significantly increased action by investors, private sector stakeholders and governments. Key examples of actions undertaken by governments, with a focus on the case of artificial intelligence, are outlined in Table 9.

Table 9. Key plans for development of artificial intelligence across different countries

Country	Key plans for development of artificial intelligence
China	In China, autonomous vehicles were identified as a key sector in the government's plans in order to become a leader in artificial intelligence. The Next Generation Artificial Intelligence Development Plan, published in 2017, aims to achieve this target in three phases. The first phase required the country to keep pace with all leading AI technology, and its application in general, by 2020. The second phase involves making major breakthroughs by 2025, which leads to the third phase of the plan – the establishment of China as the world leader in the AI field by 2030 (Robles, 2018).
European Union	The European Commission has proposed a legal framework aiming to turn Europe into the global hub for trustworthy Artificial Intelligence (AI) (EC, 2021k). The idea is that the combination of the EU legal framework for AI and a new co-ordinated plan with Member States will guarantee the safety and fundamental rights of people and businesses, while strengthening AI uptake, investment and innovation across the EU. New rules for machinery will complement this approach by adapting safety rules to increase users' trust in the new, versatile generation of products (EC, 2021e). The European objective for AI is also to leverage European strengths to expand its position in the ecosystems and along the value chain, from certain hardware manufacturing sectors to software all the way to services (EC, 2020a).
Japan	In 2017, Japan's Artificial Intelligence Technology Strategy Council formulated the Artificial Intelligence Technology Strategy, which focuses on promoting AI development and developing phases and priorities for industrialisation including productivity, health care, and mobility (Strategic Council for AI Technology, 2017). In 2018, the government announced that AI would also become an official part of its Integrated Innovation Strategy. An important element of the strategy is the unification of data formats and standards throughout various industries to enhance the ability to utilise big data techniques in Japan (Government of Japan, 2018). Japan views AI as a crucial part of its 5th societal transformation, called Society 5.0. Society 5.0 aims to deploy AI to aid an aging population and reduce pollution, in alignment with the Sustainable Development Goals (Deguchi *et al.*, 2020). In 2019, Japan updated its AI strategy, which now aims to ensure that AI will be used to help solve global issues through the realisation of Society 5.0 and resolution of the issues facing Japanese society (Integrated Innovation Strategy Promotion Council Decision, 2019).
United States	The United States published an updated version of its National Artificial Intelligence Research and Development Strategic Plan in 2019. The updates include creating robust and trustworthy AI systems, increasing access to datasets, addressing associated challenges, and supporting the development of AI technical standards and related tools. The updated version outlines a new focus area: expanding public-private partnerships to accelerate advances in AI (United States Government, 2019). The US government follows a more hands-off approach in AI, with businesses leading the way. Investment from private American companies (such as Amazon, Google, Microsoft and Apple) accounts for 50% of the global investments in AI research (Sustania, 2019).

Countries have also begun developing national regulatory frameworks to promote the development of connected and autonomous vehicles while addressing challenges related to safety and liability. China, the European Union (Germany in particular), Japan, Korea, the United States, as well as Australia and the United Kingdom are some of the countries that have been active in introducing legislation on the subject.[61]

At the international level, the establishment of the Working Party on Automated/Autonomous and Connected Vehicles (GRVA) in the framework of the World Forum for the Harmonisation of Vehicle Regulations (WP.29), which took place in 2018, signals an increased acknowledgement of the importance of regulatory action to enable the development of automated, autonomous and connected vehicles. This follows the approval, in 2017, of an amendment to the 1968 Vienna Convention on Road Traffic which aims to help all parties to lawfully accommodate and regulate automated vehicles without a uniform interpretation of the convention (UNECE, 2020). Key principles for the safety and security of autonomous vehicles, defining priority areas for the work of GRVA, were also identified and listed in a framework document on automated/autonomous vehicles (United Nations, 2019).

In June 2020, the United Nations officially adopted three new regulations by the GRVA. Two have a focus on automotive cybersecurity, namely, UN Regulation 155 on cyber security and cyber security management system (United Nations, 2021b) and UN Regulation 156 on software update and software update management system (United Nations, 2021c). The third (UN Regulation 157) focuses on Automated Lane Keeping Systems (ALKS) for Level 3[62] Automation Vehicles (United Nations, 2021a). These regulations came into force in January 2021 (UNECE, 2021b).[63]

These developments underpin the importance of ensuring that communications are resilient to cyberattacks (an issue that is further discussed in Box 8). The UN regulatory developments also underpin increased use of over-the-air software updates for road transport vehicles, a concept pioneered by Tesla and now being adopted by established major legacy manufacturers like Volkswagen and Ford (Ford, 2021c; Volkswagen, 2021c). The work of the GRVA signals the increased relevance of efforts being made internationally to increase co-operation on the subject of vehicle connectivity and automation. The rapid response by legacy automakers to new regulatory developments gives a tangible sign of the likelihood of future increases in connectivity requirements for road transport vehicles.

Box 8. Addressing cybersecurity concerns

Cybersecurity is becoming a regulatory priority not only in the context of transport vehicles, but also more broadly, due to the increased relevance of digital technologies across economic activities. It plays a key role in connectivity, particularly (but not only) in the field of vehicle automation. In the energy sector, cybersecurity concerns are particularly acute with regard to energy-related infrastructure, driving responses by the private sector and governments to strengthen preparedness, incident responses and recovery (Bailey, Maruyama and Wallance, 2020; US DOE, 2021c).

In the case of transport vehicles, the goal is to protect the integrity and confidentiality of information circulating on networks from cyber-attacks; the ultimate risk is the remote control of a connected vehicle. Means of protection already exist, but they must be integrated into the vehicle development process (ITU, 2020a). The text of UN Regulation 155 requires the establishment of a cybersecurity management system and includes audit-related provisions regarding the robustness of these systems. It covers attacks on back-end servers, vehicle communication channels, update procedures, unintended human actions facilitating a cyberattack, external connectivity and connections, and vehicle data/code. The regulation also sets an important precedent because the risks to be addressed affect not only directly manufacturers, but also their suppliers.[64] The text also imposes a number of requirements, including the obligation to monitor and report on incidents (UNECE, 2021b; United Nations, 2021b).

Using digital technologies to manage the transition towards digitally connected and cleaner vehicles

While there is no doubt that many governments are pro-actively supporting the deployment of digital technologies, this appears to be driven primarily by the economic opportunities that they offer (and the risk of missing economic opportunities without policy support), and much less from the desire to align economic opportunities and the minimisation of environmental impacts. Several analyses also indicate that an increased reliance on digitally enabled solutions for transport vehicles (in particular autonomous vehicles) will likely have major relevance for growth in transport activity (Wadud, MacKenzie and Leiby, 2016; IEA, 2017a; Sperling, 2018; Noussan and Tagliapietra, 2020; Greenwald and Kornhauser, 2019).

Governments must make sure that this transition is effectively managed, since de-coupling activity growth from energy demand and environmental impacts will be necessary to meet climate policy goals. Solutions that can help foster this decoupling by improving energy efficiency and reduce GHG emissions, including electrification and digital technologies, are essential in this context.

Energy efficiency and environmental action have not been, so far, high on the agenda of what drove the deployment of digital technologies in transport (and if they were, their potential has been subject to offsets from activity and/or performance increases). However, digital technologies can offer important opportunities to manage energy and environmental impacts from transport vehicles, especially if the vehicles are increasingly shifting towards electrification. To ensure that these opportunities are adequately seized, policy makers need to ensure that the integration of digitally enabled policy instruments is taken into greater consideration when new regulatory frameworks on digital technologies are developed.

The remainder of this report (in particular the final chapter, which offers suggestions for a resilient way forward) will build on the idea that a greater consideration of environmental goals in the deployment of digital technologies (in particular the integration of digital tools enabling the use of geofencing policies and road user charges) can help governments manage important structural impacts of electrification. These include those related with changes in material demand, thanks to optimisation of the use of materials. It includes also the management of shortfalls in government revenues from fuel taxes, thanks to the possibility to recover revenues from road use. Both add to the possibility to manage other impacts of transport activity, starting from congestion but also including noise and local pollution, as the thanks to digitally enabled instruments applying time dependent and location-specific road user charges.

The following analysis also draws from experiences developed in the transition towards greater digitalisation of the economy to identify lessons that can be effectively applied to the clean vehicles and the low-carbon energy they need, paying specific attention to the impacts that these trends will have on jobs and skillsets.

Emerging policy challenges

Three considerations suggest that policy actions aimed at fostering the transition towards transport electrification and increased digitalisation are likely to become increasingly important.

- First, the significant economic opportunities that these technologies offer in terms of economic development, thanks to cost reductions and increased economic competitiveness.
- Second, the importance to the economy of the automotive and energy industries, as they have direct implications not only for major financial and industrial actors, but also for the large number of individuals that they employ -- and are therefore very relevant in the context of the "just transition" and the desire of governments to ensure that no one is left behind.
- Third, the global effects of climate change – including rising sea levels that threaten low-lying regions, extreme and less predictable weather, and loss of biodiversity (with accompanying impacts on human health, food security, water supply and economic development).

Action to stimulate a transition to clean vehicles and energy, induced by these policy imperatives, will also have implications that go beyond the direct role for which policy is deployed. As in the case of digitalisation, the pervasive nature and effects on society and the economy of the new technologies – especially after the acceleration induced by Covid-19 – will likely lead governments to increasingly consider an integrated (or "whole of government") policy response designed to help maximise their potential benefits while also addressing their challenges.

While it is difficult to anticipate all of the implications of the clean vehicle and energy transitions, some are already evident. This chapter identifies three areas that deserve greater consideration by policy makers:

- Changes in the demand for new materials and related supply chains, induced by a change in powertrain technologies and a switch to renewable electricity.
- Structural changes in government revenues, induced by a shift towards vehicles requiring less (or no) fossil fuels to operate.
- Impacts on jobs and changes in skillsets that will accompany the shift in automotive technologies due to both electrification and digital technologies.

This chapter examines each of these areas in detail. This analysis, along with the information discussed earlier, will serve as the basis for the final chapter, which suggests ways to increase the resilience of the transition towards clean vehicles and energy in road transport while also addressing longer-term challenges.

Changes in the demand for new materials and related supply chains

Electric vehicles have a number of different material requirements compared with ICE vehicles, most importantly the minerals required to produce electric vehicle battery systems and electric motors. These distinct materials have given birth to new supply chains, the control of which offers both industrial opportunities and geopolitical challenges.

The materials associated with most vehicle batteries are high-grade lithium, graphite, nickel and cobalt. Electric vehicle motors, on the other hand, can be dependent on rare earth elements (REEs) such as dysprosium, terbium, praseodymium and neodymium (Ballinger *et al.*, 2019). Demand for these materials is set to grow dramatically; demand for lithium, for example, is expected to grow by a factor of 42 between 2020 and 2040 (IEA, 2021d).

Available evidence from literature suggests that long-term shortages of many of these minerals are not likely. In particular, lithium is shown to be abundant, its known resources are expanding and technology improvements can help mitigate resource availability challenges (Olivetti *et al.*, 2017; KPMG, 2021). Materials for which there are greater resource limitations, such as cobalt, will likely be subject to a surge in demand, but they can in many cases be substituted by modifying battery chemistries. In the case of cobalt, there is already evidence of shifts towards less-cobalt-intensive battery chemistries, such as lithium iron phosphate (LFP) and nickel manganese cobalt (NMC) with higher nickel ratios (BNEF, 2020b).

However, the pace at which the supply of battery materials can increase is constrained by the time scales involved in setting up production facilities. According to Benchmark Mineral Intelligence (2020), the average time required to build a battery production facility with over 10 GWh of annual production capacity is 2 years 7 months from breaking ground to initial battery production. On average, it then requires a further 3 years and 9 months for production to increase to full capacity at the site. Further up the supply chain, time frames associated with constructing cathode manufacturing plants are approximately 2-3 years, chemical refining facilities require 3-5 years, and setting up a lithium mine from scratch takes about 5-8 years (and can take up to 20 years). Purely to extract lithium from brine by evaporation at a fully operational facility requires between 12 and 14 months based on the concentrations of salts at the location.

The rapid growth in EV supply and demand, combined with the relatively long time scales associated with mining of new material resources, can pose the risk of short-term supply shortfalls. A number of analysts are flagging the risk of lithium supply shortages as early as 2027 (Benchmark Mineral Intelligence, 2020; Rystad Energy, 2021). Short-term shortages may hinder efforts to stimulate a shift towards EVs. Supply shortages can also lead to commodity price increases, slowing the cost reductions of EVs in the short term. The Covid-19 pandemic has reportedly further intensified these challenges by delaying a number of mining projects, while at the same time accelerating demand for battery electric vehicles due to government stimulus (Benchmark Mineral Intelligence, 2020).

In addition to potential supply shortfalls, the production and refining of battery materials and REEs is clustered in a small number of countries. Over 80% of lithium mining occurs in Australia, Argentina, Bolivia and Chile. Similarly, over 60% of global cobalt consumption is mined in the Democratic Republic of Congo (IEA, 2019a). China holds particular market dominance of battery supply chains in the chemical refining of raw materials, production of cathode and anodes and battery production (Moores, 2021). It holds even stronger market dominance in REE supply chains: by one estimate, it controls 98% of the European Union’s supply of REEs (KPMG, 2021). Market dominance of supply chains can also entail risks for stakeholders in other parts of the supply chain; for example, China temporarily imposed restrictions on the export of REEs between 2010 and 2011, causing prices to increase by a factor of 10 (Ballinger *et al.*, 2020).

Supply chain risks for battery materials and REEs can be reduced by diversifying supply; however, this is a lengthy process constrained both by the time required to build new sources of production and the intellectual property advantages of incumbents (Ballinger *et al.*, 2020). Alternatives include diversification of demand; the lithium-ion battery is difficult to replace but changes to chemistries can reduce dependence on certain materials. Permanent-magnet electric motors, which are used in the majority of EVs on the market, are constructed using a number of REEs, making them susceptible to supply chain risks. Companies can reduce their risk of supply shortages in these rare earth elements by switching to induction motors (an option pursued by Tesla) (Ballinger *et al.*, 2020).

Governments and industry can reduce risks related to battery supply chains by diversifying production across a range of industry stakeholders and promoting further vertical integration (e.g. by facilitating investments in anode and cathode material production and in battery manufacturing). This matches a dynamic investment environment in the set-up of domestic battery manufacturing facilities in Europe and could be complemented by a strengthening of midstream capabilities in the United States (Nakano, 2021).

One potential option for managing supply chain risks is strategic stockpiling of key materials, in a similar way to oil stocks overseen by the International Energy Agency today. Furthermore, because a number of critical materials used in EVs have limited price transparency, establishing reliable price benchmarks for key minerals can help stakeholders throughout the supply chain to manage these risks (IEA, 2021d).

Battery recycling can play a role in reducing the need for raw materials in the long term. However, recycling battery materials is still a relatively young industry, like lithium-ion batteries themselves. The nascent use of batteries in the automotive sector means there are only a limited number of used vehicles (and batteries) that have reached end-of-life and it will take years for this number to grow large enough to provide batteries to offset demand for newly extracted raw materials. Battery recycling faces the challenge of rapidly changing battery chemistries. It is therefore unlikely to be able to address supply constraints or geopolitical challenges in the short term (Olivetti *et al.*, 2017). However, the IEA suggests that battery recycling in 2040 could account for 10% of supply (IEA, 2021d). Vehicle battery recycling industries can be encouraged by designing for recyclability from the outset and increasing data collection on battery chemistries as well as end-of-life traceability and collection (Baars *et al.*, 2021). Efforts to develop policy actions in this direction have already started, as discussed in the section on “Clean vehicle adoption”.

As highlighted in previous chapters, maximising the distance driven by vehicles in electric mode is an effective path towards reducing GHG emissions. If the supply of batteries is constrained (e.g. because of short-term bottlenecks and other risk factors), then the greatest emissions reductions may be achieved by adopting a large number of vehicles with relatively small batteries, rather than a smaller number of vehicles with particularly large batteries. For passenger cars, a battery with a 100-200 km range in a PHEV or a small BEV would be sufficient to satisfy the majority of trips, as shown in Figure 3. Diversifying from the focus on large, high-value vehicles back towards smaller vehicles could help OEMs limit overall demand (thanks to smaller battery packs in mid-size cars), while still enabling them to have access to capital for this important transitional phase. For heavy-duty vehicles, the combined use of PHEVs and ERS solutions can enable a large share of vehicle kilometres to be electrified without the need for a very large battery, making the transition more resilient to potential battery-supply risks than for long-range BEV trucks.

The rapid growth of renewable energy is also likely to have important implications for a shift in patterns of demand for key minerals. Renewable energy resources, supporting technologies and the key minerals they need will likely play a growing role in a future low-carbon global energy system (Finley *et al.*, 2020). These effects are a part of a broader and complex range of developments that can alter the power and influence of some states and regions relative to others (Hafner and Tagliapietra, 2020; Vakulchuk, Overland and Scholten, 2020; IRENA, 2021) – with countries highly reliant on fossil-fuel exports generally seen as the most disadvantaged unless they take significant action to diversify their economies, including reaping benefits from their renewable energy resources (IEA, 2020h; CarbonTracker, 2021a).

Structural changes in government revenues from fuel taxes

A second challenge associated with the increasing adoption of low-carbon vehicles is the reduction in government revenues from fuel duties and taxes. For countries without large shares of second-hand vehicle imports or rapidly growing travel demand, the drop in fuel tax revenues is broadly dictated by three factors: 1. the share of EVs in new vehicle sales; 2. how efficient electric vehicles are compared with existing conventional ICE vehicles; and 3. how much tax is collected per unit energy of electricity vs. the tax collected per unit energy in the fuel.

Figure 13 illustrates how these three factors affect fuel revenues per vehicle. It presents scenarios for two levels of ambition in terms of EV adoption. In the first scenario (shown at left), EVs account for 100% of sales in 2030; this is in line with the most ambitious government targets. A second scenario (shown on the right) assumes less ambitious goals in which EVs reach one-third of new sales by 2030 and 100% of sales in 2050. The scenarios are further differentiated by the relative levels of taxation on electricity vs. fuel and the efficiency of EVs in comparison with existing ICE vehicles used in the country.

In all major automotive markets, government taxes on electricity use are lower, per kWh, than fuel taxes. This is shown in Figure 13 by a ratio of taxes on electricity to fuel that is lower than 1. Increasing taxation on electricity to levels higher per kWh than fuel (bringing the ratio above 1) could help to temper drops in revenues, but applying significantly higher electricity taxes will be infeasible as electricity has a wide range of other end uses.

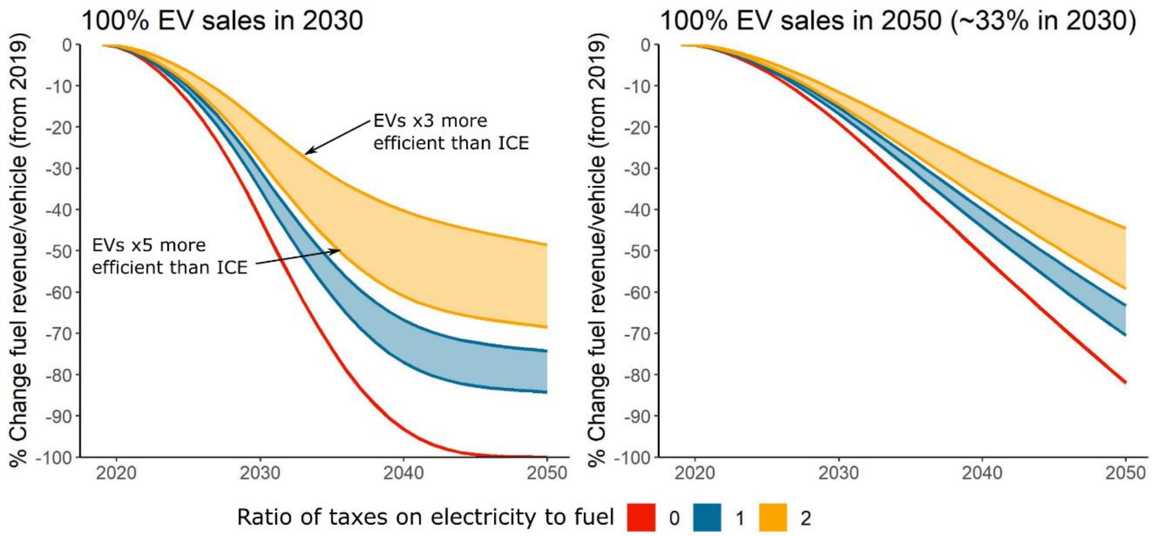
If EVs account for 100% of new passenger car sales in 2030, and the ratio of electricity to fuel taxes remains below 1, then revenues would likely drop by approximately 30% by 2030 and 70-90% by 2040. A relatively slow adoption of EVs, reaching 100% only by 2050, could limit drops in revenues to approximately 15% by 2030 and 40-55% by 2040, but slow efforts to mitigate GHG emissions and improve urban air quality.

For countries with a high share of large vehicles in their fleets, like the United States, BEVs are four to five times more efficient on a kWh/km basis than conventional ICE vehicles. The adoption of BEVs in these countries would lead to drops in tax revenues relatively quickly (at the lower end of the ranges shown in Figure 13) when compared with countries that have a lower share of large cars, such as Europe and Japan. This is because smaller BEVs are roughly three times more energy-efficient than ICE vehicles.

If no tax is collected on electricity (ratio = 0), then the fuel efficiency difference between BEVs and ICE vehicles has no effect on the speed of revenue decreases (meaning there is no range in Figure 13). Emerging economies with a growing vehicle fleet may also face a lower total reduction in revenues, even as the contributions per vehicle decrease. The assessment above was developed for BEVs for simplicity, but it applies equally to all vehicles that are capable of electric driving, as well as vehicles running on alternative fuels (such as hydrogen), which are not taxed.

Increasing fuel duties on gasoline and diesel to offset shortfalls resulting from the adoption of electric vehicles could be part of the solution, but it faces social equity challenges as lower-income households are less likely to be able to switch to new electric vehicles. Part of the reason is that fossil fuels used in road transport tend to be already subject to higher taxation levels, if compared with fossil energy sources used in other transport modes (in particular international maritime transport and aviation) and for other energy end-uses (OECD, 2019a). Increasing fuel tax levels on traditional fuels could also reduce travel demand, which may reduce potential revenue gains (OECD/ITF, 2019).

Figure 13. Percentage change in government revenues per passenger car by EV sales share, tax ratio and relative energy efficiency



Note: The ratio of electricity to fuel taxes refers to the sum of excise and sales taxes per kWh of energy (fuel taxes are calculated as the average of gasoline and diesel). When the ratio is equal to 2, taxes per kWh of electricity are double those per kWh of fuel. The lower end of the ranges indicates vehicle fleets where conventional ICE vehicles are five times less efficient than EVs (similar to North American countries); the upper end refers to vehicle fleets where conventional ICE vehicles are three times less efficient than EVs (similar to many European countries). The stock turnover rates are consistent with the lifetime of passenger cars in major car markets in the OECD countries. Countries highly dependent on second-hand vehicle imports and with a low percentage of new sales may see a more gradual transition. All EVs are assumed to be BEVs for simplicity. Vehicle size and weight are assumed to remain constant at 2019 levels. Vehicle fuel efficiency improvements are assumed to continue at their historical rate. The vehicle stock model used here is based on (Craglia, 2020).

Road user charges are a policy solution that offers the potential to make up for lost fuel-duty revenues and adequately price the use of vehicles. Opting for this solution would effectively switch the tax base to distance travelled rather than energy use. Recent work (OECD, 2019c) points to considerable scope for improving transport tax practice in road transport by increasing the use of taxes based on road use. Distance-based charges help to fit the ‘polluter pays’ principle, where those who produce pollution ought to pay a cost to help manage the damage they inflict on others or the environment. Location-specific and time-dependent distance-based charges could provide a cost-effective way to address congestion, whose costs are particularly high in urban areas and at certain times of day. Charges could also potentially be differentiated to incentivise PHEVs to drive in all-electric mode. In addition to GHG emissions, air pollution and congestion, shifting to distance-based charges can also help to address other negative environmental and social externalities of road transport, in particular noise and traffic accidents (OECD, 2019b). Since electric vehicles have fewer negative externalities than conventional vehicles, user charges should be lower than for conventional vehicles.

The shift to road user charges is likely to be complex, since governments need to find the balance between stimulating innovation and the technology transition, while also addressing the issue of revenue shortfalls and the impacts of road transport. Road user charges need to avoid increases in vehicle use driven by the lower travel costs of EVs, while maintaining incentives to switch to EVs and limiting social equity impacts. This complexity calls for a gradual shift, as well as the establishment of a solid technological basis for managing the transition, along with clear communication between stakeholders (including individuals that will adopt LZEVs) that will be affected by the change.

The presence of several other reasons to adopt road user charges further strengthens their appeal. From a technology perspective, the significant advances made to date on the digitalisation and connectivity of road transport indicate that there is a solid technological basis for enabling this transition. Major work being undertaken to continue this process – not only with GNSS systems, but also in the context of transport infrastructure (e.g. with C-ITS deployment) and on the vehicle side – also gives encouraging signals for the future. However, it will be important to make sure that the considerations coming from the perspective of policy challenges due to the transition in vehicle and energy technologies (as a response to climate and policy through innovation) are duly taken into account, making them an integral part of the regulatory policy developments on vehicle and infrastructure connectivity.

In the specific case of commercial vehicles (in particular trucks), it is also important to recall that electric road systems (ERSs) offer the potential for government revenues to be levied along with user charges as mentioned in Box 1.

The urgent need for governments to begin to develop long-term policy to manage the transition to electric passenger cars and other LZEVs is also confirmed by recent announcements in the United Kingdom (UK Parliament, 2020) and the Netherlands (Dutch Government, 2020) showing that the considerations flagged here on road user charges are moving up in the agendas of the public administration.

Other solutions to raise revenues may also come from sectors that are beyond road transport (as in the case of carbon taxes for maritime transport or aviation) and other fiscal reforms (OECD, 2019a). The latter include the prominent example of OECD-led efforts to foster international collaboration to end tax avoidance, developed under the OECD/G20 Inclusive Framework on base erosion and profit shifting (BEPS), with over 135 countries collaborating to put an end to tax avoidance strategies that exploit gaps and mismatches in tax rules to avoid paying tax (OECD, 2021c). This work has recently made significant progress, thanks to a growing consensus on the application of a global minimum threshold for corporate income taxes of large multinational enterprises (Horobin, 2021a; Lawder, 2021; Politi *et al.*, 2021; Renshaw, 2021; Shalal *et al.*, 2021), also supported by OECD analysis (OECD, 2020d).

The appropriate use of revenues resulting from these other solutions will depend on countries' specific circumstances. Using them to lower burdensome taxes on work effort, or boost productive investment, provides a benefit to the economy that counteracts the harmful effects of higher energy prices (IMF/OECD, 2021). This may therefore make them better suited to deal with challenges discussed in the next section.

Impacts on jobs and changes in skillsets

The automotive industry accounts for a significant amount of jobs. There were nearly 14 million direct jobs in manufacturing globally in 2017, along with estimates ranging close to four to five additional jobs (per direct job) in other industries in the supply chain (ILO, 2021). The geographical distribution of this employment is influenced by the location of producing facilities, with high relevance of all the major automotive markets considered for this analysis, and it has also been subject to important transitions in the recent past. These are due to structural changes in market demand, in particular the growth of emerging markets. They are also due to the impact of globalisation and trade liberalisation, which, through offshoring and outsourcing, have resulted in the emergence of globally interconnected supply chains. These are led by a limited number of major multinational enterprises (OEMs) connected with a number of component suppliers. These include some large companies as well as a large number of small and medium enterprises (SMEs).

Implications of electrification and digitalisation for jobs

Emerging trends discussed in this report, pointing to a concurrent set of shifts towards digitalisation and electrification, are recognised as important determinants of change for the automotive industry.

Key examples of areas where digitalisation is seen as a driver of rapid developments include: in design and manufacturing improvements (in particular with leaner factories, which can shorten lead times thanks to simpler supply chains and production processes), value chain enhancements resulting from data-driven solutions (such as predictive maintenance), increased reliance on digital connectivity (enabling stronger penetration of innovations, from in-vehicle diagnostics to digital driving), and even a redefinition of sales though changes in the way consumers approach vehicle purchases.

Electrification offers opportunities for cost reduction due to a lower number of moving parts, greater freedom to conceive new products, changes in material requirements and the possibility of enabling changes in the organisation of production and work. It also brings structural changes in the need for vehicle maintenance and second-life or end-of-life treatment.

These developments have repercussions on the professional profiles needed to enable and sustain the change. The rapid growth of data can reasonably be associated with a rise in demand for highly skilled workers in the fields of science, technology, engineering and mathematics (STEM), as well as information and communications technology (ICT) (ILO, 2021). Changes in material requirements associated with EVs can create new opportunities for workers involved in the battery value chains. Powertrain shifts towards EVs also lead to structural changes in energy demand. Changes in material requirements and transport energy vectors have positive effects on jobs in electricity generation; the manufacture of batteries, electrical parts and machinery; and the development, manufacturing and deployment of charging station infrastructure. However, they are mirrored by impacts on the workforce employed in sectors that are negatively affected (such as fossil fuel production and refining).

Other important impacts, beyond those occurring in automotive sector, affect the fossil fuel sector. These are briefly discussed in Box 9.

A number of analyses have attempted to estimate the potential economy-wide employment implications of an accelerated shift to road transport electrification. The results generally point towards net employment increases overall[65] (Cambridge Econometrics, 2018; ILO, 2018; ODI, 2020; UNECE and ILO, 2020), but this is indeed not uniform across sectors and geographies. Impacts on employment also depend on details that characterise different technology options. In particular, manufacturing battery-electric vehicles has been estimated to be less labour-intensive than manufacturing gasoline and diesel vehicles. However, hybrids and plug-in hybrids are expected to be more labour-intensive (Cambridge Econometrics, 2018), and therefore capable of mitigating transitional impacts.[66] A recent targeted analysis for electrification in the automotive sector found that total labour value for EVs and ICE vehicles is very similar (1% difference) (Küpper *et al.*, 2020). This assessment found also that impacts vary on the basis of developments taking place in the value chain. Automakers that outsource all the battery and power electronics reduce labour by 7%. If production remains in-house (including for battery cells), labour increases by 7%. Outsourcing battery cells and power electronics while retaining the manufacturing of rest of the battery systems and electronics leads to labour reductions by 4% compared to ICE. Similar considerations can be applied to regional (or national) contexts. Achieving a net increase in jobs is possible also if batteries and power electronic components are outsourced, provided that the suppliers are located in the same geographical area.

Box 9. Impacts on the fossil fuel sector of electrification, renewables and digitalisation in the automotive sector

The fossil fuel sector which employs 1% of the total global workforce (OECD, 2020a). The ILO's *World Employment and Social Outlook 2018* points to the risk of net job losses (for reasons including the energy and sustainable mobility transitions) in the Middle East (–0.48%) and Africa (–0.04%).

This is will be the case if dependence on mining and fossil fuels remains prevalent in these regions. The risk of job losses in the fossil fuel (namely the oil) sector are also logically associated with the concept of stranded assets. These can be defined as assets that lose significant economic value well ahead of their anticipated useful life as a result of changes in legislation, regulation, market forces, disruptive innovation, societal norms, or environmental shock (including climate change) (Generation Foundation, 2013; CarbonTracker, 2021b). They are indeed most relevant for countries highly reliant on fossil fuel exports. These are the countries subject to the strongest need for diversification of their economies, but they are not exempt from concrete possibilities to reap benefits in cases (not infrequent, for solar and also wind, in the Middle East and parts of North Africa) of a high endowment in highly cost-competitive renewable energy resources (IEA, 2020h; CarbonTracker, 2021a)

More broadly, while much attention has been paid to the stranding of physical assets and how to manage it when it comes to the literature on low-carbon transitions, it is important to recall that the stranding of human capital is also not neglected. In 2020, human capital made up 77% of total global capital (Mercure *et al.*, 2021). Economic diversification will therefore be crucial to create jobs, in countries that are heavily relying on fossil energy rents, as a global transition towards digitally connected mobility, clean vehicles and low-carbon energy unfolds.

The effects of automation and digitalisation have also been the subject of quantitative assessments on employment impacts in manufacturing, with a range of results. Some point to highly negative impacts on job losses, particularly on low-skilled workers. Others take a more conservative view and focus on the likelihood that jobs will be transformed rather than lost. These studies are based on the presumption that decisions to shift to automation depend on the economic context, the policy environment and a variety of practicalities and constraints involved, leading to likely higher negative impacts in low-income economies than in high income economies (ILO, 2021). A 2019 OECD assessment of jobs at risk of elimination by automation found no support for net job destruction at the broad country level and pointed to employment growth over the previous decade in all countries that were considered at risk – while also observing that impacts were more significant for less-educated workers (OECD, 2019d).[67]

Employment impacts also depend on the starting point, with the automotive industry being – especially in developed economies – already highly reliant on automation (ILO, 2021). Additionally, while automation will displace workers or transform jobs in the automotive industry, technological advances will create new opportunities for enterprises and workers, particularly high-skilled workers – e.g. in the development and provision of services and products to facilitate future transport solutions. Sustainable enterprises are also seen as engines of high-quality job creation and play a crucial role in promoting innovation and generating inclusive growth (ILO, 2021).[68]

Notwithstanding uncertainties to do with some of the impacts discussed, it is clear that workers in the automotive and energy industries will be exposed to a broad set of transitional impacts from the shift to clean vehicles and clean energy, and this would not happen in isolation from other developments in digitalisation, connectivity and automation.

Responding to the challenges of technology transitions

As the automotive sector is at the intersection of both of the climate and digital transitions, there are good chances that managing the transition to clean vehicles and clean energy will require a holistic response. Policy makers must recognise that changes affecting the workforce tend to take time (Louie and Pearce, 2016). They must also improve their own capacity to anticipate changes (Rosemberg, 2010), formulate policies designed to increase flexibility in product and labour markets, foster skills development and reskilling, and strengthen employment measures (such as job matching, career counselling and entrepreneurship support), along with increasing social protection benefits (ILO, 2021; OECD, 2021b).

Responses also need to take into account the specific nature of the automotive sector, in particular the presence of both multinational enterprises and local SMEs in its value chain. Multinational manufacturers account for major portions of the employment created in the automotive industry, and SMEs are (and will remain) strategically important for the creation of decent and sustainable work in the industry (ILO, 2021).

When considered through the lens of job and skills impacts, SMEs show, on one hand, a greater capacity to adapt to megatrends (and can even be major supporters of the change). On the other, they are also more exposed to disruption by digitalisation and other technological advances. Lower-tier suppliers, which are mostly small SMEs, are more likely to suffer rather than benefit from the industry-wide changes brought about by digitalisation, as they lack access to the human resources, financing, knowledge and competencies necessary to meet basic cost, quality and delivery requirements (ILO, 2021).

Improved foresight

Improving the capacity of governments to anticipate changes can help significantly in the design of appropriate responses. Achieving this requires the development of improved foresight tools that give policy makers a more granular understanding of implications for their and other jurisdictions, while allowing them to integrate dynamic changes. Improved foresight capacity will also strengthen coordination across different departments in governments. Developing an effective strategy to respond to the challenges highlighted here will also require greater co-operation and improved communication across different administrative levels.

Better foresight capacity in the public administration can also, if combined with stakeholder consultation and communication tools, help to improve the capacity of SMEs in the lower tier of the automotive supplier pool to anticipate macroeconomic changes, as these SMEs are more likely to have fewer resources than major manufacturers to do so without this sort of support.

Thanks to better foresight (and therefore greater anticipation capacity), governments can also be more effective in taking actions that favour the emergence of innovative SMEs in the automotive industry. Relevant policy support could include financial instruments that facilitate access to capital, such as loan guarantees and start-up grants (ILO, 2021).

Labour market policies

Developing policies that help workers respond to the challenges posed by these transitions can leverage the comprehensive work developed by the OECD on the topic, starting from the 2018 revision of the OECD Jobs Strategy and including the OECD Skills Strategy. This is indeed the direction in the OECD's Going Digital integrated policy framework (OECD, 2021b), which has a high degree of relevance to the challenges discussed here.

Training and re-skilling

Policy makers will have to pay attention to devising mechanisms that support workers who lose their jobs in technologies that are phased out. Timely re-training of workers for sectors and technologies for which demand is expected to increase in the future is essential. These are likely to include areas of competences required by the digital transitions, such as data analysts and scientists, process automation specialists and industrial and production engineers. Continuing education, training and lifelong learning are expected to become increasingly important for workers trying to secure employment in the automotive industry, or in other sectors if the industry declines in their country (ILO, 2021). Career guidance can complement this by helping adults successfully navigate a constantly evolving labour market through advice and information on job and training opportunities (OECD, 2021a).

Policies also need to encourage employers to invest in training, as the scale of the challenge goes beyond the capabilities of the public sector alone (OECD, 2021b). Large automotive companies have an established set of measures designed to develop the skills of their workers all over the world, but more is required to address the deep transformation that the sector faces. Investments in the capabilities of a workforce that will master new technologies and possess the right skill set to drive innovation, productivity and sustainability in the future are crucial (ILO, 2021).

Complementary action is also needed to ensure that existing technical capacity will be maintained and/or replaced as new individuals enter the workforce. Basic education remains the foundation for this, but it will need to adapt to changes in the competences needed. Governments have an indispensable role in financing basic education and ensuring equitable access to training opportunities and lifelong learning (ILO, 2021).

The relevance of retraining and further training is also emphasised, along with the importance of maintaining highly skilled jobs in the automotive industry during the transition, by a recent analysis focused on Germany. This analysis expects that the number of German automotive jobs eliminated through reduced ICE production will be higher than the number of employees retiring from the industry (IFO, 2021).

Labour force mobility

Similar to digitalisation, the effects of the transition to cleaner vehicles and energy will vary across geographies. Enabling mobility of the labour force within and between sectors and countries will therefore also play an important role in facilitating the transition.

When mobility across different regions is inevitable, governments can help displaced workers transitioning back into employment by reducing the costs of relocating, e.g. through subsidies. Well-designed housing policies can also help people to move to regions where more and better jobs are available. Tax and benefit systems also need to be extended and/or adapted to ensure that all workers are provided with minimum protection. Portability of social security entitlements should be promoted to prevent the loss of benefit entitlements when workers move between jobs (OECD, 2021b). As discussed in the next section, worker mobility also depends to a large extent on the transferability of skills and the portability of benefits, the availability of effective employment services, and the existence of active labour market programmes to facilitate job transitions (OECD, 2021b).

Social protection and social dialogue

Due to the historically high degree of disruption and insecurity faced by the automotive (and the energy) industry in this transitional phase, social protection will be crucial to enable a successful and fair evolution for all. This involves a system of well-designed and adequately resourced active and passive labour market programmes, providing workers with timely access to basic job search services, and targeting the workers that require more intensive (re)employment services or retraining (OECD, 2021b). Social protection is also important for economic growth because it strengthens people's capacities to benefit from the changing world of work, by enhancing productivity and supporting household income and thus domestic consumption and aggregate demand (ILO, 2021). Governments have a central responsibility to guarantee universal social protection for all.

Social dialogue is also essential to meet the challenges and opportunities faced by the automotive industry today and in the future, as it can help the industry find solutions and facilitate the promotion of decent and sustainable work. It is particularly critical in ensuring that investments in people's capabilities, skills development and lifelong learning systems will allow employers and workers to take advantage of new opportunities in the future (ILO, 2021). Due to higher bargaining coverage rates[69], social dialogue can play a larger role in the automotive industry than in other sectors (OECD, 2017).

Examples of actions undertaken to date to respond to these challenges

Recent moves made by the European Commission are an interesting example of actions designed not only to strengthen its capacity to define high-level policy priorities, but also to ensure that improved understanding (deriving from a high level of granularity) allows it to properly assess the implications of the technology transition discussed here for different European regions. Key actions developed in this context include (a) the establishment of a network aiming to ensure long-term policy coordination between all Directorates-General and (b) the identification of key priorities, closely related to the digital and low-carbon transitions, for defining regional policy support in the context of the cohesion policy of the European Union (EC, 2021q, 2021h).

In the aftermath of Covid-19, many countries have also paired efforts to provide immediate relief from the pandemic's negative impacts with recovery and stimulus plans integrating the creation of green jobs. In the United States, measures with direct relevance to a transition towards cleaner vehicles are part of the proposal outlined in the American jobs plan (which foresees large infrastructure investments to restart the economy, and also includes provisions for an increase in corporate income tax) and the American families plan (which aims to make education more affordable, provide economic security for families and expands tax credits that help workers and families). Both are part of a tax strategy aiming to end "the unfair system of enforcement that collects almost all taxes due on wages, while regularly collecting a smaller share of business and capital income" (White House, 2021d, 2021e). France also unveiled recently a EUR 50 million (USD 60.5 million) fund to retrain workers making cast-metal auto parts whose jobs are at risk (Horobin, 2021b).[70]

Given the scale of the challenges (which encompass both the transport and energy sectors) and the budgetary allocations needed to address them, making sure that these measures can be effectively financed could indeed be one of the priorities enabled by major tax reforms. It would allowing governments to raise revenues (see e.g. the OECD/G20 Inclusive Framework on base erosion and profit shifting, or BEPS (OECD, 2021c)) and apply a global minimum threshold for corporate income taxes of large multinational enterprises.

Suggestions for a resilient way forward

Major technology developments and cost reductions – especially in the areas of battery technologies, renewable electricity and digitalisation – are offering unprecedented opportunities for a transition towards cleaner vehicle and energy vectors in road transport.

The combination of direct electrification and renewable electricity can facilitate significant GHG emission reductions from road transport vehicles, while also facilitating net improvements in energy efficiency, cut cost and improve economic productivity. Additional opportunities may arise from low-carbon hydrogen and alternative fuels, especially in regions that have the best resource endowments, allowing for increases their cost-competitiveness. However, these face important barriers due to low energy efficiency and likely long timescales associated with their deployment at scale.

These technology developments, which were first stimulated by climate and environment policy signals (many of which have been specific to transport vehicles and the energy they use), have subsequently demonstrated that a successful pathway towards low-carbon road transport is within reach. They are now spurring major shifts in investments towards clean vehicles and energy for road transport. One tangible sign of the increasing trust in the success of this technology transition is evident in the capital markets, from the major rises in the valuation of companies that have clearly positioned themselves ahead of others.

A parallel shift has taken place in the area of digital technologies. These have benefitted from rapid technological progress and are well aligned with opportunities to increase economic productivity and expected growth in the demand for digital products and services. This is why they are also supported by policy and are attracting major flows of capital and investments. The growth in digital technologies offers a number of possibilities to address some of the challenges associated with the growth in clean vehicles, including geofencing, vehicle telematics and road user charges.

Both shifts (towards clean vehicles and energy as well as digitalisation) have been accelerated by the Covid-19 pandemic, since it required:

- policy action to provide safeguards in light of the economic crisis and to stimulate an economic rebound
- a focus on expenditures that will enable the payment of the debts it generates (such as infrastructure spending)
- a focus on solutions that are compatible with long-term policy goals (and are thus exposed to lower stranded-asset risk, reducing the chances that they could compromise the capacity of global economies to repay debts).

This situation points towards clear signals of greater action on climate and, with it, clean vehicle and energy vectors for road transport. However, ensuring that the path to carbon-neutrality goals can be successfully completed will still require policy support. Otherwise, there is a significant risk that policy makers will lose not only opportunities for stimulating economic development in a way that is compatible with climate change, social justice and other sustainability goals, but also economic competitiveness – with major potential implications, including job losses.

Support the adoption of clean vehicles with targeted policy action and by increasing transparency of their carbon footprint

In the initial phase of clean vehicle and energy technology deployment, crucial pieces of an organic policy framework include: the development of technical standards and regulation, the establishment of a clear vision and medium-to-long-term targets, the presence (or establishment) of a conducive energy pricing and taxation environment, the adoption of ambitious public procurement programmes, the use of economic incentives, the deployment of regulatory requirements for clean vehicles and energy vectors (taking a lifecycle approach on energy, pollutant and GHG emissions, as well as other environmental impacts) and support for the deployment of charging/refuelling infrastructure.

Regarding technical regulations and standards, internationally agreed texts should be prioritised, as they are best suited to avoiding barriers to trade. They are also useful in avoiding the use of region-specific protectionist practices. International co-operation is therefore crucial to ensure that a transition to clean vehicles and clean energy can be achieved on the basis of a level playing field.

The minimum requirement for a conducive energy pricing and taxation environment is the phase-out and removal of fossil fuel subsidies. Additionally, there are good reasons to increase fossil energy prices through environmental taxation. This is likely to be better accepted if revenues generated are redistributed to shelter low-income households (e.g. improving access through better public transport services and sustaining research on, and deployment of, low-emission technologies to lower the cost of alternative vehicles and fuels) and highly impacted professional categories (e.g. freight transporters). Energy and carbon taxes are also important instruments for avoiding direct rebound effects that occur because energy-efficiency improvements decrease the cost of using energy-related products and services, which in turn increases demand for these products or services.

Regarding public procurement, economic incentives and regulatory requirements, experiences from major developed and emerging economies show that ambitious plans have a proven ability to trigger changes in the supply of and demand for clean vehicles and fuels, helping set in motion a virtuous circle of cost reductions. These policies are important to ensure that significant benefits can be reaped as the cost-competitiveness of clean vehicle and energy technologies increases.

Regulatory requirements have a greater merit to foster a technology transition in vehicles with the highest lifetime travel, since this is where they have the greatest potential to lead to net savings in total cost of ownership. Given OEMs' tendency to focus on SUVs to increase profitability of car sales (resulting in higher energy use and GHG emissions/km, especially for vehicles that are not electric), regulations must require fleet-average reductions in energy use and GHG emissions, rather than focusing solely on LZEV market-share increases.

Economic incentives can help accelerate the shift to clean vehicles and clean energy, but they must be designed in a way that allows all income groups to benefit, considering distributional impacts. Incentives need to be better targeted towards low-income households. In countries with high levels of personal vehicle travel, this can lead to higher energy savings and GHG emission cuts, since low-income households may be constrained to longer commutes. In countries with greater reliance on public transport, focusing incentives on clean buses (and passing net cost savings on to users) would align them better with a just transition.

Economic incentives differentiated by vehicle weight can also help manage increases in vehicle size. For PHEVs, differentiating economic incentives based on the all-electric range would allow the maximisation of benefits derived from vehicle use in all-electric mode, provided that charging is ensured (Raghavan and Tal, 2020).

The clear definition of sustainable finance thresholds for clean vehicles and energy vectors (e.g. in terms of tailpipe GHG emissions, as illustrated in the section on policy drivers in the third chapter) is also instrumental to ensure that economic actors can effectively align their investment decisions with government visions for clean vehicle and energy technology deployment.

Efforts to foster the technology transition towards EVs should also be framed (and communicated) as a development that is destined to switch from policy support to taxation, since clean vehicle and energy vectors will be necessary to pay (at a minimum, similar to what happens today with vehicles running on fossil oil) for the development and maintenance of the transport and energy distribution infrastructure that they require to operate.

Prioritise a transition to direct electrification and renewable energy

Technology cost developments, signals from the capital markets, and major players in the industry (chiefly automotive and logistics, but also in the energy sector) are aligned in suggesting that pathways involving direct electrification of vehicles and renewable electricity are best placed to deliver significant environmental and energy efficiency benefits,[71] while also reducing costs and increasing economic productivity. Key reasons for this are grounded in prospects for increased cost-competitiveness of EVs in many road transport applications, and for an alignment of renewables and EV grid integration with the digitalisation megatrend.

This alignment of technical assessments and market signals suggests that it is important to consider these solutions as a priority area for the development of future industrial strategies, especially (but not only) in countries that are major producers of road transport vehicles. This helps maximise benefits per unit of resources invested in the transition and increases opportunities for industry to attract capital and innovate to be competitive.

In addition to policies designed to stimulate supply and demand for clean vehicles while reducing the carbon intensity of the energy they use (discussed above), making sure that a transition to direct electrification and renewable energy is feasible will require polices that favour synergetic developments of EVs and renewable energy, fostering digital technologies. These can build on decades of work in distributed energy policy to develop a regulatory framework that allows EVs to participate in demand response mechanisms for the electricity system – including the use of their battery storage capacity for bidirectional exchanges. The policies may also include frameworks allowing consumers to have access, via digitally enabled applications, to information on the carbon intensity of the electricity they use to charge their vehicles.

Address challenges in resource efficiency and sustainable supply chains

Significant challenges may still accompany direct electrification of vehicles and renewable electricity due to shifts in the type of resources they need for a large-scale deployment. Policies that can facilitate this shift in resource demands, while still allowing governments to deliver on climate imperatives, will therefore be gaining importance. Key areas requiring policy attention are the risks associated with high geographical concentration of production for materials like lithium, cobalt, nickel, copper and rare earth elements; the environmental and social performance of their extraction; and supply/demand unbalances that may lead to price volatility.

One promising technical response to these challenges involves the integration of design features that increase material efficiency. Economic incentives and regulatory requirements for lifecycle energy and material efficiency for clean vehicles can support this, as can other regulatory instruments (such as those that regulate direct emissions from vehicle operation) that do not directly target lifecycle parameters, but are still informed by lifecycle assessments.

This aligns well with policies promoting the development of digitally enabled technologies, allowing the optimisation of many systems. For example, using EV batteries to facilitate the integration of renewable electricity into the power sector can help overcome hurdles stemming from the variability of renewable electricity generation, while minimising the overall requirement for battery materials. Digitally enabled solutions that allow vehicles to be shared are also offer opportunities (provided that they have high occupancy) to optimise material requirements needed for the same level of service.

Policies promoting the extension of battery life (and even vehicles) into second-life applications and managing their end-of-life recycling or disposal, integrating it into a long-term resource-efficiency framework in line with the concept of the circular economy, also matter. These policies can integrate requirements assuring better traceability of materials, which come with additional advantages to strengthen the use of sustainable labour and environmental practices in their supply chains and additional opportunities to minimise the carbon footprint of batteries.

Right sizing of vehicles (not only of batteries) can play a critical role in improving resource efficiency. In the case of cars, this is something that is facing increasing challenges, testified by a tendency by OEMs to focus on SUVs. Key reasons for this include a desire to focus on high-value segments of the car market to maximise profit, which accompanied a shift in consumer choices towards larger cars and leading to size increases. This choice also takes place in a context where shared mobility (enabled by digital technologies) may bring risks of a shrinking vehicle market and where the industry needs liquidity to invest in clean vehicle technologies.

SUVs have much higher lifecycle emissions than sedans due to both higher energy consumption and higher embodied emissions from manufacture. The continuing rise in popularity of SUVs and other large vehicles risks offsetting a large share of energy efficiency gains, as has been the case in the past two decades (Craglia, 2020). Using a lifecycle perspective in the development of regulations on vehicle manufacturing, in addition to vehicle use, is important to manage the risk of vehicle size increase.

PHEVs have the potential to play an important role in incentivising material efficiency given their lower requirement of new/critical materials compared with BEVs. However, due to the challenges PHEVs face in delivering effective GHG emission cuts, policies that enable the maximisation of the use of PHEVs in all-electric modes are especially important. This raises the profile of policies that can already be enabled by better connectivity, such as those that – through geofencing – can allow location-specific enforcement of regulatory requirements (e.g. for all-electric driving in urban areas).

Like other connected vehicle solutions, geofencing could be best enabled by the use of native automaker telematics. Ensuring that future-proof, interoperable and backward-compatible[72] on-board vehicle technologies will be ready to handle geofencing will become increasingly important in the context of international regulatory activities being developed on vehicle connectivity, in particular at the World Forum for Harmonization of Vehicle Regulations (WP.29) of the United Nations. Similar considerations apply to regulations governing communications for intelligent transport systems. Data collection from PHEVs on their on-road use (in particular the share of all-electric driving) is also important to ensure that type approval regulations[73] can better reflect real-world driving conditions (Plötz *et al.*, 2020; Transport & Environment, 2020).

Despite the value of these policies to maximise the benefits of PHEVs, differences in the distribution of passenger kilometres (pkm) and trips indicates that they will not be sufficient to enable all-electric driving for long-distance movements. Electrifying these in a way that is climate-friendly and resource-efficient requires the use of technologies that enable the use of vehicles with smaller batteries over long distances. Electric road systems are an interesting solution in this context for heavy vehicles, and one that deserves far greater attention and policy support, especially now that (due to Covid-19 and the related recovery packages) governments are focused on defining their infrastructure-related spending plans. Battery swapping may also be an interesting option in this context.

Prepare for a transition from fuel duties by seizing opportunities arising from increased connectivity and accelerating enabling regulatory actions

Policy interventions designed to enable a resilient transition to clean vehicles and low-carbon energy need to respond to budgetary challenges. This stems from the fact that moving towards electricity, hydrogen or any other low-carbon energy vector will inevitably erode the fossil-fuel tax base that is used to pay for road infrastructure and beyond.

In road transport, the combination of (a) carbon taxes for fossil fuels (including those used for electricity and hydrogen production) that increase predictably over time[74] and (b) shifts from taxes on fuel to taxes on distances driven (ideally integrating location-specific considerations) is best placed to help governments avoid conflicts between environmental and fiscal objectives (IEA, 2019a; OECD, 2019a; OECD/ITF, 2019).

To date, drivers of policy action on digital technologies like connectivity and automation have focused on economic opportunities (e.g. enhanced infotainment, driver services like navigation) as well as increased road safety. Road user charges have been identified as an effective way to handle government revenue shortfalls (in addition to many other opportunities for transport policies) and would also be facilitated by a digital transition. Because Covid-19 has accelerated the transition towards clean vehicles and clean energy (and digital technologies), this is the right moment to bring climate-related considerations (in particular the accelerated deployment of digitally-enabled road user charges) into the regulatory framework being developed for digital technologies for road transport vehicles.

This is especially important for the development of native automaker telematics capable of enabling road user charges so that they are interoperable across borders, future-proof and backward-compatible. GNSS and C-ITS technologies can all play a part in these developments. However, satellite-based solutions (deployed for other purposes, but also relevant in this context) have demonstrated that they can offer significant opportunities to minimise costs.

As with geofencing, achieving this will require a significant acceleration in the international regulatory activities being developed at the World Forum for the Harmonisation of Vehicle Regulations (WP.29) of the United Nations on vehicle connectivity, and the full integration of the topic of road user charging into this agenda. As in the case of geofencing, similar considerations apply to regulations governing communications for intelligent transport systems.

Greater policy efforts are also necessary to ensure greater awareness among EV owners of the need for a future transition towards a system enabling, at a minimum, the possibility of paying for the development and maintenance of the transport and energy distribution infrastructure that vehicles require to operate.

Succeeding in maintaining tax revenues may also necessitate the integration of other tax reforms. The most socially productive and politically expedient use of these revenues will depend on local circumstances. Reform options include modifying the tax mix to foster inclusive growth, e.g. through changes in personal and/or corporate income taxes; increasing investment, e.g. in education, health and infrastructure; and decreasing the level of public debt (notwithstanding the near term need for debt increase for Covid-19 responses). Revenues can also fund direct transfers to households. Using carbon tax revenues for R&D and other climate policy measures is another option (OECD, 2019a). In the longer term, as the energy system approaches full decarbonisation, taxes on decarbonised electricity and/or hydrogen could be reintroduced, if so desired (OECD, 2019a).

Include infrastructure for easy access to clean energy and digital connectivity of road transport in Covid-19 recovery packages

In the aftermath of Covid-19, most countries deployed recovery and stimulus packages, following actions designed to provide immediate relief from the impacts of the pandemic. In doing so, they often relied on debt for funding. So that this debt can be repaid, recovery and stimulus packages need to be focused on solutions that stimulate sustainable economic growth. To ensure this is a resilient process, they also need to ensure that spending for this purpose is future-proof (and therefore capable of meeting sustainability requirements).

Digitalisation and innovation are central pillars of these plans. This is because of their relevance with respect to increased productivity (and therefore growth) and the importance of infrastructure spending to enable a scale-up of the opportunities that they generate (provided that societies also have the requisite skillsets). Clean vehicles and clean energy technologies that require infrastructure spending and offer cost reductions fit well, in principle, in this framework. They also have the advantage of being less exposed to financial, climate, sustainability and energy price volatility risks.

Covid-19 recovery packages are therefore very likely to provide good opportunities to support both the digitalisation agenda and the transition to clean vehicles and clean energy, notwithstanding the need to ensure that investments are approved in a way that takes into due account costs and benefits. Given the clear prospects for cost-competitiveness and the alignment with the value of focusing consistent portions of public expenses on infrastructure, there is merit to integrating the roll-out of EV charging infrastructure (where private investments struggle to enable it) in these packages. Where existing business models show that there is room for infrastructure deployment at no cost to governments (e.g. for EV chargers and digital communication networks with higher rates of utilisation), public spending is likely best suited if addressed to cases subject to less-predictable rates of returns for investors (e.g. for infrastructure needed to ensure minimum requirements in terms of geographical distribution, but subject to lower frequency of use). Electricity network reinforcements (paired with costs before the meter which can reasonably be shared across all its users) are also good candidates for Covid-19 spending on infrastructure, as they can also open up opportunities for the electrification of other energy end-uses.

Infrastructure investments are also essential for the deployment of electric road systems (ERSs), but the need to mitigate investment risks requires increased consensus among stakeholders that ERSs are a solution that can be widely adopted. Similar considerations apply to hydrogen refuelling, since the use of hydrogen in road transport requires improved prospects for cost parity and other policy action (e.g. on the certification of GHG emissions from different pathways, along with regulatory requirements for low-carbon production) to ensure that a switch to hydrogen could deliver lifecycle GHG emission savings.

Using Covid-19 recovery plans for the deployment of connectivity infrastructure to support the cost-efficient application of road user charges could also help to stimulate a more resilient transition to clean vehicles and energy. This is due to the major opportunities offered by road user charges to respond to the material demand and revenue shortfall challenges, as discussed above. This deployment also comes with additional advantages for other sustainable development goals, such as increased safety, lower noise, and improved liveability of urban environments, thanks to the possibility of managing congestion and raising funds to finance public transport.

Prepare for the impact of the sustainable mobility transition on jobs, required skill sets and social equity

Key determinants of macrotrends discussed in this report point to a concurrent set of shifts towards electrification and renewable energy. It is reasonable to expect that these shifts could be strengthened further by a parallel transition towards digitalisation and automation. This analysis also points to a likely acceleration of all these trends due to Covid-19. Despite remaining uncertainties, this suggests that it is also likely that workers in the automotive and the energy industries risk being significantly exposed to a broad set of transitional impacts.

These considerations are robust, even if there are a number of remaining uncertainties and region-specific aspects, a number of which depend on the type of policy developed by governments. Taking this into account, it will be important for governments not only to enhance their capacity to better understand the process, but also to secure adequate means of financing and developing a holistic package of measures aiming to manage this transition. Foreseeing the challenges – by developing foresight tools that will allow them to have a more granular understanding of implications for their and other jurisdictions – will be essential.

This means anticipating the impacts on jobs and a need for a transition in skillsets, but also extends to ensuring that the transition is equitable and inclusive. It will be critical to design resilient policies that ensure not only that workers at risk of unemployment are adequately supported, but also that the shift to cleaner and more environmentally sustainable mobility (including digitally enabled innovations) brings benefits to all sections of society without exacerbating inequalities. This has already started to happen in major economies, which have paired actions providing immediate relief from the negative impacts of the pandemic with recovery and stimulus packages integrating the creation of green jobs.

This transitional challenge is not limited to the automotive sector; it encompasses the entire energy sector. Factoring in the budgetary allocations needed to address it, governments will need to ensure that these transition plans can be effectively financed. This could be enabled by major tax reforms allowing the raising of revenues (see e.g. the OECD/G20 Inclusive Framework on base erosion and profit shifting, or BEPS) and the application of a global minimum threshold for corporate income taxes of large multinational enterprises.

Additional solutions include a greater reliance on technology options capable of bringing together key advantages for transport decarbonisation, along with a smoother transition in jobs and skillsets. PHEVs may be an interesting part of the solution in this respect, provided that other policy and technology developments (such as those discussed earlier for geofencing and the better enforcement of all-electric driving in cities) can allow them to deliver effective GHG emission cuts and other sustainability benefits.

Accelerate the development of other low-carbon technologies

Direct electrification is well placed to deliver a large share of the GHG emissions reductions in road transport. However, technological progress in other low-carbon technologies still needs to be accelerated. These technologies include low-carbon hydrogen and synfuels (in particular electrofuels), other forms of carbon neutral fuels and some low-carbon sustainable biofuel pathways (at least in specific global regions).

Alternative low-carbon technologies can best be supported by a focus on those that have the best sustainability credentials (in particular on their ability to reduce GHG emissions, minimise land use requirements, avoid high thermodynamic losses through their supply chain and ensure that labour conditions for the extraction of resources avoid human rights violation, conflict or financial crimes) and the best potential to compete with direct electrification on cost. Research and innovation funds can facilitate progress for low-carbon hydrogen and synfuels (in particular electrofuels), other forms of carbon-neutral fuels, and some low-carbon sustainable biofuel pathways, in addition to support for direct electrification technologies.

These alternative low-carbon technologies have greater scope to be employed in shipping and aviation, as well as other energy end-uses (such as chemicals and even steelmaking, in the case of low-carbon hydrogen). Accelerating innovation to increase their cost competitiveness can help the technologies supplement direct electrification and renewable electricity. For road transport, this is most relevant to address two areas in particular: legacy vehicles and applications that are most challenging for direct electrification. Further opportunities may arise from the combination of different subsets of technologies, allowing the potential for each to be maximised. Examples include hybrid solutions that integrate direct electrification for shorter trips or specific portions of long-distance movements, and other alternatives as a complement for long-distance transport. Optimal options may also vary across different geographies.

Accelerating the development of alternative low-carbon technologies is also important for sectors (in particular the oil and gas industry) that are particularly exposed to a shift towards direct electrification and renewable energy. Fostering innovation and a greater alignment with GHG emission reduction capacity, cost reductions, energy and resource efficiency will be important, in this context, to mitigate risks of asset and job stranding, as well as geopolitical impacts.

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Appendix A. Lifecycle emissions analysis

This Appendix details the assumptions made for Figure 1. The bars of Figure 1 represent the GHG emissions from vehicle production (with batteries separated), well-to-tank emissions and tank-to-wheel emissions. It does not include emissions associated with end-of-life treatment due to the wide variety of accounting methodologies, regional heterogeneity and limited availability of data.

The emissions intensities of material production are sourced from GREET 2018 assuming default values. The material composition of medium cars and SUVs are also sourced from GREET 2018. The material composition of LCVs is assumed to be the same as SUVs (scaled by vehicle weight). The material composition of buses and trucks is sourced from (Ricardo-AEA, 2015).

When comparing vehicle technologies, it is essential to compare vehicles of similar size segments. Global average vehicle fuel economy (NEDC) by powertrain for medium cars, SUVs and LCVs is sourced from (IEA and ICCT, 2019). These are converted to 'real-world' values by multiplying by 134%, 136% and 135% for gasoline and diesel ICEV and HEV, respectively (Craglia, 2020); FCEVs and BEVs are multiplied by 120%. Separate data on the fuel economy of PHEVs driving in ICE mode and EV mode is not widely available by vehicle size segment. The fuel economy of PHEVs is therefore calculated using the energy consumption of an HEV (which also benefit from regenerative braking) and a BEV and weighted by the share of electric driving (utility factor). Default utility factors for PHEVs are 50%, broadly in line with (Plötz *et al.*, 2020); this is varied in Figure 2 for passenger cars. Medium cars and SUVs are assumed to run on gasoline; all other vehicles with an ICE are assumed to run on diesel. Average fuel economy of buses is sourced from (ADEME, 2015; Movia, 2015; FCH and Roland Berger; 2017). The fuel economy of trucks is sourced from (ICCT, 2018; Mojtaba Lajevardi, Axsen and Crawford, 2019; Ricardo Energy & Environment, 2020).

Table 10. Assumed energy efficiencies (MJ/km) by vehicle type and powertrain

	BEV	FCEV	HEV	ICEV
Bus	4.9	10.3	11.4	13.4
Heavy Truck	6.2	12.5	16.4	17.6
SUV	0.9	1.9	2.6	3.6
LCV	0.9	1.9	2.6	3.6
Medium Car	0.8	1.5	2.1	2.7
Medium Truck	3.0	6.1	6.9	8.6

Battery capacities by vehicle and powertrain are shown in Table 11. Battery capacities for medium cars, SUVs and LCVs are market averages sourced from (EV Volumes, 2021b). Battery chemistries for passenger cars and LCVs are assumed to be NCM 622; buses and trucks are assumed to use LFP. Battery energy densities and emissions factors from GREET 2018.

Table 11. Assumed battery capacities (kWh) by vehicle type and powertrain

	BEV	FCEV	HEV	ICEV	PHEV
Bus	325	20	19	0	-
Heavy Truck	500	27	27	0	100
SUV	90	2	2	0	20
LCV	40	3	3	0	20
Medium Car	60	2	2	0	12
Medium Truck	300	7	7	0	30

Average annual mileages of vehicles (and assumed lifetime): 12 100 km for medium cars (16 years), 15 100 km for SUVs (16 years) from (Craglia, 2020) for the UK; this is in line with OECD data (ITF, 2020a). 25 000 km for LCVs (15 years), 50 000 km for medium trucks (9 years), 90 000 km for heavy trucks (7 years), 42 000 km for buses (ITF, 2020a) (9 years).

The carbon intensity of the electricity used to power vehicles (which is projected to decarbonise both globally and at different rates by country) is weighted by vehicle lifetime and mileage. A medium car purchased in 2020 with a lifetime of 16 years will use electricity until 2035. Furthermore, its mileage will decrease overtime, the average emissions intensity of the electricity it uses needs to be weighted accordingly. The annual mileage of medium cars and SUVs is assumed to decrease by 3.3% of its sales year mileage every year (Craglia, 2020), the mileage is assumed to decrease annually by 5%, 5%, 9.1%, 9% for LCVs, medium trucks, large trucks and buses, respectively, based on (Pejić *et al.*, 2019). Grid carbon intensities for the world, USA, EU28 and China are assumed to follow IEA ETP 2020 STEPS scenario values. Further accelerated adoption of renewables in the higher ambition IEA SDS scenario would further increase emissions reductions.

Importantly, the analysis of Figure 1 shows an estimate of global averages for all vehicles and powertrains. For BEVs, the grid carbon intensity is varied to reflect values for the USA, European Union and China to highlight the importance of the electricity carbon intensity. Vehicle production emissions are maintained constant at global average numbers. Regional points are not included for PHEVs (as mentioned above there is little data on the average fuel economy of PHEVs in ICE mode) or other technologies.

Figure 1 also includes the emissions intensities of BEVs powered by renewable electricity and FCEVs powered by hydrogen produced by steam methane reformation (SMR), the dominant technology for hydrogen production today, and from renewable electricity and electrolysis. The emissions intensity of SMR hydrogen is sourced from GREET (13.71 $kgCO_2e/kgH_2$). The emissions intensity for renewable electricity is not included in GREET and is therefore sourced from a comprehensive review of 153 LCA studies by (Nugent and Sovacool, 2014) who found that median lifecycle emissions intensities of renewable wind and solar PV electricity generation are 16 gCO_2e/kWh and 42 gCO_2e/kWh, respectively. In this report, renewable electricity is therefore assumed to have a GHG emissions intensity equal to 29.5 gCO_2e/kWh (the average of wind and solar). (Parkinson *et al.*, 2019) used the estimates of (Nugent and Sovacool, 2014) to develop estimates of the lifecycle emissions intensity of hydrogen produced by wind and solar PV electricity and electrolysis of 0.88 $kgCO_2e/kgH_2$ and 2.21 $kgCO_2e/kgH_2$ respectively. This report assumes renewable hydrogen has an emissions intensity of 1.55 $kgCO_2e/kgH_2$ (the average of wind and solar).

Notes

1 And therefore excluding impacts associated with the construction of new material processing plants.

2 Energy production excludes impacts associated with the construction of new capacity (e.g. for renewable electricity) and the end-of-life treatment of existing capacity (e.g. for fossil fuels). The results also integrate losses occurring during charging/refuelling and energy distribution.

3 A total cost of ownership (TCO) analysis provides comparative, case-specific information on the cost of alternative vehicle options per vkm. This calculation method determines the overall cost of owning and using a vehicle across its useful life, in a single indicator, in essence the cost borne by the vehicle owner per vkm. Key parameters included in the TCO assessment for this study include purchase price, vehicle depreciation (and therefore residual value of the vehicle once it is sold), fuel costs, and maintenance and insurance costs. The TCO calculation, which also takes into account interest rates that discount future expenditures, is well suited to integrating costs due to new energy-distribution infrastructures, where they are relevant. The TCO approach considers that owners do not usually keep their vehicle over an entire lifetime by accounting for depreciation and factoring in residual reselling values of vehicles. They also factor in vehicle taxes (e.g. circulation and/or registration), licensing and tolls. In the analyses cited here, fuel taxes are included, but not economic incentives on electric vehicle purchase. Key uncertainties involved in TCO analyses and electric vehicles include potential changes in consumer habits resulting from the use of electric vehicles which may stimulate different annual mileage or vehicle lifetime.

4 An opinion piece by a major European truck manufacturer recently argued that, unlike passenger-car fast chargers, which have extreme vacation peaks to cater for, fast chargers for trucks will have the advantage of more constant and plannable traffic volumes (Gründler and Kammel, 2021).

5 In the UK for example, 7 230 km of motorways and main roads (approximately 2.4% of the total national road network) carried almost 70% of national HDV road traffic in 2019 (UK DfT, 2019). Similar estimates for Germany show 60% of HDV tonne-kilometres are carried on the most intensively used 3 966 km of motorways (Wietschel et al., 2019).

6 If trucks use ~1.7 kWh/km, then 300 km range would require ~500 kWh, which could be delivered in half an hour with 1 MW chargers.

7 Overnight charging over long time periods also offers the possibility of accessing lower-cost electricity during periods of low demand and offer grid balancing services (ITF, 2020c).

8 Overhead contact lines connected via pantographs to trucks have an advantage over competing options in the ERS context, thanks to the progress made in standardising the technology to enable competition across suppliers. Overhead catenaries are already competitively supplied for rail and trolleybuses, enabling industry competition to extend into motorway applications. The vehicle to overhead catenary connection has also been the subject of the development of technical specifications (being finalised) that enable competition without a license. Additionally, they are the only ERS solution that, not being integrated into the road, does not have a direct impact on road maintenance activity or on the durability of road infrastructure (PIARC, 2018).

9 Estimates of the cost of an ERS range between 1.7 – 3 million per kilometre (in both directions) (Wietschel et al., 2017; Hacker, 2020; Borjesson, Johansson and Kågeson, 2021). This is a significant investment but in the context of road infrastructure is not extreme, (Hacker, 2020) put the cost of covering 4000 km of motorways in Germany with overhead ERS at approximately 12.2 billion euro, equivalent to approximately 18% of truck toll revenues over a 15 year period of construction.

10 Public investment would also help to address additional challenges that might arise if the ERS system were privately owned but the road network were public, creating split incentives. If diesel trucks are still available, their presence creates competition with ERSs and limits the user charges that firms might apply to the systems. In the long term, however, when diesel trucks are no longer available, BEVs may provide the market competition necessary to avoid excessive user charges; if not, an ERS may need to be publicly regulated to avoid monopolies.

11 Research on this subject shows that there are indeed economies of scale in the size and spread of the network of ERSs – up to a threshold, above which further expansion of the network yields marginally lower benefits due to lower traffic (Borjesson, Johansson and Kågeson, 2021).

12 This could also help drivers avoid particularly challenging and expensive stretches of road (e.g. tunnels, bridges), though battery capacity on the vehicle would have to be suitably large to deal with non-electrified road segments.

13 Despite these risk mitigation options, like many large infrastructure projects, an ERS faces a number of other risks. The first is that construction and maintenance costs are higher than expected. Another is related to uncertainty about whether technical improvements to BEVs will make them ever cheaper and more viable for long-distance routes. These risks mean that investment into infrastructure is likely too risky for private firms alone, requiring public investment.

14 The retrofit is not a substantial issue for trucks that have already an electric drive train (this includes PHEVs, BEVs and potentially even FCEVs). The main challenge would be the additional space required on the vehicle behind the driver cab. 'ERS-ready' vehicles would need to include an additional 50-100 cm of space between the cab and the trailer to allow for the pantograph retrofit (Scania, 2021). This can help address challenges related to frequency of use (and therefore help recover investment costs, provided that it can reduce the total cost of ownership of trucks vs. cases without ERS retrofits). However, it needs clear signals on the roll-out of the infrastructure to become a reality. The outline of a vision to roll out ERSs, combined with commitments from governments to start deploying the infrastructure, will likely be a prerequisite for retrofit-ready EVs to be competitively commercialised by multiple OEMs. This is because truck owners would have little interest in them without these. OEMs also need sufficient confidence to agree to move towards large-scale industrialisation of retrofit-ready vehicles. Additionally, the industrialisation of retrofit-ready solutions that are capable of running on conventional fuels (like PHEVs) is subject to lower risks than those faced by technologies that depend on the availability of dedicated/novel charging/refuelling infrastructure (BEVs and FCEVs). Voluntary action from OEMs on this could therefore play an important role in convincing policy makers to commit to ERS roll-out plans.

15 A similar cost-benefit analysis for a range of ERS configurations in Sweden (Borjesson, Johansson and Kågeson, 2021) showed that the ownership of the network and the charges applied for its use can have important effects. If the ERS user charges are set to maximise social benefits, then usage revenues can cover network maintenance and reduce CO2 emissions by a third (assuming diesel trucks fitted with ERS). Conversely, if the user charges are set to maximise profits, both the infrastructure and maintenance costs can be repaid but the higher usage costs would reduce the use of the network and reduce the CO2 savings by 20-25%. Under all scenarios the authors found that the societal benefits of electric roads are larger than their societal costs, with the benefits arising principally from lower operating costs for truck operators and lower carbon emissions.

16 Despite considerable reductions in the cost of fuel cells over the past decade (Yumiya, 2015a), high costs remain one of the hurdles faced by hydrogen fuel cell vehicles. Estimates by the US Department of Energy (DOE), based on publicly available documentation and expert opinions drawing from experience on the Toyota Mirai system design – described in (Yumiya, 2015b) – indicate that manufacturing an 80 kW automotive fuel cell system with commercially available technology costs USD 230/kW at 1 000 systems per year. At this production scale, the US DOE estimates also that the fuel cell stack account for two-thirds of the total system cost (Wilson and Kleen, G. Papageorgopoulos, 2017). Toyota aims to scale its Mirai production from 3 000 annual units to 30 000 units in 2021 (Tajitsu and Shiraki, 2018; Inagaki, 2020). If successful, the assessment from (Wilson and Kleen, G. Papageorgopoulos, 2017) suggests that this strategy could bring costs of the fuel cell system down to USD 70/kW. The scale increase plays a crucial role in achieving this, according to (Wilson and Kleen, G. Papageorgopoulos, 2017), even if technological progress is also a factor expected to contribute towards this cost reduction. Costs of storage tanks are estimated at USD 14-18/kWh of useable hydrogen storage (Vijayagopal, Kim and Rousseau, 2017), and could come down to USD 8-11.5/kWh in 2045 (Vijagopal and Rousseau, 2017). These values represent costs of around USD 3 500 today and USD 2 300 in the future for a storage tank of 225 kWh on a car, enabling a range of 600 km. They translate to costs of around USD 27 700 today and a potential reduction to about USD 16 700 for a storage tank of 1 800 kWh, estimated to enable a 700-km range for a heavy-duty truck.

17 Since trucks have a longer range and travel on more centralised, dense travel corridors, hydrogen refuelling stations for trucks would have to be significantly larger in size than passenger car equivalents. They would require roughly 10 times more fuel to be distributed per vehicle refuelling session, which would significantly increase the pressurised hydrogen storage requirements at each station.

18 In addition to these challenges, hydrogen refuelling infrastructure for heavy vehicles is not yet commercially available. Refuelling protocols for heavy vehicles with 70 MPa on-board hydrogen storage will have to be incorporated into international standards. This is also the case for specific refuelling protocols and nozzle specifications suitable for the hydrogen flows needed for trucks (ITF, 2020d).

19 The availability of biomass for energy and industrial use without adverse consequences for food supply, land-use change (e.g. deforestation), biodiversity and carbon sequestration in nature has been the subject of several assessments. Estimations of sustainable biomass availability vary based on a wide variety of assumptions (e.g. product mix, yield/productivity, fertiliser use) and also on the basis of the emphasis given to sustainability. An estimation of a sustainable technical potential up to 100 exajoules (EJ) found a higher degree of agreement in the scientific community (Creutzig et al., 2015), and work by the Energy Transitions Commission points to values at the lower end of a 45-70 EJ range (ETC, 2020).

20 The main differences between the analyses of Haugen et al. (2020) and Transport & Environment (2020) are that renewable electricity is considered to be AC in the former, meaning AD/DC conversion losses are included.

21 The work of the Energy Transitions Commission also points to stronger priorities for biomass use as a feedstock for the chemical industry and the production of biofuels for shipping and aviation, even if it does not rule out some use for heavy duty road transport (ETC, 2020).

22 Technical standards are technical texts, generally voluntary in nature (unless adopted or mandated by law), containing detailed information on test and measurement procedures, developed to ease exchanges and create a common understanding between different industrial players.

23 Technical regulations are similar to standards, but they integrate value limits, along with test procedures, and are legally binding.

24 This acronym is used here to refer to BEVs, PHEVs and FCEVs.

25 A German consortium recently applied for funding from the German Ministry of Transport (BMVI) to work on a demonstration route on the A2 freeway between Berlin and the Ruhr area. The aim is to start of real-life logistics operations in the fall 2023 (VDA, 2021).

26 ERSs based on overhead catenaries have the advantage of the possibility to build on the experience and standards already developed for other similar cases (e.g. in railways and for trolleybuses).

27 In particular, electric vehicles are found to produce lower emissions from brake wear (thanks to regenerative braking) and higher emissions from tyre wear (due to larger weight).

28 These include Canada (Prime Minister of Canada, 2020), China (Government of China, 2020a), Europe (EC, 2021a), Korea (UNFCCC, 2020a), Japan (METI, 2020b;), the United Kingdom (Government of the United Kingdom, 2020b) and the United States (White House, 2021c), following the acceptance of the Paris Agreement (White House, 2021f).

29 The “Action plan for peak emission by 2030”, announced in China as an upcoming follow up of its 14th five-year plan (a comprehensive policy blueprint released by China every five years to guide its overall economic and social development, and the first that follows China’s net-zero pledge) is also expected to promote low-carbon transportation through energy efficiency and modal shifts to railways, water transfers and multimodal transportation (Ministry of ecology and the environment, 2021).

30 A summary of pledges and other announcements illustrating objectives and targets for EV charging (and FCEVs refueling) infrastructure roll out, as of mid-2021, with a focus on major automotive markets, is available upon request.

31 In transport, the gap between road fuel taxes and other fuel taxes is particularly pronounced when comparing road transport to international aviation and maritime transport, where energy use is not taxed (OECD, 2019a).

32 Other indirect effects on prices (also weak) derive from regulatory and financial mechanisms, such as priority dispatching and feed-in tariffs, that favour low-carbon power generation sources, as they may increase system costs.

33 This is due to lower thermodynamic losses for hydrogen produced from electrolysis and renewable electricity in comparison with hydrogen produced from electrolysis and electricity from fossil energy. It is also due to comparable losses in hydrogen production from electrolysis and from steam methane reforming of natural gas (without carbon capture and storage), along with differences in GHG emission between renewables and natural gas. Flat taxes on hydrogen from natural gas with carbon capture and storage could also reduce taxation per unit energy on primary natural gas, due to additional energy efficiency losses. The effect on carbon taxation would depend on the residual emissions and the way additional energy requires for carbon capture and storage is sourced.

34 The overview, compiled until mid-2021, is available upon request.

35 Allowing to partially or fully cover interest payments on loans.

36 Co-investment helps share commercial risk between the public sector and private partners.

37 Where governments keep cash deposits to make interest and principal payments in case a private borrower fails to make scheduled payments.

38 Where a public agency agrees to take on a lower priority position for debt repayment than senior debt holders, allowing senior debt holders to be repaid fully before other debt holders. This eases the borrower's access to private capital.

39 This consists in government insurance agreeing to make bond payments in case the issuer defaults.

40 Where governments act as a guarantor for the private sector to obtain a market loan with a lower interest rate. These can also include export credits for technology, where governments can lend directly to the private sector.

41 While European governments have tended to favour differentiated taxation based on g CO2/km at the tailpipe, China has also introduced stronger signals, such as those given by the auction- and lottery-based systems (or a combination of these) for an allowance to get a license plate. Frequent episodes of very intense urban air pollution helped ease the acceptance of these strong measures (Jin et al., 2021).

42 Detailed tables are available upon request listing, for the main automotive markets. These cover: (a) current economic incentives for clean vehicle supply and demand and (b) energy distribution infrastructure.

43 The latter are more frequently applied to vehicles coming to the single market and apply across the whole European economic area.

44 In addition to the initiatives outlined in the ITF paper (2020e), in October 2020 China released a proposal for battery reuse and recycling management with the objective of optimising resource use. The scope of the proposal includes traceability across the entire battery lifespan (MIIT, 2020). In Europe, a proposed regulation on batteries released in December 2020 addresses sustainability-related aspects, including: carbon footprint (initially via a declaration, followed by comparative labelling and a minimum threshold); minimum shares of recycled cobalt, lead, lithium and nickel; supply chain due diligence, based on OECD guidance; and the facilitation of repurposing and traceability (battery passport and database) (EC, 2020c; Dilara, 2021). The Regulation establishing a carbon border adjustment mechanism in Europe proposed by the European Commission (EC, 2021l) also addresses aspects related with the carbon footprint of materials and products used in manufacturing of batteries, but not the batteries as a final product. Also in 2020, Korea issued regulations aimed at facilitating the reuse and recycling of used batteries from electric vehicles (Yonhap, 2020). In the United States, the recent Executive Order on America's Supply Chains places greater emphasis on risks related to the availability of critical materials (White House, 2021a).

45 Critiques of the carbon border adjustment mechanism point to challenges with its complexity (especially for complex products) and the possibility for companies to adopt measures that would not lead to increase adoption of lower-carbon technologies for the global market, but rather towards the creation of a low-carbon island or separate trade blocks (Tsafos, 2020; Liebreich, 2021). They also point to greater benefits, for climate change mitigation and global wealth increase through economic growth, likely to result from global low-carbon product standards and a carbon tracking system developed in a global free trade framework, calling for greater global engagement towards it (Liebreich, 2021).

46 In China, access restrictions for motorcycles were among the measures leading to the mass adoption of electric two-wheelers (IEA, 2018a).

47 In the European Union, the Energy Performance of Buildings Directive will be revised with a view to increasing the goals for charging points in buildings (EC, 2020e).

48 The FSB is an international body comprising representatives of the central banks and finance ministries of major global economies as well as intergovernmental organisations. It monitors and makes recommendations about the global financial system (FSB, 2021a, 2021b).

49 These are designed to help companies provide better information to support informed capital allocation. They are structured around four organisational areas: governance, strategy, risk management, and metrics and targets (TCFD, 2017).

50 Stranded assets are assets that at, some time prior to the end of their economic life, are no longer able to earn an economic return, as a result of changes associated with the transition to a low-carbon economy (CarbonTracker, 2021b).

51 These considerations may also help explaining the changes in the market capitalisation of automakers and energy companies that were reluctant to make investments allowing them to embrace a technology transition, in favour of competitors – including companies with far smaller outputs in terms of vehicles manufactured, energy produced or energy capacity installed, but expectation for a significant growth in market relevance for their products.

52 EV chargers are commonly classified by charging speed and connection type, and public charging stations are either level 2 (slow chargers) or level 3 (fast chargers). Fast chargers can be more convenient for users and crucial for en-route charging on long-distance trips. For instance, charging an EV with a 52 kWh battery will take 7 hours at a 7.4 kW slow charger but just about 1 hour at a 50 kW DC fast charger. However, fast chargers come with significantly higher technology costs than slow chargers and their load profile may be less suitable to complementing renewable generation curves and aiding grid integration of EVs if compared to slow chargers. Most PHEVs are not enabled for fast charging. Electric trucks and buses (i.e. electric heavy duty vehicles) require dedicated charging infrastructure with high power capacity due to their large batteries.

53 Fleet electrification programs also hedge from regulatory risks as more and more cities introduce local access restrictions to address air pollution and as countries have announced ICE phase out dates to ensure a climate-compliant development of the transport sector.

54 These are the new generation of on-board mandatory digital recorders, used to enforce European legislation on professional drivers' driving and resting times.

55 The Eurovignette defines rules for Member States willing to introduce road charges for heavy vehicles, so that the cost of constructing, operating and developing infrastructure can be covered through tolls. Charges can be complemented by a component aiming at reducing pollution from road transport and can be modulated to take account of road congestion. The 2020 agreement extends the scope to buses, vans or passenger cars and allows the introduction of differentiations of heavy-duty vehicles charges based on CO2 emission performance. The European Electronic Tolling Directive (EETD) eases the deployment and application of electronic tolls, not only ensuring the interoperability of electronic road toll systems, but also facilitating the cross-border exchange of information on the failure to pay road fees in the Union.

56 Four states (Kentucky, New Mexico, New York, and Oregon) (NC FIRST Commission, 2020), as well as New Zealand (AA Motoring, 2021) collect weight- and distance-based fees from heavy trucks, but these are not enabled by ITS technologies.

57 Key solutions allowing system optimisation using digital technologies range from specific technical aspects (e.g. for the design of vehicle and powertrain components, on-board systems and manufacturing processes, to enable predictive maintenance) to large-scale systemic improvements (enabled by better digital connectivity, artificial intelligence and automation), such as those pointed out by several ITF publications (ITF, 2021b) – to the point that this could even result in a redefinition of sales though changes in the way consumers approach vehicle purchases.

58 A number of projects and pilots have been launched in Sweden to support the development of geofencing policies, with the objective of making cities more sustainable and safer. These include measures requiring a switch, for PHEVs, to all-electric driving mode in cities. In the context of these initiatives, the city of Gothenburg has started to apply geofencing to make buses on specific routes automatically switch to the electric engine on certain digitally limited stretches of the routes. In Stockholm, geofencing requiring a switch to electric mode when entering emission-sensitive areas was employed in vehicles used for the distribution of goods (Smart city Sweden, 2017; Figg, 2020). Several OEMs have also recently launched projects to reduce inner-city emissions with PHEVs through geofencing. For example, Ford launched a trial in London, Valencia and Cologne using geofencing and blockchain to cause its commercial PHEV fleet to switch to electric mode when entering an environmental zone (Ford, 2019). BMW and Fiat also have projects designed to enable cities to influence and monitor driving behaviour within low-emission zones (Haaf, 2021).

59 These include IoT sensors on all railroads and the development of fourth-generation networks for railways.

60 One example is the 5GCar consortium, which involves 13 key players in the telecom and the automotive industries, including equipment suppliers and manufacturers. The consortium seeks to demonstrate the potential of 5G to support the implementation of vehicle-to-everything (V2X) communication. Audi, BMW and Volkswagen have partnered with Ericsson, Huawei and Nokia to implement large-scale testing of cellular technology for connected car use (ABI Research, 2020).

61 An overview of regulations and strategic plans to address risks associated with autonomous vehicles across major automotive markets is available upon request.

62 A taxonomy developed by the Society of Automotive Engineers (SAE) differentiates between various autonomous driving features and adopts an organisation divided into six levels, from 0 to 5. Level 3, Conditional Driving Automation, is the first level in which automated driving features can drive the vehicle, although drivers need to be ready to drive when features require it (SAE, 2018).

63 ITU standards also address the security of over-the air software updates to connected vehicles, as well as other aspects related to vehicular multimedia gateways and "infotainment" systems (ITU, 2020b).

64 This precedent could be useful for regulating other industries involved as suppliers for BEV batteries to verify adherence to the usual principles for human rights, work conditions and environmental considerations while extracting raw material etc.

65 The ILO's World Employment and Social Outlook 2018 also indicates that the broader sustainability transition in the energy sector is likely to have an overall positive impact on employment globally (ILO, 2018).

66 Cambridge econometrics (2018) estimates the evolution of employment in the automotive sector by considering several scenarios for Europe which assume different vehicle sales mixes in the coming decades. In the TECH scenario, jobs in the automotive sector increase through 2030 due to greater sophistication in ICEs and an increased deployment of hybrids, plug-in hybrids and fuel-cell vehicles. However, by 2050, the net impact jobs is negative as hybrids are increasingly replaced by battery-electric vehicles, which are less labour intensive. In another scenario called TECH PHEV, where plug-in hybrids remain dominant for longer, the net employment impact in the sector is positive in 2050. It should be noted that this scenario creates less employment than the TECH scenario in the wider economy, since consumers spend more on imported fossil fuels. Hence, the net effect on employment for different regions and countries is dependent on the mix of these various technologies and also on the extent to which they are imported or produced.

67 Within countries, the OECD analysis shows that employment growth has been much lower in jobs at high risk of automation (6%) than in jobs at low risk (18%). At the same time, low-educated workers have become increasingly concentrated in high-risk occupations, and occupation-level job tenure (i.e. how long a person has been in his/her present job) has fallen more in occupations at high risk of automation.

68 The potential impact on the automotive aftermarket sector is perhaps underappreciated. In general, the requirements of aftermarket automotive services can be expected to shift from lower-skill, routine servicing tasks such as changing ICE oils and filters (which would be eliminated) towards tasks involving EV powertrain diagnosis and repair of electronic components (which would increase). Another change may come from the increasing integration of software with vehicle systems, which could make repairs by third-party providers more difficult. Finally, a small but high-value part of the aftermarket today is devoted to performance enhancement of ICE vehicles. Some of those skills would be depreciated in an EV environment and would require new skills focused on software engineering.

69 Collective bargaining coverage is an indicator of the extent to which the terms of workers' employment are influenced by collective negotiation. It is the coverage rate, i.e. the number of employees covered by the collective agreement, divided by the total number of wage and salary-earners.

70 Other broader examples include Sweden's commitment to financially support the creation of such jobs to reduce unemployment within a green stimulus package (Swedish Ministry of Enterprise and Innovation, 2020). Similarly, Spain's "Plan Del Carbon" is a strategic plan aimed at support mining regions, as nearly all coal mines will be shut down over the next decade (MITECO, 2018). The measures include early retirement schemes, local re-employment in environmental restoration work and reskilling programs for green industries (WRI, 2020).

71 This consideration is in line with a growing consensus that electrifying final energy consumption is essential to reduce gasoline consumption and decarbonise energy use from road transport vehicles – especially now that electricity generation from low-carbon energy sources is proving to be cheaper than other forms of electricity production (IEA, 2020g), installed capacity of low-carbon electricity is outpacing other generation options (IRENA, 2021) and the share of electricity produced from low-carbon sources is increasing, following years of stagnation (Ritchie, 2021).

72 I.e. capable of working effectively with devices deployed previously.

73 Type approval or certificate of conformity is granted to a product that meets a minimum set of regulatory, technical and safety requirements.

74 Creating stable, predictable and credible carbon-price signals is key to providing citizens and businesses with certainty for their long-term investment decisions. The long-run business case of low-carbon technologies will improve as expectations about future carbon prices increase. Agreeing on predictable rate schedules not only makes sense in terms of ensuring fiscal sustainability; it also decreases the risk of stranded assets in the future (OECD, 2019a).

Cleaner Vehicles

This report evaluates policies for transitioning to clean vehicles and clean energy for road transport. The review includes measures that can help to scale up the transition quickly and instruments to manage it. It analyses technologies for clean passenger cars, light commercial vehicles, buses and trucks, and identifies solutions that deliver the greatest benefits. It reviews the policies for the promotion of clean vehicles currently in place and assesses the response of private sector stakeholders. The study specifically takes account of increasing digital connectivity and automation.

International Transport Forum
2 rue André Pascal
F-75775 Paris Cedex 16
+33 (0)1 73 31 25 00
contact@itf-oecd.org
www.itf-oecd.org

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